PRODUCTION ENHANCEMENT IN THE PLANING AND SPINDLE MOULDING PROCESS UTILISING A MECHATRONIC APPROACH

by

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SUMMARY

To ensure the economic survival of machine users, in an increasingly competitive world, the profitability of planing and spindle moulding machines needs to be improved. The chosen route for achieving this was enhancements in the efficiency of the process using effective data flow. This was undertaken using a holistic mechatronic approach to achieve an integrated solution.

The solution involved several interactive modules, capable of stand alone operation, to cope with a variety of environments. Initially a Reduced Down Time Unit and Computer Aided Setting System were developed. Machine setting information, calculated by the Setting System, was received by the Down Time unit of individual machines. Efficient utilisation of this data, during set up procedures, reduced the idle times of the process.

In addition, with a present absence of suitable in-process surface monitoring systems, a further system module was developed to asses product quality. The module was used to characterise surface waveforms of timber sections being manufactured, in order to identify the operating status of the production process. Mathematical modelling of the process and machine operation investigations were undertaken. The results obtained were used as a comparison between actual machining characteristics, that were observed using the measurement system, and theoretically predicted events.

The models have been verified using experimentally derived data. The designs and hardware developed within the project are in commercial production which has demonstrated the success of the modules, in terms of enhancing machine utilisation and process efficiency.

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I. Publications

ABBREVIATIONS

ADC	Analogue to Digital Convertor
ADCNT	Local Address Count
ASCII	American Standard Code for Information Interchange
BCD	Binary Coded Decimal
CAD	Computer Aided Design
CAM	Computer Aided Manufacture
CAPP	Computer Aided Process Planning
CASS	Computer Aided Setting System
CFILE	Component File
CIM	Computer Integrated Manufacture
CNC	Computer Numerical Control
DFT	Discrete Fourier Transform
DME	Direct Memory Enable
DNC	Direct Numerical Control
DTI	Dial Test Indicator
FFT	Fast Fourier Transform
FMS	Flexible Manufacturing System
f_s	Sampling Frequency
GRP	Glass Reinforced Plastic
HFILE	Head File
IC	Integrated Circuit
I/O	Programmable Input Output
LCD	Liquid Crystal Display
LED	Light Emitting Diode
LSI	Large Scale Integrated Circuit
NC	Numerical Control
P	Theoretical Feed Pitch

Ra	Roughness Average
RAM	Random Access Memory
RMS	Root Mean Square
ROM .	Read Only Memory
VDU	Visual Display Unit
VIA	Versatile Interface Adapter

NOTATION

The Machining Process

h	Depth of knife marking
R	Radius of cutting circle
P	Pitch of knife marking
f	Feed speed of workpiece
n	Cutter head spindle rotation speed
N	Number of knives in the cutter head actually producing a wave on the workpiece
A_n	Arc number (n)
R_n	Cutter circle radius number (n)
X	General displacement in the X direction
Y	General displacement in the Y direction
X_{ij}	Distance from ordinate to intersection of wave (i) with wave (j)
W_i	Wave width number (i)
δ	General radial displacement of the cutterhead relative to it's ideal position
θ_i	Difference of curvature angle

Mathematical Modelling

F	Material feed rate
r	Rolling pitch radius
α	Cutterhead rotation angle
K	Integer constant
d	Depth of cut
θ	Cutting angle within material
L_b	Angle between cutters

L	Angle of lag between the 1st and Ith cutter
w	Angular Velocity
V	Linear velocity of timber
H	Distance of Cutterhead centre line from bedplate
I	Ith cutter number

The Drive System

$2T_o$	Initial Tension applied between pulleys
T_c	Centrifugal Tension
T_1	Tight side tension
T_2	Slack side tension
ρ	Specific mass of pulley belt
A	Cross section area of pulley belt
v	Linear velocity of the pulley belt
u	The velocity of propagation of a disturbance along the belt strand
g	9.81 m/s^2
ln	Natural logarithm
μ	Coefficient of friction between belt and pulley
e	2.718
Φ	The pulley belt lap angle
β	Half the included angle of the belt
α_1	Angle of belt contact
L_c	Distance Between pulley centres
L_s	Belt strand length
B_R	Angle of belt contact on larger pulley
B_r	Angle of belt contact on smaller pulley
Rp	Radius of larger pulley
rp	Radius of smaller pulley

TERMINOLOGY

Bedplate	A feature on the machine which provides a horizontal reference face for the timber workpiece to press against.
Cutterblock	(or cutterhead) refers to the high tensile steel body in which the cutting knives are mounted.
Fence	A feature on the machine which provided a vertical reference face for the timber workpiece to press against.
Jointing	The name given to the process which dresses rotating cutting edges to a common cutting circle.
Knife	(or cutter) refers to the cutting edge which severs the timber's fibres.
Planing	The process of producing a flat rotary cut surface on timber.
Moulding	The process of producing a profiled rotary cut surface on timber.
Texture	This refers to the primary texture of the wood and the secondary texture created by the machining action.
Raised Gain	The condition caused as a result of differential recovery of spring and summer wood, after machining is complete.

1. BACKGROUND

Aims and Objectives

The global aim of this project is to improve the profitability of the production of planed and spindle moulded products. This aim is to be achieved by improvements of data flow in the design and characterisation of timber products, the production of profile cutters, product scheduling and the set up procedures essential for optimal machine operation.

These aims are to be realised using a holistic project approach. This approach is to be achieved via the top down design and bottom up implementation that is characterised by the following objectives:-

1) **Minimisation of the design process**

2) **The flow of information regarding the process**

3) **Scheduling and planning schemes for timber mill management**

4) **The manufacture of cutters using centralise design information**

5) **Enhancement in machine utilisation and quality control of the process**

The work carried out and presented in this thesis is primarily concerned with the **Enhancement in Machine Utilisation and Quality Control** aspect.

The objectives of this work were:-

1) **The development of a method for managing information flow, to enhance machine utilisation**

2) **The development of a method for assessing the quality of the process and the products manufactured**

In order to achieve these objectives it is however necessary to understand the nature of the machinery, the manufacturing process and the local environment.

1.1 The Industrial Environment

1.1.1 Woodworking Machine Manufacturer's Background

The woodworking machine manufacturer's philosophy has changed radically over the last one hundred years. At the turn of the century the approach for large woodworking machine manufacturing companies was to produce a large range of machinery which did not lend itself to production efficiency.

A typical woodworking manufacturer's premises contained a prime mover which powered complex transmissions. Often one shaft would drive another, with drives between floors or other buildings. The usual way of powering woodworking machinery was by belts from a main lineshaft to individual machine counter shafts (Simms W.L. 1985).

Towards the end of the first quarter of this century the philosophy of the woodworking machine manufacturers began to alter. Manufacturers began to manufacture new plant which was intended to produce precision batch machined components with the aid of jigs and fixtures. Gradually the approach from a large array of woodworking machines to batch producing smaller overall ranges, by manufacturers, came to be accepted as normal.

Development from prime movers and line shafts to direct drives using electric motors took place during this period. In 1928 the first integral, electrically driven, woodworking machines were shown in Britain. Such designs eventually eliminated the great maze of belts and line shafts, which up to then had been common practice in woodworking mills. The adoption of new technology helped to create the first generation of planer moulders that we know today.

Presently there a number of planer moulders manufactured by various large companies. The early principle of operation is relatively unchanged, except for the design refinements implemented to accommodate advancing technology. Many design features have evolved from early machines to the modern planer moulders of today.

Recently large increases of computerised technology have been incorporated into woodworking machinery (Timber Trades Journal 1990[1]). Computerisation in conjunction with increased material feed rates and cutter head spindle speeds are partly responsible for generating high component quality. Typically cutter head spindle speeds of modern planer moulders are in the region of 6,000-15,000 revolutions per minute. For high quality surfaces cutter head spindle speeds of 15000 rev/min (max) are required with multi knife cutter head assemblies (Wadkin Specification Literature, Leaflet No 1448/4).

