The Integration Of Geometric Information Within Design and Manufacture

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Dedication

To my parents

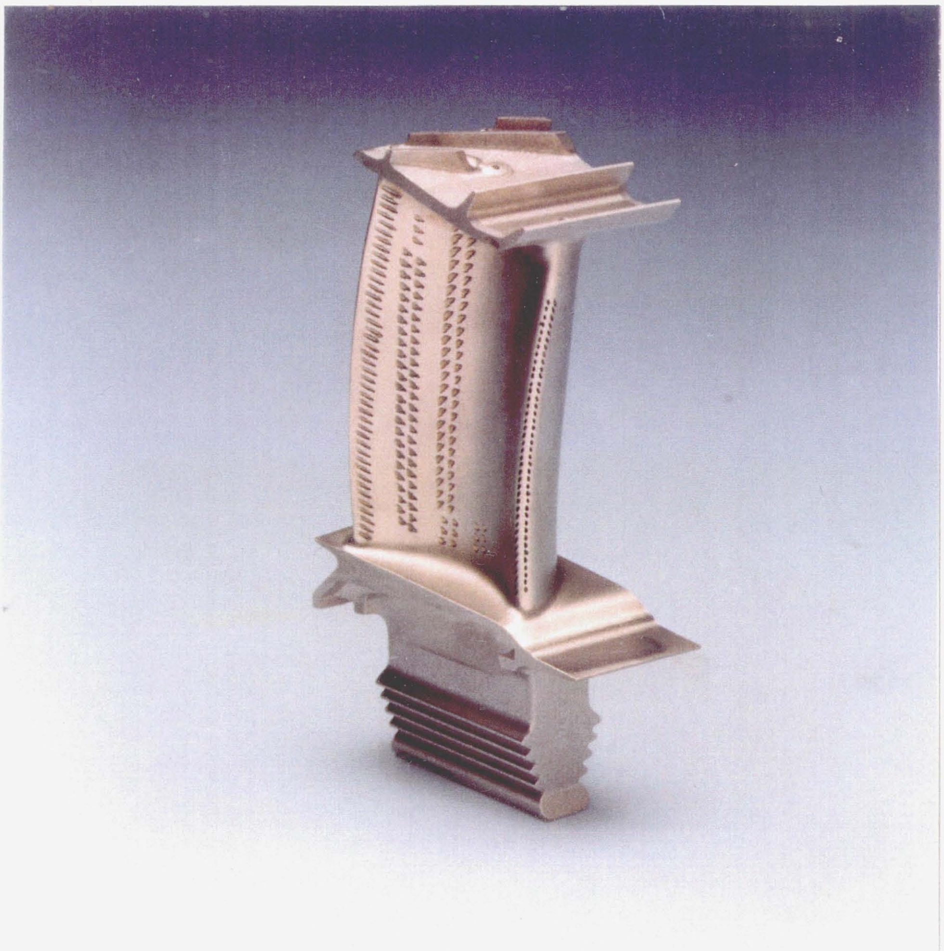

Plate 1: The RB211-524 Strategy 3 High Pressure Turbine Blade

Abstract

Design and manufacturing lead times, within manufacturing industry, represent a severe problem as they reduce a company's ability to rapidly meet market needs and they are a time of negative cash flow.

In this thesis the principles of Simultaneous Engineering and Taguchi's Quality Engineering have been used to suggest improvements to the procedures adopted for the design and manufacture of one of the most complex components that is currently produced: the high pressure gas turbine blade. The analysis has attempted not only to reduce this component's lead time but to improve the whole process of its design and manufacture.

The analysis concluded that there were large divisions between the design and manufacturing activities and very little accountability between design intent and manufacturing capability. It was therefore suggested that a far higher level of integration between design and manufacturing be achieved by the adoption of Simultaneous Engineering techniques. It was also suggested that improved accountability would be provided for by a systematic approach to feeding manufacturing capability into design. As a result an 'Integrated' Inspection system was developed which provides for the measurement of turbine blade surfaces and the analysis of the inspected results. Extensive error calculation and presentation facilities are provided for, including three dimensional best fitting.

Within the integrated inspection system the results of an inspection are modelled as surfaces, which may be readily passed to the design areas for functional analysis. For it is proposed that the manufactured geometry of highly functional components - like turbine blades - should not be assessed dimensionally but functionally. In this way a better understanding would be achieved in design of manufacturing capabilities and in manufacturing of design intents, and since functionality was being analysed it would be

directly accountable to manufacturing capability.

Acknowledgements

A very large number of people have provided assistance and contributed to the contents of this thesis and my grateful thanks is extended to them all. The list of names below is but a highlight of the total and my apologies are extended to those I have not included. My thanks to :-

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Finally I wish to express my thanks to Rolls-Royce plc for permission to publish this thesis.

Contents

Chapters:

Note : References are listed at the end of each Chapter

Appendices:

Backcover :

Lee, S.A., Tsabourakis, N., Ristic, M., Besant, C.B., "A Computer Integrated Approach To Dimensional Inspection", Proceedings of the Ninth International Symposium on Air Breathing Engines, Volume 2, September 1989, pp765-773.

List of Figures

Page

Chapter 2 :

Chapter 3 :

Chapter 4 :

Chapter 5 :

Chapter 6 :

Chapter 7 :

Appendix I :

Appendix II :

Appendix III :

List of Plates

Chapter 1

The Problems Associated With Products Of Long Design and Manufacture Lead Times

Manufacturing industry now faces extreme competition on an increasingly international basis and exists in rapidly changing markets and frequent economic cycles. In order for companies to succeed they must continually strive to meet market requirements, but new products take time to develop and the cost of these developments is increasing. The effect of new product development lead times is thus two-fold: it forces companies to forecast market requirements and it is a time of negative cash flow. By reducing development lead times companies reduce the risk of inaccurate forecasts and they provide companies with greater financial control of Research and Development expenditure.

The problems associated with long design and manufacture lead times are especially acute in the high technology industries where costs are very high, lead times often involve many years and competition is extremely strong. Thus there are very great incentives in reducing design and manufacturing lead times.

In defining a strategy to reduce design and manufacturing lead times there are many fundamental questions to be asked about the processes that make up the business. There may also be cultural problems in achieving a reduction in product lead times in industries with well established methods of design and manufacture. Where lead times involves many engineers and over long periods of time there can be extreme problems of communication.

In 1984 Rolls-Royce conducted a study into gas turbine design and manufacture development lead time which showed that the high pressure turbine blade lay on the critical path for the whole engine. It was decided that there was a strategic requirement to reduce this lead time. Strong links between Imperial College and Rolls-Royce resulted in the formation of the Imperial College/Rolls-Royce Teaching Company (see end of chapter [1] for details of the Teaching Company Scheme) who's brief was to reduce the manufacturing development lead time of this component.

High pressure turbine blades are currently manufactured using the investment casting process. Analysis of the manufacturing development lead time, by the Teaching Company Associates, showed that the principal causes of the long lead time were due to: ceramic core development lead time, the requirement to iterate the process until satisfactory yields were reached and slow manual proof inspection. As the core development was conducted outside of Rolls-Royce this was beyond the scope of the Teaching Company brief. However two main projects were instigated: Process Understanding, which aimed to reduce the number of proof cycles, and Automated Proof Inspection, which aimed to accelerate and improve the inspection process and presentation of errors.

Subsequent reappraisal of the whole design and manufacture process for high pressure turbine blades found that a reduction in lead time should not just come from manufacturing improvements but also from design. It was this more 'holistic' approach that forms the work of this thesis.

As a example for developing a strategy for reducing design and manufacturing development lead times there were few components that were more demanding than the high pressure gas turbine blade, because of its extremes of functionality, geometric complexity and manufacturing difficulty.

In this thesis it is explained how the high pressure gas turbine blade is currently designed, manufactured and developed. The corporate structures through which these activities take place are examined and some of the problems associated with employing a large number of design and manufacturing specialists to define the product and process for the high pressure gas turbine blade are observed.

In the analysis of the design and manufacture of the high pressure gas turbine blade the principles of Simultaneous Engineering and Taguchi's Quality Engineering were used. It is believed that only by achieving improvements in the manner in which design and manufacturing compromises are made will these products attain increased competitiveness.

In aiming to improve the methods by which design and manufacturing compromises are made Simultaneous Engineering stresses the importance of good communications between engineers at both interpersonal and computer system level. To this end it is recognised that the management principles of 'organic' structures over 'mechanistic' ones are more favourable and hence the development of 'integrated' design and manufacturing teams.

During the analysis it was observed that there was a lack of understanding of how to obtain and use manufacturing capabilities at the design stages of a new product. It was proposed that such process knowledge needs to be fed systematically to the design specialists and this required the design of new systems of information transfer. In formulating such process knowledge there was the requirement to develop process databases and in achieving these there was the need for the inspection philosophies of Integrated Inspection.

Whilst CAD/CAM systems are capable of passing information from design areas to manufacturing it was surmised that under the principles of Simultaneous Engineering and Taguchi's Quality Engineering information must flow freely both ways: nominal geometry from design to manufacture and process capability from manufacture to design. This combination of transferring design geometry to manufacture and manufacturing capability to design is described - in this thesis - as the integration of geometric information within design and manufacture.

To meet these two-way communication objectives for high pressure gas turbine blade design and manufacture an integrated inspection system was developed. Using the nominal design geometry of the components the inspection system controls a coordinate measuring machine to measure the surfaces of the manufactured components. The inspected data is transfered back into the inspection system where it is used to calculate surface errors which are presented as sections or contours over the surface. Realising the complex nature of cast surfaces a three dimensional least square best fitting algorithm was developed and is included in the system.

The system provides for the averaging and calculation of standard deviation over measured surfaces and hence it provides an extremely powerful tool for the process development engineer. As the surface error is known within a computing environment it may be readily related to nominal die geometry and hence used to specify die modifications in a computer integrated closed loop manner - rather than the current manual inspection and manual modification process.

Since models of the manufactured geometry are now available and in the same format as the nominal design model it is proposed that the designers and design specialists analyse the effects of the differences between nominal and measured geometry to ascertain manufactured component functionality. In a process proofing situation this could result in acceptance of a geometry which does not satisfy dimensional tolerancing specifications. The idea of assessing component functionality as opposed to dimensional acceptability relates directly the effects of manufacturing capability to component functionality. This is a far better method of balancing this extremely important compromise and one which is central to Taguchi's Quality Engineering philosophy.

Finally it is surmised that the integrating design and manufacturing philosophies developed for turbine blades are fundamentally generic to all manufactured components and hence there are lessons to be learnt for all manufactured products. Thus the thesis offers a highly integrated approach to product and process development centred about the overall costing of products and aims to meet the strategic needs of design and manufacturing development lead time reduction.

[1] The Teaching Company Scheme, of which the Imperial College/Rolls-Royce Teaching Company programme was a member, has been established by the Science and Engineering Research Council (SERC) and The Department of Trade and Industry (DTI) to achieve the following :-

- Raise the level of industrial performance by effective use of academic resource.
- Improve manufacturing and industrial methods by the effective implementation of advance technology.
- Train able graduates for careers in industry.
- Develop and retrain existing company and academic staff
- Give academic staff broad and direct involvement with industry to benefit research and enhance the relevance of teaching.

These objectives are achieved by the formation of Teaching Company programmes between academic and industrial partners. Graduates are appointed to work for these programmes as Teaching Company Associates on two year contracts. Associates spend most of their time 'in-company' but are guided in their research by the academic partners.

Chapter 2

A Design and Manufacture Case Study: The Rolls-Royce High Pressure Gas Turbine Blade

2.1 Serving The Market

For any manufacturing company existing in a free market economy it may be said that its products should be targeted at serving the market. In this respect the activities of the design and manufacturing functions within such companies should conduct their work from the specifications required to serve the market needs. With regards to the aero-engine market such facilitation may be observed within Rolls-Royce at three levels [1]:-

i. **Future engine requirements**: the potential needs in terms of thrust/weight, specific fuel consumption, cost, noise, size, life, serviceability etc. are fed through to the preliminary design departments whose task is to consider the perceived future engine requirements and to try and match these to basic configurations for new engines. Once it has been accepted that a new engine configuration is to be manufactured the component and project design groups commence the more detailed design work.

ii. **Developments to existing engines**: work will be conducted on developments to existing engines which are seen as required to maintain or improve their market competitiveness. Often this activity is conducted from the outset by the component and project design groups.

iii. **Modifications to engines in service**: this work is a quick turn-around activity conducted after requests from the customer or the customer support departments. These hopefully small modifications are made to enhance utilisation of the product.

The design and manufacturing organisations are set up at these three levels to serve the market requirements. For the purposes of this case study the design and manufacturing activities involved are considered from the point of view of designing a new engine.

2.2 Preliminary Engine Design

During this initial phase of engine design overall configurations and performance characteristics are considered. These must try to meet the specifications for engines that are perceived to be required in the future. The purpose of this work is an assessment, before more detailed design, in order to avoid futile work on mechanical impossibility or improbability. Such studies will consider the potential capabilities of materials, aerodynamics, cooling, manufacture etc. to produce engine configurations of acceptable cost, weight, size, thrust, specific fuel consumption, life, noise, emissions, durability, serviceability etc.

The work of the preliminary design departments is continuous in its study of new engine configurations. From this work will come the requirements of technology and materials for the future and this will be fed into the Advanced Engineering function who are responsible for research in order to generate the design and manufacturing databases from which future engine projects will be based. The decision for the company as to whether it should launch a new engine is made by the Main Board. Such a decision is based on many considerations including potential market size, expected market share, the pay-back period and the level of risk in the development programme.

Much of the work of the preliminary design departments is never turned into reality. However when it is decided that a new engine is to be placed onto the market the company organisation gears itself for the design, manufacture and development phases of that product. The complexity of a modern gas turbine is such that many thousands of people inside and outside of the company and all over the world will become involved by a new engine programme which may last six years before the engine reaches the market.

2.3 Detailed Performance Calculations

After preliminary design proposals are accepted the next phase for the engine is the division of responsibilities for the design, manufacture and development to the various departments concerned. In terms of generating a specification for the engine one of the first activities is detailed performance calculations. In this analysis a thermodynamic model of the engine is created. Using the inputs of predicted component capabilities from the advanced component groups the model aims to optimise the engine configuration for its principal operating conditions. This work will include transient and non-transient analysis and it will eventually lead to a 'Performance Deck'. This is principally a listing of aerodynamic and thermodynamic specifications for the engine components.

During the time that the performance deck is being prepared the component design functions are initiating the design phase from information received from the preliminary design departments. In this work different designs are considered to achieve optimum components which will meet the specifications. At the same time the manufacturing areas will be examining the manufacturing capabilities that the new engine requires to ascertain whether they are sufficient.

At some point the first performance deck will be passed to the component design groups. Work will continue with performance calculations and indeed it is not expected that the first deck will be the last, small alterations will be made to the deck right up to the time that the component designs are nearing completion. However the first deck provides a starting point for the various components and enables the initial design activity to be extended into greater detail.

2.4 The Complex Engine Design and Manufacturing Process

As more information is obtained as to the requirements of various components in the engine a greater number of departments will become involved in the design and manufacturing activities. All of the tens of thousands of parts that a gas turbine is made from must of course be designed, manufactured and tested.

It would not be practical to explain even a small fraction of the total design, manufacture and development processes of a gas turbine. However amongst all of the work which is carried out it is the high pressure turbine blade which is the most complex component to design and manufacture. It is the temperatures surrounding the high pressure turbine blade that will to a greater extent than any other determine the specific fuel consumption of the engine and the thrust to weight ratio. A high pressure turbine will be one of the most expensive modules in the engine and includes the components of shortest life.

Being such a critical component in the engine a high pressure turbine blade demands a very significant design and manufacture resourcing. Coupled with the fact that the lead time for the component is on the critical path for the engine, as will be discussed in detail in Chapter 3, the high pressure turbine blade is ideally suited for study into potential improvements in the design and manufacture process.

To begin the examination a description of the presently adopted design and manufacturing process within Rolls-Royce is given below. This leads into Chapter 3 where an analysis and proposals for improvements are made.

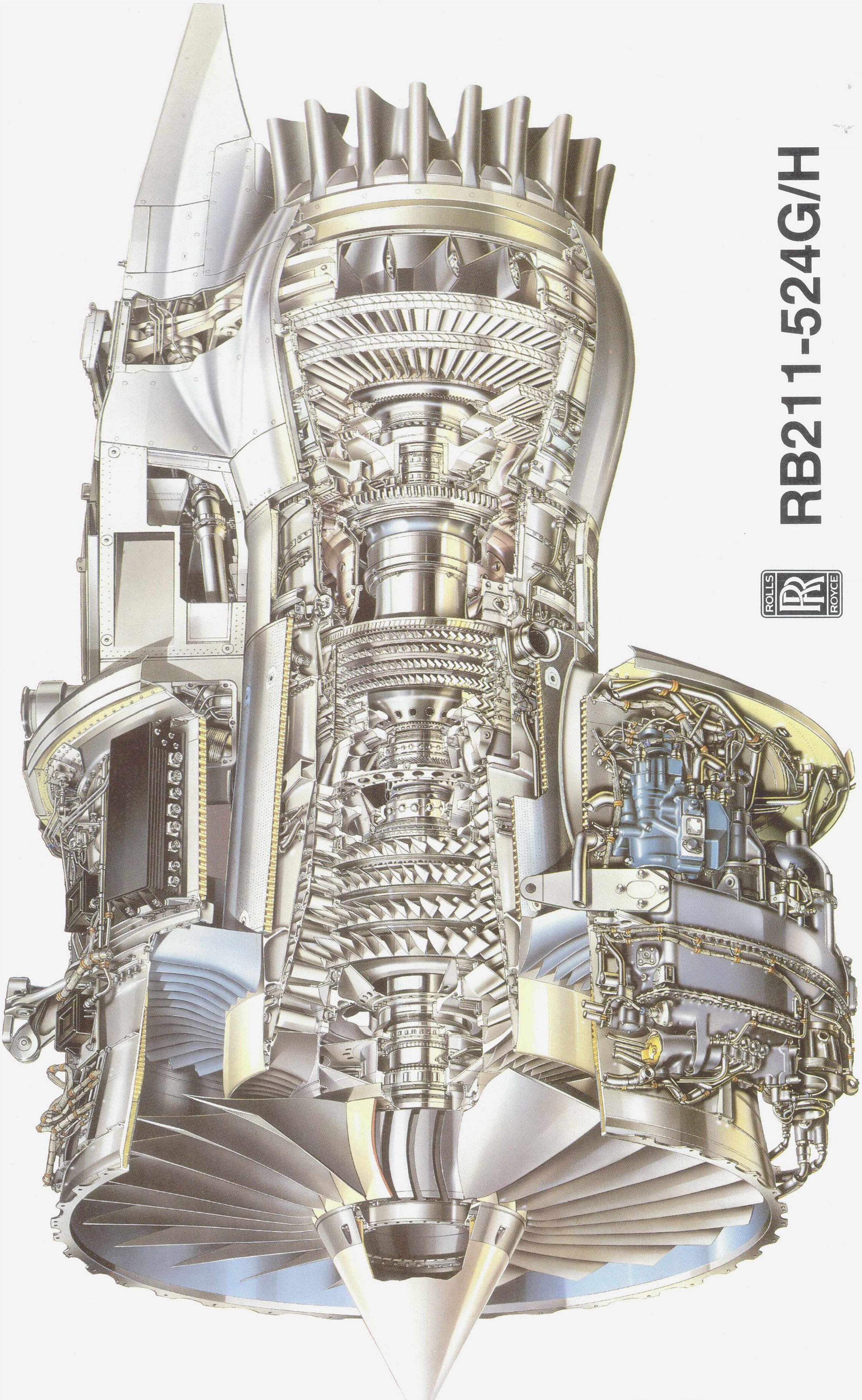
2.5 High Pressure Gas Turbine Design, Manufacture and Development

2.5.1 Specification for the High Pressure Gas Turbine Blade

Before describing in detail the design process it is perhaps useful to consider some of the overall requirements of the high pressure turbine blade. In a gas turbine these blades reside behind the nozzle at the exit of the combustion can, which is approximately in the centre of the engine (Figure 2.1). The blades are mounted on a disc which in turn drives a shaft that takes the power to the high pressure compressor.

Figure 2.1 (Overleaf)

Cutaway of the RB211-524 G/H Engine



RB211-524G/H

The specifications for the high pressure turbine blades in the Rolls-Royce RB211-524 engine are :-

1. For each blade to generate approximately 700 horse power at maximum power conditions.
2. For the blades to extract work at a 92% isentropic efficiency.
3. For the blades to last 7000 flight cycles or 20,000 hours, which ever is sooner.

In achieving this specification the blade has to exist in a 45,000 'g' field which results in a centrifugal load for each blade of approximately 10 tonnes. The blade has to turn gas moving at near sonic velocities at temperatures in excess of 200°C hotter than the melting temperature of the blade material. It is perhaps not surprising that with these specifications the design process for high pressure turbine blading is complex.

2.5.2 The Design Process

Figure 2.3 illustrates the numbers of disciplines and departments involved in the design of a turbine blade. The design process is extremely interactive and involves large iterative cycles in which the mechanical designers will search for the optimum solution [2] [3] [4]. The designer's task is to act at the hub of the wheel of the design process and to coordinate the activities of the large numbers of specialists working for them. It will be the eventual responsibility of the designers to produce the records from which the component will be manufactured.

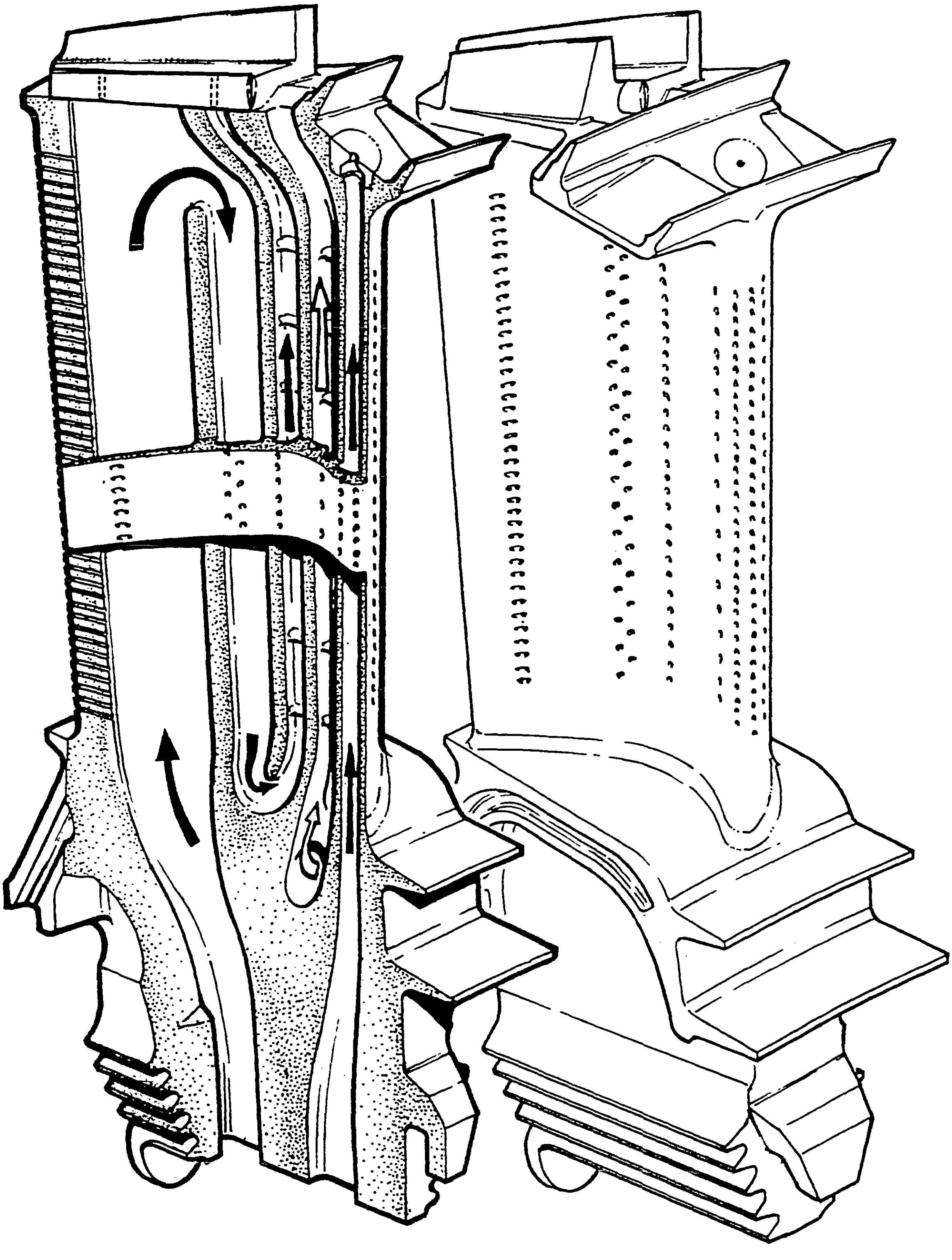


Figure 2.2

The RB211-524 High Pressure Turbine Blade

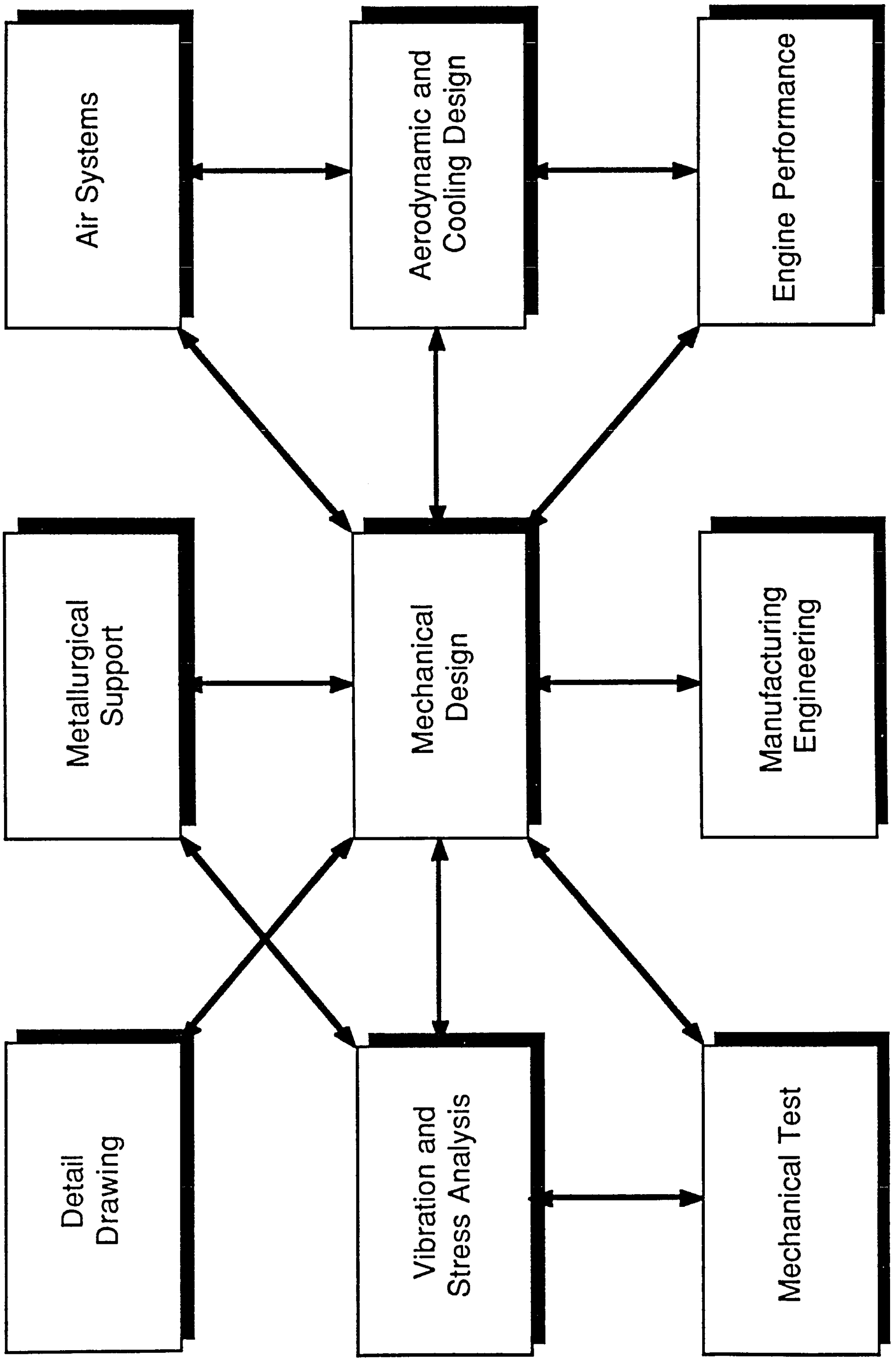


Figure 2.3

Disciplines Involved In High Pressure Gas Turbine Blade Design

The preliminary phases of the turbine design begins with a thermodynamic consideration. The blade will be required to extract a certain work from the flowing gas, this work is expressed as a change in enthalpy (ΔH) across the turbine stage. In producing this work the turbine will be expected to achieve a certain efficiency calculated from the loading/efficiency plots, see Figure 2.4.

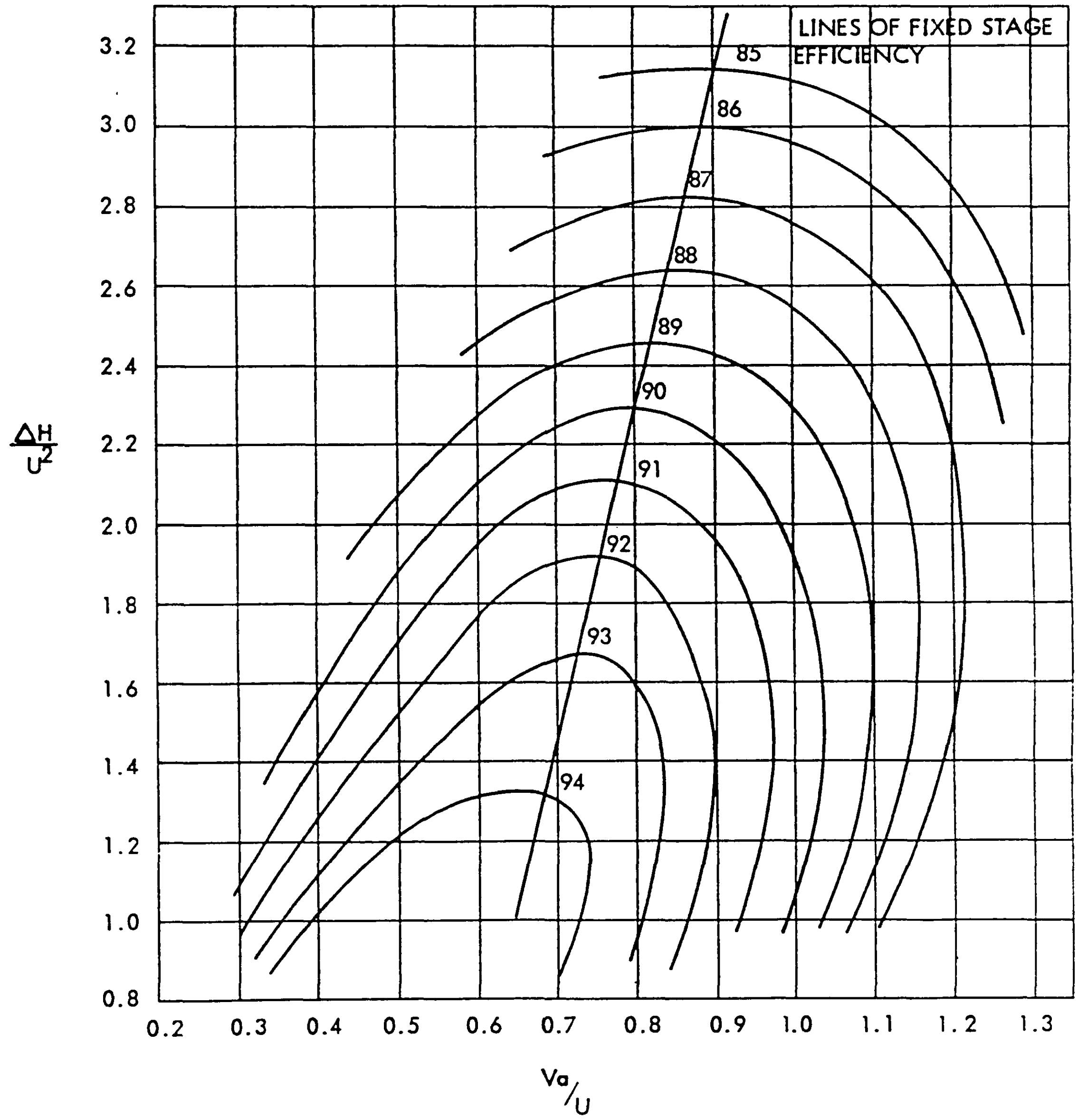


Figure 2.4

Load ($\Delta H/U^2$) against V_a/U For Turbine Blading Illustrating Bands of Efficiency (Zero Tip Leakage)

For a required efficiency it is possible to choose an axial velocity (V_a) and blade speed (U). The aim will be to achieve a high enough value of blade speed to allow a loading ($\Delta H/U^2$) in the region of 1.0 to 2.0 (depending upon application) while (V_a/U) needs to be in the range 0.5 to 0.9 to maintain high efficiency. The turbine rotational speed is targeted at that required by the compressor, the choice of blade radius will therefore dictate U and with the choice of blade height affect V_a. Both V_a and U have direct effects on the stress in the turbine blade and the ability of the disc to carry its rim load so that the choice is an interactive one between mechanical design, aerodynamics and stress.

The space/chord ratio for the turbine is selected to optimise lift coefficient, see Figure 2.5. The blade chord and hence blade numbers are then decided upon by consideration of a number of facets including secondary losses, trailing edge blockage, cooling capabilities, rim loads, cost and noise.

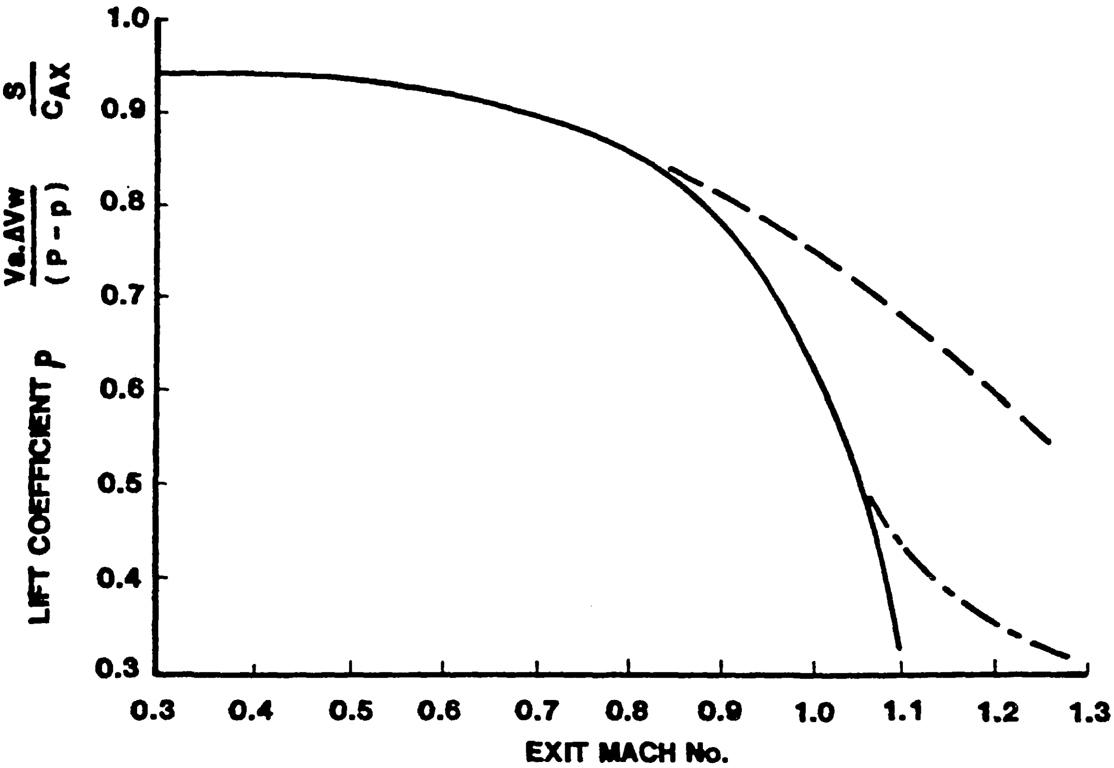


Figure 2.5

Lift Coefficient Against Exit Mach Number for Turbine Blading used for the Selection of Space/Chord Ratio

Having decided upon an aerodynamic specification it is up to the stress department to establish a material and mean temperature to meet the target blade life, and for the aerodynamic/cooling departments to convert this life target into cooling requirements.

Figure 2.6 (a) and (b) show how improvements in manufacturing capabilities and materials have enabled increases in blade direct stress levels. The development in 'Directional Solidification' casting has enabled the grain structures of materials to be aligned in such a way as to improve the creep lives.

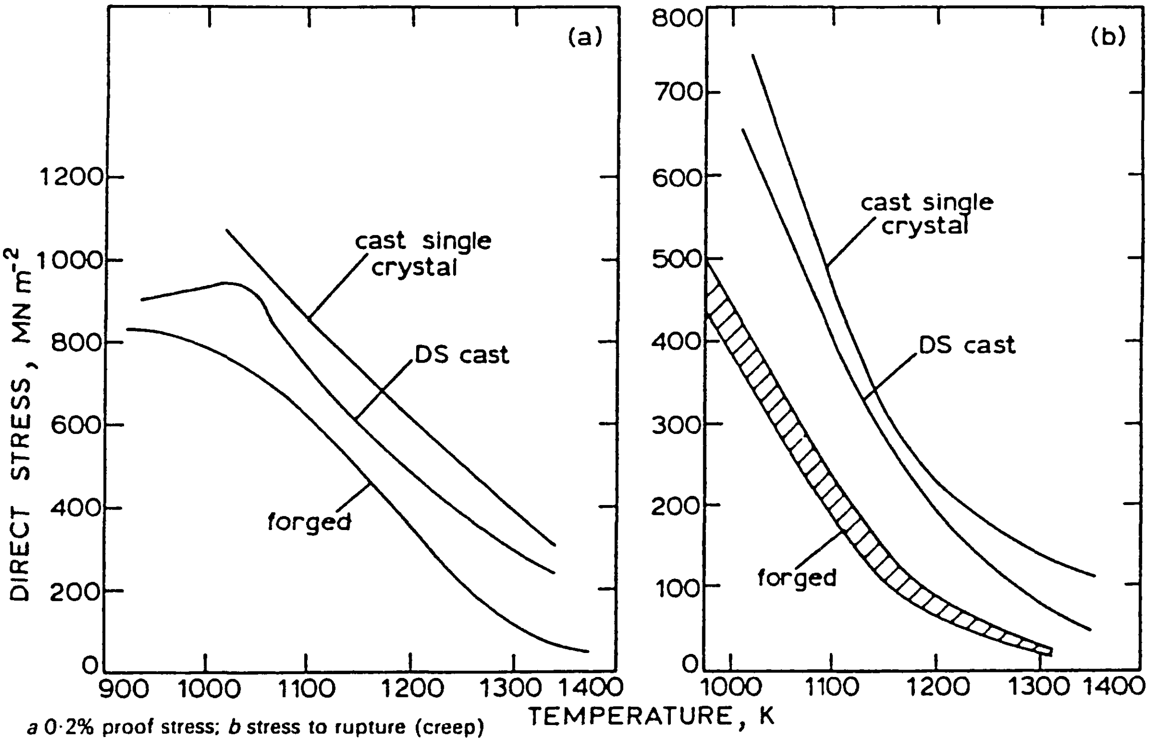


Figure 2.6

Improvements in Materials and Manufacturing Capability and their Effect on Blade Direct Stress Levels with Temperature

Creep is a diffusional process and hence temperature dependent. One of the most significant modes of creep failure is the diffusion of atoms across grain boundaries causing a relaxation of the material in the direction of applied stress. By aligning the grain boundaries in the direction of stress the creep process is reduced. A step further than directional solidification is the cast single crystal which in effect has no grain boundaries. However since inter-granular diffusion is not the only mode of creep failure single crystal casting does not imply the removal of creep but a dramatic reduction.

Of course creep life is not the only consideration, high thermal strength, castability, machinability, erosion, oxidation, corrosion and fatigue (thermal, low and high cycle). In consideration of these a safe envelope of stress is ascertained and is represented in Figure 2.7. Achieving blade stresses inside the safe envelope will determine whether a blade is to be cooled or not. Such stresses will be determined by the basic aerodynamic form of the aerofoil and whether it is to incorporate a shroud.

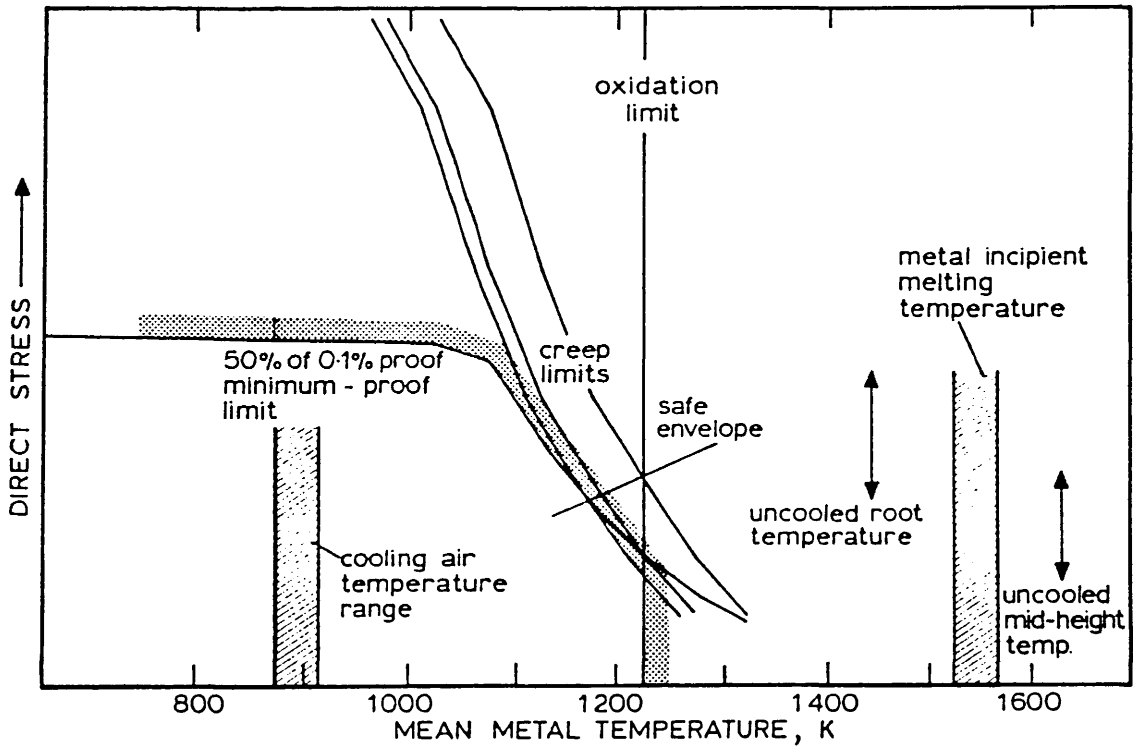


Figure 2.7

Safe Envelope Of Direct Blade Stress Against Mean Metal Temperature

Assuming that the blade is to be cooled the next phase is to consider cooling configurations. The safe stress envelopes will indicate the cooling effectiveness to be achieved. Cooling for the blade may be achieved by passing cooling air through the core passages. On its own this air will achieve convection cooling of the blade. However if small holes are drilled through the aerofoil to the core passages the cooling air flow through the core will blow a film of air onto the surface of the aerofoil and provide further cooling. Typical cooling effectivenesses of 50% may be achieved with convection and film cooling of which about 70% is provided from the convection elements.

The cooling air for high pressure turbine blades usually comes from two sources firstly air by-passing the combustor can is allowed to flow through a sealing arrangement on the high pressure disk and to pass up into holes through the disk into the blade. The second source is a pick up of intermediate pressure compressor leakage air which is passed up the blade rather than leaking directly into the air stream. The cooling air flow for high pressure blades usually constitutes 2% of total core air flow. The design for the cooling air flows that feed the blade is the responsibility of the Technical Design department who are responsible for the main engine air systems.

Vibration of the blading is an extremely important stress consideration. It arises in a number of fashions, firstly there are flap and torsion modes of the blade which may be excited from any source within the engine which coincides with the blade's resonant frequencies. Since these sources could be the result of anything from blade rubs to blade passing frequencies they are referred to simply as 'Engine Order' frequencies, (first order corresponds to a shaft rotational frequency, second order a twice shaft rotational frequency and so on).

The second source of vibration comes from a phenomenon known as flutter which is an interaction between the gas passing the aerofoil and the aerofoil natural frequencies, this is not a resonance as the driving force is not external to that which is resonating. Flutter is a very complex process to analyse, however a number of simple rules have evolved which aim to predict its occurrence.

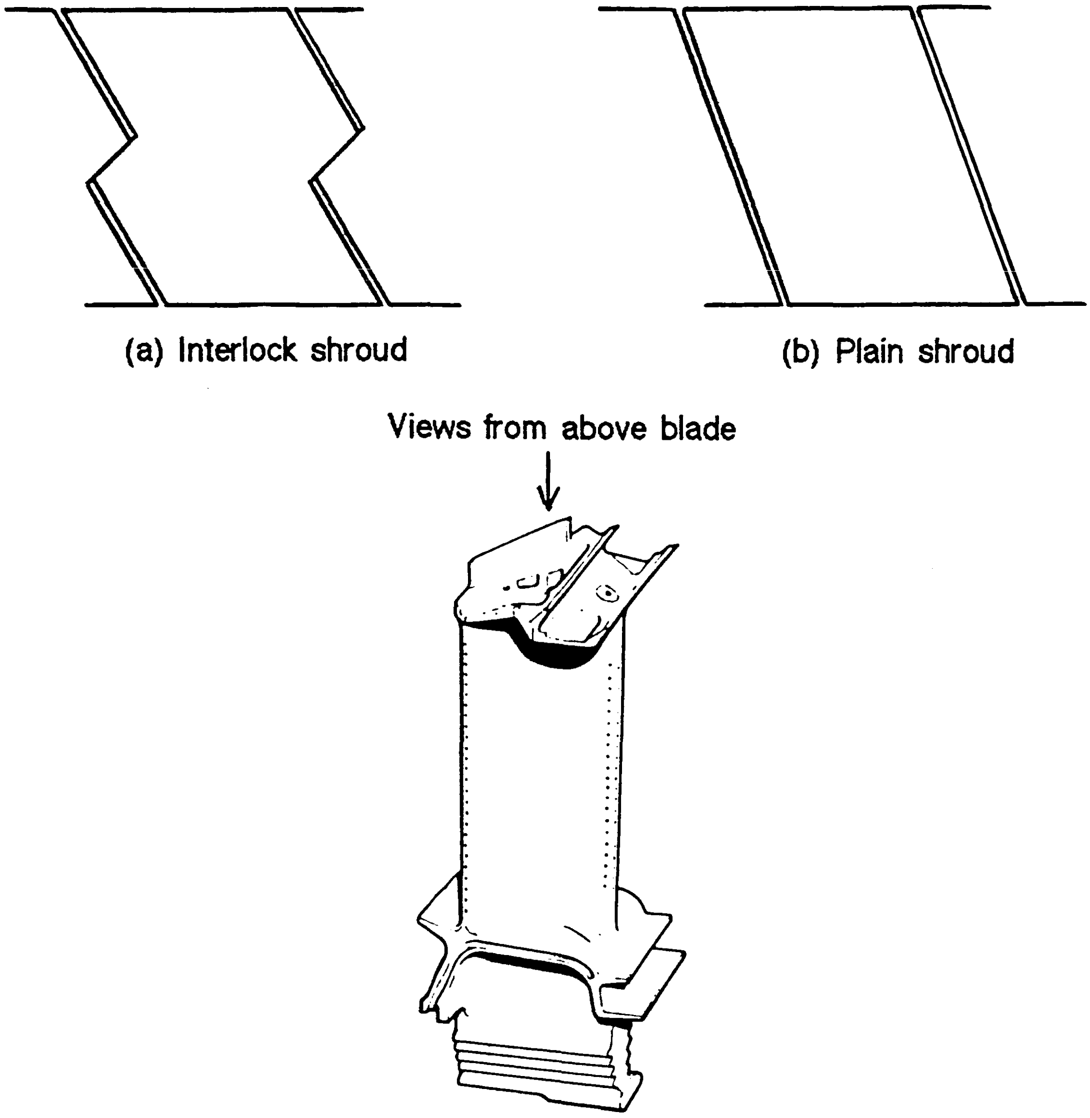
The final source of vibration involves the compound bladed disk assembly in which the entire rotating mass undergoes flexure at an engine order frequency.

It is the designer's task along with the stress office to try and either design vibration phenomenon from the blades and disk or suppress its effect. One major design consideration is the use of interlock shrouds, see Figure 2.8. These bind up on assembly of the blades in the disk to form a tight band around the rim of the aerofoils and hence stiffen the assembly against vibration.

A further method of suppressing vibration is to incorporate a damper in the blade platform, see Figure 2.11. Accepting that vibration occurs the damper aims to reduce the amplitudes to acceptable levels, if sufficiently large dampers are used it may not be necessary to use interlock shrouds. A further use of the shroud is to act as a seal for over tip leakage and thus achieve efficiency improvements. Some engines remove the blade shrouds and incorporate active tip clearance. The advantage of removing the shroud is that it dramatically reduces aerofoil stresses, blade weight and hence disk weight.

Obviously the most important part of a turbine blade is the aerofoil. Once the first design of aerofoil has been generated and the basic design considered for stress and manufacturability the aerodynamicists will work to improve the performance of the aerofoil. Initially aerofoils are designed on 2D sections by examining the velocity profiles. Figure 2.9 illustrates some of the phenomenon that are considered in the performance analysis.

The lift generated by the aerofoil is proportional to the area enclosed by the suction and pressure surface velocity plots, shown in Figure 2.10. However this area may only be increased within constraints of what can be achieved by the gas flow in practise. Diffusion rates have to be controlled to avoid separation, surface Mach numbers have to be limited to avoid shocks and losses.



(a) Interlock shroud

(b) Plain shroud

Figure 2.8

Interlocked and Plain Shroud Design

As well as the aerodynamic losses that can result from certain flow characteristics, the heat transfer rates from the gas to the blade surface are also affected. It is these values which are applied in the detailed temperature analysis of the blade.

The aerodynamic and thermodynamic analysis on the blade yield mean temperature at each flight condition and Miner's Law is used to add together the creep at each condition to establish a life. In practise the mean temperature is an over simplification. One of the designer's tasks is to stack the designed aerofoil sections, by leaning a blade over in the direction of rotation it is possible to offset the gas bending moments with a restoring centrifugal moment. By tuning this lean it is possible to offset high stresses in hot parts of the blade onto colder regions and hence increase life.

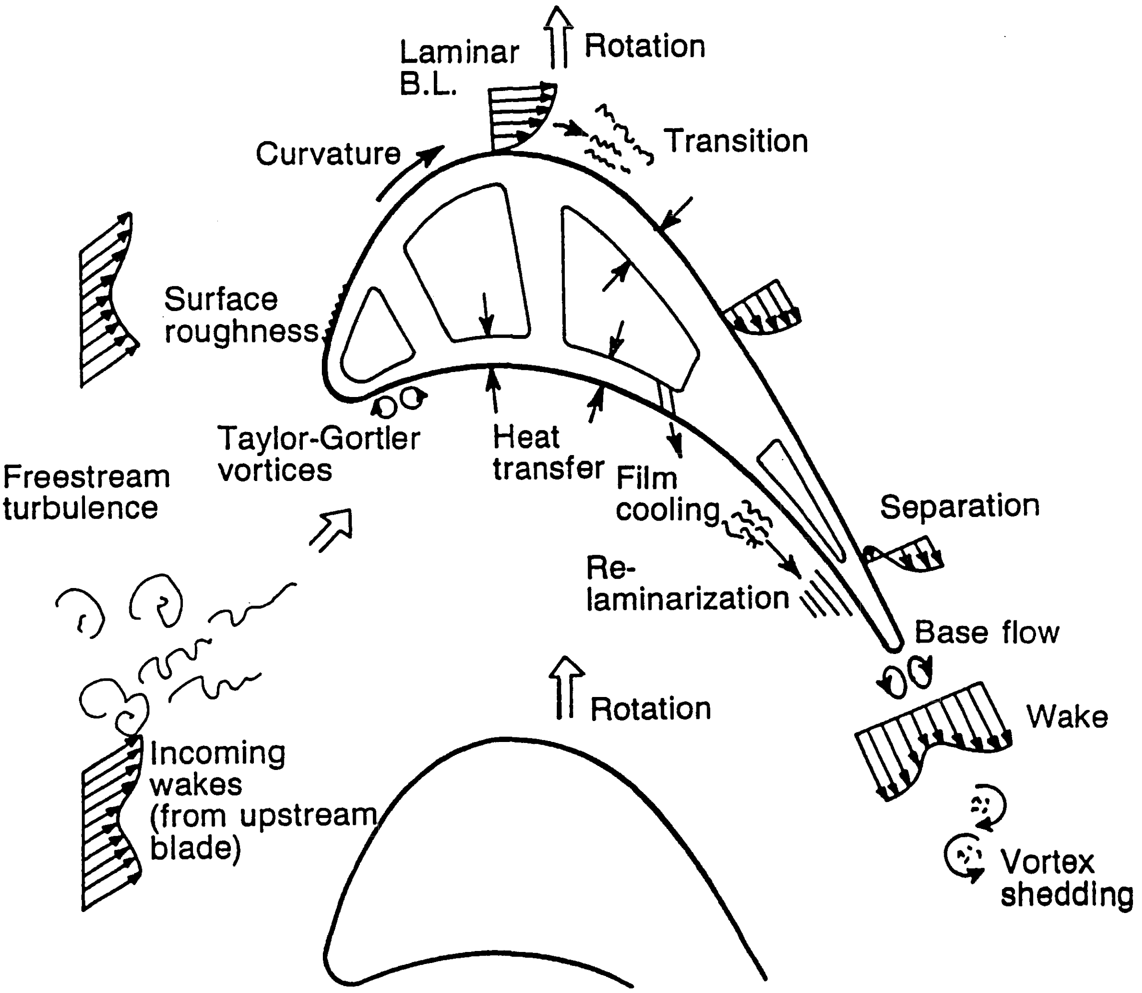


Figure 2.9

2D Aerodynamic Design Considerations for Aerofoils

Not only is a blade subject to variations in temperature but it is also subject to transient temperatures/stress distributions as the engine changes power conditions. These variations will subject a blade to low cycle fatigue for which it must be analysed.

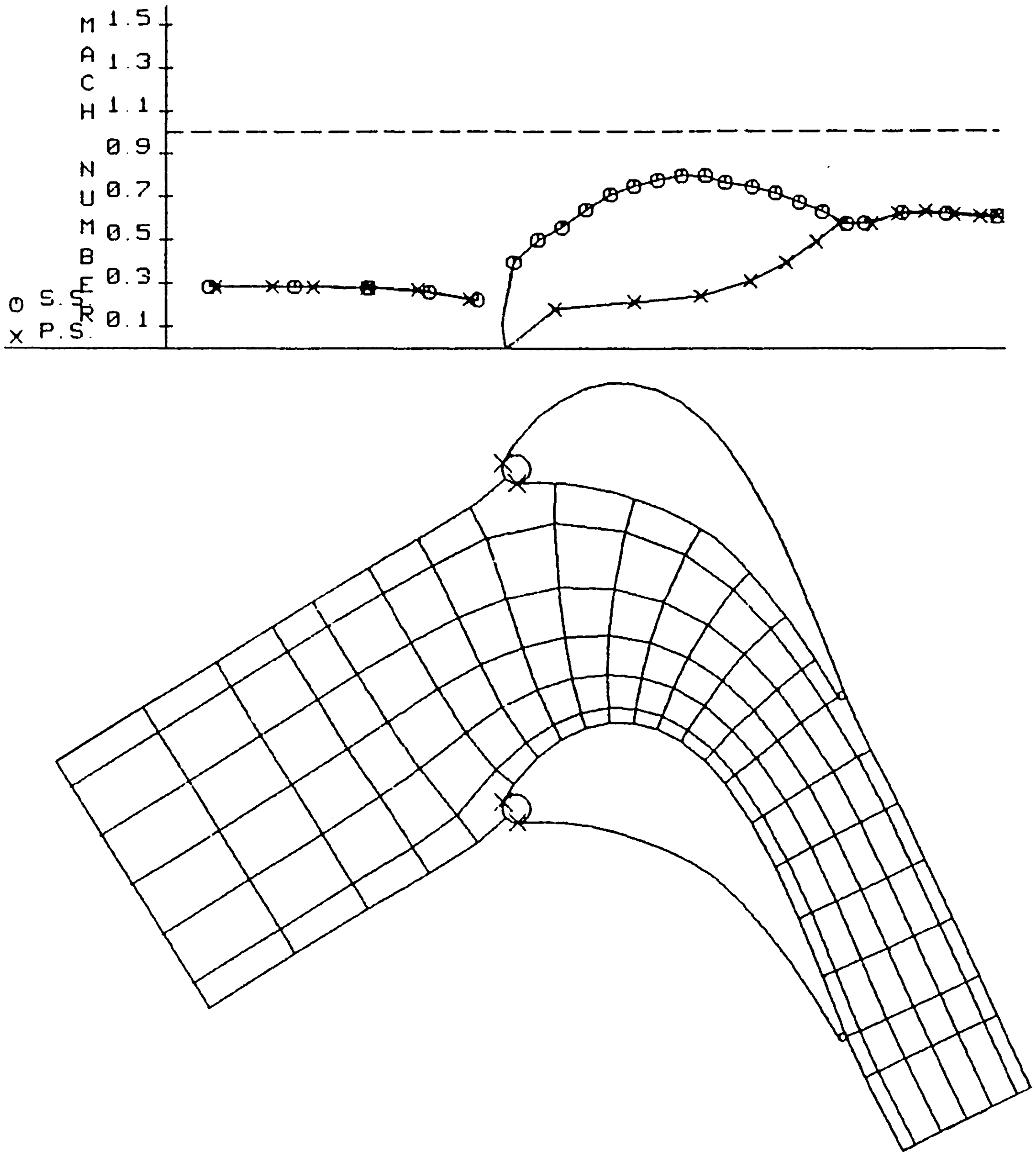


Figure 2.10

A Typical Turbine Aerofoil Velocity Profile

Once the design processes for the aerofoil and shroud are instigated considerations begin for the platform, shank neck and root, see Figure 2.11. The platform provides for the lower annulus of the blade and usually supports any dampers. The shank neck is effectively a continuation of the aerofoil into the blade root which holds the blade to the disk. The shank neck will be very highly stressed since it has the full weight of the blade above it. However it must be sufficiently flexible to allow reasonable movement of the blade at the damper height to enable the dampers to move and hence dampen oscillations.

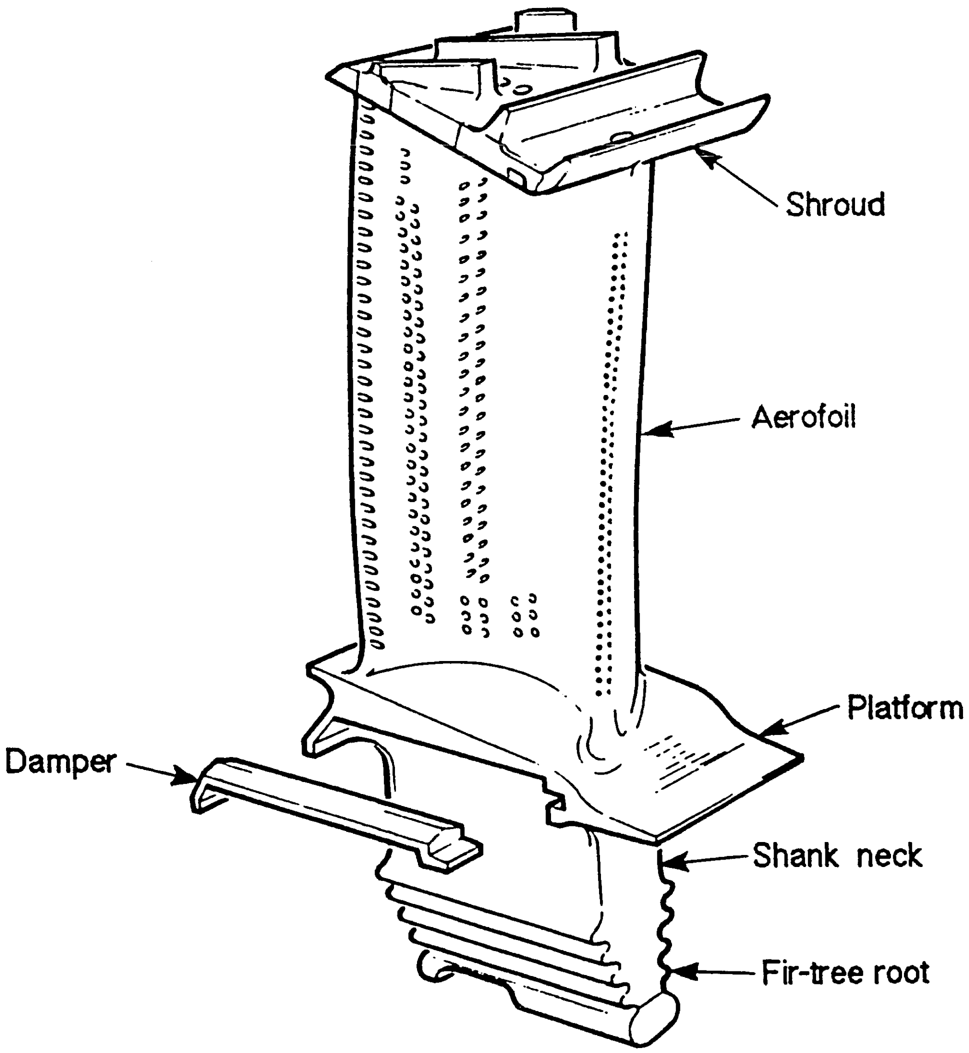


Figure 2.11

A Typical Blade Platform, Damper, Shank Neck and Fir-tree Root

Turbine blades are usually held into the disk using 'fir-tree' roots, see Figure 2.11. Again this part of the blade is extremely highly stressed and special care must be taken to consider the tooth and fillet radius proportions to minimise the stress concentrations.

The above explanation for the major considerations involved in turbine design have been included to give a brief outline of the complexity involved. It is always the mechanical designer's role to meet the compromise for all of the aspects and to ultimately produce the design records, be they drawings or CAD models, plus written documentation on design decisions.

Manufacturing information is produced by the 'detailing office' who work in liaison with design and manufacturing to convert the design records into manufacturing specifications. In the case of turbine blades the detail office produce both casting and machining drawings for the component and any NC tapes required for the cutting of both core and blade dies.

2.5.3 The Manufacturing Process

2.5.3.1 Introduction

Throughout the design phase of the blade the manufacturing departments will be in liaison to give specialist advice to the designers on castability and machinability of proposed geometries. As the design forms into a more definite proposal manufacturing will begin to decide upon how and were the component and its many associated manufacturing tools and dies will be made.

High pressure turbine blades are currently cast from Nimonic alloys using the investment casting process [5]. After casting the blade is machined at the shroud and root and the film cooling holes are drilled. The entire manufacturing process is complex and involves a great many stages including numerous geometric and metallurgical inspection processes. Figure 2.12 illustrates those disciplines involved in specifying the manufacturing process for the high pressure gas turbine blade.

The manufacturing process for high pressure blades is explained in more detail in the following two subsections.

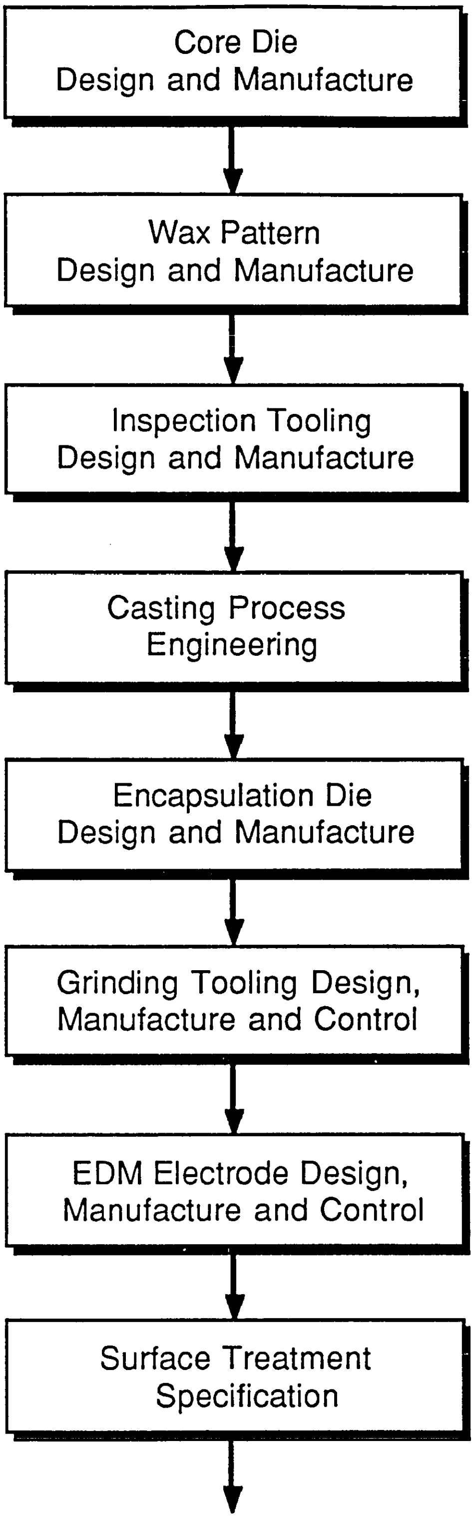


Figure 2.12

Disciplines Involved in the Specification of the High Pressure Gas Turbine Blade Manufacturing Process

2.5.3.2 The Investment Casting Process

Figure 2.13 illustrates the various processes involved in the investment casting process of high pressure turbine blade manufacture. The first stage is to produce the dies required for the manufacture of the blade wax pattern and ceramic core. The ceramic core is used to form the internal geometry of the blade and is placed in the wax pattern die before wax injection.

The core is also made by injection moulding, in this process the ceramic is mixed with a wax to produce an injectable slurry which is usually green in colour. After injection the core is removed from the die in the 'green' state and baked to remove the wax and leave a stiff ceramic core.

When a core is used in a blade wax pattern die it usually has a number of small high density polystyrene chaplets put onto its surface before insertion into the die and these support the fragile core off the walls of the die as the wax is injected into the wax-pattern die (Plate 2). Once the wax pattern has been made it is usually placed onto a drier which supports the blade while the wax is curing.

The resultant wax patterns are manually mounted on a wax runner-riser system called a tree, with between 6 and 20 other blades, depending on size (Plate 3). This total wax assembly is then coated with several layers of ceramic (Plate 4). The wax is removed leaving a ceramic which is subsequently baked hard. To support the core off the walls of the ceramic shell during the metal pouring process platinum pins are inserted through the wax pattern to touch the core and are cut off to protrude from the blade's surface by a few millimetres. These pins will be held in place by the ceramic shell and will exist for just sufficient time, before melting, to support the position of the core as the metal is poured.

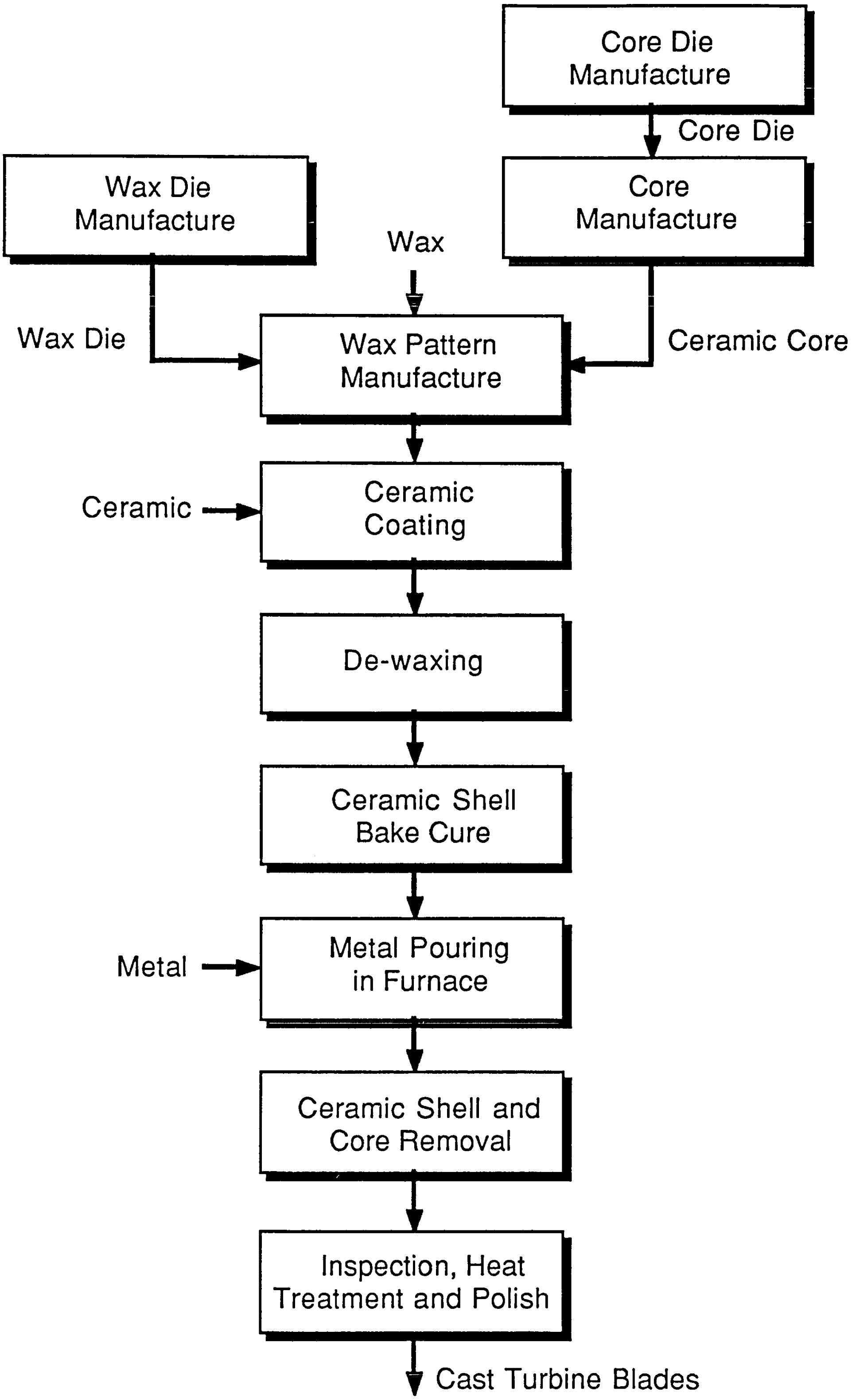


Figure 2.13

The High Pressure Turbine Blade Investment Casting Process

Plate 2 : Blade Wax Pattern Injection Around a Ceramic Core

Plate 3 : Construction of the Blade Casting Runner/Riser System

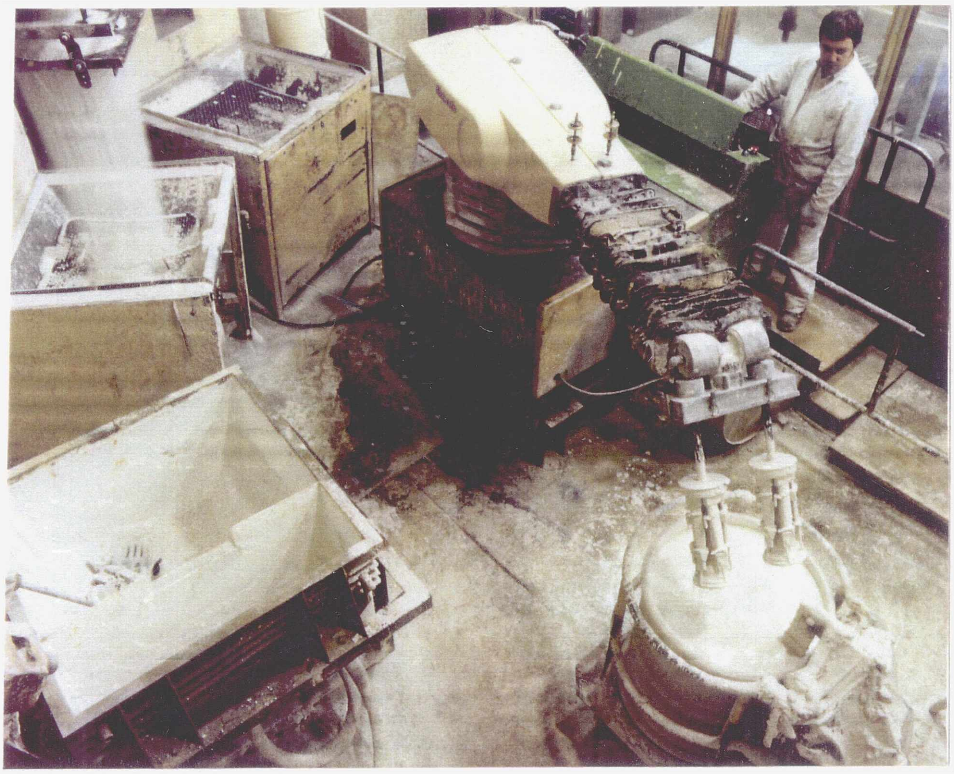


Plate 4 : Application of Ceramic Shell Coatings Around Wax Patterns

Plate 5 : Directional Solidification Furnaces

The ceramic shell is subsequently placed in a casting bucket which is filled with small stones to support the shell. The bucket is placed in a directional solidification vacuum induction furnace (Plate 5) where the metal is poured into the shell which is preheated to keep the metal molten. Slowly the shell is withdrawn from the furnace while the base of the shell is cooled. The result is that solidification occurs in a controlled manner from the base of the casting and hence enables directional growth of the grain structure within the metal (which for previously explained reasons is advantageous to the component properties). When the contents of the casting bucket has sufficiently cooled the blades are removed from the tree in the cutting-off shop. The ceramic core is removed by either grit blasting or an acid leaching process.

The casting is now ready for inspection. The first measurement is the aerofoil profile which is gauged on calliperscopes and if required manually dressed using grinding wheels (Plate 6). Further gauging processes are conducted on the bow and twist of the blade and on the annulus gas washed surfaces and shank neck (Plate 7). Wall thicknesses between the aerofoil and the internal passages are measured using ultra-sonic probes (Plate 8).

In order to obtain the correct metallurgical characteristics in the castings after dimensional inspection it is necessary for directionally solidified, including single crystal, blades to be heat treated.

Metallurgical inspection is very extensive particularly for single crystal blading. For this the surface of the blade is etched to aid the visualisation of the grain structure. For single crystal blades the orientation of the crystal structure is very important and consequently a machine was developed, by Rolls-Royce, called SCORPIO, which uses X-ray diffraction through the grain structure to ascertain if the crystal has grown to within an acceptable tolerance of the correct direction. The final step for the casting is for the aerofoil to be polished, this is performed by a stone barrelling process.

Plate 6 : Manual Grinding of Casting Surfaces

Plate 7 : Gauging of Blade Surfaces By Drop Gauge Fixturing

Plate 8 : Measurement of Aerofoil Wall Thickness by Ultra-Sonic Probe

Proof Cycling

The above explanation indicates that there are a number of processes actually involved in producing a blade casting. Some of these processes like wax and ceramic curing and metal solidification involve contractions which are extremely difficult to predict. As a result the final geometry of the first batch of blades will probably not be correct or at least within a reasonable yield. Thus modifications are made to the die geometry and process parameters after the first batch is cast to anticipate the process distortions and subsequently improve the yield. This iterative process is called 'Proof Cycling'.

During proof cycling the blades are 'Proof Inspected' rather than production inspected. This is a manual inspection process which aims to measure the blades' geometry, external and internal and inform the methods engineers of where the blade is in or out of tolerance and where material defects are. The methods engineers will then interpret the results and instruct die modifications and process parameter changes. The dies are modified by either hand dressing or copper plating.

Even the second cast batch may show significant geometric error in which case the process of die modification and process parameter change is again repeated. In extreme situations a concession may be requested by manufacturing to design for an acceptance of a geometry which, as nominally specified, cannot to be produced at reasonable yields.

2.5.3.3 Blade Machining

After the completion of the proof cycling phase and acceptable castings are being produced the blades are sent to the machining centres. In these areas the shrouds and roots are creep feed ground.

The alignment of the aerofoil in an engine is critical in obtaining the required throat areas for the turbine. Since the aerofoil will be located in the turbine disk by the root fixing all of the machining operations on the blade are performed reference to certain points on the aerofoil which will achieve the required throat area. This alignment is achieved by casting a zinc encapsulation block over the aerofoil and enables all of the shroud and root machining tools to pick up the blade easily and in the correct orientation (Plate 9).

The film cooling holes are produced by electro-discharge machining (EDM). Rakes of copper wire are produced which are fed into the blade surfaces using CNC EDM machines (Plate 10).

The blade may also incur some surface hardening treatments, for example the laser hard surfacing at the interlock abutment faces.

Finally coatings will be applied, for example pack aluminising, to reduce corrosion and erosion suffered by the gas washed surfaces.

It may be observed that the manufacturing techniques involved in high pressure turbine blading are both varied and complex. However this is not the end of the story for once a blade has been made it must be tested and developed with the aim of certifying the component for civil or military use.

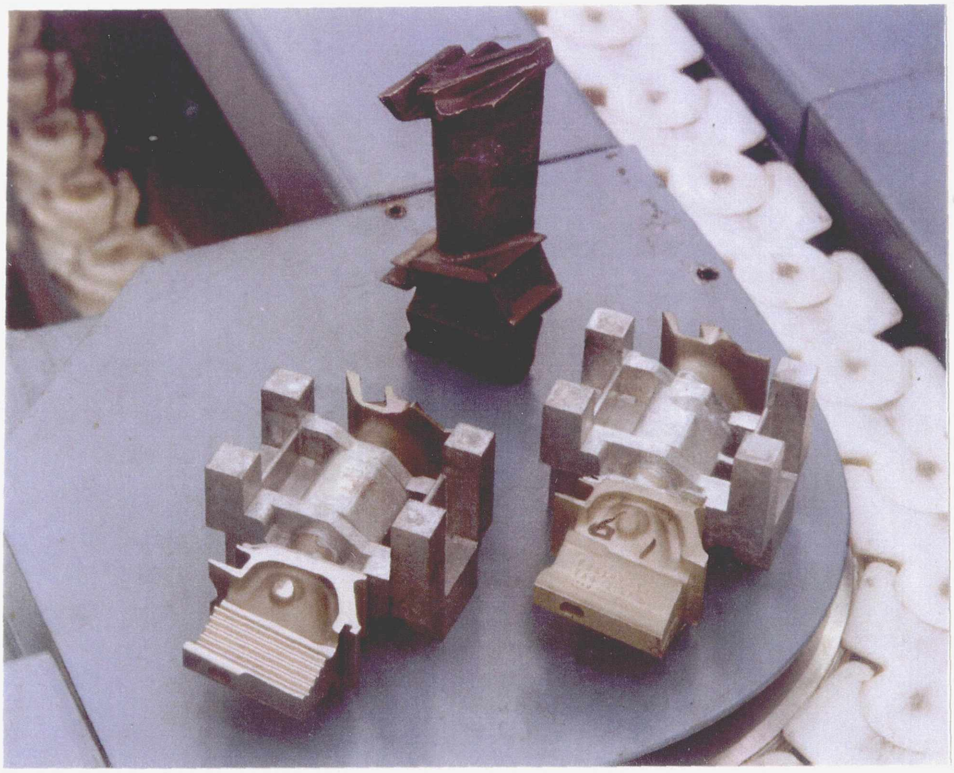


Plate 9 : Zinc Encapsulation of Blade Castings Enables Aerofoil Aligned Root and Shroud Grinding

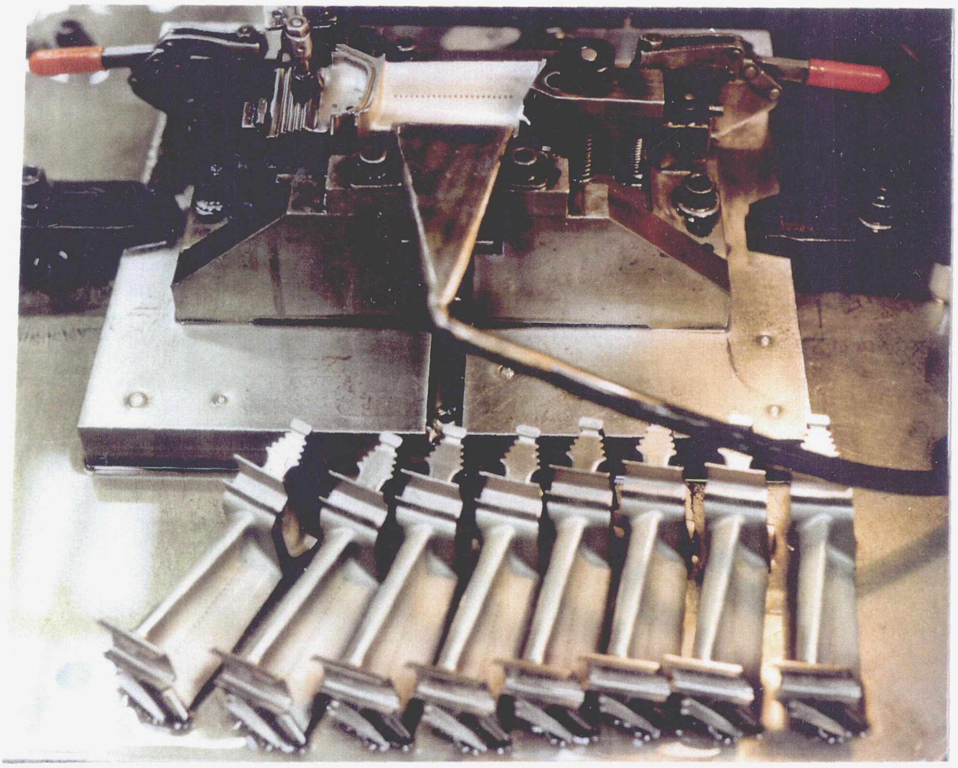


Plate 10 : Electro-Discharge Machining of Blade Film Cooling Holes

2.5.4 The Development Process

A blade design is verified in two types of test, firstly in rigs, which ascertain basic aerodynamic and vibration characteristics and secondly in engine tests, which ascertain component matching and expected life characteristics. Figure 2.14 illustrates the number of major tests which a high pressure gas turbine blade must undergo for certification.

The rig tests are conducted at about 300°C and enable the running lines of the blade to be mapped (the running line is the relationship between pressure drop and mass flow, from which efficiencies are determined). Vibration testing of the bladed disk assembly is also carried out on rigs because the temperatures are far more suitable for strain gauge readings and pressure probe equipment than in engine testing.

The engine test is obviously the most crucial assessment, to ascertain surface temperatures the blades are coated in a thermal paint which changes to a certain colour dependent on the maximum temperature it reaches.