1.1.2 The Modern Planer Moulder

Modern planer moulders are expensive and complex pieces of equipment (Figure 1.1). This equipment is primarily used in the manufacture of moulded wooden products. As each woodworking manufacturer's product size, quality and intricacy requirements vary, machine manufacturers have had to provide a vast array of optional hardware choices on each range of planer moulders (Wadkin Specification Literature Leaflet No 1461/432).

With high speed artifact production approaching 120 metres/min, beneficial vibration free operation is promoted using a full cast iron machine base structure design (Figure 1.2a). Usually fitted to the machine base structure is an infeed straightening table and a manually oil lubricated precision bed and fence (Figure 1.2b). Oil lubrication is employed to reduce stock friction and minimise the build up of timber resin. Idling bed rollers also assist in reducing friction over the machine bed (Figure 1.3a). Where oil stained timber is not acceptable (e.g. furniture components or materials requiring a further lacquering process) air lubrication is used.

Smaller standard planer moulders (Timber Trades Journal 1990[1]) usually have independent electric motor driven top, bottom, near and fence cutting heads (each cutter head being fitted with a multi knife cutter block **Figure 1.3b**). However, the capability of any standard model can be extended further by the use of additional heads which, under certain circumstances, can be retrofitted. Larger series moulders can use as many as 10 heads to accomplish the most comprehensive production of complex mouldings. Continuous positive material feed, during machining operations, is achieved by automatically compensating, pneumatically loaded, feed rollers (Figure 1.4a). These rollers are necessary to cope with varying timber thickness. Pressure pads and side pressure rollers provide extra top and side pressure in areas opposite the bottom and fence cutting heads respectively (Figure 1.4b & 1.5a).

As different woodworking manufacturer's application requirements are dissimilar (e.g. production of door sills, skirting boards or cornices), machine parameters alter. Standard machines admit timber sizes of 110mm by 140mm max, however, it is common for the larger high speed moulders to admit material sizes up to 130mm by 310mm. All sizes of machines are capable of attaining a safe cutting depth of 30mm (Willbond A.D. 1990).

Present machines, to control product quality, are capable of a range of material throughput speeds and cutter head spindle velocities. Varying material throughput speeds are obtained using optional size feed motors (motors used to power the Carden feed roller drive shaft Figure 1.5b). The power and speed rating ranges, of the feed motors that are fitted to smaller machines, lie between 2KW To 22.5KW and 6 metres/min to 36 metres/min respectively. Each cutter head, dependent on the cutting and quality requirements, is fitted with either a standard 3,000 rev/min independent electric motor or a higher speed 4,500rev/min motor. In some applications the larger series machines incorporate cutter head motors that run at 7,500 rev/min. All series moulders have some form of mechanical digital readout fitted for accurately controlling and setting the vertical/horizontal displacements of the machine's cutting head spindles (Figure 1.6a).

The larger more expensive machines, as an option, allow a 3 or 4 position universal head to be fitted (Figure 1.6b). This type of head covers 270° or 360° of rotation and provides intermediate cutter settings for the top, near side, fence side and bottom heads. Frequently built into these machines are combined straight and profiled jointers (cutter block knife sharpening stones **Figure 1.7a**), standard hydro outboard bearings (used on the top head spindles to provide extra support) and intermediate feed rollers (Figure 1.7b). These extra features enable true multi knife finishes to be achieved without sacrificing prolonged set up benefits.

All ranges of planer moulders have, as standard or as an option, close fitting Glass Reinforced Plastic (GRP) sound enclosures (Figure 1.8). These enclosures are fitted with lighting and dust removal duct connections, giving effective control of the external environment when manufacturing a planed or moulded wooden component.

1.1.3 Manufacture of a Planed and Moulded Wooden Component

The process of planing and moulding is a far more complex task than it might appear at first sight. There are a number of consecutive operations involved in the production of different timber sections.

The initial step to produce a planed and moulded component is the generation of a two dimensional drawing file depicting the desired timber section (Figure 1.9a). Draughtsmen still create these timber section files manually due to the relative simplicity of the sections (i.e. no intricate design details). The timber sections are drawn with reference to the fence and bottom table of the moulder. A single arbitrary feature on each face of the section is then chosen on the drawing file (Figure 1.9b). A horizontal and vertical measurement to each arbitrary point is calculated (referenced from moulder fence and table). The horizontal and vertical measurements obtained, for all faces, are typically referred to as "timber data" (Figure 1.9c). The timber section drawings produced are additionally required in the production of sheet metal templates, used on copy grinders, to produce machine cutter block profile blades.

Typical moulded components range from skirting boards and banisters to the components necessary for production of complete window frames. Although there is a vast range of moulded components, the timber sections needed remain relatively simple. Thus, due to this limited complexity, it is the general opinion (Garrett B. 1988) that large general purpose Computer Aided Design (CAD) packages are not cost effective in this type of application.

A moulded component is "extruded" on a multi cutter head machine (Figure 1.10). Different features of the component section, due to dissimilar geometric requirements, are produced using different cutting heads. Each machine head spindle is fitted with a cutter block containing a set number of knives, dependent on the surface finish requirements of the customer. Separate machine cutter blocks, for the production of different geometric features, contain a different set of profile blades to the next (Figure 1.11).

Once the profile cutters have been manufactured, using the timber data information, they are fitted to the corresponding cutter blocks (i.e. fence, near, bottom or top). These blocks are then referenced on an existing Computer Aided Setting System (CASS) and measuring stand (Figure 1.12a&b). Each cutter block, using the CASS system, is referenced from it's spindle axis and end. Radius and length measurements are obtained to the corresponding feature datums (arbitrary points), on the cutter profile, which had previously been identified on the timber section circumference (Figure 1.13).

Machine spindle offsets (x,y co-ordinates), necessary for the production of timber sections, are thus calculable from the timber and cutter block data held in the CASS unit. The calculations performed by the CASS unit to attain the (x,y) co-ordinates differ for cutter blocks of different orientation (Figure 1.13).

The manufacture of a wooden component, due to the nature of the process, is not without a number of production problems. Thus for the industry to maintain competitiveness in terms of direct labour overheads, component quality and machine utilisation, prevailing undesirable production features require quantifying.

1.2 Manufacturing Difficulties

1.2.1 Manufacturer's Dilemma

With many areas of the woodworking industry now being characterised by highly sophisticated computerised machinery eg bulk timber sawing, length cutters etc (Cowdery M.J. 1990) the market has become exceptionally competitive. However, the planing and moulding areas of the industry by comparison, and in the main, due to the lack of prior demand and conservatism of the machinery users is relatively unsophisticated (Parkin R. 1988[1]). To increase competitiveness the woodworking machine manufacturers also require computer control of their machines; as modern planing and moulding machinery is capable of producing high quality components at very high production rates, computer control of the process would be beneficial in several problem areas.

Large planing and moulding machines "extrude" timber sections at rates tending towards 3 metres per second. Usually in excess of twenty tooling and job changes are required per day. In addition the cutters may require sharpening (a process technically known as jointing) after only twenty minutes of use. Such operations are in part responsible for long periods of "down time" (idle time) resulting in machine utilisation levels of 30% or less (Garrett B. 1988). The reduction of down time is of paramount importance to the machine manufacturers, in increasing the utilisation and hence profitability, of these large and relatively expensive pieces of equipment.

A futher proportion of this down time results from the significant and expensive difficulties incurred by the manufacturer when accurately referencing cutter blocks. This procedure is required to establish the set up information that is necessary for cutter head spindle positioning.

Quality control in conjunction with efficient machine utilisation, is essential for competitiveness within the planing and moulding industry. This is due to the woodworking manufacturer's diverse production range and varied selection of customers. In addition varying component quality levels are required due to the nature of each customers products.

The manufacturer's of high quality wooden components require superior product surface finishes (surface wavelengths approaching 1mm in length). In addition to this, for acceptable aesthetic quality, these surface waveforms should exhibit little variation in periodicity (a typically good surface is shown in Figure 1.14). This type of quality surface requires multi knife cutter blocks and spindle speeds in the region of 15000 rev/min with high material feed rates. With high volumes of material throughput it is not difficult to envisage the concern generated, from the manufacturers, as to the lack of commercial quality control monitoring systems available.

With the absence of suitable monitoring and control systems coupled with high material feed rates, large quantities of machined timber could be, and are being, lost when a machine develops a typical fault, such as a blunt cutter or an out of balance cutter head, which goes unnoticed for several minutes.

With the price of raw materials constantly escalating large volumes of waste material, resulting from the development of undetected machine faults (eg a chipped cutter), are now unacceptable.

However, an immediate problem facing the manufacturers is the inherently long down time periods generated as a result of "mechanical" set-up procedures. These procedures are necessary for setting the profiled knife cutter blocks (located on the cutter head spindle) to the correct machining offsets.

Many production limitations experienced have resulted from original, broad and unfocussed single phase design and production programmes. A total review of historical production problems, essential in establishing successful system evaluation for future redesign and development, will thus be necessary due to previously limited project research and planning.

1.2.2 Historical Production Limitations

Traditional CASS systems and measuring stands were jointly operated, usually within factory tool rooms, to obtain essential cutter block referencing data. With manual timber data input combining with previously held cutter data, calculations to determine machine spindle offset values were performed and stored within the system's memory. Transportable offset information, necessary to aid head setting by the operators, was presented as printed alphanumerics on self adhesive labels. Subsequently these labels were physically adhered to the surface of corresponding assemblies before transference to specific machines.

The original system arrangement however, due to its design and development, generated several operational restrictions including:-

1) Commercial predesign resulting in expensive and cumbersome unit modules.
2) Incompatible system formats.
3) An inadequate transfer medium.

Commercial predesign of the constituent components making up manufacturer's original CASS systems resulted in disjointed, large and relatively expensive unit consolidation. In addition independent development of the "ad hoc" configuration promoted incompatibility and system isolation.

Early self adhesive labels proved to be inadequate primarily due to unsuitable adhesive characteristics. Often labels would be lost and subsequently replacements had to be issued. As cutter blocks were frequently stored prior to component production, verification by the operators was required on any block exhibiting an unsecured adhesive label. Changes in the labels adhesive properties resulted in removal difficulties. Occasionally unremoved labels detached from the cutter blocks during component production, resulting in undesirable machining conditions.

Planing and moulding machines, using label technology, only incorporate limited operator setting aids as essential identification and offset information was transferred on individual cutter blocks. The resulting characteristic setting procedures created two main process limitations:-

1) Low machine utilisation periods.
2) Potential operator errors leading to inaccuracies.

Low machine utilisation periods resulted from unsatisfactory production information presentation and distribution. Unproductive machine time elapsed as operators established correct cutter block and spindle identification links. This procedure was inherently susceptible to inaccuracies generated, by the operator, as a result of the cross reference requirements between the label data, offset readout and cutter block identification values.

Quality control monitoring of the manufactured component was also performed by the machine operator. However, the post process, visual technique employed was highly subjective as it was possible for the same sample to be analysed as good or bad by independent inspectors.

In addition to the quality control technique being subjective, it was also a relatively slow post process operation. Using this type of analysis, large quantities of substandard (poor surface finish) material could be produced before effective evaluation, detection and remedial feedback action initialisation.

Original production restrictions were largely created with poor design strategies, market conditions and unacceptable research procurement periods. Presently however, these problems can be surmounted with the aid of advanced electronic and mechanical technology, enhanced powered computers, integrated design philosophies and directional project consolidation.

Resolving many of the historical production problems will however require intelligent, reliable and compact solutions incorporating several well interfaced technologies. Development philosophies will be required in establishing compatible, fully integrated modular designs at low costs.

1.2.3 Development Philosophies for the Solution of Historical Production Problems

Beneficial solutions to the typical historic production difficulties, discussed previously, would require the definition of a comprehensive business plan. The strategy, for its successful implementation, would require the inclusion of clear and detailed executive management corporate aims. Integration at all levels between organisational functions such as design, production, marketing, personnel and finance would be essential in obtaining the initial predesignated intentions set by company management.

Successful design philosophies would also be required in local function research and development areas. All objectives would need the formation of detailed designs outlining specific solutions. For universal project integration, local and global normalisation procedures would need development to match all environmental boundaries of the system.

To achieve the objectives effectively, a mechatronic design approach would be required in reviewing, conceptually developing and embodiment of project strategies. This type of approach, using common iterative design procedures, would promote the multi technological development required within the provincial system environments. Fundamental mechatronic philosophies, drawing on multidisciplinary knowledge, would ensure intelligent, reliable, low cost and fully integrated system development.

Each design strategy would need systematic development to achieve effective resolution of specific production problems. However, the broad philosophies adopted would be ultimately governed by a thorough appreciation of the corporate project requirements. To adequately achieve the initial targets of the total project, at an affordable cost to the industry, an overall guiding concept such as this would be of paramount importance (Timber Trades Journal 1990[2]).

Modular system development within a committed corporate philosophy would thus promote directionally, phased research and development. With clarification of executive management support, the development of local sub systems employing a mechatronic design approach could be initiated (Bolzing D et al 1987).

1.3 Mechatronic Solution Approach

1.3.1 Mechatronics Background

In the post war period Japan first concentrated its efforts on the gradual recovery of its heavy industry. Site locations of these industries were coastal in order to capitalise on low cost sea transportation. These low cost transportation facilities enabled Japan to become, within these industrial spheres, very competitive in the world market. Basic industries such as steel, Aluminium and Petrochemicals flourished during the nineteen sixties and early seventies until the 1973 oil crisis. The resulting fourfold rise in oil prices had devastating financial effects on Japan's raw material (e.g. iron ore) import costs, with additional but equal side effects on their energy dependent industries.

Due to continual oil price escalation and world demands, Japan became increasingly uncompetitive in these manufacturing fields. The subsequent decline of Japan's domestic industries, dependent on energy and heavy raw materials, swiftly encouraged government investment into the knowledge based industries. Redirection into areas such as microelectronics, mechatronics and the science based industries was directly due to the lack of natural resources but an abundance of people (McLean M. 1983). Thus the industrial transition progressed because of Japan's underlying need to export in order to finance essential imports such as food and raw materials.

Japan's success and high technological concentration within certain market areas eventually caused, with their lower unbalanced import and trade restrictions, varying degrees of trade friction with the rest of the world and in particular Europe. Trade friction, however, has now been largely alleviated due to Japan's progress of internationalisation. This development, due to division of labour, has allowed more harmonious trading relationships essential for future consolidation of prosperity.

Mechatronics has developed due to the maturity of its two fundamental and combined technologies. Several prerequisites within both the electronic (including computer technology) and mechanical industries were necessary for mechatronic amalgamation. For mechatronic progression high precision and reliable mechanical parts were of paramount importance. This direct quality requirement was achievable with the close integration of a number of academic and industrial fields.

The electronic development from vacuum tubes to large scale semiconductor integrated circuits allowed manufacturer's production costs and furthermore, device costs to dramatically decline. The advent of the integrated circuit, also quickly improved reliability and reduced the integration costs within mechanical systems. In conjunction other component improvements in areas such as sensors, actuators and new materials meant that electronics was no longer a constraint on the application of mechatronics.

Over twenty years of conventional research and development, coupled with extensive investment, has enabled Japan to produce large quantities of high precision machinery at low costs, without the loss of quality or reliability. Due to mass produced consumer commodities (with very short life time cycles) manufactured for export such as cars, washing machines, cameras, etc, their mechanical and electronic engineering facilities have subsequently been revitalised.

With precision, quality, cost and reliability all improved in the mechanical and electronic fields, Japan created a formidable industrial base for the development of mechatronics.

1.3.2 The concepts of Mechatronics

Mechatronics is a term which describes the integration of mechanical and electronic engineering and represents a new approach to the development of modern products (Taylor G.T. 1990). However, mechatronics is not purely a "symbiosis of mechanics and electronics" (Konstantinov M.S. et al 1987). It is now becoming clear that the metaphor "mechatronics" includes more than this and embodies design, and manufacture in addition to computer control and software engineering. Within mechatronics, traditional mechanical, electronic and computerised design procedures are not regarded as separate disciplines (Daniel R.W, Hewit J.R. 1991). Mechatronic design philosophies make use of the integration to take account of the constraints imposed and the possibilities created, by the final aim of a computer controlled product or system. The definition "mechatronics" thus relates the philosophies on which the creation of such products or systems are founded.