During cooled blade development it is extremely likely that the initially designed pattern of film cooling holes will be altered to improve the cooling pattern over the blade. As has been stated: modelling the heat transfer coefficients over the surface is difficult and it is only the engine, in the final analysis, which will provide the absolute cooling requirement.

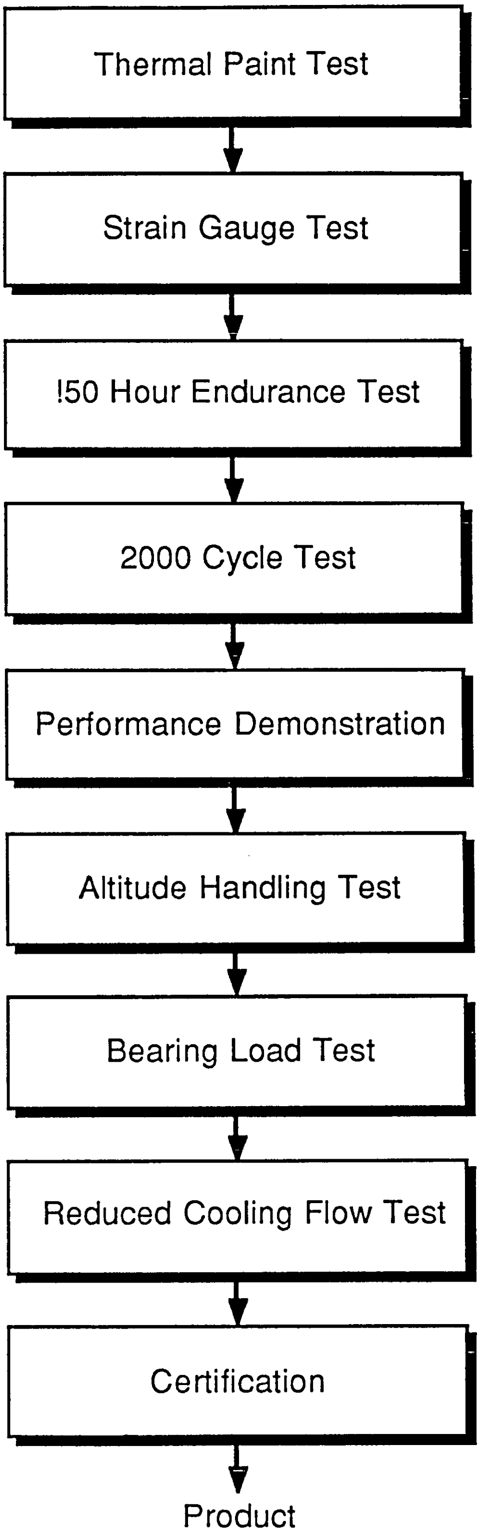


Figure 2.14

Development Procedure Required for the Certification of a High Pressure Gas Turbine Blade

2.5.5 Resume Of High Pressure Gas Turbine Blade Design, Manufacture and Development

This chapter has attempted to illustrate the highly complex processes involved in high pressure gas turbine design, manufacture and development. The cost of producing a new high pressure gas turbine blade is high and consequently new designs do not appear frequently. Figure 2.15 illustrates various developments of the high pressure gas turbine blades used in the RB211 family of engines.

One of the largest breakthroughs in turbine technology was achieved by the move from forging to investment casting which not only enabled significant metallurgical improvements but also complexity in cooling passage design. Which in its extreme has enabled the quintuple pass, directionally solidified blade.

The complexity of the high pressure gas turbine blade design and manufacture illustrates as an supreme example the problems involved in producing mechanical components. It may be said that one of the largest problems for the design and manufacture of such components is managing the increasing complexity. Therefore the high pressure gas turbine blade is ideal in demonstrating the task of integrating the various organisations, functions and systems to improve the design and manufacture process.

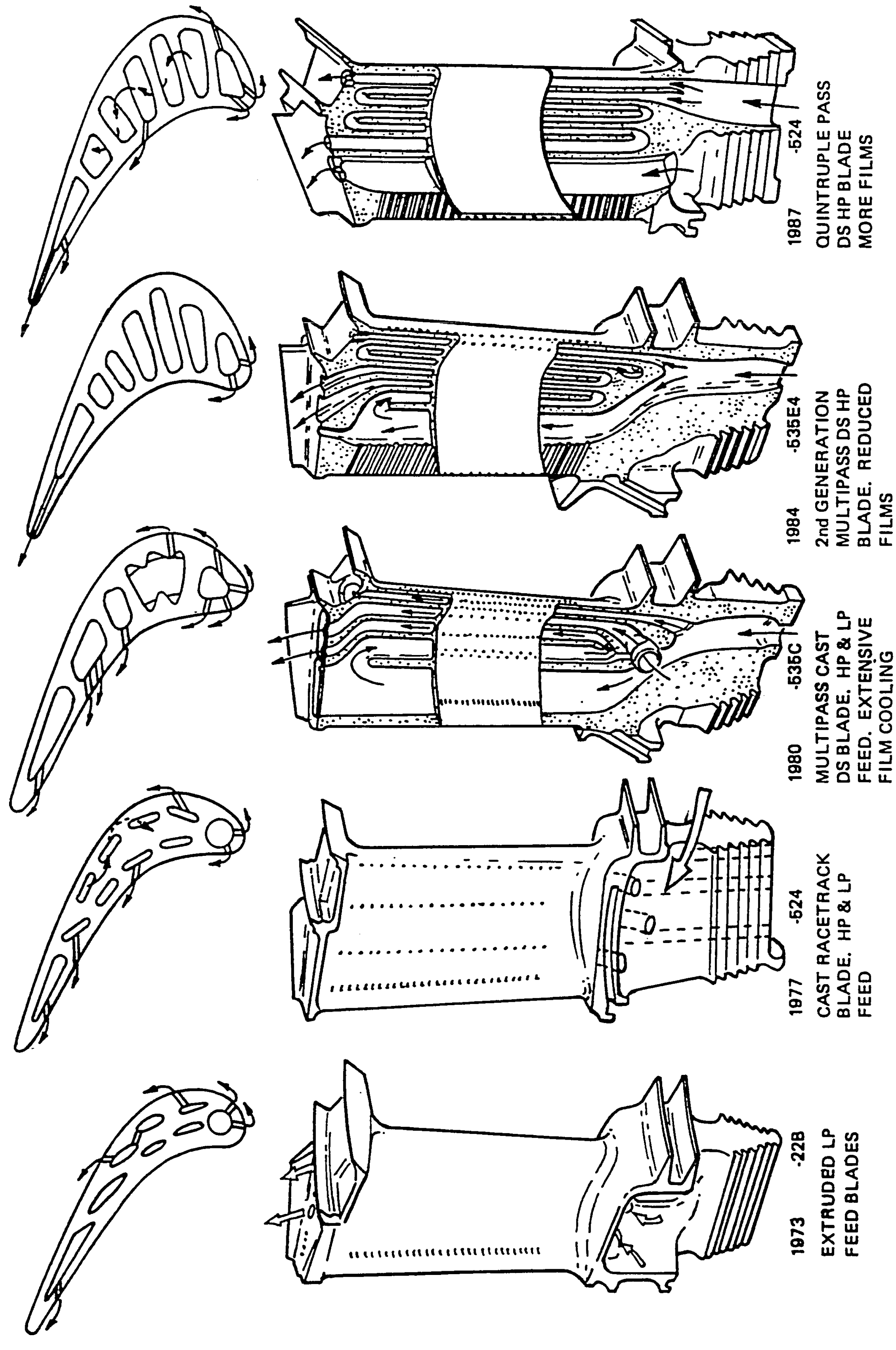


Figure 2.15

Developments In High Pressure Gas Turbine Blade Design For The RB211 Engine Family

References

[1] Ruffles, P.C., "Keys to Excellence in Design and Manufacture", Proceedings of Aerotec 90, Society of American Engineers, October 1990.

[2] Dodd, A.G., "Mechanical Design of Gas Turbine Blading in Cast Superalloys", Materials Science and Technology, Volume 2, May 1986, pp476-485.

[3] Langley, K.R., "Turbine Blade Design", Cranfield Institute of Technology Gas Turbine Design Course, May 1986.

[4] Ramsden, K.W., Melling, A., "Preliminary Turbine Design", Cranfield Institute of Technology Gas Turbine Design Course, June 1987.

[5] Higginbottom, G.J.S., "From Research To Cost Effective Directional Solidification and Single Crystal Production - an Integrated Approach", Materials Science and Technology, Volume 2, May 1986, pp442-460.

Chapter 3

Analysis For The Improvement In The Design and Manufacture Of High Pressure Gas Turbine Blading

3.1 Introduction

In 1984 a study was conducted at Rolls-Royce into the design, manufacture and development phases for the gas turbine. It was found that the high pressure turbine blade was on the critical path for the engine, and hence it was decided that it would be advantageous for the company to reduce this lead time. Further analysis of the development lead time for the high pressure turbine blade showed that probably the easiest time reduction would be achieved by shortening the manufacturing element.

Strong links at this time between the Department of Mechanical Engineering at Imperial College and Rolls-Royce suggested that the CIM technology being researched at the College could be exploited to reduce the manufacturing development lead time. Consequently an Imperial College/Rolls-Royce Teaching Company was set up to enhance and transfer the technology into Rolls-Royce.

The first part of this Chapter is principally concerned with the work that the Teaching Company performed in the reduction of manufacturing development lead time for the high pressure turbine blade. Subsequently the author has broadened the outlook of this work and has conducted a detailed study into the entire design and manufacture process. In the light of concepts such as Simultaneous Engineering and Taguchi's Quality Engineering suggestions are made for improvements in the component's lead time, design and manufacturing process and the technical assessment of the manufactured product.

3.2 Reduction In Manufacturing Development Lead Time

3.2.1 Analysis Of The Manufacturing Development Lead Time

The first task of the Teaching Company was a detailed analysis of the manufacturing process and its associated lead time [1]. This work was conducted at the Rolls-Royce Precision Casting Facility in Derby. Figure 3.1 illustrates the major elements of the manufacturing development process while Figure 3.2 illustrates the time taken for these activities. The major conclusions from the study were as follows :-

i. The requirement to proof cycle the investment casting process and the high scrap rates experienced during manufacture implied a lack of process understanding.

ii. Slow ceramic core die manufacture resulted in a large contribution to the lead time.

iii. Proof Inspection was manual, slow and provided virtually no statistical information, for only one blade, from the proof batch, was fully dimensionally inspected.

iv. The analysis of geometric error by Methods Engineers, for die modifications, was achieved by reading pages of numerical errors for positions over the blade surface and an interpretation of this error would be given to the pattern makers to dress back or plate up on the die surfaces. Such techniques in error handling were proving very limited.

v. During the various stages of production the castings were often waiting to move onto the next phase and not actually being worked on. There was therefore a large work-in-progress problem.

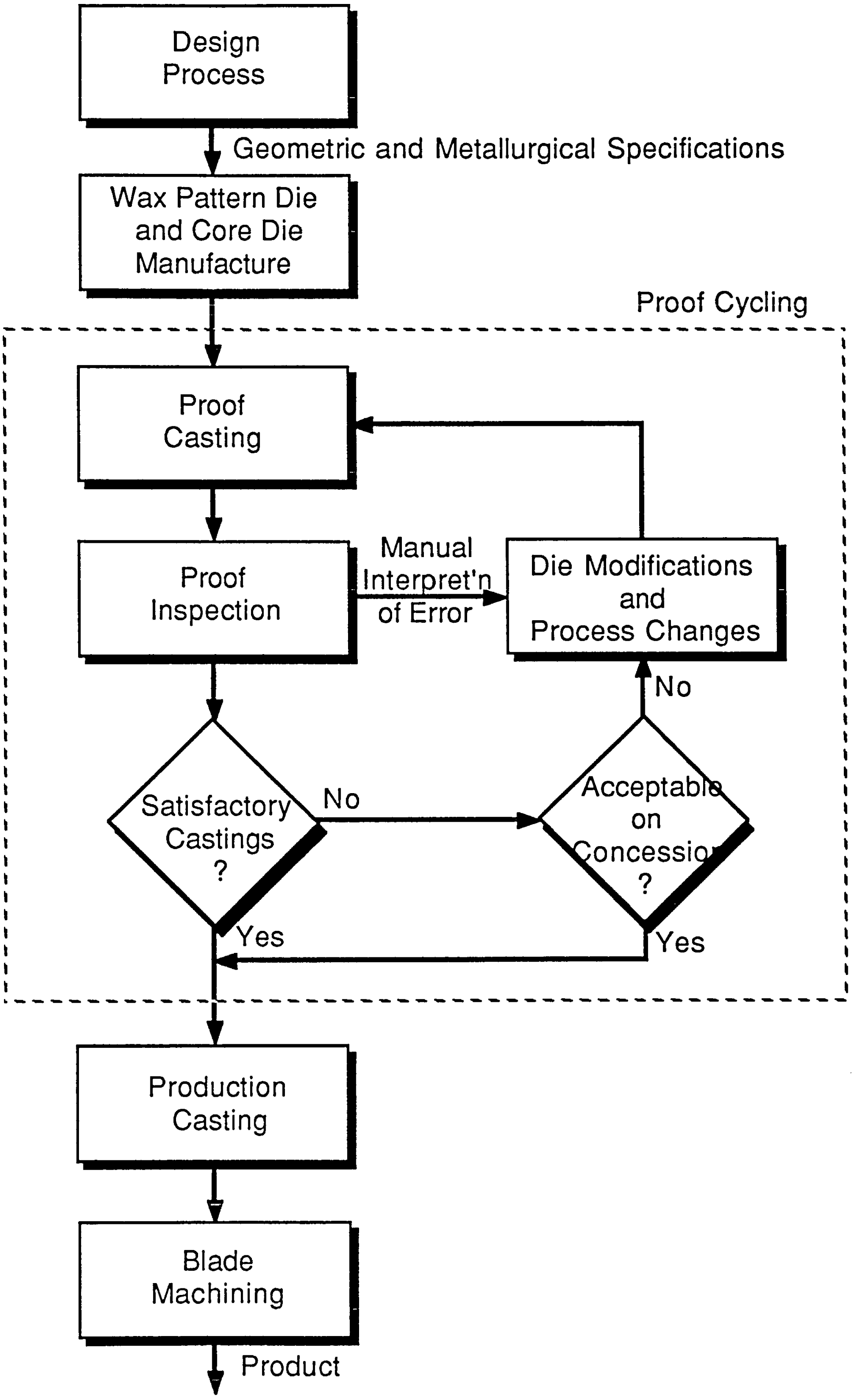


Figure 3.1

The High Pressure Gas Turbine Blade Investment Casting Proof Cycling Process

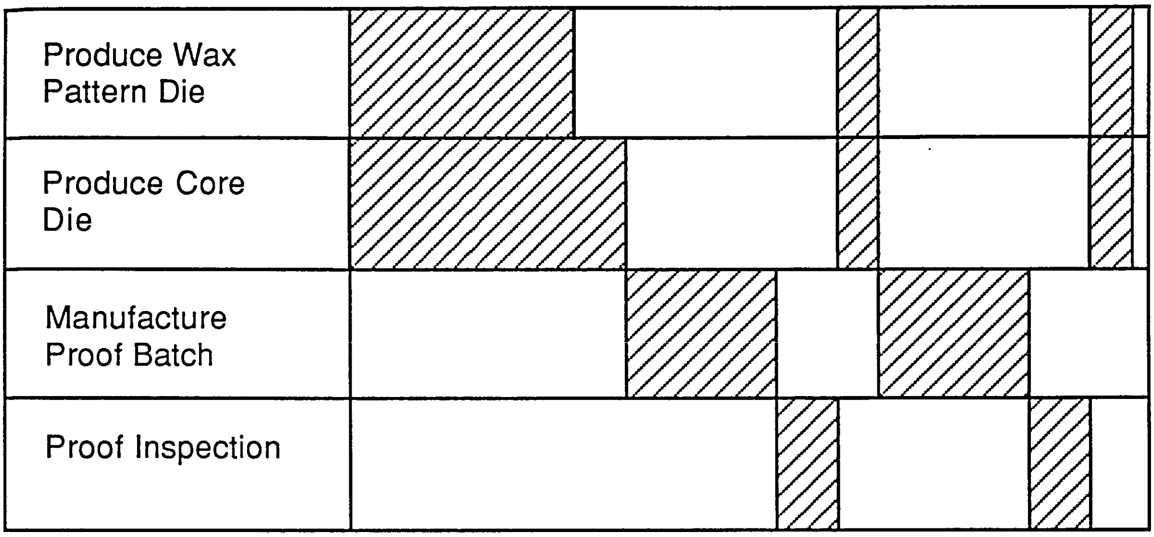


Figure 3.2

A Gantt Chart For The Manufacturing Development Lead Time of the Investment Casting Process for the High Pressure Gas Turbine Blade

From the analysis of the manufacturing development lead time some progress was made in reducing work-in-progress although it was felt that the largest improvement would be made by reducing the number of proof cycles. As the ceramic cores were manufactured by sub-contractors it was not possible for the Teaching Company to reduce this element of the lead time.

To reduce the number of proof cycles the Teaching Company instigated two main projects: Process Prediction and Automated Proof Inspection. The former was undertaken by N. Kumar and involved the development of a model of the casting process to enable new blade geometry to be analysed and optimum die geometry and process parameters calculated: ultimately this would lead to a system which removed the need to proof cycle.

The Automated Proof Inspection Project was undertaken by M. Cardew-Hall and attempted to use nominal blade geometry to control a coordinate measuring machine to measure blade surfaces. Inspection results would be obtained much faster from such a system than could be manually obtained and as a result statistical information could be produced by measuring the batch of proof castings. Since the results were to be obtained on a computer system they would be readily available for graphical presentation.

The work on Process Prediction and Automated Proof Inspection was started in 1985; a brief resume of the work of Kumar and Cardew-Hall is given below.

3.2.2 A Study Into Process Prediction

A detailed analysis of the casting process was undertaken from which it was concluded that there were approximately 300 variables which effected the geometry and metallurgical characteristics of the castings, ref [2] and [3] . Of these about 30 were considered to be highly significant and work was conducted in an attempt to gain an understanding of the relationship between these variables and their effect on the product. The aim was to produce a process predictor which would optimise process settings and required die geometry and be able to predict scrap rates and hence product costings.

It was realised that in order to understand dimensional casting an efficient method of measuring blades and trial shapes was required and hence a strong link formed between the process predictor and the automated proof inspection project. During his work Kumar was able to map out the effects of the variables in the casting process but was unable to move onto process prediction as the complexity of this subject was unrealised at the time of the project instigation.

After Kumar had finished his contract with the Teaching Company the work on Process Understanding was continued by C.Booth [4] who extended the work on trial analysis. Using experimental design techniques a large number of trials were conducted to produce optimum process parameters in the furnaces and shell coating procedures. Using the dimensional measuring system, developed by the author, Booth was able to analyse many of the dimensional effects of wax injection and casting finishing processes on blade geometry. Booth's work has lead to the development of a number of techniques to optimise process parameter settings in the casting process and a far better understanding of the various processes involved in the lost wax casting of turbine blades.

3.2.3 A Study Into Automated Proof Inspection

Prior to M. Cardew-Hall's work on automated proof inspection a number of projects had been instigated to assist in dimensional measurement. One of these projects, also at the Rolls-Royce Precision Casting Facility, became the starting point of the Teaching Company study. This work had attempted to use a Cordimet 3-axis Coordinate Measuring Machine (CMM) controlled by a Hewett-Packard computer to measure aerofoil surfaces [5]. Alignment of the blades was achieved on a fixture which was especially manufactured and enabled the blade to be clamped into the correct position before it was moved onto the Cordimet to be measured. Unfortunately the complexity of blade geometry, the use of large inaccurate fixturing and the severe limitations of the Hewett-Packard computer prevented success of the project which lead Cardew-Hall to conclude that a far better system was required.

Detailed analysis of the inspection process showed that a more advanced CMM control technology was required. It was concluded that an inspection system should be capable of aligning the blade on the CMM and hence remove the need for complex and expensive fixturing. To facilitate this the Teaching Company work was extended to the design of a laser-triangulation measurement system at Imperial College, Heath [6] and Tsabourakis [7], capable of measuring aerofoil surfaces.

As well as the project at Imperial College it was also decided to buy a more conventional CMM incorporating a touch trigger probe. Following a market survey it was concluded that the Mitutoyo company produced a machine that was best suited to interfacing with a proposed off-line programming system.

The complexity of aerofoil surfaces implied to Cardew-Hall that is was necessary to explicitly control the motion of the CMM. This he chose to do by modelling the blade geometry and generating probe paths from it, in a similar manner to the way in which the blade dies are machined using NC tapes generated from blade surface geometry. To model the geometry the PANACEA CIM system, written by Glover [8], was chosen. This offered a number of advantages over commercially available packages :-

i. It was a fast Unix based programming environment.

ii. It had a powerful graphics display facility.

iii. Additions to the program could be quickly and easily made by Glover or in consultation with Glover, as he too was based at Imperial College.

By the time Cardew-Hall had left the Teaching Company a simple probe path generator existed within the PANACEA system which used nominal blade geometry constructed in a blade modelling package also within the PANACEA system [1] [9]. The continuation of this work to achieve blade measurement was carried out by the author and forms a major part of this thesis.

3.2.4 The Development Of The Computer Integrated Blade Manufacturing System

The need for both the process predictor and the automated proof inspection projects to use blade geometry indicated that they should use a common database. This work and the integration of the two projects was carried out by a further Teaching Company Associate N. Brookes. It was perceived that a central data logging computer could monitor the process parameters and feed them to the process predictor. Results from dimensional inspection would simply be a part of the monitoring facility. Brookes created the concept of the monitoring facility which became known as the Computer Integrated Blade Manufacturing System (CIBMS) [10].

Central to the CIBMS was the 'Modeller Interface' between the nominal geometry, the monitored process parameters and manufactured geometry. Brookes spent a significant time in generating the blade modelling facilities within the PANACEA system and the host of programs required to facilitate its use. By the time Brookes left the Teaching Company a blade modelling facility existed on a SUN 3/60 computer for use by the process prediction and automated proof inspection projects.

3.2.5 Resume Of Work Carried Out For The Reduction in Manufacturing Development Lead Time

The high pressure gas turbine blade design and manufacture development lead time was shown to exist on the critical path of the gas turbine, from which it was decided that this development time should be reduced. Further study showed that changes to the manufacturing development lead time were probably the easiest area in which to achieve improvement. To facilitate this work an Imperial College/Rolls-Royce Teaching Company was instigated.

The principal reasons for long manufacturing development lead times were put down to the need to proof cycle which illustrated a lack of process knowledge. To improve this situation work was started on process understanding and automating dimensional inspection. The very strong links between these two subjects resulted in proposals for an integrated system under the title of the Computer Integrated Blade Manufacturing System. A reduction in manufacturing lead time from such a system would come from :-

i. A reduction in the number of proof cycles.

ii. A shortening of the lead time for each proof cycle.

Although the above studies were proposals for the reduction in lead time for the high pressure gas turbine blade the development of philosophies like Simultaneous Engineering and Taguchi's Quality Engineering suggested that an optimum reduction in the product development lead time would not come from consideration of one element of the overall process alone. It could be said that it is only possible to achieve optimisation of the lead time by consideration of the entire design and manufacturing process. It is the analysis of the whole process for the high pressure gas turbine blade which forms the remainder of this chapter and the consequences from this that form the work of this thesis.

3.3 Further Analysis For The Improvement Of The Design and Manufacturing Process

Simultaneous Engineering [11] [12] [13] [14] [15] [16] and Taguchi's Quality Engineering [17] [18] philosophies have been designed to achieve total balance if the compromises made in the product design and manufacture process. That a designed and manufactured item has resulted from meeting compromises at all would suggest that an optimum component may only be achieved when all the compromises are considered and weighed up together. In this respect the concepts of product and process development are reiterated by Alexander and Douglas in their Totally Integrated Engineering philosophy [19]. This 'holistic' approach to product and process development will only come by the integration of the design and manufacturing activities.

Within the framework of a free-market economy the balance between the design and manufacturing compromises should be accounted by the overall costing of a project, this is a basic principle of Taguchi's Quality Engineering philosophy.

Before describing how the principles of Simultaneous Engineering and Quality Engineering could be implemented for high pressure turbine blade design and manufacture it is worth briefly considering again the process from the point of view of the people and systems involved, see Figure 3.3.

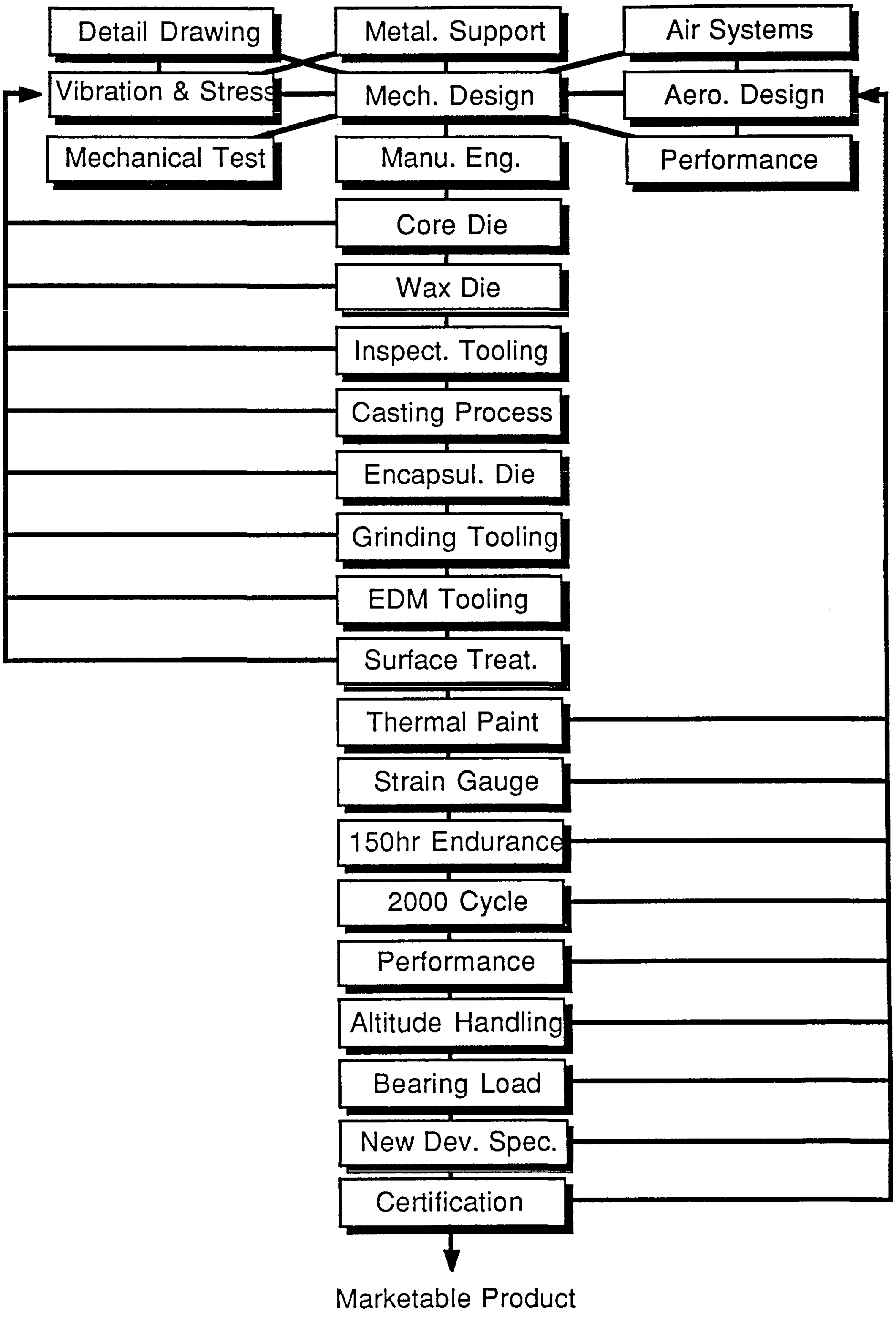


Figure 3.3

The Total Activity Directly Employed in the Design, Manufacture and Development of the High Pressure Gas Turbine Blade

Reiterating the high pressure gas turbine blade design and manufacture process: design specifications produce the iterative loop between the design specialists that eventually yield a product definition. Manufacturing take the product definition and convert it into a process definition. As the first production blades are produced development testing commences and the results are fed back into design for validation and subsequently any product definition changes that are required.

It is always worth remembering that despite the enormous analysis that goes into the design of components like high pressure gas turbine blades it is the engine that will decide whether a product is good or not. Thus the entire process from design to development may be seen as a large iterative loop in specifying the final product.

From Figure 3.3 it may be observed that the design, manufacture and development of a high pressure blade involves a very large number of people and over a significant time scale. Consequently achieving an overall compromise with this many specialists is a major challenge. Indeed one of the observed phenomena of such a process is the lack of understanding between engineers in their roles and the constraints that each person is working within.

One of the reasons for this is the separation of the engineers, from the organisational point of view into different departments, and the difficulties in communications that follow from this. The divisional structure of large companies and the increasing numbers of specialists involved in the design and manufacture process tends to create false barriers between concerned groups. In the long term these divisions may be observed to lead to a mismatch in understanding of the product and process development: 'Design become unaware of manufacturing capability and manufacturing of design intent'.

To exacerbate this communications problem the design and manufacture process has become so complex that the information must now be passed between corporate structures or even out to sub-contractors. Yet design and manufacture information must be able to flow as freely as possible between them. Each divisional structure will employ engineers and train them separately. Pay structures may be different as well as working environments. The long term effect of these divisions is that people working along the chain of design and manufacture become separated.

Under the principles of overall compromise, as suggested by Simultaneous Engineering, and the need to derive, in financial terms, all design and manufacturing parameters, as suggested by Taguchi's Quality Engineering, it is necessary to structure the systems of organisation and communication within the design and manufacturing process to overcome such divisional tendencies.

One of the best methods of achieving high levels of integration has been the development of 'integrated' design and manufacture teams. The principle of such 'organic' working practises is that natural lines of communications will evolve which will be helped by good leadership and a strong sense of group identity.

Central to the process of communication between engineers is the design drawing, represented more and more within CAD/CAM systems. In the past specialist groups have tended, to develop their own systems which has led to the long term problems of information exchange. A further problem is that often CAD systems and previous design philosophies have been centred about passing information one way - design to manufacture. However under the principles of Simultaneous Engineering and Taguchi's Quality Engineering it is now extremely important that information flows freely both ways. For only by analysing the relationship between manufacturing capability and component functionality can the financial justifications for improvements in either design or manufacturing capability be made.

By aiming to achieve total compromise within the design and manufacturing process it is worth considering one of the improvements to the design and manufacturing philosophy that would follow. If during design the true limitations and variabilities of manufacturing constraints are known then the product can be designed so that the effect of these constraints are optimised to the functionality of the component. Within manufacture, effort on process improvement can be concentrated on those areas which are responsible for limiting the functionality of the product.

An optimum design and manufacturing compromise will only be met by consideration of every element within that compromise. The overriding issue being the overall costing on which the entire project is based. Such considerations will only be achieved by the correct organisation of the design and manufacturing activities and the communication systems set up within them.

3.4 A Proposal For The Improvement Of The Design and Manufacturing Process For High Pressure Gas Turbine Blades

Following the principles of Simultaneous Engineering and Quality Engineering Figure 3.4 illustrates the type of procedure that could be adopted for the design and manufacture of high pressure turbine blades.

3.4.1 Reduction in Lead Times

One of the key features of Simultaneous Engineering is in reducing lead times. It does this by stresses two activities; firstly it asks for the involvement of all key engineering staff, who will be involved in the project, to input their ideas at an early a stage as possible in the design process - this enables a well balanced design to be formulated. Secondly it asks for as many of the design and manufacturing processes as possible to be carried out in parallel.

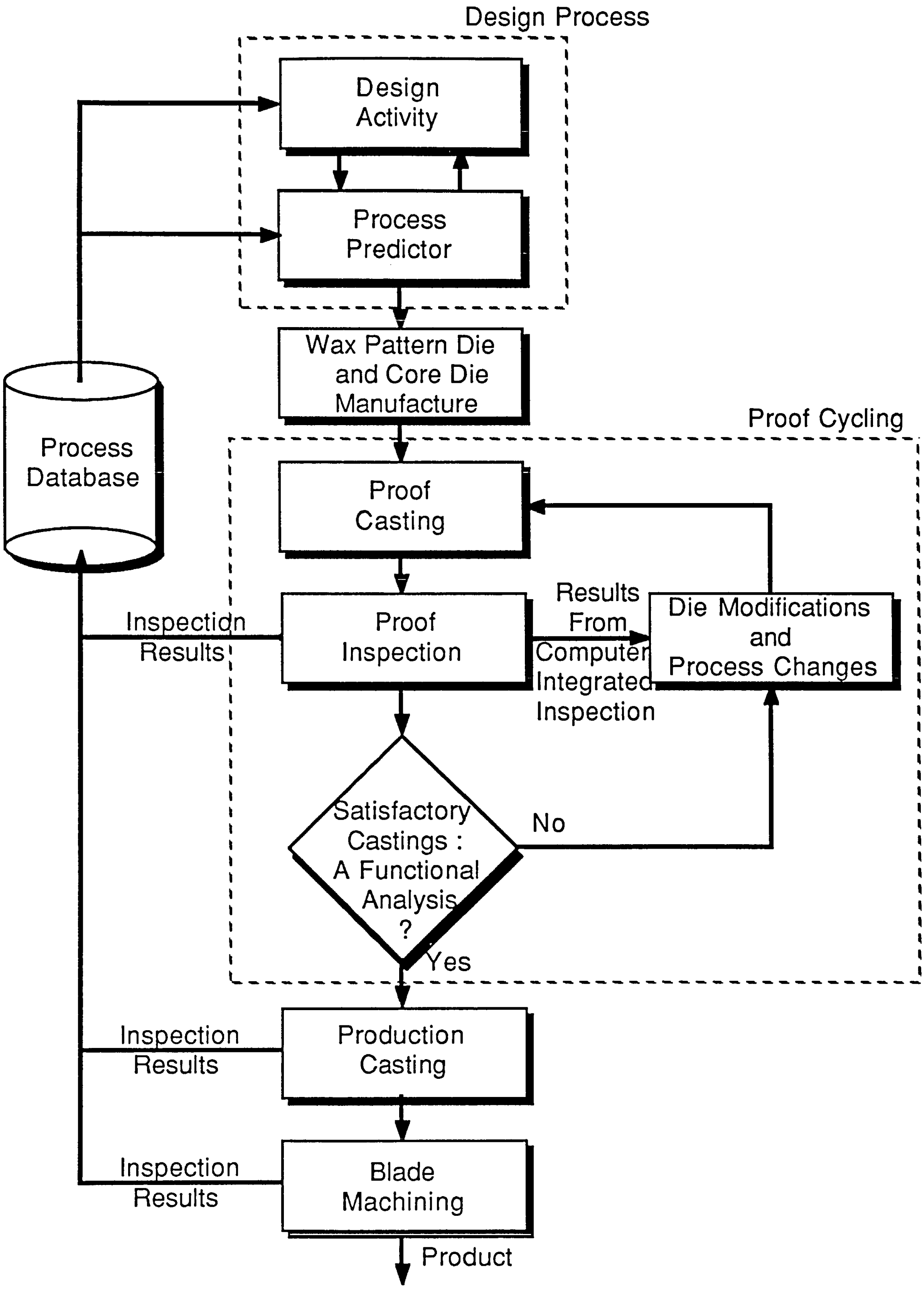


Figure 3.4

A Proposal For Improvement In The High Pressure Turbine Blade Design and Manufacture Process

By including all of the engineering staff that will be involved in a project at an early stage in the design process and by continuing to involve them as major decisions are made it is possible to avoid producing designs which do not meet a good overall compromise. Such discussions also illustrate where improvements should be made to methods, be they design or manufacturing, and provide time for such developments to be made.

One problem with large organisations which have very many departments involved in the design and manufacture of components is that there is a tendency to plan projects along the line of departments, the idea that when one group has finished their activity it is passed onto the next. However as the number of departments increases this line gets longer. If lead times are to be reduced there is no reason why all the engineers involved on the product and process definition should not become involved as early as possible, ignoring the departmental divisions.

It could be argued that while a project is being undertaken departmental divisions are meaningless for what is important is that the right product is produced in the right time. In an ultimate scenario it could be envisaged that during a project, integrated team members would have no loyalty other than to their particular project team.

Another extremely important issue concerning the transfer of information between departments involved in design and manufacture is that key aspects of functionality are not well expressed on engineering drawings or CAD/CAM models. What is meant by this is that the transfer of nominal geometry says nothing for the functionality. Some areas of a geometry may be far more critical to functionality than others and unless everyone is aware of these issues some functionality may be compromised unnecessarily.

A good example of the loss of functional information between design and manufacture is exhibited in turbine blade manufacture where the effort applied to the control of manufactured aerofoil geometry is same over the entire surface, when from the point of view of functionality the regions responsible for controlling diffusion are far more important.

To overcome this loss of functional information when transferring data between engineers it is vital that these problems are appreciated and that effort is applied to communicating key functional issues.

3.4.2 Common Computing Databases Throughout a Product and Process Definition

Increased competitiveness in design and manufacture comes from the ability to reduce the cost of a product. Computing systems have enabled designers and manufacturing engineers increasingly to model the conditions in terms of the stresses, aerodynamic loadings, manufacturing processes etc to which components will be subjected. This has provided more 'right first time' designs of lighter weight, increased performance and reduced cost. However for advanced aero-engine components the number of design iterations required to achieve a satisfactory design is increasing.

Once a basic design configuration has been agreed often the remaining design process is simply a matter of iterating to solution. Obviously the faster these iterations the shorter the lead time. Therefore it is vitally important, if the design iterations are based on computing systems, that all of the design and manufacturing databases are common. Transferring data between different systems is often very time consuming and is entirely non-value added activity.

3.4.3 Process Modelling

During the early phases of design it is essential to gain some understanding of how easy it will be to manufacture the proposed components. To this end the experience of manufacturing and design engineers is used to estimate the complexity of the manufacturing task. Unfortunately because of the currently adopted procedures of inspection very little process knowledge is stored and may be used to calculate process capabilities. In an ideal world design proposals could be tested in the foundry to ascertain manufacturing capability. However the cost and time scales involved would make this financially unjustifiable.

As a step towards test manufacture a 'Process Predictor' [20] could be envisaged. Perhaps a computer system which accepted designs and analysed the process capability on the grounds of previous knowledge. In its simplest form a process predictor is a database which may be called upon to present process spreads for example in wall thichnesses or surface profiles. In its most complex form a process predictor would calculate die geometry and set process settings, indicate scrap rates and their causes.

With any degree of process predictor the designer is matching process capability with design intents. It may be concluded that a level of functionality cannot be achieved within the offered process capabilities, in which case the process would have to be improved or the level of functionality accepted. By a detailed study of the process the designer and manufacturing engineers will see clearly those parts of the process which need to be improved and those which are beyond reasonable cost effective process development.

3.4.4 Integrated Inspection Database

The casting and machining processes involved in high pressure turbine blade manufacture are so complex that in order to analyse the various stages involved some type of systematic storage and retrieval system for inspected data is essential. Such a database could serve as an on-line process monitoring system illustrating problems with any of the processes and conveying these to the methods engineers.

One problem with process databases for casting and machining operations is the enormous quantity of data that becomes available for storage. This presents two challenges; firstly the physical storage of the information and secondly providing reasonable speed and ease of data retrieval. The errors over the complex surfaces of turbine blades present enormous volumes of information which is useful only if presented in a suitable manner.

A further problem is the storage of non-geometric information and its presentation. For example grain structure defects or shell composition. All of this information is useful to the process development engineer and process predictor programs but represents significant difficulty in concise storage and retrieval.

3.4.5 Computer Integrated Proof Inspection

The current process of proof inspection is limited by manual inspection techniques. However advances in computer control suggest that the inspection could be assisted by the use of measuring machines which offer significant time savings. The use of a computer to record the inspected data and present it enables fast and easy representation of the error. However such systems offer more than just a replacement of a manual process.

The complexity in functionality of turbine blading is such that the decision as to whether the manufacturing process warrants further proof cycling should surely be based on whether the component that is being produced is capable of performing the required task, not is it inside or outside of a certain geometric size. The interactivity between the critical aspects of turbine blade functionality are such that to assign a tolerance to a specific dimension says very little as to how the component will actually function. Therefore it is proposed that the decision as to whether to continue to proof cycle be a joint design and manufacturing one based on functional analysis of the manufactured geometry.

This method of decision making would not only serve to determine true acceptability of the product but also integrate design and manufacturing by illustrating manufacturing capabilities to designers and design specialists and the effects of manufacturing capabilities on functionality to manufacturing engineers.

With a computer record of the manufactured geometry it is be possible to analyse the effects of any distortion in exactly the same manner and with the same tools and computer programs used to analyse the nominal geometry. In this way manufacturing capability is compared directly with the loss of component functionality.

If after proof inspection it is decided that modifications are required to the process dies and these errors are recorded within a computer system there is no reason why these errors could not be used to modify the NC tapes that cut the original die. In this way the results from the computer controlled inspection may be used to respecify the required die geometry in a computer integrated closed loop modification process. In other words the manual proof inspection, manual interpretation of error and manual die modification is replaced with a computer integrated technique.

3.4.6 Process and Production Measurement

As manufacturing becomes increasingly competitive the needs to achieve quality at low cost are growing. As a method of achieving this the philosophies of inspection are changing [21] [22]. Rather than measuring the end product the process is now being inspected, this imposes new requirements for inspection systems.

The need to provide designers and process development engineers with process information implies the need for systematic methods of logging inspection data. Such information needs to be numerically based and not simply the results of the numbers of parts inside or outside of a dimensional or process tolerances. The consequence of requiring numerical information from production geometry and process parameters is that gauging needs to be replaced with dimensional measurement equipment capable of logging inspection results.

Using the concept of functional analysis rather than dimensional tolerancing it would be possible to envisage a production measuring machine performing a functional analysis of the final component it was measuring rather than a purely dimensional comparison. Dimensional tolerance limits could be replaced by an analysis to determine maximum stress and aerodynamic performance which would become the new acceptable 'limits'.

3.4.7 Resume Of Proposed Improvements To Design and Manufacture Procedures

One of the major principles outlined by the philosophies of Simultaneous Engineering and Quality Engineering is that since a product definition process involves compromises all of these compromises should be weighed up together. With the overall balance being struck by the financial strategy being adopted in the particular market that is being targeted.

Where products involve extremely long and complex development lead times it becomes difficult to meet the overall compromise because of the numbers of people involved and the level of communications that must be achieved between them. In a large company often information must flow across corporate structures. The long term effects of these departmental structures is to separate knowledge between groups along the line of communications which results in the type of problem where design are unaware of manufacturing capabilities and manufacturing of design intents.

Within a design and manufacture process it is observed that beyond geometric and metallurgical specifications good communications should also involve the reasons why specifications are made. This information may often be useful when other engineers further along the design and manufacture process have to make decisions that effect the functionality of the component.

One useful tool for improving communications is the 'integrated team' which brings together all of the design and manufacturing specialists involved in a project. This aims to provide for a project identity which encourages and directs the activities of the team. It is an example of an 'organic' form of project management.

Computing systems are an ever increasing method of transferring engineering specifications; however in the past these have tended to be specialist based and difficulty has been experienced in communications between them. Further to this information flow has tended to be one way - design to manufacture - which has further exasperated the divisions between the design and manufacture groups.

Using the principles of Simultaneous Engineering and Quality Engineering a number of proposals have been made for improvements in the design and manufacture procedures. These have primarily been centred about more integration of the whole process.

Improved understanding of the manufacturing capabilities and their effect on the product should be made early on in the design process. This could be aided by the use of process predictors. Such tools would enable designers to reduce the effect of manufacturing capability on product functionality and for the process development engineers to target improvements in those areas of the process most responsible for limiting product functionality.

Such process predictors require integrated inspection databases, which store the manufacturing results in a convenient and easy to retrieve manner. These would serve not only process predictors but could be used as on-line process monitoring facilities. Integrated inspection databases require dimensional measuring machines and not gauging machines. Information on component metallurgical characteristics is also required.

For manufacturing processes which undergo iterations, for example the proof cycling of cast turbine blades, it is proposed that computer integrated proof inspection would not only be faster than manual proof inspection but also be capable of presenting results in a clearer manner. Such inspection enables completely integrated feed back of modifications to die geometry. More over since the actual geometry of the product is known within a computing environment it would be possible to feed this up to the design areas for an appraisal of the component for its functionality.

For extremely complex components such as high pressure turbine blading it may be said that geometric tolerancing is an extremely 'crude' method of assessing the compromise between manufacturing capability and loss in component functionality. Thus it is proposed that measured geometry be modelled to allow for its functionality ascertained. Such a philosophy could be applied during the proofing of a process to determine whether a process requires further iterations, it could ultimately be extended into production measurement procedures. A further advantage of assessing functionality is that it directly relates design intent to manufacturing capability.

Using the principles of Simultaneous Engineering and Taguchi's Quality Engineering on the design and manufacture of high pressure gas turbine blading it was concluded that two-way communications must flow between all parties within the design and manufacture process. These communications should be at all levels. Good communications can be fostered by appropriate organisation, for example the use of integrated teams, but one area which had received little attention was the two-way flow between design intent and manufacturing capability. It was therefore proposed that integrated inspection techniques and systems be developed along with methods for appraising manufactured geometry and metallurgical properties. The next four chapters are dedicated to the design and development of an integrated inspection system capable of providing the two-way communications of geometry and manufacturing capability between turbine blade design and manufacturing activities.

References

[1] Cardew-Hall, M.J., "Modelling and Integrated Inspection of Cast Turbine Blades", PhD Thesis, Imperial College, University of London, June 1988.

[2] Kumar, N., Besant, C.B., Ristic, M., "Process Variables Determining the Dimensional and Metallurigal Properties of Directionally Solidified Cored Turbine Blades Produced by Investment Casting of Super-Alloys", The International Journal of Advanced Manufacturing Technology, Volume 3, 2, May 1988, pp3-19.

[3] Kumar, N., "Modelling of Precision Investment Casting Processes", PhD Thesis, Imperial College, University of London, September 1988.

[4] Booth, C., PhD Thesis, Imperial College of Science, Technology and Medicine, University of London, In Preparation.

[5] Rolls-Royce plc, "Cordimet CMM Control System", RR Report EIR14077, Derby, England, 1981.

[6] Heath, A.J., "Non-Contact Profile Gauging of Turbine Blades and Wax Patterns", BSc(ENG) Thesis, Department of Mechanical Engineering, Imperial College, University of London, June 1986.

[7] Tsabourakis, N., Ristic, M., Besant, C.B., "Development of a Profile Gauging Sensor", The International Journal of Advanced Manufacturing Technology, Volume 3, 2, May 1988, pp51-66.

[8] Glover, R., Besant, C.B., "A Graphics Environment for CIM Applications",

The International Journal of Advanced Manufacturing Technology, Volume 3, 2, May 1988, pp31-39.

[9] Cardew-Hall, M., Cosmas, J., Ristic, M., "Automated Proof Inspection of Turbine Blades", The International Journal of Advanced Manufacturing Technology, Volume 3, 2, May 1988, pp67-88.

[10] Brookes, N.J., Besant, C.B., "Reduction in the Development Lead Times of Complex Investment Castings by the Application of CIM technology", The International Journal of Advanced Manufacturing Technology, Volume 3, 2, May 1988, pp41-49.

[11] Miller, S.C., "Getting It Together", The Fellowship of Engineering Presentation given at Newcastle University, July 1990.

[12] Broughton, T., "Simultaneous Engineering in Aero Gas Turbine Design and Manufacture", Rolls-Royce plc, December 1990.

[13] Ziemke, M.C., McCollum, J.K., "Simultaneous Engineering: Innovation or Resurrection ?", Business Forum, Winter 1990.

[14] Whitney, D.E., "Manufacturing by Design", Harvard Business Review, July-August 1988, pp83-91.

[15] Putnam, A.O., "A Redesign for Engineering", Harvard Business Review, May-June 1985, pp139-144.

[16] Dean, J.W., Susman, G.I., "Organizing for Manufacturable Design," Harvard Business Review, January-February 1989, pp28-36.

[17] Taguchi, G., "Introduction to Quality Engineering", Asian Productivity Organisation, Unipub, Quality Resources, White Plains, New York.

[18] Henshall, E., "The Application of Taguchi Techniques", Institute of Mechanical Engineers, Seminal Papers: "Quality Techniques", C399/39, January 1990.

[19] Alexander, J.D., Douglas, J., "Integrated Total Engineering", Advanced Manufacturing Engineering, Volume 1, October 1988, pp11-14.

[20] Towers, O., "Modelling of Turbine Blade Casting (DS/SC) and Review of Pouring Simulation", BICTA Satellite III on Solidification Modelling, Rolls-Royce Advanced Engineering Brochure, PVJ530D, January 1987.

[21] Waldz, D.B., "Automated Inspection: Boon or Boondoggle", Proceedings of the 8th International Conference of Automated Inspection and Product Control, June 1987, pp363-374.

[22] Douglas, J., "Integrated Inspection for 'Fast-Make' Facilities", MTL50037, Rolls-Royce plc, 30 October 1988.

Chapter 4

Design Of An Integrated Inspection System For Gas Turbine Blading

4.1 Specification Of The Integrated Inspection Task

In Chapter 3 it was shown that applying the philosophies of Simultaneous Engineering and Taguchi's Quality Engineering to the design and manufacture of turbine blades implied the need to inspect these manufactured products so that the results may be passed throughout the entire design and manufacture activity. 'Integrated Inspection' has become the name commonly used for inspection under these integrating philosophies.

With regards to process development it was recognised by Booth [1] that it is necessary to measure, not just the final product but also the various stages in the process from which the product is derived. So for example in the lost wax casting process it is necessary to measure the dies, cores, waxes and shells as well as the final castings.

During the proofing of processes it is necessary to measure batches of products and present errors and process spreads quickly and in an easy to interpret manner. For the investment casting process the inspection must be capable of measuring complex surfaces, calculating errors and performing error minimisation calculations. Potentially such systems should be linked to programs which calculate the functionality of the product as well as the geometric distortions.

The work of this thesis is concerned principally with geometric inspection, considerations of material property inspection are made by Booth [2]. The remainder of Chapter 4 reviews various methods of inspection for their potential use in an integrated inspection system for turbine blade measurement. This is followed by a description of the design of such a system. Chapters 5, 6 and 7 describe the implementation and development of the system.

4.2 Categories In The Physics Of Geometric Inspection

4.2.1 Introduction

One of the basic requirements of geometric inspection is to know where a position in space is relative to another. From this fundamental description various physical principles may be employed to achieve this task. Such principles tend to fall into one of two categories; contact or non-contact. Contact being the employment of instruments which make physical contact with the point of inspection. Non-contact being those processes which do not involve solid instruments, but instead other physical properties such as light's finite time of flight or amplitude variation with distance. A brief resume of contact inspection techniques is presented in section 4.2.2 and non-contact techniques in section 4.2.3.

4.2.2 Contact Inspection Techniques

The traditional instruments of manual inspection are the micrometer, vernier or height gauge, dial test indicator, sine bar and rotary table. These are tools for fundamentally one dimensional inspection. The accuracy of these devices depends greatly on what the user is prepared to pay and the skill of the operator. Over complex surfaces such tools are difficult to use and take significant time. From the point of view of systematic data logging they are very unsuited to complex surface measurement.

Another well established tool for measurement is the optical projector. In this device a small penny is run along the surface to be inspected, by the use of cantilevers and rods another penny is made to move through space in exactly the same manner. By shining a light onto the second penny a shadow of its image is projected onto a large screen, magnifying the image perhaps 10 or 50 times. With the aid of enlarged drawings comparisons are made between the drawing and the path of the penny. This is very much a comparison technique of inspection but measurement is possible with the use of scale drawings over the projected image. Systematic data logging can be less of a problem with optical projectors than with manual inspection tools, although such devices often have problems projecting over areas of high curvature.

Further contact tooling includes the use of fixtures which are specifically manufactured, usually mechanical, devices which when applied to an object indicate the relative position of chosen target points. Such mechanisms, including drop gauges, have become increasingly sophisticated and may be connected to electronic recording devices. With regards to systematic data logging such systems may be ideally suited, although over complex surfaces fixtures have limited capability.

Within the framework of increasing computer numerical control Coordinate Measuring Machines (CMM) have emerged over the past 25 years. Derived from reconditioned jig boring machines current CMMs have developed their own style of design (which will be discussed in more detail in section 4.3.3). CMMs usually carry probe heads which inform the machine's controller of a collision with the target point. By recording the machine's axis positions at the moment of probe contact and by knowing the geometry of the CMM it is possible to relate these values to real coordinates. As these machines are computer controlled they are potentially extremely powerful at both complex surface measurement and systematic data logging.

4.2.3 Non-Contact Inspection Techniques

One of the largest developments in non-contact inspection has been three dimensional light imaging techniques. McCollum et al [3] illustrate that there are several methods of acquiring depth information and these may be classified into two types: direct and indirect, see Figure 4.1. Direct methods produce raw images which are immediately related to range, whereas indirect methods infer depth information from secondary characteristics of a scene such as texture or reflectivity. Further subdivision is possible for both types of three dimensional imaging methods into passive and active techniques, depending upon the kind of lighting involved.

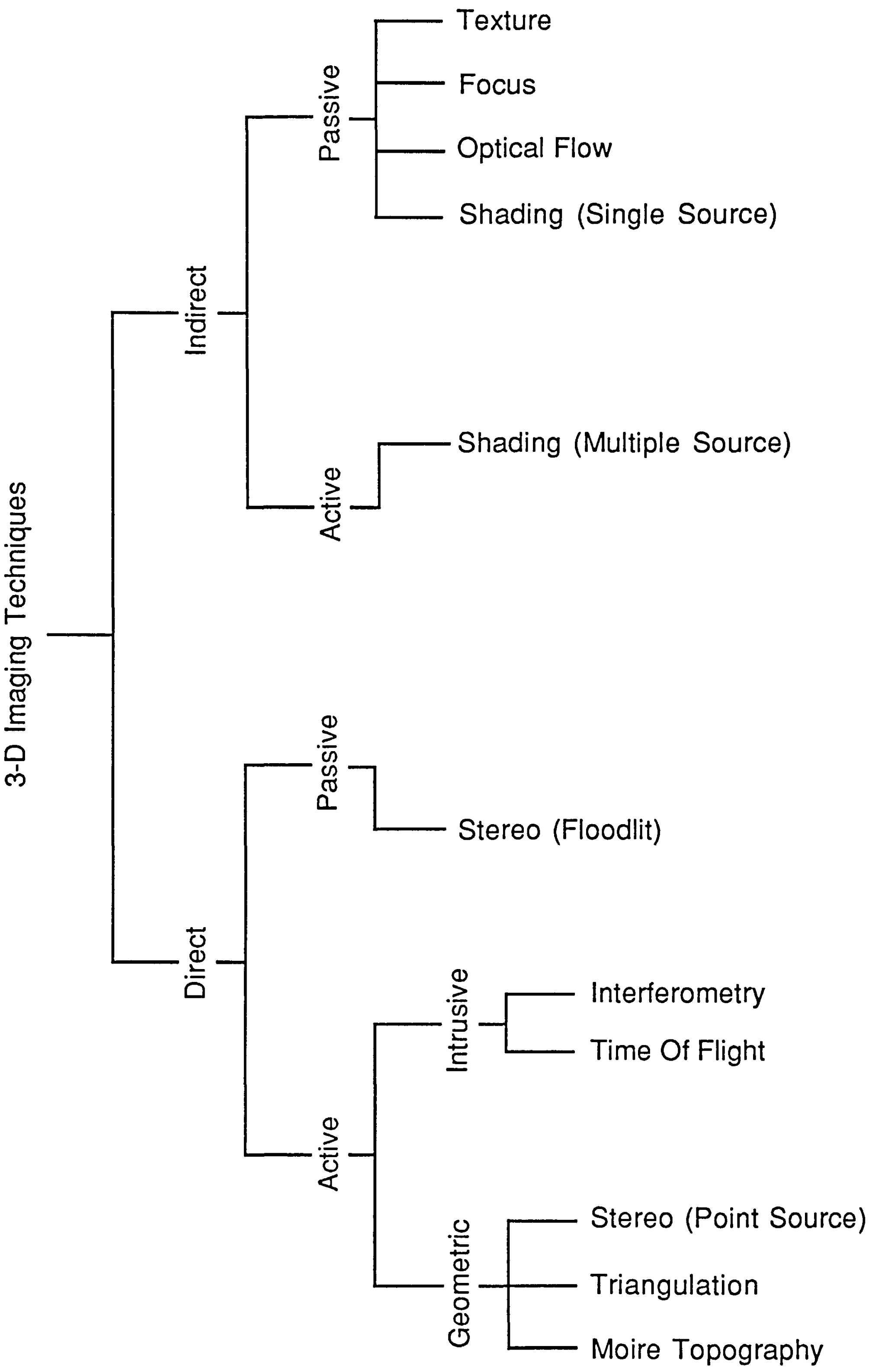


Figure 4.1

Classification of 3D Imaging Techniques

4.2.3.1 Optical Alternatives

i. Structured Light Range Finding

Two typical techniques within this category are stripped light and grid coding. The former involves a strip of light being projected over the subject, when the light is received by a T.V. camera, displaced from the light source, the camera's view of the slope shows displacement along the strip which is proportional to depth. A kink indicates a change in plane and discontinuity a physical gap between surfaces.

Grid coding is a method by which the locations and orientations of the plane areas of polyhedral solids are extracted through linear frequency domain filtering applied to images of scenes illuminated by a high contrast rectangular grid of lines. Edges are defined through the intersection of extracted planes.

ii. Image Brightness

Image brightness varies with surface orientation and this permits relative range information over part of a scene to be calculated by integration. Central to the method is the concept of a reflectance map which captures the relationship between image intensity and surface orientation.

iii. Stereo Disparity

This refers to the phenomenon by which the image of a three dimensional object shifts as a camera is moved laterally in the depth coordinate axis. For two such camera positions simple geometry indicates that the image displacement disparity in inversely proportional to depth as measured from the cameras.

iv. Interferometric Principles

Three such techniques in this category are Moire Fringe, time-of-flight and optical contouring. Moire Fringe involves the development of interference patterns over a scene using an equi-spaced optical grating and viewing the scene through an identical grating in a camera displaced laterally from the light projection system. The fringe pattern so produced represents contours of equal range.

Optical time-of-flight methods such a laser range finders are becoming farely common. One advantage with this technique is that range is directly available.

Optical contouring involves the projection of a fringe of light onto an object. The fringe lines of maxima represent lines of equal height in the plane of projection. When viewed from an angle different from the projection direction it is possible to relate fringe positions on the surface to values of height above the surface.

v. Focusing

A knowledge of the focal length and focal plane to image plane distances permits evaluation of focal plane to object distance for components of a three dimensional scene in sharp focus.

vi. Laser Triangulation

This technique relies on the principle of optical triangulation based upon the geometric consideration of the imaging properties of simple lenses. A refined system projects a spot of light from a gauge head onto the surface of the part being measured and then an image of the spot is focused on the centred of a photodetector mounted within the gauge head with its viewing axis inclined to the projection axis. If the part, or gauge head, is translated such that the surface to be measured moves along the axis of the photodetector the image of the surface spot will move across the photodetector. By qualifying these image movements the actual movement of the spot may be calculated.

4.2.3.2 Other Alternatives

Further to optical techniques of measurement within the non-contact inspection category are such methods as X-Ray Tomography, Nuclear Magnetic Resonance and Ultrasonics. X-Ray Tomography involves the direction of X-Ray sources at a target and an X-Ray detector which determines levels of absorption by the ray as it passes through the target. The target is then rotated and the process repeated. Software is then used to interpolate the image from the results of each rotation.

Nuclear Magnetic Resonance involves the use of super-conducting magnets to set up three dimensional linearly increasing magnetic fields. Photons are fired at the object and absorbed, the resultant re-admitted photons have an energy (frequency) proportional to the position in the magnetic field. Intensity at a given frequency gives effective density in a region.

Ultrasonic techniques involve the measurement of time between transmission of an ultrasonic signal and reflected wave occurring against a border between two significantly different mediums.

4.3 A Survey Of Geometric Inspection Systems

4.3.1 Introduction

After the analysis of the high pressure gas turbine blade manufacturing process it was concluded, by Cardew-Hall [4], that an inspection system was required which could quickly and systematically measure complex surfaces. A similar study was conducted by the author and extended to incorporate the philosophy of integrated inspection.

A review of inspection tooling which is capable of being incorporated into an integrated inspection system for measuring turbine blading is presented below. The presentation is divided into two categories contact and non-contact devices.

4.3.2 Contact Inspection Tooling

i. AE plc's Computer Controlled Caliperscope

This device, see Figure 4.2, works on the same principle as the optical caliperscope, but rather than magnifying the image of the moving penny a computer records it.

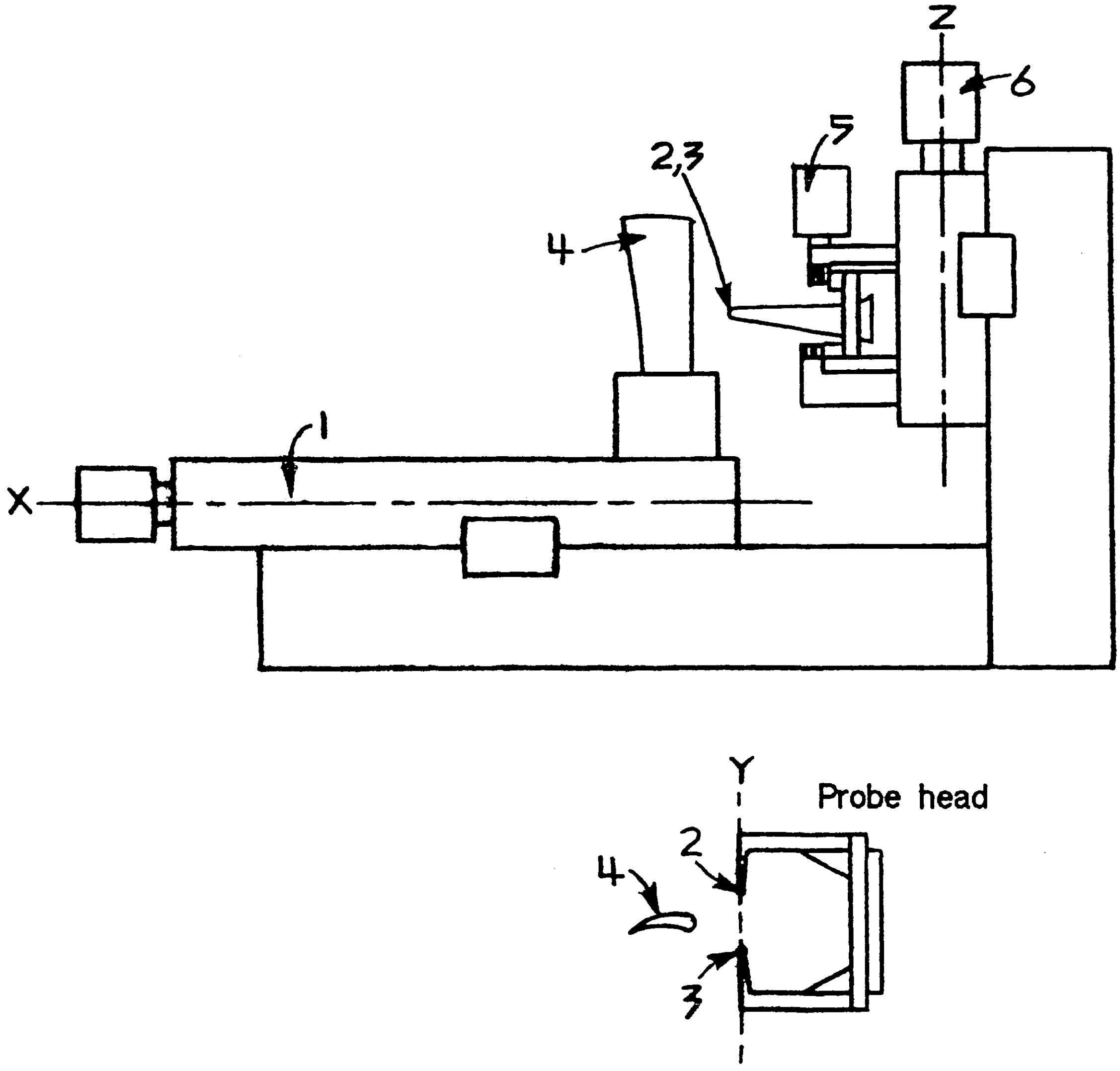


Figure 4.2

Schematic of the A.E. Computer Controlled Caliperscope

Referring to Figure 4.2 the object to be inspected is held on the x-slide (1). A computer, pre-programmed, moves the probe head (2,3) towards the aerofoil (4) at a desired section defined in the z-direction. Just one of the probes will touch a surface. The probe head in contact with the aerofoil will map out the path of the aerofoil. The y-axis is controlled using overdrive motors (5), thus maintaining the pressure at all times along the aerofoil surface. When one side is complete, the y-motor is driven in the opposite direction to move the second probe onto the other side of the aerofoil. Various sections of the aerofoil are measured by scanning at different heights controlled by the z-motor (6).

In the actual design a computer is used to display the results of each scan. Nominal design data is fed into the machine and an error map is obtained, see Figure 4.3. Further use of the errors is made in a proposed design of a system which controls a robot on a belt grinding station, this orientates the aerofoil against the belt to remove material excesses.

This invention is a good example of an inspection system exploiting nominal design data. Unfortunately the nature of the device provides for rather weak results on areas of high curvature such as leading and trailing edge forms on aerofoils, as Figure 4.3 clearly shows.

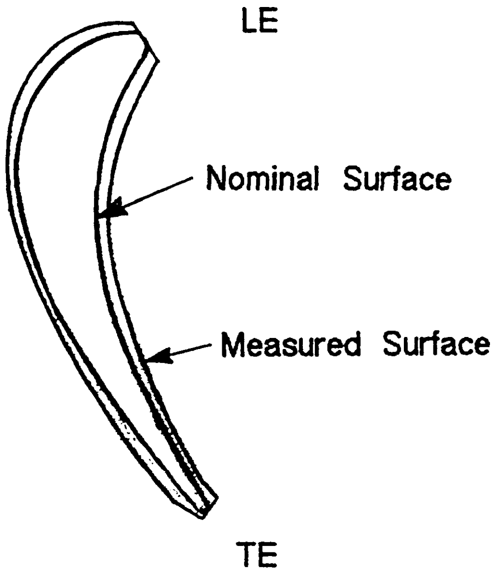


Figure 4.3

Typical Results from the Inspection of an Aerofoil Using the A.E. Caliperscope - Note the Poor L/E and T/E Definition

ii. Coordinate Measuring Machines

For flexible inspection machinery one of the greatest step forwards in recent years has been the development of coordinate measuring machines. There are currently a number of manufacturers around the world, including LK tools, Ferranti, Mitutoyo, Cordax and Leitz, who offer a large range of machines.

The design of three dimensional CMMs tends to fall into four basic categories; cantilever, moving bridge, overhead gantry and horizontal arm, see Figure 4.4. These designs usually involve X,Y and Z movement of a probe inside a working volume, to a typical positional accuracy of 5 microns. In order for this degree of accuracy to be maintained designs have focused on structural stability. This is achieved with good length/depth ratios, known and low thermal expansion coefficients, symmetrical structures, stable and stress relieved materials and good kinematic design.

The effects of inertial deflection are minimised by the use of high stiffness/mass ratio materials such as steel and aluminium which are relatively inexpensive. In more recent years ceramics have been increasingly incorporated in CMM designs. Such materials have very high stiffness/mass ratios and low coefficients of thermal expansion.

Air bearings have also tended to be used in CMMs, these enable compensation in structural deflection as the cross-slides move around. Repeatable errors involved in the CMM cross-slide movements may be taken out in software. The combination of stable design and software error compensation enables the very high degrees of accuracy obtained by CMMs.

Measurement of the positions of CMM cross-slides is usually achieved with the use of Moire Fringe scales. An NC controller monitors these scales, enabling feedback control to the CMM. Instructions for movement and other operational codes are normally obtained via a computer which sends instructions to the NC controller. The control system matches the drives so that the motion is held within what is called a tolerance tunnel.

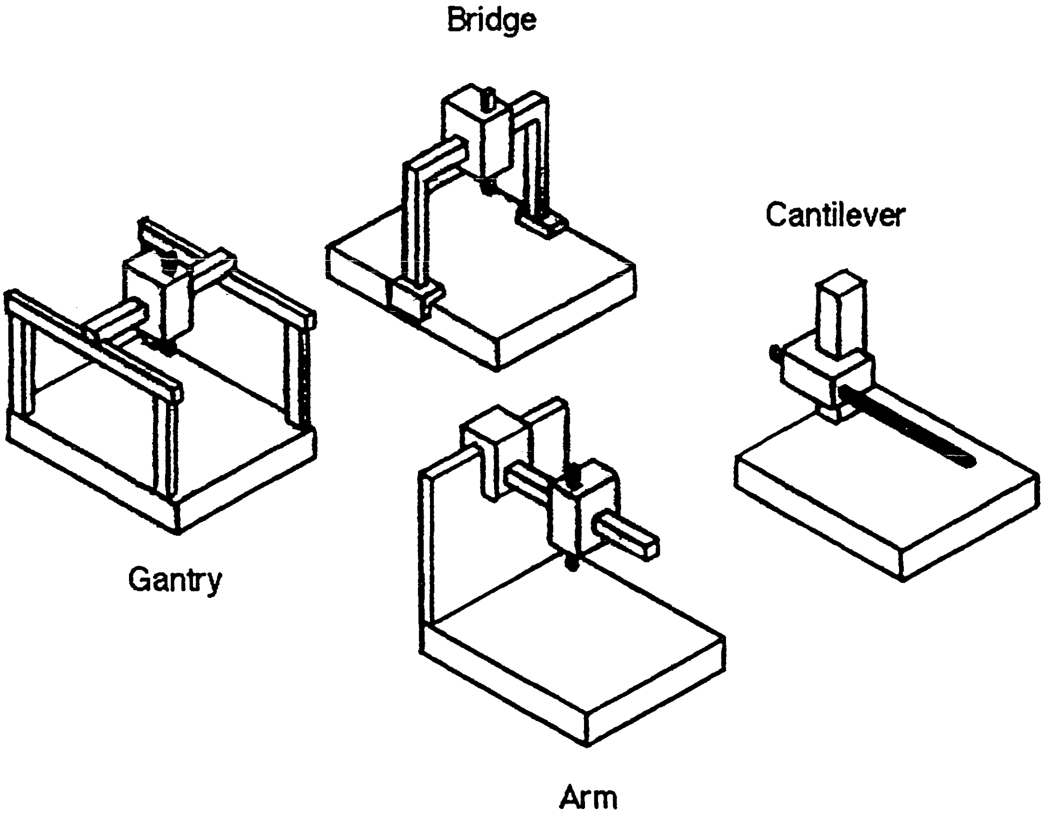


Figure 4.4

Basic Design Categories of Coordinate Measuring Machines

In more recent years CNC control of the measurement probe heads has become possible. For example the Renishaw PH9 is motorised in two axes. Orientation of such probe heads is specified by the CMM's computer which sends the request to the device's controller. Detection of collision and measurements is made by this controller.

The computing facilities offered to the CMM operator vary greatly between manufacturers. There are no standard formats for the control of CMMs, as there are with machine tools which have part programming languages, like APT. Usually programming facilities on CMMs enable the user to move the probe within a working envelope in a point to point manner.

One of the great advantages of CMM computing systems is their ability to construct coordinate systems around measured objects, this type of ability is extremely useful when measuring complex components, and is one of the main attractions with this type of measuring machine.

CMMs have a growing number of error processing facilities. Such tools include tolerance comparison routines, statistical analysis packages and linear best fitting. There is also an increasing use of graphical output of results onto plotters and colour graphics monitors.

Most programming is currently on-line, however there is a slow move towards facilitating the use of off-line generated programs as this reduces machine down time and permits more complicated inspection paths to be constructed.

Overall CMMs offer an excellent facility for interfacing with integrated inspection systems.

4.3.3 Non-Contact Inspection Tooling

i. Optical Probe Heads

One of the most predominant categories of non-contact inspection tools available to date have been based on the laser triangulation principle. For example Renishaw have produced a number of devices including the OP10 which is capable of a resolution of 12.5µm over a measuring range of 10mm. The OP2 is capable of a 10µm resolution over a range of 4mm but is significantly smaller and capable of being mounted on a PH9 probe head.

Another probe head, from Optocator, is capable of measuring distances to 2048 levels on a series from 8mm to 256mm. It uses an extremely accurate position sensitive photodetector and is capable of a maximum accuracy of 4μm.

Optical probe heads require mounting on moving gantries in order to measure blades and some problems may be experienced in measuring some of the more intricate geometry involved in turbine blading.

ii. The Diffracto Programmable Aerofoil Contouring System

For the inspection of aerofoils the American company Diffracto have produced a system known as PACS (Programmable Aerofoil Contouring System). Its accuracy has been proved to 2.5μm and it is capable of inspecting three sections of a typical aerofoil in two minutes or less with a data acquisition rate of up to 1000 measurements per second. It may be linked to a computer to anticipate dramatic shape changes into increased scanning rates. PACS has also been shown to measure wax patterns accurately and without damage.

Unfortunately this system is very expensive and it is incapable of measuring fillet radii and annulus gas washed surfaces.

iii. The VIDI System

A further example of an aerofoil scanning system is VIDI from Elor Optics, of Tel Aviv, Israel [5]. The system is capable of measuring aerofoils to 5μm at 60μm intervals and can perform measurement around one section of a compressor aerofoil in 20 seconds. Although the system is less expensive than PACS it too is unable to measure annulus gas washed surfaces.

iv. Optically Generated Contouring Systems

At Liverpool University and other research centres surface measurement is being attempted using optically generated contours [6] [7]. The contours may be generated using a number of techniques for example dual index and dual frequency holography, interferometric fringe projection and Ronchi and cosine squared grating shadow projection.

The principle of the contouring technique is to view the projected fringes at an angle different to the in-coming fringe projection. Successive maxima in the pattern may be interpreted as equal height difference contours above some arbitrary reference plane. The location of the fringe maxima within the image may be used to yield (x,y) coordinate data of a point on the surface, while the fringe order number, along with knowledge of the fringe spacing yields the (z) information.

Interpretation of the (x, y, z) data depends on the type and complexity of the surface and the analysis that is required of that surface. One example at Liverpool measured a parabolic automobile headlight and fitted the results into a parabolic equation. In this way the designer of the headlamp was able to compare his intent with that which was manufactured. A closed loop inspection process.

Work on more complex surfaces has included the building up of cubic b-spline surfaces from inspection results.

Optical contouring techniques certainly have the potential to be used to measure turbine blade surfaces. But at the current development of such methods a blade would have to be measured from a number of positions and the interpolated surfaces brought together afterwards. This leaves optical contouring as a rather complex procedure to adopt for turbine blade measurement.

4.4 Review Of Work On Integrated Inspection Systems

i. The National Research Council of Canada System

The National Research Council of Canada is developing a closed loop inspection system for a manufacturing cell which produces core aero-engine components [8]. The cell is made up of a five axis machining centre, a six axis robot, a cell control computer, a parts storage and retrieval system and a CMM (Brown and Sharpe 8202 carrying a PH9 probe).

Off-line programming of the CMM is integrated with the cell CAD/CAM system. Inspection data is passed back to the CAD/CAM system for analysis and comparison with design geometry.

The CMM probe path is generated by modifying a cutter path hopping program, although there is the additional problem that the CMM may only measure along one axis of motion and hence the probe path must be modified to this restraint. The target point surface normals are also used to calculate probe orientation for measurement.

The analysis of the inspection results is performed by a 2D best fitting program. This produces errors for position, orientation and surface form.

The project makes reference to what it calls 'adaptive control' of manufacturing processes. This it describes as the modification of cutter paths, to reduce form errors, as a result of inspection. It describes the potential of this type of manufacturing analysis as enormous.

This closed loop inspection technique is an excellent example of the use of inspection as being a part of the overall process of manufacture and not just an 'end-of-the-process', 'bringer-of-bad-news' operation.

ii. The General Electric Company System

The General Electric Company of the United States, are currently producing CATFEM a Computer Assisted Tomography to Finite Element Modelling system [9]. This aims to automatically convert computed tomography into 2D and 3D finite element models.

The system works on two concepts, the first, a digital replica generator, operates on discrete spatial data received from the measurement device and is basically a solid modelling system. The second is a fully automated mesh generator based on a recursive spatial decomposition, known as Quadtree in 2D and Octree in 3D.

CATFEM itself in a combination of software and hardware. The measurement of geometry is achieved by an X-ray computer tomography system which feeds back geometry to the digital replicator and the fully automotive mesh generator.

The resolution of the X-ray tomographic system is 0.125mm.

3D models are obtained by stacking 2D sections. The model of the object is stored as cubes of pixels. From this representation a finite element mess is generated using the Quadtree/Octree cell decomposition technique.

Like all finite element modelling techniques one of the largest problems is the attachment of non-geometric properties to the model (loads, boundary conditions etc). Hence work is being concentrated on the automated application of these properties.

CATFEM is surely an excellent example of the analysis of manufactured geometry. The turbine blade examples which they use have extreme geometric complexity, although as they state there is currently considerable work to be performed before geometry is fully automatically measured and analysed. One problem with the system is its resolution - 0.125mm - which for turbine blades is not sufficiently high for aerodynamic analysis of the surfaces.

iii. The ICAMP System

The ICAMP system is a currently developing closed loop inspection system from the United States [10]. The system includes a 3D modelling facility which may either be used interatively to generate nominal geometry or may be fed IGES files of the geometry from other CAD systems. All geometry may be assigned geometric tolerances. Using the nominal geometry ICAMP has been designed to control almost any measuring device - contact or non-contact - using the DMIS (see section 6.5) as interface language with the

CMMs. The data returning from the inspection system as points is mapped onto the CAD model and it is claimed that these results may return in any order.

The results may be best fit within specified degrees-of-freedom. Errors from a surface are represented as vectors, which may be magnified, these error vectors, or whiskers, are colour coded depending on the size of the error relative to the tolerance. It is also possible to use the system to determine if two parts will mate.

This is another good example of a closed loop inspection system, although the idea of mapping inspection points freely to free-form surfaces may cause some problems as was discovered when developing the system described in this thesis (this is discussed in detail in section 5.3.4.).

4.5 Choice Of Proposed Developments For The Imperial College Rolls-Royce Integrated Inspection System

4.5.1 Introduction

A study by Heath [11], in 1985, of inspection tools capable of measuring turbine blades showed that despite extremely high prices there was not a machine capable of measuring anything beyond the aerofoils themselves. As a result it was decided that Imperial College and Rolls-Royce should build their own machine for this task.

The study showed that of all the physical principles available for geometric inspection laser triangulation offered the best solution in terms of potential speed, accuracy and simplicity. To build such a machine it was decided to call upon the robotic control and visual analysis work being carried out at Imperial College.

A schematic of the inspection system which came out of the work between Imperial College and Rolls-Royce [12] is shown in Figure 4.5. The object to be inspected is mounted on a rotary table, which may also travel up and down. The surface map is obtained by monitoring a horizontal laser beam shone onto the surfaces with two CCD cameras. The laser and camera constitute the gauge head which is mounted on an X/Y table.

The two cameras view the laser spot from either side of the laser beam at a fixed 30° orientation and are in the same horizontal plane. These cameras monitor the displacement of the laser spot from the calibrated range at each point that is inspected.

The X/Y table allows the gauge head to scan sections of the object and also track the spot when it moves out of the restricted range of the cameras. The video information is fed via a real time image processor into a UNIX based Codata microcomputer which also controls the movements of the inspection table through a four axis controller.

The effects of back-lash on the measurement of the table are minimised by the use of precision ground shafts, pre-loaded linear bearings, precision rolled ball-screws with anti-back-lash nuts. The tachogenerator and encoders are coupled directly to the motor shaft to ensure accurate close loop feed back control.

Since it was necessary to control the inspection machine using a model of the nominal geometry in the UNIX microcomputer it was decided to analyse the inspected data in the same computer.

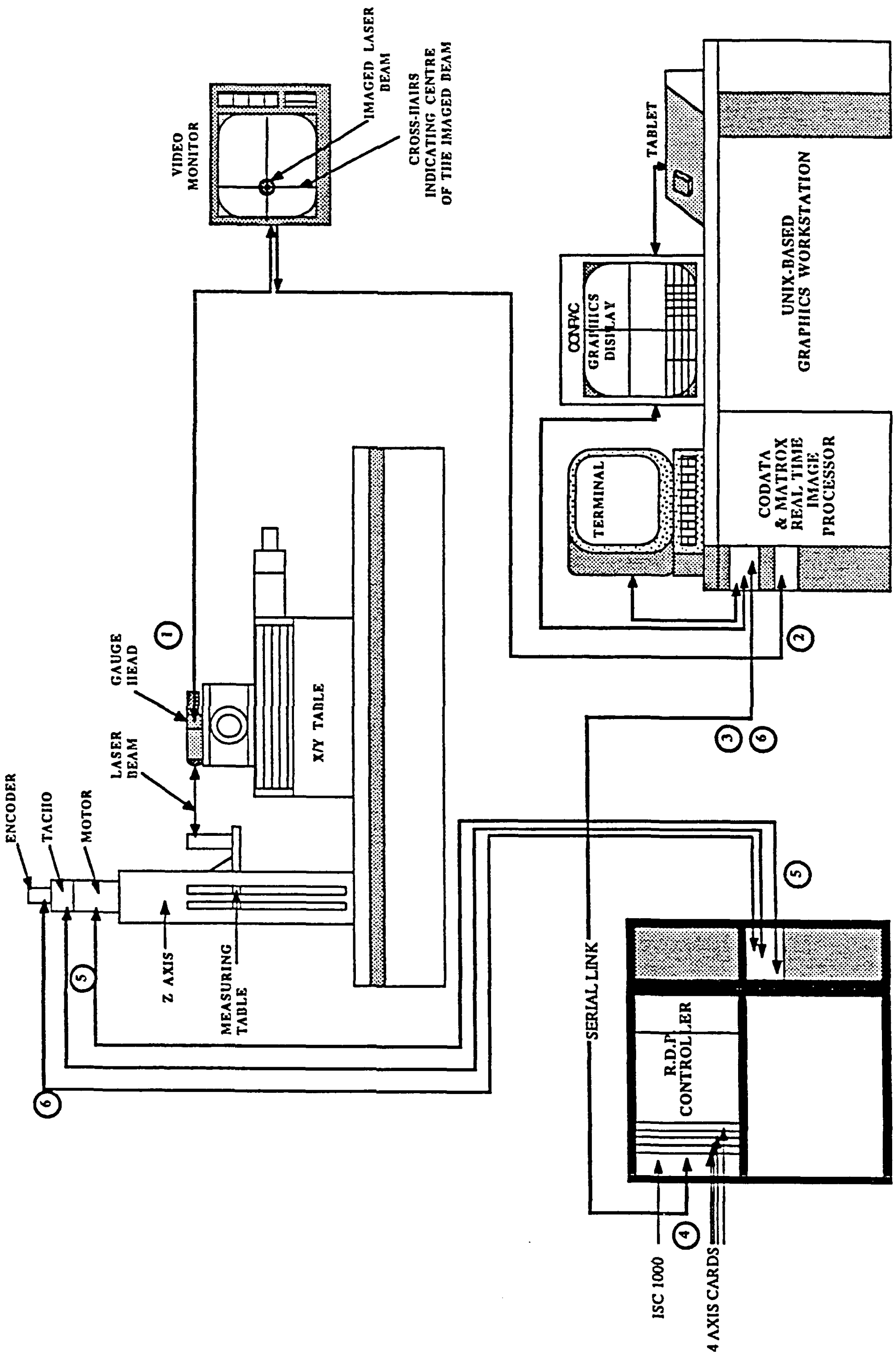


Figure 4.5

Schematic of the Imperial College/Rolls-Royce Inspection Machine

4.5.2 A Mitutoyo Coordinate Measuring Machine For Proof Inspection

While developments were being made at Imperial College by Heath and Tsabourakis it was realised by Rolls-Royce that contact inspection had reached the stage where it was possible to buy a coordinate measuring machine to assist proof inspection. A survey by Cardew-Hall [4] revealed that the best value for money at the time (1986 - 87) was a Mitutoyo CMM with a Renishaw probe head. The machine was not capable of inspecting data at the rates of the Imperial College machine. This was not important, however, as the CMM was to be used for proof inspection and not production inspection, where was be capable of improving the manual inspection times.