Mechatronic evolution, using advanced technology, has created energy and resource saving highly intelligent systems. Devices which had previously relied on ingenious machine complexity are thus, from the philosophical and technical development, being supplanted by low cost reliable intelligent substitutes exhibiting enhanced performances. However, for mechatronic products to endure the fast moving international markets, a broader range of expertise must be used in the development of the products and systems employing combinations of the overlapping technologies is required.

Integrated design, produced in cooperation between various departments (design, manufacture, marketing, finance and accounting) is self evidently a must (Salminen V, Verho A.J. 1990). The significance of the product for the business must be the starting point of product development. Consolidated systematic design is thus required when considering the development of a mechatronic product. The design and development process associated with a mechatronic artifact, would therefore need to be divided into several phases. However, understanding the project in its entirety requires a design process which originates at the project's common centre (overlapping technological areas) and progresses towards each of its expert areas.

Initially general outlines of system requirements, objectives and potential design complications would be reviewed in what could be termed a task setting design phase. For technical product design the tasks required in developing a new product would have to be carefully considered and defined. Total comprehension of the local environment in conjunction with the aims of the system would be required in appreciating possible development problems.

With a detailed overview, project development would progress to a conceptual design phase. This phase would be necessary in establishing an overall draft picture or concept of the product alternatives (Disney J. et al 1990). This juncture, within the design structure, would allow extensive creative activity. It is important within this period for a general language, common to all participants to be established. Each alternative principle solution, for the overall system, would need further investigation in terms of energy, material and information flow. The remaining solutions, after critical reviewing, would be prio ritised until the appropriate conceptual structure emerged. Mechatronic development would prevent hard and fast traditional design concept adherence through all phases of the products development, including the product embodiment stages.

Because numerous technological bases are embodied within mechatronics, important system and interface concepts are required in achieving efficacious product development. The system concept would be required to attain technological integration and organisation by dividing the system into its constituent main, structured, power and control information functions. The structural function could usually be termed as the function of the system because in many cases the structure has great influences on the system performance. The main function of the system would convert, preserve and transmit material, energy and information respectively. During normal operations of the system the power function would control the energy, cooling, lubricating requirements of the system. However, the overall control of the system would be through the control information function, which controls the system's internal conditions. Additionally it is usual for the control information function capabilities to also be externally controlled. Figure (1.15) shows the function configuration for a general engineering system.

Compound mechatronic systems, initially within the design phases, encounter several technological boundary incompatibilities. An interface concept is therefore required in linking and matching the mechanical, physical, information and environmental system functions. As interface aligning capabilities alter, dependent on the overall system objectives, extensive consideration is required in introducing suitable boundary interfaces. Passive, active, intelligent and zero interfaces can be applied in matching any inconsistent system fringe. A passive interface is employed when passive conversion, transmission and preservation is performed, but no boundary alignment is required. The active interface is required when matching incompatible system fringes. Where adaptable conditions are required (areas where conditions need quick modification) intelligent microprocessor interfaces are necessary. The simplest system fringe coalition comes with a zero interface, here the input is identical to the output with no special matching functions needed (Kajitani M. 1989).

1.3.3 Mechatronic Integration

The embryonic stages of mechatronics first began as early as the late nineteen forties when the mechanical engineering scene became increasingly shared with electronics, albeit hardware only. At that time machines were controlled using hard wired electronic controllers which represented the first generation of mechatronics (Dinsdale J. 1989). Early roles adopted by the electronic/mechanical hardware was later replaced, with the advent of Large Scale Integrated circuits (LSI) using micro processors and application specific software in conjunction with precision mechanical engineering.

Initially to improve the essential prerequisites for technological integration such as precision, reliability and quality within mechanical engineering, closely integrated manufacturing spheres developed. Coherent integration, to achieve improvements in areas which include production, raw materials, costing and quality control were attained with the aid of Flexible Manufacturing Systems (FMS), Numerically Controlled (NC) machine tools and scheduling algorithms (Parrish D.J. 1988).

Enhanced mechanical engineering and the mercurial electronic revolution consequently presented the realisation of mechatronic's second generation. Continual but beneficial integration has thus been intimately associated with precision mechanical engineering and the fabrication technology of the Integrated Circuit (IC), which provides many complex electronic functions at low costs and power. In addition to these advantages, the ability of the IC to provide additional features, which enhance the functionality of the final system, provides the integration foundations necessary for the implementation of these type of devices, within a potential mechatronic system.

Increased complexity of advanced engineering, through electronic and mechanical engineering refinements, has significantly contributed in the fusion of product technologies at the design and development process stages. Amalgamation of the technologies have been achieved using multidisciplinary design and development strategies to combine mechanical, electrical and computer engineering. However, successful technological integration also requires a common project language, to surmount specialisation barriers, and incremental design strategies (Buur J. 1990).

The concept of mechatronics is traditionally unfamiliar, instead of a new specialised subject area developing out of an existing discipline, mechatronics draws together elements of existing subject areas. Mechatronics therefore cannot be regarded as a new specialisation but rather as an integration discipline which opposes the traditional style of sequential or combinational system design and manufacture. Mechanical technology has thus absorbed advancing electronics predominantly semiconductors. Most significantly when the microprocessor was developed, it became possible to integrate systems with information with the fusion of computer architecture and information technology into mechanical technology (Figure 1.16). This amalgamation has thus allowed regions of mechanical technology to evolve into mechatronics .

1.3.4 Mechatronic approach to project solutions

Throughout artifact manufacture, important production and control mechanisms of the planing and moulding process were extensively investigated. A comprehensive appreciation of the manufacturer's machining problems was considered essential to establish fundamentally improved system design philosophies. However to attain global integration within the manufacturing sphere, consideration in all areas of manufacture, within the planing and moulding industrial region, required evaluation.

If we examine the general model of a mechatronics system (Figure 1.17) it is evident that it incorporates all the features of a conventional control system. However where the mechatronic system differs from that of the conventional is in its increased accuracy and reaction times of operation, enabling the development of a more flexible system which can rapidly reconfigure to meet active operating conditions (Dorey A.P. et al 1989).

Initial philosophical design stages of the project included the agreement of a universal and directional development strategy. However, due to the nature of the industrial environment, in conjunction with a capacious research period, it was concluded that a highly compatible but modular project development programme would proceed. Early design fragmentation of the global system subsequently permitted the emergence of two basic subsystem modules. The initial modular concepts (CASS & Reduced Down Time (RDT) systems), with foresight to the final mechatronic system, successfully incorporated the system concepts required in integrating mechanical, electronic, computer control and information technology disciplines. Passive, active, intelligent and zero type interfaces were all required in the basic systems. These concepts were necessary in surmounting incompatibilities between differing technological boundaries.

The two initial subsystem modules, in combination, were conceived to significantly alleviate planer moulder idle periods. A reduction of unprofitable down time cycles of the machines, it was concluded, would be achieved using embedded computer control and integrated circuit level electronic design within the control and power functions of each unit respectively. Additionally the information functions of each system required interactive procedural objectives to achieve efficient, compatible and accurate information interchange.

The universal synopsis relating the surface characterisation system, to resolve the absence of in-process material monitoring, would need interactive analysis and initialisation in parallel with primary system's design ideology transfer, to that of the conceptual and embodiment project stage. However, the development of a surface characterisation system, through design, conceptual and embodiment phases, would require close integration with both the primary subsystems. The overall mechatronic system would thus systematically consolidate as the implementation of the measurement module, due to its inherent operation mode, would necessitate a variety of active sensors and actuators.

The perceived coherent amalgamation of the modular design concept would be accomplished using a common interactive data base of information. The depth, speed and accuracy of precise timber, cutter block, and grinding template, information and data transfer, between each of the important production departments, required in timber planing and moulding, would undoubtedly re-establish high profitability.

With a common database structure other departments including sales, finance, purchasing and material planning could all actively contribute and extract essential up to date system, raw material cost and progress information. The extent of this type of manufacturing integration, to establish beneficial competitiveness, would additionally require computer integrated manufacture between the intelligent mechatronic subsystems.