The Mitutoyo machine chosen was an FN1106, which was a three axis CMM with a working volume of 600 x 800 x 500mm (Plate 11). The basic design was an overhead gantry, moving on air bearings over ground metal slides. To the end of the z-axis motion was fitted a Renishaw PH9 probe head, with two degrees of rotational freedom, carrying a TP2 touch probe (Plate 12). In all the machine was capable of moving in five degrees of freedom. The lateral position of the gantry axes were measured using Moire Fringe gratings and axis positions were controlled using closed loop servo controllers. The Renishaw probe was controlled separately by its own controller. Requests for movements in the machine axes and Renishaw probe were made by a control program 'GEOPAK' running on a Hewett-Packard Vectra computer. This program enabled the user to write CNC programs - on-line - and was responsible for constructing coordinate systems and the processing of measured data.

There was no off-line programming facilities on the Mitutoyo machine and it was not possible to use nominal geometric data to automate any of the inspection processes. It was a stand alone machine.

Plate 11 : The Mitutoyo FN1106 Coordinate Measuring Machine

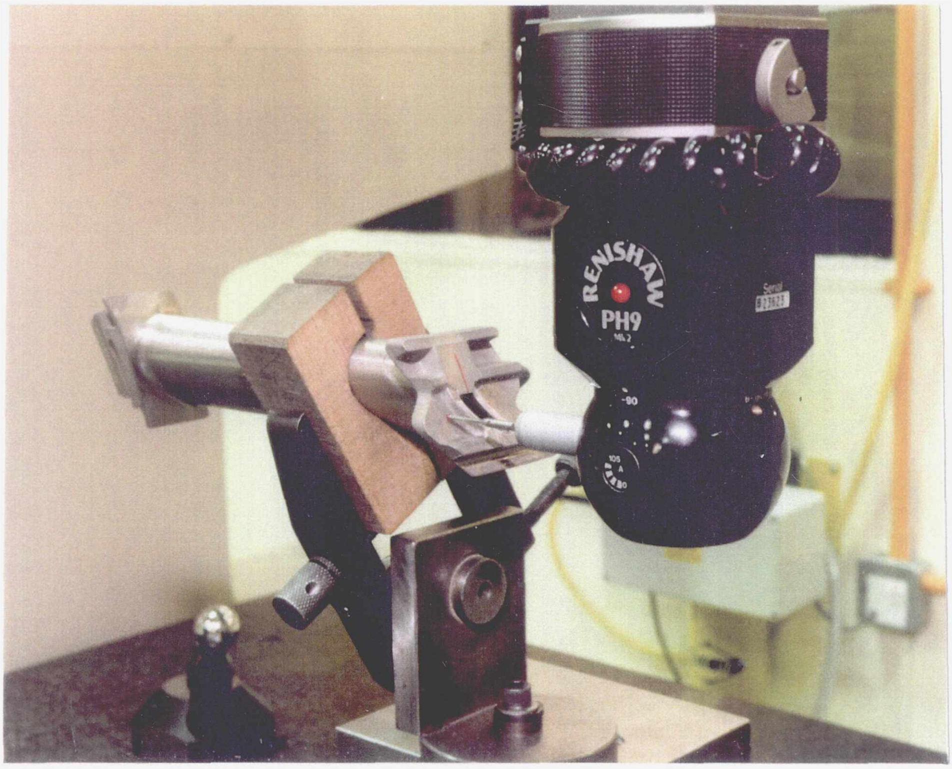


Plate 12 : The Renishaw PH9 Motorised Touch Probe Carrier with TP2 Touch Probe

4.5.3 A Common Control and Analysis System For Coordinate Measuring Machines

The development of the laser triangulation inspection system at Imperial College and the purchase of the Mitutoyo CMM brought advances in inspection technology to Rolls-Royce. However in order for such machines to achieve maximum utilisation it was realised that it would be necessary to control them from systems using nominal geometry and for the inspected data to be analysed against that nominal geometry. Since the Imperial College/Rolls-Royce and Mitutoyo inspection systems and any further machines were likely to require such similar control it was realised that a common system was required which would be capable of controlling most inspection machine types and for analysing inspected data from them.

It was appreciated that the development of a computing control system which handled nominal blade geometry and compared it with inspected data was a complex task. However the aim was to write as much code as possible which could be used for other types of inspection machine.

4.6 Design Of The Integrated Inspection System

4.6.1 Introduction

The first objective for the integrated inspection system was set at the off-line control of the Mitutoyo CMM. Since this machine was principally concerned with proof inspection it was decided that as an overall objective the inspection system should be designed to calculate the minimum die modifications required during proof cycling.

From the outset it was realised that a total system capable of achieving these goals would be large and that initial ideas for the requirements may well be superseded as the system developed. However a basic outline of the major elements of the inspection system was drawn up, this is illustrated in Figure 4.6 and a brief explanation of these elements is given below.

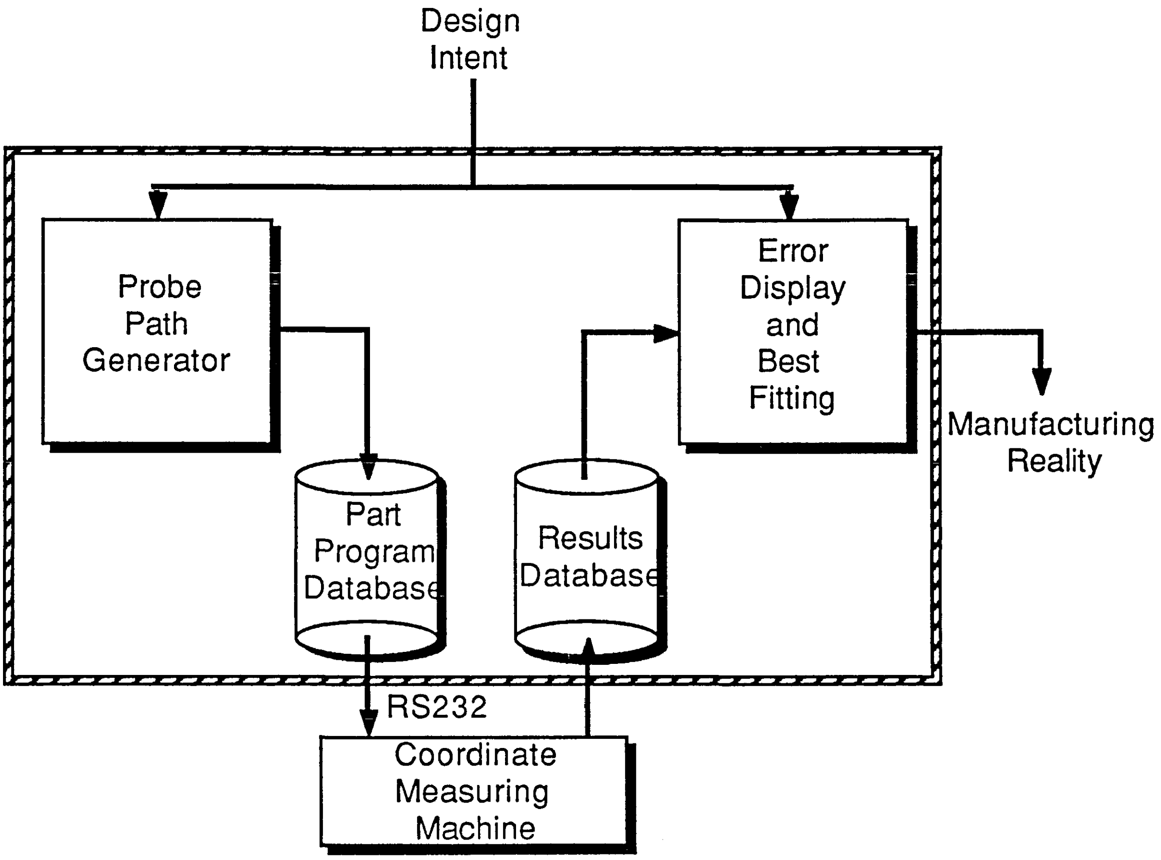


Figure 4.6

The Initial Design of The Integrated Inspection System

4.6.2 Probe Path Generation

It was ascertained from very early project work that any envisaged measurement system required explicit control in order to measure turbine blade surfaces. Therefore a probe path generator was required, this had the task of using nominal blade models to assist in the control of the CMM for the surface measurement.

The probe path generator had to provide a user-friendly interactive facility for creating part programs to measure specified points on the modelled surfaces. The programmer would specify the points to be measured and the probe path generator using the nominal geometry would calculate the surface normals at these points which would provide vectors along which the probes should measure. In the case of contact probes the probe head must move along the surface normal to take a measurement. In the case of non-contact probes - like laser triangulation systems - the surface normals represent the vector along which the laser should be aimed.

Not only had the probe path generator to provide direction for measurement but it also had to provide collision avoidance for the probe. As a means of checking the probe path it was decided to display the path on the graphic monitor around the nominal geometry.

A further role for the probe path generator was to create alignment part programs. Alignment is the process in which a coordinate system is built up around an object to be measured. Without alignment a measurement program may not be used since the measurement positions are all reference to a coordinate system around the object.

4.6.3 Coordinate Measuring Machine Compatibility

As has been previously explained it was recognised that the inspection system should be capable of controlling different types of CMM. This requirement for off-line inspection systems was also recognised by the United Kingdom Coordinate Measuring Machine Manufacturers Association, who proposed the Neutral Datafile (NDF) Exchange language [13]. The idea being that if a measurement probe path was written in NDF any CMM, supporting NDF, would be able to use it.

Since, in principle, this seemed a worthy objective it was decided that the integrated inspection system's probe path generator should deliver part programs in NDF, while CMMs would be bought on the understanding that NDF translators were to be supplied as part of the machines' controllers.

4.6.4 Feeding Inspected Data Back Into the Inspection System

In order for an analysis of the inspected data to be performed and for this to be available to the other computing systems within the design and manufacturing process it was necessary to facilitate the feeding of inspection data back into the integrated inspection system.

For the presentation of surface error sectional views were to be used. This type of display was provided by a number of companies including Mitutoyo. However the complexity of turbine blade surfaces is such that this presentation of errors is not completely useful and therefore it was proposed that a number of other methods of presentation be explored.

4.6.5 Three-Dimensional Best Fitting

The methods by which surfaces are aligned, in order to be measured, do not necessarily yield the minimum error which could be measured from the surface.

A number of techniques have been developed for minimising alignment errors, Braley [14], Cosmas [15]. Rolls-Royce has traditionally used techniques such as 'fare-alignment'. The minimising of surface errors is necessary to obtain a realistic impression of the surface error and is extremely important in die modification calculations as it minimises the modifications required. Best fitting is also important before analysing manufactured geometry in stress and aerodynamic programs.

Since the results of the measurements were to be fed back into the inspection system and to be compared with the nominal the opportunity arose for the best fit to be performed against all the measured data. A facility which had not been truly feasible up to then.

As no work on three dimensional best fitting could be found one requirement for the project was to develop the mathematics.

4.6.6 Relating Surface Error To Blade Dies Modifications

Under the initial development of the system relating surface errors to blade die modifications was the last facility to be provided for. The initial ideas for relating surface errors to dies were to continue to use the manual modification philosophy but to use the error presentation from the inspection system to aid the die maker in a visual understanding of the errors and hence provide him with better information with which to perform the modifications.

4.6.7 Choice Of Computing System

At the time of the system development there were no examples of integrated inspection systems. Therefore it was necessary to find or design a computer system about which the integrated inspection system could be based. The fact that the inspection system was new meant that some requirements of the system would probably be unknown at the initial phase of the system development. Therefore any computer system had to be flexible and quickly and easily changed to incorporate evolving specifications. There were two principal alternatives for the choice of computing system :-

i. To use the Rolls-Royce CAD/CAM package CADDS from Prime. This had many facilities but was slow and expensive to incorporate changes.

ii. To use an Imperial College CIM package PANACEA written by Glover [16]. This did not have many facilities but was extremely flexible, could be altered quickly and was relatively inexpensive.

It was decided that the best alternative would be to develop the inspection system within PANACEA.

4.6.8 A Blade Modeller

Basing the integrated inspection system within PANACEA necessitated the development of a blade modeller program which could model the nominal blade geometry. Within the project time scales it was soon realised that with the complexity of blade geometry only facilities for modelling and hence measuring gas washed surfaces could be provided for. However these surfaces are the most important to the function of the blade and being extremely complex would illustrate the integrated inspection philosophy while providing useful results.

From the outset of the project the inspection system was designed for use by the proof inspectors. As these people did not have intensive computer training the blade modeller and inspection system had to be as user-friendly as possible. This formed a further area of investigation for the research group.

References

[1] Booth, C., Douglas, J., "Integrated Inspection - Implementation", RR Report MTL50061, Derby, UK, 1989.

[2] Booth, C., PhD Thesis, Department of Mechanical Engineering, Imperial College of Science, Technology and Medicine, University of London, In Preparation.

[3] McCollum, A.J., Batchelor, B.G., Cotter, S.M., "Three Dimensional Optical Sensing", Proceedings of the 7th International Conference on Automated Inspection and Product Control, Birmingham, UK, 26-28 March 1985.

[4] Cardew-Hall, M.J., "Modelling and Integrated Inspection of Cast Turbine Blades", PhD Thesis, Department of Mechanical Engineering, Imperial College of Science,

Technology and Medicine, University of London, June 1988.

[5] Orchard, N.B., "Evaluation of Elor Optronics VIDI and VIGA Non-Contact Measurement Systems", MTD/10/86, Rolls-Royce plc, Bristol, U.K., 1986.

[6] Burton, D.R., Lalor, M.J., "The Precision Measurement of Engineering Form by Computer Analysis of Optically Generated Contours", Coherent and Electro-Optics Research Group, Liverpool Polytechnic, Liverpool, U.K., 1988.

[7] Burton, D.R., Lalor, M.J., "Software Techniques for the Analysis of Contour Maps of Manufactured Components", Coherent and Electro-Optics Research Group, Liverpool Polytechnic, Liverpool, U.K., 1988.

[8] Van den Berg, B., "Closed Loop Inspection of Sculptured Surfaces in a Computer Integrated Environment", Proceedings from the 8th International Conference of Automated Inspection and Product Control, June 1987, pp145-156.

[9] Finnigan, p., Hathaway, A., Lorensen, W., "Merging CAT and FEM", Mechanical Engineering, July 1990, pp32-38.

[10] ICAMP Inc., Sales brochure, 186 Bolton Center Road, CT06043-7638.

[11] Heath, A.J., "Non-Contact Profile Gauging Machine to Measure Turbine Blade Profiles", Third Year Project Report, Department of Mechanical Engineering, Imperial College of Science, Technology and Medicine, University of London, June 1986.

[12] Tsabourakis, N., Ristic, M., Besant, C.B., "Development of a Profile Gauging Sensor", The International Journal of Advanced Manufacturing Technology, Volume 3, 2, May 1988, pp51-66.

[13] Coordinate Measuring Machine Association of the United Kingdom, "Neutral

Datafile Specification, Level 1", Revision 1, 1985.

[14] Braley, J.W., "Development of 3 and 4 Axis Measuring Machines for Use in PC02 and PC22 Inspection Areas", Rolls-Royce Report Number TSR1065, Derby, U.K., September 1978.

[15] Cardew-Hall, M., Cosmas, J., Ristic, M., "Automated Proof Inspection of Turbine Blades", The International Journal of Advanced Manufacturing Technology, Volume 3, 2, May 1988, pp67-88.

[16] Glover, R., "PANACEA: A CIM Programming Environment", PhD Thesis, Department of Mechanical Engineering, Imperial College of Science, Technology and Medicine, University of London, March 1989.

Chapter 5

Implementation Of The Integrated Inspection System

5.1 Phased Implementation

The concept of using geometric models of surfaces to control machines to perform tasks against those surfaces, as was being proposed by the integrated inspection system, was not new. The principles have been illustrated by CAD/CAM systems in which models are used to generate cutter paths for the component manufacture. However in the proposed integrated inspection system the operation differed in that data from the CMMs was to be fed back into the inspection system and this feed-back loop was to be something of a new concept.

The basic integrated inspection system was designed from a large number of sub-systems, but little was known about feeding inspection data back into such systems, about error calculation and display or best fitting. Therefore it was believed that the overall system should not be developed from one end. Rather the system should be implemented in a number of phases in which an initial system would illustrate the very basic principles and provide a foundation for further development. Such a staggered introduction would also provide visible growth of the system to everyone involved in the project.

In practice the phased implementation proved to be extremely successful for as extra facilities were added it often turned out that these subjected the other facilities to conditions which were not realised at the project outset. Hence as the system grew previously written code would have to be changed but since the system was initially farely simple such changes did not imply large programming alterations.

5.2 Phase 1 - Measurement Of A Test Piece

5.2.1 Introduction

Having decided to implement the system in a number of phases in which the first was to illustrate the basic principles of an integrated inspection system it was realised that a far simpler object than a turbine blade should be targeted for the first measurement. As shall be discussed later the alignment of a coordinate system around a turbine blade is an extremely complex procedure and one which was considered too involved for the purposes of Phase 1. Therefore it was decided that a simple shape should be made, one which could be modelled in the same manner as a turbine blade, but aligned by a simpler procedure.

The objectives for Phase 1 were :-

i. Manufacture a simply shaped test piece which could be modelled in the same manner as a turbine blade in the PANACEA blade modeller.

ii. Produce a probe path generator for the measurement of the test piece on the Mitutoyo CMM.

iii. Produce an NDF compiler.

iv. Produce a NDF post-processing facility for the Mitutoyo CMM, for at the time of the system development the machine did not facilitate translation of NDF files .

v. Facilitate the transmission of the post-processed part programs to the CMM and for their subsequent arrangement for use by the CMM controller.

vi. Facilitate the transmission of the inspected data from the CMM into the workstation for subsequent conversion of the data into models within the inspection system.

5.2.2 The Integrated Inspection System Computing Platform and The PANACEA Blade Modeller

The PANACEA Blade Modeller was written by Cardew-Hall [1] and Brookes [2] (a brief resume is included in Appendix I, section 4). From the point of view of the inspection system the PANACEA Blade Modeller provided for a database from which points on the blades' surfaces and their associated surface normals could be calculated. The Blade Modeller was initially set up to model the gas washed surfaces of the blade, that is to say the aerofoil and the upper and lower annulus surfaces. Figure 5.1 illustrates a typical example of a PANACEA blade model with an aerofoil and upper and lower annulus.

The initial work on the PANACEA Blade Modeller was conducted on a Codata microcomputer operating under the UNIX operating system. Phase 1 of the Integrated Inspection System development was also conducted using this machine.

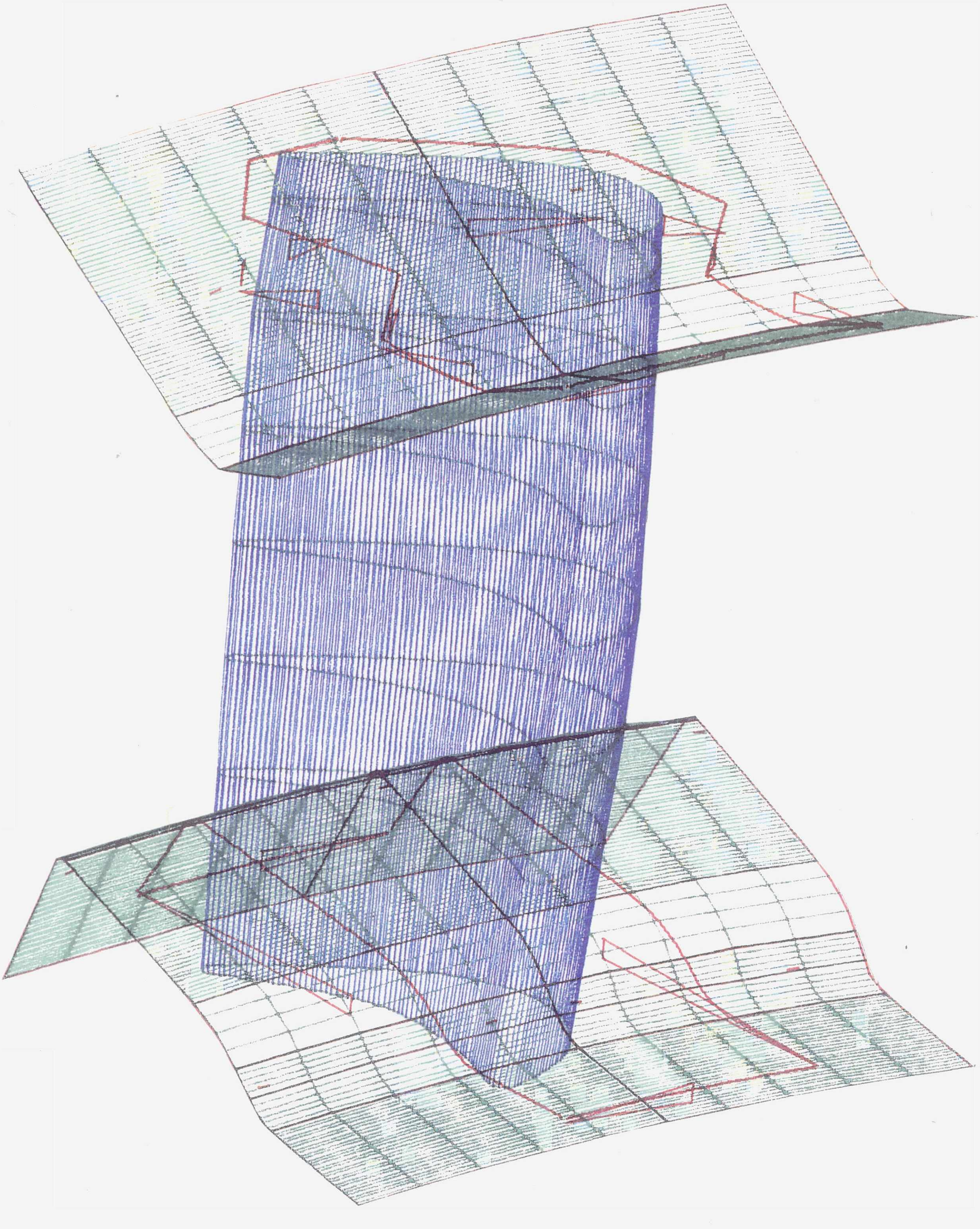


Figure 5.1

A Typical PANACEA Turbine Blade Gas Washed Surface Model

5.2.3 Generation Of Surface Normals From A PANACEA Blade Model

Having produced a modelling system for turbine blades it was then necessary to generate surface normals from the surface models so that probe paths could be constructed. One method of surface normal generation from a geometric model is to take the cross-product to two vectors of tangency to the surface at the point of consideration. For the aerofoil surfaces the procedure developed for producing two tangent vectors was as follows:-

i. To intersect the aerofoil surface around a specified XY plane section and in so doing produce a closed b-spline intersection.

ii. At the point of inspection calculate the vector of tangency on the closed b-spline produced by the plane of intersection.

iii. At the point of inspection calculate the vector representing the ruling line between the two lines defining the surface.

Figure 5.2 illustrates the two vectors of tangency that are produced from the nominal aerofoil surface in order to calculate a surface normal.

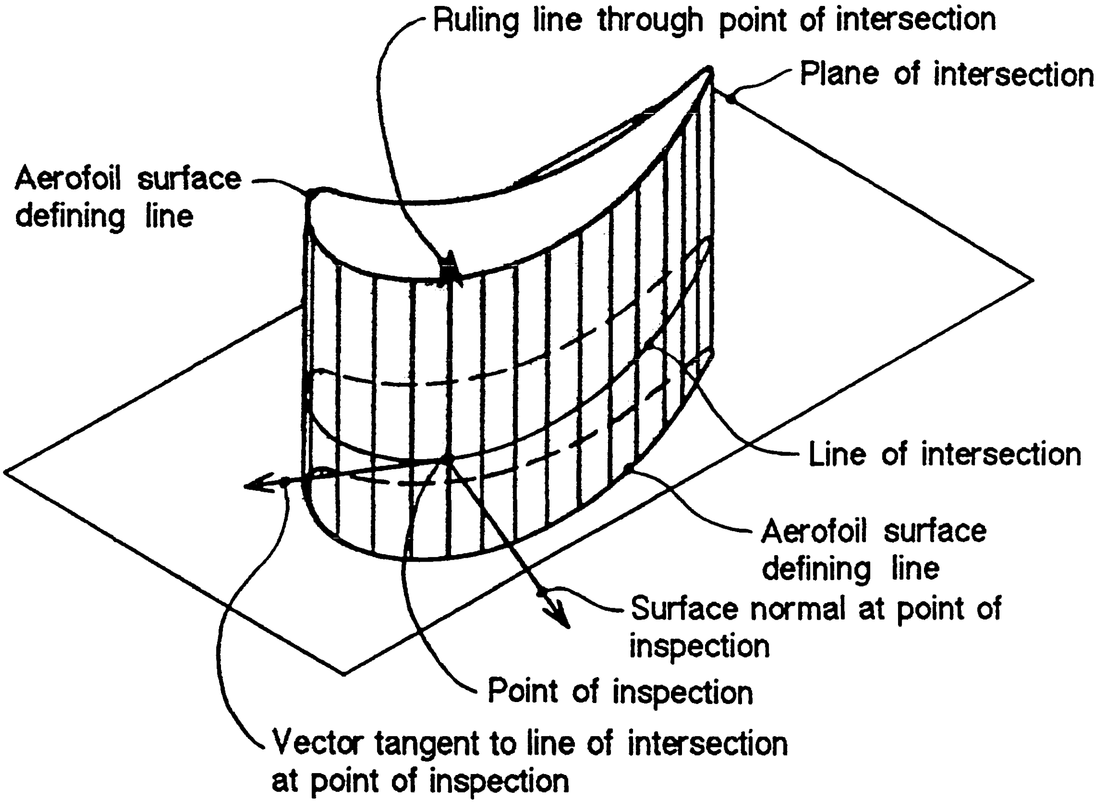


Figure 5.2

Vectors of Tangency Produced on a Nominal Aerofoil Surface in Order to Calculate a Surface Normal

For the annulus surfaces the procedure developed for producing two tangent vectors was as follows:-

i. To intersect the annulus surface along a specified plane and in so doing produce a open b-spline intersection.

ii. At the point of inspection calculate the vector of tangency on the open b-spline.

iii. At the point of inspection calculate the vector representing the surface tangent relative to the rotation of the sweeping of the annulus surface.

Figure 5.3 illustrates the two vectors of tangency that are produced on a nominal annulus surface in order to calculate a surface normal.

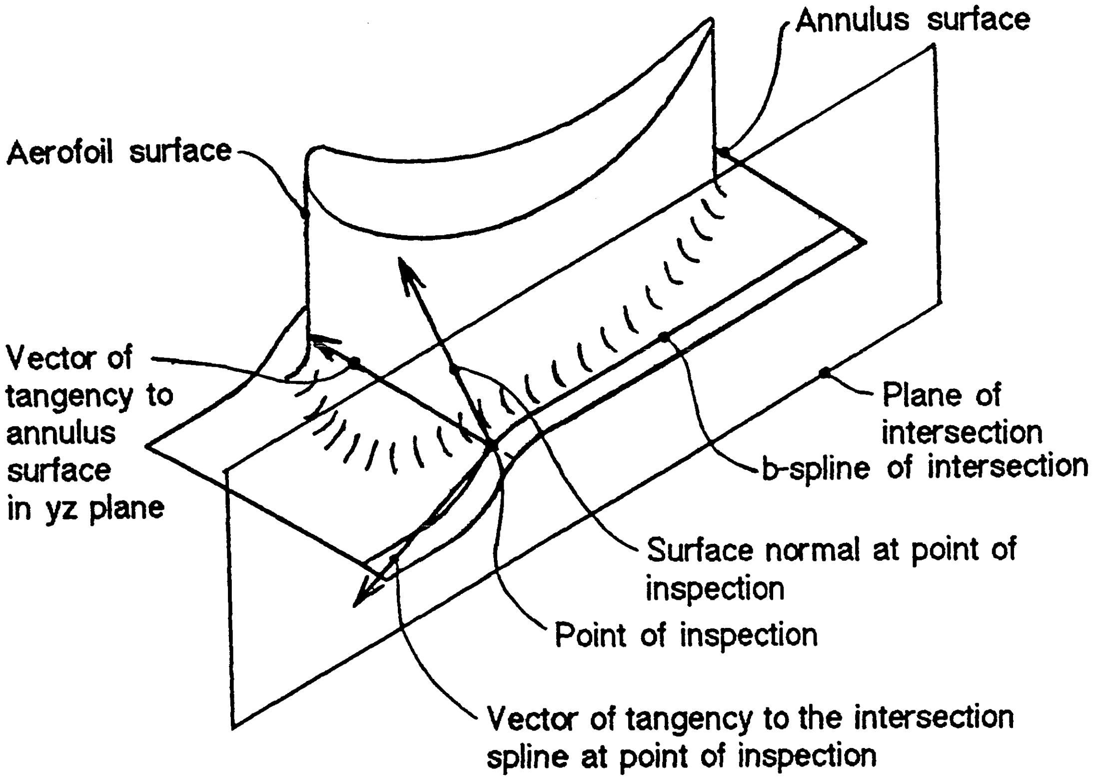


Figure 5.3

Vectors of Tangency Produced From a Nominal Annulus Surface in Order to Calculate a Surface Normal

5.2.4 A Simple Probe Path Generator

The design of test piece chosen for Phase 1 of the development of the inspection system is illustrated in Figure 5.4. The work concentrated on measuring the extruded race track shape, which represented an aerofoil. The alignment program was written on the CMM controller itself.

For the Phase 1 development programme the probe path generator was required to control a Renishaw PH9 probe head carrying a TP2 touch probe on the Mitutoyo Coordinate Measuring Machine - FN1106. In order to do this it had to meet the following specifications :-

i. Control the CMM so that the ruby ball on the TP2 would contact the target points on the test piece surface.

ii. Prevent collision of the machine with anything but the ruby ball and the target points during the process of measurement.

iii. Prevent collision of the machine while moving between measurements and to be efficient in the time expended while travelling between measurements.

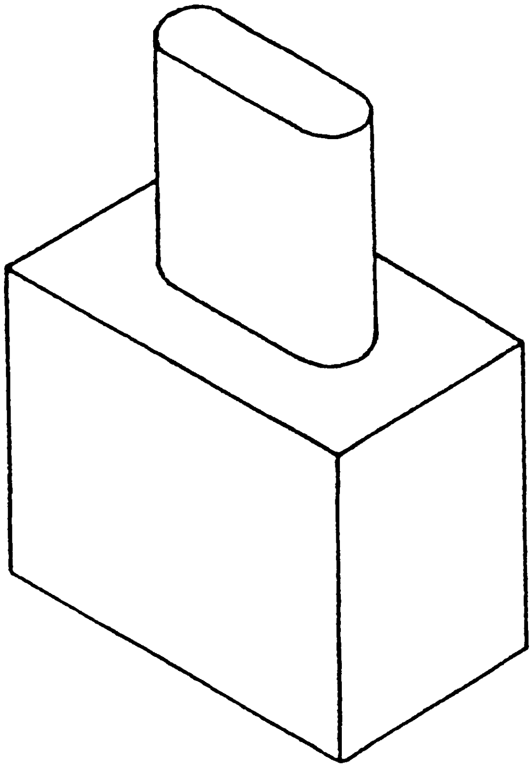


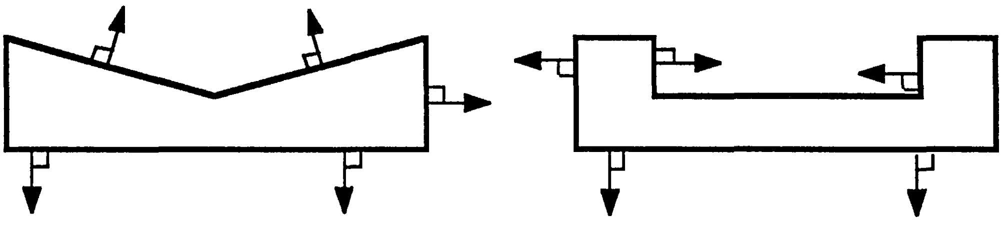
Figure 5.4

The Design of the Test Piece Chosen for Phase 1 Development of the Integrated Inspection System

A solution to the probe path generator was found by exploiting the $2^1/_2$D nature of the pseudo-aerofoil. In this way collision avoidance could be ignored except for the pseudo-aerofoil itself. The algorithm is explained below. (The meaning of $2^1/_2$D in this context is that the form of the pseudo aerofoil was basically a 2D race track shape extruded into the third dimension).

To provide for a path along which the touch probe should move during measurement the surface normal vector was added to the target point to provide a 'stand-off' position. Initially this stand-off position was set at 5mm from the surface. The path for measurement was defined as existing between the stand-off position and the target point.

A further requirement for the probe path generator was to orientate the probe head so that it could measure the target points. One geometric property of the pseudo-aerofoil was that a line passing surface normal from any point on the surface would not make contact with any other part of that surface. From this property it was deduced that if a narrow object such as a TP2 touch probe were aligned along the surface normal it would reach the target point without contact with any other part of the surface. This property was described as 'inspectional convexity' and enables a large simplification of the probe path generator rules, see Figure 5.5.



(a) 'inspectionally convex'

No surface normals
point towards any
part of the surface

(b) 'inspectionally concave'

Some surface normals
point towards parts
of the surface

Figure 5.5

Illustration of Inspectionally Convex and Concave Surfaces

The most obvious solution to probe orientation was to orientate the probe along the surface normal vector. The probe itself could orientate in 7.5^o steps in two axes of rotation and hence a close match between surface normal and probe orientation could always be met. However if a large number of points were measured this algorithm would correspond to a large number of different probe orientations being used. The disadvantage with this is that each orientation had to be calibrated (a time consuming process of 2 minutes per calibration).

To overcome this problem a property of the TP2 probe was used in that it could be triggered from virtually any direction of contact. By using this property it was possible to employ a limited number of probe orientations, see Figure 5.6, and then match the closest orientation to each surface normal. In this way only a limited number of probe orientations had to be calibrated, there was no loss in accuracy and since there were fewer reorientations of the probe during measurement the programs ran faster.

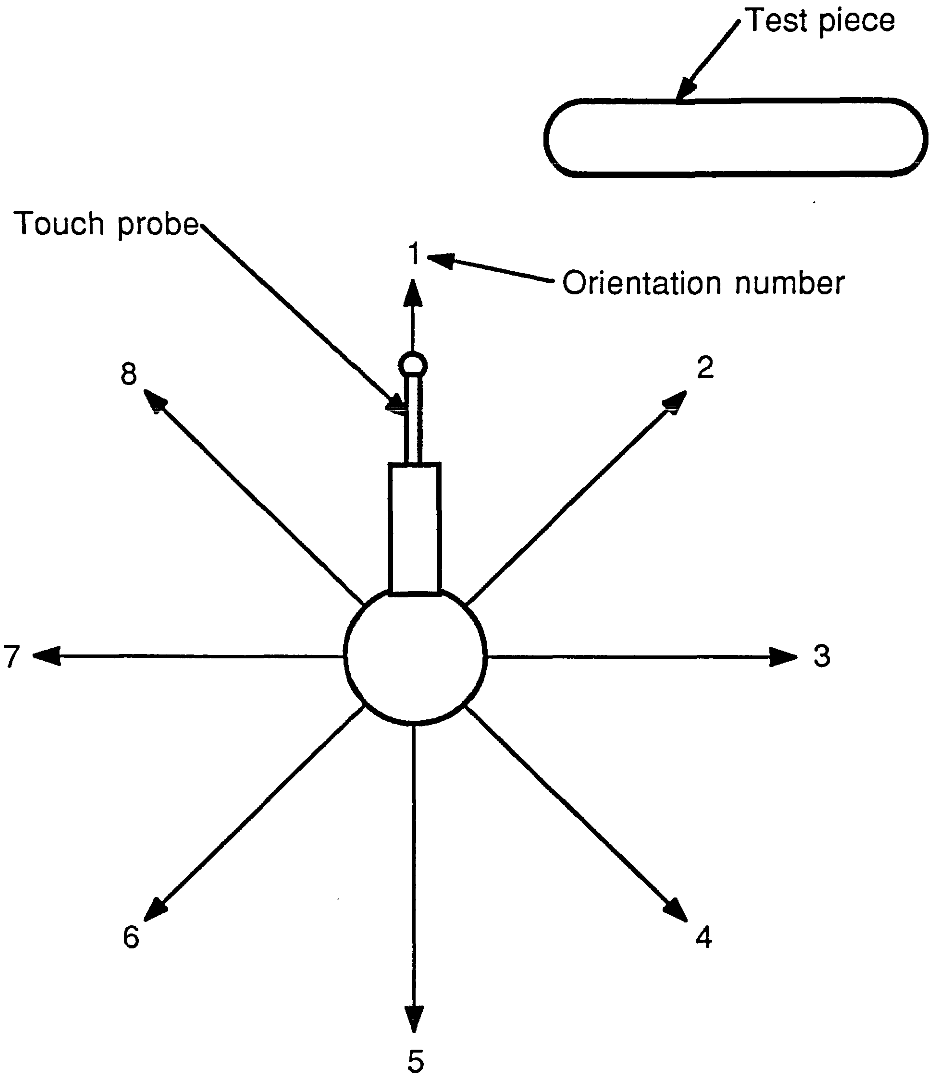


Figure 5.6

The Predefined Probe Orientations Used for the Test Piece Measurement

Having provided an algorithm for orientating the probe for measurement and a path along which the probe should be moved for the measurement it was necessary to provide a method of moving the probe between successive stand-off positions without collision and in a time efficient manner. A solution to this was found by exploiting a geometric property of the pseudo-aerofoil: if there was a sufficient density of measurement points over the surface, lines joining adjacent stand-off positions did not intersect with the surface of the aerofoil. This meant that the probe could be moved between adjacent measurements along a path joining adjacent stand-off positions, see Figure 5.7.

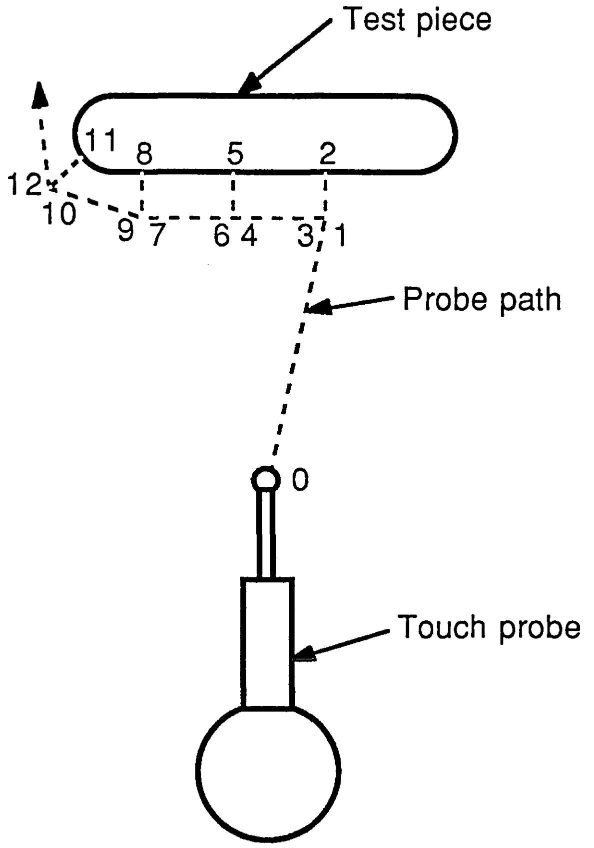


Figure 5.7

Illustration of a Simple Probe Path Around the Test Piece

The probe path algorithm worked satisfactorily except when the probe needed to be reorientated before the next measurement. If the probe was reorientated in close proximity to the test piece it was quite likely that it would collide with it. To overcome this problem it was decided to define a number of positions around the outside of the test piece, called 'home' positions, see Figure 5.8, to which the probe could be moved and reorientated, knowing that it was at a safe distance from the test piece and as such would not collide with it.

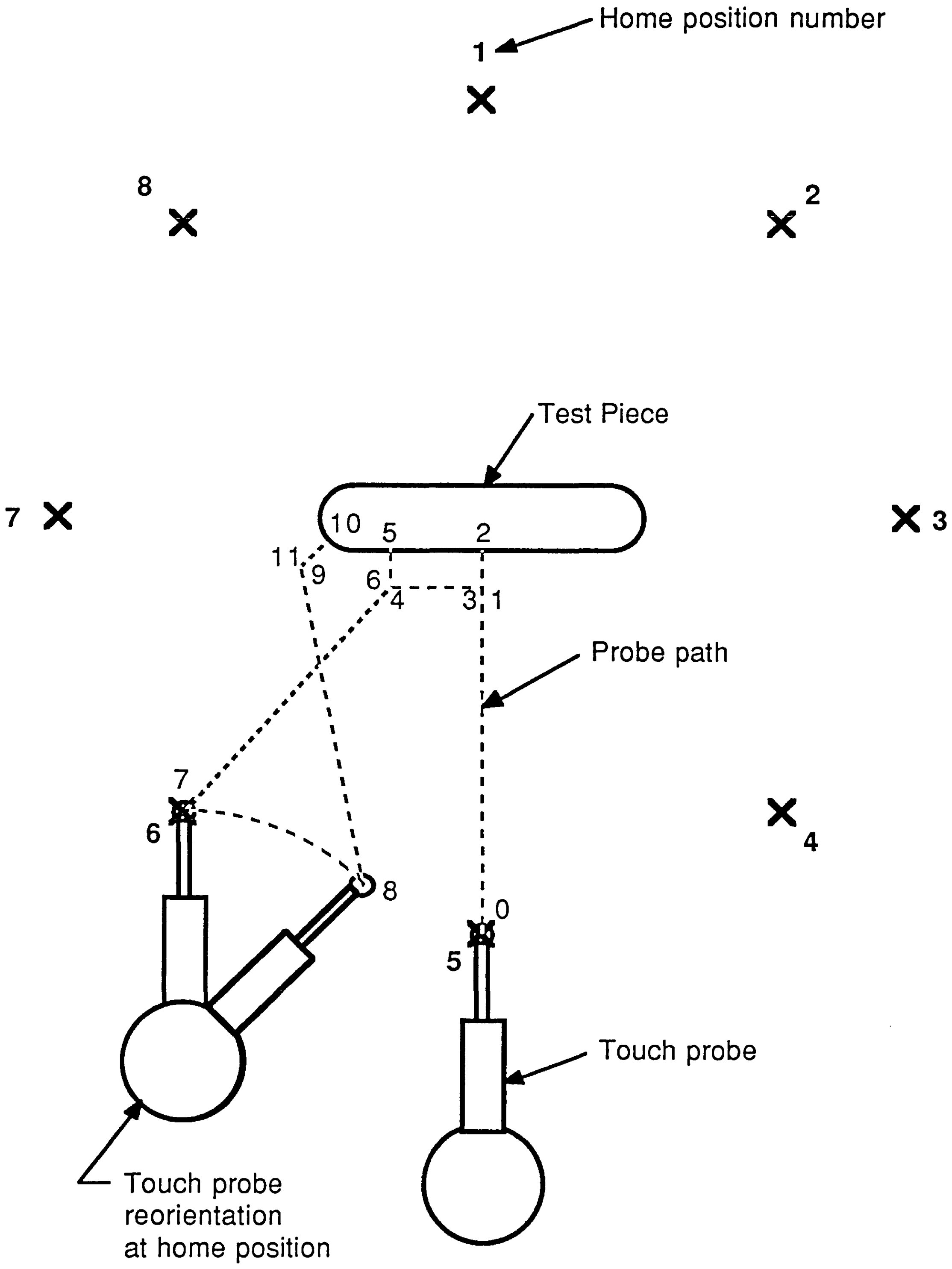


Figure 5.8

The Use of 'Home' Positions When Constructing a Probe Path Between 'Stand-off' Positions

The rules for moving between stand-off positions was defined as:-

i. Between adjacent stand-off positions if no probe reorientation was required.

ii. Between a 'home' position if a probe reorientation was required.

It is worth noting that even for a simple object such as the test piece the probe path generator becomes complex. It was realised that if more complex geometry was to be inspected, by a generalised control program, that a finer form of algorithm would have to be found than that described above. However for the purposes of Phase 1 of the integrated inspection system development the algorithm proved to be adequate.

In brief, the probe path generator produced a path from a set of target points and surface normals which were generated interactively from the surface intersection routines. The path was a simple set of instructions involving changes in probe orientation, movement between points and measurements along paths. The next step was to convert these instructions into a format for use by the Mitutoyo CMM.

5.2.5 A Neutral Datafile Compiler

In order that the measurement instructions in a probe path could be used by the CMM various set up instructions such as coordinate system number, probe type and traversing speeds were required to be added to the part program. The part programs also had to be presented in an ASCII file according to a specific standard laid down by the Neutral Datafile Format (NDF) specifications, as discussed in section 4.6.3.

To convert the probe paths into the NDF standard a program was written that read in the probe path, added the set up instructions and wrote out the complete part program. It was noted that one problem with the NDF standard was that it generated very large program files, typically 1 kilobyte of code for every 2 measurements.

5.2.6 Mitutoyo Post-processing and Transfer Of Measurement Programs

At the time of the development of the inspection system the Mitutoyo machine did not support NDF or any other type of exchange language translator. As a result it was necessary to post-process the NDF codes into the Mitutoyo part program format. The method chosen for this was to convert the part programs in the workstation and send the converted programs over to the Mitutoyo controller.

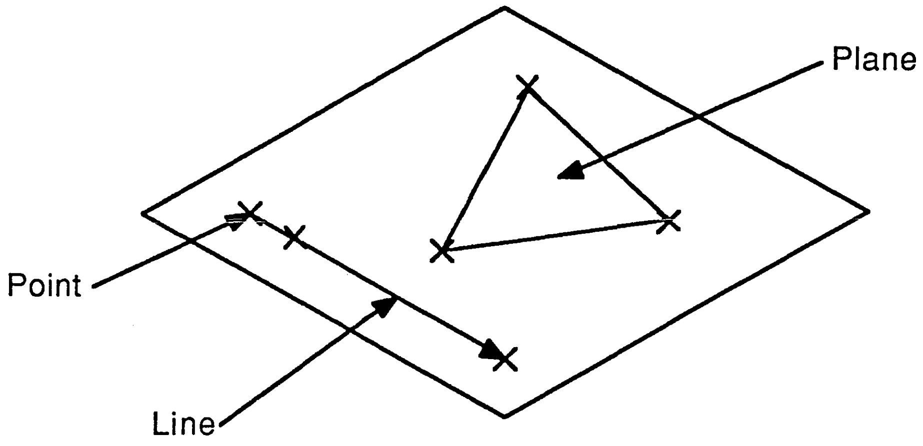
The details of this procedure are in ref[3]. It is interesting to note that the post-processing of NDF files and their transfer to the CMM proved extremely complicated. As with most CMMs at that time the basic controllers had not been designed to be linked with other equipment and they were very much 'Islands of Automation'.

5.2.7 Execution Of The Inspection Programs

Once the part programs had been loaded into the Mitutoyo controller they could be used in exactly the same manner as any part programs that had been written on-line on the system.

For Phase 1 the writing of an alignment program for the test piece was carried out on-line. Before explaining briefly how the test piece was aligned it is important to realise how a coordinate system may be built up around an object:-

On most CMMs it is possible to construct an imaginary coordinate system using the software in the machine's controller. In this way an object need not be moved around as part of the alignment process and there is no need for expensive dedicated fixturing. This is one of the great advantages of CMMs. In order to create a coordinate system within the software of a CMM controller a procedure is usually adopted which involves the construction of a plane, a line and a point. The plane requires a minimum of three points to define it, the line requires a minimum of two. The line orientates an axis in the plane and then the point fixes a position along the axis, see Figure 5.9.



Three points define a plane, two points a line and a further point provides sufficient information to define a coordinate system

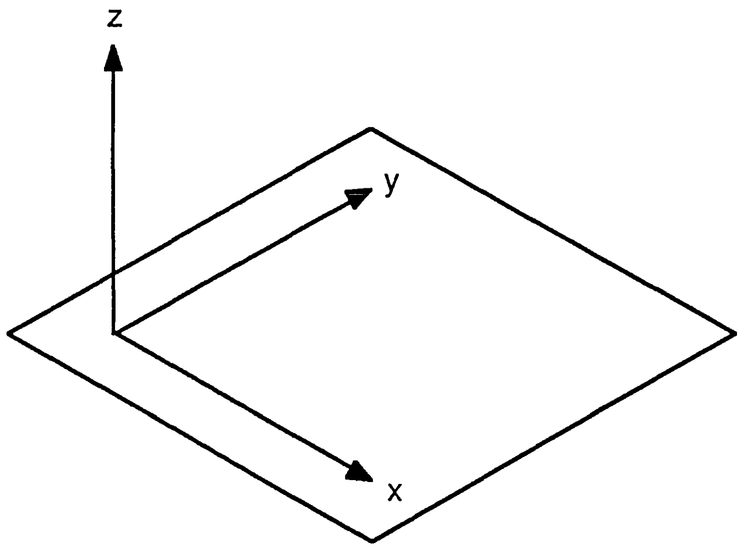


Figure 5.9

The Use of a Plane, Line and a Point in the Construction of a Coordinate System

To align the test piece the surfaces around one of the corners was used to provide for the plane, line and point. As Figure 5.10 illustrates this coordinate system then had to be translated in order to represent the coordinate used to define the test piece model.

There is an important limitation in the NDF language, to be noted at this stage. The designated orientations of the probe, specified when writing the probe path, cannot be altered as a result of the alignment of a coordinate system on the CMM. In affect an object must be placed on the bed of the CMM in an orientation which is as close as possible - usually within 10 degrees - to the one in which the probes where calibrated. The inability of the NDF language to accommodate iterative input in this manner is one of the limitations found in using the language, although in this case the problem was easily overcome.

During the execution of the measurement programs the results were sent back to the workstation via RS232 communication protocols and were logged by a program to a specific file. The inspected results were actually obtained by intercepting the printer port on the CMM controller and hence the file of results obtained resembled a print-out of the results.

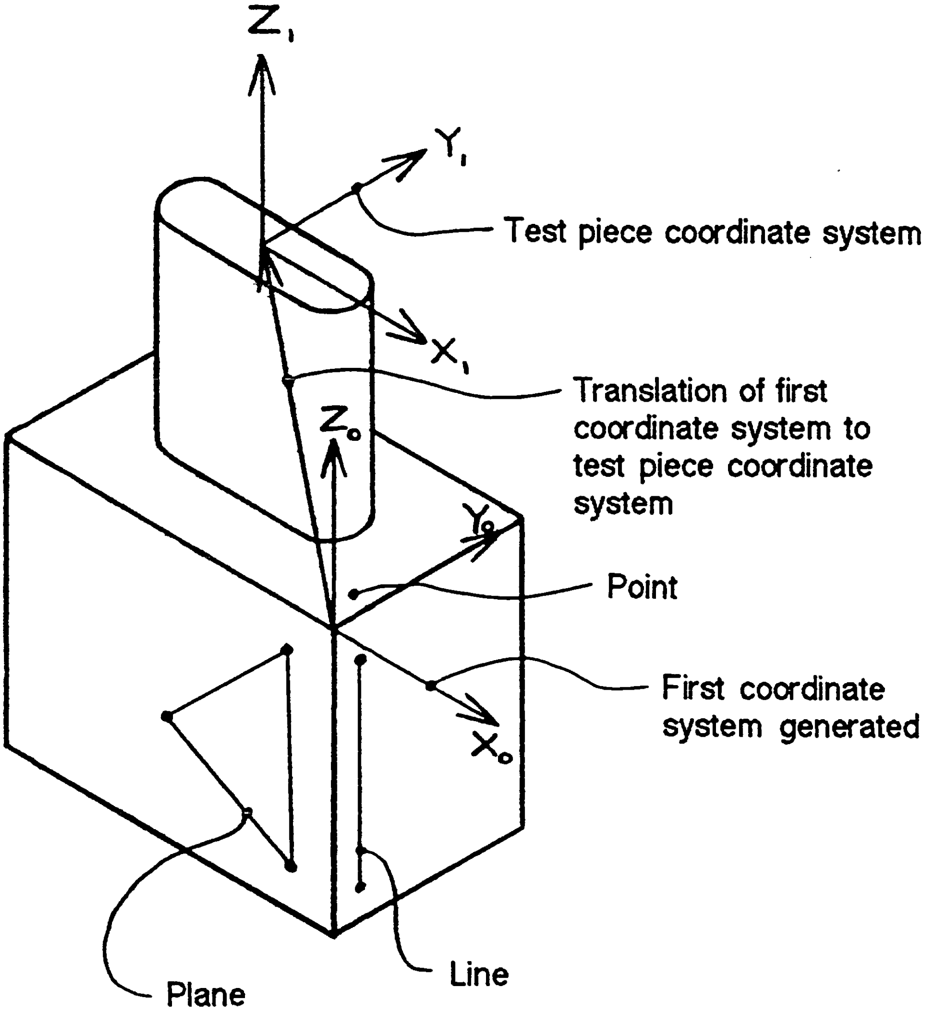


Figure 5.10

The Construction of a Coordinate System Around the Test Piece

5.2.8 Conversion Of Inspected Results Into PANACEA Models

The inspected data was read into the integrated inspection system and converted into points within the PANACEA modeller. Once the inspected data was converted into points the nominal surface could be loaded into the system. The surface error was then the shortest distance between each measured point and the nominal surface.

5.2.9 Resume Of Phase 1

In principle Phase 1 of the development of the integrated inspection system illustrated how an integrated inspection system could work. A nominal model of a surface was used to generate a probe path to control a CMM to measure the surface and after measurement the data was fed back into the workstation where it was analysed. The next phase of work was to extend this system to measure modelled turbine blade surfaces.

5.3 Phase 2 - Measurement Of A Turbine Blade

5.3.1 Introduction

In order that the modelled surfaces of a turbine blade could be measured the Phase 1 inspection system was required to be extended. This work was specified as Phase 2 of the system development for which the following objectives were specified :-

i. To extend probe path generator to be capable of turbine blade alignment and aerofoil and annulus measurement.

ii. To extend the NDF compiler and Mitutoyo post-processor to facilitate i..

iii. To convert the results of an inspection, to sufficiently high standards of integrity, into models within the PANACEA system.

iv. To develop surface error calculations.

v. To find a satisfactory method of displaying errors over a measured surface.

5.3.2 A Probe Path Generator For Turbine Blade Alignment and Aerofoil and Annulus Measurement

The probe path generator had proved successful in the measurement of the test piece, but for blade alignment and measurement it was realised that the algorithm would have to be extended, specifically in the control of the probe head between measurements. During blade alignment and annulus measurement it was necessary for the probe to take measurements where subsequent target points were located on opposite sides of the blade. In this case the probe would obviously be required to reorientate and move around the blade without taking a significant time.

In order to accommodate the large movement of the probe an algorithm was developed which employed only one probe orientation change between each measurement. The rules for this algorithm were dependent on the size of the rotation that the probe head had to undergo during reorientation.

For probe reorientations of no more than 90 degrees the following algorithm was adopted, see Figure 5.11:-

i. Move the probe to the 'home' position associated with the current measurement point.
ii. Reorientate the probe for the next measurement.
iii. Move the probe to the 'home' position associated with the next measurement point.
iv. Move the probe to the 'stand-off' position associated with the next measurement point.

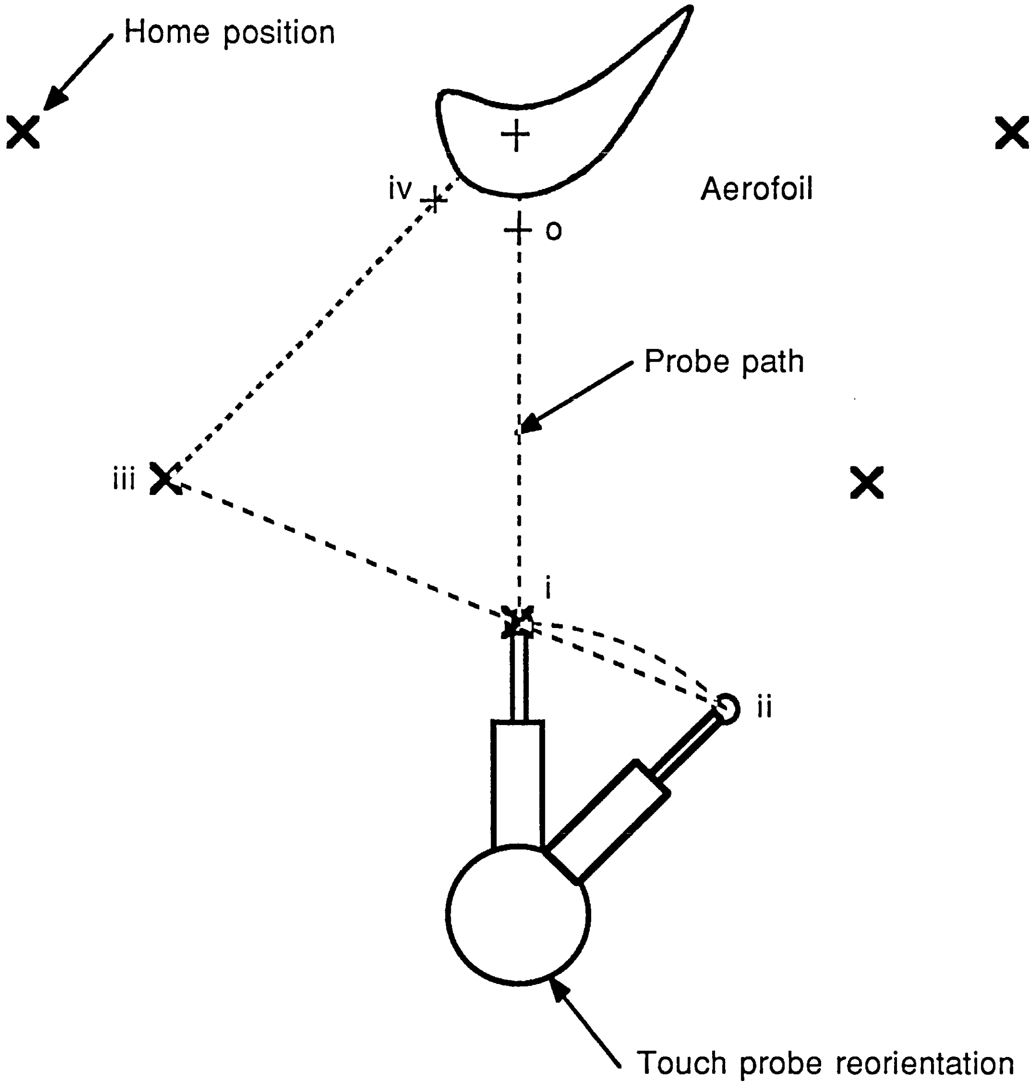


Figure 5.11

The Probe Path used for Probe Reorientations of No More Than 90°

For probe reorientations of more than 90 degrees the following algorithm was adopted, see Figure 5.12:-

i. Move the probe to the 'home' position associated with the current measurement point.

ii. Move the probe to the 'home' position above the blade.

iii. Reorientate the probe for the next measurement.

iv. Move the probe back to the 'home' position above the blade.

v. Move the probe to the 'home' position associated with the next measurement point.

vi. Move the probe to the 'stand-off' position associated with the next measurement point.

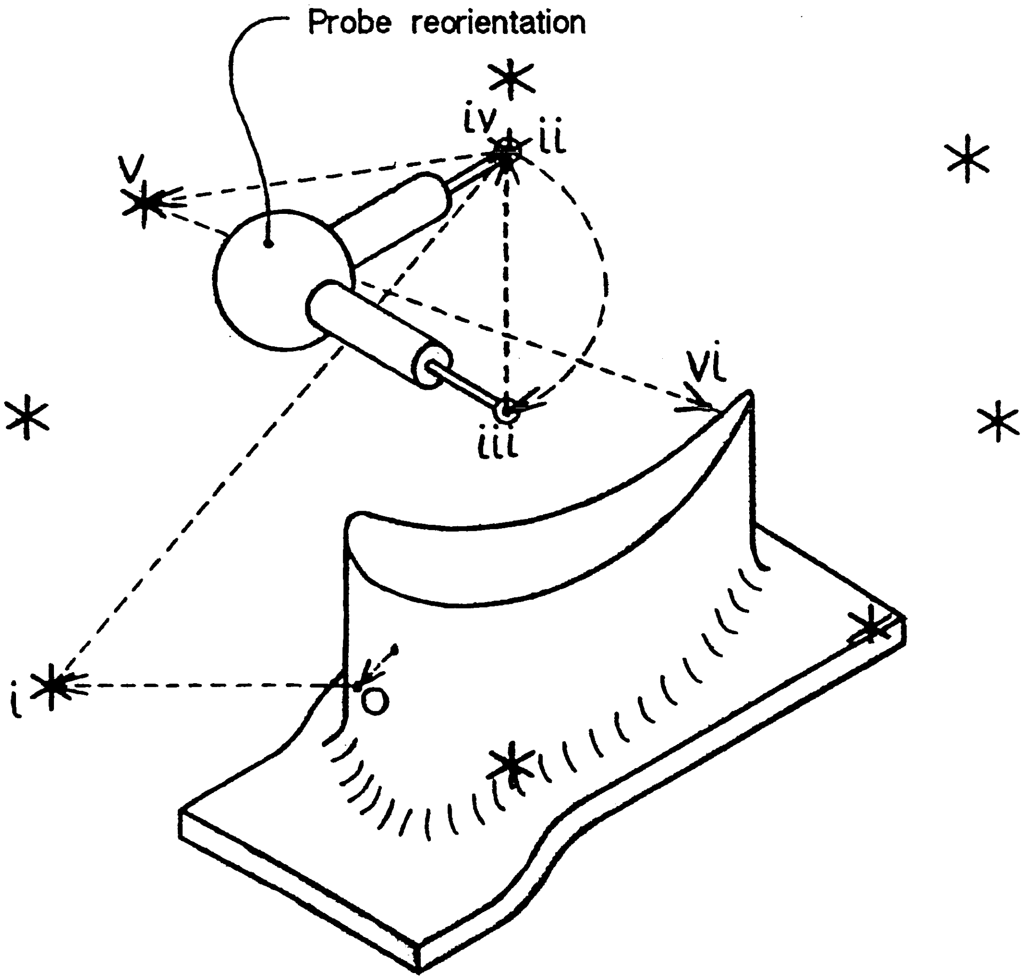


Figure 5.12

The Probe Path used for Probe Reorientations of More Than 90°

These algorithms proved very successful for Phase 2 development but again they were not a general algorithm for probe path generation. One further extension to the probe path generator was to overcome the problem of directing the probe for measurement on annulus surfaces. For if the probe were orientated alone an annulus surface normal it would collide with the blade. To overcome this problem the surface normal vector, which was to be used to calculate the probe orientation, was forced to a new vector which pointed away from the centre of the blade by 45°, see Figure 5.13.

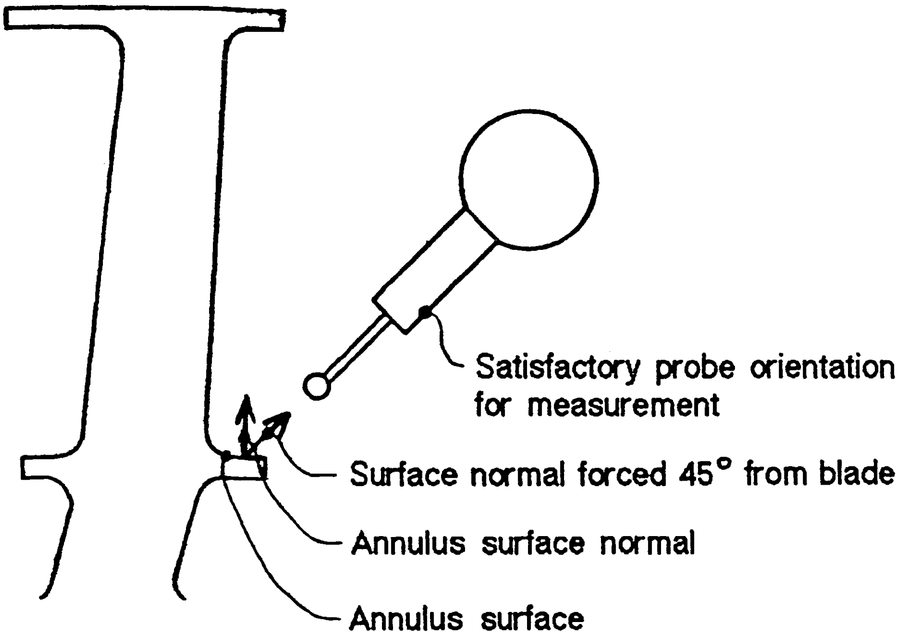


Figure 5.13

The Forcing of Annulus Surface Normal Vectors for Probe Orientation Calculation.

Annulus surfaces were measured along lines of intersection with specified YZ planes, the precise algorithm is explained in Appendix I, section 3.4 and ref[4].

5.3.3 The Construction Of Alignment Part Programs

The method by which most turbine blades are aligned is extremely complex. The basic concept is to locate the blade on a number of points which fix the throat area of the passages between the blades. This throat area sets the 'reaction' of the turbine, which is one of its most basic properties ('reaction' is defined as the change of fluid enthalpy over the turbine rotor divided by the change of fluid enthalpy over the turbine stage (stator and rotor)).

The points on a turbine blade surface used to define its coordinate system are called A, B and C points, for which Figure 5.14 defines the A and B points for a particular high pressure blade and Figure 5.15 defines the C point. They are defined as zero error target datums. Although extremely complex in definition the basic rules for constructing the blade coordinate system are to define a plane, a line and a point. The coordinate system for a blade is called a 'stacking axis', principally because it forms the frame of reference to which the aerofoil sections are stacked on top of one another during the design of the blade.

The procedure for ABC point alignment is extremely complex and is specified in Appendix I, section 3.3, Appendix II, section 4.3 and ref[3]. The alignment procedure written within the system is fully automatic but in order for the program to start it must receive an estimate for the location of the coordinate system to within 4mm. To accomplish this a manual alignment procedure is performed, this is known as pre-alignment.. This is described in Appendix I, section 3.2, Appendix II, section 4.2 and ref[3]. Both the pre-alignment and ABC point alignment part programs may be written interactively on the inspection system.

To compile the alignment part programs into NDF format the number of functions used was increased from 8, required for measurement programs, to 48. It is worth noting that 75% of these were not available under normal NDF standards.

Another problem with the NDF standard and indeed the Mitutoyo controller was that they did not facilitate the type of interactive programming required for alignment. For example during the alignment process - which is iterative - it was not possible to repeat the process until a certain accuracy had been achieved and stop. The convergence of the ABC point alignment process might take 3, 4 or 5 iterations but there was no way of conditionally iterating.

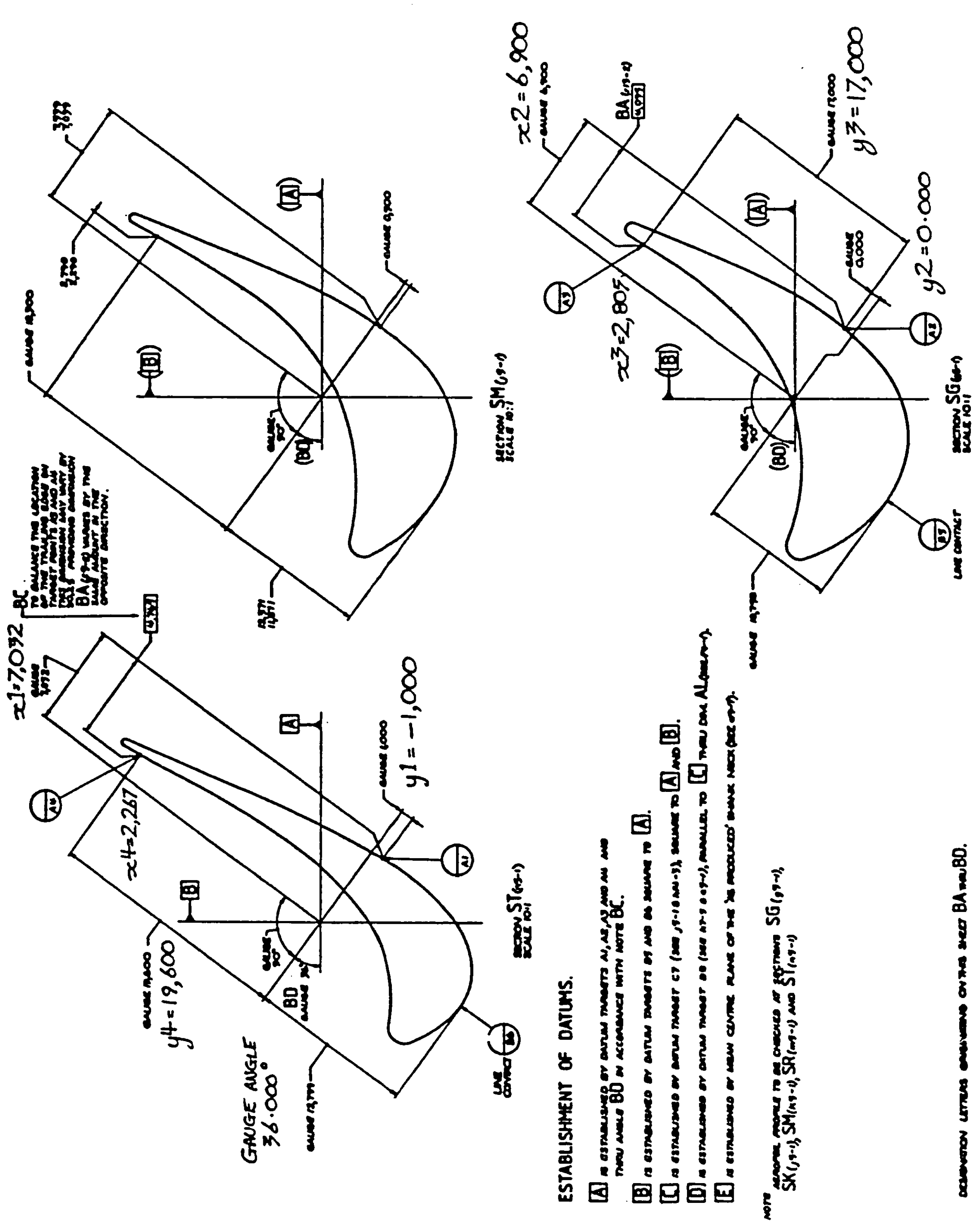


Figure 5.14

Specification of the A and B Points on a High Pressure Turbine Blade

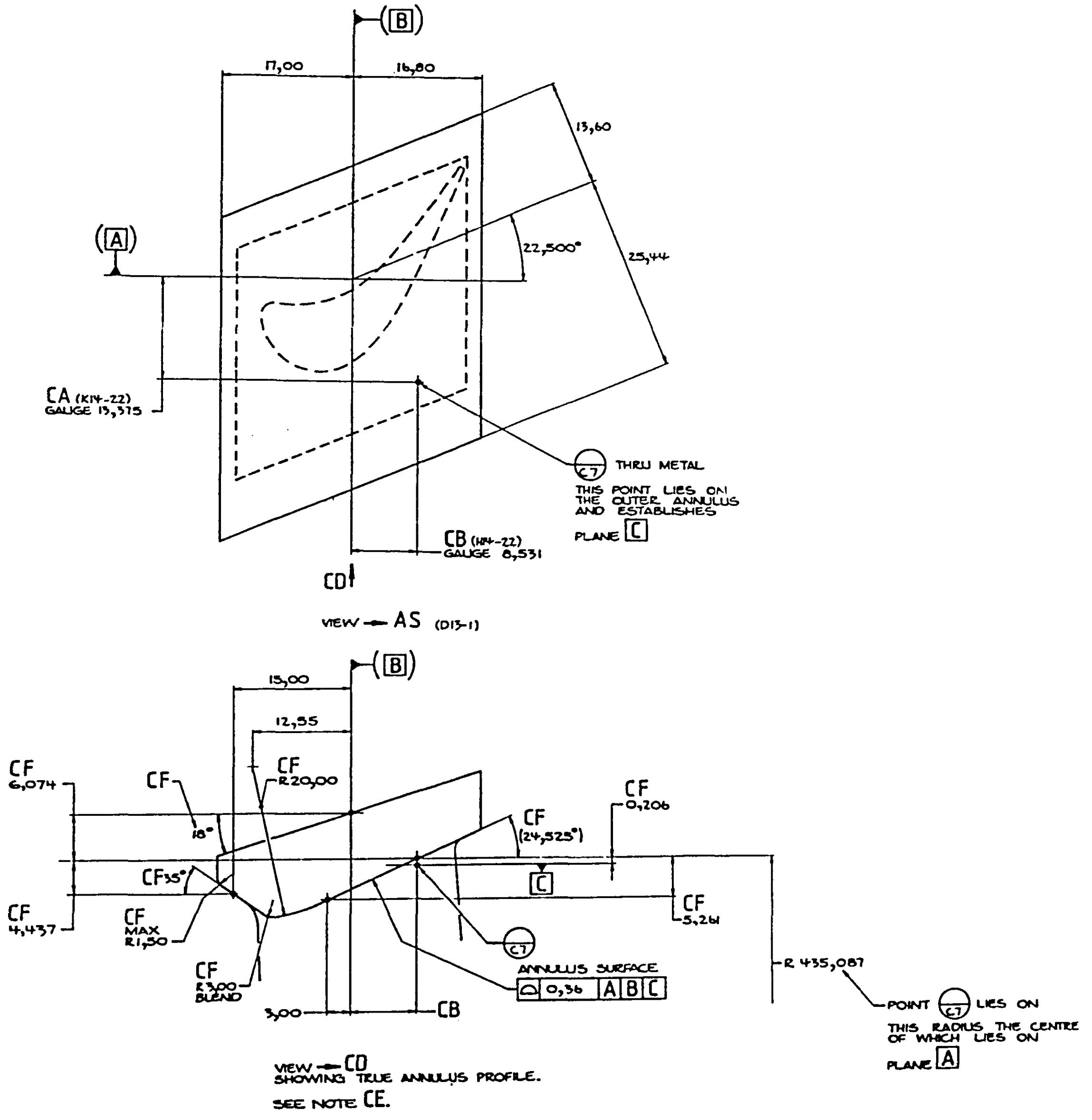


Figure 5.15

Specification of the C Point on a High Pressure Turbine Blade

One major problem experienced with the system during the Phase 2 development was in part program file transfer through RS232 to the CMM. It was found that large measurement programs were taking exceptionally long times to transfer. A 170 point aerofoil measurement program would take 25 minutes and during this time transfered information was liable to electrical interference from production machinery in the vicinity of the inspection machine.

5.3.4 The Conversion Of Inspected Data Into PANACEA Models

As experience was gained on modelling inspected data it was realised that simply presenting the measured results as points was rather confusing when perhaps as many as 200 points per aerofoil section were displayed on the graphics screen.

Plate 13 illustrates a probe path for the measurement of one section of an aerofoil and shows just how many points can be measured (The probe path is represented by the blue lines - note the probe movements to 'home' positions).

To overcome the problem of representing hundreds of points on the screen the measured results were used to model surfaces. In Plate 14 the nominal aerofoil surface is defined by the green lines and the surfaces generated by the measured results are defined by the white lines. At various heights up the aerofoils the error between the two surfaces has been calculated at discrete positions, these errors are the small red vectors.

Work on surface error calculation showed that models of the measured surfaces were far easier to use than just inspected points. Other work suggested that the transfer of models of measured surfaces to other systems within the company would be useful and that a definition of the these surfaces that was in the same format as the nominal surfaces would be a great advantage. Measured annulus data was converted into open b-spline lines. It was not converted into surfaces as this was felt to be unnecessary.

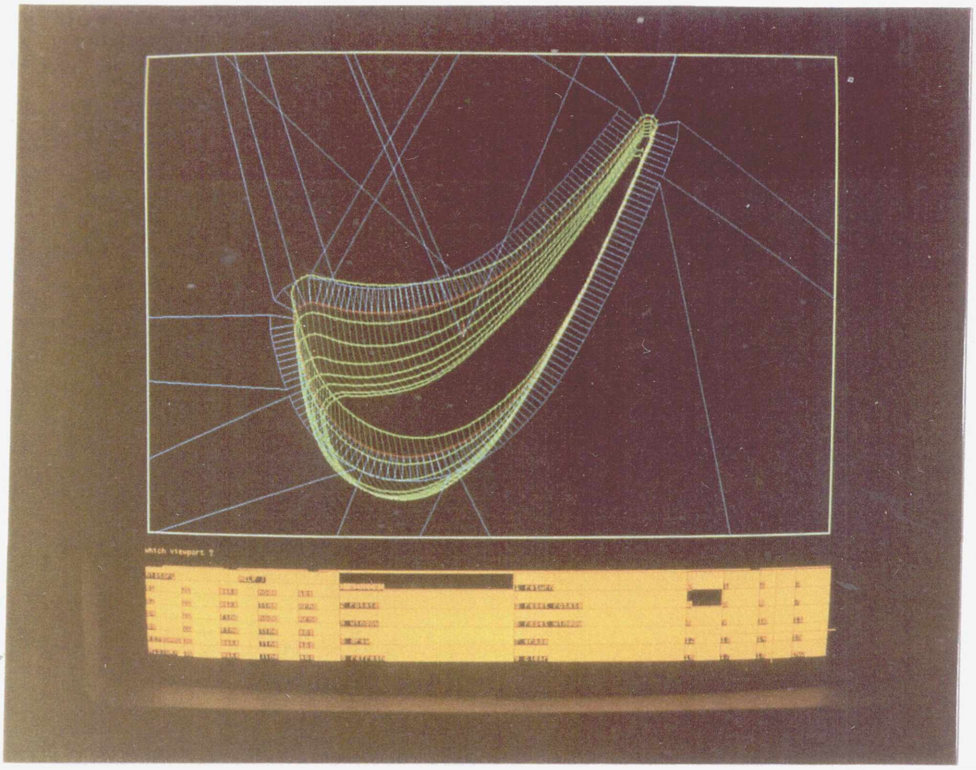


Plate 13 : A View of a Probe Path Around an Aerofoil

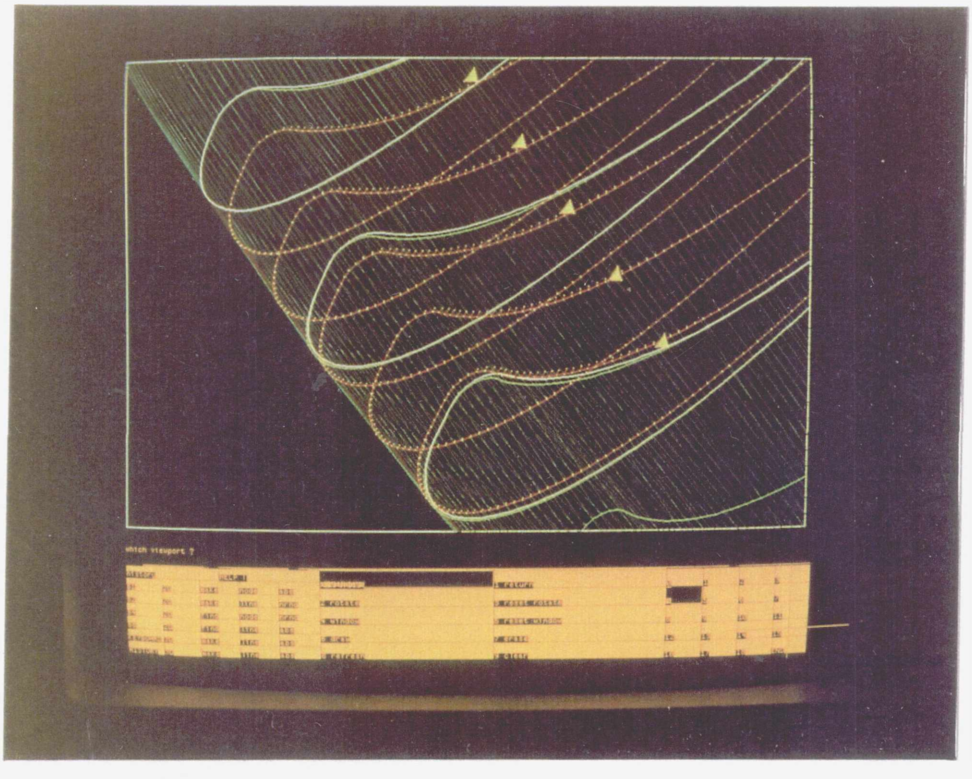


Plate 14 : Error Vectors Between a Nominal Aerofoil Surface (Green) and an Aerofoil Surface Modelled Using Measured Points (White)

One problem of modelling surfaces from inspected points was to guarantee the integrity of the modelled surfaces. In exactly the same manner as nominal b-spline surfaces required careful control point distribution so did surfaces modelled from inspected points. Appendix II, section 4.5 explains in detail the method in which the integrity was achieved, however for completeness a brief explanation is included here.

For turbine blades it was found that the best distribution of control points for modelling a surface from inspected results was the same as that distribution used for modelling the nominal surface. One method of achieving this was to measure each surface at every control point defined on the nominal surface. However for aerofoils of perhaps 180 control points per section this implied a very large number of measurements.

Fortunately a method was found which enabled fewer points to be measured. Simply it involved measuring aerofoils at a specified number of points and during conversion of the measured results into surfaces sufficient extra control points were inserted. To provide for the information necessary to insert extra control points the probe path generator produced geometric information between the control points on the nominal surface chosen to be measured and those control points which were not. This information was written to a file which was used when the inspected data was modelled into surfaces.

This technique developed for point insertion may be applied to any free-form definition of a surface. It may be used whenever a surface type requires more control points to smoothly define it than are actually required to measure the surface and obtain errors to a sufficient accuracy.

The process of transferring information from the probe path generator to the measured surface modeller had other advantages. The measurement points received from the inspection of turbine blades did not include probe compensation (that is to say the points represented the position of the centre of the probe ball at the moment of impact with the turbine blade surface and not the surface point itself). To account for this the probe path generator wrote the compensation in the form of a 3-D vector to the same file as was used to define the extra control point distribution, and these vectors were added to the inspection results during the modelling of the measured surfaces.

5.3.5 The Development Of Surface Error Calculation Algorithms

The initial algorithms, within the integrated inspection system, for calculating surface errors were based on the principle that the error between a measured point and a nominal surface existed along the shortest line joining the point with the surface. For low curvature surfaces like annulii this criterion proved successful. However for aerofoils with regions of very high curvature the criterion often broke down, as Appendix I, section 3.8 describes. As a result a different rule for calculating the surface errors was adopted :-

'The difference between two surfaces exists along vectors emerging surface normal from one surface and intersecting with the other along the most positive length of the intersecting vector'.