1.3.5 Project Structure

The fundamental requirements of the mechatronic concept were formulated as a team effort. The team consisted of two research workers, with their supervisors, in conjunction with significant industrial inputs from areas including design, development, manufacture and marketing.

Within an iterative design environment, and after presentation of the concepts and formulation of requirements, a solution was proposed with effort concentrated in individual work areas (Figure 1.18).

Parallel development of individual work areas enabled high levels of integration to be achieved during the projects development. Iterative design procedures and a common project language enabled the inputs and outputs (that were originally specified), of each module, to be realistically defined and rigidly maintained.

Figure 1.18 shows the development of two distinct work packages. The first work package centred around the development of a method of retaining timber section and cutter data. The second work package was directed at reducing the down time of the machines.

High levels of integration between the two work modules were essential as efficient data flow, between the modules, would realise an enhancement in machine utilisation.

The work undertaken by the author was:-

1) **The development of the measurement circuitry for the Computer Aided Setting system (under work package No1)**

2) **The entirety of work package No2 (the Reduced Down time System and Quality Assessment)**

The reduction in operator supervision requirements that follow from the adoption of the Reduced Down Time system results in a potential quality problem. Machine faults developing during the production process can result in high levels of defective product. For this reason an in-process quality assessment method was investigated.

During the local environment investigation an integrated relationship between the global objectives of the system was established and is described within the following chapter.

2. REVIEW

2.1 Computer Integrated Manufacture

2.1.1 The Traditional Environment

Engineering manufacturing industries were traditionally associated with mass production which required dedicated, large and expensive machinery. As with all mass produced items, standardisation is high, with product and product design changing little over the short to medium term. The cost of capital investment, required for mass producing components, is however recouped using long and continuous production periods.

The Nineteen Fifties saw a transition from human, to automatically controlled machines. Automation was achieved using NC on conventional machines such as lathes, enabling them to be soft programmed (machine programmed via a tape reader using paper punch tape). Programming was performed, on these types of machines, using a unique set of numbers/symbols (Figure 2.1). These programming techniques provided complete control of the machines resulting in the elimination of skilled operators which were previously essential. Manufacturing automation development, up to this period, had generally been concerned with single machines or functions (known as Point Automation).

A numerical control system would consist of a program of instructions, a controller unit and a machine tool or similar controlled process. The relationship among the components of a NC machine are illustrated in **Figure 2.2.**

The programmed instructions serve as the input to the controller unit, which in turn commands the machine tool or similar process.

Numerically controlled machines brought with their implementation, significant production advantages which included reduced non-productive machine time, reduced manufacturing lead time, improved quality and reduced inventories (Koren Y 1983). The NC machine, along with these benefits also generated certain, but out-weighed, disadvantages such as higher investment and maintenance costs, increased factory floor area and the necessity of retraining suitable operators.

Specific functions that were performed by the controller units of NC machines however, could not be easily altered to incorporate new control actions. This restriction was due to the fixed nature of the controllers hard wired design (eg the generation of a parabolic curve), which emanated from the technology available at that period. The flexibility limitations and unreliable NC tape drive units, in conjunction with the rapid emergence of the digital computer, encouraged machine designers to develop the concept of Direct Numerical Control (DNC).

The first computer controlled DNC systems were introduced around 1968 (Zimmers E. W. JR, Groover M. P. 1984). At that time the most feasible production approach was for one large computer, due to the cost of early computer hardware architecture, to control a number of machine tools on a time shared basis. The main advantage of these systems was that a direct link was established between the computer and the machine tool, hence eliminating the necessity for using punch tape as the input medium.

As smaller more reliable and less expensive computer systems developed it became practicable to apply a single small computer to an individual machine. These Computer Numerically Controlled (CNC) systems were commercially introduced around 1970 (Figure 2.3). These types of controllers were termed the "soft wired controller" as one standard computer could be adapted (programmed) for various types of machine tools. Flexibility was achieved by storing the control functions, required for part production, into the computer's memory. Advances in computer technology continued to provide smaller digital control devices which exhibited greater speed and accuracy at lower costs. This continued development permitted machine tool designers to incorporate the CNC control panel as an integral part of the machine tool, rather than in a separate stand alone unit.

Manufacturing automation development, up to the direct and computer numerically controlled system juncture, had generally been concerned with single machines or junctions (referred to as point automation). Initial automation philosophies had not incorporated any preconceived strategies, for the integration of different numerically controlled machines. Later however, with the introduction of greatly enhanced electronics and computers (relative to the earlier designs) the expansion of the point solutions to more integrated automation islands, within factories, evolved (Brown J. et al 1988).

The design and development of the FMS (Figure 2.4), being an island of integration, represents a single large scale system in which the production of parts is controlled with the aid of a central computer and a material handling system. This type of arrangement enabled high integration and flexibility in terms of the small amount of effort and the short time required to manufacture a new part (Koren Y. 1983). This type of system approach was undertaken to bridge the vacuum that existed between traditional high production transfer lines and low production NC machines. This type of system thus provided the efficiency of mass production for batch produced products.

Developments such as the FMS and special manufacturing cells represent the integration achieved from point automation solutions (such as NC, CNC and DNC systems), to the islands of integration (Brown J et al 1988). The proliferation of such locally expanding islands of functional inte gration has given rise to a global computer integrated manufacturing problem.

2.1.2 Foundation

With the transformation of the manufacturing environment over the past one hundred years (Figure 2.5), manufacturers increasingly seek to give their customers diversity and confidence in the components they supply (Willows P. 1987). This commitment requires the adoption of new technology and techniques, which in turn demands breaks with tradition. It is arguable that a computer integrated manufacturing system would achieve the efficiency and associated product quality necessary to attain these standards.

The generally recognised father of CIM is Joseph Harrington. In 1973 Harrington described CIM as a new control and communication structure resulting from the assemblage and integration of existing and future automated capabilities that comprise the factory (Coleman E. et al 1987).

The term computer integrated manufacture is now understood within the engineering community to describe the integration of all company functions, through the effective use of computer technology (Crookrall J.R. 1986). Computer integrated manufacture comprises of a number of different technologies and philosophies which, when integrated, bring about greater company competitiveness through increased quality, flexibility and improved responsiveness to market conditions. CIM can thus be regarded as an effective approach in reducing manufacturing costs and requirements (Hinmon D. 1987).

As discussed there are many reasons for the emergence of CIM, ultimately it is driven by the desire to apply ever increasing levels of automation to the manufacturing process to improve efficiency, productivity and costs.

Installation of a CIM operation however, can be a formidable task due to the complexity of effort involved. True integration of business, social and technical requirements of a company, when they are subjected to rapid change due to external and internal forces, demands a structured and systematic approach.

Generally CIM implementations occur in steps or phases that allow knowledge acquired in one phase to be transferred to the next. This development allows personnel changes to be managed quickly and effectively. As CIM is more than hardware and software implementation, people, company culture, capital investment, equipment and communication requirements require careful consideration. Integration of capital, people and procedures controlling production operations should extensively figure in long term managerial plans, when contemplating complete CIM implementation (Johnson D. 1988).

The issues involved and the problems encountered when implementing a CIM environment deal with the essence of the company and separating extraneous or secondary issues and problems from the fundamental ones is not always clear. Understanding a company's objectives, needs and operations is essentially necessary before analysis of the control systems, be they computer based or otherwise.

2.1.3 Concepts

Fundamentally CIM is an integrated manufacturing philosophy which encompasses information integration between computer aided design, production, manufacture, quality and production planning facilities (Balteschwiler M, Gantert F 1988). Universally, however, CIM should be encouraged not purely as a technical concept but rather as an organisational strategy which involves the entire organisation, representing it as a coherent entity (Bölzing D, Liu F 1987). For effective functional integration, an organisation has then to be viewed as a whole, unified, system rather than a mere collection of individually automated functions.

For the philosophy of CIM to proliferate, considerable evaluation of an organisation's strategic corporate growth areas are required. To maintain and establish future market competitiveness, these aims must be clearly defined, and outlined. Initially, the executive management of an organisation would have to establish a unified CIM proposal, which includes business goals in conjunction with product, manufacturing, integrated operation and automated system strategies.