Figures A1.7 and A1.8 in Appendix I illustrate that this rule yields more realistic errors in regions of high curvature.

The consequence of applying this rule to error calculation was that it required intersection routines to interpolate around modelled surfaces of inspected results. However, it was shown, and is discussed in more detail in section 7.2.2, the nature of blade surfaces enables interpolation to provide errors within 4μm, providing the surfaces are measured with a sufficient density of points.

5.3.6 Sectional Error Presentation

The presentation of the surface errors was obviously an important feature of the inspection system. The first choice of error presentation was to represent errors around inspected sections. A number of commercially available inspection systems provided this type of facility and it can be a very useful method of displaying errors.

In order to present the errors with tolerancing information a farely crude technique was developed where by upper and lower profile tolerances could be read into the system from a file. Figure 5.16 shows error around a section of an aerofoil.

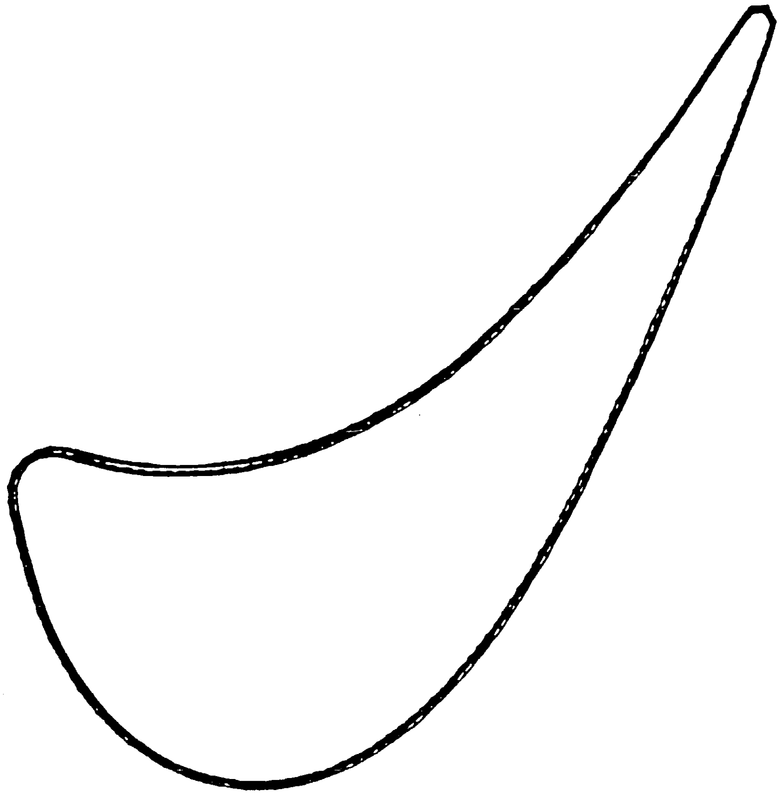


Figure 5.16

Measured Error Around a Section of an Aerofoil

One problem with this form of error presentation is that the size of the error is small in comparison with the size of the aerofoil, making the error difficult to visualise. As a result magnification of the surface error was adopted, Figure 5.17 illustrated the same error as in Figure 5.16 but magnified 10 times.

One consequence of using error magnification is that strange effects in the presentation may result in regions of high curvature, as is shown in Figure 5.17 at the trailing edge. To reduce the difficulty in visualisation of the error another form of presentation was developed which unwound the nominal sections into straight lines. Starting from the leading edge the surface was unwound along the suction surface, around the trailing edge, along the pressure surface and back to the leading edge. Figure 5.18 represents the surface in Figure 5.17 unwound in such a fashion.

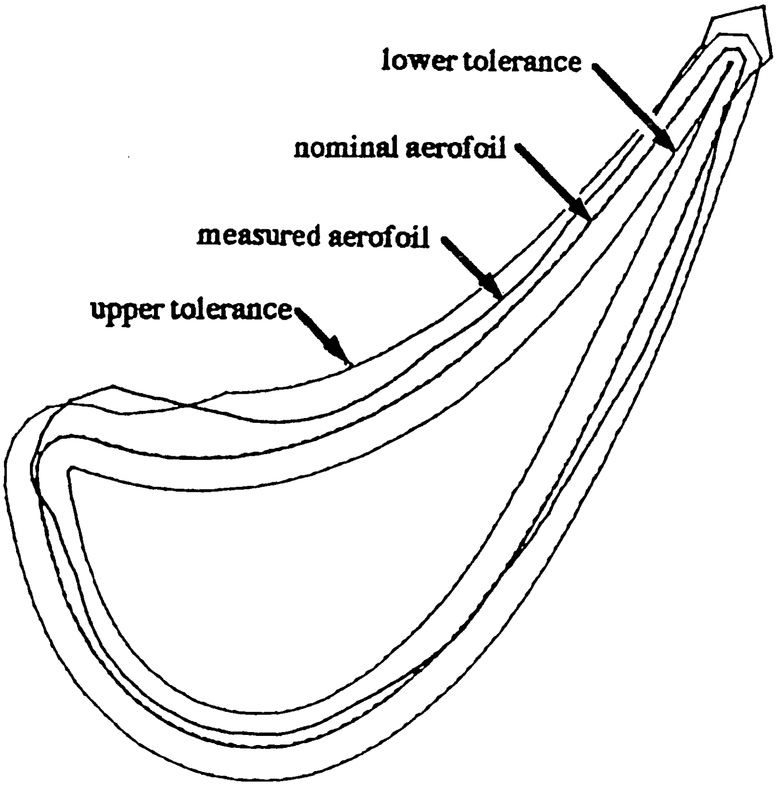


Figure 5.17

Measured Error Around a Section of Aerofoil, With the Error Magnified 10 Times

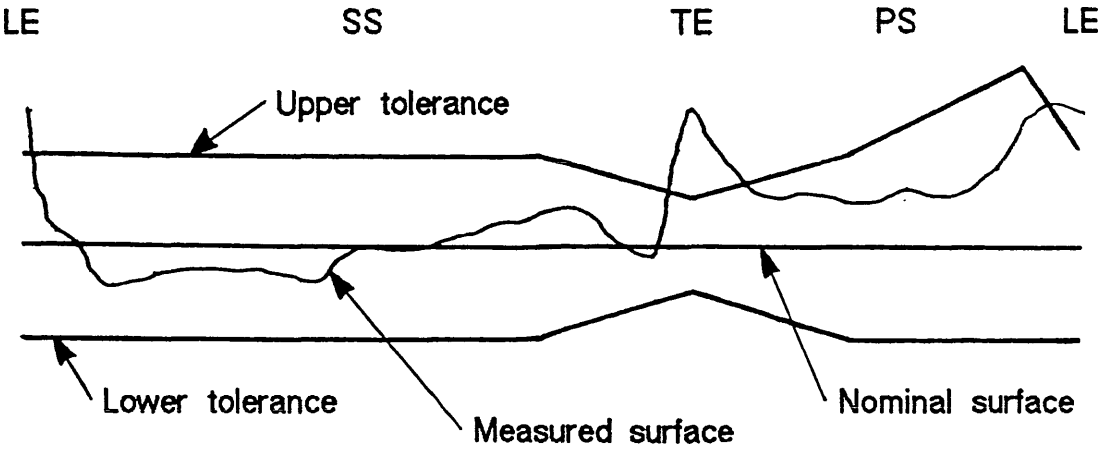


Figure 5.18

An Unwound Surface Error Presentation

Presentation of annulus errors along measured sections proved to be less successful than for aerofoils, as it proved to be more difficult to visualise the location of the errors. This problem was overcome by the use of contour plots of error which is discussed in detail in Chapter 6.

5.3.7 Resume of Phase 2

The completion of Phase 2 illustrated the use of an integrated inspection system for the measurement and presentation of error on turbine blade gas washed surfaces. However a three dimensional best fitting facility was still required and as a result Phase 3 of the system development was launched. During this period various other improvements were made to the inspection system and these are discussed in the next chapter. The development of a three dimensional best fitting facility is discussed in Chapter 7.

References

[1] Cardew-Hall, M.J., "Modelling and Integrated Inspection of Cast Turbine Blades", PhD Thesis, Imperial College of Science, Technology and Medicine, University

of London, June 1988.

[2] Brookes, N.J., "Product Definition: A Systemic Approach to its Improvement", PhD Thesis, Imperial College of Science, Technology and Medicine, University of London, In Preparation.

[3] Lee, S.A., "Discussion of the Automated Proof Inspection System After the Completion of Phase 2: The Measurement of a Turbine Blade", Department of Mechanical Engineering, Imperial College of Science, Technology and Medicine, University of London, April 1988.

[4] Lee, S.A., "Introduction to an Automated Turbine Blade Proof Inspection System and Implementation of Phase 1: The Measurement of a Test Piece", Department of Mechanical Engineering, Imperial College of Science, Technology and Medicine, University of London, November 1987.

Chapter 6

Developments Of The Integrated Inspection System

6.1 Introduction

As experience was gained in the use of the integrated inspection system it became apparent that various improvements needed to be made both from the programming and operator's points of view. This additional work concentrated on the following areas :-

i. Transfer of all software to a SUN 3/60 workstation.

ii. Greater generality in the capability of the system, specifically the probe path generator.

iii. Improved communications between the inspection system and the CMM, both in terms of software and hardware.

iv. Facilities for the measurement of batches of components.

v. Improvements in the speed of error calculations.

vi. Improvements in the presentation of errors.

vii. Systematic approaches to relating surface errors to modifications of dies.

As the Blade Modeller and Integrated Inspection System grew the Codata microcomputer, on which they were originally based, became unsuitable as a computing platform as it had insufficient processing power and memory capacity. Consequently a SUN 3/60 workstation (Plate 15) was purchased. This provided a twenty fold processing power increase and a Winchester disk with 141Mbytes of memory. However all of the software had to be transported to the SUN and many changes made to PANACEA. This work was carried out by Brookes [1].

Plate 15 : The SUN 3/60 Workstation onto Which The Blade Modeller and Integrated Inspection System were Transported

6.2 Generality In Probe Path Generation

6.2.1 Introduction

The need for generality in the generation of probe paths became obvious, from the programmer's point of view, since it would be ridiculous to have to consider new rules for every form of surface that was to be modelled and for every probe type which was to be controlled by the system.

For the more general probe path generator the principal type of inspection technique was of the discreet point measurement type, for example single contact touch probes, e.g. The Renishaw PH9-TP2, or the laser headed probes, e.g. The Renishaw PH9-OP2. The probe path generator was not to be concerned with controlling any type of machine employing 3D imaging techniques except those based on laser triangulation.

Although the more generalised probe path generator was designed for controlling certain types of inspection machines over certain surfaces it is extremely important to recognise that this is only a part of the overall inspection system and that it represents only one method by which surface information could be fed into an integrated inspection system. For processes like error calculation, error display and best fitting the method by which inspection results are obtained is immaterial. So if a Computer Tomography scanner was to be used to obtain geometry, although the probe path generator would be of no use, the error processing facilities would remain unchanged.

6.2.2 Specification Of A General Solution To Probe Path Generation

The basic requirement for the algorithm was to control a probe to measure specified positions on a geometrically defined surface. As section 5.2.4 has stated this task may be divided in 3 sub-tasks, which are again listed, but extended for incorporation of laser triangulation measuring devices :-

i. To move a contact probe or align a laser probe along the surface normal in order that measurement may take place.

ii. To prevent collision of the measuring device, except for the contact probe with the target point, during the act of measurement.

iii. To prevent collision of the machine while moving between measurements and to be efficient in the time taken between these measurements.

For contact and laser triangulation probes measuring 'inspectional convex' surfaces a solution to the first and second requirements may be obtained by aligning the probe along the surface normal to the target point.

A solution to the third requirement could be obtained by extending the concept of 'home' positions or 'home' regions, in which probe reorientations and large probe movements around an object are provided for by dropping back a 'safe' distance from the object being inspected. This method worked well in Phase 3 and is applicable to 'inspectionally concave' surfaces.

Thus the major challenge to the generalisation of probe path generation is the optimum orientation of the probe head for measurement.

6.2.3 Methods For A Generalised Solution To Probe Path Generation

The problem of optimising a probe orientation for measurement is in principle one of collision avoidance. However the solutions to collision avoidant algorithms often suffer from very large computational requirements and with a typical inspection of a turbine blade requiring over 1000 points to be measured simpler solutions were required.

One concept which became apparent when working with probe path generation is that the target points and surface normal vectors play the most important role in the calculations. It may be said that once the target points and surface normals have been extracted from the surface there is no further need for the algorithm to concern itself with the definition of the surface. Therefore what is required is a method of generating target points and surface normals from model surfaces and then to pass these to the probe path generator.

A number of methods to a solution of optimum probe orientation from target points and surface normal data were explored. Three are presented below :-

i. Potential Method

In this case it is assumed that a collision free probe orientation lies along a line achieving minimum potential from the surfaces of the inspected object. Another way of considering this is to imagine that the probe head was fixed to the target point, while having rotational freedom about the fixing. If the inspected object and the probe where to be statically charged in a zero gravity field, the algorithm would assume that, the probe would repel itself from the surface along an orientation without collision. This line would be suitable for a TP2 type of probe, but for a laser probe, where the closest orientation to surface normal is required, the line would have to be brought back to a position as close as possible to the surface normal without causing collision.

The major problem with this technique would be the computational requirement necessary to define the potential field around the modelled geometry. As a result no work was carried out on defining a probe path generator algorithm based on potential methods.

ii. Reversed RISP Element Method

Bloor [2] defined a RISP element by linking surface normals from edges of a geometry. Such an algorithm could be applied in generating successive RISP surfaces produced from normals pointing out of a surface. So that rather than closing up on an area as a normal RISP the successive surfaces would be moving out from the surface and in this sense would be 'reversed'. Once defined for the object, the RISP surfaces would provide a potential field definition which could be used in the same manner as described above.

The major problem with this technique would be the large computational requirement that would be necessary to define the RISP surfaces around the modelled geometry. As a result no work was carried out on defining a probe path generator algorithm based on 'Reversed RISP' methods.

iii. Line-of-Sight Method

The principle of this technique is based on the fact that a thin probe could approach a target measurement point from any direction providing it is along a clear line-of-sight with the target. With a complex surface the problem is how to define the line-of-sight domain and obtain an optimum orientation within it. One of the simplest assumptions is to assume that this domain may be defined by a cone. The cone would be formed when its apex was placed on the target point and the surface of the cone did not quite touch any part of the modelled geometry, see Figure 6.1.

Of all of the algorithms, that were considered capable of defining an optimum probe orientation, the line-of-sight method, based on a cone domain, was the least computationally demanding. Therefore this method was adopted for further work and an algorithm is presented in Appendix III.

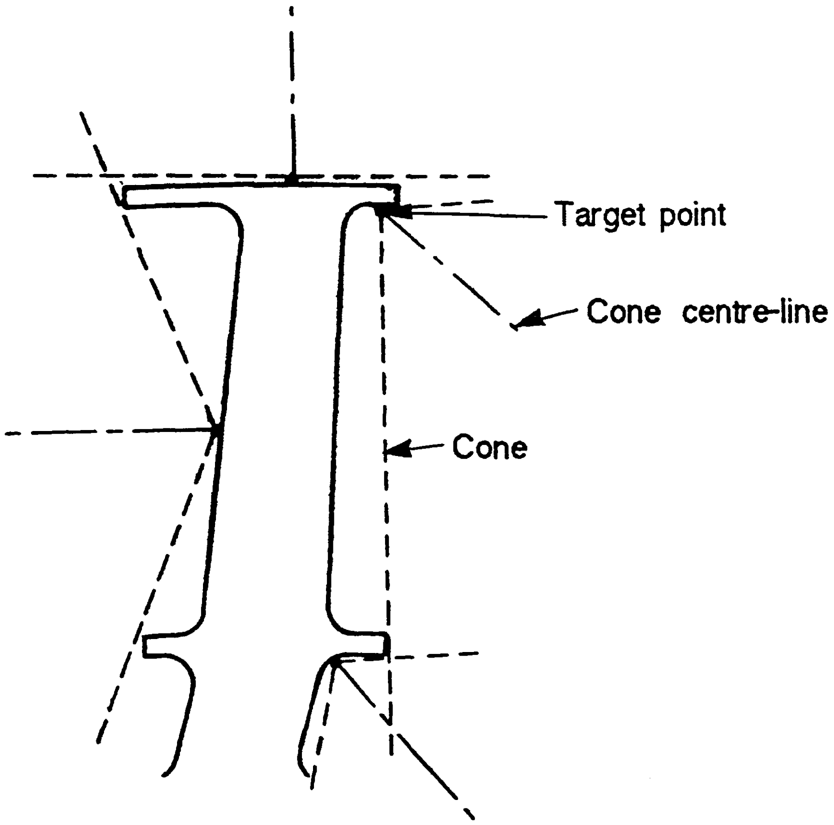


Figure 6.1

Line-of-Sight Cones Around a Complex Geometry

6.2.4 Resume Of Generality In Probe Path Generation

The objectives of generality in probe path generation are to provide a technique to control discreet measurement devices to measure over a wide range of geometries modelled using a number of surface definitions. It has been shown that one technique for coping with different surface definitions is to use the surfaces to generate sets of target points with associated surface normals that are subsequently passed to the probe path generator which never needs to be concerned with the surface definition.

In seeking a solution to the control of measuring probes it has been shown that the major problem is the orientation of the probe for the measurement. Orientation may be obtained by a number of techniques although the least computationally demanding method to be found was based on forming line-of-sight domains. An algorithm based on this principle generates cones with the apex at the target point while the cone surface never quite touches the modelled geometry thus providing a collision avoidant domain.

A further use of line-of-sight cones is in determining a probe's movements when in close proximity to the object being measured. By combining the cones of two adjacent measuring positions the combined region represents a collision avoidant domain through which the probe may be moved. For large probe movements and for probe reorientations it is recommended that the principle of 'home' positions/regions be maintained.

6.3 Improved Hardware and Software Communications Between The Inspection Systems

6.3.1 The Neutral Exchange Language

From the work carried out during phase 2 of the development of the Integrated Inspection System a number of criteria for a Neutral Exchange Language between the integrated inspection system and the CMM control systems were deduced :-

i. The CMM should be programmed at an explicit control level, rather than at an object level, e.g. measure circle. Object level programming is capable of measuring only the most obvious of forms.

ii. The complex alignment functions available in most inspection systems should be accessible through the exchange language. If this is not provided, objects like turbine blading will not be able to be aligned using off-line written code.

iii. The exchange language should facilitate conditional programming. For example a program should allow the measurement and selection of the highest point on a surface.

iv. Provision should be made for the feed-back of inspected data from CMMs to integrated inspection systems.

It is unfortunate that NDF has not been able to provide for these criteria, and it is perhaps for these reasons that NDF has not been adopted more substantially within the industry as a communication standard. It is interesting to note the similarity between NDF and most CNC control languages for they too are non-conditional and provide for only one-way communications.

In the United States of America the Illinois Institute of Technology Research Institute released, in April 1986, the Dimensional Measuring Interface Specification (DMIS) [3] which is an equivalent concept to NDF but appears to have some advantages. It explicitly aims to provide for the bi-directional communication of inspection data between computer systems and inspection equipment. Like NDF DMIS is designed to be human readable and writable.

DMIS version 1.0 was developed by the IIT under contract to the Computer Aided Manufacturing - International (CAM-I) organisation. However since 1986 Pratt and Whitney, a division of United Technologies Corporation, has taken over from the IIT and has been developing the language to cater for an increasing number of types of machine -

including vision systems.

The DMIS language is very similar to the NC programming language APT in format. Indeed some of the words are identical although their meanings are usually slightly different. DMIS is now an ANSI standard.

The language offers high level language program control functions such as 'if', 'then', 'else' statements and nested loops. It also allows program flow control to be altered based on the results of measurements.

Overall it would appear that DMIS offers a far better neutral exchange language than NDF. Various CMM manufacturers, such as LK tools, are now offering DMIS on their machines in this country and it may not be a surprise, therefore, if DMIS supersedes NDF in the UK.

6.3.2 File Transfer

As has already been stated the inspection system after phase 2 development used RS232 standards for file transfer between itself and the CMM. This method was not only extremely slow but it was found that data being transfered was susceptible to corruption due to electrical interference. A further problem was incurred when sending inspection results back to the workstation, for it was necessary to re-configure the CMM printer port.

To overcome these communications problems PC-NFS DOS was installed on the CMM controller with an Ethernet link to the SUN 3/60 workstation. This provided the following advantages :-

i. Ethernet communications are extremely fast.

ii. The part programs need not be sent to the CMM before they are executed. For the PC-NFS provides for the CMM controller to observe the part programs in the workstation in exactly the same manner as if they were on its own disk-drive.

iii. The Ethernet link provides for an easy facility for the CMM controller to write inspected data to files on the workstation.

iv. As a file server the workstation may be used to serve a large number of CMMs.

It may be said that the Ethernet was an extremely powerful addition to the integrated inspection system, it provided exactly the type of communications required.

6.4 A Batch Measurement System

It was found when using the integrated inspection system that there was a need to calculate averages and standard deviations from measurements of batches of blades. In order to facilitate batch measurement the inspected data conversion program was redesigned to enable multiple surfaces to be measured from which the average and standard deviation were calculated. To enable the processing of batches of inspected data a number of additions had to be provided for within the inspection system :-

i. At the end of each surface measurement the part program sent a string of information to the inspected data file. The string enabled the inspected data conversion program to separate each surface. It also contained the name of the file which stored the conversion information and hence it was possible to open this file automatically.

ii. The surface modelling program provided a systematic method of naming batches of inspected surfaces, see Appendix I, section 3.7. Batch naming techniques proved extremely useful for batch error calculation programs.

iii. After a batch of inspected results was converted into surfaces a further surface was produced which represented the average of the batch. The standard deviation of the measured points was also calculated and written to a file. By treating the standard deviation as values over a surface it is possible to display it in exactly the manner as surface error, this is discussed in detail in the next section.

iv. A further facility enabled the user to interactively select a number of surfaces from which the average and standard deviation was calculated. This was found to be useful if, for example, it is felt that one or more surfaces in a batch was unrepresentative and thus should be ignored in the average and standard deviation calculations.

6.5 Contour Plotting

The inspection of blade surfaces yielded two main problems; firstly they are extremely complex free-form surfaces and hence the interpretation of the error is complex and secondly batches of surfaces yield very large quantities of data. For example an aerofoil might be measured at 500 points and 25 blades might be measured in a batch.

It was clear from the outset of the project that graphical output of the inspected results was probably going to yield a satisfactory method of presenting error. Initially sections of error were presented, as explained in section 5.3.6, but even this fell short of a quick method of illustrating surface errors on batches of blades. As a consequence it was proposed that contour maps of surface error be used. Using the algorithm from Petty [4] the errors and standard deviation of error were plotted as contours. Figure 6.2 illustrates how the error on 5 inspected sections of an aerofoil may be presented, either as sections or as a contour map.

In Figure 6.2 the perimeter of the aerofoil has been divided into 170 equally spaced lengths. These divisions have been numbered from the leading edge and proceed along the suction surface around the trailing edge, along the pressure surface and finally back to the leading edge. The aerofoil perimeter thus forms the abscissa of the contour map. The ordinate represents height up the aerofoil. The 5 measured sections at 380, 390, 400, 410 and 420mm above engine centre line are marked on the ordinate axis of the contour map. The colour coding for error displays is:-

For Contour maps : -

Black - no error

Blue - negative error

Green - positive error

Red - out of tolerance, positive or negative error

For Sectional Views :-

Green - nominal surface

Black - measured surface

Blue - positive and negative profile tolerance

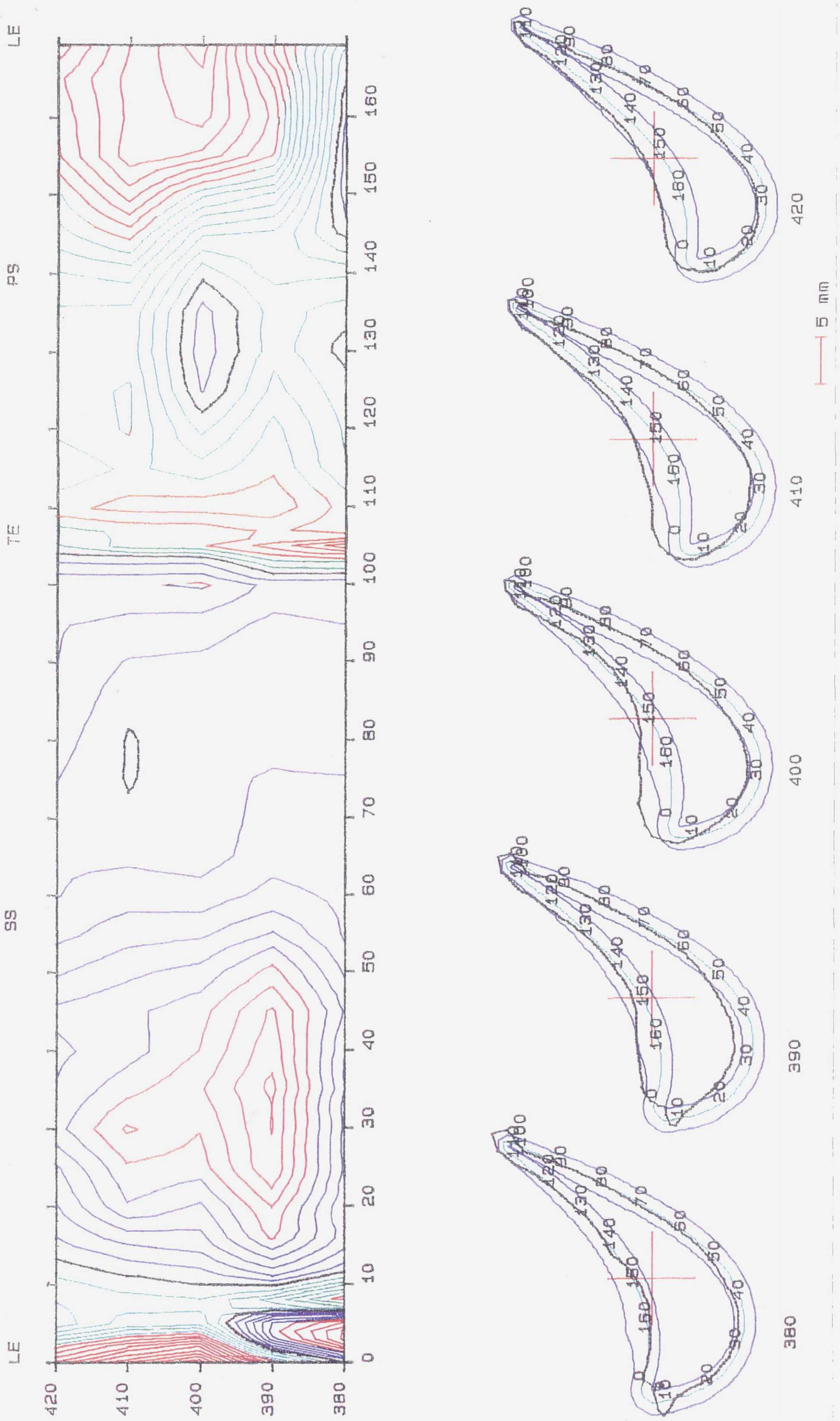


Figure 6.2

A Contour Map and Sectional Views of Surface Error from a Measured Aerofoil

In Figure 6.2 the contours are in 0.025 mm increments. It was found that the contour plots are an extremely powerful method of illustrating surface error. Initially these maps are hard to use and require constant cross-reference to sectional views of error, but after some practise it is possible to look at a contour map and almost immediately perceive the nature of the errors. A number of examples of contour plots have been included to illustrate their use.

Figure 6.3 illustrates the pattern of errors on a bowed aerofoil. On the suction surface (10 - 60) the contouring is showing a concave form of error towards the middle of the aerofoil while the pressure surface (63 - 110) is showing a convex form of error. The net interpretation is bow. The contour plot is enabling the user to very quickly interpret the hundreds of measured results as a single phenomenon of bow distortion.

Figure 6.4 illustrates the power of the contour map in illustrating enormous quantities of measured results. In fact in Figure 6.4 2300 results are represented. Maps 1 to 6 represent error on 6 measured aerofoils, blades 1, 2, 3 and 5 clearly show bow while 4 and 6 are not bowed. Map 7 represents error on a resin produced from the same wax pattern die that was involved in producing the blades. The resin shows no bow, illustrating in this case that the bow in blades 1, 2, 3 and 5 was imposed on the blades during the casting process and not by the wax pattern die. The resin is larger than the blades , this is to allow for solidification effects. Since the blade nominally has twist, the effect of measuring the resin and comparing it to the nominal aerofoil is that it is slightly untwisted. This is shown on the contour map by the angled contour lines.

Figure 6.5 illustrates a contour map of surface error on an average aerofoil produced from the measurement of a batch of blades along with a contour plot of the standard deviation over the surface. Standard deviation will always be a positive number and hence the surface is never blue. In the case of this contour map the standard deviation has been set to be displayed in red above 0.030mm.

Figure 6.6 illustrates three aerofoil contour maps of surface error. The upper contour represents the average error of a batch of manufactured aerofoils. The middle contour represents the error on an aerofoil of the same type after running at type test conditions in an engine. It is interesting to note that after running the meat of the aerofoil has bowed while the trailing edge region has remained farely unscathed. The lower contour represents the difference between the engine run aerofoil and the manufactured average.

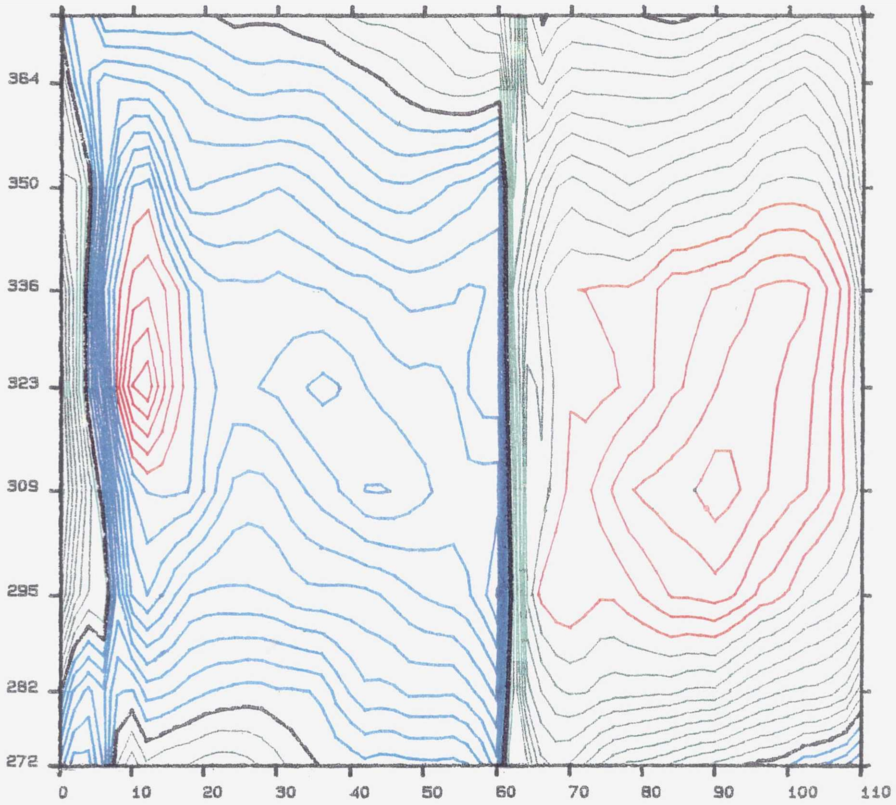
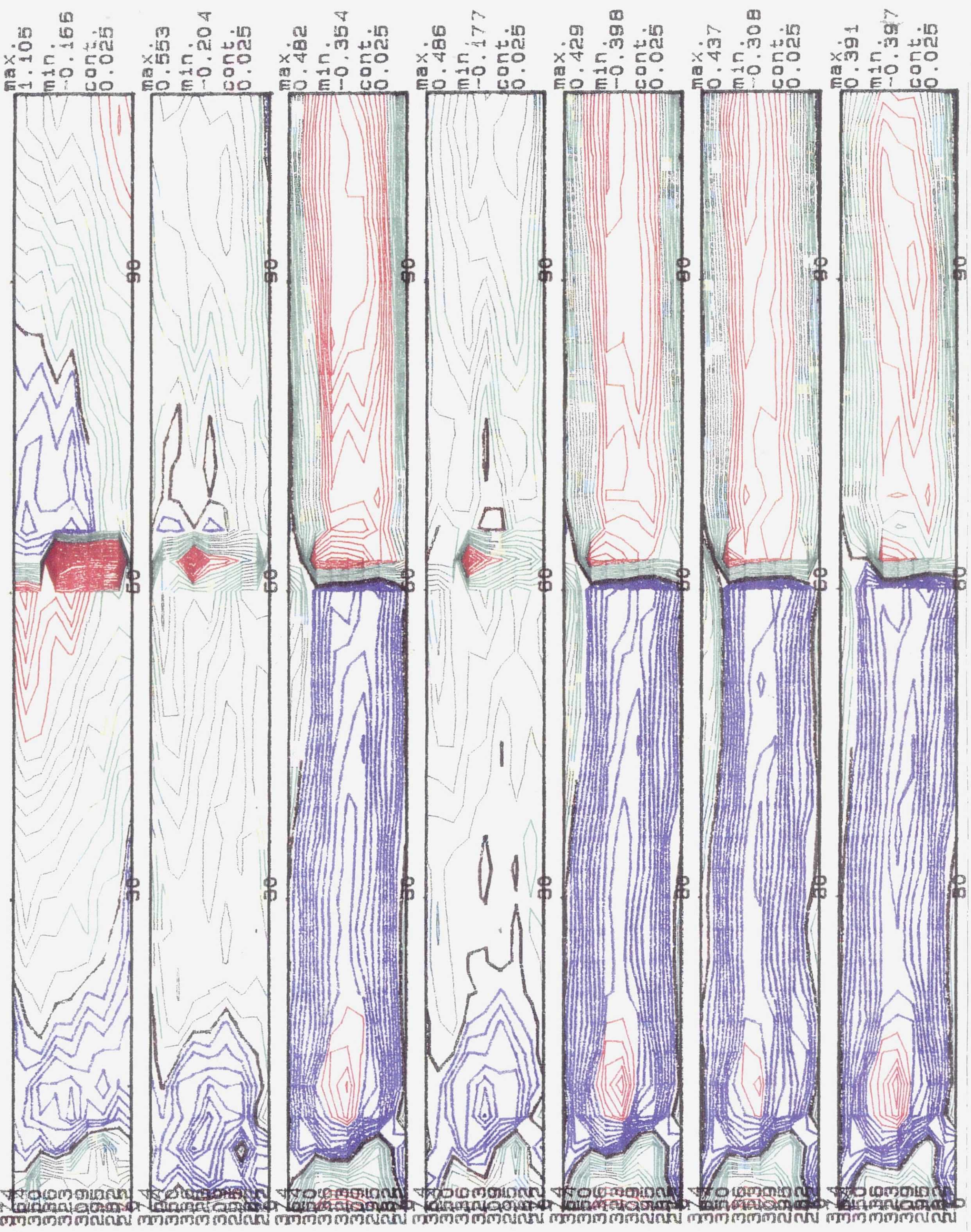


Figure 6.3

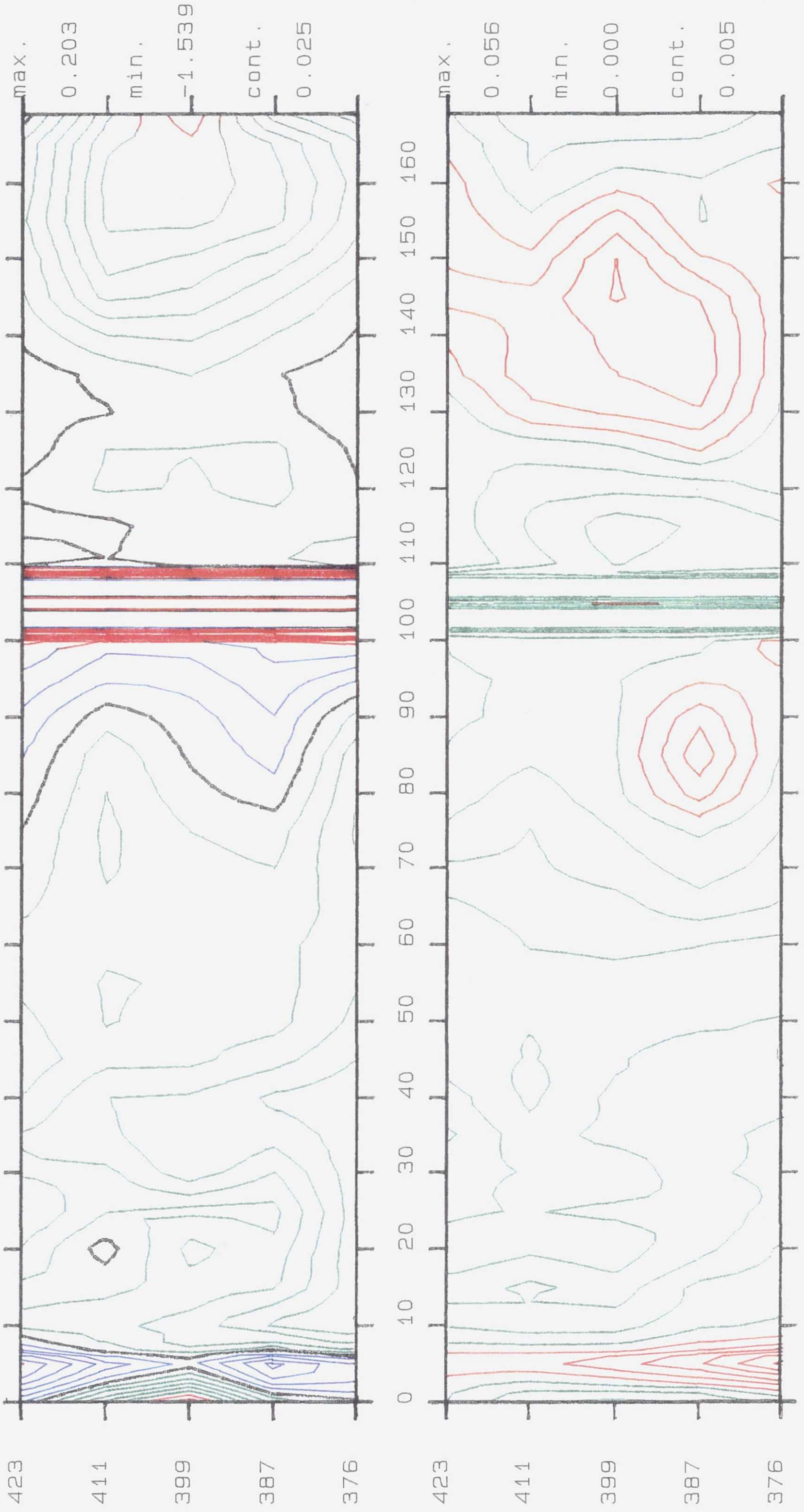
A Contour Map of Surface Error from a Bowed Aerofoil



Resin 6 5 4 3 2 1

Figure 6.4

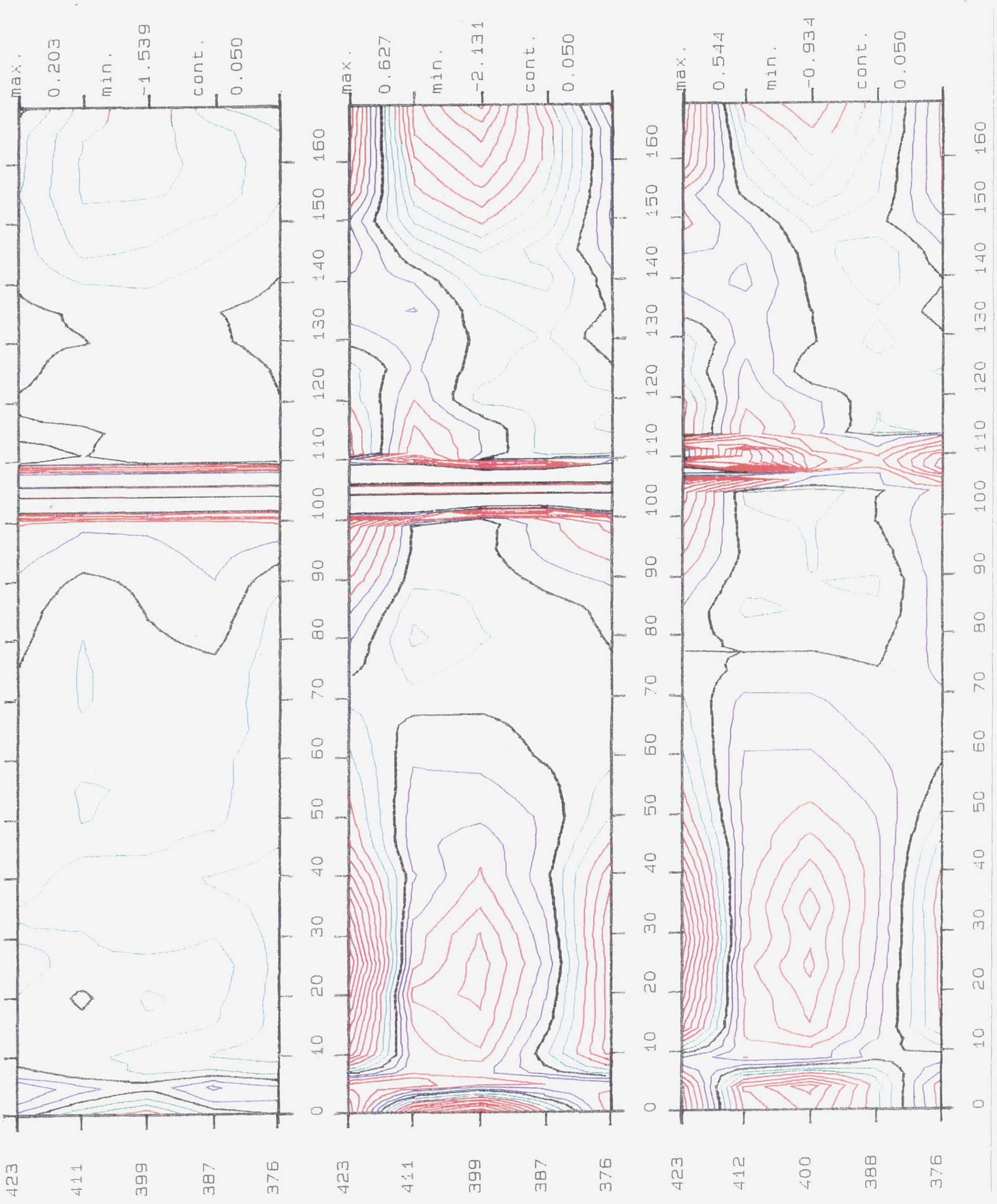
Contour Maps of Aerofoil Surface Error from Six Blades and One Resin



(a) (b)

Figure 6.5

Contour Maps of (a) Average Aerofoil Surface Error and (b) Standard Deviation of Error Obtained from the Measurement of a Batch of Blades



(a) (b) (c)

Figure 6.6

Three Contour Maps of Aerofoil Surface Error:- (a) Average Manufactured, (b) A Type Test Engine Run Blade and (c) Engine Run Blade Minus Average Manufactured Error

Figure 6.7 illustrates a contour map of error on an annulus surface. The lack of smoothness in the edges of the presentation is due to the interpolation technique which is used between inspected results which does not necessarily yield smooth edges. However the form of the aerofoil may be perceived in the centre of the presentation. The cross in the centre of the diagram represents the blade's stacking axis.

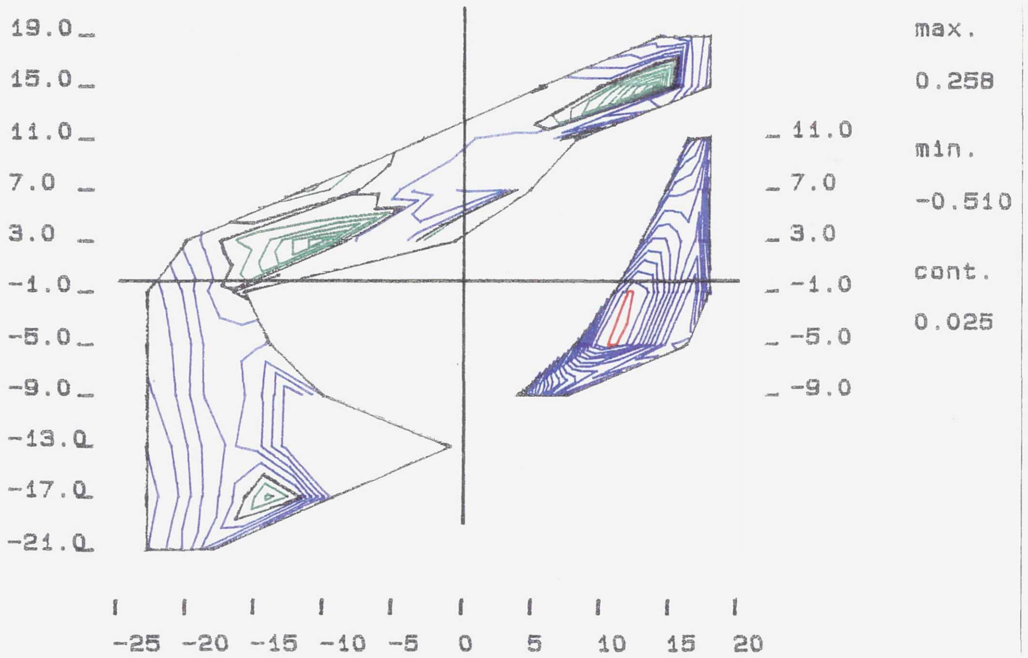


Figure 6.7

A Contour Map of Error on a Lower Annulus Surface

The basic principle of the contour map is to illustrate error over the surfaces of an inspected object in a manner which enables extremely fast interpretation of the results. It may be said that the contour map fulfils this function surprisingly well and has indeed proved to be a very powerful tool for illustrating surface error.

6.6 Relating Surface Errors To Die Modifications

The integrated inspection system provides the ability to produce an excellent presentation of turbine blade surface error. The system provides average and standard deviation of errors over batches of measured surfaces.

During the proof cycling of a casting process it is up to the Methods Engineers to decide what modification is required to a die and or the process to improve the yield of castings. Before considering how to use the results from an integrated inspection system to calculate die modifications for complex geometry castings let us consider these requirements for the imaginary case of a component which has only one critical dimension. It may be said, that given a normal distribution of dimensional variation, the minimum quantity of scrap will be produced when the average dimension of the product lies between the division of the upper and lower tolerance limits. As illustrated in Figure 6.8.

If a complex casting is now considered it may be said that the least scrap will be produced when the average surface corresponds to that defined as existing between the division of the upper and lower tolerance bands over that surface. The surface defined between the upper and lower tolerance bands shall be referred to as the 'bilateral surface'. Dimensional variations in the surface of a casting are caused by the sources of variation inherent in the manufacturing process. It is up to the designers and manufacturing engineers to decide on the compromise between the effects of variability on the product functionality and the cost of improvements in reducing the variability.

The consequence of the bilateral surface is that it implies that the shape of a die should be such that it yields on average a bilateral surface from the castings. How can this be achieved? The current process is to manually measure the proof batch, to manually interpret the errors and then manually modify the die - by hand-dressing or copper plating. Using this technique and given the extreme complexity of aerofoils it is perhaps small wonder that the process requires repeated proof cycling.

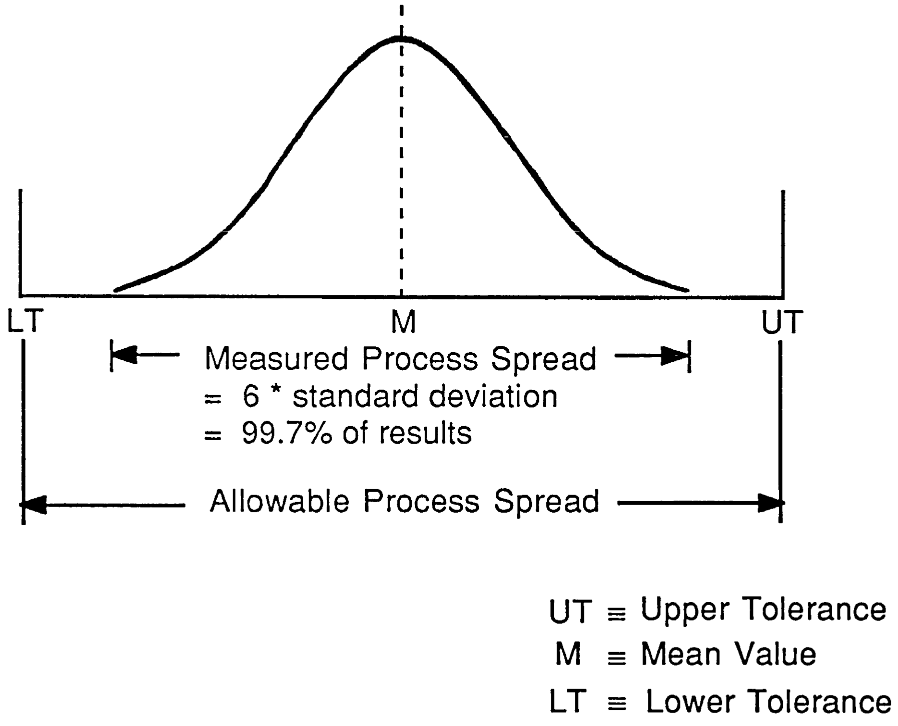


Figure 6.8

Minimum scrap is produced when the mean error exists at the division of the tolerance limits

Since the integrated inspection system is capable of producing the average error from a batch measurement it was proposed that a better method of die modification would be to relate these errors directly to the geometric model which was used to cut the initial die and then to simply re-cut the die with a modified set of tapes. In other words instigate a completely computer integrated closed loop die modification system, see Figure 6.9.

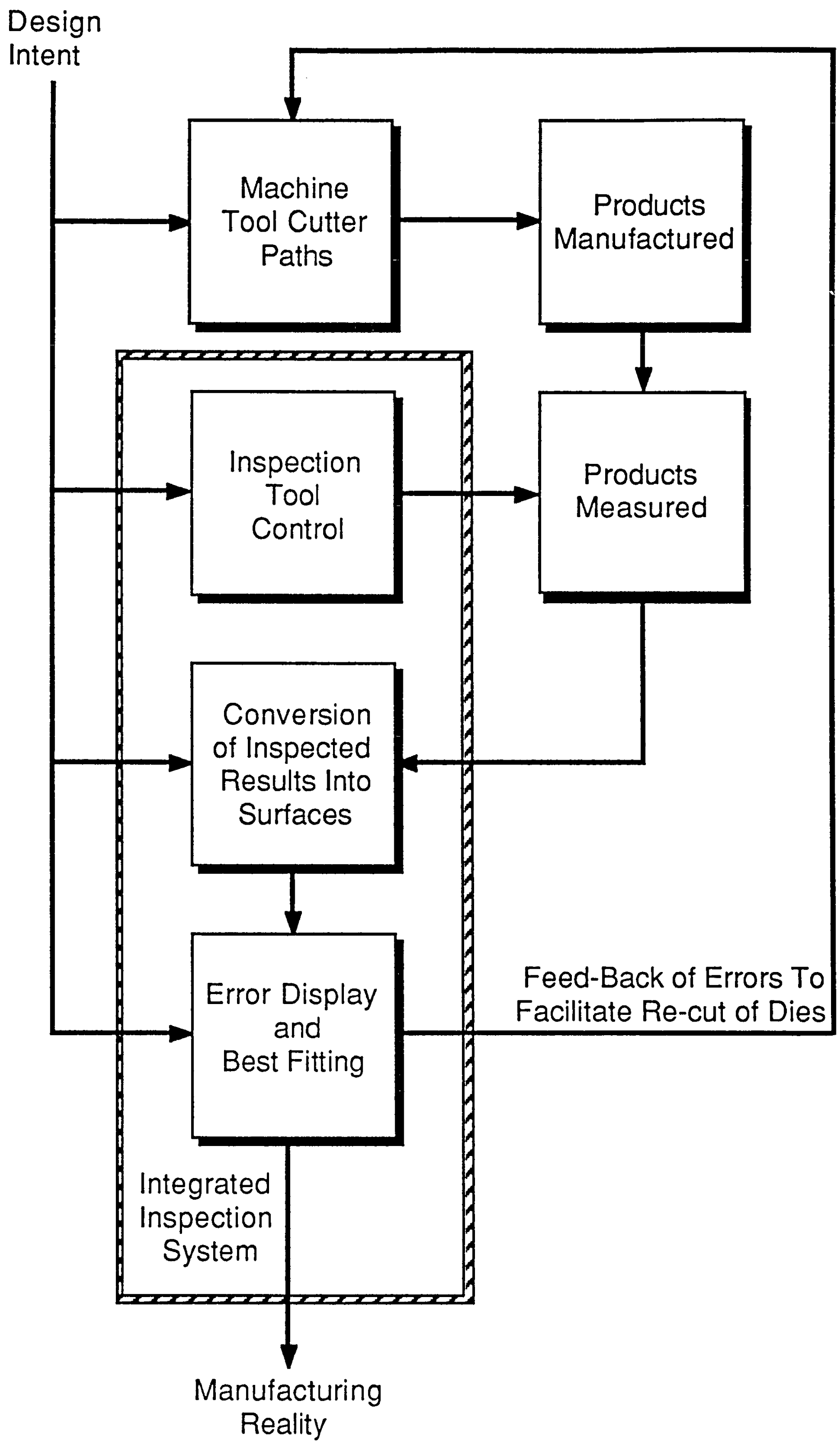


Figure 6.9

Computer Integrated Closed Loop Die Modification

There are a number of methods by which the die could be re-cut, it could be a new piece of metal, or the original die plated up and re-cut. Which ever method is chosen the concept for the re-cutting of dies enables the entire surface to be targeted to yield a bilateral surface. It should be noted that hand finishing of die surfaces should be kept to a minimum, in order to reduce this variability within this process.

By introducing a closed loop die modification system it would be possible to build up a database of dimensional distortion which could be used to develop process prediction models. A simple technique would be to take the errors from a previously produced component of similar geometry and add them to the die geometry of a new component.

It is believed that the computer integrated closed loop procedure is one of the best methods of improving complex surface manufacture. Whether that process be casting, forging or machining.

6.7 Resume Of The Integrated Inspection System

The principle of the integrated inspection system was to provide a systematic approach to the dimensional inspection of complex surfaces, see Figure 6.10. Using nominal geometry the system provides for the control of discreet measurement devices. It facilitates the feeding back of inspected data from the CMM into the inspection system where it is converted into surface models from which errors may be subsequently calculated, presented and best fit.

One advantage of this integrated approach to dimensional inspection is that it provides for information on surface errors to be easily integrated with other computing systems. For example the models of measured geometry could be analysed by aerodynamic and stress programs. The measured geometry could be used within a process database to provide information on manufacturing capabilities and be used as information to develop process prediction models. A further use of the errors would be to relate them to die cutting geometry to provide a closed-loop feed back system for die modifications.

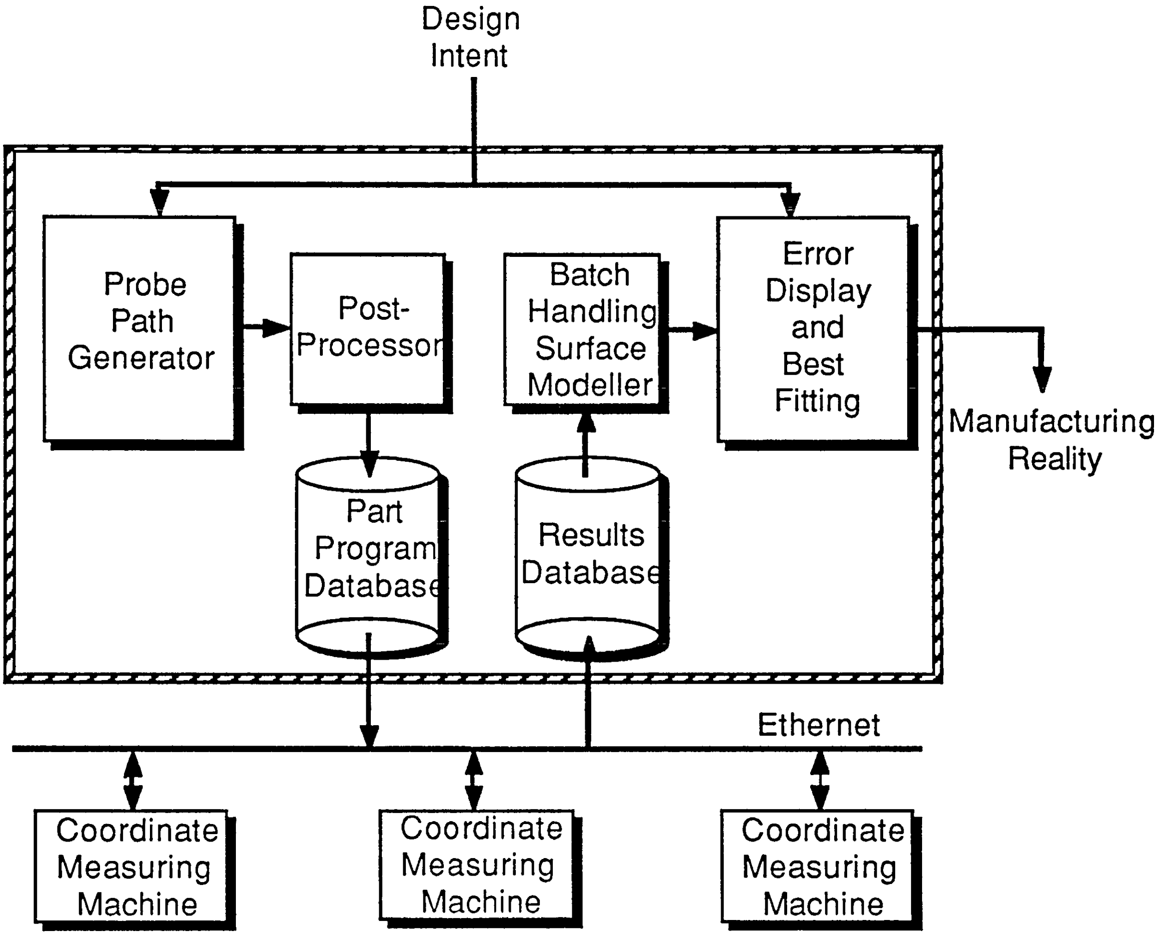


Figure 6.10

The Basic Integrated Inspection System After Phase 3 Development

References

[1] Brookes, N.J., "Product Definition: A Systemic Approach to its Improvement", PhD Thesis, Department of Mechanical Engineering, Imperial College of Science,

Technology and Medicine, University of London, In Preparation.

[2] Bloor, S.M., Pennington, A. de., Woodwark, J.R., "RISP: Bridging the Gap Between Conventional Surface Elements", Department of Mechanical Engineering, University of Leeds.

[3] Aubin, R.F., "Dimensional Measuring Interface Specification", Proceedings of the 8th International Conference of Automated Inspection and Product Control, June 1987, pp25-32.

[4] Petty, J.S., Mach, K.D., "Contouring and Hidden-Line Algorithms For Vector Graphics Displays", AFAPL-TR-77-3, Wright-Patterson A.F.B., OH 45433, January 1977.

Chapter 7

Development Of A Three-Dimensional Best Fitting Facility

7.1 The Concept of Best Fitting Surfaces

The basic concept of best fitting surfaces involves the alignment or construction of a coordinate system about an object so that the minimum error is achieved between nominal and measured geometry. Figure 7.1 illustrates a simple example of surface error where although both the surfaces of measured geometry are identical, the first alignment represents a best fit while the second shows an error moved over to one side.

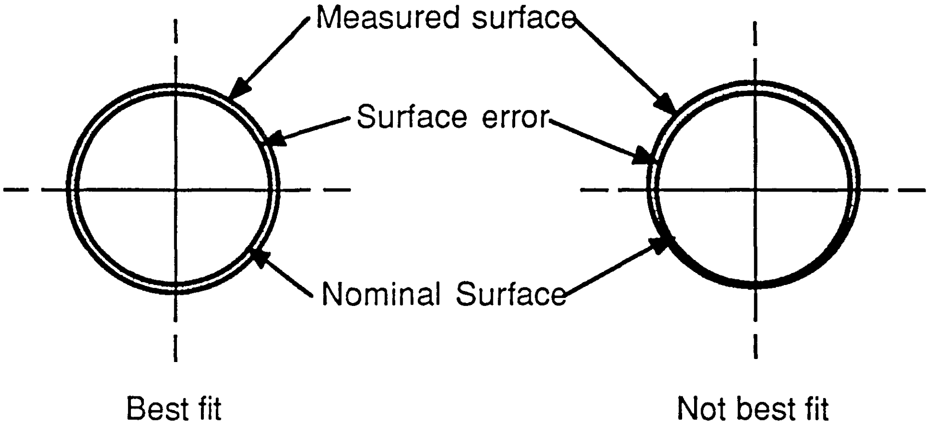


Figure 7.1

Error on a Surface Aligned in Two Different Coordinate Systems

In an ultimate best fit alignment a coordinate system would be generated by considering all of the measured points. In practise a compromise is met between the numbers of points used to align a surface and the expected accuracy obtained in the use of those points.

In the alignment of turbine blades certain points on the gas washed surfaces, known as A, B and C points, are used to construct the blade's coordinate system. These points are 'zero error target datums' and are chosen because they fix the exit throat area for the turbine - which is an extremely important characteristic. However these points will not necessarily construct a coordinate system which will produce the minimum error over the whole of the aerofoil surface. For this reason during turbine blade production the inspectors are allowed to best fit the aerofoil inside a profile tolerance. In this procedure the aerofoil is measured at three sections and physically moved around to see if it may be aligned inside the tolerance bands.

During the proof cycling of the turbine blade casting process it may also be necessary to perform a best fit calculation if the ABC point alignment produces significant errors around the blade. In the past, since the best fit has been a manual process, only certain areas of the surface have been used. These have typically been leading and trailing edge regions in a process known as 'Fare Alignment'. Obviously this limited region best fit is not an optimum solution and the fact that the calculations have been manual has imposed further restrictions in time. Therefore significant effort has been given in the past to finding faster and more accurate methods of best fitting. Braley [1] suggested that an improved method would be to use a specified distribution of points over the surface. By considering the realities of casting errors on the surfaces he suggested a method of balancing the errors on opposite sides of the aerofoil at two sections. However the method incorporated only a limited number of points and did not address a further issue which was a consideration of the importance of error to the functionality of the component.

In section 3.3 it was emphasised that the error from nominal specification is only important if it effects the functionality of the component. Around an aerofoil surface the importance of an error to functionality varies a great deal, those areas controlling diffusion, as illustrated in Figure 7.2, are the most important.

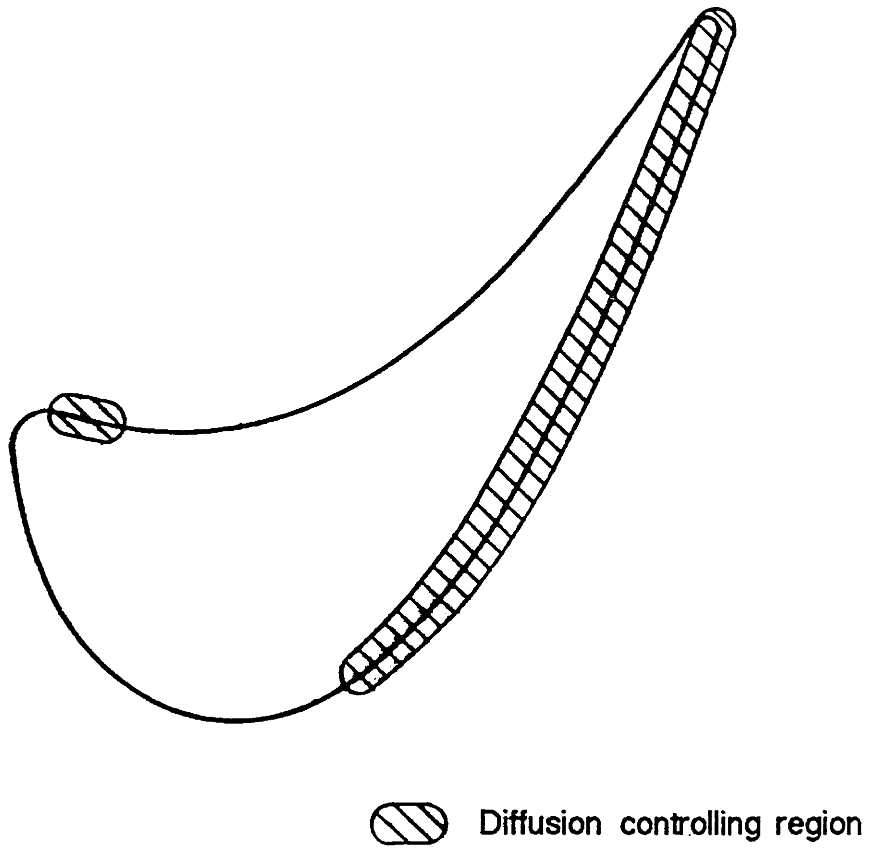


Figure 7.2

Regions of an Aerofoil Responsible For Diffusion

From the aerofoil's point of view it is more important that the error is small and the surface smooth in gas diffusing regions than it is in accelerating regions. The issue being illustrated here is that conventional tolerancing on surfaces like aerofoils is perhaps some what limited in terms of relating errors to product functionality and hence should be reconsidered in the light of developments in integrated inspection. This issue will be discussed in detail in section 7.6.

One method of perceiving the difference of importance in errors is to say that some degree of 'weighting' should be applied to the errors around the aerofoil.

Ideally there is a requirement to perform a best fit calculation with as many points as is required to represent the entire surface and for the errors to be assigned weightings of importance. A possibility for performing this task in an integrated inspection system was one of the reasons that the work on the integrated inspection system was instigated. In the initial proposals for the system the turbine blades were to be casually positioned on the inspection machine, measured and for the best fit to be calculated within the inspection system. In reality it was found that the blades had to be aligned accurately on the inspection machine to allow for the probe to take measurements in regions of very high surface curvature, like trailing edges. The method of alignment chosen was the ABC point process. This was used because it offered high consistency between blades and because the surface errors from this method represented those which the engine itself sees, since the ABC point alignment is used to datum the blades for machining the fir-tree roots that hold the blades in the disk.

7.2 A Mathematical Solution to Three Dimensional Best Fitting

7.2.1 Methods Of Solution

In attempting to minimise the error between surfaces within the best fitting facility there were a number of alternatives in the choice of a mathematical solution.

i. Analytical Methods

The full definition of error between two surfaces is volumetric. Within the integrated inspection system there exists a definition of both nominal and measured surfaces and hence it is possible to fully describe the volume. It is also possible to construct an expression to minimise it. This method although precise offers a number of disadvantages :-

a. The derivation of equations minimising the volumetric definition of error would be extremely complex and dependent on the surface definition.

b. A best fitting procedure based on this method would be extremely computationally demanding.

c. The incorporation of weightings into the solution would be very complex.

ii. Integral Of Error Methods

If the full definition of the volume could not be represented easily another approach would be to define the volume by integrating it using an approximation method between discreet error vectors. Within the Integrated Inspection System the discreet vectors could be taken from the error calculation algorithms - which are used for error presentation - and the integration over the volume could be an approximated using a technique like Simpson's rule. As Cosmos [2] points out the sum of error above and below the nominal surface would equal zero when a surface was best fit.

This technique is certainly feasible and has been illustrated by Cosmos, however it offers a number of disadvantages :-

a. The integration is difficult to define over open surfaces like annulii.

b. The incorporation of weightings is difficult.

iii. Discreet Error Methods

In this case a mathematical solution is sought to the errors as defined by discreet error vectors. Again the error vectors could be taken from the error calculation algorithms, however this technique has the disadvantage that it does not concern itself with the full definition of the error, but just discreet errors between the surfaces.

7.2.2 Choice Of Method

Of the three methods of best fit solution explored the analytical approach was considered too complex and surface dependent to warrant as a practical method. The choice was thus between the integral and the discreet error methods. It was believed that the discreet method offered the following advantages over the integral method :-

i. It was not concerned with surface definition, just vectors of error between nominal and measured surfaces. This was a large advantage over the integral method particularly over annulus surfaces where the definition of the volume of error is complex.

ii. The applications of weightings to the best fit appeared to be easier.

The only concern with the discreet error technique was whether discreet vectors could be used to represent the surface sufficiently accurately. As a result a number of trials were conducted to determine the applicability of discreet vectors in defining surface error. Figure 7.3 was a typical example of such a trial, they showed that down to about 40 measured points per aerofoil section very little discrepancy occurred between the error displays obtained from 40 points per section and those obtained from an effective infinite number of points per section. It was thus concluded that discreet error methods could be used over a surface if the density of points was sufficiently high. Combining this result with the easier usage of discreet methods over integral methods in the application of weightings it was considered that a discreet method should be sought.

It was recognised that the development of the three dimensional best fitting equations would be a considerable step. Therefore the initial work concentrated on a solution to two dimensional best fitting for which a solution to the transformation function may be easily reached using complex number theory. Although the solution was reasonably easy this approach enabled quick development of all of the programming code required for best fitting, which was substantial.

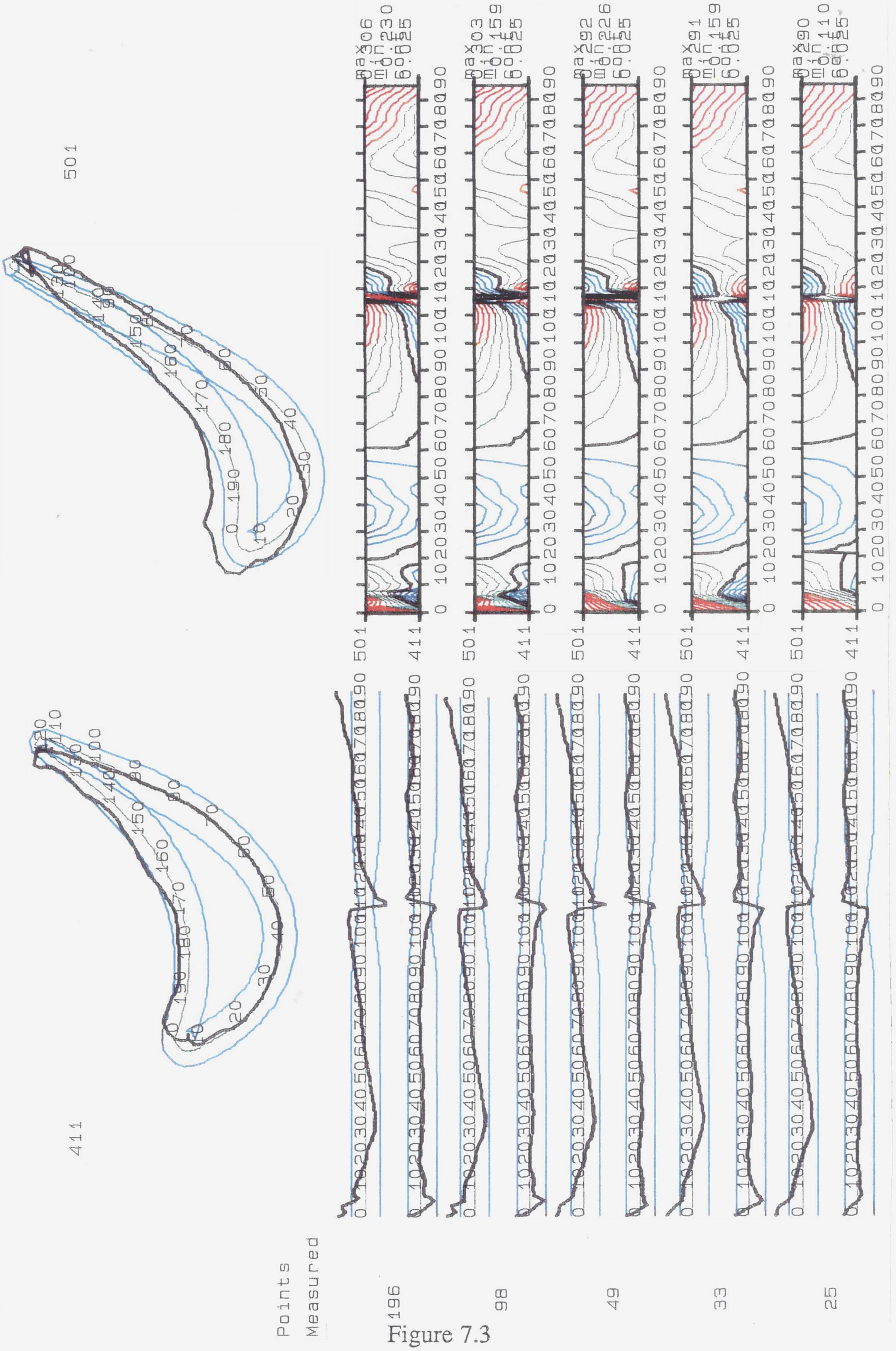


Figure 7.3

Results From a Measurement Point Density Trial

Only once it was believed that two dimensional best fitting had been understood was a solution to the three dimensional problem sought. This phased implementation proved successful with a solution to the three dimensional transformation function being found, this is presented below.

7.2.3 Derivation Of A Three Dimensional Best Fitting Transformation

The author would again like to express his thanks to Chris Booth and Alec Wilson, of Rolls-Royce, for their assistance in the derivation of the three dimensional best fitting mathematics.

It is assumed that by using the least squares criterion for best fitting there exists a transformation function which will minimise the error vectors between two surfaces (a nomenclature of symbols used in the derivation below is included at the end of this chapter):-

$$E^2 = \sum_{i=1}^{N} (\underline{y}_i - t(\underline{x}_{0_i}))^2 \qquad (1)$$

where :-

E = Sum of errors.

$t(\,)$ = Transformation function to be found.

$\underline{y}$ = Vector to the intersection of the error vector with the nominal surface, $\underline{y}_i = (y_{1_i}, y_{2_i}, y_{3_i})$, see Figure 7.4

$\underline{x}_0$ = Vector to the intersection of the error vector with the measured surface, $\underline{x}_{0_i} = (x_{0_{1_i}}, x_{0_{2_i}}, x_{0_{3_i}})$, see Figure 7.4

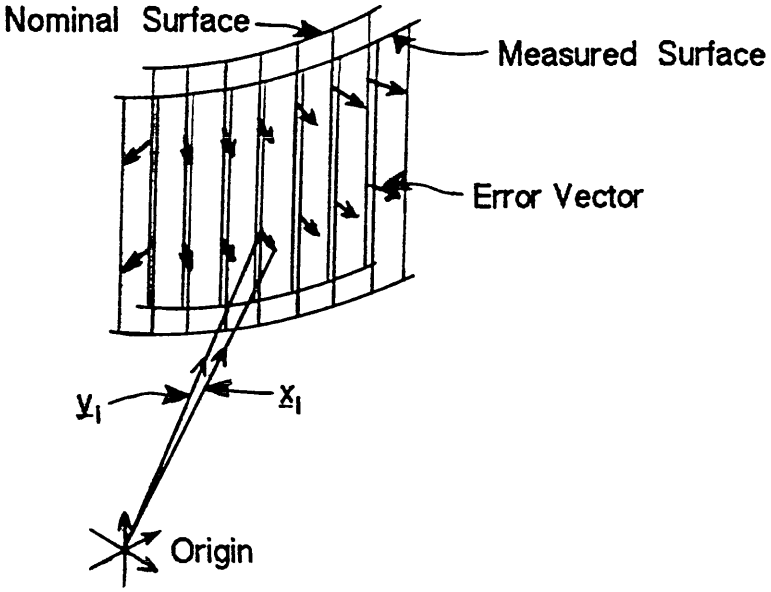


Figure 7.4

Definition of Vectors in Equation 1

The task of constructing the transformation may be split up into a rotation and then a translation.

$$t(\underline{x}_{0_i}) = A\underline{x}_{0_i} + \underline{\delta} \qquad (2)$$

where :-

A = A matrix of rotational best fit to be found.

$\underline{\delta}$ = A vector of translational best fit to be found.

Substitute equation 2 into equation 1 and let $\underline{x}_{1_i} = A\underline{x}_{0_i}$.

$$\Rightarrow E^2 = \sum_{i=1}^{N} (\underline{y}_i - \underline{x}_{1_i} - \underline{\delta})^2 \qquad (3)$$

$$= \sum_{i=1}^{N} (\underline{y}_i^2 + \underline{x}_{1_i}^2 + \underline{\delta}^2 - 2\underline{y}_i\underline{x}_{1_i} - 2\underline{y}_i\underline{\delta} + 2\underline{x}_{1_i}\underline{\delta}) \qquad (4)$$

Differentiate w.r.t. $\underline{\delta}$:-

$$\frac{\partial E^2}{\partial \underline{\delta}} = \sum_{i=1}^{N} (2\underline{\delta} - 2\underline{y}_i + 2\underline{x}_{1_i})$$

Set $\frac{\partial E^2}{\partial \underline{\delta}} = 0$, for minimum error :-

$$\Rightarrow \sum_{i=1}^{N} (\underline{\delta}) = \sum_{i=1}^{N} (\underline{y}_i - \underline{x}_{1_i})$$

$$\Rightarrow \underline{\delta} = \frac{1}{N} \cdot \sum_{i=1}^{N} (\underline{y}_i - \underline{x}_{1_i}) = \bar{\underline{y}} - \bar{\underline{x}}_1 \qquad \text{(5)}$$

Thus yielding the translational vector for the transformation function. However it is still necessary to find the minimisation in terms of rotation. To do so substitute equation **5** into equation **4** :-

$$\Rightarrow E^2 = \Sigma(\underline{y}_i)^2 + \Sigma(\underline{x}_{1_i})^2 - 2\Sigma(\underline{y}_i \cdot \underline{x}_{1_i}) - \frac{1}{N}\Big(\Sigma(\underline{y}_i)\Big)^2$$

$$- \frac{1}{N}\Big(\Sigma(\underline{x}_{1_i})\Big)^2 + \frac{2}{N}\Big(\Sigma(\underline{y}_i)\Big)\Big(\Sigma(\underline{x}_{1_i})\Big) \qquad \text{(6)}$$

where :-

$$\Sigma = \sum_{i=1}^{N}$$

Since $\Sigma(\underline{y}_i)^2$, $\Sigma(\underline{x}_{1_i})^2$, $\Big(\Sigma(\underline{y}_i)\Big)^2$ and $\Big(\Sigma(\underline{x}_{1_i})\Big)^2$ are values that are not effected by rotation.

$$\Rightarrow E^2 = -2\Sigma(\underline{y}_i \cdot \underline{x}_{1_i}) + \frac{2}{N}\Big(\Sigma(\underline{y}_i)\Big)\Big(\Sigma(\underline{x}_{1_i})\Big) + C_1 \qquad \text{(7)}$$

$$\text{Let } \Sigma\,(\underline{y}_i) = 0 \;\text{ w.l.o.g.} \qquad (8)$$

i.e. shift the $\underline{y}$ and $\underline{x}$ values by $\bar{\underline{y}}$.

so:-

$${}^{l}\underline{y}_i = \underline{y}_i - \bar{\underline{y}} \qquad (9)$$

$${}^{l}\underline{x}_i = \underline{x}_{1_i} - \bar{\underline{y}} \qquad (10)$$

$$\Rightarrow E^2 = -2\,\Sigma\,({}^{l}\underline{y}_i \cdot {}^{l}\underline{x}_{1_i}) + C_2 \qquad (11)$$

The problem has been reduced to maximising the sum of the dot products of the nominal vectors with the measured surface rotated vectors.

To form an expression for the rotation matrix define the best fit rotation as occurring about the axes of a cartesian coordinate system, let $\underline{\lambda}$ represent the parameters of the rotations about each axis, differentiate equation **11** with respect to $\underline{\lambda}$ and set equal to 0 :-

$$\frac{\partial E^2}{\partial \underline{\lambda}} = \frac{\partial}{\partial \underline{\lambda}}\left(\Sigma\,({}^{l}\underline{y}_i \cdot {}^{l}\underline{x}_{1_i})\right) = 0 \qquad (12)$$

$$\Rightarrow \Sigma\,{}^{l}\underline{y}_i \cdot \frac{\partial\,{}^{l}\underline{x}_{1_i}}{\partial \underline{\lambda}} = 0 \qquad (13)$$

$$\Rightarrow \Sigma\,{}^{l}\underline{y}_i^{T} \cdot \frac{\partial A}{\partial \underline{\lambda}}\,{}^{l}\underline{x}_{0_i} = 0 \qquad (14)$$

In equation **14** $\underline{y}$ is shown as transposed for the correct syntax of the dot product.

Equation **14** now provides a relationship between $\underline{y}$ and $\underline{x}$ with which the rotation matrix may be determined. To do so assume that the rotations, about each cartesian axis, are small so that the effect of each rotation has no interaction with the calculation of the other rotational parameters. Although this is not true the best fitting algorithm is iterative and thus will act to oppose any inaccuracies due to this assumption as the routine converges to solution.