Successful integration would be achieved with information interchange compatibility, using standardised protocols, between the organisation areas that create, maintain and disseminate information. The availability of this information, to exceed restricted local interdepartmental communication, would have to be "on-line", centralised and actively available in effective storage facilities. A database infrastructure would be necessary in providing the level of integration required for effectively controlling, managing and manipulating data acquired from multiple application areas (Ralston D, Munton T. 1987).

Computer integration would thus include all relevant control and information functions in a single interactive and centrally based hierarchy. The CIM concept (Figure 2.6) would serve standard organisational functions including design, process control, manufacture, commercial and financial issues, enabling rapid product development and modification potential (Crookall J R 1986).

The initial constitute part of CIM has to be engineering design (Plossl K. R. 1987). It is here using CAD and Computer Aided Manufacturing (CAM) systems that product part information vital in all sectors of the company originates. Within the design environment, product areas including manufacturability, design for automation, marketability and part capacity utilisation are analysed. The design processes however, does not result purely with the use of computers or software, but rather management.

Resulting product development requires manufacturing planning facilities to plan raw material movement and product procurement strategies. Sales and Marketing forecasts must also be integrated to establish essential inventory, process performance, software and plant rough cut capacity data.

Integrated scheduling is required to maintain high facility utilisation, even work flows and minimise work in process levels. Effective scheduling procedures need accurate capacity information, efficient plant layouts and manufacturing control data. Such integration needs computer assistance (such as Computer Aided Process Planning (CAPP)) however, the common objectives are management directed not computer dictated. Importantly CIM requires factory automation, which includes automated material handling, assembly, test and inspection, robotics and material processing. These technologies, to achieve the objectives of CIM, need to be arranged into FMS systems or special manufacturing cells.

A unified view of computer integrated manufacture is shown in Figure 2.7. The lines of communication highlight the integration of organisational functions and closed loop feedback, through data collection, to production management, financial, engineering support and other systems.

The production management function (Figure 2.8) is responsible for coordinating manufacturing related activities in order to achieve an appropriate balance between the objectives of customer services, process efficiency and minimum inventory investments. Consequently administrative and financial functions are more concerned with costing production and raw materials in addition to the financial and administrative concerns of the company. Technical functions of the organisation include engineering support and the execution layer. These areas are responsible for the design and development of products, and production execution respectively.

Successful development of CIM concepts requires top down design and bottom up implementation (Thomlinson J 1987). Also required is a centralised database, combined with sufficient communication links between factory hardware and supporting computer systems. Progressive CIM development must then be capable of handling communication problems inherent in data transfer, throughout the manufacturing process (Machine Design 1987).

CIM can therefore be summarised by the integration of organisational functions served by computer communications and data storage facilities (Brown J et al 1988).

2.1.4 Within the Woodworking Industry

Computer integrated manufacture within the woodworking industry requires an approach different than that of say, within the engineering industry. A typical engineered component is manufactured usually by several machines or processes sequentially. The component generally begins as a piece of raw material (as within the woodworking industry) which is initially machined by a single machine to produce some desired features (e.g. a milled flat surface). The component is then routed to another machine where subsequent machining operations are carried out. This procedure duplicates itself until the component has been completed. As the engineered component is manufactured on several machines, sometimes being situated in different areas of the factory, routing, machine priority and utilisation need evaluation. An existing CIM configuration would promote manufacturing benefits, within this type of industry, due to the variety of machines used and the number of potential production plans created.

However, the manufacture of a planed or moulded wooden component is generally accomplished on a single, multi head machine. These complex pieces of equipment machine the geometry of the component as it traverses a number of cutting heads, usually in a single pass. As a finished component is created by a single machining station there are limited production facilities (timber sawing and length cutting) required prior to the planing or moulding process and usually none afterwards. These operational features, in conjunction with component design simplicity, greatly reduce component scheduling procedures and design requirements.

The planing and moulding industry would thus, due to the process application, initially require the development of a simple design package allowing the creation of computerised timber section designs, datum values and machining parameters. The information generated would, for it to be globally beneficial, need centralised storage within a common database. Profile grinders would be able to directly produce profile cutters using related interactive data. A cutter block file would also need maintaining to provide current cutter calibration data, necessary during production. Machine setting information could be collated from various timber section and cutter block database fields. The data would then be directly transmitted to the machines, for either automatic or manually assisted setting.

Using a database structure, current machine production status and product quality could be critically evaluated. This important information would be beneficial when evaluating individual machine performance and planning preventative maintenance schedules.

With the planing and moulding processes being unlike that of other manufacturing industries it is apparent that CIM systems presently available would not be suitable for this area of the woodworking industry. Due to the woodworking industry being very cost conscious, the complexity and expense of these systems would prove prohibitive and over sophisticated (Parkin R. 1988[1]: Sanusi T, Parkin R. 1989).

It is evident that the planing and moulding process requires some form of simplified CIM system in order to reduce long down time periods, increase productivity and monitor in-process machined material quality (Timber Trades Journal 1990[2] (The Clock Watcher)). From this it is envisaged that any development of a CIM package would have to be custom designed and written in its entirety, for this particular application to obtain optimum performance and cost.

Prior to the design and development of a common database and a fully amalgamated computer integrated manufacturing environment however, it is deemed essential that the fundamentals of the manufacturing process be completely understood.

2.2 Surface Measurement

2.2.1 Machine Characteristics

Planing and moulding machines, being some way analogous to milling machines, remove excess wood from the workpiece, using straight or profiled knives secured on the machines cutter blocks. The wood removal process of these machines, as with milling machines, is intermittent as shown in Figure 2.9 (Martellotti M.E. 1941). The intermittence of the knives cutting through the raw material is dependent on, spindle rotational speed of the cutting head, the feed rate of raw material traversed through the machine, the number of cutters on each cutting head and the depth of cut. The resultant surface finish generated on the component surface consists of a series of undulating knife traces.

The apex height of surface undulations produced on a component due to the cutter head cutting action, and assuming ideal machining conditions (i.e. no out of balance cutter heads), can be calculated using equation (1):-

$$\text{Height } (h) = R - \{R^2 - P^2/4\}^{0.5} \qquad \text{---(1)}$$

(Goodchild R. 1963)

h = Depth of knife marking
R = Radius of cutting circle
P = Pitch of knife marking

Figure 2.10 shows one of the highest points (apex) of a typical surface profile, which on an ideal surface would be equispaced by a pitch distance (P). The pitch of the knife markings, i.e. the frequency at which the markings repeat is defined as:-

$$\text{Pitch (P)} = f.10^3/n.N \qquad \text{---(2)}$$

P = Pitch of the knife marking (metres)
f = Feed speed of workpiece (metre/min)
n = Cutter head rotational speed (rev/min)
N = Number of knives in the cutter head actually producing a wave on the workpiece.

The locus taken by a cutter head knife tip relative to the material being cut, while in the process of chip severance, is cycloidal or more broadly speaking trochoidal (Koch P. 1955). However the equations, when used, are based on the geometry of circular arcs. These geometric surface equations are adequate, due to discrepancies between circular and trochoidal arcs being small, for this type of simple application (Goodchild R. 1963).

Their are however, several other machining errors produced when planing or moulding, which include waviness and error of form. Waviness is the component of texture upon which the undulating surface knife traces (roughness) are superimposed. Waviness results from machine deflections, vibrations, or more apparent in the moulding process, out-of-balance cutter heads.

Error of form is defined as the general shape of the surface from the ideal, neglecting variations caused by roughness or waviness. This error is usually caused, in an engineering environment, by errors in the slideways or flexure of the machine. It must be noted however that the "error of form" caused by inaccurate slideways does not arise in the moulding process. Other errors of form inherent in the components used to construct the moulding machine, such as a twisted machine bed may cause a non horizontal cut across the surface of the workpiece. This type of error is constant and does not undulate along the surface as with a milled component. Uneven wear of the machine beds can also cause this type of error.

Planed and moulded surfaces thus appear, when viewed, as a series of repeating waves, generated on the surface, in the direction the workpiece was traversed through the machine. The depth and space of these surface waveforms are dependent on the machining set up i.e., raw material feed rate through the moulder, rotational speed of the cutter heads as well as the number of knives secured on each head (Stumbo D.A. 1960).

The geometric surface undulations, produced by the cutting action, partly contribute to the resultant surface quality and texture on the manufactured components. Other smaller irregularities are present on a machined surface. These are formed by the cutting action in relation to the material itself. These surface texture characteristics all contribute to the surface quality of the machined component.

2.2.2 Surface Texture Characteristics

The surface quality of a component, manufactured by a planing or moulding machine, is partly controlled by the machining parameters set (i.e. depth of cut, material feed speed and cutter head spindle speed) in addition to the physical condition and timber species machined (Davis E.M, Nelson H. 1954).

The anisotropic nature of wood, considered in relation to rotary planing, inherently causes difficulties in assessing the quality of surface a particular species will produce. A principle factor when planing or moulding is that the rotating cutters do not constantly move in the direction of the material's fibres (grain). Cutting conditions thus becomes more complex when machining timber exhibiting natural defects such as wavy, curly or diagonal grain (Petter C. 1954). These natural defects increase the difficulty in producing a good, rotary cut, surface finish (Thomlinson R, Harrington J.S. 1960).

No timber is completely free of defects. Certain imperfections such as knots are unavoidable due to the natural growth of the tree. Other faults however, are linked to unfavourable growing conditions or develop as a consequence of improper handling during manufacture (Brown H.P. et al 1952).

Surface texture produced on a planed or moulded component is generated primarily by the characteristics of the process in combination with the machining properties of the raw material. Usually dominant surface curves are created by the trochoidal chip severance path of the cutter tips. Also vibrations emanating from the machines structure periodically superimpose themselves onto the component under manufacture.

Smaller surface perturbations are produced by the cutting action in relation to the characteristics of the material itself. The cellular structure of wood, with its thin cell walls, makes cutting without tearing difficult if not impossible (Patronsky L.A. 1953). With lightly jointed cutters the machining action is one of splitting the cells apart, rather than cutting them. Such splitting occurs along the line of least resistance (parallel to the cellular elements). The bending of the wood elements as they are forced under and up the face of the cutter causes the cells to buckle and crush (Stumbo D.A. 1960). This action, with the appropriate timber species and post environmental conditions, can cause raised, fuzzing or loosened grain. This cellular surface texture in conjunction with machining geometry and natural defects, such as knots, cross or diagonal grain, form the basis of planed and moulded component surface texture.

Surface texture measurement is important when assessing machining characteristics and component quality of a process. Currently, using a number of surface measurement systems, important evaluation of a component's quality is available. The information obtained, when using these systems, can be used indirectly to assess the quality of processes (The process used to manufacture the artifact inspected).

Process quality is important as the surface quality of a manufactured component is of great importance in securing customer acceptance. This is particularly true in the case of highly finished products such as pieces of furniture. Often a purchaser, of such articles, has a limited ability to evaluate the intrinsic value of the piece and tends rather to be guided by the articles design and surface finish (Deal R.C. 1951).

2.2.3 Present Surface Measurement Applications

There is presently a plethora of surface measurement instruments, widely used, throughout industries requiring surface information of manufactured components. These instruments can be characterised by their mode of operation and environmental application. Initially the instruments can be distinguished as either contact or non contact systems. Depending on the process application these systems can be further separated into post or in-process modes of operation.

Irrespective of the mode of operation, and in some cases the environmental applications, these instruments can be again divided into three additional classifications. This distinction being between absolute, relative and subjective measurement techniques. The development of such an array of systems has provided a large number of different processes with essential, effective and permanent component surface data.

For many years the most popular device used to measure surface topography has been an absolute measurement technique (universally known as the stylus instrument). These widely used stylus instruments however, generate several forms of inherent inaccuracies but the sources of error are well documented (Stumbo D.A. 1963).

Surface assessment can also be carried out by numerous relative mode measurement instruments that use comparative approaches. Usually the principle of operation is based upon a physical phenomenon, such as inductance or capacitance, which follows some dependence of the surfaces roughness (Sherrington I, Smith E.H. 1988).

In certain industries, subjective judgments can be made using both visual and tactile techniques. Evaluation of a surface's consistency and appearance involve comparative decisions. The surface under inspection is often matched against empirical standards, which incorporates additional absolute measurements. Accuracy with which the judgments are made can however vary considerably between individuals (Brown I.D. 1960).

It is possible for the operation principles of surface measurement instruments to vary considerably. A further more detailed review of existing instruments, using dissimilar techniques, is required for the evaluation of application and technique limitations.

2.3 Surface Measurement Techniques

2.3.1 Contact

2.3.1.1 Tactile Assessment

Probably the most well known contact measurement technique is the tactile test. In a tactile test the finger nail is drawn across a specimen. Its touch characteristics are compared with a set of calibrated samples (known as standards) manufactured by the same process. The standard that most closely resembles that of the specimen is recorded. It has been found that the tactile test is significantly more sensitive than general visual inspection as a method for assessing surface roughness (Peters C.C, Cumming J.D. 1970). This technique is more sensitive to the range of surface roughness rather than average roughness. However, due to technique limitations and the absence of permanent recording facilities, very small surface features are commonly examined using stylus instruments (Whitehouse D.J. et al 1987).

2.3.1.2 Stylus Instrumentation

Surface profiles generated by the stylus instrument, devised by Schmaltz in 1929, showed that the measurement of surface texture would have to be based on a sampling procedure. The sample first conceived was one which included all the irregularities found within a given length of trace (the sampling length). The development of electrical stylus instruments subsequently required specifying the sample length, in terms of the transmission of an electric wave filter having a bandwidth nominally equal to the sample length (Reason R. E., Bellwood P. R., Parkin R. 1982).

These absolute contact measuring instruments presently use a tracer or pick-up incorporating a diamond stylus and a transducer that generates an electrical signal as the stylus moves across the surface under inspection (Drews W. E. 1987). The analogue signal generated is amplified and then filtered by means of an anti-aliasing filter. The resulting signal is digitised, using an analogue to digital convertor. Sample lengths using electrical cut off filters are used in conjunction with a selection of magnification levels to obtain suitable profile recordings (Peters J. et al 1979).

There have been several precision stylus instruments designed and manufactured for the measurement of surface texture. Of these instruments, two have received deserved prominence. The first of these instruments being the Forster apparatus manufactured by Ernest Leitz in Germany and the second being the Talysurf 10 instrument manufactured by Rank Taylor Hobson of Great Britain (Elmendorf A, Vaughan T.W. 1958). Later development by Rank Taylor Hobson produced the Talysurf 5, Talysurf 6 and Form Talysurf instruments. The Form Talysurf uses laser interferometry to achieve a maximum stylus displacement of 4mm, with a corresponding resolution of 10nm. Other Talysurf instruments use inductive coils or optics, with an amplitude modulated signal, to translate the stylus movement or displacement to an electrical signal for processing. Although the signal conditioning of these instruments vary, they all use a stylus to obtain a surface profile. As the objectives of these instruments are similar only the operation principle of the Talysurf 10 instrument and the Forster apparatus will be discussed in more detail.

Talysurf 10 Instrument. A schematic diagram of the Talysurf 10 instrument is shown **Figure 2.11.** Surface contact is made, between the instrument and the workpiece, by a four sided $2.54.10^{-3}$ millimetres wide diamond pyramid stylus. The pickup is driven slowly across the workpiece with the stylus following the profile of the surface's irregularities. The pickup has an optical transducer and vertical movements of the stylus are sensed photo-electrically (Figure 2.12). The signal is processed and displayed either on a pen recorder or on a Roughness Average (Ra) meter.

The Talysurf 10 instrument can incorporate a skid, when necessary, to provide a surface orientated datum (Figure 2.13a). The pickup body of the instrument traverses a path, using the datum, parallel to the general shape of the surface. This action filters out vertical movement due purely due to surface roughness. To achieve this the skid length must be greater than the surface texture spacing. If the surface irregularity spacing is too large, an independent straight line datum can be used (Figure 2.13b). A maximum traverse length of 50mm (1.97 inch) is possible. Results of surface profiles, using this instrument, can be magnified vertically from x1,000 to x50,000 and horizontally from x20 to x100 as shown in **Figure 2.14**.