Solution to the rotational best fit :-

Let α, β and γ be rotations about the x, y and z cartesian axes respectively :-

Let $A = A_x.A_y.A_z$ ________ **(15)**

where :-

$$A_x = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{pmatrix} \quad \text{(16)}$$

$$A_y = \begin{pmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{pmatrix} \quad \text{(17)}$$

$$A_z = \begin{pmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \text{(18)}$$

To determine the minimum error with respect to rotations these are differentiated :-

$$\frac{\partial A_x}{\partial \underline{\lambda}} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \sin\alpha & \cos\alpha \\ 0 & -\cos\alpha & \sin\alpha \end{pmatrix} \quad \text{(19)}$$

$$\frac{\partial A_y}{\partial \underline{\lambda}} = \begin{pmatrix} \sin\beta & 0 & -\cos\beta \\ 0 & 0 & 0 \\ \cos\beta & 0 & \sin\beta \end{pmatrix} \quad \text{(20)}$$

$$\frac{\partial A_z}{\partial \underline{\lambda}} = \begin{pmatrix} \sin\gamma & \cos\gamma & 0 \\ -\cos\gamma & \sin\gamma & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \text{(21)}$$

For the rotational best fit about the x-axis equation **14** implies that

$$\Sigma\, {}^{I}\underline{y}_i^{T} \cdot \frac{\partial A_x}{\partial \underline{\lambda}}\, {}^{I}\underline{x}_{0_i} = 0$$

$$\Rightarrow \Sigma \begin{pmatrix} {}^{I}y_1 & {}^{I}y_2 & {}^{I}y_3 \end{pmatrix} \cdot \begin{pmatrix} 0 & 0 & 0 \\ 0 & \sin\alpha & \cos\alpha \\ 0 & -\cos\alpha & \sin\alpha \end{pmatrix} \begin{pmatrix} {}^{I}x_1 \\ {}^{I}x_2 \\ {}^{I}x_3 \end{pmatrix} = 0$$

$$\Rightarrow \Sigma\,({}^{I}y_{2_i} \,.\, {}^{I}x_{2_i})\sin\alpha - \Sigma\,({}^{I}y_{3_i} \,.\, {}^{I}x_{2_i})\cos\alpha + \Sigma\,({}^{I}y_{2_i} \,.\, {}^{I}x_{3_i})\sin\alpha$$

$$+\ \Sigma\,({}^{I}y_{3_i} \,.\, {}^{I}x_{3_i})\sin\alpha = 0$$

$$\Rightarrow \tan\alpha = \frac{\Sigma\ ({}^{I}y_{3_i} \,.\, {}^{I}x_{2_i}) - \Sigma\ ({}^{I}y_{2_i} \,.\, {}^{I}x_{3_i})}{\Sigma\ ({}^{I}y_{2_i} \,.\, {}^{I}x_{2_i}) + \Sigma\ ({}^{I}y_{3_i} \,.\, {}^{I}x_{3_i})} \qquad \textbf{(22)}$$

For the rotation about the y-axis :-

$$\tan\beta = \frac{\Sigma\ ({}^{I}y_{1_i} \,.\, {}^{I}x_{3_i}) - \Sigma\ ({}^{I}y_{3_i} \,.\, {}^{I}x_{1_i})}{\Sigma\ ({}^{I}y_{1_i} \,.\, {}^{I}x_{1_i}) + \Sigma\ ({}^{I}y_{3_i} \,.\, {}^{I}x_{3_i})} \qquad \textbf{(23)}$$

For the rotation about the y-axis :-

$$\tan\gamma = \frac{\Sigma\ ({}^{I}y_{2_i} \,.\, {}^{I}x_{1_i}) - \Sigma\ ({}^{I}y_{1_i} \,.\, {}^{I}x_{2_i})}{\Sigma\ ({}^{I}y_{2_i} \,.\, {}^{I}x_{2_i}) + \Sigma\ ({}^{I}y_{1_i} \,.\, {}^{I}x_{1_i})} \qquad \textbf{(24)}$$

The construction of the transformation function may now take place :-

Equations **22, 23** and **24** produce values for α, β and γ which may be used to form A_x, A_y and A_z from equations **16, 17** and **18.** Matrix A may then be calculated from equation **15.** Now that the rotational best fit matrix and the translational best fit vector have been determined the best fit transformation function is defined. In the form of an homogeneous concatenated transformation matrix, as used in most graphics software, the transformation function may be written as below. The best fit position of the measured surface being obtained by pre-multipling this matrix with the homogeneous form of the control points defining the measured surface :-

$$T = \begin{pmatrix} A_{11} & A_{12} & A_{13} & \delta_1 \\ A_{21} & A_{22} & A_{23} & \delta_2 \\ A_{31} & A_{32} & A_{33} & \delta_3 \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad \text{(25)}$$

7.2.4 Extension Of The Best Fitting Mathematics To Incorporate Weightings

In the practical use of best fitting it is often necessary to assign weightings to the errors. In this way it is possible to bias the best fit for regions of errors in favour of others. To accommodate weightings equation **1** was extended to :-

$$E^2 = \sum_{i=1}^{N} \left(\left(\underline{y}_i - t(\underline{x}_{0_i}) \right) w_i \right)^2 \qquad \text{(26)}$$

where :-

w_i = the weight of the i^{th} error $0 \leq w_i \leq 1$

To solve for the best fit parameters incorporating weightings the equations have to be redefined. Where in equation **8** $\Sigma (\underline{y}_i) = 0$, this becomes $\Sigma (\underline{y}_i . w_i) = 0$.

Thus :-

$$\bar{\underline{y}} = \frac{1}{\Sigma w_i} . \Sigma (\underline{y}_i . w_i) \qquad \text{(27)}$$

and equations **10** and **11** become :-

$$'\underline{y}_i = (\underline{y}_i - \bar{\underline{y}}).w_i \qquad \text{(28)}$$

$$'\underline{x}_{0_i} = (\underline{x}_{0_i} - \bar{\underline{y}}).w_i \qquad \text{(29)}$$

These new values ${}^{\prime}\underline{y}_i$ and ${}^{\prime}\underline{x}_{0_i}$ may be used in equations **22**, **23** and **24** to determine the rotational best fit parameters and hence the rotation matrix A.

To solve for the translational best fit with weightings equation **6** becomes :-

$$\underline{\delta} = \frac{1}{\sum w_i} . \sum \left((\underline{y}_i - \underline{x}_{1_i}) w_i \right) \qquad \textbf{(30)}$$

Although the above weighting equations have been found to be useful for best fitting surfaces, in the cases where multiple surfaces exist it has been necessary to extend the weightings theory so that each error has a weighting in each degree of freedom of the best fit. (In the case of best fitting turbine blade gas washed surfaces it is usual to fit the aerofoil with x, y and z rotation and x and y translation, while the annulii are fitted with z translation only). This may be accounted for by treating the solution to the parameter for each degree of freedom in the best fit model totally independently from the others, that is to say that each degree of freedom has its own solution to equation **27**, $\sum (\underline{y}_i . w_i) = 0$. So for the kth degree of freedom :-

$$\bar{\underline{y}}_k = \frac{1}{\sum w_{ik}} . \sum (\underline{y}_i . w_{ik}) \qquad \textbf{(31)}$$

where :-

w_{ik} = the ith weight in the kth degree of freedom.

Equations **28** and **29** become :-

$${}^{\prime}\underline{y}_{ik} = (\underline{y}_i - \bar{\underline{y}}_k).w_{ik} \qquad \textbf{(32)}$$

$${}^{\prime}\underline{x}_{0_{ik}} = (\underline{x}_{0_i} - \bar{\underline{y}}_k).w_{ik} \qquad \textbf{(33)}$$

These new values ${}^{\prime}\underline{y}_{ik}$ and ${}^{\prime}\underline{x}_{0_{ik}}$ may be used in equations **22**, **23** and **24** to determine the rotational best fit parameters and hence the rotation matrix A.

To solve for the translational best fit each degree of freedom must be dealt with separately, equation **5** becomes :-

$$\underline{\delta} = \frac{1}{\sum w_{ik}} \cdot \sum \left(\left(\underline{y}_i - \underline{x}_{1_i} \right) w_{ik} \right) \qquad \textbf{(34)}$$

where :-

k = either the x, y or z translational degree of freedom

7.2.5 Application Of The Best Fitting Transformation Function

The best fitting procedure developed in this report is an iterative one and would normally be used in the following manner :-

i. The error vectors are calculated and displayed.

ii. The degrees of freedom of the best fit and the error weightings are specified.

iii. The best fit transformation matrix is calculated.

iv. The measured surface(s) are transformed by the best fit transformation.

v. Convergence to solution is checked, if found to be satisfactory the process is stopped, if unsatisfactory the process repeats from iii. Typical convergence is said to have occurred when the transformation results in less than a certain translation of the surfaces (typically 0.001mm for turbine blade surfaces).

The overall best fit transformation matrix is the multiple product of all of the best fit transformations produced during convergence to solution. Each additional transformation matrix is pre-multiplied to the previous result. The number of degrees of freedom used in the best fit will determine the rate of convergence. Typically a 2D best fit of an aerofoil in two axis translation and one axis rotation will take 15 iterations while a full 3D best fit may take 100 iterations. The requirements of the best fit model must be offset by the time taken for solution.

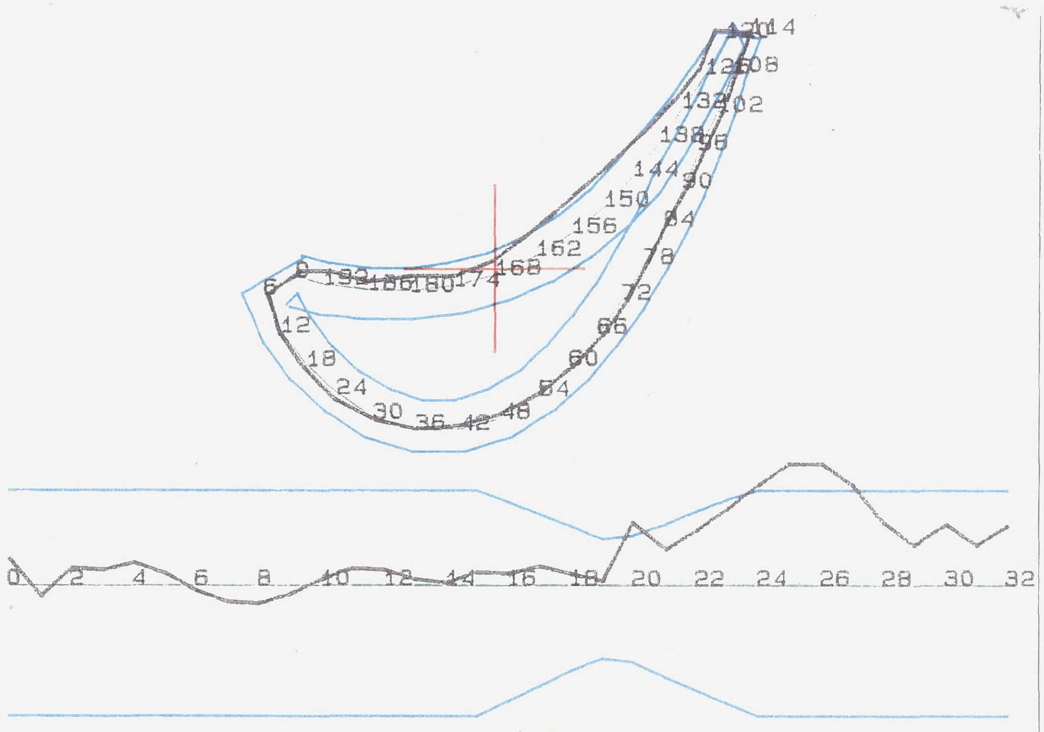
The assumption that the best fit rotational parameters have only small interactions with one another dramatically simplifies the rotational best fit equations. More over it has been shown that since the algorithm is iterative in nature this assumption has little effect even for large rotational best fits as each subsequent best fit calculation acts to reduce any error incurred by the assumption in the previous calculation. It is important to remember that the overall transformation matrix is the cummulative multiple of all of the best fit matrices produced during convergence to solution.

The large number of iterations and the requirement for the accuracy of the best fit solution to be within 0.001mm, while often employing numerical values greater than 100, necessitates the use of 'doubles' rather than 'floats' for the computer processing of the best fit.

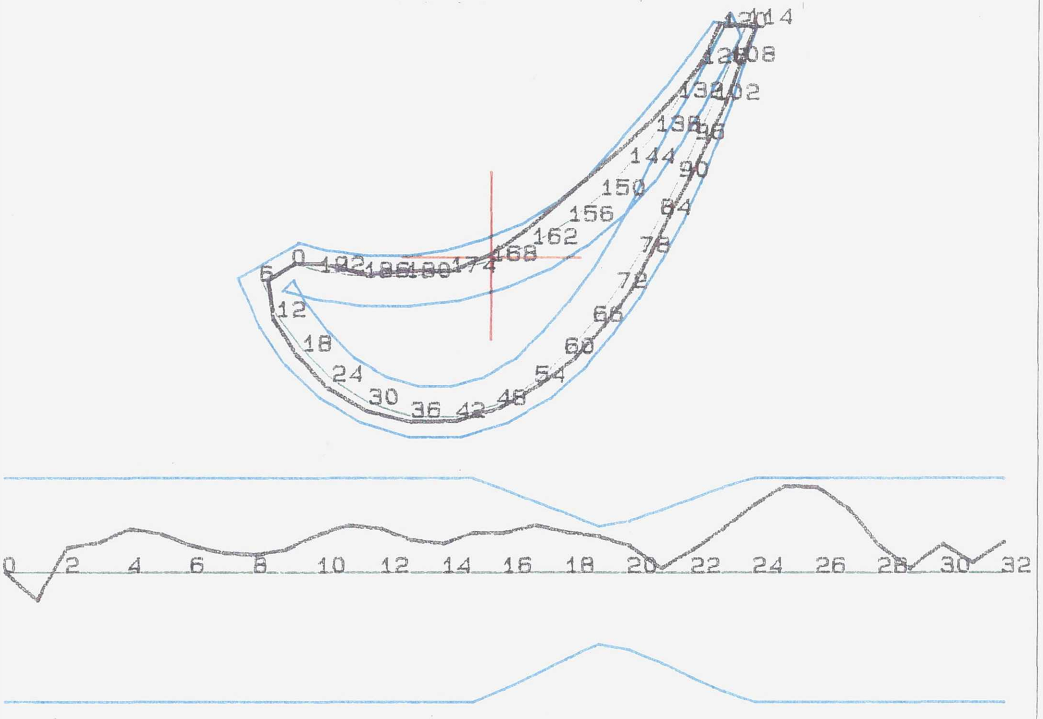
7.3 The Results Of Best Fitting

The results presented below were obtained from both two dimensional and three dimensional best fitting. As it is possible to specify the degrees of freedom required when applying a three dimensional best fit, it is possible to completely duplicate a two dimensional best fit, consequently the two dimensional best fitting facility was removed from the system.

During the course of the investigation into the best fitting it was found that a satisfactory value of the convergence tolerance was 1µm. It is of course important to remember that the results of the surface inspection were obtained to 2µm.



(a) As measured



(b) As best fit

Figure 7.5

Illustration of The Surface Error Around a Section of an Aerofoil Before and After a 2D Best Fit.

The error has been magnified over the surface 10 times to present it more effectively. Each error was fitted with a weighting of unity.

The method by which the best fitting algorithm calculates the transformation function involves obtaining the mean of errors along each of the principal axes. If an object is very much longer in one direction than another (such as the sausage form in Figure 7.6) and is being best fitted then there is a bias of information in one direction which results in a slower convergence rate to solution. To reduce the bias effect it is possible to weight the errors according to the number of error vectors pointing in a certain direction. To calculate these weightings the error vectors are split into groups depending on their direction within equally sized sectors of a circle. The normal method of applying directional weighting is to specify the weightings until convergence to solution is reached, then to release them and to continue to iterate until convergence to solution is again reached. Figure 7.7 illustrates the reduction in iterations achieved by the application of directional weighting in the best fitting of three different aerofoils.

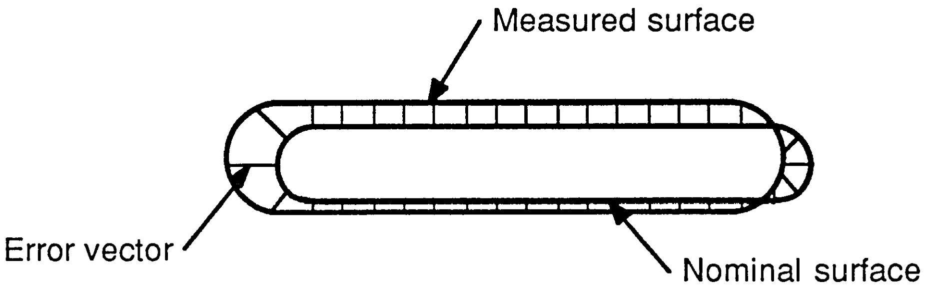


Figure 7.6

Example of an Object with a Bias of Errors Along an Axis - Which Results in a Reduction in the Convergence Rate of the Best Fit Solution.

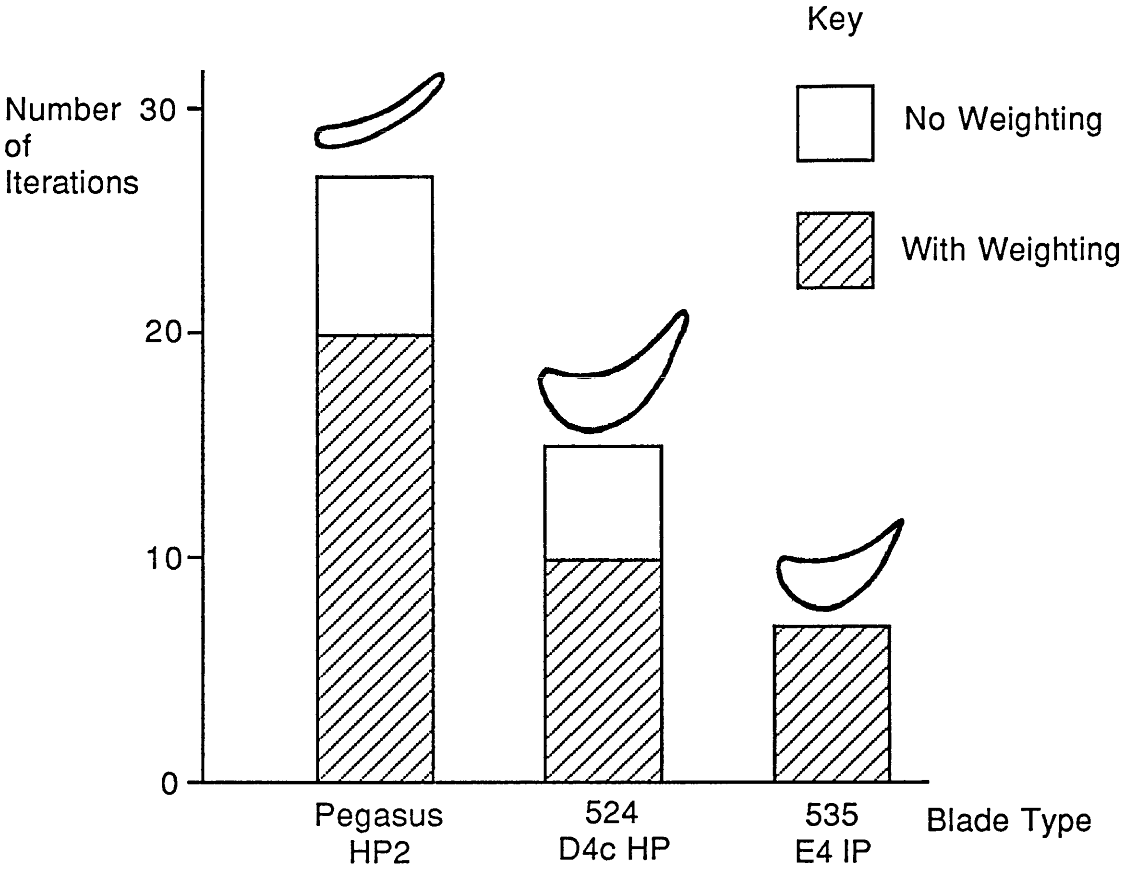


Figure 7.7

The Reduction in the Number of Iterations Required to Achieve a Best Fit Convergence to Solution for 3 Different Aerofoils Undergoing a 2D Best Fit With and Without Directional Weighting

The numbers of degrees of freedom used in a best fit calculation determines the convergence rate to solution. Figure 7.8 illustrates a typical relationship between degrees of freedom and the number of iterations.

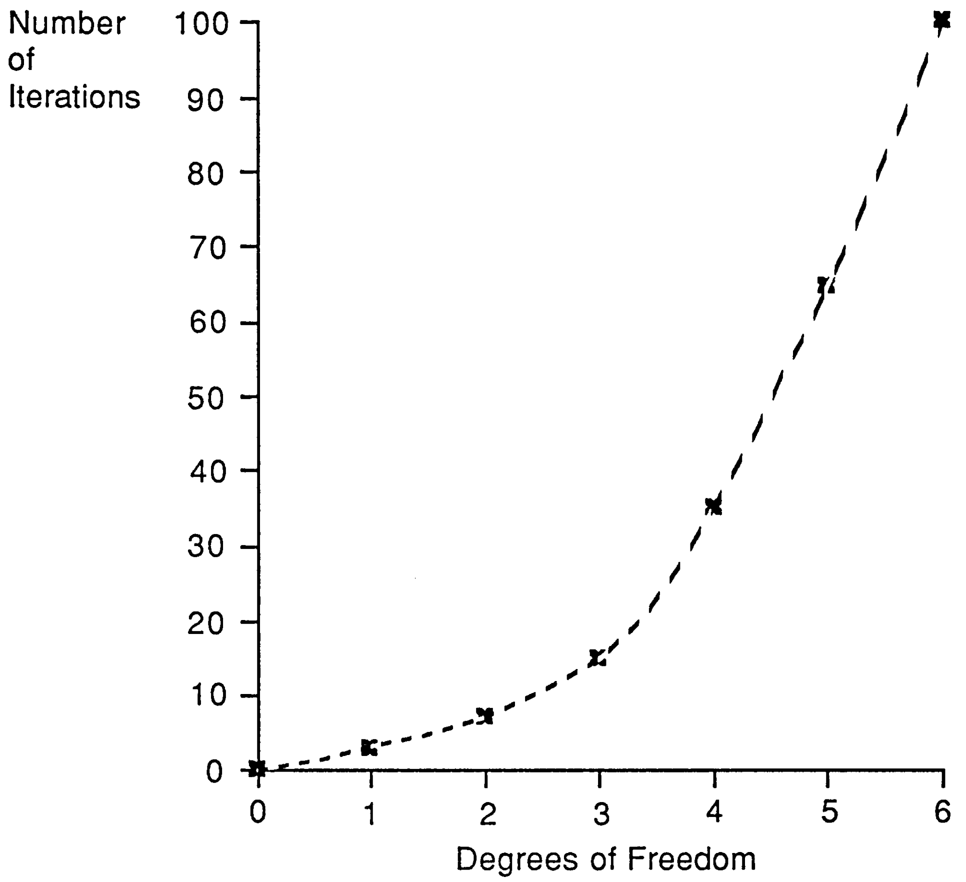


Figure 7.8

A Typical Relationship Between Best Fit Degrees of Freedom and the Number of Iterations to Solution

Not all surfaces may be best fitted with all degrees of freedom. For example annulus surfaces which being defined as rotations of lines and arcs about the engine centre line have no unique solution to the best fit in terms of rotational position about the engine centre line. In these cases it must be decided which degrees of freedom are applicable to be used in the best fit. If a best fit is conducted on a surface for which there is no unique solution the iterations will tend to diverge rather than converge. Figure 7.9 illustrates the best fit of the aerofoil error presented in Figure 6.2, for this best fit the error was given three rotational and two translational (x and y) degrees of freedom.

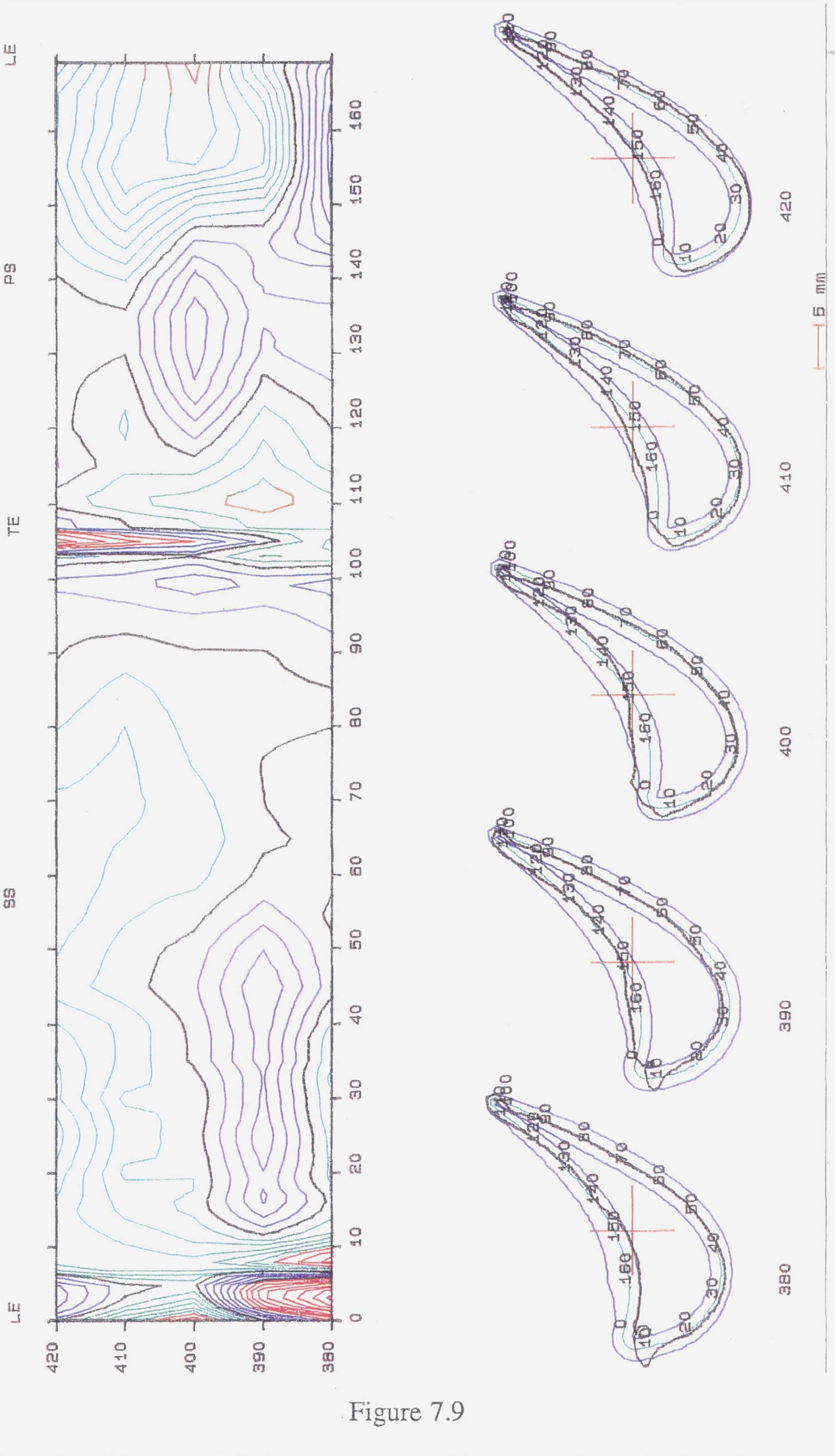


Figure 7.9

A 3D Best Fit of the Aerofoil Surface Presented in Figure 6.2. The Best Fit Has Shifted the Blade Towards the Suction Surface and has Dramatically Reduced Those Areas of the Aerofoil out of Profile Tolerance.

When combining a number of surfaces for a best fit it is important to be able to define the degrees of freedom that each surface will contribute to the transformation function. Figure 7.10 illustrates a combined best fit which was performed on the aerofoil and upper and lower annulus gas washed surfaces of a measured turbine blade. In this case the aerofoil contributed full rotational freedom and x-y translational freedom while the annulii contributed z translational freedom only. Obviously all three measured surfaces are moved by the same transformation.

The use of discreet error vectors in the solution of the best fit formula, described in this chapter, enables a multitude of different surface types to be incorporated in the best fit model relatively easily. This is because it is concerned with vectors of error between surfaces and not the surface definitions themselves. The best fit mathematics is capable of incorporating any number of surfaces of any type.

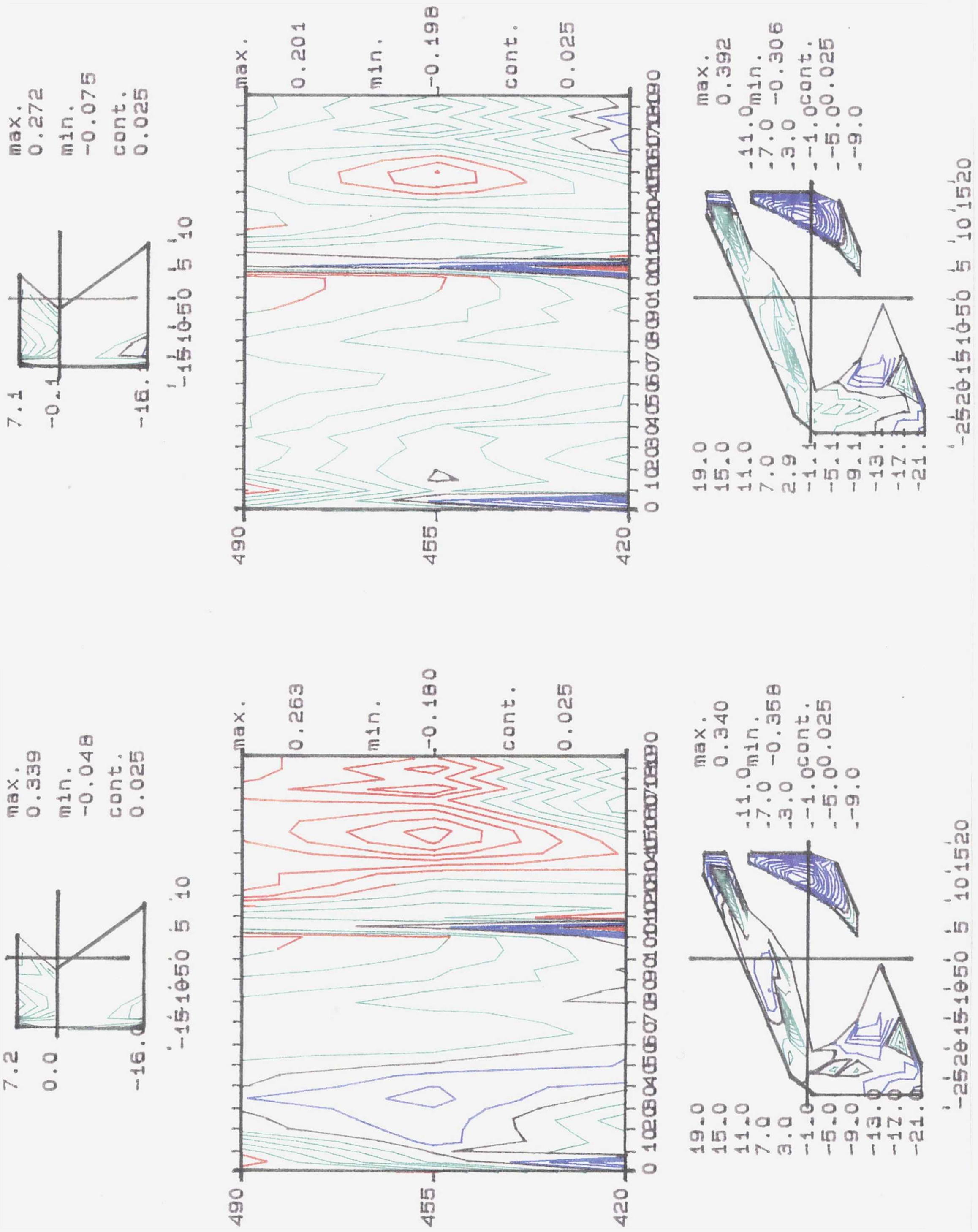


Figure 7.10

A Best Fit of the Aerofoil and Upper and Lower Annulus Gas Washed Surfaces of a Measured Turbine Blade

7.4 The Use Of Transputers For Three-Dimensional Best Fitting

In the previous section it was illustrated that using the described best fitting formula a full three dimensional best fit may take up to 100 iterations to converge to solution. This means that an aerofoil surface, defined within the PANACEA CIM system, and best fitting say 170 points may take an hour to reach solution on a 4 MIPS machine. A study of the best fitting showed that in excess of 99% of the elapsed time was involved in the intersection calculations of vectors with the measured surfaces. Each intersection was totally independent therefore they were a very suitable candidate for parallel processing. It was also found that the intersection routines could be parallelised in a very process dominant manner. The combination of easy parallelisation and process dominance suggested that the intersections could be implemented on a parallel processing network such as these offered by transputers.

In an arrangement of parallel processing for the best fitting of surfaces Figure 7.11 illustrates the split of work between the Master Process and the Worker Processes. The Master distributes the measured surface definitions and allocates a share of the intersection vectors. The Worker processes are activated and the Master waits for error data to return. When all of the intersections are finished the Master process calculates the best fit transform and convergence to solution is checked. If convergence has been reached the best fit is complete, otherwise the best fit transform is passed to the worker processes which transform their measured surfaces and again calculate the intersections.

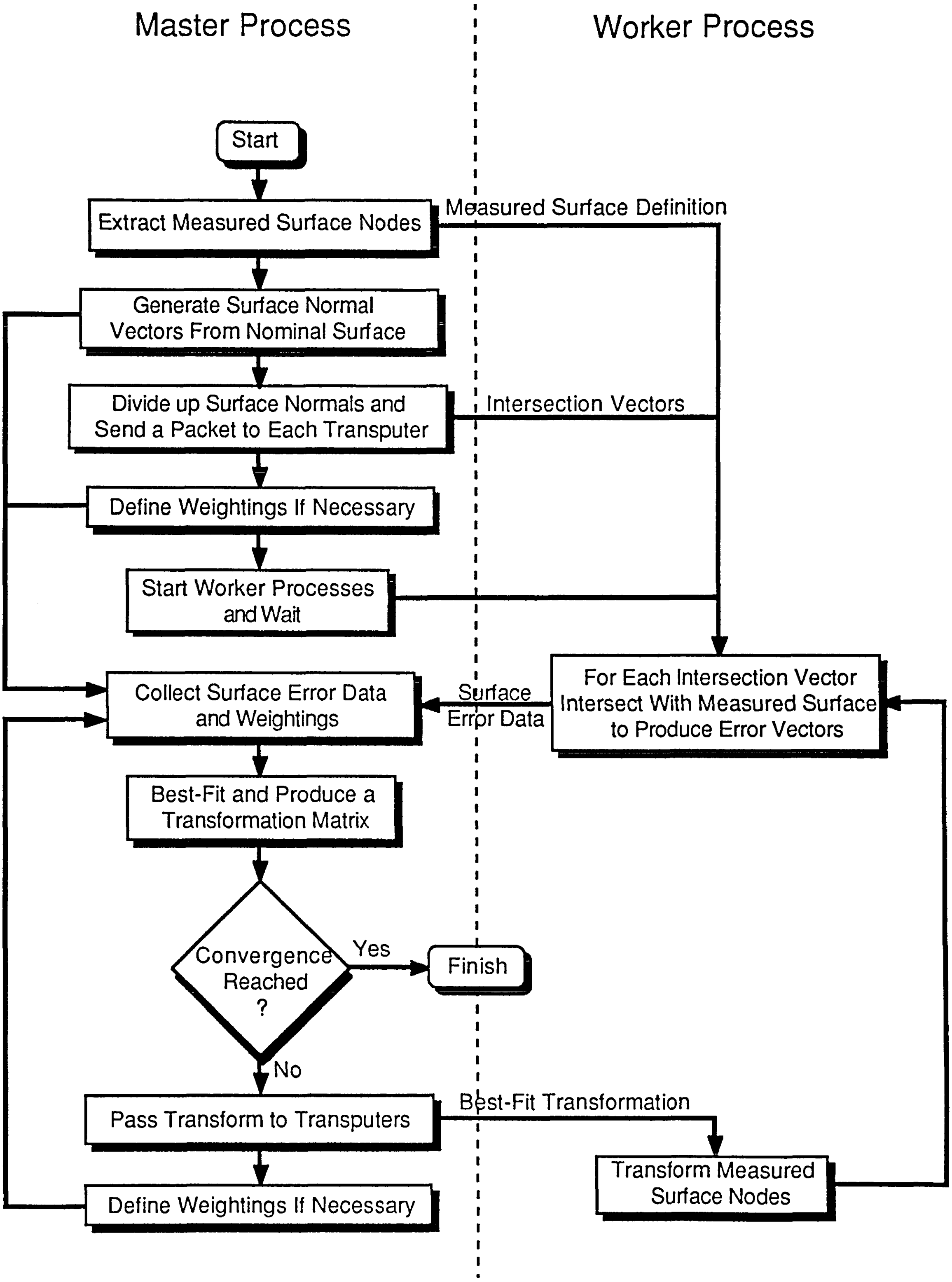


Figure 7.11

The Use of Transputers for the Best Fitting of Surfaces

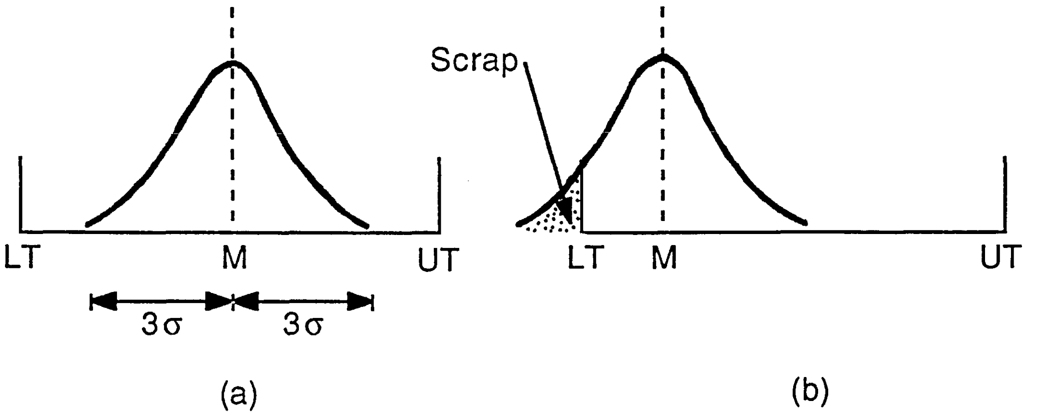
This use of the transputer network is obviously process dominant since the large number of calculations required to perform each intersection results in only one vector per intersection being communicated back to the Master process. Another advantage of this process layout is that it is relatively easy to add additional transputers to, which because of the process dominant nature of the intersections, would result in a farely linear reduction in processing time.

7.5 Process Capability Fitting

Although the best fit of a measured surface indicates if it is inside or outside of tolerance this analysis on a single surface says nothing about the spread of geometries that will occur during production. To provide an indication of where geometric scrap will occur over the surfaces and to minimise this for a given batch, the concept of 'process capability fitting' was developed.

Consider the spread of measurements that might be expected for a given position on a surface. If the spread is normal, it may be said that the vast majority of the measurements (99.7%) will be within a band equal to 3 times the standard deviation on either side of the average. Figure 7.12 illustrates two typically spreads. It may be observed that even if the average measurement is inside the tolerance band some scrap may be produced.

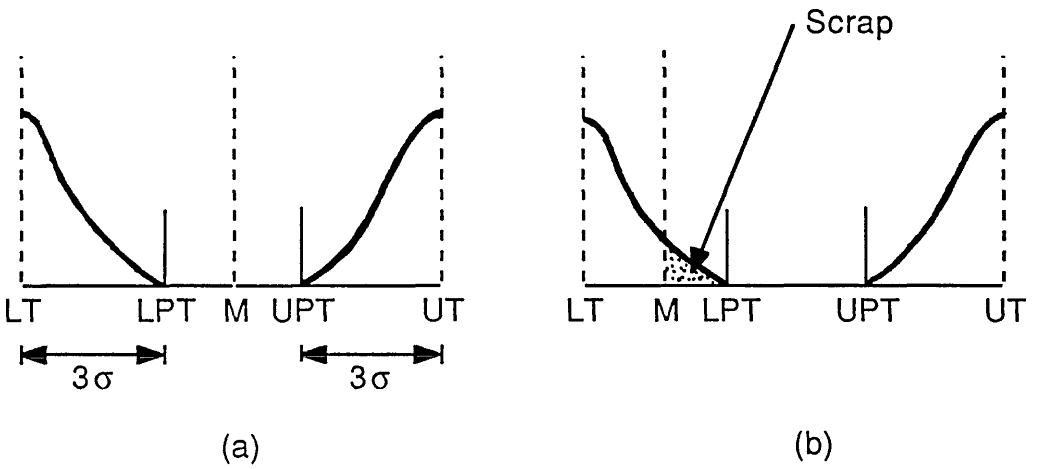
Reconsider the distributions in Figure 7.12 by subtracting 3 times the standard deviation from either side of the tolerance band, see Figure 7.13. The new limits shall be referred to as 'Process Tolerance Limits'.



UT ≡ Upper Tolerance
M ≡ Mean Value
LT ≡ Lower Tolerance

Figure 7.12

Two Typically Process Spreads



UT ≡ Upper Tolerance
UPT ≡ Upper Process Tolerance
M ≡ Mean Value
LPT ≡ Lower Process Tolerance
LT ≡ Lower Tolerance

Figure 7.13

Illustration Of Process Tolerance Limits

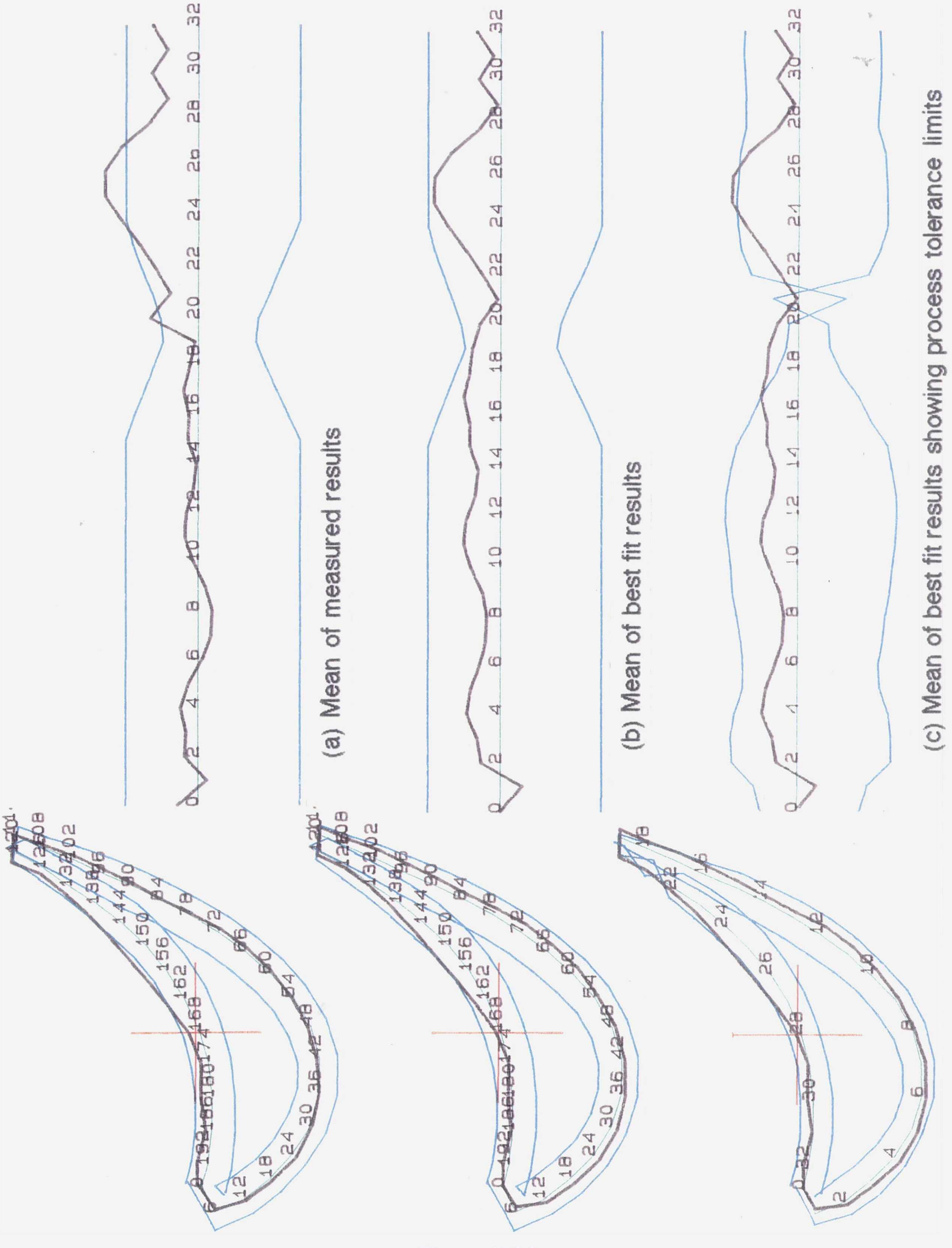
In the case illustrated by Figure 7.13.a the average measurement is inside the process tolerance which indicates that virtually no scrap will be produced at this position. In the case illustrated by Figure 7.13.b the average measurement is outside of the process tolerance indicating that significant scrap will be produced at this position.

Since the Integrated Inspection System stores the standard deviation at each measured point it is possible to present the tolerance limits around the aerofoil incorporating the process spreads. Figure 7.14 illustrates three presentations of the average error for the same section of a measured batch of aerofoils. Figure 7.14.a represents the mean error of the aerofoils as measured and Figure 7.14.b the mean error of the best fits. In the best fit case the aerofoil is acceptably inside tolerance, however this does not account for process spread. Figure 7.14.c, which incorporates the subtraction of three times the standard deviation from the tolerances, indicates that scrap would be produced in the regions between 16 and 20 and 24 and 26 on the aerofoil.

As a tool during proof cycling this technique of process capability fitting illustrates two properties of the process :-

i. Whether the spread at a particular position is acceptably low, which at position 20 on Figure 7.14.c it is not, as the process tolerances are crossing over, indicating that the process is out of control.

ii. If an average position is shown to be beyond a process tolerance the diagram illustrates how far it has to be moved back to prevent scrap being produced. In the case of the lost wax casting process this movement should be related to die modifications, since the die is responsible for setting the average position of the surface.



(a) Mean of measured results

(b) Mean of best fit results

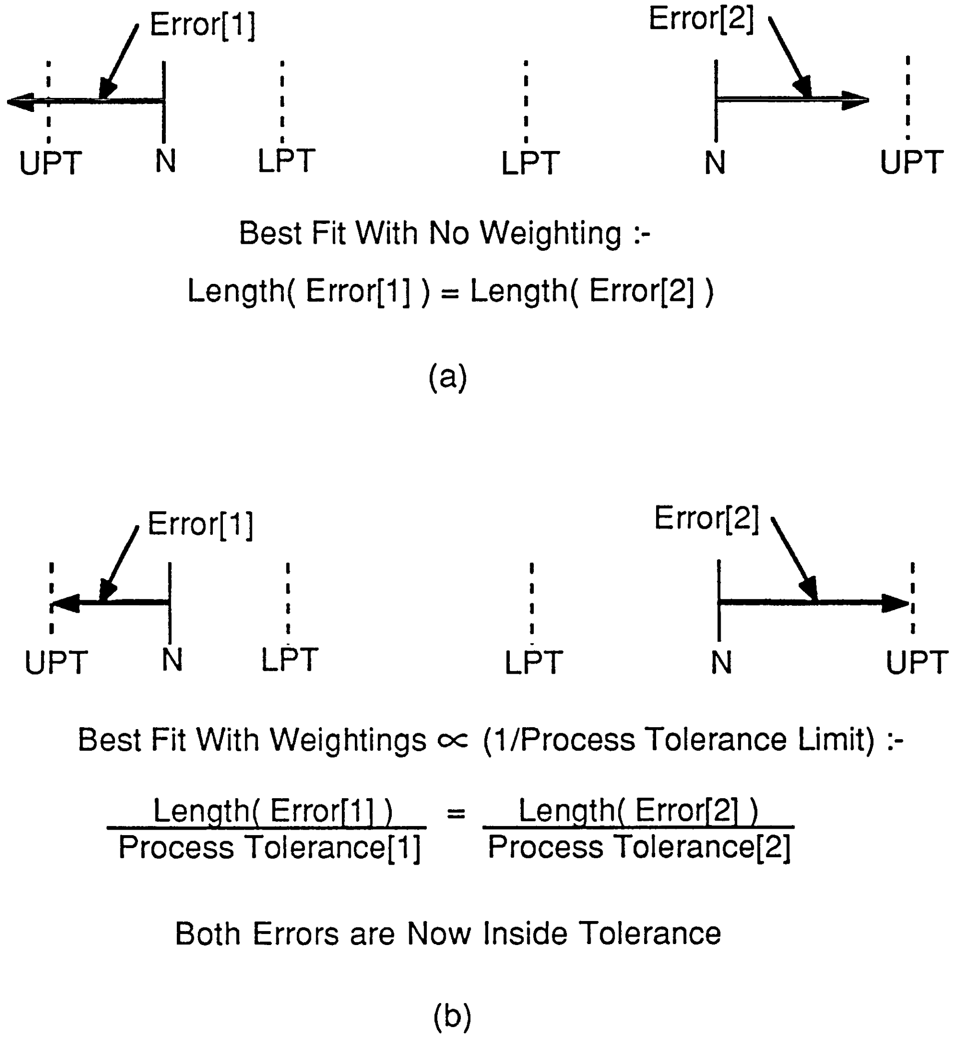
(c) Mean of best fit results showing process tolerance limits

Figure 7.14

Illustration of Sectional Errors: (a) Mean of Measured Results, (b) Mean of Best Fits and (c) Mean of Best Fits Incorporating Process Tolerance Limits.

One further step in indicating true production yields, by best fitting, is to weight the errors during the best fit as a function of their relationship to the process tolerance limits. Consider the imaginary case of the two errors in Figure 7.15.a, which are geometrically related, both errors are of equal size but the first error is outside of its process tolerance limit while the second is not. With no weighting a best fit would average these errors to the same length. However if the errors were weighted by a function proportional to (1/process tolerance limit) the best fit would reduce the out of tolerance error, at the cost of the inside tolerance error, until the ratio of (error length/process tolerance limit) was the same, as illustrated in Figure 7.15.b.

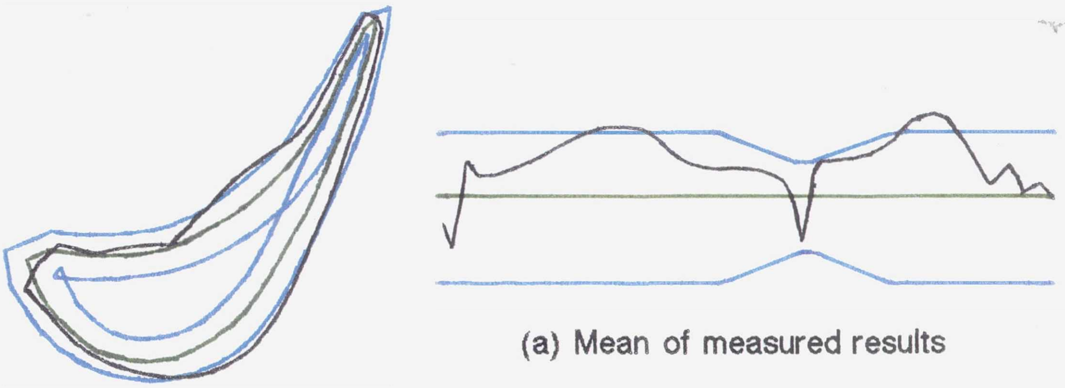
The above technique when applied to entire surfaces has been called 'Process Capability Fitting'. Figure 7.16 illustrates the process capability best fit for an aerofoil section.



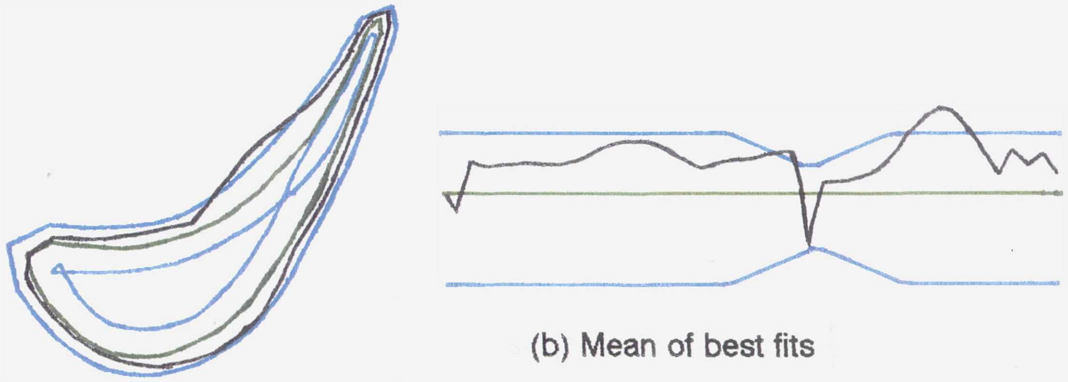
$$\frac{\text{Length(Error[1])}}{\text{Process Tolerance[1]}} = \frac{\text{Length(Error[2])}}{\text{Process Tolerance[2]}}$$

Figure 7.15

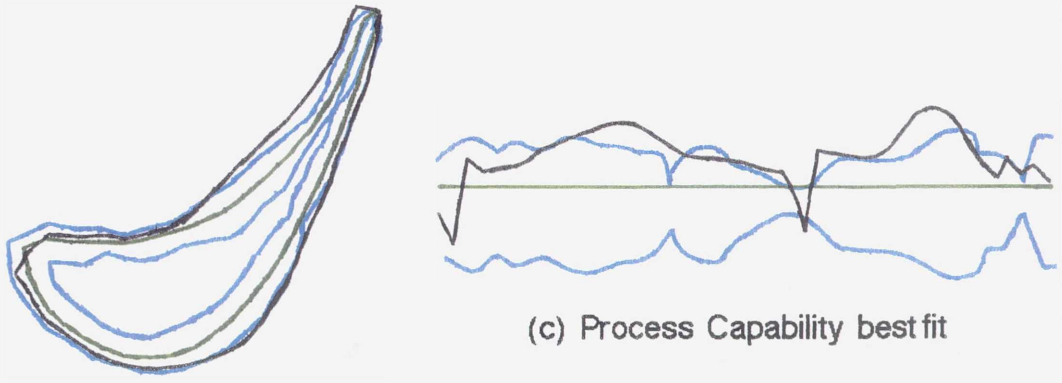
Illustration of Two Related Errors: (a) Best Fit Without Weightings, (b) Best Fit With Weightings Proportional to (1/Process Tolerance Limit)



(a) Mean of measured results



(b) Mean of best fits



(c) Process Capability best fit

Figure 7.16

An Illustration of the Process Capability Best Fitting of an Aerofoil Section

7.6 Tolerancing Philosophy Within Integrated Inspection

7.6.1 Introduction

The concept of tolerancing within design and manufacture is to provide a relationship in the compromise between manufacturing capabilities and variabilities in component functionalities. G. Taguchi [3] defines quality as the 'loss experienced by society after a product is shipped, other than any losses caused by its intrinsic functions'. From this definition he derives the 'Loss Function' which is concerned with the analysis of quantifying this loss. The main philosophy stemming from this work is that loss is experienced when anything other than perfection is manufactured, this is quite different to the western style of analysis in which a product is seen as good or bad, inside or outside a tolerance range. By producing the 'loss function' for a product an analysis of the costing of the imperfections yields a relationship, based on the business case, for improvements in manufacturing over hurt to the customer. Thus process tolerances, however expressed, should be analysed on the business case and not be based on the process capabilities as they stand.

For the vast majority of manufactured components tolerancing takes the form of acceptable dimensional variations. For example the ability of a bolt to fit through a hole may be expressed in terms of minimum and maximum permissible sizes for both the bolt and the hole. However dimensional variations when used to assess the functionality of a complex component such as a turbine blade are extremely crude. An aerofoil does not fit into another component it resides in free space and is required to perform a certain function against air flowing around it. The consequence of this type of functionality would suggest that the method by which the aerofoil is assessed to achieve that functionality may not best be served by dimensional tolerancing techniques.

In assessing the functionality of an aerofoil in a turbine blade the key issues are :-

i. Capability of generating lift at an acceptable loss.

ii. Sufficient cross-sectional areas and radial distribution of cross-sectional areas for acceptable weight, stress/life.

iii. Sufficiently small levels of twist and bow for acceptable stress/life.

iv. For hollow blades, acceptable minimum and maximum wall thickness for integrity, cooling hole drilling and bulging stresses.

The current technique for determining these capabilities is to specify profile, twist, bow and wall thickness tolerances. There are also various standards for allowances in surface finish and the rates of change of profile errors. However if more accurate information about the functionality of the component is to be achieved a better method of ascertaining the components capabilities is required.

One method of ascertaining a better measure of functionality would be to measure the turbine blade, model it in a geometric manner and actually calculate its mechanical and aerodynamic capabilities from analysis programs used on the nominal design geometry. Then decide if the component was acceptable. Will the aerofoil generate lift with acceptable loss? Is the blade stacked to induce acceptably low stresses? Will the throat window geometry in a turbine set be sufficiently consistent? All of these questions could be answered from measuring the blade and performing aerodynamic and stress calculations on the model of the geometry.

Analysing a component for acceptable functionality rather than dimensional distortion changes tolerancing from a dimensional to functional definition. This assessment technique could be applied during the proof cycling process for turbine blade manufacture to ascertain the requirement for further die modifications against the cost of a further proof cycle.

A further consequence of this style of accessing manufactured blade functionality is that it indicates to manufacturing, far more than the current technique, the effects of variability on the functionality. Assessing a blade for profile, bow and twist tolerances is somewhat unrelated to actual limits of stress permissible for the material. Similarly achieving profile tolerances around aerofoils is some what unrelated to the actual loss that will occur when the air is passing over it. Certain areas of an aerofoil namely diffusion controlling regions are extremely geometrically sensitive. In practise this fact is not known to manufacturing and no more emphasis is applied to the quality of one region of an aerofoil than any other. Therefore functional tolerancing should provide a tool from which manufacturing effort would be concentrated on producing highly functional components.

A further consequence of assessing the manufactured blade functionally is that it relates manufacturing capabilities to component functionality and hence it is possible to construct the 'loss function' from which a proper business case for manufacturing capability improvements can be made. In addition to this, with a better understanding of manufacturing capabilities it is possible to reduce the effects of manufacturing variability on the component functionality during the design of the product and for efforts on improvements to manufacturing capability to be concentrated on those areas most responsible for limiting component functionality.

In determining a component's functionality the question arises as to what to do if that functionality does not obtain the levels set as minimum. In terms of stress certain components may be unbowed or untwisted in a process known as 'stretching'. From the modelled geometry it would be possible to calculate the degree of stretching required to achieve an acceptable component. From the point of view of profile losses around an aerofoil relating these to geometric modifications is not so easy. If the profile tolerance is expressed in terms of dimensions then the blade may be dressed back to achieve these. However as has previously been explained acceptable profile variations are not expressed well using normal dimensional tolerances. For this reason another concept was derived which more accurately related aerodynamic performance to dimensional variations. This is the concept of 'Form'.

7.6.2 Derivation and Use Of Profile Form

In terms of aerodynamic performance of an aerofoil far more critical to loss than just error from nominal is the smoothness of the surface. Figure 7.17 illustrates four typical types of profile error.

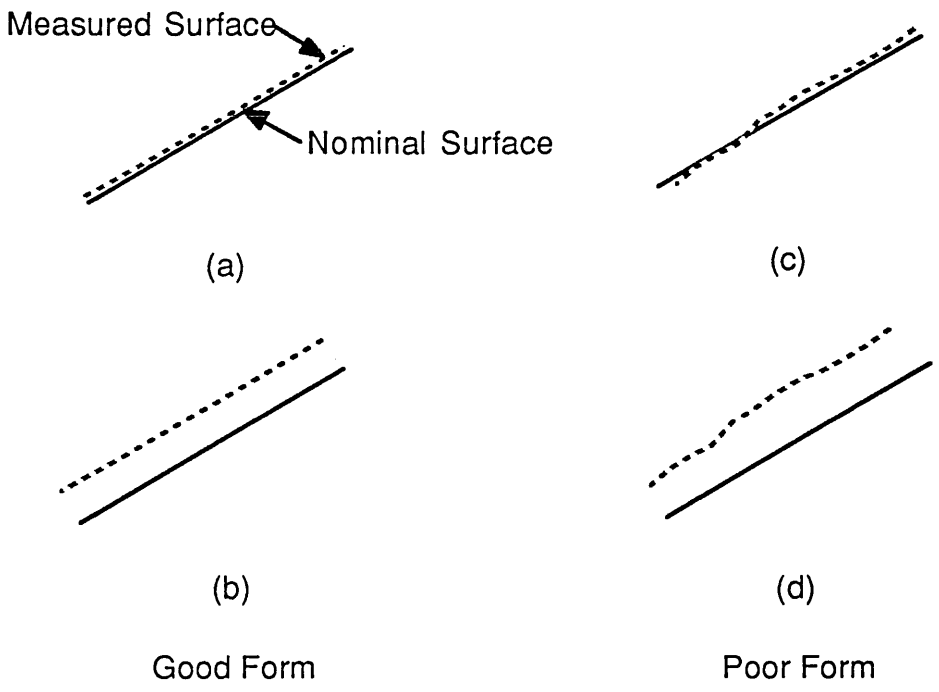


Figure 7.17

Typical Aerofoil Profile Errors

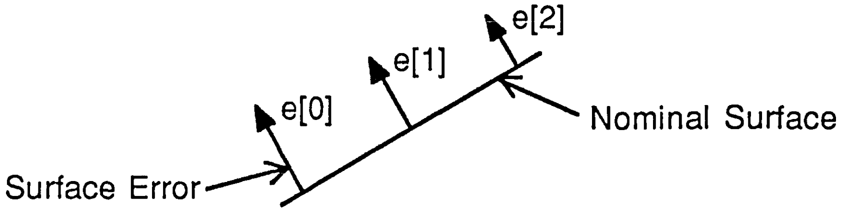
Losses, due to manufacturing errors, around aerofoils are caused by rapid changes in the rate of change of curvature on the surfaces. It is far better to have a surface which is smooth to design nominal eg Figures 7.17.a and b than a rough surface eg Figures 7.17.c and d. The mean error is not so crucial

Cardew-Hall [2] introduced the concept of 'surface defect filtering' in best fitting, which applied weightings to the errors according to variations between nominal and measured curvature. This work illustrated the use of best fitting to find poor surface regions, although it's derivation was not very applicable to 3D surfaces. Therefore another technique of quantifying the 'quality of smoothness' was derived and is known as 'form'. In the definition, see Figure 7.18, a relationship between the size of adjacent errors is used to quantify the 'smoothness' of the errors.

A weighting provided by the aerodynamicists may be applied to the value of form to indicate the loss that that part of the surface will incur. The integration of the losses over the whole of the surface indicates the level of loss from the aerofoil.

If an aerofoil was found to have too higher loss the value of the 'form' would indicate where the aerofoil required modification. Figure 7.19 shows how one area of an aerofoil has a very low 'quality' and that this area requires modification.

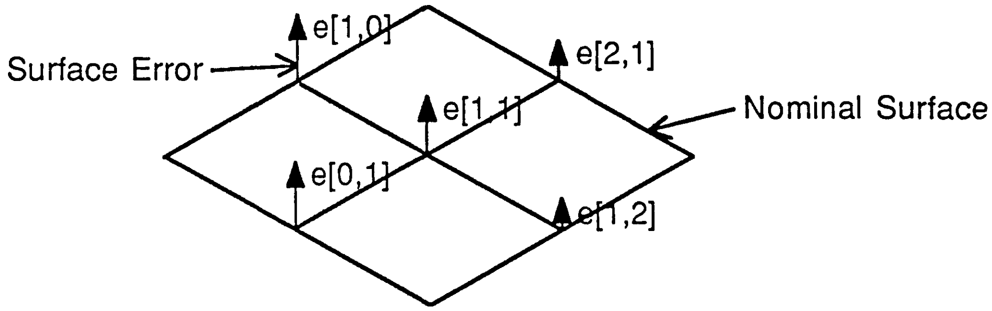
Definition of 2D Form :-



$$\text{Form}[1] \propto \frac{1}{|\, e[1] - e[2] \,| + |\, e[1] - e[0] \,|}$$

(a)

Definition of 3D Form :-



$$\text{Form}[1,1] \propto \frac{1}{|\, e[1,1] - e[1,0] \,| + |\, e[1,1] - e[1,2] \,| + |\, e[1,1] - e[0,1] \,| + |\, e[1,1] - e[2,1] \,|}$$

(b)

Figure 7.18

Definition of Profile 'Form'

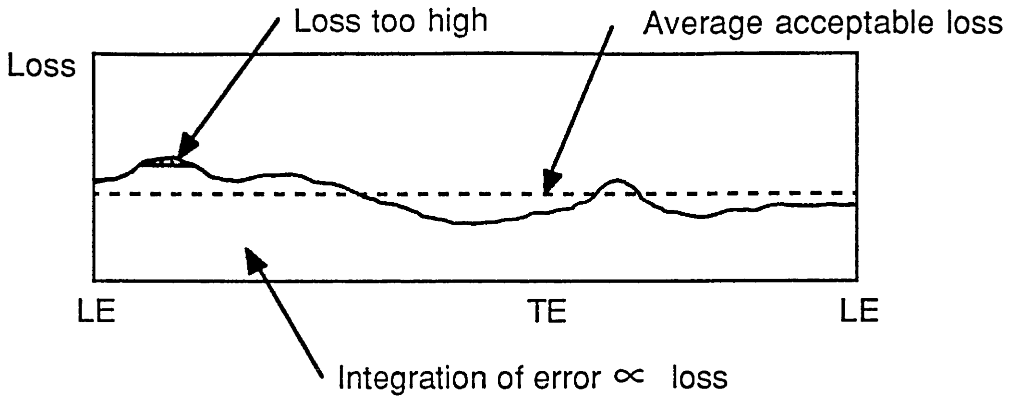
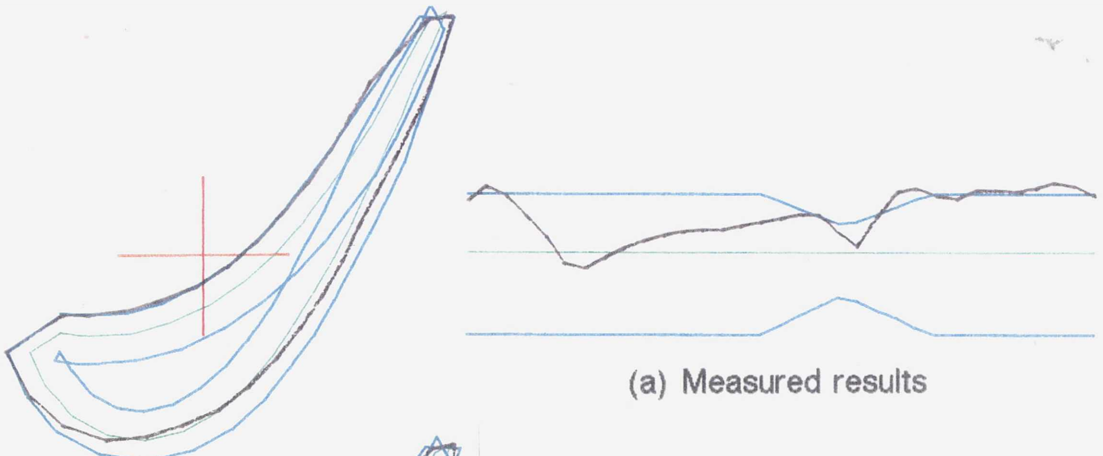


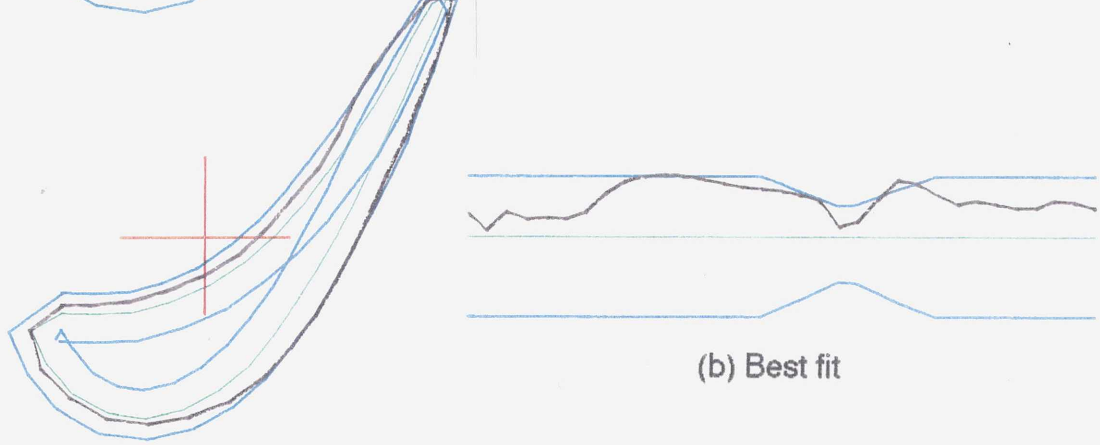
Figure 7.19

Unwound Plot of 'Form' Around an Aerofoil Section, Indicating That One Area Requires Modification

Another use of the concept of form is during the proof cycling of the lost wax process. For form is a measure of the minimum die modification requirement. Without an aerodynamic weighting the weightings produced from the calculation of form imply where a surface is 'good' or 'bad'. A manual die modification should utilise the good areas and change the bad ones. By form-fitting a surface the poor areas are pushed off nominal to reveal them for die modification. This is illustrated in Figure 7.20 where the form fit has pushed the trailing edge pressure surface - which is a region of rapidly changing error - away from the nominal.

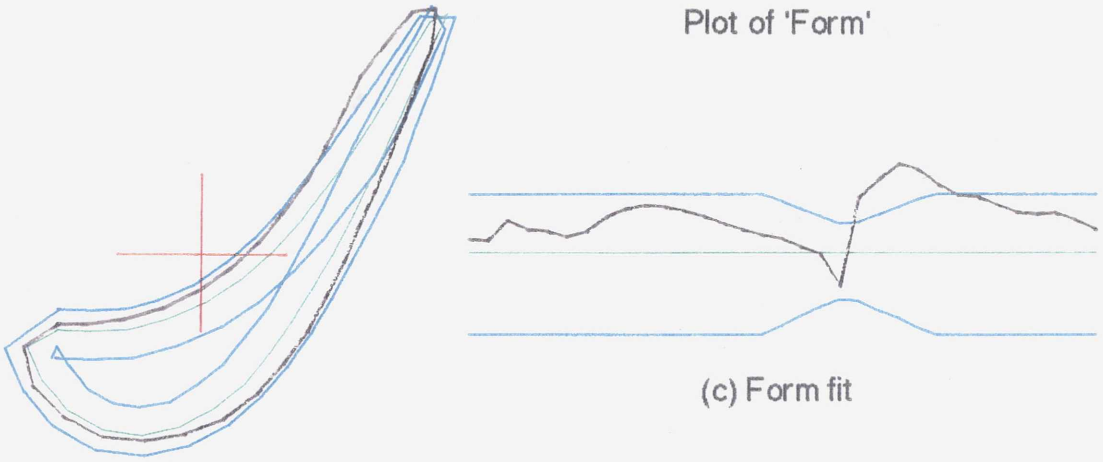


(a) Measured results



(b) Best fit

Plot of 'Form'



(c) Form fit

Figure 7.20

Form-Fitting of an Aerofoil Reveals Poor Surface Regions for Die Modifications

7.6.3 Resume Of Functionality Tolerancing

The complexity in functionality of modern gas turbine blading is such that the dimensional tolerancing techniques being employed for inspection of the geometry are inadequate in relating process variability to component functionality. Therefore a new technique is proposed in which models of inspected geometry are passed to stressing and aerodynamic programs which ascertain the functional capabilities of the components. In the case of unacceptable geometry a concept defined as 'form' could be used to relate required modifications to profile geometry, while degrees of bow and twist could be calculated directly from the inspected model to indicate requirements in stretching.

The advent of integrated inspection technology should reduce the numbers of dedicated fixtures required for measurement and provide for a process database. It should also facilitate a change in tolerancing philosophy to ascertain true component functionality, which in turn should lead to a better understanding in manufacturing of design intents and in design of manufacturing capabilities.

7.7 Nomenclature of Symbols Used in the Derivation of The Three-Dimensional Best Fitting Transformation Function

A	Best fit Rotation matrix, (3 * 3)
A_x	Best fit Rotation matrix about the x-axis.
A_y	Best fit Rotation matrix about the y-axis.
A_z	Best fit Rotation matrix about the z-axis.
E	Sum of errors.
N	Number of errors in the best fit model.
$t(\,)$	Best fit Transformation function.
$\underline{x}_0$	Point of intersection of error vector with actual surface.

$\underline{x}_1$	$\underline{x}_0$ after rotation by the best fit rotation matrix A.
$\underline{y}$	Point of intersection of error vector with nominal surface.
w_i	Weighting of the i^{th} error vector, $0 \leq w_i \leq 1$.
w_{ik}	Weighting of the i^{th} error vector, in the k^{th} degree of freedom.
α	Best fit Rotation angle about the x-axis.
β	Best fit Rotation angle about the y-axis.
γ	Best fit Rotation angle about the z-axis.
$\underline{\delta}$	Vector representing the parameters of the translational best fit.
$\underline{\lambda}$	Vector representing the parameters of the rotational best fit.

References

[1] Braley, J.W., "Development of 3 and 4 Axis Measuring Machines for Use in PC02 and PC22 Inspection Areas", Rolls-Royce Report No. TSR1065, Derby, United Kingdom, September 1978.

[2] Cardew-Hall, M., Cosmos, J., Ristic, M., "Automated Proof Inspection of Turbine Blades", The International Journal of Advanced Manufacturing Technology, Volume 3, 2, May 1988, pp41-49.

[3] Taguchi, G.," Introduction To Quality Engineering", Asian Productivity Organisation, Unipub, Quality Resources, White Plains, New York.

Chapter 8

Discussion and Conclusions From the Application of Simultaneous Engineering and Quality Engineering To Design and Manufacture

8.1 Introduction

For manufacturing companies existing in competitive markets it has been recognised that the design and manufacturing development lead time for the introduction of new products represents a severe problem. Firstly because it reduces the ability of a company to respond rapidly to market needs and secondly because this time represents a period of negative cash flow.

The question then arises of how should a reduction in design and manufacturing development lead time be achieved? This is an especially difficult problem to solve in industries such as the aerospace business where lead times are very long and where there are often a great many specialists involved in the design and manufacture process.

Simultaneous Engineering has been designed to address these problems. It states that the most balanced and optimised solution to an engineering problem will only come when a total integration of the entire design and manufacturing process is considered. Taguchi's Quality Engineering philosophy states that this balance must be based on financial considerations.

To facilitate the financial calculation of improvements to component functionality and manufacturing capability it follows that there is a need to compare manufacturing reality with design intent. While many CAD/CAM systems currently exist as examples of information systems transferring nominal design geometry to manufacturing there has been little attention to the concepts of transferring manufacturing data to design either for analysis at an early design stage of a new product or for calculations of manufactured product functionality. The transfer of manufactured data into design, in this manner, implies the need for the development of integrated inspection systems and databases.

In this thesis it has been concluded that there is a need for accountability between design intent and manufacturing capability. Where products are extremely complex this accountability must be provided for in a highly structured manner. Hence the need for two-way communication systems for the transfer of design intent and manufacturing capability. Such systems provide for the numerical determination of satisfactory process capability at the design stages of the component and for the functional analysis of manufactured geometry. Thus this thesis has attempted to describe the integration of geometric information within design and manufacture.

8.2 Lessons Learnt In The Development Of An Integrated Inspection System

The task of the integrated inspection system designed for the measurement of turbine blades was defined as using nominal blade definitions to control inspection machinery to measure the blades and then to construct models of the measured geometry from the inspected results. From these models surface errors were calculated, best fit and presented in suitable formats. As the measured blade models existed in the same format as the nominal geometry they could be sent to design areas for functional analysis.

The following are a list of conclusions that have followed from the development of the gas turbine blade integrated inspection system :-

1. As the whole philosophy of feeding inspected data back into an inspection system was new at the time of the system's development it was recognised that many of the initial specifications would need to be updated as the system developed. In recognition of

this it was decided to base the inspection system on the highly flexible CIM system PANACEA, from Imperial College. This enabled new code to be rapidly implemented and at a low cost. This is something which would not have been possible if the system had been based on a commercially available CAD/CAM or CIM package.

2. During the development of the integrated inspection system it was soon realised that the particular method by which measured data was obtained into the system was not important - be it laser triangulation, contact probe or computer tomography - the overriding issues were how to use the nominal geometry to instruct the measurement, how to create models of the measured surfaces, calculate surface errors, present errors and best fit them.

3. The development of probe path generators for turbine blade free-form surface measurement has highlighted the need for a probe path generator coding which is more generalised and capable of controlling a number of types of probe head over almost any surface definition. This 'Entity Independent Probe Path Generator' (EIPPG) is complex but it is believed that enough has now been learnt to define such an algorithm.

From the work that was conducted on the EIPPG it is believed that such an algorithm could be defined from a set of surface target points and associated surface normals alone.

The task of the entity independent probe path generator has been divided into three sub-tasks :-

i. To move the probe head, along the surface normal, to facilitate the act of measurement.

ii. To orientate the probe head, during the act of measurement, to prevent collision with anything but the target point.

iii. To move the probe head between measurements in a time efficient manner.

In Chapter 6 it was explained that the first task may be achieved by using the surface normal to the target point and that simple concepts such as home positions may be employed for an algorithm to the third task. By far the most complex problem is a solution to the second task. For this three algorithms were explored; reversed RISP, potential fields and line-of-sight. It is strongly believed that line-of-sight methods hold the best solution to the probe orientation problem, for which Appendix III describes a particular algorithm.

4. Work with the Neutral Datafile (NDF) CAD/CAM to CMM command language showed great weaknesses in this communications standard. It is clear that the language was principally derived from the one-way communications requirements of CNC machines. The following are a list of improvements which would be recommended for a better CAD/CAM to CMM exchange language.

i. The programming should be at discreet rather than at object level.

ii. There is a need for a more complex alignment facility. NDF was certainly not designed for the alignment of turbine blades. 75% of the codes used for ABC point alignment of turbine blades on the Mitutoyo CMM were non standard NDF instructions.

iii. There is a need to construct conditional statements within an inspection program. For example find the highest point or converge alignment to a certain value.

iv. There is a need to facilitate the transfer of measured data from the inspection machines to other computing systems.

Many of these recommendations are to be found in the DMIS language, developed by Pratt and Witney of North America. Since this language would appear to have so many advantages over NDF it would not be surprising if, in Europe, NDF was eventually replaced by DMIS.

5. If integrated inspection is to be adopted within a Simultaneous Engineering philosophy it will be important that this is recognised by the manufacturers of coordinate measuring machines. CMM controllers will have to become more compatible with other computers to prevent them being 'Islands of Automation'.

6. The principle of feeding inspected data back into an inspection system for analysis relies on the ability to model inspected data with integrity, often to microns. It was found that the problems of integrity in modelling measured free-form surfaces are principally the same as those incurred in the generation of nominal surfaces and hence it was concluded, for turbine blades, that inspection results from measured surfaces should be modelled with the same control point distribution as nominal surfaces. This imposes rules on the positions of measurements made to the surfaces and has given rise to the modelling philosophy described in Chapter 5.

The great advantage of modelling measured and nominal surfaces in the same format is that the measured surfaces may be readily transfered to design for analysis by the same programs as the nominal surfaces.

7. One of the most powerful capabilities of the turbine blade integrated inspection system is to facilitate batch measurement. This enables any number of surfaces to be measured from which mean and standard deviation data is derived. Plots of standard deviation and mean errors are readily obtained which present extremely useful information to both designers and manufacturing engineers.

8. Graphical error presentation was found to be one of the most powerful techniques for presenting surface errors, especially over complex surfaces. It was found that error presented around sections was very useful. However the most powerful

graphical presentation of error - that has been found to date - is contour plotting. Once the ability has been acquired to interpret contours they provide a technique which enables the user to gain a picture of the error over an entire surface in seconds, even if that surface is extremely complex and involves the measurement of hundreds of points.

9. The fact that the method by which a surface is aligned before measurement will not necessary yield the minimum error measurable over that surface produces the requirement to best fit measured data. An integrated inspection system, such as the one developed for turbine blades, provides for the ability to include all of the measured data in the best fit calculation.

The three dimensional best fitting technique developed for the turbine blade integrated inspection system uses discreet error vectors between measured and nominal surfaces to perform the calculations, rather than a volumetric definition of the error. This enables a dramatic simplification of the mathematics, no significant loss in accuracy, multiple surface fits to be accommodated easily and weightings to be applied to all surfaces and in all degrees of freedom.

One problem with best fitting is that it is an iterative procedure and as such makes severe demands on computation. Fortunately these demands are to a very great extent dominant on surface intersections which parallelise easily and hence are highly suitable for transputer based processing.

Although the best fit mathematics has been developed for use with gas washed surfaces of turbine blades it may be applied to any 3D geometry optimisation problem e.g. software gauging.

10. During the development of the integrated inspection system the transfer, of the computing platform, from the Codata microcomputer to the SUN 3/60 workstation was

one of the most important factors in the successful completion of the system. The SUN 3/60 is estimated to have increased programming rates by a factor of four.

11. It is important to reiterate that integrated inspection is about the ability to send manufacturing data throughout the entire design and manufacturing activity. It is therefore important that integrated inspection systems are part of a corporate computing capability. In this way integrated inspection provides for :-

i. The on-line monitoring of manufacturing processes.

ii. The closed loop modification of process tooling.

iii. The generation of process prediction models.

iv. The feed back to design of manufactured geometry for functional analysis.

v. The replacement of dimensional tolerancing with functional analysis.

8.3 The Application Of Simultaneous Engineering and Quality Engineering Techniques To The Design and Manufacture Of Gas Turbine Blading

The following are a list of conclusions for improvements in the design and manufacture of gas turbine blading :

1. It has been observed that by managing engineers in different departments and corporate structures that engineers tend to form a misunderstanding of their role, even when they are working on the same project.

To overcome this situation the use of 'integrated' teams is employed, which bring together the large numbers of specialists as early as possible in a product and process definition. Integrated teams attempt to minimise departmental allegiances and focus the direction of the team.

It is proposed that all the engineers involved on a product and process definition exercise are grouped together in well lead 'integrated' team. In this way their allegiances will form to the project and not to their departments.

2. The increasing capability of computing systems has enabled more accurate analysis of components during their design. The need to reduce the cost of components has led to increased design iterations and it can be foreseen that more computing analysis will become a part of product and process definition procedures. However the transfer of data between computing systems can be extremely time consuming and is entirely non-value added activity. Therefore if lead times are to be reduced, whilst accommodating increasing analysis, it is of paramount importance that all the computing systems within a definition procedure use a common database.

3. A further advantage of 'integrated' teams is that they enable a maximising of parallel working practises between engineers involved in a project. When projects are managed within department structures there is a tendency for information to be managed between the groups in an end-on-end fashion. This is slow and in reality is quite unrepresentative of how information actually flows between the members of a large project team.

Thus by employing engineers together in integrated teams the product and process definition evolves as quickly as possible and, if managed correctly, in a well balanced manner. This lead time reduction technique is one of the principle advantages of Simultaneous Engineering.

4. The very large numbers of engineers involved in a product and process definition of an advanced aero-engine component will in total deal with a quite staggering volume of information. Each specialist being responsible for one small part of the overall definition. Information transfer between specialists is usually geometric or material

characteristics, while the reasons for these specifications are not formally transfered. The consequence of this is that engineers further along the line of specialists may make decisions which effect product functionality because they are unaware of the reasons for previous decisions. It is therefore proposed that all engineers within a product and process definition make sure that there is an understanding of the important functional issues throughout the project team.

5. One of the basic principles of Taguchi's Quality Engineering is that compromises made within a product and process definition must be financially justified. It is therefore of great importance that an understanding of the relationship between manufacturing capability and component functionality be achieved. Without this relationship it is not possible to base business decisions on improvements to either.

To facilitate the generation of such understanding it is necessary to develop Integrated Inspection systems capable of sending models of manufactured geometry to design areas where it may be analysed and related to functionality.

Such systems also improve the understanding between design and manufacturing engineers of component functionality and manufacturing capability.

6. The enormous quantity of information that has to be assessed during proof cycling of advanced aero-engine component manufacturing processes demands systematic measurement capability. There is a need to gather geometric and material characteristics quickly and consistently and for the results to be presented in an easy to understand manner.

7. There is a need to inspect the sub-processes that make up an entire manufacturing process, not just the final product. In other words for the investment casting process there is the need to measure and control the geometry of waxes, cores,

shells and castings, and measure and control the critical process parameters, like wax injection temperatures and pressures, shell coating concentrations, metal pouring temperatures, metal solidification rates etc.

8. During the proof cycling process for turbine blade manufacture there is a need to functionally analyse the proof batches of components. Remembering that for advanced aero-engine components dimensional tolerancing is a very crude method of relating manufacturing capability to component functionality it may be said that striving to improve dimensional accuracy need not necessarily improve component functionality. It is therefore proposed that decisions made for modifications to dies and process variables be based on component functionality and not dimensional accuracy.

9. The need to improve manufacturing capabilities on critical geometry components implies the requirement to improve die modification processes. The current manual inspection, manual interpretation of error and manual modification of dies has surely reached a limit in its capability. On the other hand integrated inspection offers possibilities of computer integrated die modification. For since geometric error is recorded within the inspection system it is readily available for relating to the NC programs that specified the initial die cutter paths.

10. In striving to improve the balance of compromises made during a product and process definition and in aiming to justify these compromises within a financial framework it is necessary to provide process capabilities at the earliest stages of the design of a new product. In this way requirements for improvements in manufacturing capabilities and component functionalities can be made as early as possible.

The most useful method of providing process capabilities is to produce process predictors which take nominal geometry and ascertain the manufacturing scrap rates e.t.c.. Such predictors for the investment casting of turbine blades should also aim to provide optimum die geometry and process parameter settings.

The overriding conclusion from the analysis of the advanced aero-engine components design and manufacturing process using the principles of Simultaneous Engineering and Taguchi's Quality Engineering is that there is the need to introduce far greater integration and accountability of activities and that these should be controlled by the overall project costing.

8.4 The General Application Of Simultaneous Engineering and Quality Engineering Techniques To Design and Manufacture

It is recognised that there are strategic advantages for manufacturing companies in reducing design and manufacturing lead times, but this must be achieved along with defining highly competitive products.

Simultaneous Engineering and Taguchi's Quality Engineering philosophies may be combined to produce methods for focusing the full spectrum of design and manufacturing processes to the business requirements.

The overriding issue for achieving effective design and manufacture is the integration both in terms of the engineers and the systems they use. This integration must now take place on a global scale. No longer are the designers and manufacturing engineers based in the same building, where quick and easy communications happen naturally. Thus the balance of compromises met in the product and process definition must be highly structured.

A basic principle of Simultaneous Engineering is that total compromise will only be met by the integration of the design and manufacturing activities. Simultaneous Engineering aims to recognise the divisional tendencies of corporate structures and of the groups of specialists employed within them and achieve integration.

Simultaneous Engineering encompasses the philosophy of product and process development. For any product existing within a competitive market it is important to account for the costs of these developments to improvements experienced by the customer, a concept which is central to Taguchi's Quality Engineering. In this way the value added activity of the design and manufacturing process is maximised.

Increased accountability implies the need for strong communications between design and manufacture. The use of common computing databases throughout a product and process definition procedure enables fast and balanced development of the specification.

Whilst current CAD/CAM systems provide information flow from design to manufacture integrated inspection systems would provide systematic transfer of manufacturing information to design. In this way designers and manufacturing engineers will become more aware of the effects of manufacturing capability on component functionality.

An improved design philosophy that follows is that designers should work to minimise the effect of manufacturing capability on component functionality while manufacturing engineers work to improve those areas of manufacturing capability which have most effect on component functionality.

Tolerancing is one area of consideration which may be subject to change under a philosophy where manufacturing capability is directly related to component functionality. While there are many examples of components where pure limits on dimensional extents are totally sufficient to define this relationship, there are some products involving extremely complex functionality where it may be said that trying to relate dimensional distortion to functionality is extremely difficult. In these situations a further disadvantage of dimensional tolerancing is that it does not inform manufacturing engineers of what issues are truly important.

It has been recognised by Rolls-Royce that integrated inspection is of paramount importance to it adoption of Simultaneous Engineering philosophies. As a result it has been able to obtain funding from the European Community via the BRITE scheme to develop production integrated inspection systems. This work will be conducted in partnership with Imperial College.

Appendices

Appendix I

User's Guide To The Turbine Blade Integrated Inspection System

Summary

This appendix is part of the documentation of the Turbine Blade Integrated Inspection System. It presents the technical background of the various programs that make up the system, how to execute them and what information is required to do so. With this guide the user should be able to follow the sequence of events that make up the Proof Inspection of turbine blade gas washed surfaces i.e. blade modelling through measurement part program generation, execution of part programs, analysis of inspected data and finally the best fitting of surface errors. Included in this guide are explanations of various tools available in the PANACEA CIM programming environment and a brief overview of the Blade Modeller system.

Contents

1 Introduction

1.1 History Of The Turbine Blade Integrated Inspection System

In 1984 a project was undertaken at Rolls-Royce to examine the development lead times for a gas turbine. It was found that the production of turbine blading stood on the critical path. On further examination it was found that there were 3 major elements to the manufacturing development lead time of the turbine blade :-

i. Lack of process understanding resulting in 'Proof Cycling'.

ii. Slow and inadequate dimensional inspection of blading during 'Proof Cycling'.

iii. Slow ceramic core die manufacture.

It was decided these problems should be investigated. At the time there were strong links between a CAD/CAM group at Imperial College and Rolls-Royce and consequently it was decided to set up a Teaching Company to examine the manufacturing development lead time of the turbine blade. In 1984 ceramic core dies were manufactured outside of the company and so only Process Understanding and Proof Inspection were to be investigated by the research group. In September 1984 M. Cardew-Hall joined the Teaching Company to work on improving proof inspection and in December 1984 N. Kumar joined to work on process understanding. This appendix forms part of the documentation for the inspection system that has resulted from the work of the Teaching Company.

It was quickly realised that if proof inspection was to be improved it needed to be automated and so a proposal was made; this was to use a 5-axis Coordinate Measuring Machine (CMM) to measure the surfaces of the blades. In order to drive the CMM a part program generator was proposed to reside on a UNIX based workstation. The part program generator would use a geometric model of the blade to obtain target points with which to measure the surfaces. The nominal model of the blade would also enable a comparison to be made between measured points and the nominal surfaces thus generating surface error. These errors were also to be used in a 'Best Fitting' (surface error minimisation) process.

In April 1986 N. Brookes joined the Teaching Company, her brief was to integrate the proof inspection project with the process predictor, which required dimensional information on casting behaviour. Unfortunately when Brookes started her work the process predictor had not been formulated and so she concentrated her work on providing the blade modelling and integrating facilities necessary for the inspection system.

In September 1986 M. Cardew-Hall left the Teaching Company along with N. Kumar in December of that year. S. Lee joined the Teaching Company in April 1987 to continue the work on proof inspection. By the time S. Lee left in March 1989 a system existed to automate the proof inspection process for the gas washed surfaces of turbine blades. That system is commonly known as the APIP, the Automated Proof Inspection Package, and is the culmination of work carried out by M. Cardew-Hall, N. Brookes and S. Lee. For the purposes of this documentation the APIP shall be referred to as the Turbine Blade Integrated Inspection System or more simply as the Integrated Inspection System (IIS).

1.2 Capabilities Of The Teaching Company Computing Systems On 31 March 1989

i. A Blade Modelling facility interactively generates gas washed surface models of turbine blading in the PANACEA CIM environment. Aerofoil surfaces are generated from IGES format turbine blade files and annulii surfaces from an interactive program taking dimensions from blade drawings.

ii. An Inspection System which uses the blade geometry to construct part programs to enable a Mitutoyo Coordinate Measuring Machine to align and measure the gas washed surfaces of the modelled turbine blade. The system analyses the inspected data to enable errors to be calculated between nominal and measured surfaces. The errors may be graphically displayed around sections or as contours over the inspected surfaces. The system facilitates a best fitting procedure to minimise surface error and in so doing produce a best fit transformation. The best fitting algorithm may be set up to optimise error according to various requirements, for example minimum modification of wax dies.

1.3 Limitations Of The IIS On 31 March 1989

i. The system may only measure the gas washed surfaces of a turbine blade. The basic reason for this is that the Blade Modeller and PANACEA are not capable of modelling the complex geometry involved in the shroud and root of turbine blades. However as part of a Key Systems approach the author believes that the inspection system should be extended to measure all of the external and eventually internal geometry of a blade.

ii. The system is not yet capable of feeding error data back to the die cutting programs to enable a new die to be cut which accommodates for the errors on the proof blades. This facility would be a fairly simple extension to the system. It has not been included as it is believed that the NURBS surface model would provide a better environment in which to carry out such a procedure.

2 Technical Review Of Integrated Inspection System

This section has been sub-divided into 3 further sections, firstly to describe the design of the system, secondly to overview the computer systems involved and finally to overview the sequence of operations required to achieve a minimum die modification calculation. If the reader is unfamiliar with the IIS it is recommended that he or she reads the paper 'A Computer Integrated Approach To Dimensional Inspection' [1] as this will provide a further overview of the system.

2.1 Design Of The Integrated Inspection System

The objective of the system is to enable minimum modification to a wax pattern die to take place during 'proof cycling', so that the subsequently produced blades would be dimensionally more accurate. Die modifications would be achieved by either :-

i. Changing the die cutting model and re-machining the die block. or,

ii. Presenting the errors to the pattern makers in such a way as to enable modifications by manual dressing of the die.

The consequence of this objective implies the following set of requirements for the Integrated Inspection System:-

i. The re-cutting or hand dressing of die blocks requires information on the error between nominal and measured blade surfaces. This error should be mathematically minimised in order to optimise die modifications.

ii. Point i. implies the need to calculate the error between nominal and measured blade surfaces. It is believed that this is best facilitated for within a CAD/CAM programming environment.

iii. Point ii. implies the need to represent measured blade surfaces which further implies the need to measure the surfaces accurately and systematically e.g. on a Coordinate Measuring Machine, which still further implies the need to construct alignment and measurement part programs.

The system designed to fulfil these requirements is illustrated in Figure AI.1 and is described below :-

The Blade Modeller (1) provides information on blade geometry which is used by Alignment (2) and Scanning (3) programs. These interactively extract surface points and their associated surface normals from the model. These points and surface normals are sent to the Probe Path Generator (4) which constructs a collision avoidant probe path. The probe path is then combined with CMM instruction code in the Part Program Generator (5). The part program is then compiled into Neutral Database Format (6). For the Mitutoyo Coordinate Measuring Machine (CMM) the part programs are post processed (7) and stored in the workstation (8). Using the Ethernet link (9) between the CMM controller (10) (a Hewett-Packard Vectra Computer) and the workstation the postprocessed part program may be executed simply by running them as any other part program on the CMM. Inspected data is currently logged back through the HP IB (11) to the workstation, although this link should be replaced by the use of the Ethernet when Mitutoyo provide the facility. The inspected data is converted in the Remodeller (12) to PANACEA databases in the form of measured surface models. Errors between the measured and nominal surfaces are then calculated at discrete positions around the surfaces and transfered to the error display packages (13) which provide sections and contours of error over the measured surfaces. A best fitting facility (14) may be used to mathematically minimise the surface errors. The best fitting of errors around the blade may be used to illustrate the required wax die modifications.

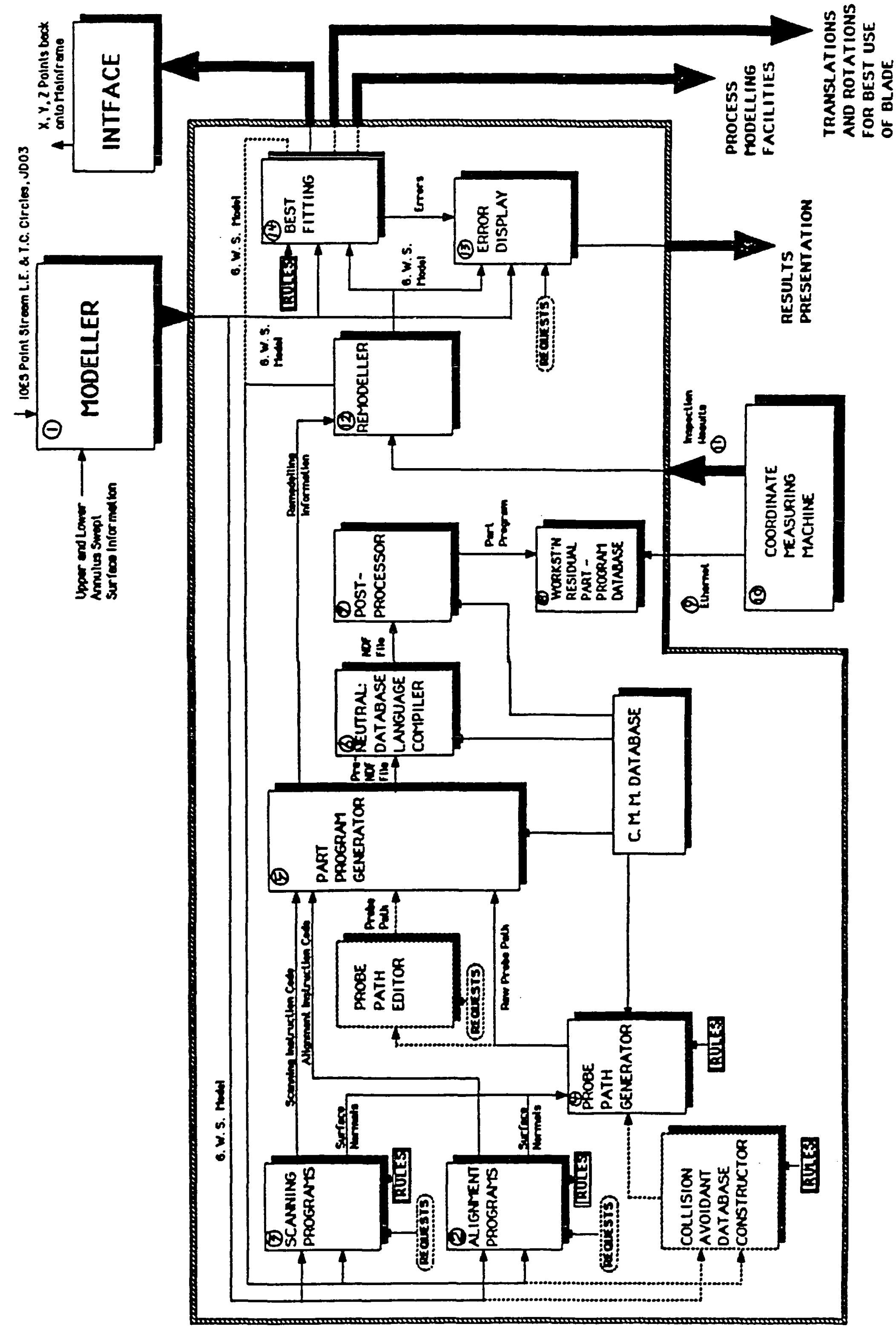


Figure AI.1

The Integrated Inspection System

2.2 Overview Of The Computing Systems Involved In The IIS

2.2.1 What is PANACEA ?

PANACEA is a CIM programming environment, produced by Glover [2], for UNIX workstations. It provides an interactive programming facility for modelling various entity types. It also provides a database management, graphical display and hard copy facility. The source code for PANACEA is located in the subdirectories of directory '/usr2/fesystem' on the SUN 3/60 computer used by the Teaching Company. One of the advantages of the PANACEA system is that it enables new programs to be easily strapped into the basic program to produce new systems. Examples of two such systems are the Blade Modeller and the Integrated Inspection System.

It was decided by the Teaching Company that the development of the Blade Modeller and the Integrated Inspection System should take place with the help of Glover, enabling any additional code to be written and brought on-line quickly. Despite the development of the IIS within PANACEA it has been accepted that a production package of the IIS should be converted to run in the CADDS-4X environment.

2.2.2 What is the IIS ?

IIS stands for the Integrated Inspection System, and as explained above is built around the PANACEA system. It uses PANACEA models of turbine blade gas washed surfaces generated in the Blade Modeller (a further PANACEA package developed by N. Brookes [3]). Despite the fact that the IIS exists within PANACEA much of the coding is independent of the database structure. Usually the database serves only to provide surface target points and surface normals. Therefore it is believed that a transfer of the IIS code into another CAD environment is more of a front end database interface change than a total change in program philosophy. The various programs which make up the IIS are described in detail in section 3 of this appendix.

2.2.3 What is the Mitutoyo Coordinate Measuring Machine ?

The Mitutoyo Coordinate Measuring Machine is a 3-axis computer controlled coordinate measuring machine (CMM). M. Cardew-Hall realised that dedicated fixturing was an insufficient tool for determining errors on turbine blade surfaces. In order to use the CMM to its full potential it was realised that it should be linked to a part programming facility i.e. some type of CAD/CAM system which could be used to drive the machine for blade measurement and for the analysis of inspected data. A number of criterion in terms of accuracy, speed and programmability were determined and after a study of the market it was found that the Mitutoyo Company provided the best value for money at the time for a CMM. The CMM itself provides for 3 axes of translational movement while the measuring head, a Renishaw PH9 probe head with TP2 touch probe, provides a further 2 axes of rotational movement. The inspection machine is controlled by a program, called GEOPAK, which runs on an HP Vectra computer and provides a programming environment for manual and CNC programming. Part programs written off-line within the SUN workstation are also executed by GEOPAK. Normally CNC programs are stored locally by the Vectra on its hard disk, but by using an Ethernet it is possible to execute part programs stored on the SUN's workstation as well.

There have been a number of problems with the Mitutoyo part program database format as it is extremely complex (non-ascii etc). This continued to provide problems as new versions of the GEOPAK program arrived (see the Mitutoyo post-processor documentation of more details). A further problem with the Mitutoyo is that the HP Vectra must be set up especially to log data to the workstation. This involves the use of an HP IB/RS232 converter and the downing of the IIS system just to log the inspection data back to the workstation. A request to Mitutoyo in April 1988 was submitted to enable logging of data back through the Ethernet, but this had not been provided by 31 March 1989.

2.3 An Overview of the IIS Programs

Before any minimum die modification programs could take place it was ascertained that a detailed knowledge of the blade's surface must be obtained by measurement. Since a Mitutoyo CMM was chosen for this task the IIS system had to provide suitable blade measurement programs to this machine. Once such programs were running facilities had to be provided for sending inspection data back to the workstation and for the results to be modelled into measured blade models. Surface errors could then be calculated, best fit and presented in a suitable format. The following are a set of overviews which outline the purpose of the various programs which make up the IIS system and thus perform the tasks outlined above.

2.3.1 Turbine Blade Alignment

When a turbine blade is positioned on a CMM the machine usually has no idea of where the blade actually resides. Therefore before any measuring of the blade's surfaces may take place a coordinate system must be built up around the blade (the coordinate system that is constructed around a turbine blade is called the blade's 'Stacking Axis'). The computing systems on CMMs are sufficiently sophisticated to construct coordinate systems in their software without the need to physically move the blade. The process of constructing such a coordinate system is called blade alignment. On a CMM this process may be split into two parts: pre-alignment and ABC point alignment. ABC point alignment is an iterative process in which target datums on the blade's surface are repeatedly measured and used to construct the stacking axis position. An ABC point alignment procedure may be constructed in a CNC part program, however before it may be executed an estimate for the position of the stacking axis to within 4mm is required. This task is provided by a pre-alignment procedure. This is a manual process in which a certain point on the blade is measured and used to construct an estimate for the stacking axis to within sufficient accuracy for the ABC point alignment program to be executed. Once a blade is aligned on the CMM the measuring programs may begin.

2.3.2 Turbine Blade Measurement

The PANACEA blade model provides geometric information on the gas washed surfaces only and so blade measurement is currently limited to these regions. Aerofoils are measured in XY plain sections, specified by their height above engine centre line. A full aerofoil measurement is built up by measuring around a number of sections. The probe path is built up using the surface normals calculated at the target measurement points. For measuring annulii surfaces specified XZ planes are intersected with the annulii surfaces to determine paths along which the probe may measure the surface. During part program generation certain information is stored to file which will latter be used in the modelling of the inspected data. Part programs are written in an ascii format language, the Neutral Datafile, which was explained in section 2.1 of this appendix.

2.3.3 Post Processing of Part Programs For The Mitutoyo CMM

Originally the Mitutoyo CMM controller was to have an NDF translator, which would have enabled the part programs written by the IIS to have been executed as they came out of the basic system. However no translator became available and so the IIS part programs have to be post-processed. This involves converting the NDF codes to GEOPAK database format and storing them in specified files in the workstation.

2.3.4 Execution of the IIS Part Programs on the Mitutoyo CMM

Before part programs may be successfully executed on the Mitutoyo CMM two procedures must be adopted. Firstly the correct GEOPAK set up program must be run on the HP Vectra. Secondly communications between the CMM and the workstation must be set up for logging inspection results. Once correctly set up the GEOPAK program may be run and IIS part programs executed in exactly the same manner as any other part program written for the Mitutoyo. Any number of blades may be inspected on the Mitutoyo before analysis of the results need take place.

2.3.5 Modelling of Inspected Data

Once logged the inspected data may be used along with modelling information generated at the time of part program construction to formulate measured surface models within the PANACEA system. If more than one blade has been measured an average surface model is produced along with the standard deviation of the measured points.

2.3.6 Calculation of Errors Between Surfaces

The difference between a measured and a nominal surface is volumetric. However because of the nature of the defining surfaces it would be practically impossible to define this volume in full definition. To overcome this problem errors between the surfaces are calculated along discreet vectors, if the distribution of these vectors is sufficient it is possible to represent the volume of error.

2.3.7 Display of Errors from Blade Surfaces

It has been found necessary to provide 2 main facilities for displaying surface errors:-

i. Sectional Plotting: this facility provides the ability to draw out sectional views of the surfaces with error magnification. This magnification is necessary as errors are orders of magnitude smaller than the form of the surface and so are difficult to visualise unless magnified.

ii. Contour Plotting: this facility provides the ability to plot out the errors over a surface representing the errors with contours. It has proved to be an extremely powerful method of displaying errors.

2.3.8 Best Fitting of Surface Errors

This facility provides the ability to mathematically minimise the error between surfaces. More than one surface may be involved in the best fit, for example in the typical IIS situation the aerofoil and upper and lower annulii are brought into the same best fit model. The program starts by calculating the errors between the surfaces and allowing them to be plotted as contours or sections. The best fitting program provides for weightings to be given to specified areas of the surface either explicitly or by a number of criterion, for example minimum die modification. Output from the best fitting of the surfaces is in the form of sectional or contour error display and the best fit transformation matrix.

2.3.9 Resume of The IIS System

The IIS is a relatively complex set of programs in which models of blade geometry are used to construct alignment and measurement part programs for Coordinate Measuring Machines. The results of the inspections may be fed back into the system for errors to be calculated, displayed and if necessary best fit. The various programs involved in the system may be considered as separate entities which when linked together perform the proof inspection process.

3 Executing The Programs In The IIS System

Chapter 2 of this appendix attempted to outline the rationale behind the various programs that make up the IIS system. In this section an explanation of how to execute these programs is given. The order of the explanation follows a typical analysis path for blade errors, from turning on the SUN 3/60 machine through writing blade alignment and measurement programs, running the coordinate measuring machine, analysing surface errors and finally best fitting. Blade modelling is explained in section 4 of this appendix.

3.1 Turning On The SUN 3/60 Computer And Executing The IIS Program

Description

This section describes how to get into the IIS system and explains how to select the various options from within the PANACEA environment.

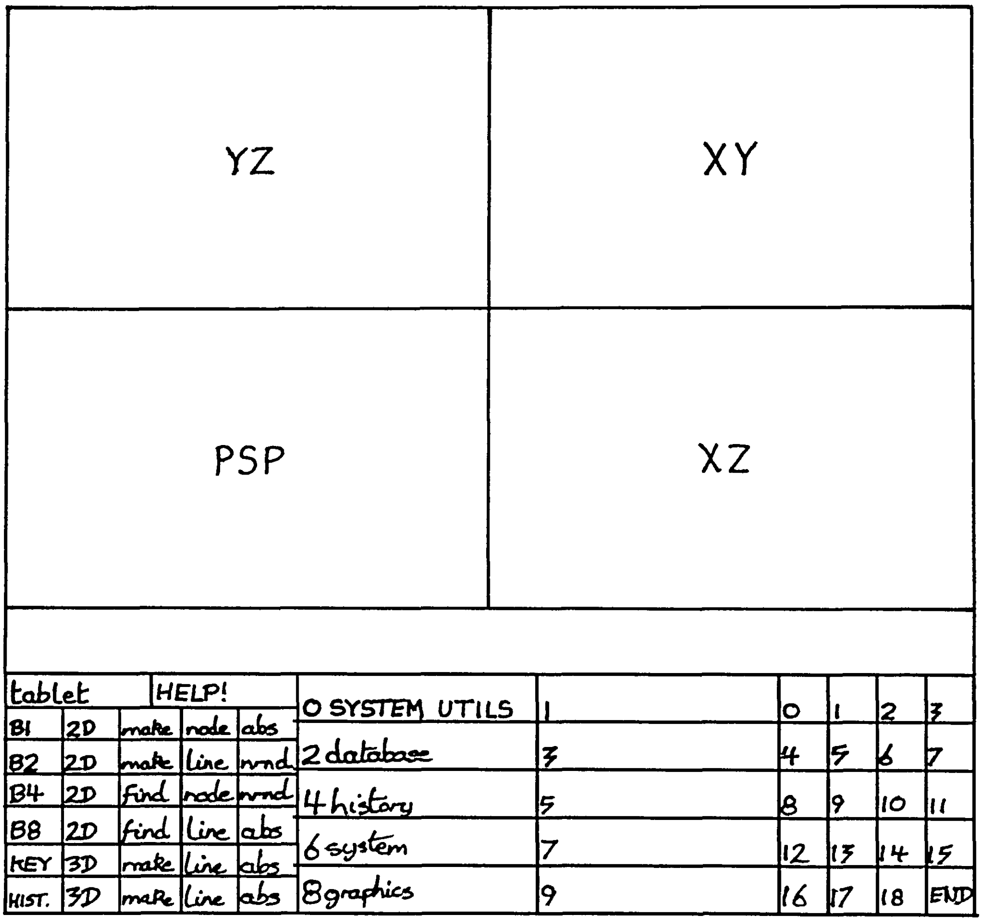
i. Turning on the SUN 3/60 Computer : usually the computer is not turned off, only the monitor. So if presented with a blank screen check to see if the monitor has been turned off (the button is on the back of the monitor). If the whole computer has been turned off then turn the Winchester disk on first, wait 20 seconds, and then the Computer. In order to run the IIS it is also necessary to turn on the WYSE terminal to the left of the SUN 3/60.

ii. Once the computer has booted up a login prompt should be seen on the screen, enter 'u4256ad' (not with the quotes), there may be a password. After logging in the prompt "1 stuart > " should appear.

iii. If the whole computer has just been switched on it is necessary to run suntools simply to define some graphics options. To do this enter 'sun' at the prompt, on entering suntools exit immediately (see the suntools manual for more information).

iv. Before executing the IIS it is necessary to move to the correct working directory, to do this enter 'cdg', the correct directory will be called and a listing of the files will appear, including "apip".

v. The IIS may now be executed, to do this enter 'apip' and after a few seconds the following should appear on the screen :-



tablet		HELP!		
B1	2D	make	node	abs
B2	2D	make	line	rnd
B4	2D	find	node	rnd
B8	2D	find	line	abs
KEY	3D	make	line	abs
HIST.	3D	make	line	abs

0 SYSTEM UTILS	1	0	1	2	3
2 database	3	4	5	6	7
4 history	5	8	9	10	11
6 system	7	12	13	14	15
8 graphics	9	16	17	18	END

The 4 large blank areas in the top $^3/_4$ of the screen are 4 viewports XY, YZ, XZ and perspective. The lower $^1/_4$ section represents the menu driver for the system. The menu area is divided into many regions. To select one of these regions and in so doing select the function represented by that region it is necessary to move the cross-hairs, using the mouse, onto the required region and press one of the keys on the mouse.

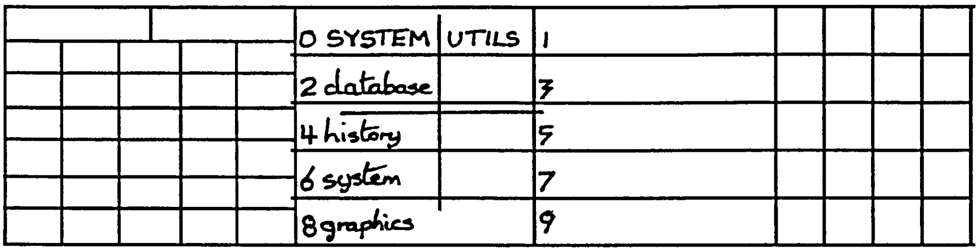
NOTE :- For the remainder of this appendix to 'select' an option from a menu will refer to the above procedure.

The IIS text output and input is handled through the WYSE terminal to the left of the SUN 3/60. No input is entered through the SUN 3/60 keyboard. On executing the IIS certain text will appear on the WYSE terminal, the last statement to appear will state that it is necessary to ALWAYS run a history file after the initial execution of the IIS program.

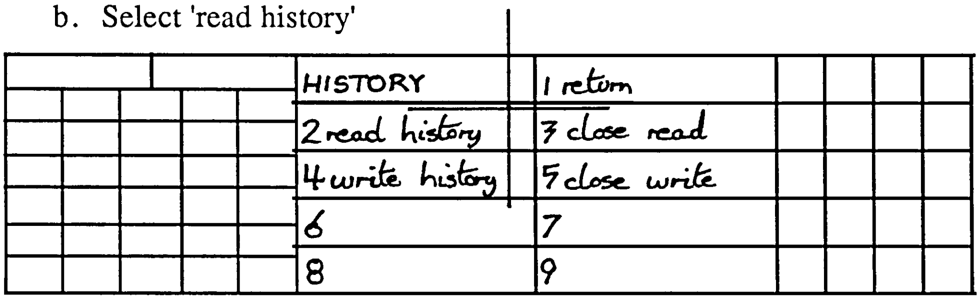
vi. Running History Files :- When the IIS system is running, it is set to have viewports with a -1mm to 1mm x, y and z window, this is obviously too small for turbine blades. The system also has only a 10K database size which is too small for blades which need about 8 Mbytes. One method of setting new window and database sizes is to go through the various required options individually. However as it is always necessary to perform this task after executing the IIS a 'history' file may be constructed which enables these set up procedures to be repeated more easily.

Selecting History File Sequence :-

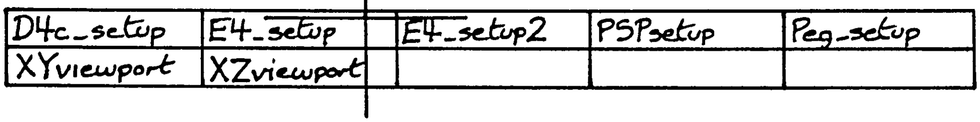
a. Select 'HISTORY'



b. Select 'read history'



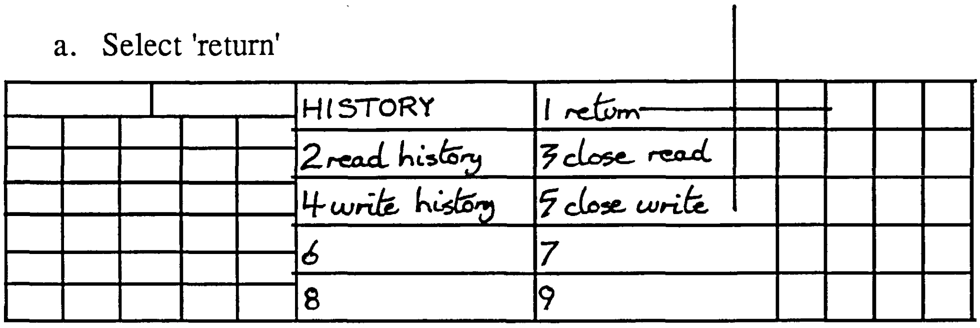
c. Select required history file from the menu that appears above the main menu



This menu shows a number of history files already written. To select one e.g. 'E4_setup' move the cross-hairs over the region of the menu displaying 'E4_setup' and press one of the mouse buttons. The screen will then change rapidly through the history file set ups. (To write a history file see section 5 Heading 1 of this appendix).

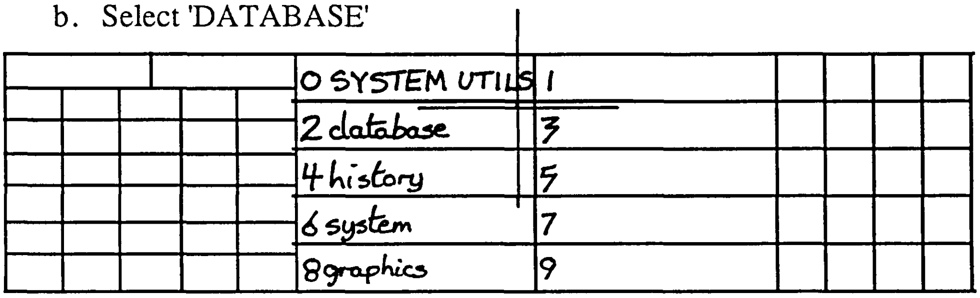
vii. Loading in Blade Databases :- In order to write any part programs, calculate errors, best fit e.t.c. it is necessary to load the required databases into the system. For example to write an aerofoil part program it is necessary to load in an aerofoil. To load in a database it is necessary to return to the system's main menu.

a. Select 'return'

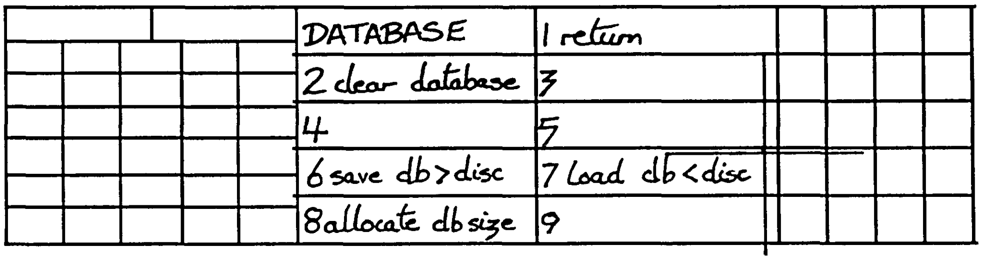


Selecting a Database :-

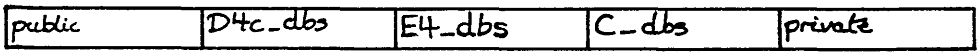
b. Select 'DATABASE'



c. Select 'load db < disc'



A menu above the main menu will appear



This is a list of database directories :-

public	contains general databases
D4c_dbs	contains D4c HP blade models
E4_dbs	contains E4 IP blade models
C_dbs	contains C HP blade models

private	contains modelled surface models

d. For the purposes of this exercise select 'E4_dbs', another menu will appear

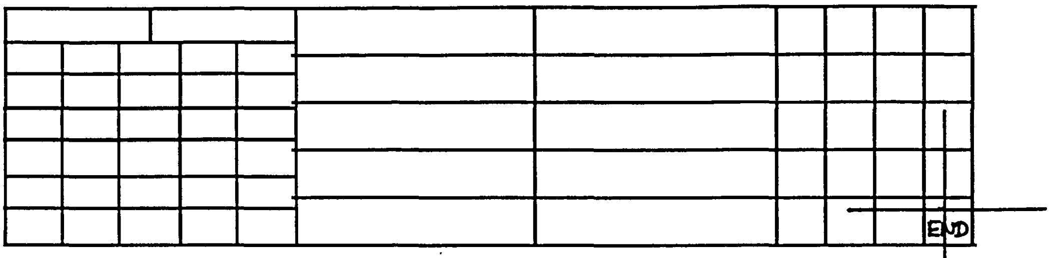
E4_aero	is the E4 IP nominal aerofoil surface
E4_l	is the E4 IP lower annulus swept surface with boundary planes and fillet intersection
E4_lann	is the E4 IP lower annulus swept surface with boundary planes
E4_lsurf	is the E4_IP lower annulus swept surface
E4_u	is the E4 IP upper annulus swept surface with boundary planes and fillet intersection
E4_uann	is the E4 IP upper annulus swept surface with boundary planes
E4_usurf	is the E4 IP upper annulus swept surface

For the purposes of this exercise select 'E4_aero'. After about 5 seconds you should see an image of the E4 IP aerofoil in the 4 viewports.

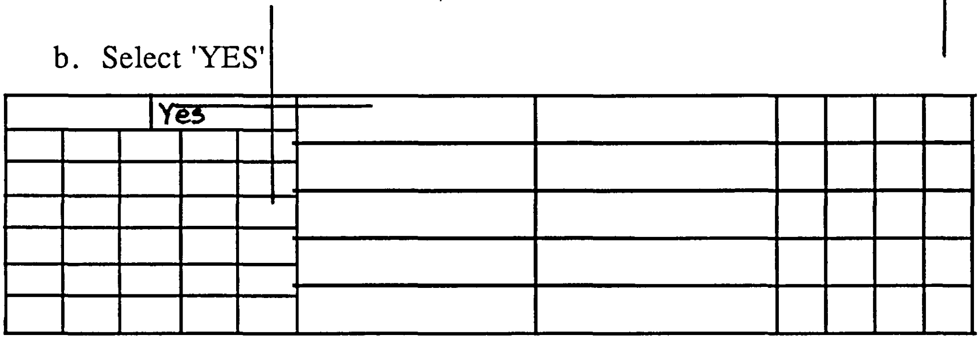
Once the required databases have been loaded into the system the various options in the IIS may be called.

viii. Quitting from the IIS :- Once all of the operations required by the IIS have taken place it is obviously necessary to quit from the IIS, the procedure is as follows :-

a. Select 'END'



b. Select 'YES'



The C Shell prompt should then appear.

Resume

This subsection attempted to inform the IIS user of how to turn on the computer and execute the IIS program. It was also explained how to set up the IIS with the necessary viewport and database sizes using 'history' files and how to load databases into the system.

3.2 Blade Pre-Alignment

This is the simplest program in the IIS. The role of pre-alignment is to establish a stacking axis for the blade when it is placed on the CMM to within 4mm positional accuracy so that the accurate ABC point alignment procedures may commence. Facilities within GEOPAK enable pre-alignment to be achieved by measuring just one point on the blade's surface. The procedure is to set the blade on the Mitutoyo machine in such a way that the blade's stacking axis is in the same orientation as the machine's coordinate system, see Figure AI.2. A single measurement on the blade will then enable a simple shift of the machine's coordinate system to establish an estimate for the blade's stacking axis.

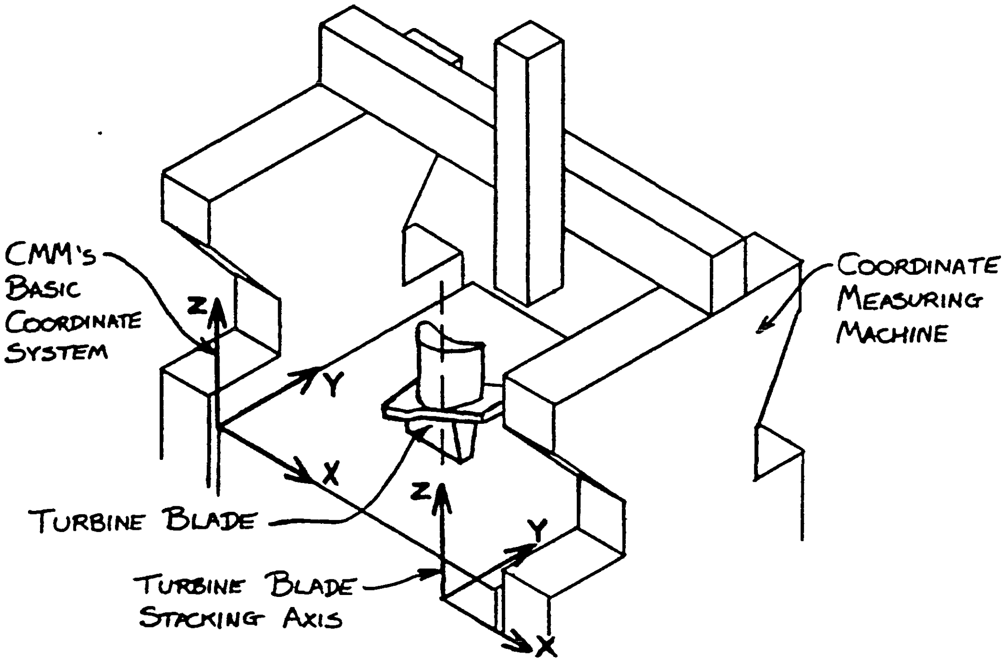


Figure AI.2

Diagram of Turbine Blade Fixtured To The Mitutoyo CMM

In order to write a pre-alignment procedure the operator must know the answer to 3 questions :-

i. Which point on the blade's surface does he wish to measure for pre-alignment.

ii. The position of this point with respect to the stacking axis.

iii. The best probe orientation with which to measure the point.

For the E4 IP blade Figure AI.3 shows the position on the blade that was chosen for the pre-alignment. From the blade drawing the relationship between this point and the stacking axis was found to be x = -9.400mm, y = -6.800mm and z = 522.000mm. To compensate for the probe ball size of 1.0mm the x value was increased by the value of the ball radius to x = -9.900mm. To decide on the best available probe orientation for the pre-alignment Figure AI.4 is consulted, the arrows point in the direction of the TP2 probe. For the E4 IP blade the orientation number 1 is satisfactory. There is now sufficient information to run the pre-alignment routine.

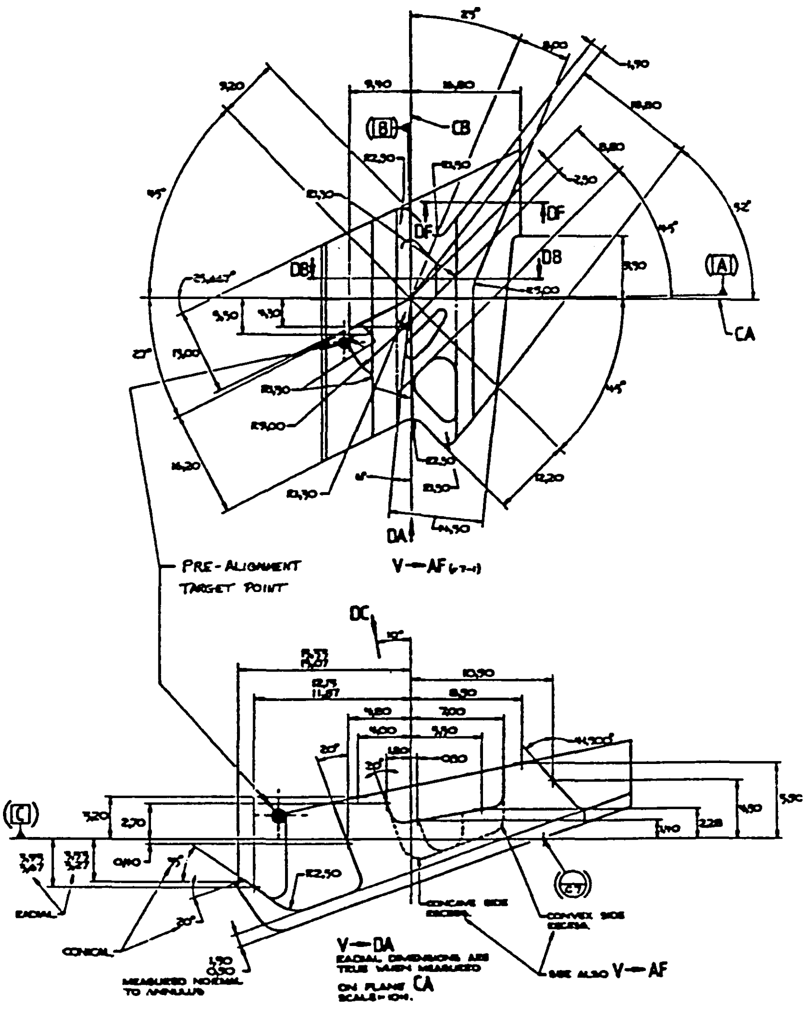
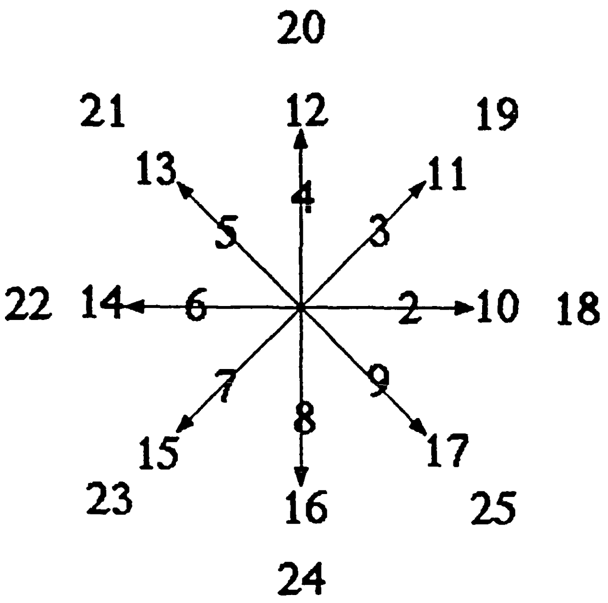
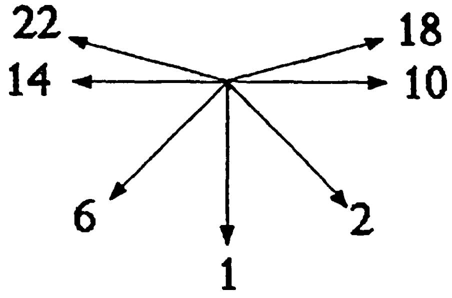


Figure AI.3

Position on E4 IP Blade Chosen for Pre-Alignment

NDF Probe Orientations





NDF CODE	A ANGLE	B ANGLE
1	0	0
2	45	90
3	45	135
4	45	180
5	45	-135
6	45	-90
7	45	-45
8	45	0
9	45	45
10	90	90
11	90	135
12	90	180
13	90	-135
14	90	-90
15	90	-45
16	90	0
17	90	45
18	105	90
19	105	135
20	105	180
21	105	-135
22	105	-90
23	105	-45
24	105	0
25	105	45

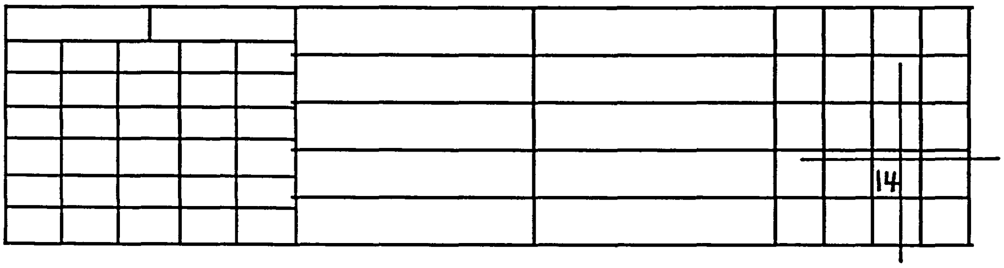
Figure AI.4

Probe Orientations used for Part Programs Written within the IIS

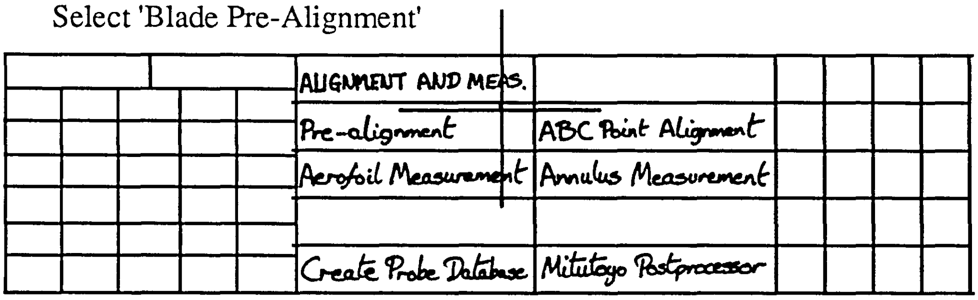
Running the Pre-Alignment Part Program Generator :-

i. Run the IIS program

ii. Select overlay menu 14 (No database required)



iii. Select 'Blade Pre-Alignment'



The procedure will request the shifts in x, y and z that the measure point represents to the stacking axis. So for the E4 IP blade enter '9.4 6.8 -522.0' (note the need to enter the negative of the values of the true position) . Remember to use to WYSE terminal keyboard for input.

The procedure will then request the probe orientation for the measurement, on simply pressing the carriage return button the system will default to using probe number 1. The operator knows what the default is as the request for information ends with "<1>". These brackets mean that the value contained within then will be taken as default. Extensive use of this defaulting capability is used throughout the system.

The procedure will continue by requesting a name for the pre-alignment program. It is a convention to postfix a pre-alignment program name with "_preal". For the E4 IP blade the program would be called "E4_IP_preal". In order to execute a pre-alignment program on the Mitutoyo CMM it is necessary to post process it, see section 3.5.

NOTE:-

All part programs written in the IIS are written in the Neutral Datafile Format Language. The programs themselves are stored in directory '/usr2/u4256ad/apip/resfiles/NDFfiles'. It is possible to read these file as they are in ascii format. An alias for a quick change to the NDF directory is "cdN", however this may only be perform when running a normal C Shell environment.

3.3 Blade ABC Point Alignment

The purpose of ABC point alignment is to construct a stacking axis around a blade when it is positioned on the CMM so that measurement of the surfaces may take place. It is necessary to run a pre-alignment program before an ABC point alignment program. In order to write an ABC point alignment program it is necessary to have an upper annulus model of the blade in the IIS system, for the E4 IP blade this is the 'E4_u' database. It is also necessary to have the blade drawings specifying the gauge angles and lengths of the A, B and C points around the blade. For more details see ref [5].

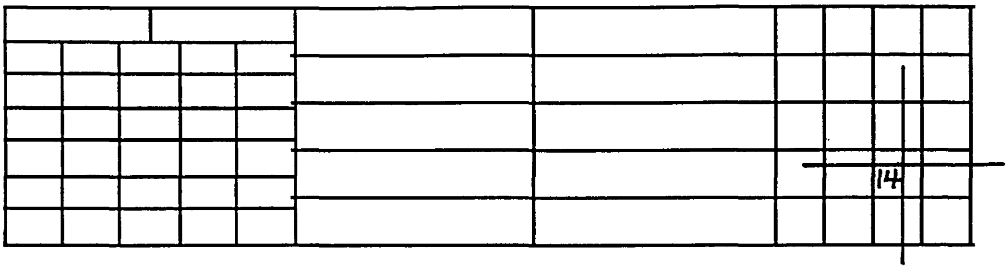
Running the ABC Point Alignment Part Program Generator :-

i. Run the IIS program.

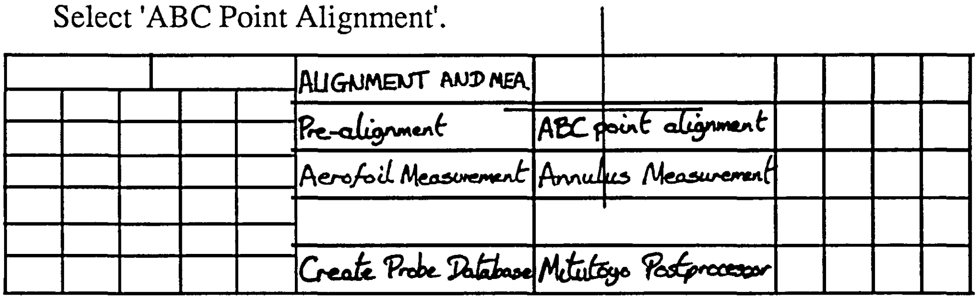
ii. Select a history file 'E4_setup'.

iii. Load in an upper annulus database 'E4_u'.

iv. Select overlay menu 14.



v. Select 'ABC Point Alignment'.



iv. Input the height of the Upper Gauging Section, for the E4 IP blade '501'.

(The default values in the system are for the E4 IP Blade (FRE102453)).

v. Input the height of the Lower Gauging Section, for the E4 IP blade '411'.

vi. From the appearing menu select the aerofoil 'macroblock' i.e. 'E4_aero'.

NOTE : The word 'macroblock' is a type of PANACEA database which is used to hold a group of entities.

Once selected xy-planes at the gauging heights are intersected with the aerofoil to produce splines around the gauging sections. When the intersections are complete the program will ask the operator to enter a carriage return if the intersections appear satisfactory, otherwise to enter 'no' and the program will allow respecification of the gauging heights.

vii. The next task is to input the A, B and C point gauge angle and lengths, see Figure AI.5. The values defaulting in the system are again for the E4 IP blade. It is important to observe the use of negatives. Once entered the gauge angle and lengths will be printed out. If they appear satisfactory enter carriage return otherwise enter 'no' and respecify the values.

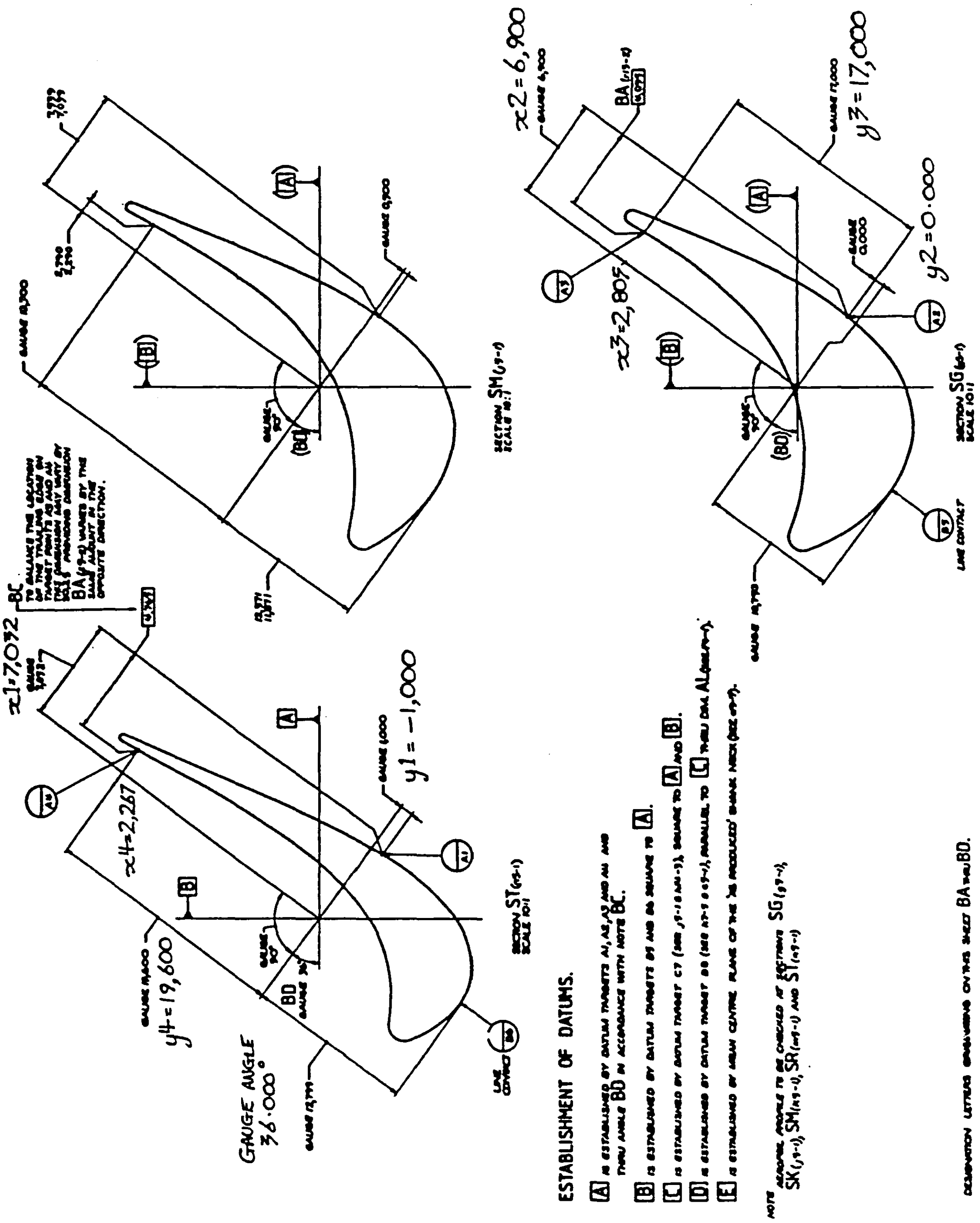


Figure AI.5

A and B Point Definition on a High Pressure Turbine Blade

viii. The calculation of A and B point positions and surface normals will then take place. For the C point the operator is asked if he wishes the C point to be calculated by intersection or for the values to be entered manually. This is useful if no annulus macroblock actually exists. If the C point intersection is to take place the operator will be asked to select the upper annulus macroblock 'E4_u'. After the intersection the operator will be asked to specify the probe ball radius, usually 0.5mm.

ix. The operator will then be asked to specify if the lower alignment points should be measured using probe orientations of 45^o below the horizontal. This is usually performed if the fixture that is to hold the blade on the CMM comes farely close to the lower annulus surface, e.g. the wax holding fixture. If this is not the case the routine is quicker without the use of this option.

Using the blade database and entering values for the questions the operator has now produced sufficient information for the target measurement points and their surface normals to be passed to the probe path generator. For collision avoidance purposes 'Home' positions around the blade have to be specified, see ref [4]. For the E4 IP blade the system defaults to satisfactory values.

Once the home positions have been specified the probe path will appear as blue lines around the blade, representing the path of the centre of the probing ball.

x. The part program may now be compiled into NDF. The operator should enter a name for the file. The convention for ABC point blade alignment part programs is to end the name with '_valn'. For the E4 IP blade the file would be 'E4_IP_valn'.

xi. The operator will be asked to specify the number of loops the alignment process should follow, 4 is the usual number.

xii. Finally the operator will be asked to specify the traversing speed of the CMM, 70mm/s is usual, and the measuring speed, 4.0mm/s for metal and 2.0 mm/s for wax.

Resume of ABC Point Alignment

By following the above instructions a part program for aligning a turbine blade on a Mitutoyo CMM will have been constructed in NDF format. Using information from blade drawings and a PANACEA blade database the positions of the A, B and C points have been found along with their surface normals. These values have been used to construct a probe path which has been combined with alignment instruction code in a part program generator to produce an NDF ABC point alignment part program.

3.4 Measuring Turbine Blade Gas Washed Surfaces

Surface measurement philosophy is not as difficult to understand as blade alignment, however there are a few concepts which must be understood for both aerofoil and annulus measurement. For aerofoil measurement the over riding aspect concerns the integrity of modelling inspected data into measured aerofoil surfaces. To obtain integrity a methodology has been adopted which measures aerofoil surfaces along XY sections at the positions of the control points which define the nominal surface. There are usually somewhere between 100 and 200 control points around a PANACEA aerofoil, which gives the option of measuring this many points per section. However trials have shown that as few as 40 points are sufficient to define the error around an aerofoil section. It follows that if an aerofoil were to have a 200 control point surface that a 1:5, measure point : control point, ratio could be used to specify the number of points to be measured and it is in fact this ratio which is used when specifying the probe path.

Annulus measurement is along specified XZ planes. The annulus surface models are intersected by these XZ planes to provide open b-splines along the annulus surface.

These splines are then intersected with the annulus edge boundaries to provide limits to the splines along which a probe path is constructed.

See refs. [4] and [5] for more information on surface measurement philosophy.

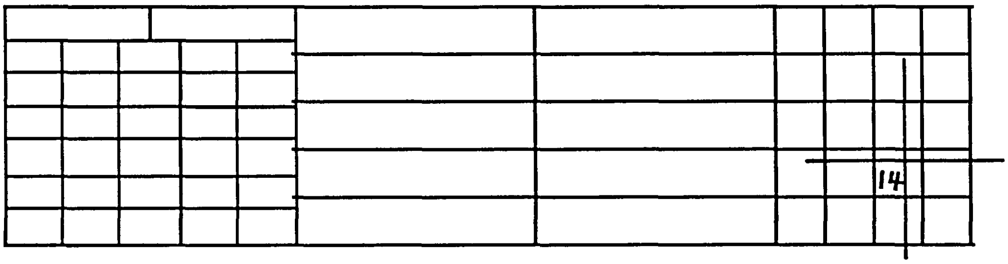
Running The Aerofoil Measurement Part Program Generator

i. Run the IIS program.

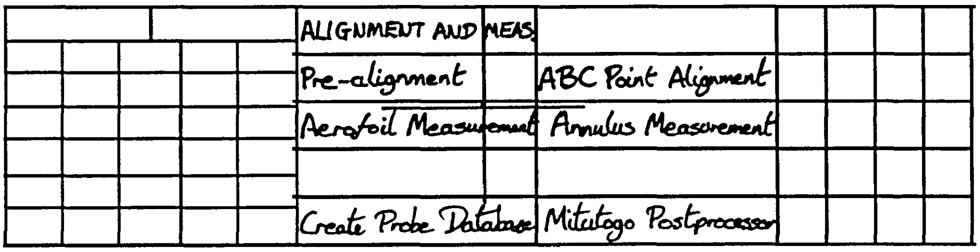
ii. Select a history file 'E4_setup'.

iii. Load in an aerofoil macroblock 'E4_aero'.

iv. Select overlay menu 14.



v. Select 'aerofoil measurement'.



vi. If there is only one aerofoil macroblock in the system the aerofoil measurement program will use that one, otherwise it will ask the operator to identify which macroblock is to be used for part program generation.

vii. The system will state that it is loading probe data (dimensional information) from the standard source. As the system existed at 31 March 1989 this information does not really concern the operator.

viii. The operator will then be asked to specify the height above engine centre line of a section at which he wishes to measure the aerofoil. (For the E4 IP blade the aerofoil exists between 420 and 500mm, enter 430mm for an example).

ix. The operator will be asked to specify the name of a 'manipulation' file. This is the name of the file for which modelling information is to be stored for conversion of inspected data. The naming convention is :-

'(blade_name)_(control point : measure point ratio)aero(number of measured sections)'

For example 'E4_IP_5aero2' would represent the E4 IP aerofoil measurement with a 5 : 1 control point to measure point ratio on 2 sections.

x. The operator will be asked to specify the probing ball radius, 0.5mm is the most common. Followed by the control point : measure point ratio i.e. 5 in the above case.

xi. The operator will be asked to specify the 'Home' positions around the blade, as in section 3.3 above. (For the E4 IP Blade the system defaults to satisfactory values).

xii. The operator will be asked to specify the vertical probe orientations for the measurement.. They may be specified as $+15^{o}$, 0^{o} or -45^{o}. Which orientation to use depends on how close to the blade annulus surfaces the measurement section is. In general it is good practise to use $+15^{o}$ when near the upper surface and -45^{o} when near the lower surface.

After the above specification the probe path will appear as a blue line on the screen representing the path of the centre of the probing ball, see Figure AI.6.

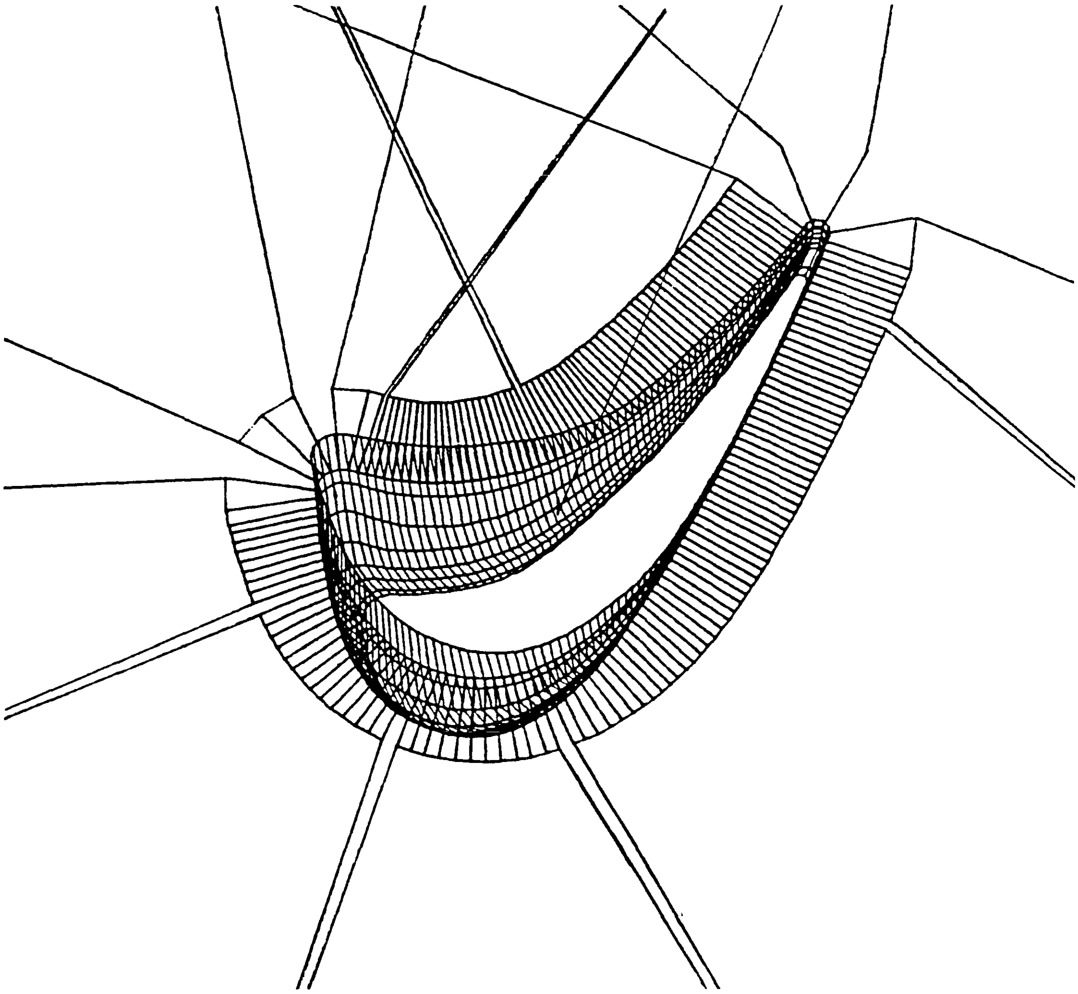


Figure AI.6

A Typical Aerofoil Probe Path

xiii. The operator will be asked to specify the height of another measuring section. ALWAYS specify measuring heights sequentially up the aerofoil. For each new height the probe orientation will be requested. Continue to specify heights until the part program has been satisfactorily built up, entering 'no' to the question "Another Section <yes> ? ... ", in order to finish the part program generation.

xiv. The part program may now be compiled into NDF format, to do so specify the name of the part program. The naming convention is the same as for the manipulation file.

xv. As with the alignment routine the CMM traversing and measuring speeds will need to be specified.

An aerofoil measurement program has now been written. It will require post processing before it may be used.

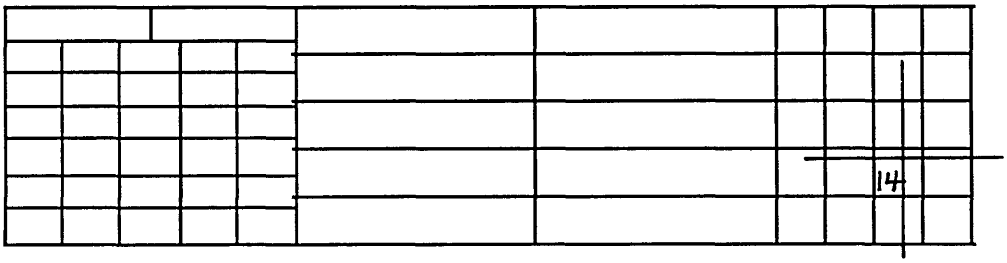
Running The Annulus Measurement Part Program Generator

i. Run the IIS program.

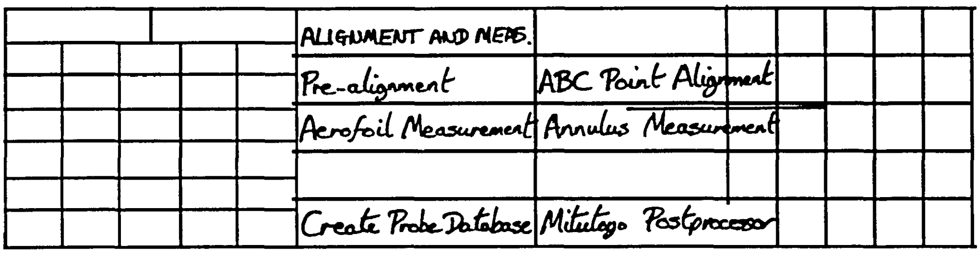
ii. Select a history file, 'E4_setup'.

iii. Load in an annulus macroblock, ('E4_1' as an example).

iv. Select overlay menu 14.



v. Select 'Annulus Measurement'.



vi. Select the Annulus macroblock to be used for the measurement, ('E4_1').

vii. Annulus measurements are specified along xz planes which are defined by entering y values. (In the case of the E4 IP Blade enter -10.0mm as the first plane value). On entering this value a small triangle shape will appear in the specified xz plane. The system will continue to ask for y values of zx planes until 'no' is entered at the question "Another Section <yes> ? ... ". (For the E4 IP blade enter 0.0mm and 10.0mm as other y values).

The specified cutting planes will be intersected with the annulus surface. These calculations do take time, but eventually blue lines should appear along the annulus surface in the specified xz planes. When these surface intersections have taken place, the resultant splines are intersected with annulus boundary splines to provide realistic limits along the surface for the probe to measure the blade surface.

viii. The operator will then be asked to specify whether the macroblock is a lower or an upper annulus surface.

ix . Each pass over the surface will contain at least 7 measurements, but the operator will be asked to specify the number of probing measurements to be made per cm length, 5 is the most commonly used value.

x. The operator will be asked to specify the 'In From Edge Length', (1.0mm is typical). This length is used to prevent the probe from measuring the very edge of the annulus surface, and in doing so incur some peculiar results.

xi. The operator will be asked to specify the manipulation file name, i.e. the modelling information file name for inspected data, the convention for annulus surfaces is :-

'(blade_name)_(No. of XZ Planes)(l/u)ann'

For a 3 section E4 IP Lower annulus measurement the file name would be 'E4_IP_3lann'.

xii. The 'Home' positions will need to be specified as with the aerofoil measurement. The system defaults to values for the E4 IP blade.

The probe path will then appear. Collision detection is very difficult for annulus measurement.

xiii. The part program may now be compiled into NDF. To do so enter the name of the part program. The naming convention is the same as for manipulation files. ('E4_IP_3lann' would be used with the current example).

xiv. As with the aerofoil routine the CMM traversing and measuring speeds will need to be specified.

An annulus measurement program has now been written. It will require post processing before it may be used.

Resume of Gas Washed Surface Measurement

PANACEA surface models have been used to generate part programs for the measurement of Gas Washed Surfaces. By specifying cutting planes, surface points and their associated surface normals have been extracted for the model. This information has been passed to probe path generators to construct the measurement part programs. Data has also been constructed to enable the later modelling of inspected data into measured blade surfaces.

3.5 NDF Part Program Post Processing For the Mitutoyo CMM

The purpose of post processing is to convert the NDF part programs into the Mitutoyo CNC program format so that they may be used by the inspection machine. The Mitutoyo controller is capable of running an Ethernet link to the workstation so the post processed database may be stored in the SUN 3/60. Mitutoyo part program databases are stored in the '/usr2/u4256ad/pp' directory as '.PP' files. The file which the Mitutoyo controller observes for the part programs is '/usr2/u4256ad/pp/partprg'. This enables the system operator to have many different databases and run the one he wishes to use by copying the required '.PP' file to the 'partprg' name. To create a new '.PP' file move into directory '/usr2/u4256ad/pp/backup'. There is an empty 'partprg' file in this directory. To create a new part program file copy this empty file up one directory and give it a new meaningful name with a '.PP' postfix i.e.

```
'cd /usr2/u4256ad/pp/backup'

'cp partprg ../newname.PP'
```

For more information see the READ_ME file in '/usr2/u4256ad/pp'. Once the desired '.PP' file has been created the postprocessor may be run.

Running the Mitutoyo Post Processor

i. The post processor may be run from overlay 14 in the IIS, but it is more usual to run it as a separate program in directory '/usr2/u4256ad/apip/generator'. To do so move to directory '/usr2/u4256ad/apip/generator' and enter 'postp'.

ii. A list of all of the NDF part program files will appear. Enter the prefix of the file which you wish to post process. (For example for file E4_preal.NDF enter 'E4_preal').

iii. The post processed file may be called another name than its NDF original. When asked for the post processed name enter '1' for the same name or enter a new name. It is not usual to give the post processed file a different name to the NDF file name.

iv. The operator will be asked to specify the probe number conversion file. This file contains information for relating the probe orientations in the part programs to the probe orientations calibrated in the Mitutoyo machine. The usual file for this is 'probe4.dat'. These files exist in directory '/usr2/u4256ad/apip/generator/postpmaps'. They simply relate the NDF probe orientations defined in Figure AI.4 to the ones calibrated in the Mitutoyo at the time of inspection. The CMM calibrations may be listed from the controller and checked against 'probe4.dat' if different a new '.dat' file should be written.

v. Depending on which type of file is being post processed the operator may be asked if he wishes to send 'Stand-Off' positions across. Answer 'yes' for alignment programs and 'no' for measurement programs. Part programs are smaller without stand-off positions, but it is not totally safe to run alignment part programs without them.

vi. The operator will be asked to specify the '.PP' file that the post processed program is to be inserted into. After the list of '.PP' files appears enter the prefix only. During insertion a number of figures will appear on the screen and are used for checking the procedure, the operator should not concern himself with these numbers.

vii. Finally the operator will be asked if the '.PP' file that has been inserted with the part program should be copied to 'partprg' ready to be used by the Mitutoyo.

Resume of Post Processing

The post processing facility enables NDF part programs to be converted into a Mitutoyo CNC program format and be loaded ready for use. The next section explains how to run part programs and log inspected data into the workstation.

3.6 Running Part Programs On The Mitutoyo CMM and Logging Data Back To The Workstation

Once the required part programs have been assembled in a part program '.PP' file and that file has been copied to the name 'partprg' the programs are ready to be run on the Mitutoyo. Before running these programs the Mitutoyo must be set up for Ethernet use and for logging data back to the workstation.

Mitutoyo and Workstation Set Ups

i. The Mitutoyo machine should be turned on (ask for Inspectors Help).

ii. The HP Vectra should be in the program menu mode and not GEOPAK.

iii. The HP Vectra Printer should be turned off.

iv. The Tastronics Box should be set, by the micro-switches, for logging data. (See the diagrams underneath the box).

v. The 'ttya' cable in the back of the WYSE terminal, to the left of the workstation, should be removed and inserted in the back of the Tastronics box.

vi. The Tastronics box should be switched on.

vii. The 'log' program in directory '/usr2/u4256ad/apip/generator' should be executed. Do not stop this program until the measurement is finished.

viii. From the main menu on the HP Vectra select the 'TCA Setup ' option. This file will set up some default files for GEOPAK to use the Ethernet.

ix. Reboot the HP Vectra.

x. From the main menu on the HP Vectra select the 'TCA GEOPAK' option. During the program set up make sure that the printer is on-line, if it is not make sure that the Tastronics box is on and has the correct settings for logging data, then restart the GEOPAK set up menu to make sure that the printer is on-line.

xi. Continue into GEOPAK, once through the date and time questions enter '3' to load probe data from disc at the probe data question. The GEOPAK control environment will then be accessed. Enter 'DM' (Directory Mode) and a listing of the part program files should appear on the screen.

xii. Fixture the blade to the bed of the CMM. It is extremely important that the blade is orientated on the table with an alignment to the XYZ axes of the CMM. See section 3.2 of this appendix for more details.

xiii. To run a part program press the 'F6' key on the HP Vectra and with the arrow keys move the marker up and down the listing until it resides on the desired file, where upon the 'Carriage Return' should be pressed and the program will start to run.

xiv. Running Pre-Alignment Part Programs :-

In this type of program the operator will be asked to measure the point on the blade's surface identified for pre-alignment. Ask a proof inspector how to drive the CMM for measurement if unsure of the procedures.

xv. Running ABC Point Alignment Part Programs :-

These are fully automatic routines which will take about 14 minutes to run. Usually the manual positioning of blades on the CMM is not very good and the first run of the alignment sequence results in a miss of the A3 and A4 points on the trailing edge. It will be necessary to watch for this and offer an artificial object to the ruby ball if it travels past the trailing edge.

xvi. Running a Measurement Part Program :-

These are again fully automatic routines. It is usual to occasionally watch the lights on the Tastronics box after a measurement to check that information is indeed being sent to the workstation.

xvii. Measuring More Than One Blade :-

As the blade alignment programs take a long time to run it is advisable to measure all the required surfaces on each blade before moving on to the next one. C. Booth designed a fixture to speed up multiple blade measurement, basically it enables each blade to be placed in roughly the same place on the CMM as the previous blade, thus removing the need to pre-align each subsequent blade. With respect to the modelling of surfaces do not worry about the order in which surfaces are measured as this is accounted for.

Shutting Down The GEOPAK and Data Logging Programs

Once all the blades have been measured it is necessary to shut down GEOPAK and the data logging program and set the HP Vectra for normal use.

i. Kill the 'log' program on the workstation by pressing the 'control' and 'c' keys at the same time.

ii. Turn off the Tastronics box and return the cable to the WYSE terminal.

iii. In the GEOPAK program exit the part program area by pressing the 'F8' button and exit GEOPAK by entering 'EX'.

iv. On the HP Vectra menu select 'RR setup' and reboot the computer.

v. Turn the HP Printer on.

vi. Remove all of your equipment from the Mitutoyo and return control to the inspectors.

Resume of Using The Mitutoyo Coordinate Measuring Machine

The above sequences enable post processed part programs to be run on the Mitutoyo CMM and for the inspected data to be logged into the workstation. The Mitutoyo software is not very user-friendly and if any problems are incurred the Proof Inspectors are the best people to consult.

3.7 The Modelling Of Inspected Data

The basic concept of modelling inspected data is to convert the measured results from the CMM into surfaces. To assist in the modelling task certain information was produced at the time of probe path generation and stored to file. The name of this file forms part of the part program which is instructed to print the name at the end of the measurement. When the modelling process takes place the program is able to interrogate the inspected data for the file name and open it automatically.

For all surface types the modelling file contains probe radius compensation, which is not provided for by the CMM. For the modelling of aerofoils the file also contains extra points around aerofoil sections to provide a sufficient point stream distribution for a b-spline to be passed through the section while maintaining model integrity. For more detailed information see the IIS Programmer's guide.

When modelling more than one surface the program will also produce an average surface and write standard deviation data to file. When modelling in this batch mode the surfaces will be named sequentially i.e. E4_aero0, E4_aero1, E4_aero2 e.t.c. while the average surface will be named E4_aero_av. Average surfaces may be treated in the same way as any other surface within the PANACEA system.

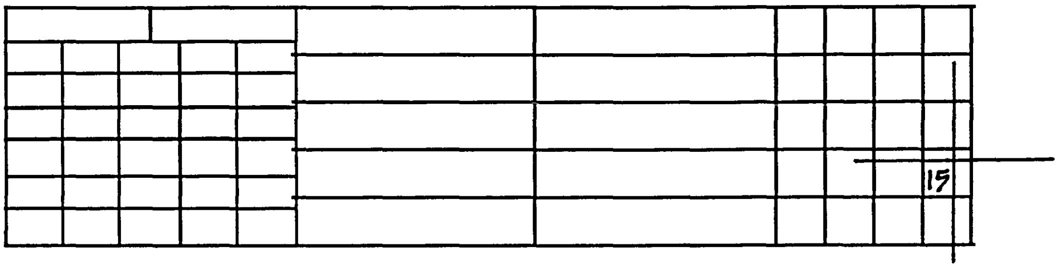
Inspected data is logged to a file called '/usr2/u4256ad/apip/resfiles/REMfiles/insp.dat'. Every time more data is logged the old insp.dat is lost, therefore if the operator wishes to save inspected data he should move or copy the current insp.dat file to a new file name.

Running the Modelling Procedure

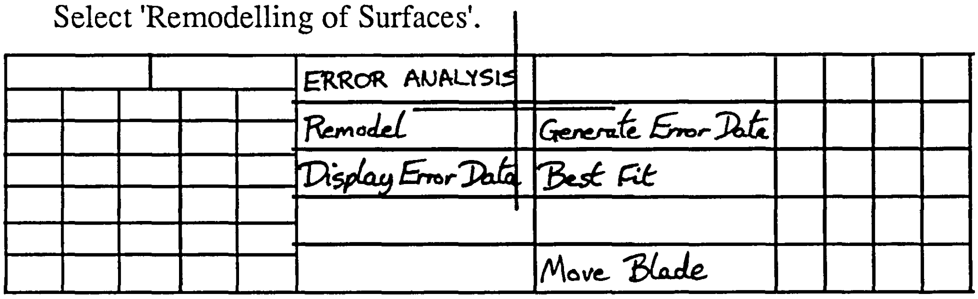
i. Run the IIS program.

ii. Select a history file, 'E4_setup'.

iii. Select overlay menu 15.



iv. Select 'Remodelling of Surfaces'.



v. A listing of the current files in the inspected results directory will appear. Input the file name of the file which contains information requiring modelling. Usually this will be the 'insp.dat' file which is set up as the system default.

vi. Input a batch name for the modelled surfaces. This name should be less than 4 letters in length, the name will be postfixed by the program with the surface type and number in the measurement batch. i.e. if a batch name of 'E4' was entered to an aerofoil model this would produce databases of the name 'E4_aero0', 'E4_aero1', 'E4_aero2' e.t.c.

vii. Select the material option metal or wax, this is purely a colouring convention for modelling the surfaces.

The modelling of all of the surfaces should then take place, each surface will appear on the screen before being saved and then cleared ready for the next surface.

Note on the storing of Standard Deviation data :-

For aerofoil surfaces every control point in the modelled database is used to produce standard deviation data. The data is stored in a separate file for each section in the '/usr2/u4256ad/apip/resfiles/STDfiles' directory. Each file is appended with the height of the section that it relates to. So if an E4 aerofoil had been measured at section heights 411, 456 and 501mm there would be 3 files of standard deviation E4_aero411, E4_aero456 and E4_aero501.

For annulus surfaces the standard deviation of each measured point is recorded to file in the directory '/usr2/u4256ad/apip/resfiles/STDfiles'. Each section of measurement has a separate standard deviation file which are numbered sequentially. For example in the case of an E4 lower annulus measurement of 5 measured sections there would be 5 files of standard deviation :- 'E4_lann0', 'E4_lann1', 'E4_lann2', 'E4_lann3' and 'E4_lann4'.

Resume of Modelling Inspected Surfaces

The above section has illustrated how inspected data logged from the Mitutoyo CMM can be converted into measured surface models within PANACEA. In the case of more than one surface measurement an average surface model will be produced along with standard deviation data which is written to files under a described format.

3.8 Calculation Of Surface Errors

The difference or error between two surfaces is volumetric in nature, however in the case of b-spline surfaces the calculation of such a volume would be a practically impossible task. To overcome this problem it has been postulated that a sufficient density of vectors joining between the two surfaces would enable an adequate representation of the error. It is on this vector basis that the error between measured and nominal surfaces within IIS are determined.

For the two types of blade surface measured, aerofoils and annulii, there exists two different methods of determining surface error, each one chosen because of the nature of the surface involved. For annulii surfaces a routine has been constructed which determines the shortest distance from a measured point to the nominal surface. For the aerofoil surfaces a different philosophy has been adopted because of the very high curvature of the surface in the region of the trailing edges. If the shortest distance criterion is used for aerofoils the errors tend to be incorrect as Figure AI.7 illustrates, therefore another criterion was found which calculates errors on the basis of determining the most positive intersection with the measured surface of a line emerging surface normal from the nominal surface. This later criterion produced a better error result as Figure AI.8 illustrates. For more details see the IIS Programmer's Guide.

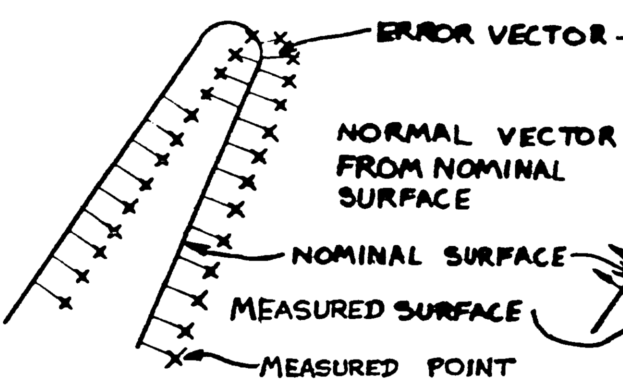


Figure AI.7

A Shortest Distance Criterion Yields Poor Error Results Around Trailing Edge Regions

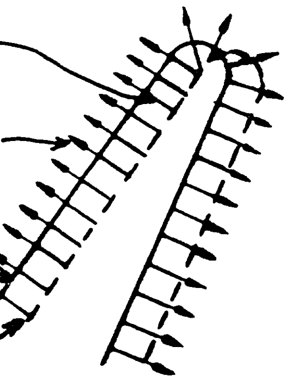


Figure AI.8

A Most Positive Intersection of a Line Criterion Yields Good Results Around Trailing Edge Regions

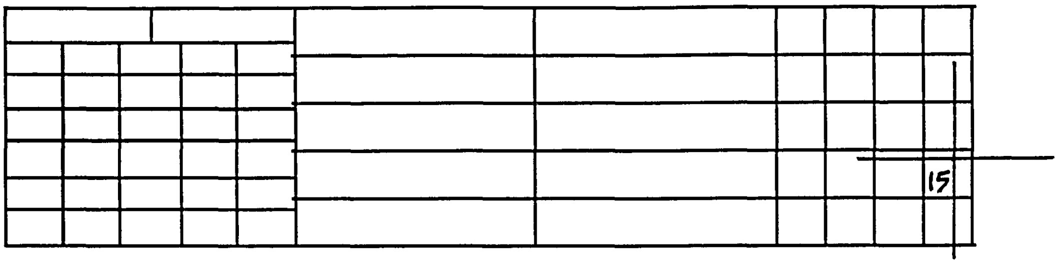
Running An Aerofoil Surface Error Calculation

i. Run the IIS program.

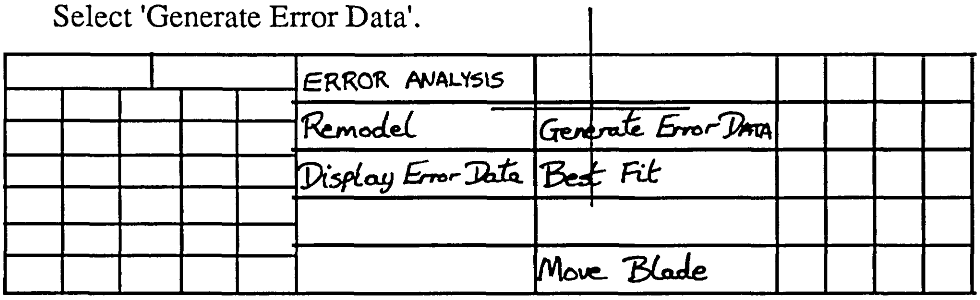
ii. Select a history file, for example 'E4_setup'.

iii. load in a nominal aerofoil macroblock, for example 'E4_aero', and load in an measured aerofoil macroblock, for example 'E4_5aero4', from the 'private' database.

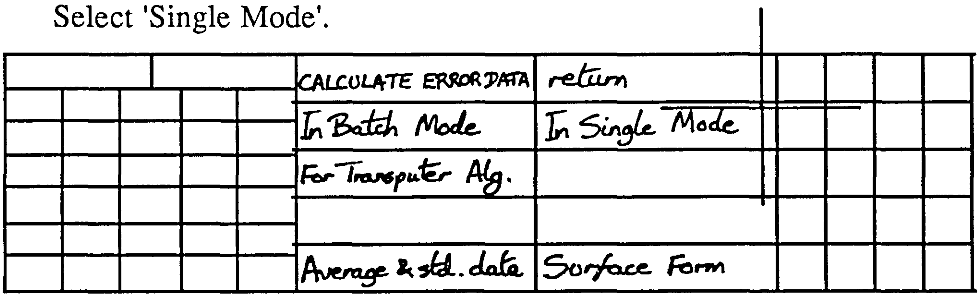
iv. Select overlay menu 15.



v. Select 'Generate Error Data'.



vi. Select 'Single Mode'.



vii. Select the nominal surface macroblock, in the example 'E4_aero'.

viii. Select the measured surface macroblock, in the example 'E4_5aero4'.

ix. Input the sectional height, above engine centre line, for the calculation of errors. ALWAYS specify sectional heights sequentially from the lower to the higher values, for the E4 IP example enter the value 430.

These sectional heights are used to cut the nominal aerofoil to generate sets of surface normal vectors.

x. Input the ratio of required error vectors to control points around a section. This ratio should be the same as the ratio used to measure the aerofoil, which in the case of the example 'E4_5aero4' is 5.

xi. If errors on more than one section are to be calculated enter carriage return to the question 'Another Section <yes>... ?', else enter 'no'.

xii. Continue to enter heights at which errors are to be calculated until all the heights have been specified, for the E4 example enter values 450, 480 and 500.

After all of the required heights have been entered the program will output the number of intersections that have been specified and the predicted the time for completion.

xiii. After completing the error intersections the program will ask for a name to which the error information should be written, in the case of the example enter 'E4_test'.

Running An Annulus Surface Error Calculation

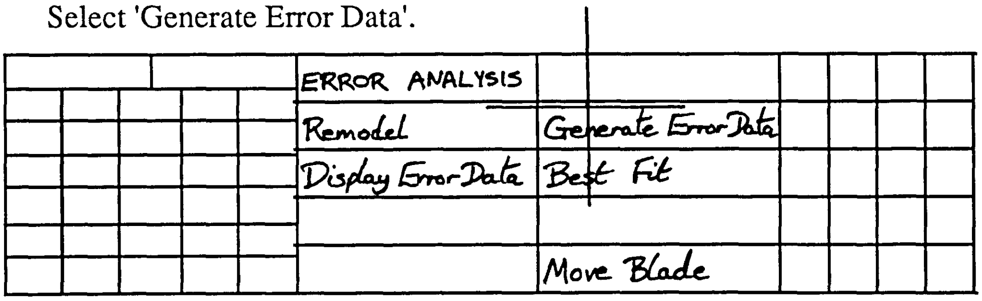
i. Run the IIS program.

ii. Select a history file, for example 'E4_setup'.

iii. Load in a nominal annulus macroblock, for example 'E4_1surf', and an measured annulus macroblock, for example 'E4_1ann0.

iv. Select Overlay menu 15.

v. Select 'Generate Error Data'.



vi. Select 'Single Mode'.

vii. Select the nominal surface macroblock, in the example 'E4_lsurf'.

viii. Select the measured surface macroblock, in the example 'E4_lann0'.

ix. Select 'upper' or 'lower' surface, in the example the annulii are lower surfaces.

The program will then output the number of intersections specified and the time for completion.

x. As with the aerofoil error calculation after the completion of the intersection the program will ask for the name of a file to which the error information should be written, in the case of the example enter 'E4_latest'.

Extra Error Calculation Facilities

After selecting 'Generate Error Data' in overlay menu 15, a number of options appear :-

					CALCULATE ERRORDATA	return				
					In Batch Mode	In Single Mode				
					For Transputer Alg.					
					Average & Std. Data	Surface Form				

Previously the single mode facility has been explained, the other facilities will now be explained:-

Batch Mode

This facility provides the operator with the ability to calculate errors on the surfaces of a batch of measured blade surfaces. In order to do this DO NOT load any databases into the system before entering this routine, the routine itself will load in the specified nominal database and the first measured database (the first measured database in a batch of aerofoils named 'E4_aero0', 'E4_aero1', 'E4_aero2' e.t.c. would be 'E4_aero0'). For aerofoil errors the routine will require sectional heights at which to calculate the errors and the required error : control point ratio. A separate error file for each surface will be produced and so the program requires a batch name for the error files it will produce. If two or more surfaces are being used by the routine an average and standard deviation error file will be produced, this may be used in the display facilities just as any other error file.

Transputer Data

This option enables loaded nominal and measured surfaces to be prepared for the stand-alone best fitting program which is to be implemented on a transputer based processor. On 31 March 1989 this program only worked for aerofoils and it had not been implemented on a transputer system.

Average and Standard Deviation Data

This facility enables the operator to find average and standard deviation data from individually specified measured surface databases. The operator may choose to calculate this from either measured PANACEA surface databases or from error files. During the program the operator will be asked to interactively specify the databases from which the average and standard deviation are determined.

Surface Form

This facility enables the operator to quantify the 'quality' of a surface by a formula used to represent its smoothness or 'form', see section 7.6 of this thesis. The operator is asked to identify the error file from which the form is to be calculated. A further error file is then written containing the numerical values of the form around the surface.

Resume of Surface Error Calculation

This section has explained how to generate surface errors between nominal and measured gas washed surfaces. The errors are stored in ascii format in a file located in the directory '/usr2/u4256ad/apip/resfiles/ERRfiles'. It has been explained that errors may be found from batches of measured surfaces yielding average errors with standard deviation.

3.9 Displaying Of Error Data

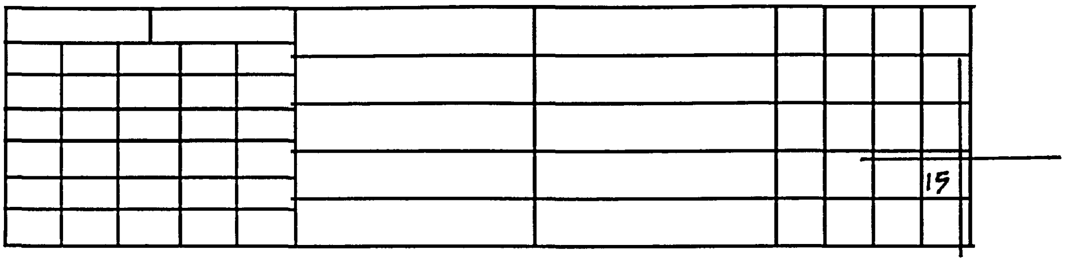
The purpose of the programs in the Error Display suite is to present surface errors in a graphical manner. Two main programs enable the errors to be plotted either around individual sections or as contours over the measured surface. With individual sections the errors are plotted against nominal with a surface error magnification. This magnification is required because the errors are so small in relation to the size of the blade that they are not usefully presented unless magnified. Surface tolerance information may be added to the plot as may process spread calculated from the results of batch measurement. Individual sections of error are presented in XY planes but may be displayed with the nominal surface straightened out into a line while the error is plotted in the XZ plane. For contour plots an entire error file is read into the program and the error is presented as contours over a surface straightened out into an XZ plane. Again tolerance and process spread information may be included in the plot. A further facility in the display suite enables additional screen information to be plotted e.g. stacking axes and scales.

Running The Sectional Error Plotting Routines

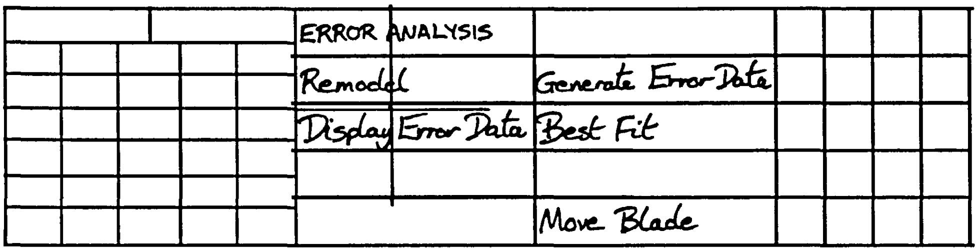
i. Run the IIS program.

ii. Select a history file, for example 'E4_setup'.

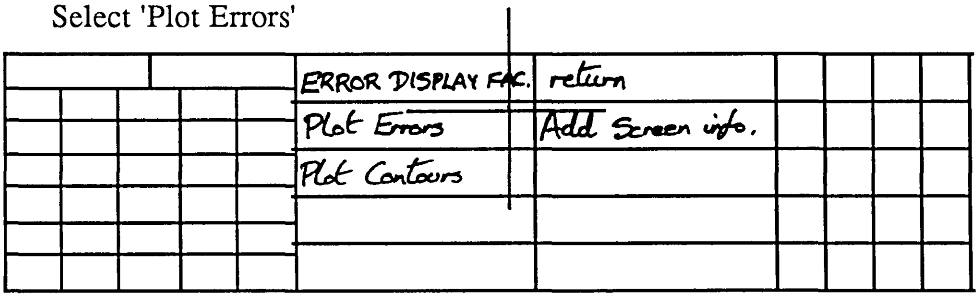
iii. Select overlay menu 15.



iv. Select 'Display Error Data'.



v. Select 'Plot Errors'



vi. Select from either an 'aerofoil' or 'annulus' plot

vii. A listing of all of the error files available will appear on the screen, enter the prefix of the file required to be displayed.

viii. Enter the section number that is required to be displayed. The first section is 0, if all the sections are to be plotted simply enter carriage return.

ix. A listing of the tolerance files will be presented. If tolerances are required to be added to the display enter the prefix of the required file (for the E4 IP aerofoil the tolerance file is E4_aero). If no tolerances are required simply enter carriage return.

x. A listing of the standard deviation files from batch measurements will be presented. There are then three choices of action :-

a. Enter carriage return for no standard deviation to be added to the display.

b. Enter the prefix of the file associated with the particular section.

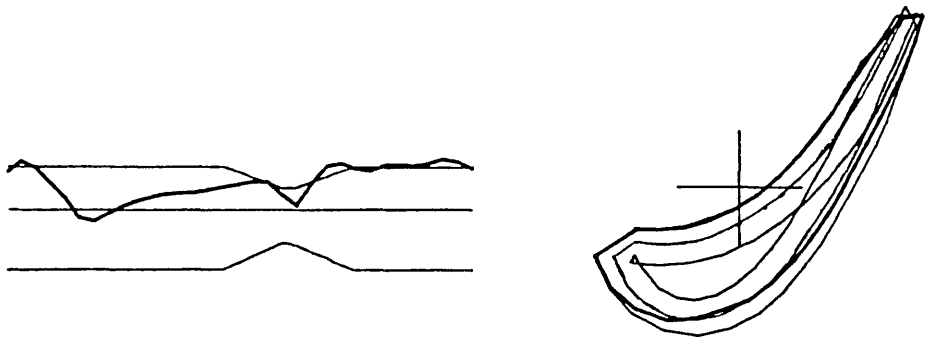
c. Enter '1', in this case it will then be necessary to enter the prefix of the standard deviation file, however the height of the section should not be included as this will automatically be appended. What is more all subsequent sections will have the name of their standard deviation file automatically generated and included for display.

xi. Select from the choice of 'Annulus', 'Aerofoil' and 'Raw ' Display :-

'Annulus' will plot annulus sections of error with a straightened nominal surface and the error displayed in the XZ plane.

'Aerofoil' will plot aerofoil sections of error with a straightened nominal surface and the error displayed in an XZ plane.

'Raw' will plot annulus and aerofoil sections with the nominal surface unchanged, annulus errors appear in the XZ plane and aerofoil errors appear in the XY plane.



(a) (b)

Figure AI.9

Error Display Types: (a) 'Annulus' or 'Aerofoil' Type of Display, and (b) 'Raw' Type of Display

xii. Select from 'upper', 'lower' for annulii or 'closed' for aerofoils.

xiii. Select for 'Spline numbering' 'Yes' or 'No'. Spline numbering will display the values of the 'u' parameter along the nominal sections (as displayed above). This facility is useful for cross-referencing sections plots with contour plots.

xiv. Input the start x, y and z values. These values enable the sectional plots to be shifted from the default location (x = 0, y = 0, z = section height). This facilitates the operator to display sections of error side by side rather than all on top of one another.

xv. Input the Surface Error Magnification. For aerofoils displayed in the 'raw' state the usual value is 10. For straightened aerofoils and annulii the value is 30.

The first section should then appear on the screen. If only one section was requested to be displayed the program will stop otherwise it will request the following information for each new section:-

xvi. Enter the prefix of the tolerance file for each new section, since this is usually the same as the file for the first section the prefix appears as the default entry.

xvii. Enter the prefix of the standard deviation data file, this will only be requested if the previous section used standard deviation data and the automatic specification was not set.

xviii. Input the start x, y and z values.

The next section should then appear. Inputs for xvi. xvii. and xviii. will be repeated until all of the specified sections have been displayed.

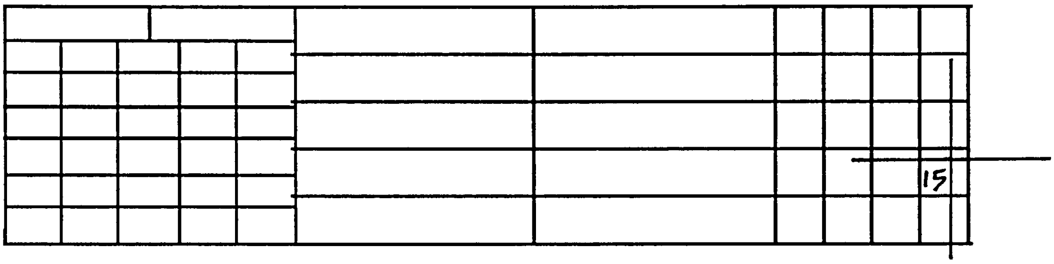
The rather large number of inputs required for sectional error displaying have been found to be necessary from experience. Unfortunately this makes the routine difficult to learn but once mastered it is a very powerful error display tool.

Running The Contour Plotting Routines

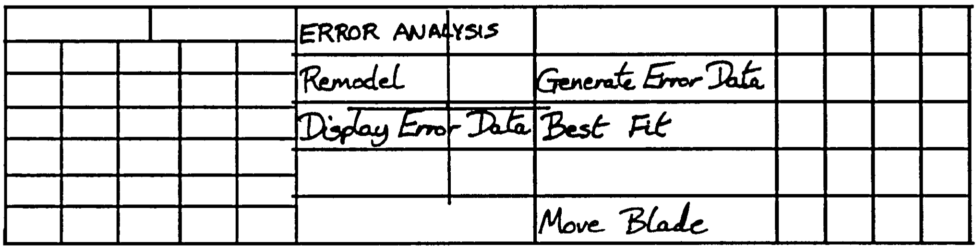
i. Run the IIS program.

ii. Select a history file, for example 'E4_setup'.

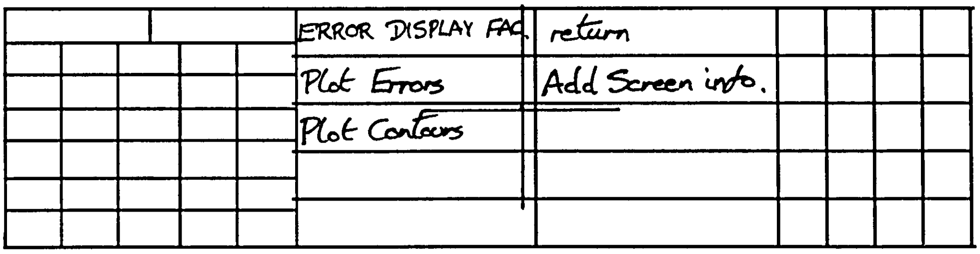
iii. Select overlay menu 15.



iv. Select 'Display Error Data'.



v. Select 'Contour Error'.



vi. Select 'Aerofoil' or 'Annulus' Contour.

vii. A listing of error files available for plotting will appear. Enter the prefix of the required file.

viii. A listing of the tolerance files will be presented. If tolerance is required enter the file name prefix, if no tolerance is to be included enter a carriage return.

ix. A listing of the standard deviation files from batch measurements will be presented. There are then three choices of action :-

  a. Enter carriage return for no standard deviation to be added to the display.

  b. Enter the prefix of the file associated with the particular section.

  c. Enter '1', in this case it will then be necessary to enter the prefix of the standard deviation file, however the height of the section should not be included as this will automatically be appended. What is more all subsequent sections will have the name of their standard deviation file automatically generated and included for display.

x. Stages viii. and ix. will be repeated until all of the required tolerances and standard deviation data for the whole surface has been loaded into the program.

xi. Input the 'Expansion Factor'. This is the relationship between the length of the contoured surface and the number of measured points around each section. If 40 points per section had been measured an Expansion Factor of 2 would produce an 80mm long contoured surface.

xii. Input the start x, y and z values. These enable the contoured surface to be shifted from its default position (x = 0, y = 0, z = height of section).

xiii. Input the Surface Magnification. This enables the contours to be displayed at their height above the surface with a magnification factor. 50 is a typical value.

xiv. Input the maximum height of error to be displayed. The default value represents the highest point on the surface.

xv. Input the contour step height, 0.025mm is the usual value.

The contoured surface should then appear.

As with the sectional error the contour plotting routine takes some time to master, but contours have proved to be an extremely powerful method of displaying surface errors.

Running The Extra Screen Display Facilities

In the Display Error Data menu is an 'Extra Screen Display' option. On selection the operator may choose from two options 'Stacking Axis' or 'Scale'. The Stacking Axis enables the operator to define a cross of specified length at a specified position. The scale option enables the operator to position a scale of specified length at a specified position. The scale may be positioned graphically by use of the mouse or by keyboard input.

Resume of Error Display Facilities

The error display facilities enable error files of information to be displayed in two different ways, sectionally or as contours. Many of the display parameters are variable enabling a large range of illustrations to be prepared. The error display programs have been used extensively and found to be very powerful in dealing with blade surface errors.

3.10 Best Fitting Of Surfaces

The purpose of the best fitting program is to mathematically minimise the difference, i.e. the error, between two surfaces. In the case of the IIS this process involves finding the error vectors between nominal and measured surfaces and passing these errors to a best fitting routine which produces a transformation matrix which when applied to the measured surface acts to minimise the error.

In the program the operator is asked to specify error calculations in exactly the same way as for normal error generation. A menu for displaying the error as contours or sections and for windowing etc enables the operator to view the surface errors before specifying the best fit options in terms of degrees of freedom and weightings. When complete the operator may plot the minimised errors with the same graphical menu as before the best fit. Output from the best fit procedure comes as an error file and a transformation matrix which may be stored to file.

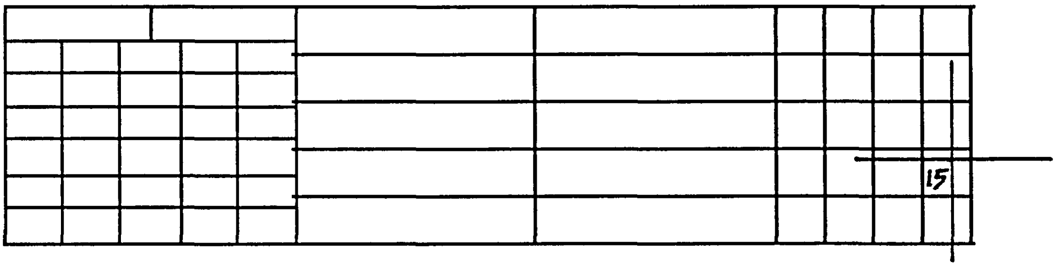
Running The Best Fitting Routine

i. Run the IIS program.

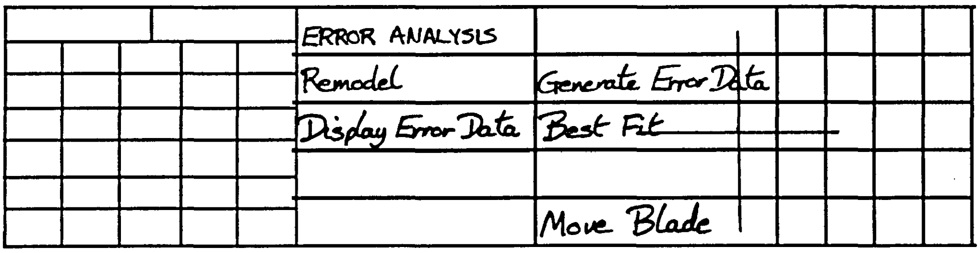
ii. Select a history file, for example 'E4_setup'.

iii. Load into the system all of the nominal and measured surface databases that are required to be best fitted, both aerofoil and annulus surfaces may be fitted in the same program. For example load 'E4_aero' and 'E4_lsurf' as nominal surfaces and 'E4_5aero5' and 'E4_lann5' as measured surfaces.

iv. Select overlay menu 15.



v. Select 'Best Fit'.



vi. Select pairs of nominal and measured macroblocks to be best fitted together. The convention for pairing surfaces is to select the nominal and measured aerofoils first, then the nominal and measured lower annulii and finally the nominal and measured upper annulii. In the example 'E4_aero' and 'E4_5aero5' would be declared first and then 'E4_lsurf' and 'E4_lann5'.

vii. If an aerofoil surface is involved in the best fit, which in the case of the example there is, the heights of the sections at which errors are to be calculated for the best fit will have to be specified.

viii. If any annulii surfaces are to be best fit it will be necessary to specify which are lower and which are upper.

ix. For each surface it will be necessary to define the ratio of control points to best fit points. For an aerofoil this will be the control point to measure point ratio, which in the case of the example is 5. For annulii the ratio is usually taken as 1.

x. The best fitting routine is iterative and a facility exists, although is rarely used, to stop the routine in between each iteration, if the operator wishes to stop the routine in this manner he should enter 'no' to the continuous best fitting question otherwise enter carriage return.

The surface error calculations will then take place after which the operator will be asked to specify any tolerance and standard deviation data to be attached to the errors. This should be performed in exactly the same way as for the displaying of errors routine in the above section.

xi. A menu of error display options will then appear :-

					BEST FITTING DIS.	return to best fitting				
					change model limits					
					plot sections	contour sections				
					windows	viewports				

This menu enables the operator to display the surface errors by the options explained below. The operator may not use any other PANACEA options than are displayed in this menu.

a. 'model limits' : enables the viewport limits to be redefined. Select this option and the old model limits will be displayed, enter the new required values and the viewports will be changed.

b. 'plot section' : enables the surface errors to be plotted along sections in exactly the same manner as for the sectional plotting in the 'displaying of errors' section above. If more than one surface is being best fitted the operator will be asked to select which surface is to be displayed.

c. 'contour section' : enables the surface errors to be displayed as contours in exactly the same manner as for contour plotting in the 'displaying of errors' section above. If more than one surface is being best fitted the operator will be asked to select which surface is to be displayed.

d. 'viewport' : enables the operator to define a new or redefine an existing viewport, for more details see section 5 heading 5 of this appendix.

e. 'return to best fitting' : returns the program to the best fitting routine.

The operator may stay in this graphical display menu for as long as is required, he may plot as many sections and contours in as many viewports as he wishes. When the operator is happy that he understands the errors on the surface he should select 'return to best fitting' to continue with the routine.

xii. On returning to best fitting the operator will be asked to specify the degrees of freedom he wishes to apply to the best fit of each surface. For aerofoil surfaces the best fitting is usually set to ALL Rotation and XY Translation, while for annulus surfaces the best fitting is usually set to No Rotation and Z Translation.

xiii. Further to degrees of freedom 'weightings' may be specified to each error as a number from 0 to 1. For each surface the weight type is selected. A brief explanation of the weight types is given below :-

a. 'whole surface weighting' : Every error is given a weighting of 1.

b. 'regional weighting' : Weightings may be specified to each error.

c. 'SS' or 'PS Fitting' : Weightings may set so that the Suction Surface have weightings of 1 and the Pressure Surface of 0 or visa versa.

d. 'Tolerance Fitting' : Weightings are set as a function of whether the errors are in or out of tolerance.

e. 'Process Capability Fitting' : Weightings are set as a function of whether errors are in or out of Process Capability. Process Capability is the region that is specified between the tolerance bands minus process spread. It may be said that if an average error exists within the Process Capability region that despite the spread of errors incurred during production the blade will still be within design tolerance.

Once the weightings have been specified over the surfaces the best fitting procedure will start. It is a very slow iterative routine in which the errors are calculated and passed to the best fitting mathematics which produces a transformation matrix. The transformation is then applied to the measured surfaces and the errors are recalculated. The process repeats until the routine converges to solution.

By observing the best fit results after each interation the operator may observe the rotation and translation produced. The Mean Surface Error value may actually increase before reducing, 70 iterations are not uncommon for large surfaces. It is possible that a unique solution to a best fit does not exist and instability will result in the solution. In these cases the program should be restarted and fewer degrees of freedom given to the surfaces.

xiv. After convergence of solution the screen will be redrawn with the new measured surface positions. The operator may then display the best fit errors with the same display menu as before the best fit calculations.

xv. On selecting 'return to best fit' the operator will be asked to enter a name of the file for the best fit output. Results will be sent to error files and to .TRANS files in directory '/usr2/u4256ad/apip/resfiles/BFRfiles'.

xvi. Finally the operator will be asked if he wishes to exit the best fit program or repeat the best fit with different parameters. If the best fit is to continue the operator will be taken back to procedure xii., otherwise the procedure will be terminated.

Resume of Best Fitting

The above procedure enables the best fitting of Gas Washed Surfaces For Turbine Blades. Various weightings and degrees of freedom may be defined in the best fit and full use of graphical displaying of surface errors is made before and after the best fit for visualisation of the results. The results of a best fit are in the form of an error file and a transformation matrix.

4 PANACEA Turbine Blade Gas Washed Surface Modelling

This section is designed to give the reader an insight into how nominal gas washed surfaces of turbine blades are modelled and handled within the PANACEA system. The explanation starts with an overview of the aerofoil and annulus surface types and proceeds by detailing how to model these surfaces in the PANACEA Blade Modeller.

4.1 Modelling A Surface In PANACEA

The PANACEA database is designed around entity types which may be used to build up other entity types. For example a line entity would be defined by a set of node entities and a surface entity by a set of line entities. A set of surface entities may be combined to form a nominal blade surface such as an aerofoil or an annulus. A full aerofoil or annulus may be referred to by one entity known as a 'macroblock'. Macroblocks may be given names which enables a PANACEA operator to distinguish between them when running the system.

The modelling of aerofoil surfaces within the PANACEA system is handled through an automated process using IGES files of Turbine Blade Files. The aerofoil is modelled as plain sections straight ruled together, the sections are defined by b-splines which are in turn defined by point streams. The modelling of annulus surfaces is handled through an interactive routine which was written by N. Brookes. An annulus surface is made up of lines and arcs swept about engine centre line. The surface is bounded by lines and the intersection of the aerofoil fillet radius. An annulus macroblock is made up of a macroblock of swept surfaces and the bounding lines plus the fillet radius intersection. The bounding lines are determined by intersecting the swept annulus surfaces with planes, the intersections come in the form of open b-splines. The fillet intersection is created by intersection of a 'fat' aerofoil surface with the swept annulus surfaces, the intersection comes in the form of a closed b-spline. A 'fat' aerofoil is generated by defining an aerofoil surface which is at a fillet radius from the nominal aerofoil surface.

4.2 Modelling An Aerofoil Macroblock

i. Ask 'Blade Computation' to place the nominal aerofoil sections used to manufacture the blade's wax die onto the Blade File.

ii. Run the mainframe program JD03 on the blade file to produce an IGES file of the blade file and tar this file onto a mag. tape.

iii. 'tar' the IGES file onto the SUN 3/60 into the directory '/usr2/u4256ad/apip/generator/store/conversion/arrivals.

iv. Copy the file up one directory and rename it 'filename.blade', where filename is the specific name defining the blade.

v. Run the 'bfcon' program in the conversion directory.

If this program fails then there is a real problem. However assuming that the program works it will produce a large number of files. The ones that are required are 'filename.0', 'filename.1', 'filename.2', e.t.c., 'filename.set'.

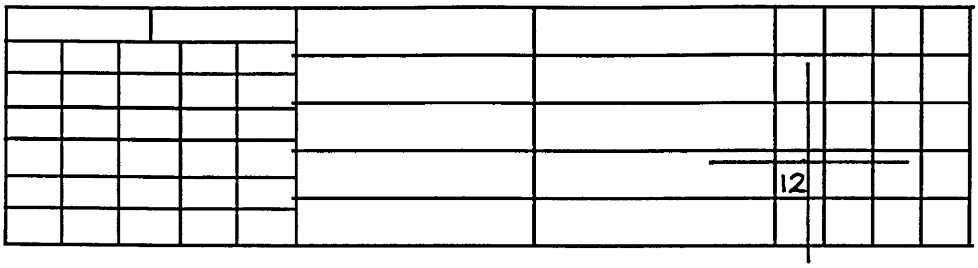
vi. Create a new directory 'filename' in the directory '/usr2/u4256ad/apip/generator/store'.

vii. Copy 'filename.0', 'filename.1', 'filename.2', e.t.c. 'filename.set' to the new directory '/usr2/u4256ad/apip/generator/store/filename'.

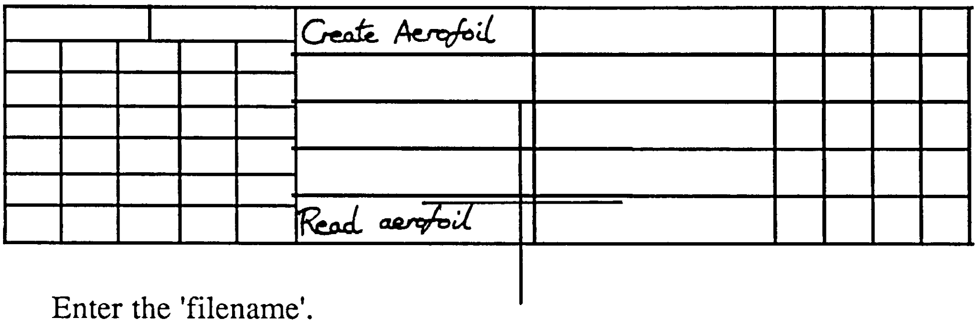
viii. Run the IIS program.

ix. Select a history file.

x. Select overlay menu 12.



xi. Select 'read aerofoil'



xii. Enter the 'filename'.

After a few seconds the aerofoil should appear on the screen.

xiii. The program will ask if the blade should be called by a certain name, do not call it this but by another name post fixed with '_aero'. For example 'D4c_aero', 'E4_aero'.

xiv. Select overlay menu 0.

xv. Select 'database'.

xvi. Select 'save db < disk'.

xvii. Save the blade in the 'public' directory, under the same name as the macroblock.

The preceding routines have illustrated the method by which a Turbine Blade File is converted into an aerofoil surface in the PANACEA database.

4.3 Modelling An Annulus Macroblock

Modelling of annulus macroblocks is performed by the 'blade' program in directory

'/usr2/fesystem/blade_mod'. Before explaining how to run this interactive program it is important to understand the basic philosophy behind the program.

4.3.1 Annulus Modelling Philosophy

i. Using blade drawings extract the definition of the lines and arcs that make up the annulus and with the 'blade' program create a macroblock of swept surfaces.

ii. Save the swept surfaces as a database with the naming convention '(bladename)_(l/u)surf', for example 'E4_lsurf'.

iii. Intersect the swept surfaces with boundary planes defined from the blade drawings, to create boundary lines.

iv. Save the swept surfaces and boundary lines as a database with the naming convention '(bladename)_(l/u)ann', for example 'E4_uann'.

v. Load the blade nominal aerofoil into the system, create a 'fat' aerofoil and intersect it with the swept surfaces to create the fillet intersection line.

vi. Create a macroblock containing the swept surface macroblock, the boundary lines and the fillet intersection line.

4.3.2 Running The Annulus Modelling Program

i. From the 'FRE' blade drawings extract the x, y and z positions of the beginnings and ends of the arcs that make up the swept surfaces. Each surface is to be defined in a separate file. For an example of a swept arc surface file see the file '/usr2/fesystem/blade_mod/D4c/fil0', for an example of a swept line surface file see the file '/usr2/fesystem/blade_mod/D4c/fil1'.

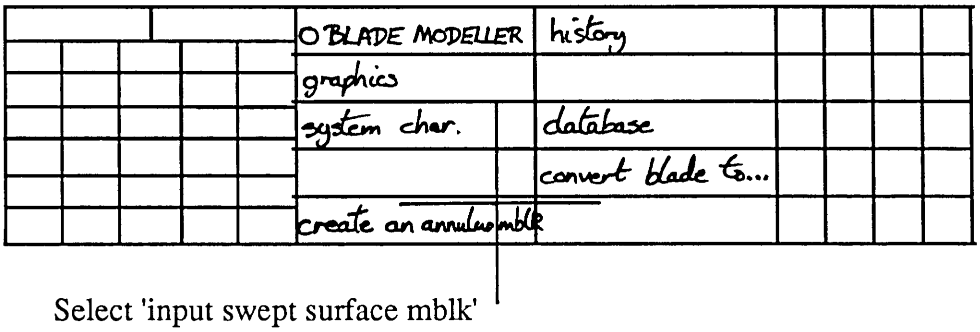
ii. From the 'FRE' blade drawings extract the boundary limits of the swept surface, i.e. the corners of the shroud or platform, these should be found as x, y and z positions. The z positions should then all be set to the same value usually 20mm above or below the swept surface. This is so that the planes that will be generated by these values and displayed as small triangles are out of the way of the useful part of the blade model, thus making the image clearer. The lower and upper boundary limits are stored in the files 'lanbnd' and 'uanbnd' respectively. Examples of these files are in the directory '/usr2/fesystem/blade_mod/D4c'.

It is good practise to store all of the surface and boundary files in their own directory in the '/usr2/fesystem/blade_mod' area and to copy them up to directory '/usr2/fesystem/blade_mod' when required.

iii. Run the 'blade' program in the '/usr2/fesystem/blade_mod' directory, from a C Shell owned by 'panacea'.

iv. Select a history file and return to the main menu.

v. Select 'create an annulus macroblock'.



vi. Select 'input swept surface mblk'

vii. Select 'input a surf'.

viii. Select 'by file'.

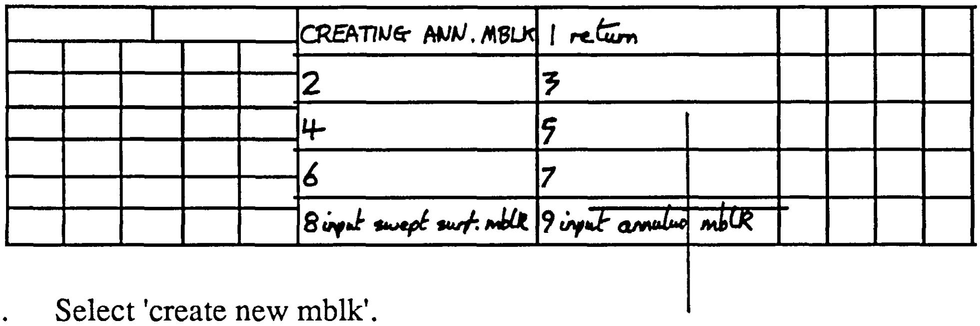
ix. Enter the name of the first file defining a surface, the surface then should appear on the screen.

x. Continue to enter the names of the files defining the annulus surface, when complete select 'make a mblk' rather than 'input a surf' and give the macroblock a name. The convention for naming is '(bladename)_(l/u)surf', for example 'E4_lsurf'.

xi. Save the database to a file, with the same name as above.

xii. Select 'create an annulus macroblock', from the main menu.

xiii. Select 'input annulus mblk'.



xiv. Select 'create new mblk'.

xv. Select 'input plane'.

xvi. Select 'by file'.

xvii. Select 'z-axis', when specifying which axis the slicing vectors are parallel to.

The intersection of the planes defining the boundary of the annulus surface will then take place (these calculations take some time to perform) when complete the database should be saved. The naming convention is '(bladename)_(l/u)ann', for example 'E4_uann'.

xviii. Using the 'database' option in the main menu the nominal aerofoil database should be loaded into the system.

xix. Select 'create an annulus macroblock', from the main menu.

xx. Select 'input annulus mblk'.

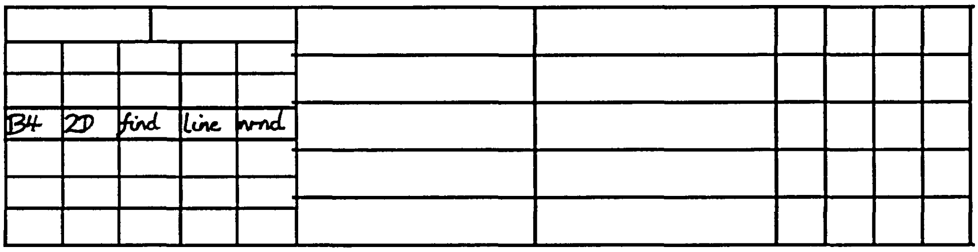
xxi. Select 'create new mblk'.

xxii. Select 'find aero int'.

xxiii. Select 'account for fillet rad'.

xxiv. Select 'ltype' and then 'b-spline'.

xxv. Select the mouse button options for the left button to be set to 'find', 'line', 'nrnd'.



xxvi. Using the mouse move the cross-hair onto the aerofoil section just below the annulus surface and press the left mouse button, then select 'return' on the menu.

xxvii. Using the mouse move the cross-hair onto the aerofoil section just above the annulus surface and press the left mouse button, then select 'return' on the menu.

xxviii. Enter the fillet radius, the value has to be common all of the way around the aerofoil.

The intersection of the 'fat' aerofoil with the annulus surface should then take place yielding a closed b-spline around the intersection.

xxix. Save the database to a name like 'junk', then clear the database from the system and load 'junk' back in again. All of the lines will appear more clearly for the next operation.

xxx. Select 'create an annulus macroblock', from the main menu.

xxxi. Select 'input annulus mblk'.

xxxii. Select 'create new mblk'.

xxxiii. Select 'make mblk'.

xxxiv. Using the left button on the mouse pick up all of the splines that define the boundary of the annulus surface, after selecting each line remember to select 'return' and the target line should go blue, if it does not select 'reput in last spline', otherwise select 'put in another spline.

xxxv. When all of the lines defining the boundary, including the fillet rad, have been picked up select 'make mblk'. Then select the swept surface macroblock, for the example 'E4_lsurf'. After this enter a name for the annulus macroblock. The convention for naming is '(bladename)_(l/u)', for example 'E4_l'.

xxxvi. Save the database to the public directory by the same name as above.

As the annulus modelling program is not in a complete state the user will find it unfriendly and it will probably not work properly. It will invariably require values to be tweaked to obtain successful intersections. It should be noted that the boundary line definitions do not need to be precise to enable the IIS programs to work.

5 PANACEA Facilities Useful To IIS And Blade Modelling

In this section some of the facilities within PANACEA which have not been explained thus far are described. PANACEA does contain more facilities but they will probably not be needed when running either the IIS or the Blade Modeller. For more details the PANACEA user's guide should be consulted.

1 Menu 0

This is the main system menu, database, history and model limits control

0 SYSTEM UTILS	1
2 database	3
4 history	5
6 system	7
8 graphics	9

i. 'database'

DATABASE	return
clear database	
save db > disc	load db < disc
allocate db size	

a. 'clear database', will clear the database and graphics screens.

b. 'save db > disk', dumps the current database to the specified directory by a specified name.

c. 'load db < disk', loads a specified database from a specified directory.

d. 'allocate db size', enables specification of the database size, 8000K is usual for blades.

ii. 'history'

					HISTORY	/ return				
					read history	close read				
					write history	close write				

a. 'read hist', enables a specified history file to be read through.

b. 'write hist', enables a new history file to be written. After selection enter a name for the file and run thought the sequence of operations that are required to be recorded, when complete return to the history directory and select 'close write', this will close the file and a new history file will have been written.

iii. 'system'

					MISCELLANEOUS	return				
					model lims.	set debug				

a. 'model limits', enables the graphics viewports to be set to a required visibility box. e.g. the E4 IP Blade is viewed with x_{min} = -100, y_{min} = -100, z_{min} = 350, x_{max} = 100, y_{max} = 100 and z_{max} = 550. Having set new model limits it is necessary to 'reset' the windows, in order that a change to the graphics limits also occurs. To reset the windows select - overlay menu 4 - windows - reset windows - all.

iv. 'graphics'

Not used during IIS operations

2 Menu 1

This is the interactive modelling facility, it is not used during IIS operations.

3 Menu 2

This is the graphics editor, it is not used during IIS operations.

4 Menu 3

This is the attribute constructor, it is not used during IIS operations.

5 Menu 4

This is the window and viewport menu, it enables the operator to interactively specify his own viewports and windows.

0 VIEW UTILS	1
2	3
4	5
6 set displays	7 dynamics
8 windows	9 viewports

i. 'Set Displays and Dynamics' is not used during IIS operations.

ii. 'Windows'

0 WINDOWS	1 return
2 rotate	3 reset rotate
4 window	5 reset window
6 draw	7 erase
8 refresh	9 clear

a. 'rotate', 'reset rotate', 'draw', 'erase', 'clear', 'refresh' are not used during

IIS operations.

b. 'window', enables the operator to zoom in at an image in a viewport. Select window and a list of viewports will appear. Select the viewport to be zoomed in on. Move the cross-hairs into the specified viewport. Press the right mouse button over the bottom left corner of the required zoom box and release it. Move the cross-hairs up and right and a red box will appear, when the box covers the area of interest press the mouse button again. The zoom box area will then expand out to fill the viewport.

c. 'reset window', enables the windows to be redraw, it is used after a change in model limits.

iii. 'Viewports'

					0 VIEWPORTS	1 return				
					2 rename vp	3				
					4 define vp	5				
					6 deactivate	7				
					8 activate	9				

a. 'rename vp', is not used during IIS operations.

b. 'define vp', enables the operator to interactively redefine the size of the viewport. Select 'define vp' and a list of viewports will appear. Select the viewport desired to be changed. Move the cross-hairs to the nominal position of the bottom left corner of the required viewport. Press the right-hand mouse button and release it. Move the mouse up and right and a red box will appear, when the box reaches the desired position of the top right hand corner of the viewport press the mouse button again and the model image should appear in the new viewport.

c. 'deactivate vp', enables the operator to shut down specified viewports.

d. 'activate vp', enables the operator to open up specified viewports.

6 Menu 5

All of these options enable various output of the graphics.

					0 GRAPHIC I/O	1 Scaled digitiser				
					2 pixel dump	3 to plotter				
					4 to binary file	5 to ascii file				
					6	7				
					8 file limits	9 plotter limits				

Within the IIS hard copy plots may be obtained through the function 'to ascii file'. This enables an ascii screen dump of graphics to be sent to a file. Always call the dump file 'ascii/filename', so that it is stored in the '/ascii' directory of the IIS run directory and may be readily accessed by the plotting program.

7 Menus 6, 7, 8, 9, 10, 11, 13, 16, 17 and 18

These menus have not been allocated any software within the IIS system.

8 Menu 12

Holds the PANACEA aerofoil modeller , see the 'Blade Modelling' section.

9 Menu 14

Holds the IIS Probe Path Generator Programs.

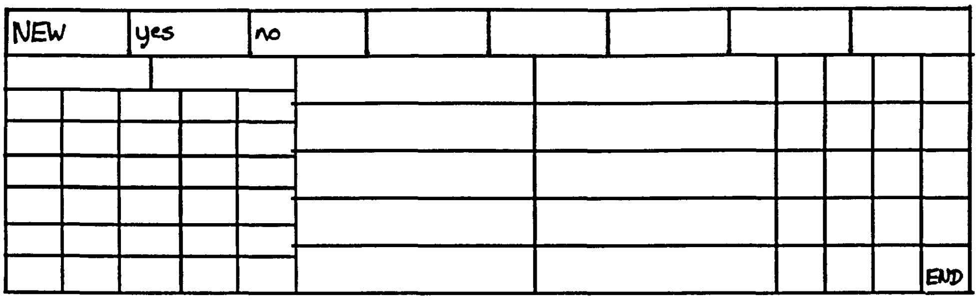
10 Menu 15

Holds the IIS Error Analysis Programs.

11 Extra PANACEA Facilities

i. Quitting IIS

a. Select 'END'



and select 'YES' to the 'REALLY quit ?' prompt, using the 'YES', 'NO' menu buttons, or

b. Press the 'control' and 'c' keys on the console keyboard simultaneously.

Enter 'yes' to the 'Quit ?' prompt, using the monitor.

Enter 'no' to the 'core dump ?' prompt, using the monitor, or

c. Log into the system on another terminal and kill the IIS program.

12 Plotting Ascii Dumps of PANACEA Screens Using An HP Plotter

Having made a dump of a graphics screen the output may be plotted on a HP Plotter, which in the case of the IIS system at the P.C.F. is the HP Plotter on the Mitutoyo CMM.

Procedure :-

i. Make sure that the GEOPAK program is not running on the HP Vectra.

ii. Unplug the HP IB cable at the back of the HP Vectra that runs to the plotter.

iii. Set the A3-A4 option on the microswitches on the plotter.

iv. Turn the plotter on, or if it is already on turn it off and then on again.

v. Put the required paper in the plotter.

vi. Unplug the 'ttya' port RS232 cable in the back of the WYSE monitor and put it in the back of the Tastronics box.

vii. Set the microswitches on the Tastronics box to 'plotting'. (See underneath the box).

viii. Turn the Tastronics box on.

ix. Run 'suntools' on the SUN 3/60.

x. Change directory to '/usr2/u4256ad/apip/generator'.

xi. Run the 'plot' program and a list of files that may be plotted will appear.

xii. Enter the name of the file to be plotted.

xiii. Enter a title for the plot.

The plot should then commence.

When finished :-

xiv. Turn off the Tastronics box.

xv. Replace the RS232 cable in the back of the WYSE monitor.

xvi. Replace the HB IP cable in the back of the HP Vectra.

6 Nomenclature

ABC Points	The Zero Error Target Datum Points defined on a blade surface for defining the stacking axis of the blade
APIP	Automated Proof Inspection Package
Blade Modeller	A PANACEA system developed for modelling Gas Washed Surfaces of Turbine Blades
CAD	Computer Aided Design
b-spline	A type of curved line interpolation between control points
CIBMS	Computer Integrated Blade Manufacturing System; a computer system philosophy developed by N.Brookes for the manufacture of turbine blading
CIM	Computer Integrated Manufacture
CMM	Coordinate Measuring Machine
CNC	Computer Numerical Control
Ethernet	An inter-computer communications system
GEOPAK	The Mitutoyo CMM control program
HP	Hewett-Packard

IGES	International Graphics Exchange Standard for the transfer of CAD database information between systems
IIS	Integrated Inspection System
Macroblock	A PANACEA database type for grouping other database types together
Mitutoyo	A manufacturer of measuring equipment
NDF	Neutral Datafile Format; a common language between CAD systems and Coordinate Measuring Machines
Nodes	PANACEA database type for 3D points
NURBS	Non-Uniform Rational B-Spline; a type of curve line interpolation between control points
Overlay	An additional PANACEA program
PANACEA	An Imperial College CIM Programming Environment
PH9	A Renishaw Probe Head
PRIMINDEX	A PANACEA variable type for storing databases
RS232	Inter-computer communications standard
SUN 3/60	The Computer used to develop the IIS
Tastronics Box	An RS232/HB IB converter

TP2	A Renishaw Touch Probe
Transputer	A computer processor capable of being linked with other such processors to form a parallel network of processors
UNIX	A Multi-User Computer Operating System
WYSE	The name of the dump terminals attached to the SUN 3/60

7 References

[1] Lee, S.A., Tsabourakis, N., Besant, C.B., Ristic, M., "A Computer Integrated Approach To Dimensional Inspection"; 9th International Symposium On Air Breathing Engines, Athens, Greece, September 1989, pp765-773

[2] Glover, R., "PANACEA A CIM Programming Environment"; PhD Thesis, Imperial College of Science, Technology and Medicine, University of London, November 1987.

[3] Brookes, N.J., Besant, C.B., "Reduction In The Development Lead Times of Complex Investment Castings by the Application of CIM Technology", The International Journal of Advanced Manufacturing Technology, Vol. 3, 2, May 1988, pp41-49.

[4] Lee, S.A., "Introduction To An Automated Turbine Blade Proof Inspection System and Implementation of Phase 1 The Measurement Of A Test Piece", Department of Mechanical Engineering, Imperial College of Science, Technology and Medicine, University of London, November 1987.

[5] Lee, S.A., "Discussion Of The Automated Proof Inspection System After the Completion Of Phase 2: The Measurement Of A Turbine Blade", Department of Mechanical Engineering, Imperial College of Science, Technology and Medicine, University of London, April 1988.

Appendix II

Programmer's Guide To The Turbine Blade Integrated Inspection System

Summary

This appendix is part of the Rolls-Royce documentation of the Turbine Blade Integrated Inspection System. It aims to inform any future programmers of the system of the algorithms involved and how the source code is laid out within the directory structure in which the system existed on the 31 March 1989. The main algorithms involved in the system are documented in this report, although the source code is not explained in depth as this is left to the various files and comments within the source code itself. This report includes an overview of the PANACEA system and the Blade Modeller involved with the Inspection System, more information on these systems should be sort from the relevant documentation.

Contents

1 Introduction

The IIS system may be considered as 10 separate programs existing within the PANACEA CIM environment which when run sequentially perform the Proof Inspection Process For Turbine Blades. That is to say the processes of blade alignment and measurement part program generation through to best fitting of surface errors.

The documentation for the 10 IIS programs exists in two types of format, firstly this appendix and secondly the listings of the source code. In the case of the latter every directory concerned with the IIS contains a 'READ_ME' file which explains the purpose of the programs and or code in that directory. The program source code itself contains the detailed program documentation.

2 Overview of the IIS Programs in the PANACEA Environment

2.1 Introduction

The IIS source code has been written in 'C' and is compiled with PANACEA source code to create the IIS. The programs which make up the IIS use the PANACEA system for geometric database and graphic handling facilities. Most of the IIS programs proceed through the following basic algorithm:-

i. Extraction of surface positions and normals from a nominal blade database.

ii. Processing of surface positions and normals to give required output e.g. a probe path or surface errors.

iii. Output of processing to file and or graphical display e.g. a probe path is written to a file and is displayed as a blue line on the screen.

The importance of this sequence is to realise that once the surface normals have been extracted from the nominal surface the geometric database plays no further part in the processing routine, and thus most of the IIS processing is independent of the CAD environment in which it is compiled. Output from the IIS programs is either graphical or written to ascii files.

2.2 The PANACEA Programming Environment and Linking The IIS Into It

As has been stated before PANACEA is principally a CAD database and graphics handling facility to which other programs may be linked and in this way the IIS and the Blade Modeller system are produced. The various programs that are added to the basic PANACEA program may be accessed by the system operator through a menu on the graphics screen. For reasons of history such programs are known as overlays.

PANACEA has 8 overlays of its own 0 to 7. When linking a new system the programmer must decide from the provided overlays in the '/usr2/fesystem' directory area which ones he requires. When writing a new overlay the programmer declares it as an overlay with a different number to any of the PANACEA overlays, for example the probe path generator has been declared as overlay 14, function name 'ovl14()'. When compiling and linking a new PANACEA system the required PANACEA overlays and any new overlays are declared in a file called ovcontrol.c which exists in the system run directory and is compiled and linked with the new system.

Any overlay program must obviously exist somewhere within the source code. Usually an overlay will lead to a number of programs which the system operator sees as a list of options appearing in the centre of the menu area. For example after selection of overlay 14 the operator is presented with a choice of alignment and measurement programs.

The source code for an overlay may exist anywhere and is linked with the basic PANACEA overlays by specifying the path name of the compiled overlay program in the 'make' file of the new PANACEA program. In the case of the IIS the 'make' file is the 'make.noov' file in the '/usr2/u4256ad/apip/generator' directory. The location of the IIS overlay source code is described in section 3 of this appendix.

2.3 How To Extract Dimensional Information From A PANACEA Database

A program written within the PANACEA facilities obviously requires the ability to extract database information. The following paragraphs describe what different database types exist within PANACEA and how to extract information from them.

PANACEA has the following database types (also known as primitives):-

Nodes, Lines, Surfaces, Volumes, Attributes, Text and Macroblocks.

An aerofoil database is held as a macroblock, this is effectively a label which points to the data inside it. An aerofoil macroblock will contain a number of surfaces each being defined by straight line ruling between two closed b-spline lines around plain sections of the aerofoil. Each b-spline line is defined by a number of nodes (points). An annulus surface database is also held as a macroblock. This points to a number of swept surfaces, these are defined by lines and arcs swept about a vector along the engine centre line. The lines and arcs are defined by nodes (points).

When an operator is running an IIS program he must first load a blade database from disk. When such a database is loaded it has a name and an associated macroblock number. When the operator enters into say a probe path generator program he will be asked to identify which macroblock he wishes to use.

Within a program a macroblock is selected using the mblkmen() function:-

```
mind = mblkmen( sys_status.cnlevel, sys_status.cn_mask)
```

This function will display to the system operator a list of macroblocks from which he must choose and in so doing the function returns the index of the macroblock. This index is a variable type 'PRIMINDEX'. 'sys_status.cnlevel' and 'sys_status.cn_mask' are PANACEA global variables used when handling databases. Once the program has a macroblock index it may extract the various surfaces, lines and nodes e.t.c. from within it. This is done by using the enq_cons() function. In this example the surface indexes are enquired from the selected macroblock:-

```
enq_cons( mind, MBLK, SURF, slist, &scnt, ELNINDS, GDEFLINK);
```

'mind' represents the macroblock PRIMINDEX.

'MBLK' represents a flag indicating that 'mind' is a macroblock database type.

'SURF' represents a flag indicating the requirement to enquire the surfaces within 'mind'.

'slist' represents a pointer to an array of PRIMINDEXS which is to contain the PRIMINDEXs of the surfaces in 'mind'.

'scnt' is an integer and is to have the value of the number of surfaces in 'mind'.

'ELNINDS' is a database handling flag.

'GDEFLINK' is another database handling flag.

After calling such a function 'slist' would contain an array of surface indexes. To extract the lines in each of the surfaces a further call to enq_cons() would be used:-

enq_cons(slist[i], SURF, LINE, llist, &lcnt, ELNINDS, GDEFLINK)

This would place the line indexes that define 'slist[i]' in the 'llist' array. To extract the nodes in each of the lines a still further call to enq_cons() would be necessary:-

enq_cons(llist[i], LINE, NODE, nlist, &ncnt, ELNINDS, GDEFLINK)

This would place the node indexes that defined 'llist[i]' in the 'nlist' array. To extract the x, y and z values of the nodes the enq_xyz() function is called:-

enq_xyz(nlist[i], &x, &y, &z)

This would place the x, y and z values of the nlist[i]'s node in the float variables x, y and z.

2.4 How To Define A PANACEA Database and Graphically Display It

In this section the methodology behind building PANACEA databases is discussed along with the graphical displaying of database information. In the example below a set of x, y and z values has been received from the inspection machine and a measured aerofoil model is to be generated and displayed. To build a measured surface model the process is split into 3 sections:-

1. Create 'nodes' from the inspected measurements.
2. Create 'b-spline lines' from the 'nodes' around each measured section.
3. Create straight ruled 'surfaces' between the 'lines'.

2.4.1 Creating Nodes From Inspected Measurements

In this example assume that the previous algorithm has identified the x, y and z positional values of a measured section and stored them in an array of floats 'measpoints', such that:-

measpoints[0] = the x value of the first point

measpoints[1] = the y value of the first point

measpoints[2] = the z value of the first point

measpoints[3] = the x value of the second point, e.t.c.

It is required in order to construct the measured surface that these measured values be converted into 'nodes' within the PANACEA database. In the case below the i^{th} element in an array of PRIMINDEXs 'nodeind' would be filled with an index created by the 'mk_node()' function:-

nodeind[i] = mk_node(measpoints[(3 * i) + 0], measpoints[(3 * i) + 1], measpoints[(3 * i) + 2], level, mask];

level and mask represent database handling facilities that effect colours and other various database properties they are usually set to values in the PANACEA global structure 'sys_status'.

To display the nodes it is first necessary to make a graphical record of the them with the 'mkgnode()' function, after which they may be displayed by the 'dnvpall()' function.:-

mkgnode(nodeind[i]);

This will make a graphical record of the i^{th} element of 'nodeind'.

dnvpall(nodeind, nodecnt);

This will display the first 'nodecnt' nodes in the array 'nodeind'. Note that PANACEA has a number of display options and the user's guide should be consulted for more information.

2.4.2 Creating Lines From Nodes Around a Section

Given that the previous algorithm has identified the nodes obtained around a measured aerofoil section it is now necessary to create a b-spline line from the measured nodes. Since the b-spline interpolation produces a 'concave hull' effect around control points it is necessary to convert the measured nodes into another set of nodes that will interpolate a line through the measured points, this is performed by the 'spconv()' function:-

spconv(ltype, measpnts, knots, nodecnt - 1);

'ltype' represents a flag for the type of b-spline to be created i.e 9 for closed and 10 for open.

'measpnts' represents the array of floats containing the measured x, y and z values.

'knots' represents another float array holding x, y and z values in the same way as 'measpnts', but will contain the positions of the points required to interpolate the b-spline through the measured points.

'nodecnt' represents the number of measured points.

Having generated the control points necessary to produce a b-spline line through the measured points it is necessary to make PANACEA nodes out of them with the 'mk_node' function as with the 'measpnts' array above. Assuming that an array of PRIMINDEXS 'points' contains the node indexes of the new control points the 'mk_spline()' function would be used to generate the spline:-

```
pspline = mk_spl( ltype, points, nodecnt, level, mask);
```

'pspline' represents the PRIMINDEX of spline.

All other variables adopt their previous meanings.

To display this line it is first necessary to create a graphics record of it with the 'mkgline()' function after which it may be displayed with the 'dlvpall()' function:-

```
mkgline( pspline);

dlvpall( &spline);
```

2.4.3 Creating Surfaces From Lines

Once a set of line indexes has been obtained from which the measured aerofoil surface is to be made they must be sorted into ascending order using the 'secsort()' function:-

```
secsort( index, section - 1 );
```

'index' represents an array of b-spline line PRIMINDEXs.

'section' represents the number of lines in array 'index'.

For reasons of history the first two indexes should be swapped. The surfaces may then be generated and displayed. The function 'mk_s6()' is used to create a PRIMINDEX of a straight-ruled b-spline surface:-

```
surfind = mk_s6( 2, index[ i ], index[ i + 1], 2 * nodecnt, level, mask );
```

'surfind' represents the PRIMINDEX of the created surface.

All other variables adopt their previous meanings.

To display this surface it is first necessary to create a graphics record of it with the 'mkgsurf()' function after which it may be displayed with the 'dsvpall()' function:-

```
mkgsurf( surfind );

dsvpall( &surfind, 1 );
```

Finally all of the surfaces may be grouped together as a 'Macroblock' which represents the aerofoil surface with the mk_m1() function:-

```
aeroind = mk_m1( name, SURF, surfind, ptype, ( section - 1), level, mask);
```

'aeroind' represents the macroblock index returned by the function.

'name' represents a string containing the name of the aerofoil macroblock.

'SURF' represents a macro used as a flag for the type of macroblock to be created.

'ptype' represents an array of integers set equal to 'SURF' and declares the type of the primitive in each element of 'surfind'.

All other variables adopt there previous meaning.

2.4.4 Resume For Creating PANACEA Databases

In the previous 3 subsections it has been illustrated how to create and display measured surfaces from a set of nodes. If the reader wishes to implement such a procedure it is recommended that he refers to the algorithm in the modelling source code (/usr2/u4256ad/APIP/src/ov15/remodel) since the above attempts only to illustrate the basic principles of modelling surfaces in PANACEA.

3 Overview of the PANACEA, Blade Modeller and IIS Source Code

3.1 Introduction

In reference to directory structures see Figure AII.1.

Most of the PANACEA, Blade Modeller and IIS source code is held in two main directories in the '/usr2' partition on the SUN 3/60 machine. PANACEA and Blade Modelling code is held in '/usr2/fesystem' while the IIS is held in '/usr2/u4256ad'. Only the 'include' files are not held in these areas, they exist in the '/usr/include' directories. Every subdirectory of the '/usr2/fesystem' and '/usr2/u4256ad' areas contains a 'READ_ME' file. These files explain the purpose of the directory and in the cases where programs exist will also explain how to run them. Where source code exists the 'READ_ME' file will overview the algorithm in the code and describe the role of each file.

3.2 PANACEA and Blade Modelling Source Code

PANACEA and Blade Modelling source code was written by R. Glover and N. Brookes respectively and for this reason only an overview of the code is given in this documentation. Inside the '/usr2/fesystem' directory are 29 subdirectories and these may be divided into 5 types:- PANACEA databases, PANACEA basic code, PANACEA Overlays, The Blade Modeller and Miscellaneous.

The PANACEA databases contain the blade models which have been used during the development of the IIS system. Although these blades have been allocated separate databases i.e. /C_dbs, /D4c_dbs, /E4_dbs, it is suggested that all subsequent blade databases be stored in /dbs to prevent the complication of changing PANACEA to accommodate new database directories.

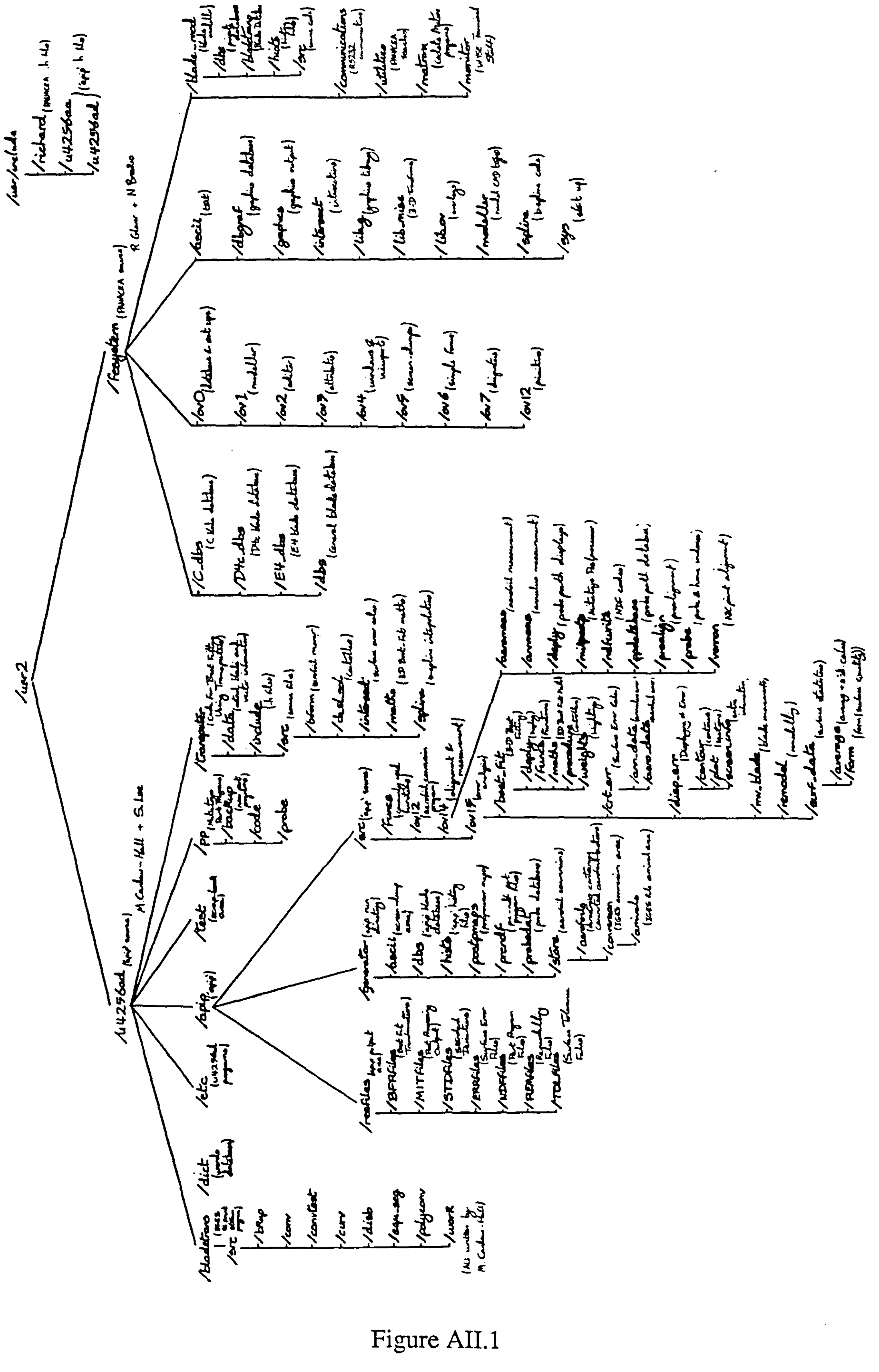


Figure AII.1

Directory Structure for PANACEA and IIS Source Code

The PANACEA basic code area contains those functions which are an essential part of any linking of a PANACEA based program, this includes those functions which are compiled into library code in the 'usr/lib/librik' directory. The PANACEA Overlays contain those optional elements of PANACEA that a programmer may choose from when linking a new PANACEA based program. The Blade Modeller is held in '/usr2/fesystem/blade_mod', the program 'blade' is the blade modelling program. The geometric data defining the annulus surfaces is located in various subdirectories in this area, the subdirectories '/dbs', '/hists' are blade modelling work areas while '/src' contains the blade model source code.

The PANACEA Miscellaneous directories are:-

'/communication', which contains the programs for RS232 communications with the HP Vectra. This method of communications is no longer used, but has been left here for reference purposes.

'/utilities', which contains the program 'fegrep' which searches through all of the PANACEA source for a string given as first argument.

'/matrox', which contains those programs used by the Codata machine for controlling the graphics Matrox boards. These play no part in PANACEA on the SUN workstation.

'/monitor', which contains the WYSE monitor control programs.

3.3 The IIS Source Code and Documentation

3.3.1 Introduction

The source code for the IIS exists in a more complex structure than PANACEA within the '/usr2/u4256ad' directory. There are 4 main program subdirectories plus 3 minor scrap-book type subdirectories:-

Main Subdirectories

i. '/apip', contains the IIS program, source code and output areas.

ii. '/bladetrans', contains the source code for the program 'conv' which converts IGES blade file information into point streams which are converted into PANACEA b-splines for aerofoil modelling.

iii. '/pp', contains the Mitutoyo part program databases and the GEOPAK 4.2 program.

iv. '/transputer', contains a stand alone best fitting program which will hopefully be extended by the use of transputers.

Scrap-Book Directories

i. '/dict', contains some files containing words. These were copied over from '/usr' when the '/usr' partition became full.

ii. '/etc', contains a few useful programs for IIS programmer's, for example 'srcgrep' which searches through all of the IIS source for a string passed as first argument.

iii. '/test', is a program test area.

3.3.2 Documentation For Directory '/usr2/u4256ad/apip'

This area contains the vast majority of the IIS code and is divided into 3 main directories:-

i. '/generator', this is the run area for the IIS, it also contains the postprocessor, data logging and plotting programs. The IGES files of Turbine Blade Files are converted into point streams in the subdirectories of '/store'.

ii. '/resfiles', this is the output area for the IIS, e.g. part programs, error files, best fit transformations e.t.c.

iii. '/src', contains the source code for the IIS and is further divided into 4 subdirectories:-

   a. '/ov12', the aerofoil modelling program

   b. '/ov14', blade alignment and measurement program

   c. '/ov15', error analysis program

   d. '/funcs', commonly used IIS functions plus some source code for plotting and data logging programs

Each of the above areas is described in more detail below, but remember every directory has a 'READ_ME' file which contains a greater explanation of the source code within it.

3.3.2.1 Documentation For Directory '/usr2/u4256ad/apip/src'

In this section an explanation of the source code is given. This is followed by information on accessing programs from within a PANACEA system, how to compile code into a PANACEA system and some useful IIS programming tools.

i. '/ov12', contains a program for converting point streams around aerofoil sections into b-splines and then into aerofoil models. The program was written by M. Cardew-Hall.

ii. '/ov14', contains the programs for blade alignment and measurement of Gas Washed Surface models of turbine blades, the process for achieving blade measurement is as follows:-

   a. Pre-alignment, manually controlled measurement of a particular point of the blade to establish a stacking axis to within 3mm positional accuracy around the blade.

b. ABC Point Alignment, automated alignment of the turbine blade on the CMM to produce a stacking axis to within 0.002mm positional accuracy.

c. Measurement, automated measurement of specific points on the Gas Washed Surfaces.

This process is facilitated by the programs in the following directories:-

a. '/prealign', interactively identifies a point on the blade surface from which to determine an estimate of the blade stacking axis. The program is constructed in NDF (Neutral Datafile Format).

b. '/vernon', interactively identifies the A, B and C zero error target datums on the surface model of a blade and uses them to construct an automated NDF program for defining the stacking axis around the blade.

c. '/aeromeas', interactively identifies sections around an aerofoil to be measured.

d. '/annmeas', interactively identifies sections along the annulus surfaces to be measured.

e. '/dsply', contains code for the visual display of a probe path.

f. '/ppdatabase', contains code for the probe path databases.

g. '/probe', contains code for the calculation of probe orientations and 'home' positions.

h. '/ndfwrite', contains code for writing the part programs in NDF format

i. '/mitpostp', contains code for the post processing of NDF files into a format suitable for use by the Mitutoyo CMM.

iii. '/ov15', contains programs for the analysis of inspected data. The usual process for analysing inspected data is as follows:-

   a. Model inspected data into measured surface models within the IIS. This will produce statistical distributions in the case of batches of blade measurement.

   b. Calculate the error between nominal and measured surfaces along discreet vectors.

   c. Display errors either as sections or as contours.

   d. Best Fit the measured surfaces to the nominal surfaces.

These processes are facilitated by the programs in the following directories:-

   a. '/remodel', contains programs for extracting measured points from inspected results from the Mitutoyo CMM and converting them into plain section b-splines and then into measured surface models.

   b. '/crt_err', contains surface error calculation routines. Subdirectories '/ann_data' for annulus surfaces and '/aero_data' for aerofoil surfaces.

   c. '/disp_err', contains routines for displaying surface errors. Subdirectories '/plot' for sectional plots, '/contour' for contour plots and '/screen_info' for displaying stacking axes and scales.

   d. '/best_fit', contains routines for 3-D best fitting of measured to nominal surfaces. Within the routines it is possible to define weightings to the errors according to a number of criteria. Subdirectory '/procedure' holds the main control functions, '/maths' holds the 3-D best fitting mathematics, '/dsply' holds the extensive error display facilities for best fitting, '/weights' holds the weighting functions and '/funcs' provides for some general best fit functions.

e. '/surf_data', contains routines for surface error analysis. '/average' holds code for averaging surface error data, either from the modelling stage or from the analysis of surface error files. '/form' provides for a quantitative measure of surface quality.

iv. '/funcs', this contains a few functions used throughout the IIS. It also contains other programs useful to a system operator:-

a. loghpdata.c is a program compiled to the name 'log' which is used for logging inspected data from the Mitutoyo by RS232.

b. plot.c is a program compiled by the make.plot file into a program called 'plot' which is used to plot ascii screen dumps on the HP plotter.

v. Accessing programs from within a PANACEA system:-

As has previously been explained PANACEA is a CAD environment which enables a programmer to write his own programs into. A system operator may access these programs through the overlay call area to the right of the menu on the graphics screen. In order to do so the programmer must obviously declare these overlays and menus to the PANACEA system. In '/usr2/u4256ad/apip/src' are the IIS overlays 12, 14 and 15, in each of these areas is a file called menu.c or menu15.c, these files contain the functions ovl12(), ovl14() and ovl15(). These functions are called when the operator selects the option on the respective overlay menu. In the case of overlays 12, 14 and 15 a new centre menu is defined so that the various program options available in each overlay may be called up. A menu display is completely defined in a menu.c file, any changes to such a file are totally legitimate, however the syntax is farely complex. Any new functions to be called must be defined at the top of the menu.c file as well as in the defining menu structure.

vi. Compiling the IIS Source Code:-

The source code for the IIS is stored in the subdirectories of '/usr2/u4256ad/apip/src', obviously any changes made to a file within the source involves the recompilation of that changed file and the subsequent relinking of all of the object files up to and including the IIS program itself. Each source code directory contains a 'make.noov' file which is the makefile for the directory. If for example a change was made to a file in '/src/ov15/disp_err/contour' it would be necessary to:-

'make -f make.noov' in '/usr2/u4256ad/apip/src/ov15/disp_err/contour'

'make -f make.noov' in '/usr2/u4256ad/apip/src/ov15/disp_err'

'make -f make.noov' in '/usr2/u4256ad/apip/src/ov15'

'make -f make.noov' in '/usr2/u4256ad/apip/generator'

Since a programmer will often wish to recompile in this way every directory containing IIS source contains a 'C' script file called 'panmake', this will automatically perform the compilation and linking of the IIS from the directory of the changed file. The use of 'panmake' has proved to be a very powerful tool in speeding up program development.

vii. Useful Programming Tools in '/usr2/u4256ad/apip/src

It is often necessary to search for a function name through the IIS source code. Various special 'C' scripts have been written to perform this task, e.g. 'srcgrep' defined in '/usr2/u4256ad/apip/src'. This file will search through the IIS source for a string passed to the program as first argument. '/ov14' and '/ov15' have their own grepping files 'ppgrep' and 'bfgrep' respectively.

As it may be necessary to recompile all of the source code from time to time the 'C' script files 'ppmake' and 'bfmake' in '/ov14' and '/ov15' respectively have been written to remake the source code in each of these overlays.

3.3.2.2 Documentation For Directory '/usr2/u4256ad/apip/generator'

This is the area from which the IIS is executed, along with Mitutoyo post processor, the data logger and the HP plotting program. IGES files of Turbine Blade Files are converted, in the subdirectory '/store/conversion', to point streams and stored in subdirectories '/store/blade_name' ('blade_name' corresponds to the particular name of any blade).

The IIS requires a local database, which is provided by the subdirectory '/dbs', where modelled blade databases are stored and a subdirectory '/ascii' where screen dumps may be sent to. The probe paths are stored to file in the subdirectory '/prendf' before being compiled into Neutral Database Format. Probe characteristics are stored in files in subdirectory '/probedat'. Finally PANACEA 'history' files for the IIS are stored in subdirectory '/hists'.

The RS232 HP Vectra data logging program 'log' is executed from the '/usr2/u4256ad/apip/generator' directory. In this case the Tastronics box is set up for logging data, which is performed through the 'ttya' port, and the results are sent to a file called '/usr2/u4256ad/apip/resfiles/insp.dat'.

The HP plotter program 'plot' is executed from the '/usr2/u4256ad/apip/generator' directory. In this case the Tastronics box is set up for sending data from the 'ttya' port to the HP plotter. The program will plot the screen dumps that have been made from the IIS and stored in the subdirectory '/ascii'.

The Mitutoyo postprocessor program 'postp' is executed from the

'/usr2/u4256ad/apip/generator' directory. The program converts part programs in Neutral Datafile Format into a Mitutoyo database format. Postprocessed files are stored in specially prepared Mitutoyo database files in the directory '/usr2/u2456ad/pp'. The subdirectory '/postpmaps' contains files for converting the probe orientations defined in the part programs to the calibrated orientations defined in the Mitutoyo machine itself.

3.3.2.1 Documentation For Directory '/usr2/u2456ad/apip/resfiles'

This area holds the various outputs from the IIS programs the subdirectories of '/resfiles' contain the following information:-

i. '/NDFfiles', holds the inspection part programs. These programs are in Neutral Datafile format and are given the '.NDF' postfix.

ii. '/REMfiles', holds the modelling information for the inspected data. When a part program is produced a modelling file is also produced which enables the modelling programs to read the inspected data and convert it into measured surface models. Such files are given a '.REM' postfix. Produced at the same time as the '.REM' file is a file containing the x, y and z values of the nominal points to be inspected, such files are given a '.NOM' postfix. When inspected data is being logged it is sent a file called 'insp.data' in '/REMfiles'.

iii. '/MITfiles', holds the postprocessed files of NDF part programs. Each part program is postprocessed into two files. The first file is the full part program in Mitutoyo database format and is given a '.MIT' postfix. The second file is a short file containing the program name, data of creation and program length and is given a '.MITSPF' postfix. These two files are inserted into the main Mitutoyo database, Lee [2].

iv. '/STDfiles', holds the standard deviation of measured data from a batch measurement. An aerofoil measurement produces a '.STD' postfixed file, which contains the standard deviation of the position of each of the control points around the section. For identification the height of the section is postfixed to the name of the file e.g. E4_aero354.STD. A batch annulus measurement also produces a series of '.STD' files who's names contain the section number of the inspection postfixed to the name e.g. E4_ann1.STD.

v. '/ERRfiles', holds the error files generated when calculating surface error. The files are given a '.ERR' postfix.

vi. '/TOLfiles', holds surface tolerance files, these are generated by a program called 'tolgen' and enable the IIS programs to associate tolerance information to the surfaces. Such files are '.TOL' postfixed and contain a lower and upper tolerance for each control point along an inspection section.

vii. '/BFRfiles', holds the best fitting transformation files produced after a best fit calculation. Such files are postfixed with '.BFR'.

3.3.3 Documentation For Directory '/usr2/u4256ad/bladetrans'

This directory contains the program, written by M. Cardew-Hall, for converting IGES files of Turbine Blade Files into point streams. These point streams are converted into closed b-splines by the program in overlay 12 of the IIS and then straight ruled to form aerofoil surfaces. The program for the IGES conversion is independent of the IIS and is called 'bfcon', with the source code residing in the directory '/usr2/u4256ad/bladetrans/src'. Not all of the source code in this area is compiled to form 'bfcon'. The program uses a uniform distribution of control points around the aerofoil sections, this has the problem of yielding hundreds of control points per section although the b-splines are farely stable in areas of high curvature.

3.3.4 Documentation For Directory '/usr2/u4256ad/pp'

This directory contains the Mitutoyo part program databases and the GEOPAK 4.2

program. When a part program written in Neutral Datafile Format is post processed for the Mitutoyo it is inserted into a part program database in this directory. The operator may define a new part program database, this is done by copying the file 'partprg' in the directory '/usr2/u4256ad/pp/backup' up to the '/usr2/u4256ad/pp' directory, giving it a meaningful name and postfixing it with a '.PP'. The executing GEOPAK program is set up to look in the file '/usr2/u4256ad/pp/partprg' for the part programs. Therefore which ever '.PP' file is to be used by GEOPAK should be moved or copied to the 'partprg' name.

The Mitutoyo CMM control program GEOPAK 4.2. resides in the workstation in the '/usr2/u4256ad/pp' directory. It was decided to store a version of GEOPAK and run only that version when executing IIS generated part programs because upgraded GEOPAK programs were not upwardly compatible and hence required changes to the post processor for every up grade of the program. The GEOPAK 4.2. program stored in the SUN 3/60 is called up through the Ethernet and occupies about 30 files in the '/usr2/u4256ad/pp' directory.

3.3.5 Documentation For Directory '/usr2/u4256ad/transputer'

This area contains a stand alone program for best fitting aerofoil surfaces. The source of the program exists in the subdirectory '/src' and has been extracted from the relevant IIS and PANACEA source code. Nominal surface normal vectors and actual blade definitions are stored in the subdirectory '/data'. The best fitting program currently runs serially however it is believed that it can be made to run in parallel on a transputer network. More surface normals and actual blade definitions may be obtained by running the IIS, see the User's Guide for more information.

3.3.6 Resume of the IIS Source Code Documentation

This section has attempted to describe the layout of the source code through the subdirectories of '/usr2/u4256ad', that is to say the coding that is required to produce all of the programs that make up the IIS system. More detailed documentation of the programs is given in the source code itself and in all of the directories in the 'READ_ME' files.

4 Documentation of the Complex Algorithms Involved in the IIS

4.1 Alignment of a Turbine Blade on a Coordinate Measuring Machine

Before any measurement program may be executed on a blade surface a coordinate system must be constructed around the blade. This is simply because the CMM does not know where the object is when it is initially placed on the bed of the machine. Turbine blade alignment is extremely complex and involves the measurement of certain points on the blade's surface, known as zero error target datums. These points are used to generate the Stacking Axis Coordinate System around the blade. The process of creating the Stacking Axis is iterative and may be written into an automated routine described in section 4.3 of this appendix. However before this routine may be executed the stacking axis must be approximated to within 3mm positional accuracy in a process called pre-alignment described in section 4.2. below.

4.2 Pre-Alignment of Turbine Blades on the Mitutoyo Coordinate Measuring Machine

During the early stages of the IIS development turbine blade pre-alignment involved the manual measurement of certain simple features on the blade's surface to construct the stacking axes, Lee [2]. However the Mitutoyo CMM provides for a simplification of this process. This simpler algorithm involves the use of the machine's own coordinate system which effectively exists in the front left hand corner of its marble bed. Within the software on the CMM controller it is possible to translate this coordinate system to anywhere within the working envelope of the machine. The consequence of this feature is that if a blade to be measured is placed on the CMM with its estimated stacking axes in a similar orientation to the machine's coordinate system a single measurement on the blade's surface is sufficient to establish a stacking axes accurate enough to commence the automated ABC point alignment program. The pre-alignment procedure is very simple:-

i. Place the blade to be measured on the bed of the CMM with the estimated orientation of the stacking axis in line with the machine's coordinate system.

ii. Measure the designated pre-alignment point on the blade's surface.

iii. Construct a coordinate system with the origin at the measured point and with the same orientation to the machine's coordinate system.

iv. Translate the new coordinate system origin to the Stacking Axis, by the x, y and z values of the measured point relative to the Stacking Axis origin.

In the IIS system this algorithm may be constructed as a part program. All that the program requires as input is the x, y and z positions of the designated measure point and the probe orientation to be used to measure the point with. This algorithm is certainly much faster and easier to use than the original pre-alignment algorithm, however it does rely on the blade being placed on the CMM in a stacking axis orientation similar to that of the machine's own coordinate system.

Once pre-alignment has taken place the ABC point alignment program may be executed.

4.3 ABC Point Alignment of Turbine Blades on the Mitutoyo Coordinate Measuring Machine

Usually turbine blades are aligned on the ABC point zero error target datums using a specifically made fixture called a Vernon block, Lee [2]. The use of a Vernon block on a CMM for blade alignment would be extremely cumbersome and certainly not make best use of the facilities available on a modern CMM. The software in the Mitutoyo CMM is sufficiently sophisticated to construct a blade stacking axis without the need for expensive mechanical fixtures while leaving the blade free of intruding objects which would make surface measurement extremely complex.

To produce a blade's stacking axis within software the CMM must measure the ABC points on the blade's surface. However the ABC points are defined relative to the stacking axis, thus we are left with the dilemma that we may not define the stacking axis without measuring the ABC points, but that the ABC points may not be measured without a defined stacking axis. To solve this problem a procedure has been developed which is iterative; an estimate for the stacking axis is used to measure the A, B and C points. These new points are then used to establish a new stacking axis. The pre-alignment process is used to produce the first stacking axis before the automated iterative ABC alignment program is executed. Due to the geometry of the blade and the locations of the ABC points on the surface usually only 4 iterations are sufficient to establish the stacking axis to within 2μm.

4.4 The Probe Path Generator

4.4.1 The Purpose of The Probe Path Generator

The probe path generator has three functions which in the case of a contact probe are independent:-

i. To move the probe along the surface normal towards the measurement point.

ii. To orientate the touch probe during measurement to avoid collision with any part of the blade other than the target measurement point.

iii. To move the probe around the blade between measurements in an efficient manner without collision.

4.4.2 The Solution To The Probe Path Generator in the IIS

The solution developed for the probe path generator in the IIS is very much dependent on blade and PH9 / Mitutoyo geometry. Despite this the algorithm could be used for some other geometries and inspection machines. It has also shown the way forward for a probe path generator which is less dependent on geometry and inspection tooling, known as the Entity Independent Probe Path Generator.

The explanation of the probe path generator algorithm is presented in two parts. Firstly how the touch probe is orientated and driven along a surface normal to take a measurement and secondly how the probe head is controlled between taking measurements.

4.4.2.1 Taking Surface Measurements

For taking surface measurements the nominal blade model serves two purposes:-

i. Drive the touch probe along a surface normal path to take a measurement.

ii. Orientate the touch probe to enable measurement without collision of the probe head with any part of the blade other than that which is being targeted.

1 The Measurement Path Algorithm

Each point that is specified to be measured represents a target for the Ruby ball on the touch probe. In order to hit this point the ball must move along the path of the surface normal corresponding to that target point.

In practise it has been found that a 'Stand-Off' distance of 2mm from a blade's surface is sufficient to provide for a path running along the surface normal to the measure point. Therefore the probe is moved around the blade at high speed but for a measurement it is brought to the corresponding Stand-Off point and then moved at a measurement speed to the target.

2. The Probe Orientation Algorithm

The most obvious but actually not necessary orientation of the TP2 touch probe is along the surface normal vector corresponding to the measure point. As the PH9 probe may be calibrated in 7.5° orientations in its two axes of motion this would enable a very close matching of probe orientations to surface normal vectors. Unfortunately this philosophy means that for a typical blade inspection 50 to 60 probe orientations would have to be calibrated, a manual operation taking up to 3 hours. Therefore another algorithm was proposed which made use of the fact that the TP2 may be struck in a range of directions to initialise the sensor. The principle of the algorithm is that 8 equi-divided probe orientations are defined and the nearest orientation to a given surface normal is chosen. This reduces the number of probes required for any measurement dramatically at no cost to accuracy and in fact improves measurement speeds (See the Appendix I for the calibrated probe orientations used, also known as NDF probe orientations as they are the orientations present in the NDF part programs).

NOTE: For the annulus measurement the probe may not be orientated along the surface normal as it will collide with the blade. To compensate for this the x and y components of the surface normals are forced to new values which point away from the blade, thus providing a safe vector with which to calculate the probe orientation.

4.4.2.2 Collision Avoidance Between Taking Measurements

Once a set of Stand-Off positions has been defined the next task is to move the probe head between them without collision. If the probe head does not require to be reorientated between two measurements then on turbine blade gas washed surfaces it is sufficient to move the probe straight from one stand-off position to the next. However if the probe head does require reorientation a method of preventing collision is required, this has been overcome by defining 'Home' positions at a safe distance around the blade (for more details see the IIS User's Guide). When the probe needs to be reorientated it is simply moved out to the nearest home position, reorientated and then moved to the next measurement stand-off. There are two simple algorithms depending on whether the probe is reorientated by more or less than 90° between two consecutive measurements:-

1 Collision Avoidant Algorithm for a No More Than 90° Probe Reorientation Between Measurements

   i. Move the probe out to the home position corresponding to the previous measurement stand-off.
   ii. Reorientate the probe for the next measurement.
   iii. Move the probe to the home position corresponding to the next measurement stand-off.
   iv. Move the probe into the stand-off position corresponding to the next measurement point.

2 Collision Avoidant Algorithm for a Greater Than 90° Probe Reorientation Between Measurements

   i. Move the probe out to the home position corresponding to the previous measurement stand-off.
   ii. Move the probe to the home position above the blade.
   iii. Reorientate the probe for the next measurement.
   iv. Move the probe back to the home position above the blade.
   v. Move the probe to the home position corresponding to the next measurement stand-off.
   vi. Move the probe into the stand-off position corresponding to the next measurement point.

These two algorithms mean that movements due to reorientation are farely efficient as only one reorientation of the probe head ever takes place between measurements. The probe always starts and ends a measurement program from the home position defined above the blade.

4.5 The Processing of Inspected Data

4.5.1 Introduction

The purpose of measuring turbine blade surfaces is to find the error between measured and nominal surfaces. The true error between a measured point and a nominal surface is along that line which joins the point to the surface along the shortest distance. This criterion works well for producing an error calculating algorithm on low curvature surfaces such as annulii, however in regions of high curvature such as those incurred in aerofoils such a definition proves difficult to use in specifying an error calculation algorithm.

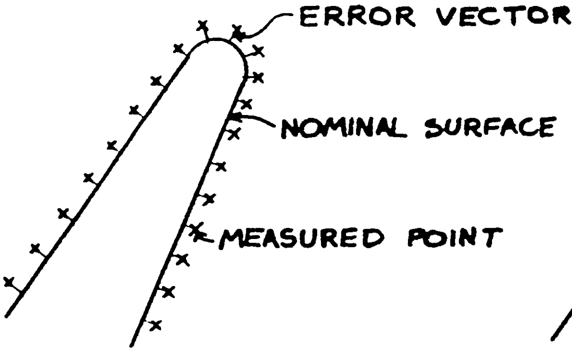


Figure AII.2

Method 1: Satisfactory Error Calculation

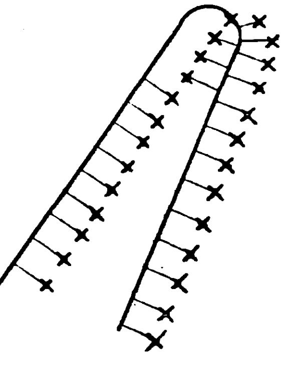


Figure AII.3

Method 1: Unsatisfactory Error Calculation

It may be observed from Figure AII.3 that the simple criterion for error calculation does not produce satisfactory errors in regions of high curvature. To overcome this a different philosophy has been adopted for calculating the errors around aerofoil surfaces:-

'The difference between two surfaces exists along vectors emerging surface normal from one surface and intersecting with the other along the most positive length of the intersecting vector'

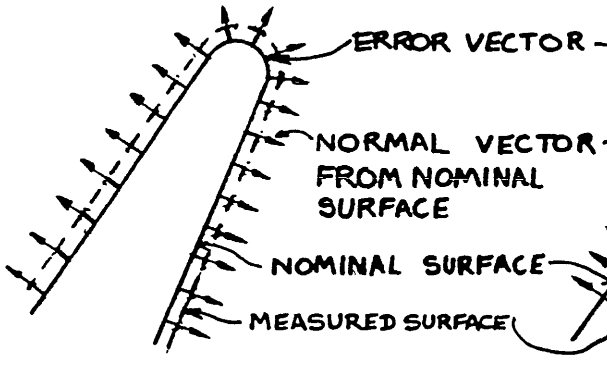


Figure AII.4

Method 2: Satisfactory Error Calculation

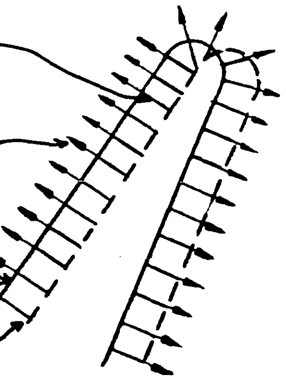


Figure AII.5

Method 2: Satisfactory Error Calculation

It may be observed from Figure AII.5 that the more complex criterion produces more realistic errors in the regions of high curvature. However this more complex criterion necessitates the creation of a model of the 'measured' surface with which the error calculation may interpolate vector intersections. This interpolation of the measured surface between measured points may not result in a truly valid error. To overcome this potential problem an algorithm has been developed to enable inspected data to be modelled as a measured model to a sufficiently high integrity. This algorithm is explained below in section 4.5.3. The interpolation process has been validated by trials and it has been shown that the nature of blade surfaces enables interpolation to provide errors to within 0.002mm, assuming that the errors are calculated in the vicinity of the inspected points. Typically no more than 40 points around a section are required to determine an accurate picture of the error around the section and usually 9 sections on a more conventional blade is sufficient to gain a radial picture of blade error.

4.5.2 Algorithm To Generate An Measured Aerofoil Model

One of the greatest problems with control point surfaces, such as the b-spline aerofoils, is the control point distribution. In modelling b-splines through measured points the distribution is as important as for the nominal aerofoil model. The simplest solution would be to measure a surface at the positions corresponding to a nominal control point, this would automatically provide the correct distribution for the measured model. However this philosophy implies two conditions:-

i. The surface is only measured at nominal control point positions.

ii. All of the nominal control point positions would need to be measured.

The first condition is not a problem as most aerofoils have as many as 180 control points per section and since only 40 points are usually sufficient to gain an accurate picture of the surface error no accuracy will be lost by measuring only at control points. The second condition is a problem as it implies that all control points should be measured i.e. 180 per section, which is unnecessarily high. To overcome this a technique has been developed which 'inserts' extra points between measured points enabling a high integrity measured model to be generated from the measurement of fewer points than define the nominal surface.

The principle is to insert those control points which are 'not measured' into the measured model between those control points that are. This is achieved by storing, to file, geometric relationships between measured and non-measured control points which may be used at the time of modelling the measured surface to insert extra control points between measured points.

4.5.3 A Geometric Relationship Between Measured and Non-Measured Control Points Of A Nominal Surface and Its Use In Modelling Measured Aerofoil Surfaces

4.5.3.1 Creating Modelling Information for Constructing Measured Surfaces

When a measurement probe path is being constructed in the IIS the operator decides upon those control points he wishes to measure. A geometric relationship between those control points being measured and those not being measured is then calculated and stored to file. The relationship is described below:-

Consider 6 adjacent control points around an aerofoil section. In this case 0 and 5 are to be measured.

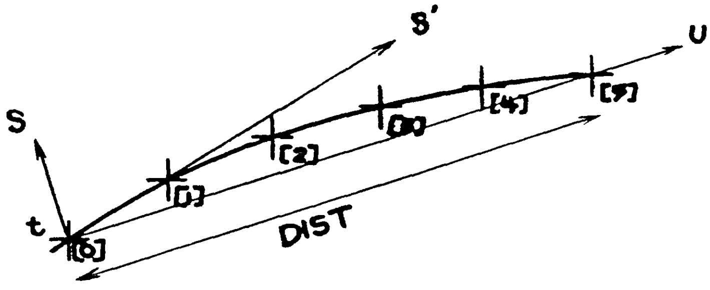


Figure AII.6

Geometric relationship between measured and non-measured control points

i. Create the u-axis [0] -> [5].

ii. Create the s'-axis [0] -> [1].

iii. Cross product the u-axis and s'-axis to give the t-axis (out of the paper).

iv. Cross product the u-axis and the t-axis to give the s-axis.

v. Using the s, t and u coordinate system determine the position of the non-measured control points [1], [2], [3] and [4].

vi. Determine the scalar length ' dist'.

vii. Divide the s, t and u values of the non-measured control points by 'dist' and store these new values to file. Also store the s-axis as a unit vector.

4.5.3.2 Modelling Inspected Data

The inspected data file is examined and the measured points are extracted. In the case below the geometric relationships determined in 4.5.3.1. are used to insert the extra control points in between the measured points [0] and [5].

i. Create a new u-axis between measured points [0] and [5].

ii. Cross product the new u-axis with the stored s-axis to give a new t-axis.

iii. Cross product the new u-axis with the new t-axis to give a new s-axis.

iv. Determine the value of 'dist' for the measured points.

v. Multiply the stored s, t and u values of the non-measured points by the new 'dist' value to determine the inserted control point positions in the new s, t and u coordinate system.

vi. Convert the s, t and u values to the absolute coordinate system, thus determining the positions of the inserted control points in the blade stacking axis.

4.5.4 Resume of Modelling Surfaces from Inspected Results

The above technique has shown to work well on aerofoil surfaces and has a number of advantages:-

i. The ability to pass information from nominal to measured surfaces may be used to modify the inspection results themselves. In the case of the Mitutoyo CMM this is necessary as the results from the inspection represent the position of the centre of the ruby ball at the moment of impact with the blade surface and not the position of the contact point. To overcome this problem surface normal vectors are passed as part of the modelling information and are used to correct the inspection results.

ii. The geometric modelling technique although developed for b-spline surfaces could be very easily adopted for any type of control point surface i.e. NURBS.

iii. The principle of modelling the measured points into surfaces enables a common design and manufacturing database which facilitates easy transfer of the data to design for aerodynamic and stress calculations on manufactured geometry.

4.6 The Calculation Of Surface Error For Aerofoil Surfaces

In section 4.5 of this appendix it was explained that aerofoil errors are found in the IIS by defining surface normal vectors from the nominal surface and intersecting them with the measured surface. In this section the algorithm for intersecting a vector with an aerofoil surface is explained.

Consider an aerofoil surface:-

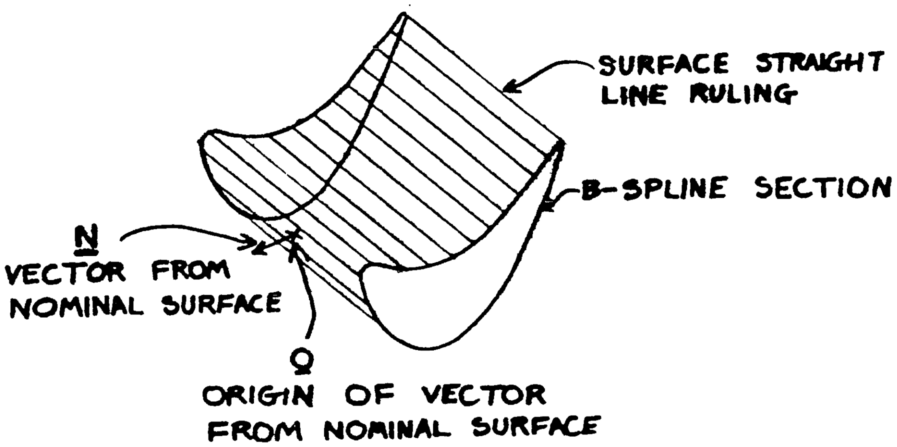


Figure AII.7

A Typical Aerofoil Surface

The algorithm for intersecting the surface normal with the surface is as follows:-

i. Generate ruling lines joining adjacent control points between the two splines defining the aerofoil surface.

ii. Determine the 20 ruling lines that pass nearest to the vector N.

iii. For the 20 nearest passing ruling lines determine the line which produces the most positive dot product of the two vectors d and N, see Figure AII.8.

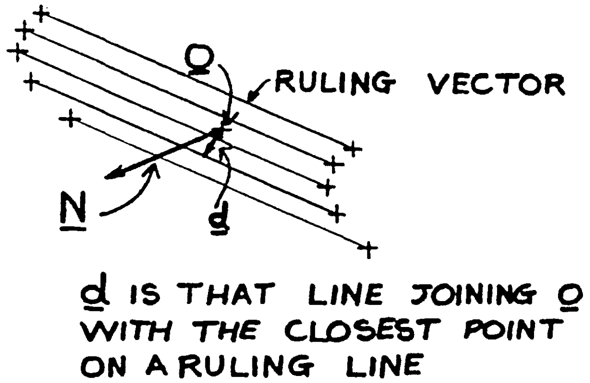


Figure AII.8

Definition of the Vector d

iv. Determine the two ruling lines adjacent to the line found in procedure iii..

v. Project lines through the control points from the 3 ruling lines determined from procedures iii. and iv. in a direction parallel to N and into a plane orthogonal to N, see Figure AII.9.

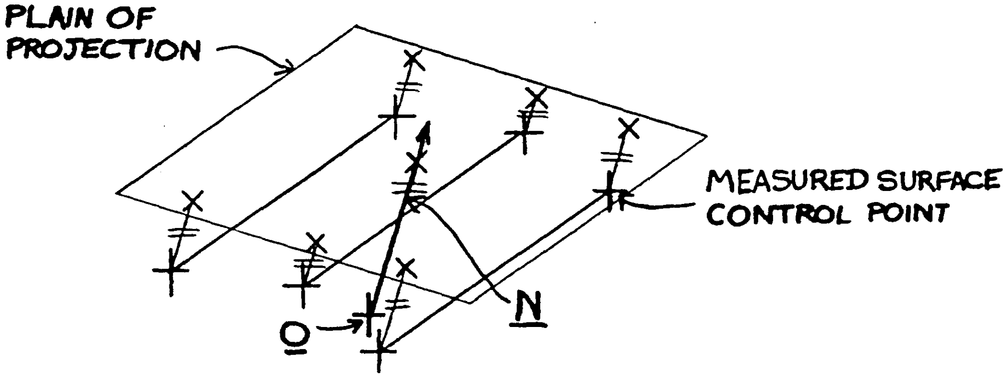


Figure AII.9

Projection of Control Points into a Surface Normal to N

vi. In the projected plane all lines will appear as points. If the point representing the vector N is bounded by the limits of the project plane, as in Figure AII.10, an intersection will occur through the surface in the vicinity of these ruling lines.

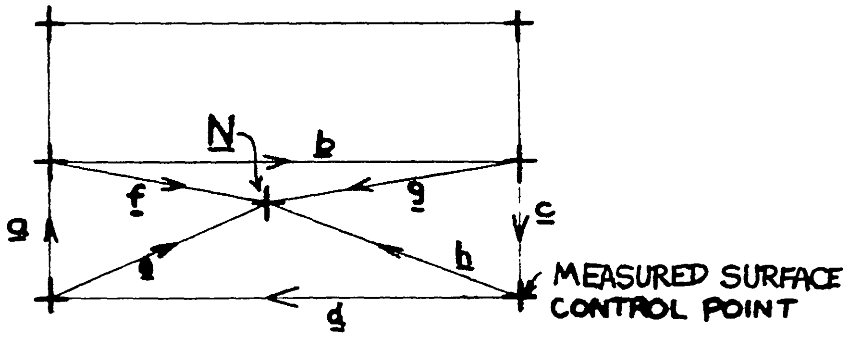


Figure AII.10

Projected Plain Normal To Vector N, Illustrating N Bounded By Plain Limits

$\underline{N}$ is bounded by the limits of the plane if the following dot products all have the same sign $\underline{a} . \underline{e}$, $\underline{b} . \underline{f}$, $\underline{c} . g$, and $\underline{d} . \underline{h}$. If this procedure fails it means that there is no intersection with this part of the surface and so the algorithm moves onto another area or declares no intersection.

vii. If procedure vi. yields a positive intersection it is now necessary to interpolate the precise location of the intersection with the surface. To do this determine the distance between $\underline{N}$ and the closest ruling vector. Use this distance to estimate a nearest ruling vector along the surface, see Figure AII.11. Continue to interpolate to a closer and closer ruling vector until the distance between $\underline{N}$ and the ruling vector is less than a specified tolerance, usually 0.0001mm.

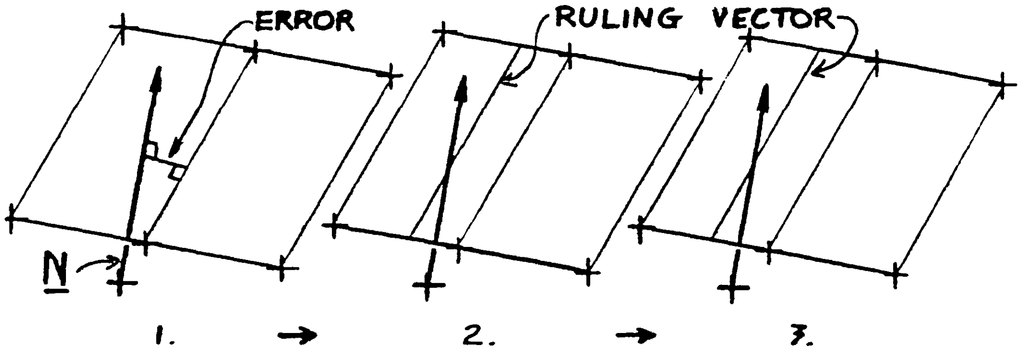


Figure AII.11

Interpolation of Ruling Vectors To Determine Intersection With Surface

viii. The position along $\underline{N}$ closest to the ruling vector $\underline{I}$ represents the intersection of $\underline{N}$ with the aerofoil surface, see Figure AII.12. Therefore the surface error is given by ($\underline{I}$ - $\underline{O}$).

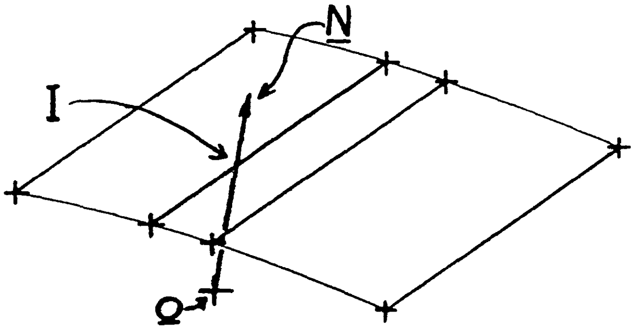


Figure AII.12

Illustration Of Calculation For Aerofoil Surface Error

4.7 The Calculation Of Surface Error For Swept Annulus Surfaces

An annulus surface is made up of a number of simple surfaces defined as the rotation of arcs and lines about the engine centre line. To determine the surface error between a measured point and the nominal annulus surface each simple surface is tested until the measured point is found to be above a particular surface. Once a surface has been identified it is passed to a routine which recursively subdivides the surface into smaller patches which lie below the measured point. When the patch identified below the point becomes smaller than a predetermined size the centre of the patch is said to join the surface to the measured point along the shortest distance and hence the error is found. For this algorithm a surface patch is specified in a certain manner according to Figure AII.13.

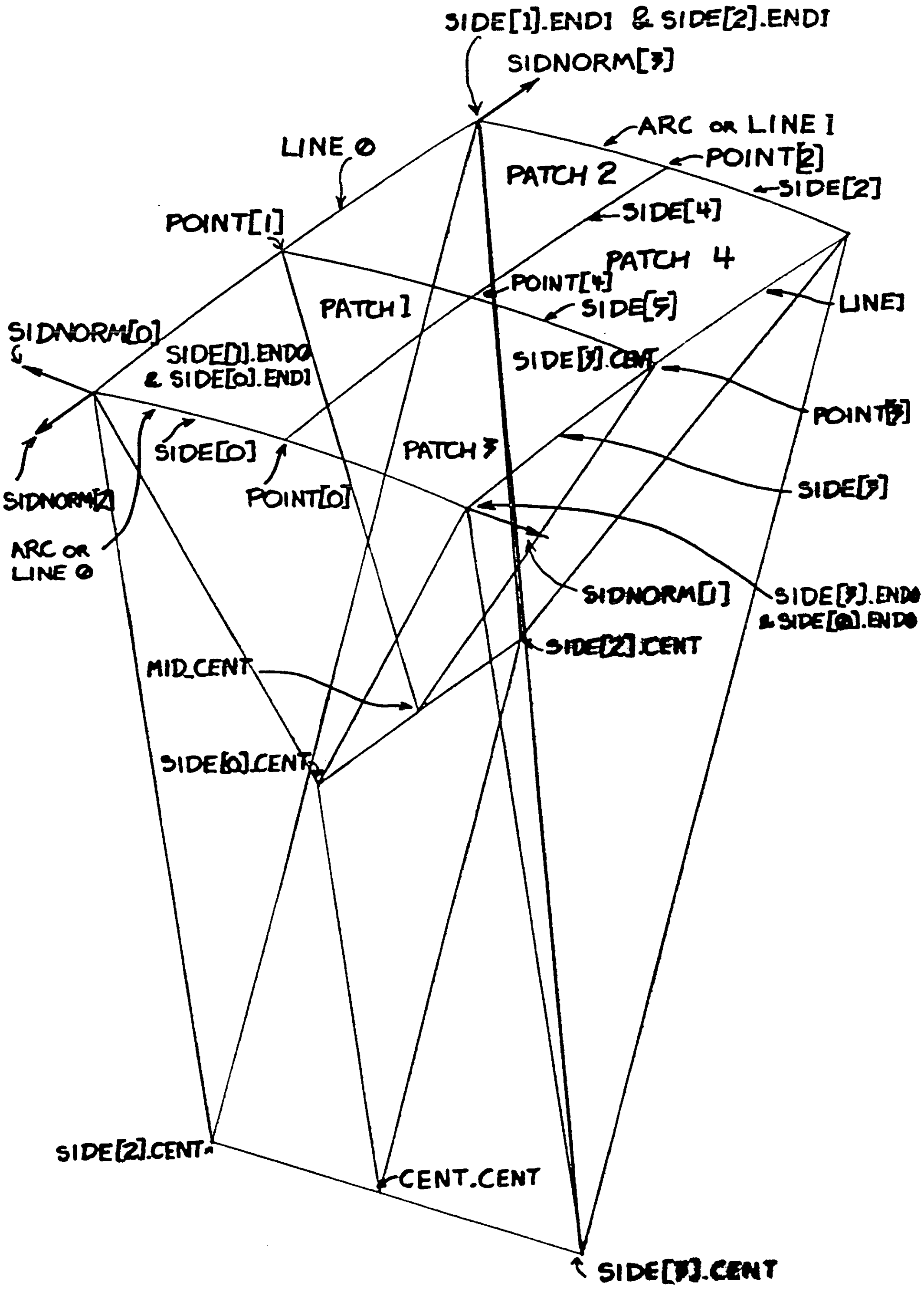


Figure AII.13

Convention Of Names For a Swept Surface Patch In The Surface Error Calculation Algorithm

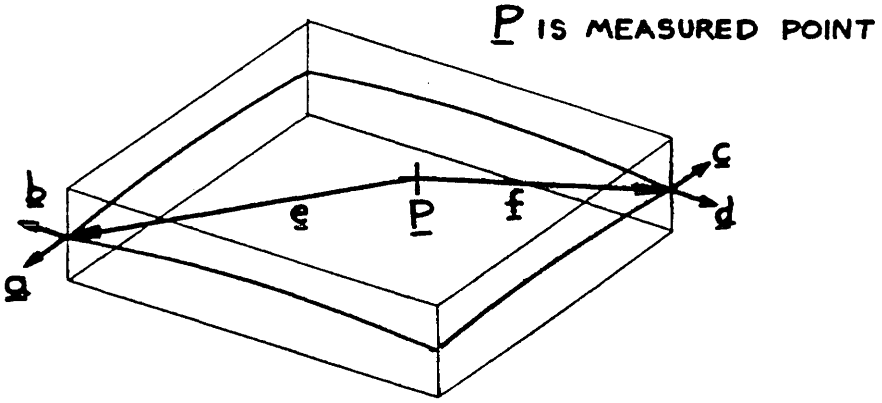
4.7.1 The Swept Surface Error Algorithm

i. The controlling function passes through the set of swept surfaces in an annulus until it finds the surface above which the point exists. This check is performed in the following manner:-

   a. Divide the surface into the 4 patches as shown in Figure AII.13.

   b. Define the 4 planes that bound each patch, shown in Figure AII.14.

   c. For each patch determine if the point exists on the same side of all of the planes, if it does then the measured point is above that patch.



P IS MEASURED POINT

a, b, c & d ARE BOUNDING PLANE SURFACE NORMALS

e & f ARE LINES JOINING P TO PATCH CORNERS

Figure AII.14

Planes Bounding A Swept Surface

The point is bound by the planes if the dot products of a . e, b . e, c . f. and d . f all have the same sign.

ii. If a point does exist above a patch, the patch is recursively subdivided until the patch below the point has a greatest width of 0.0005 mm. The centre of the patch will represent to a certain tolerance the shortest distance between the surface and the measured point.

iii. Because of the definition of the swept surfaces the patch below the measured point is not the truly shortest distance between the point and the surface. Therefore a correction is applied to the error. See Figure AII.15.

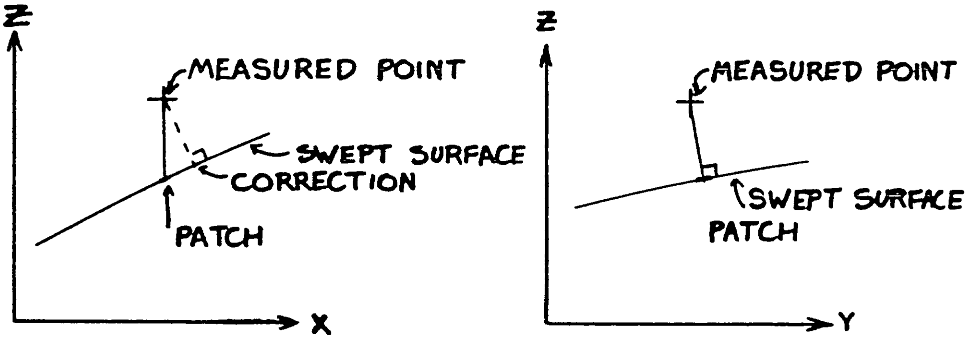


Figure AII.15

Correction To Error Obtained By Swept Surface Algorithm

The diagram shows the relationship between the measured point and the patch, a correction is applied to the error in the xz plane.

5 Nomenclature

ABC Points	The Zero Error Target Datum Points defined on a blade surface for defining the stacking axis of the blade
APIP	Automated Proof Inspection Package
Blade Modeller	A PANACEA system developed for modelling Gas Washed Surfaces of Turbine Blades
CAD	Computer Aided Design
b-spline	A type of curved line interpolation between control points
CIBMS	Computer Integrated Blade Manufacturing System; a computer system philosophy developed by N.Brookes for the manufacture of turbine blading
CIM	Computer Integrated Manufacture
CMM	Coordinate Measuring Machine
Ethernet	An inter-computer communications system
GEOPAK	The Mitutoyo CMM control program
HP	Hewett-Packard
IGES	International Graphics Exchange Standard for the transfer of CAD database information between systems

IIS	Integrated Inspection System
Macroblock	A PANACEA database type for grouping other database types together
NDF	Neutral Datafile Format; a common language between CAD systems and Coordinate Measuring Machines
Nodes	PANACEA database type for 3D points
NURBS	Non-Uniform Rational B-Spline; a type of curve line interpolation between control points
Overlay	An additional PANACEA program
PANACEA	An Imperial College CIM Programming Environment
PH9	A Renishaw Probe Head
PRIMINDEX	A PANACEA variable type for storing databases
RS232	Inter-computer communications standard
SUN 3/60	The Computer used to develop the IIS
TP2	A Renishaw Touch Probe
UNIX	A Multi-User Computer Operating System
WYSE	The name of the dump terminals attached to the SUN 3/60

6 References

[1] Lee, S.A., "Introduction To An Automated Turbine Blade Proof Inspection System and Implementation of Phase 1 The Measurement Of A Test Piece", Department of Mechanical Engineering, Imperial College of Science, Technology and Medicine, University of London, November 1987.

[2] Lee, S.A., "Discussion Of The Automated Proof Inspection System After the Completion Of Phase 2 : The Measurement Of A Turbine Blade", Department of Mechanical Engineering, Imperial College of Science, Technology and Medicine, University of London, April 1988.

Appendix III

A Line-of-Sight Algorithm For Optimum Measurement Probe Orientation and Close Quarters Collision Avoidance

1 Introduction

The principle of the algorithm described in this appendix is to provide a generalised method by which either contact or laser non-contact probe heads may be controlled to measure specified points on a modelled geometry. It assumes that the modelled geometry is capable of providing points from its surfaces and associated surface normals at these points. By using only points from the modelled surface and their surface normals this algorithm is independent of the surface types used in the model.

The algorithm is based on the principle that a probe may approach a specified measurement point along a straight line provided that the line is free to extend to infinity without intercepting any part of the geometry. In other words it is possible to see the measurement point from a distance - it is on a line-of-sight.

The domain of lines-of-sight for any measurement point represents a region in space through which a probe may be passed without fear of collision. In the particular algorithm described below the domains of lines-of sight are defined by cones.

2 Defining a Line-of-Sight Cone

Line-of-sight cones described below are defined with their apex at a 'stand-off' distance from the measurement point, a vector representing the centre-line of the cone and an angle about which the cone sweeps from the cone centre-line.

In order to construct a probe path a line-of-sight cone must be defined for each point that is to be measured.

The algorithm :-

i. Specify an array of points over the entire surface and calculate their surface normals. Project these points a short distance from the surface along their surface normal (e.g. 1-2 mm for turbine blades). These points will be referred to as cone calculation points.

ii. Specify which points are to be measured and calculate their surface normals.

iii. To define the line-of-sight cone for a particular measurement point start by defining the apex at a 'stand-off' distance (e.g. 2mm for a touch probe measuring a turbine blade) from the measure point, with the cone centre-line parallel to the measurement point surface normal and with a cone sweep angle of 90°, i.e. a plane.

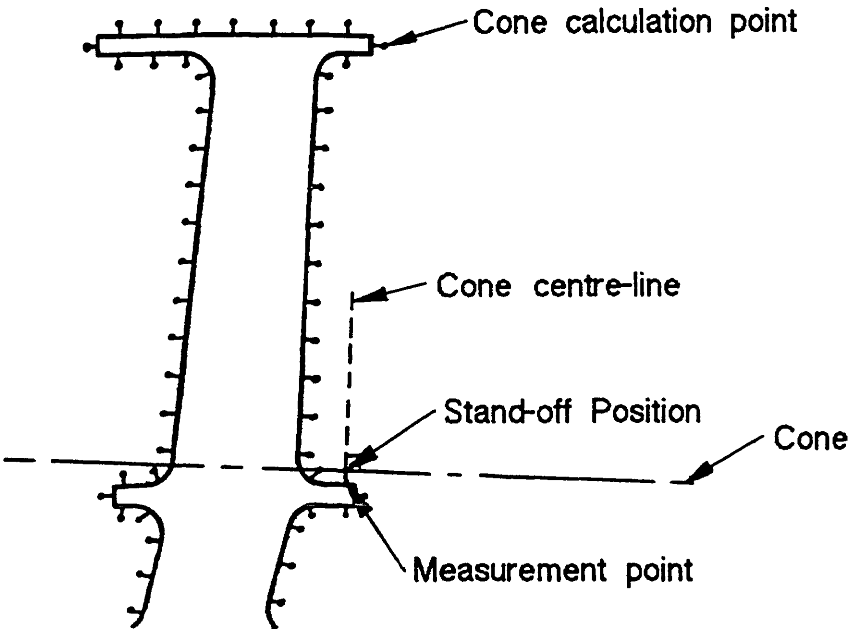


Figure AIII.1

Initial Line-of-Sight Cone Definition before Processing with Cone Calculation Points

iv. Calculate the shortest distance between each cone calculation point and the line-of-sight cone disregarding those points below it.

v. Starting with the closest point to the line-of-sight cone, put the cone calculation points in order of distance from the cone.

vi. For each of the cone calculation points above the line-of-sight cone calculate if the point is encompassed within the currently defined cone. If it is not proceed to the next cone calculation point. If it is redefine a new cone as being the largest cone that may be placed in the original cone but lies on the new limit of a line joining the 'stand-off' position with the cone apex.

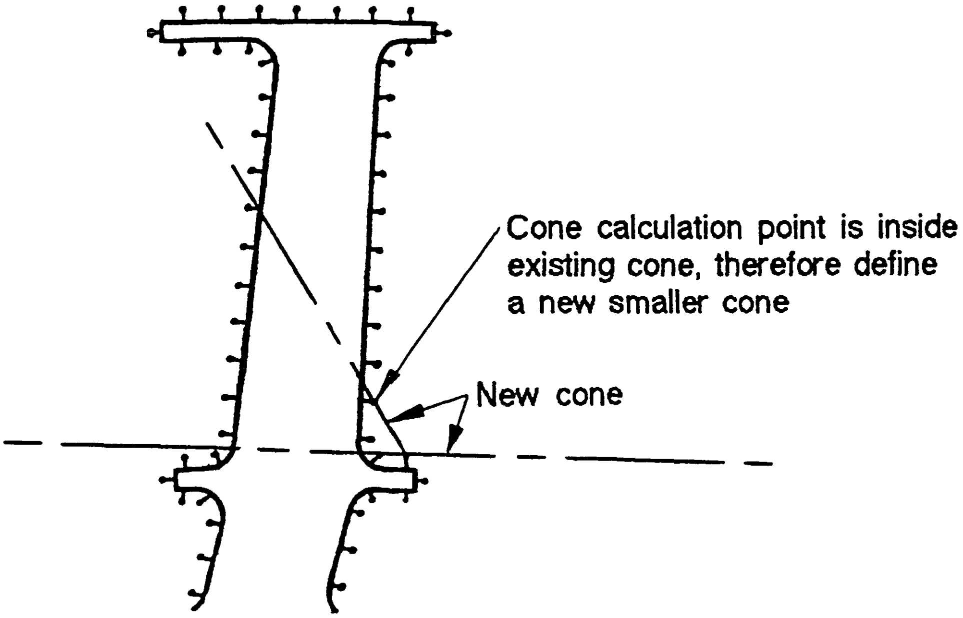


Figure AIII.2

Redefine the Line-of-Sight Cone From The Cone Calculation Points

Once all of the cone calculation points have been processed a cone is defined which provides a collision avoidant domain in which the probe may be moved into the 'stand-off' position before taking a measurement.

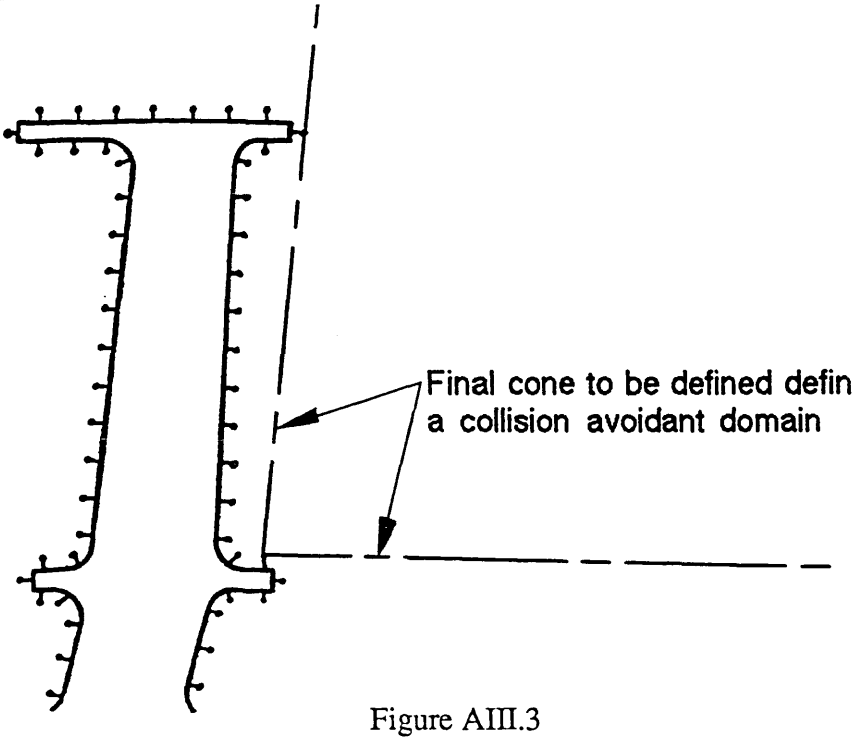


Figure AIII.3

After Processing all of the Cone Calculation Points the Line-of-Sight Cone Represents a Collision Avoidant Domain for Probe Path Construction

3 Calculation of Probe Orientation within a Line-of-Sight Domain

The algorithm for choosing the optimum probe orientation within a line-of-sight domain will depend on the type of probe being used. If the probe is optical then it should be aligned along a line inside the domain that is the most parallel to the surface normal. If the probe is a contact device the best orientation may be through the centre of the domain.

For optical probes which scan over a surface a series of target points and orientations may be combined together to form a path for 'on-the-fly' measurement.

When choosing orientations for touch probes it is possible to use adjacent cones as a means of determining whether the same probe orientation may be used for both measurements.

When moving a probe between 'stand-off' positions the intersection of the current and next cone provides an intermediary position which is on a collision avoidant path between the two 'stand-off' positions.

After calculation of all of the probe orientations for measurement of an object it would be possible to select into groups all measurements that use the same orientation and to measure these together, thus reducing probe reorientating time. By storing the measurement order in which the object is to be measured it would be possible to interpret the results with no real difficulty.

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A COMPUTER INTEGRATED APPROACH TO DIMENSIONAL INSPECTION

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Abstract

It has been identified that in order to gain a better understanding of the casting process used in the manufacture of Turbine Blades, a full dimensional inspection of dies, wax patterns, and of the blades themselves at the various stages of the manufacturing cycle needs to be carried out. Storing the inspection data in a database will facilitate understanding of the effect and interelation of all process variables. This understanding will eventually lead to process modelling and prediction. With conventional inspection techniques this would lead to unacceptably prolonged manufacturing lead times for a new design along with a tremendous quantity of numeric data to be processed and correlated against the design. However a significant improvement can be realised by automating the lengthy manual inspection processes, as well as the correllation and the interpretation of the inspection data. As a result, it was decided to develop a Computer Integrated Dimensional Inspection System supporting contact and non contact methods of surface digitisation. An extensive error handling facility enables errors to be found between nominal and actual surfaces. These errors may be presented, for example as contours of error, or be used in a 3-D best-fitting process which minimises error between actual and nominal surfaces. The design and development of the system are given in outline with a resume of its use. The system has proved to be very powerful in dealing with the inspection of the highly complex forms involved in turbine blading.

1. Computer Integrated Turbine Blade Manufacturing System

1.1. The Investment Casting of Turbine Blades

Figure 1 shows a simplified diagram of the investment casting process for a hollow turbine blade. As may be appreciated from the diagram the process is complex compared to metal removal manufacturing processes. It is difficult to determine the precise geometric distortions that the blade will undergo and the metallurgical characteristics of the resulting casting. In the past this has meant that loops through the process ("Proof Cycles") had to be repeated, changing process variables on a 'trial-and-error' basis, until an acceptable casting was achieved. These proof cycles greatly contributed to the blade development lead time.

The problems of investment casting turbine blades are compounded by the fact that inspection of the geometry of blades is a difficult procedure. For inspection purposes the blade is clamped about two sections which are taken to have zero error. If these sections are out of tolerance, all the errors will be "thrown onto" the rest of the blade, which may be correct. Only a small number of sections are inspected and therefore only a limited knowledge of the blade geometry can be gained. The inability to detect geometric errors has tended to increase the number of proof cycles that the blade would undergo. With this background a Teaching Company was proposed to apply CIM techniques to achieve a reduction in manufacturing development lead times.

1.2. Task for the Teaching Company: The Development of The Computer Integrated Blade Manufacturing System

Before applying any CIM techniques the present system was considered in terms of lead time components. Some simplification and improvement of the system was achieved as a result of this study, but in order to further improve the process the use of CIM techniques was necessary (Brookes [1]). The following projects were therefore instigated with the object of being integrated to form the Computer Integrated Blade Manufacturing System (CIBMS).

1.2.1. Modeller Interface

The turbine blade was modelled using the PANACEA system, developed at Imperial College (Glover [2]). The modelled blade was derived from IGES point strings of aerofoil sections and drawings of the annulus configuration. A reverse process was also devised to derive point string sections from inspected blades to be sent back to the Rolls-Royce Mainframe for analysis by performance programs.

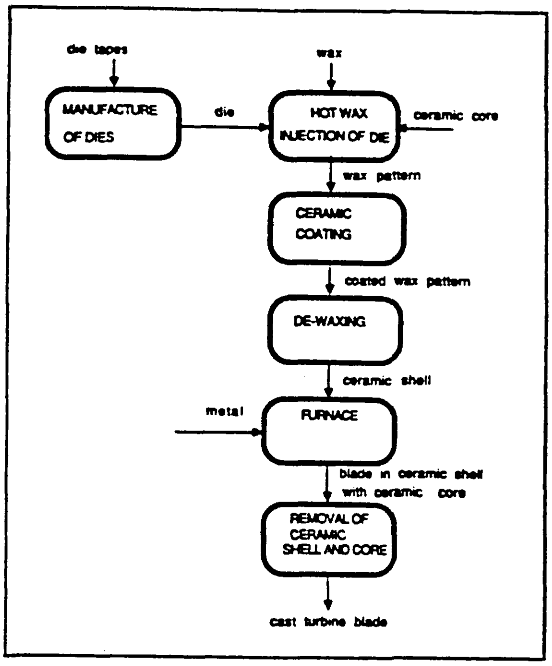


Figure 1 : Investment Casting of Hollow Turbine Blades

1.2.2. Process Understanding

A project to develop a "Process Predictor" was instigated. The predictor would give the recommended die geometry to produce the casting and also the necessary process settings (e.g. furnace temperature, ceramic shell thickness). The Process Predictor would achieve this by Expert Systems and Finite Element Analysis techniques. The rules used within the Predictor would be cummulatively updated by feedback of actual casting geometry produced and process variables. Work is still being carried out to gain an initial understanding of the casting process using experimental design techniques.

In order to gain geometric knowledge of the casting process there is an important need to measure dies, cores, waxes and blades. To do this accurately and efficiently a second task was specified to Automate Proof Inspection of these items (Proof being the term used to describe the full dimensional inspection given to blades during "Proof Cycling").

1.2.3. Automated Proof Inspection

This aimed to reduce the lengthy manual proofing process by the use of a Coordinate Measuring Machine (CMM). The use of the CMM removes the need for inspection fixturing and the inspection data it provides allows for a full three dimensional model of the actual blade to be created, thus enabling 3-D error display and best-fitting.

1.2.4. Automated Generation of Die Machine Paths

The design model can be used to generate the cutter paths for the die machining. Using Process Models properties like metal shrinkage e.t.c. can be accounted for in the manufacturing of the die. If after proof inspection, the die is not correct, then the process modeller could be improved to generate cutter tapes for a new die.

All the processes outlined above would on there own produce a reduction in development lead times. However, by integrating the processes, the lead times may be further reduced by speeding the data flow between the systems, and eliminating the need to duplicate the blade modelling procedure by holding data that is required by more than one process in a common database. A system diagram for the CIBMS is shown in figure 2.

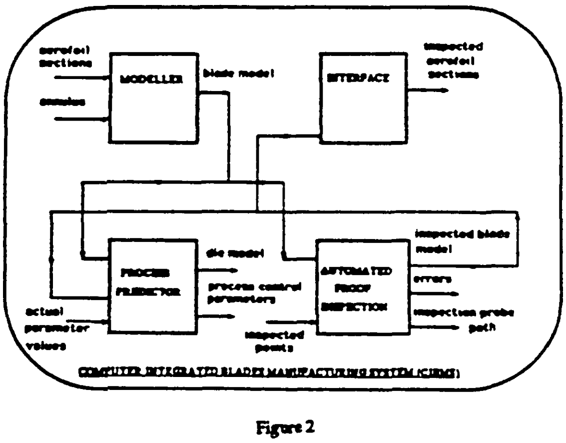


Figure 2

1.3. Benefits Of The CIBMS

The object of the Teaching Company Program was to reduce the manufacturing development lead times for turbine blades. This will be achieved in the following manner :-

i) Reduction of the number of proof cycles.
ii) Shortening the lead time for each proof cycle.

Not only will there be a reduction in the development lead time, but complex geometry blades with better performance characteristics can be developed more quickly. Feedback of actual blade sections to the designers will provide them with better information on which to base decisions on whether a particular blade is acceptable.

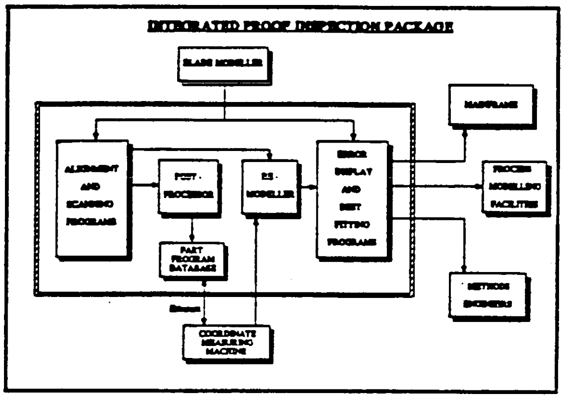


Figure 3

2. Design of an Integrated Dimensional Inspection System to Measure Turbine Blades

The purpose of the Integrated Dimensional Inspection System for the CIMBS was that it should provide geometric information not only about the cast components but about the various stages involved in their production i.e. dies and waxes. It was recognised that in order to measure such items some knowledge of the nominal blade would be necessary to drive the measurement devices. Since blade surfaces are extremely complex containing a great deal of information this some what dictates the need for computer systems when ever handling such data. A programming environment for the inspection system would however, enable the handling of nominal blade information not only to assist in the measurement of the blades but also in comparison of actual with nominal blade surfaces. The basic requirements of the system to obtain geometric data of both nominal and actual blade surfaces meant that two way communications would be necessary with both Design databases and Measurement devices. After consideration with all the factors involved a system was designed which is illustrated in Figure 3.

The Blade Modeller brings the various design databases together to form a blade model inside the PANACEA database. Alignment and Scanning part program generators use these models to enable CMMs to measure actual blades. By writing the part programs in a standard CMM language different CMMs can use the same part programs through their own translators (It should be noted that some CMMs are fundamentally different from others and consequently full part program compatibility does not apply to all machines, however many aspects of the part program generation for any CMM are the same and consequently a new CMM type may be accommodated into the system without having to write a completely new part program generator).

For communications between the Inspection System and the CMMs a simple RS232 cable could be used, however the use of an Ethernet System [3] would enable may different types of CMM to communicate with the Inspection System more quickly and efficiently. The Ethernet could also be used for logging inspection data to the workstation.

Once logged the inspection data must be processed in order to find surface errors. The easiest way of performing this would be to remodel the inspected points back into sections inside the PANACEA database, thus generating an actual blade model. The error between actual and nominal surfaces is a volumetric difference which because of its piece-wise nature would be practically impossible to find in full definition. A simpler alternative would be to send vectors normal to the nominal surface to intersect with the actual surface thus generating discrete error vectors which could be used to represent the volumetric difference if their density over the surfaces was sufficient. Once found the error vectors could be plotted, for example as contour plots or be used to mathematically minimise surface error between the surfaces, a process commonly known as "Best-Fitting".

3. Present and Future Inspection Technology

The basic requirement for almost any inspection system is to be able to take dimensional information from surfaces, in the case of blades from 3-D free-form surfaces. In the past many different types of equipment have been developed in order to do this, all tending to fall into one of two categories Contact or Non-Contact tools.

Contact tools involve the positioning of a device onto the surface in question and using the pre-calibrated position of the device to determine the surface measurement. Probably the most advanced contact measuring device is the Coordinate Measuring Machine (CMM), they now offer accuracies of 0.005mm or better and may be controlled to measure 3-D surfaces. They are however slow at data acquisition and could not be used for measuring turbine blades in production environments.

Non-Contact tools tend to employ one of the many types of physical techniques of remote sensing, for example laser triangulation. Being newer in design most non-contact devices are not as flexible as many contact tools for blade measurement. However they do offer potential advantages over contact tools in terms of data acquisition rates and the ability to measure soft objects like waxes.

For the Integrated Inspection System II was recognised that there was a need to measure large quantities of data from surfaces, some of which would be soft. Since there was no machine on the market capable of meeting the required specification it was decided to design and build a flexible laser triangulation non-contact device (Tsabourakis et al.[4]). It was also recognised that because of the long lead times required for this machine's development that the 'Inspection System' should be developed with an existing contact measuring device. The machine chosen was a Mitutoyo CMM with a 800*600*600 mm working volume. The 3 axes on the machined were to be complemented with a Renishaw PH9 motorised head carrying a TP2 touch probe, adding a further 2 axes. The Mitutoyo had proven repeatability and accuracy and had software support.

3.1 Development of a non-contact gauging system

The range sensor is based on the principle of laser triangulation, shown in figure 4. When the scattered surface is translated by D_x in a direction parallel to the incident beam, the imaged spot will move across the sensor by an amount D_y. Thus, by measuring D_y the translation amount D_x can be calculated from the following relationship:

$$D_y = \frac{(f+r).\sin(\theta).D_x}{L\ \sin(\phi) - \sin(\phi+\theta).D_x}$$

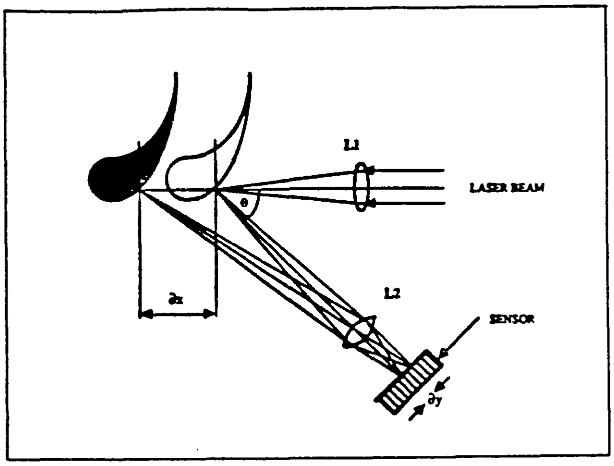


Figure 4: Triangulation principle

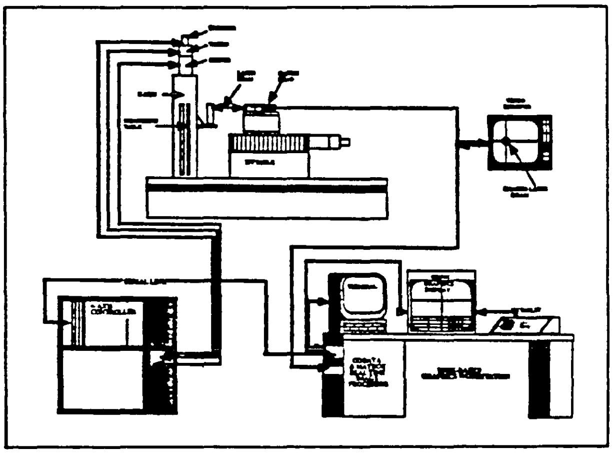


Figure 5: Profile inspection system

The design of a non contact optical probe faces problems relating to the curvature of the blade surface, the interaction of the incident radiation with the object surface, as well as occlusion problems common to triangulation type of measurements. Two phenomena precede when electromagnetic radiation interacts with a rough surface: a) Scattering, and b) Diffraction. The result of scattering is that the reflected power in a solid angle varies exponentially with the observation angle and surface roughness. This restricts the range of usable viewing angles. The result of diffraction is the generation of a noise pattern (Speckle) which reduces the information content of the reflected energy. Because of the speckle noise the optical magnification cannot exceed unity. To achieve a resolution of 5-10 μm, subpixel interpolation algorithms were employed.

The complete inspection system is seen in figure 5. The object to be inspected is mounted on a rotary table which can also move up or down. These movements enable measurement of all the surface points. A laser beam (He-Ne) is focussed onto the surface of the object and the signature of the beam is monitored by two CCD area sensors each featuring a total of 300K individual elements (640x480). The gauge head, consisting of the laser source and the sensors, is placed on a X/Y table.

The sensors view the laser spot from either side of the laser beam at a fixed 30° orientation and in the same horizontal plane as the beam. From the displacement of the laser spot across the sensor and the sensors and the servoing values along the X, and Y axes, the range at each point is computed. The range value is then related to the coordinates of the positioning system to compute object dependent X, Y, Z values which are stored in the database and also displayed in real time.

The X/Y table allows the gauge head to scan sections of the object and also track the spot when it moves out of range. This action is necessary to compensate for the restricted dynamic range.

The video information is fed to the multiplexed input of a real time image processor. The video memory of the image processes is mapped onto the memory space of a UNIX based microcomputer which also controls all the movements through a 4-axes controller.

The development of the prototype proved that triangulation based probes are able to achieve accuracies of 1-10 μm with relatively simple and inexpensive hardware, provided that the laser intensity is controlled in order to compensate for excessive errors caused by reflectivity changes due to surface finish and curvature.

The measurement speed for the prototype is 0.2 secs/point for small increments. Although this figure compares favourably with a typical speed of 2 secs/point for a contact probe, it is still less than the true capability of the system. The reason is that the controller stops before a new measurement is taken. Also, intensity tests have to be carried out to avoid saturation and low returned energy conditions. The speed can be increased up to 50 points/sec if linescan CCD sensors are used, and a continuous path motion can be maintained over a complete cross-section. This can be achieved if a probe path is generated for each section and then downloaded to the controller. That way the measurements will be collected on the fly.

4. Required Computer Technology For The System

In order that the Mitutoyo CMM or Laser Based Inspection machine could measure a blade surface it was recognised that information about the nominal blade would be required. Being highly complex the best environment from which to provide nominal data was a digital blade model in a computer system. The Mitutoyo CMM and the proposed laser system would be controlled by a computer and so would be suitable for communications with digital blade information.

4.1. Software Requirement

Having established that a computer environment was indeed the best way to proceed it was necessary to find a suitable choice of system. However there were no examples of CAD/CAM to CMM links for surfaces as complicated as those of blades, making it necessary to develop a new system. At the time Glover [2] was working on a CIM system PANACEA and it was decided to work with him in developing a CIM environment capable of CMM communications. Onto the system a blade modelling facility was to be developed along with the Inspection facilities.

The Mitutoyo CMM was to run on an MS-DOS type computer which facilitated the use of Ethernet. This would enable the part programs to be stored in the workstation and be run from the CMM without duplication and for inspected data to be logged back from the CMM to the workstation easily and efficiently. It was also necessary that the CMM software was vendor supported as it was felt that additional functions would be required as a CIM system was interfaced with it.

4.2. Hardware Requirements

The sophistication of the CIM system, Blade Modeller and Inspection Facility meant that realistic computing performance could only be obtained from the power of a workstation. The cost of a modern workstation was a problem, however it was not substantial when compared with the cost of the measuring machines while the extra facilities available, like multi-tasking, made the workstation an ideal environment for the development and running of the overall Inspection System.

5. Resume of The Use of The Inspection System

The following paragraphs describe the various stages involved in the use of the Inspection System :-

1. The blade to be measured is modelled in the PANACEA Blade Modelling Facility, at the moment this is restricted to the Gas Washed Surfaces of the blade.

2. A part program generator interatively produces part programs to measure the blade on the CMM. Usually this involves 3 types of program:-

a) 'Pre-alignment' a simple routine used to establish the blade's coordinate system to within 2mm when the blade is first placed onto the CMM.

b) 'Alignment' a complex routine used to establish the true blade definition coordinate system after pre-alignment.

c) 'Scanning' which controls the CMM to measure points on the surface of the blade.

All of these routines are compiled into a standard CMM language which allows for the use of the part program on most similar types of CMM. The language chosen was Computer Vision's Neutral Datafile (NDF) Language.

3. If the CMM does not have an NDF translator a postprocessing facility may be strapped to the system to enable the NDF programs to be postprocessed into the CMM's specific database structure and stored in the workstation.

4. The CMM operator may run the part program through the Ethemet, logging inspected data back through the Ethemet to the workstation.

5. A remodelling facility enables logged data to be converted into actual blade surface models in the PANACEA database.

6. Intersection and Display facilities enable surface errors to be calculated between actual and nominal surfaces and displayed either as sections or as contour maps of error.

7. 3-D Best-Fitting facilities enable minimisation of errors between surfaces, incorporating requested criteria. For example a calculation of mimimum die modification or optimum aerodynamic performance.

8. The inspection and best-fitting results may be presented on the screen or plotted as hard copy or even passed to another computer in digital format. Thus information on the actual blades may be presented to Method Engineers, Designers e.t.c or onto other computers for detailed analysis.

6. Results

The following diagrams are from a sequence of operations performed when using the Inspection System and the laser probe:-

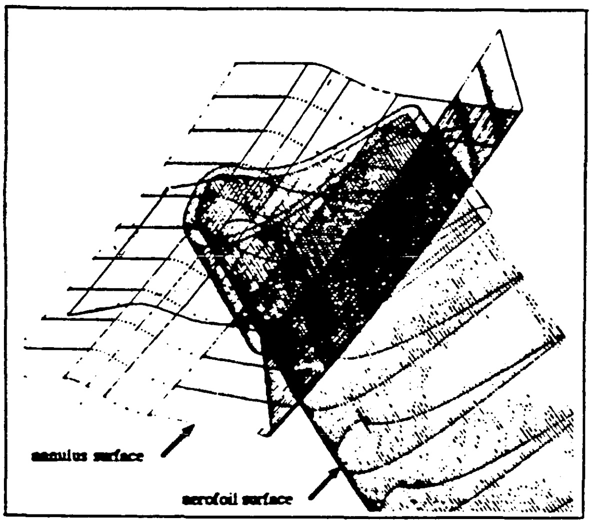


Fig. 6: Lower Annulus Gas Washed Surface Model of a High Pressure Blade.
This view illustrates the blade aerofoil and how it intersects with the lower annulus surface to form a blade model.

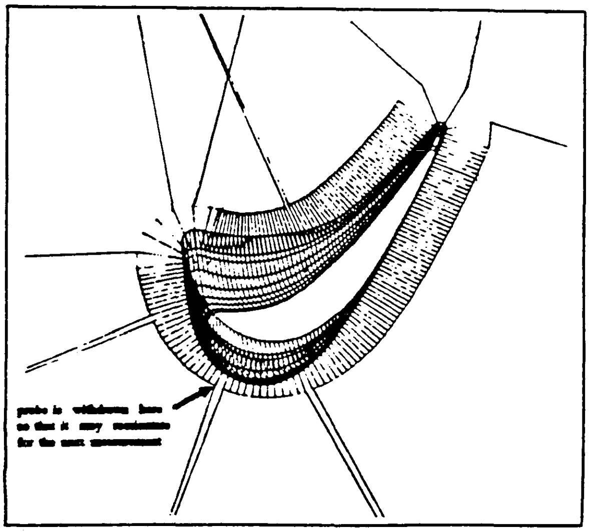


Fig. 7: Scanning a Section of an Aerofoil.
This view illustrates how a probe path, for a contact probe, is built up around a section of an aerofoil. Note that the probe moving along the path travels surface normal when touching the blade to take a measurement.

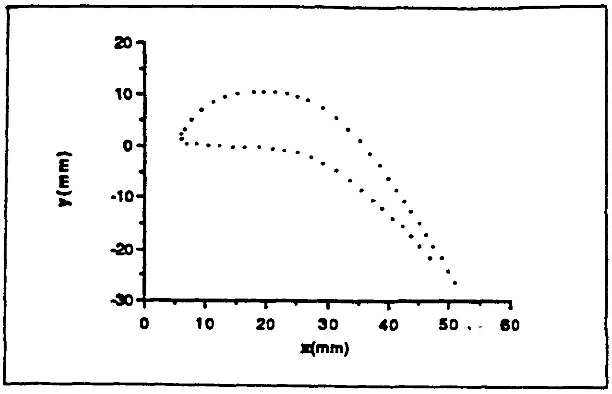


Fig. 8: Results of a Single Scan using Laser Probe.
This view illustrates the measurement results obtained when one section of an aerofoil was scanned using the laser probe.

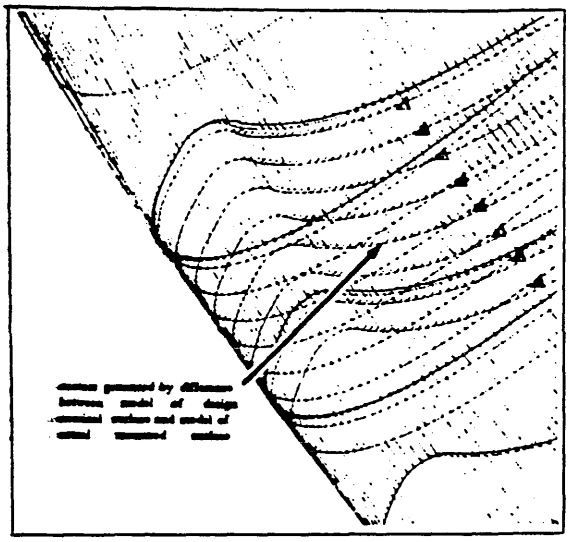


Fig.10: Errors Between Actual and Nominal Surfaces of an Aerofoil.
This view illustrates vectors of error between two surfaces. At certain heights up the aerofoil surface sets of vectors have been sent out surface normal to the nominal aerofoil. These vectors are intersected with the actual aerofoil model, thus generation vectors of error.

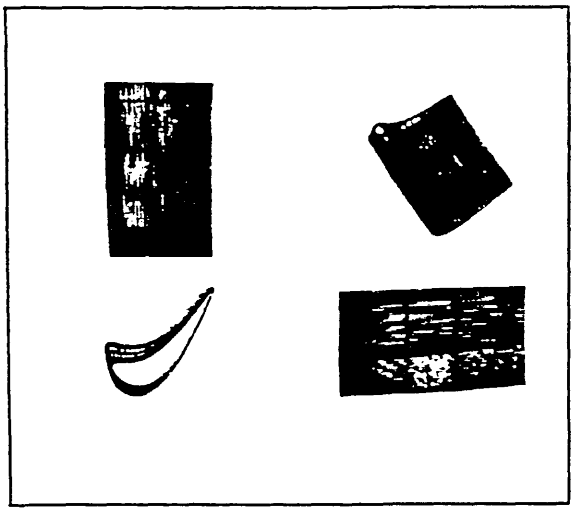
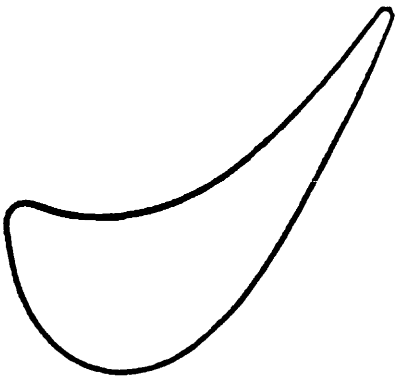
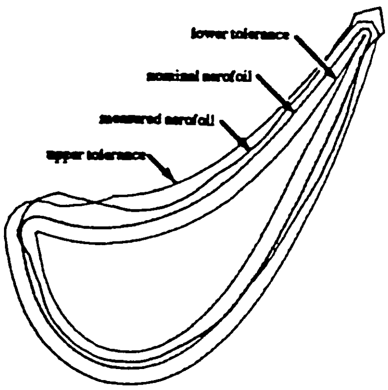


Fig. 9: A Remodelled Aerofoil Surface..
These four views of the aerofoil surface illustrate how six measured sections have been remodelled to form an actual blade model.



No Surface Magnification



10 * Surface Magnification

Fig.11: Error Displays of Measured Aerofoils. The large quantities of data from the inspection of surfaces requires careful display consideration. Here surface error is magnified in order that a realistic observation may be made of the surface error.

7. Conclusions

The following are a list of major conclusions from the use of the Inspection System:-

1. The complexity of incorporating a Blade Modelling System to the overall Inspection System has shown that there is a need for a full blade model generated by the Design Departments. It is not the inspectors job to spend time modelling blades.

2. The generation of part programs has been successful in the CIM environment. The various stages of alignment and scanning having been shown to run satisfactorily, although speed is a problem on the current CMM.

3. The use of the Ethernet has enabled the storing of part programs in the workstation. The fast access speeds of the Ethernet enable many CMMs to be attached to the same database and for inspection data to be logged back into the workstation.

4. The complex geometry of blade surfaces dictates the necessity for extensive error handling facilities.

5. The inspection side of the Computer Integrated Blade Manufacturing System has illustrated the use of an Integrated Inspection System. The principle of using a CIM system to use design models to compare with actual manufacturing products has shown to be very powerful, especially with the highly complex surfaces of gas turbine blading.

6. The feedback of inspection data may be used by a variety of departments, Design, Methods, Process Modelling e.t.c.. It is a feedback loop for better quality.

7. The use of the system has shown the need to be able to measure large quantities of components at speed. A facility probably most easily met in the future by optical probe devices

8. Nomenclature

- CAD/CAM: Computer Aided Design/Computer Aided Manufacture
- CCD: Charged Coupled Device
- CIBMS: Computer Integrated Manufacturing System
- CIM: Computer Integrated Manufacturing
- CMM: Coordinate Measuring Machine
- NDF: A standard CMM control language proposed by Computervision for CIM or CAD/CAM to CMM communications
- PANACEA: An Imperial College CIM system

9. References

1. Brookes, N.J. (1988) Reduction on the Development Lead Times of Complex Investment Castings by the Application of CIM Technology, The International Journal of Advanced Manufacturing Technology, 3 (2), 41-49.

2. Glover, R. (1988) A Graphics Environment for CIM Applications, The International Journal of Advanced Manufacturing Technology, 3 (2), 31-39.

3. 3 Com Ethernet II Users Guide

4. Tsabourakis, N., Ristic, M., Besant, C.B. (1988) Development of a Profile Gauging Sensor, The International Journal of Advanced Manufacturing Technology, 3 (2), 51-66.

Bibliography

Chapter 2:

[1] Ruffles, P.C., "Keys to Excellence in Design and Manufacture", Proceedings of Aerotec 90, Society of American Engineers, October 1990.

[2] Dodd, A.G., "Mechanical Design of Gas Turbine Blading in Cast Superalloys", Materials Science and Technology, Volume 2, May 1986, pp476-485.

[3] Langley, K.R., "Turbine Blade Design", Cranfield Institute of Technology Gas Turbine Design Course, May 1986.

[4] Ramsden, K.W., Melling, A., "Preliminary Turbine Design", Cranfield Institute of Technology Gas Turbine Design Course, June 1987.

[5] Higginbottom, G.J.S., "From Research To Cost Effective Directional Solidification and Single Crystal Production - an Integrated Approach", Materials Science and Technology, Volume 2, May 1986, pp442-460.

Chapter 3:

[1] Cardew-Hall, M.J., "Modelling and Integrated Inspection of Cast Turbine Blades", PhD Thesis, Imperial College, University of London, June 1988.

[2] Kumar, N., Besant, C.B., Ristic, M., "Process Variables Determining the Dimensional and Metallurigal Properties of Directionally Solidified Cored Turbine Blades Produced by Investment Casting of Super-Alloys", The International Journal of Advanced Manufacturing Technology, Volume 3, 2, May 1988, pp3-19.

[3] Kumar, N., "Modelling of Precision Investment Casting Processes", PhD Thesis, Imperial College, University of London, September 1988.

[4] Booth, C., PhD Thesis, Imperial College of Science, Technology and Medicine, University of London, In Preparation.

[5] Rolls-Royce plc, "Cordimet CMM Control System", RR Report EIR14077, Derby, England, 1981.

[6] Heath, A.J., "Non-Contact Profile Gauging of Turbine Blades and Wax Patterns", BSc(ENG) Thesis, Department of Mechanical Engineering, Imperial College, University of London, June 1986.

[7] Tsabourakis, N., Ristic, M., Besant, C.B., "Development of a Profile Gauging Sensor", The International Journal of Advanced Manufacturing Technology, Volume 3, 2, May 1988, pp51-66.

[8] Glover, R., Besant, C.B., "A Graphics Environment for CIM Applications", The International Journal of Advanced Manufacturing Technology, Volume 3, 2, May 1988, pp31-39.

[9] Cardew-Hall, M., Cosmas, J., Ristic, M., "Automated Proof Inspection of Turbine Blades", The International Journal of Advanced Manufacturing Technology, Volume 3, 2, May 1988, pp67-88.

[10] Brookes, N.J., Besant, C.B., "Reduction in the Development Lead Times of Complex Investment Castings by the Application of CIM technology", The International Journal of Advanced Manufacturing Technology, Volume 3, 2, May 1988, pp41-49.

[11] Miller, S.C., "Getting It Together", The Fellowship of Engineering Presentation given at Newcastle University, July 1990.

[12] Broughton, T., "Simultaneous Engineering in Aero Gas Turbine Design and Manufacture", Rolls-Royce plc, December 1990.

[13] Ziemke, M.C., McCollum, J.K., "Simultaneous Engineering: Innovation or Resurrection ?", Business Forum, Winter 1990.

[14] Whitney, D.E., "Manufacturing by Design", Harvard Business Review, July-August 1988, pp83-91.

[15] Putnam, A.O., "A Redesign for Engineering", Harvard Business Review, May-June 1985, pp139-144.

[16] Dean, J.W., Susman, G.I., "Organizing for Manufacturable Design," Harvard Business Review, January-February 1989, pp28-36.

[17] Taguchi, G., "Introduction to Quality Engineering", Asian Productivity Organisation, Unipub, Quality Resources, White Plains, New York.

[18] Henshall, E., "The Application of Taguchi Techniques", Institute of Mechanical Engineers, Seminal Papers: "Quality Techniques", C399/39, January 1990.

[19] Alexander, J.D., Douglas, J., "Integrated Total Engineering", Advanced Manufacturing Engineering, Volume 1, October 1988, pp11-14.

[20] Towers, O., "Modelling of Turbine Blade Casting (DS/SC) and Review of Pouring Simulation", BICTA Satellite III on Solidification Modelling, Rolls-Royce Advanced Engineering Brochure, PVJ530D, January 1987.

[21] Waldz, D.B., "Automated Inspection: Boon or Boondoggle", Proceedings of the 8th International Conference of Automated Inspection and Product Control, June 1987, pp363-374.

[22] Douglas, J., "Integrated Inspection for 'Fast-Make' Facilities", MTL50037, Rolls-Royce plc, 30 October 1988.

Chapter 4:

[1] Booth, C., Douglas, J., "Integrated Inspection - Implementation", RR Report MTL50061, Derby, UK, 1989.

[2] Booth, C., PhD Thesis, Department of Mechanical Engineering, Imperial College of Science, Technology and Medicine, University of London, In Preparation.

[3] McCollum, A.J., Batchelor, B.G., Cotter, S.M., "Three Dimensional Optical Sensing", Proceedings of the 7th International Conference on Automated Inspection and Product Control, Birmingham, UK, 26-28 March 1985.

[4] Cardew-Hall, M.J., "Modelling and Integrated Inspection of Cast Turbine Blades", PhD Thesis, Department of Mechanical Engineering, Imperial College of Science, Technology and Medicine, University of London, June 1988.

[5] Orchard, N.B., "Evaluation of Elor Optronics VIDI and VIGA Non-Contact Measurement Systems", MTD/10/86, Rolls-Royce plc, Bristol, U.K., 1986.

[6] Burton, D.R., Lalor, M.J., "The Precision Measurement of Engineering Form by Computer Analysis of Optically Generated Contours", Coherent and Electro-Optics Research Group, Liverpool Polytechnic, Liverpool, U.K., 1988.

[7] Burton, D.R., Lalor, M.J., "Software Techniques for the Analysis of Contour Maps of Manufactured Components", Coherent and Electro-Optics Research Group, Liverpool Polytechnic, Liverpool, U.K., 1988.

[8] Van den Berg, B., "Closed Loop Inspection of Sculptured Surfaces in a Computer Integrated Environment", Proceedings from the 8th International Conference of Automated Inspection and Product Control, June 1987, pp145-156.

[9] Finnigan, p., Hathaway, A., Lorensen, W., "Merging CAT and FEM", Mechanical Engineering, July 1990, pp32-38.

[10] ICAMP Inc., Sales brochure, 186 Bolton Center Road, CT06043-7638.

[11] Heath, A.J., "Non-Contact Profile Gauging Machine to Measure Turbine Blade Profiles", Third Year Project Report, Department of Mechanical Engineering, Imperial College of Science, Technology and Medicine, University of London, June 1986.

[12] Tsabourakis, N., Ristic, M., Besant, C.B., "Development of a Profile Gauging Sensor", The International Journal of Advanced Manufacturing Technology, Volume 3, 2, May 1988, pp51-66.

[13] Coordinate Measuring Machine Association of the United Kingdom, "Neutral Datafile Specification, Level 1", Revision 1, 1985.

[14] Braley, J.W., "Development of 3 and 4 Axis Measuring Machines for Use in PC02 and PC22 Inspection Areas", Rolls-Royce Report Number TSR1065, Derby, U.K., September 1978.

[15] Cardew-Hall, M., Cosmas, J., Ristic, M., "Automated Proof Inspection of Turbine Blades", The International Journal of Advanced Manufacturing Technology, Volume 3, 2, May 1988, pp67-88.

[16] Glover, R., "PANACEA: A CIM Programming Environment", PhD Thesis, Department of Mechanical Engineering, Imperial College of Science, Technology and Medicine, University of London, March 1989.

Chapter 5:

[1] Cardew-Hall, M.J., "Modelling and Integrated Inspection of Cast Turbine Blades", PhD Thesis, Imperial College of Science, Technology and Medicine, University of London, June 1988.

[2] Brookes, N.J., "Product Definition: A Systemic Approach to its Improvement", PhD Thesis, Imperial

College of Science, Technology and Medicine, University of London, In Preparation.

[3] Lee, S.A., "Discussion of the Automated Proof Inspection System After the Completion of Phase 2: The Measurement of a Turbine Blade", Department of Mechanical Engineering, Imperial College of Science, Technology and Medicine, University of London, April 1988.

[4] Lee, S.A., "Introduction to an Automated Turbine Blade Proof Inspection System and Implementation of Phase 1: The Measurement of a Test Piece", Department of Mechanical Engineering, Imperial College of Science, Technology and Medicine, University of London, November 1987.

Chapter 6:

[1] Brookes, N.J., "Product Definition: A Systemic Approach to its Improvement", PhD Thesis, Department of Mechanical Engineering, Imperial College of Science, Technology and Medicine, University of London, In Preparation.

[2] Bloor, S.M., Pennington, A. de., Woodwark, J.R., "RISP: Bridging the Gap Between Conventional Surface Elements", Department of Mechanical Engineering, University of Leeds.

[3] Aubin, R.F., "Dimensional Measuring Interface Specification", Proceedings of the 8th International Conference of Automated Inspection and Product Control, June 1987, pp25-32.

[4] Petty, J.S., Mach, K.D., "Contouring and Hidden-Line Algorithms For Vector Graphics Displays", AFAPL-TR-77-3, Wright-Patterson A.F.B., OH 45433, January 1977.

Chapter 7:

[1] Braley, J.W., "Development of 3 and 4 Axis Measuring Machines for Use in PC02 and PC22 Inspection Areas", Rolls-Royce Report No. TSR1065, Derby, United Kingdom, September 1978.

[2] Cardew-Hall, M., Cosmos, J., Ristic, M., "Automated Proof Inspection of Turbine Blades", The International Journal of Advanced Manufacturing Technology, Volume 3, 2, May 1988, pp41-49.

[3] Taguchi, G.," Introduction To Quality Engineering", Asian Productivity Organisation, Unipub, Quality Resources, White Plains, New York.

Appendix I:

[1] Lee, S.A., Tsabourakis, N., Besant, C.B., Ristic, M., "A Computer Integrated Approach To Dimensional Inspection"; 9th International Symposium On Air Breathing Engines, Athens, Greece, September 1989, pp765-773

[2] Glover, R., "PANACEA A CIM Programming Environment"; PhD Thesis, Imperial College of Science, Technology and Medicine, University of London, November 1987.

[3] Brookes, N.J., Besant, C.B., "Reduction In The Development Lead Times of Complex Investment Castings by the Application of CIM Technology", The International Journal of Advanced Manufacturing Technology, Vol. 3, 2, May 1988, pp41-49.

[4] Lee, S.A., "Introduction To An Automated Turbine Blade Proof Inspection System and Implementation of Phase 1 The Measurement Of A Test Piece", Department of Mechanical Engineering, Imperial College of Science, Technology and Medicine, University of London, November 1987.

[5] Lee, S.A., "Discussion Of The Automated Proof Inspection System After the Completion Of Phase 2: The Measurement Of A Turbine Blade", Department of Mechanical Engineering, Imperial College of Science, Technology and Medicine, University of London, April 1988.

Appendix II:

[1] Lee, S.A., "Introduction To An Automated Turbine Blade Proof Inspection System and Implementation of Phase 1 The Measurement Of A Test Piece", Department of Mechanical Engineering, Imperial College of Science, Technology and Medicine, University of London, November 1987.

[2] Lee, S.A., "Discussion Of The Automated Proof Inspection System After the Completion Of Phase 2 : The Measurement Of A Turbine Blade", Department of Mechanical Engineering, Imperial College of Science, Technology and Medicine, University of London, April 1988.