Forster Apparatus. The operation principle for the measurement of surface profiles using the Forster Apparatus is illustrated in (Figure 2.15). The workpiece under inspection is moved sideways past an oscillating stylus at a rate of 5mm per minute. The stylus used has a radius of 50 to 60 microns (when used on wood surfaces), and a needle pressure of 0.6 to 1.0 grams. A tilted mirror above the stylus reflects a beam of light generated from a built-in-light source on to photographic film. Using this arrangement the oscillations of the stylus (representing the workpiece surface profile) is recorded. Vertical and horizontal magnifications of x1,000 and x20 to x100 respectively are obtainable with this instrument.

To ensure consistency and reproducibility of results it has been necessary to standardise a number of features on these instruments. This has been achieved using a benchmark such as the Australian standard **AS 1965-1977** (the measurement of surface roughness with direct-reading stylus electronic instruments). This guideline specifies such things as the stylus radius and force, the minimum traversing length and the filtering characteristics of the system (Thwaite E. G. 1977).

The main advantage of the stylus instruments are that they are easy to use and that they are able to give a profile along a well defined path. The vertical displacement of the stylus is converted into an electrical signal which allows statistical analysis of features such as height, slopes and curvatures (Mignot J, Gorecki C 1982).

The stylus tips of these general purpose instruments can however, damage the surface of soft materials. This effect has been reduced, using special research instruments, by substituting the normal diamond tips with various radii chrome steel balls (Han R. A. 1957).

To completely overcome the detrimental effect of such instruments however, non contact measurement techniques are used.

2.3.2 Non Contact

2.3.2.1 Visual Technique

The visual method of assessing surface finish is a very simple and inexpensive technique carried out by manufacturers (a technique extensively employed within the woodworking industry). This is probably one of the simplest evaluation techniques known and has shown that roughness values in the order of 0.5μm can be sensed (Maycock K.M. 1987). It has also been established that the unaided eye is capable of sensing changes of reflection angle in the order of 1.5° on materials such as wood. However this type of surface assessment is very subjective, as the inaccuracies with which the judgments are made can vary considerably between individuals. This approach is known to suffer diurnal fluctuations (Brown I.D. 1960). These effects can be eliminated using the optical sectioning method.

2.3.2.2 Optical Sectioning (Schmaltz Technique).

The principle of optical sectioning is to focus a thin section of light onto the surface of the workpiece (Dagnall H. 1980). The beam of light is angled and viewed at 45° to the workpiece surface, in order to produce the clearest profile (Figure 2.16). The observed surface, through the eyepiece, represents an apparent surface profile height, and is equal to $h.(2)^{0.5}$ (Where h is the actual height of the profile).

To obtain accurate measurements the eyepiece contains a measuring graticule or micrometer. Optical sectioning techniques are more suited for surface measurements of soft materials, where contact techniques could possibly damage the surface layers of the material (Takenada N. 1979). This measuring technique is appropriate for obtaining, post process, roughness values between the range of 2 and 200μm but only provides a graphical representation of the surface. The restrictions of this technique can be overcome using optical profilometers, which provide non contact measurement and surface data that can be manipulated and statistically evaluated.

2.3.2.3 Optical Profilometers

Optical profilometers are used for the reasons previously discussed and because mechanical profilometers yield values of roughness averaged over the size of a diamond point, which contacts the specimen's surface. Furthermore the diamond stylus is usually angled at 45° , therefore measurement of a roughness profile steeper than that would generate inaccuracies. This source of error is reduced and the undesirable contact feature, of the stylus based instruments, are removed using optical profilometers. A number of optical profilometers employ different operating principles such as, for example, Foucault's method or intensity feedback to obtain indirect representations of a surface's topography.

The principle of Foucault's Method is shown in **Figure 2.17**. A perfect objective is illuminated by a light source emanating from a point source S which forms an image at S'. If a blade (C) is positioned at the images focal point then the result, when an observer views the objective from behind the blade, is as in **Figure 2.18a**. If the source is moved a very small amount towards or away from the objective, the resultant views are as in **Figure 2.18b and 2.18c** respectively (Dupuy M. O. 1967).

Foucault's Probe Foucault's principle is incorporated into the Foucault knife probe (Figure 2.19). The illumination or object spot is focused onto the specimen's surface by a lens (O). A half silvered mirror is used to form a reflected image at point S'. As the specimen is traversed horizontally, the object spot moves vertically, as a result of the components surface roughness. The illumination spot on the surface and the image at point S' are kept in focus by movements of the lens (O). The objective's movement is controlled by a feedback signal generated by any non-uniformity of the image detected by the photomultipliers.

Intensity feedback This is a similar principle, to the above, that uses a photo detector to monitor the maximum intensity of a reflected illumination spot, which is focused on the surface of a specimen. **Figure 2.20** illustrates the arrangement of such a device. A laser beam is focused onto the surface of the specimen. Back reflected light is collected through a beam splitter and a lens over a photo diode. The objective continually oscillates, along the optical axis, at a rate much faster than the translating work piece using a micro movement. When the focal point of the objective coincides with the specimen's surface the photo detector output is a maximum. The output of the detector and the specimen's position (corresponding to the maximum intensity) is recorded. The sensitivity of the instrument is dependent on the size and depth of focus, on the magnification of the optical system, photo diode sensitivity and electronic amplification (Arecchi F.T. et al 1979).

Other operating principles used within optical profilometers include the defect of focus technique (Mignot J, Gorecki C. 1982); and Interferometric measurement (Dobosz M 1984 : Bhushan B. et al 1987 : Stevens D.M.G. 1989).

Due to their operation speeds, limited use is made of these visual and optical post process techniques. On-Line measurement would eliminate the difficulties incurred as in-process measurement of surface finish, for commercial application, requires operation speeds that match the monitoring technique to the process (ie the process is not restricted in any way).

2.3.2.4 In-Process optical techniques

With the progress of automation in manufacture, in-process detection of machined surface roughness is required. Several techniques are presented, which monitor the quantity of light scattered from machined surfaces.

Reflected Light Position Detection Figure (2.21) shows the principle of operation for component surface detection by micro displacement. A laser beam is focused on to the surface of the workpiece at an angle of 45°. When the surface travels from the solid to the broken line profile (Figure 2.21), the reflected point moves from position A to that of B. The returning beam is magnified through an object lens, of a microscope, and projected onto a one dimensional photo diode array (Mitsui K. 1986). The 25μm spaced array elements need to be sampled at a suitable rate, to obtain an accurate capture of the focused laser beam displacement.

The laser Scattering Instrument When electromagnetic radiation is incident on a surface it may be reflected specularly, diffusely or both. For smooth surfaces (that is when Root Mean Square (RMS) roughness is much less than the wavelength of illuminating light :Teague E. C. et al 1981 ; Young R. D. et al 1980) most of the radiation is reflected specularly at an angle equal to the angle of incidence "Snell's Law". As the roughness value increases the radiation becomes more diffuse. Reflection becomes totally diffuse when the energy in the incident beam is distributed as the cosine of the angle of reflection. Figure (2.22a & 2.22b) shows specular and diffuse reflection patterns (Clarke G.M, Thomas T. R. 1979).

Exploiting these principles, the general features of the laser scattering instrument are shown in **Figure 2.23**. When light from the laser strikes the sample target, both specular and diffuse reflection results. A detector mounted on a goniometer is rotated through an angle (c) which is ±10° from the location a=b. The power of the detected light is recorded on a strip chart as shown in **Figure 2.24a**. The result represents the specular power obtained using a laser power meter, which was connected to the output of the detector, for a piece of, Ra=0.2μm, stainless steel. **Figure 2.24b** shows the effect on the specular power when a piece of, Ra= 0.08μm, stainless steel was tested. This specimen produced a specular power recording 20 times greater than the first sample. To minimise the detection of diffuse reflection a 2mm aperture was placed in front of the detector. This specular reflection technique is only suitable for relatively smooth surfaces due to the characteristics of the helium neon laser used (Whitley J. Q. et al 1987: Vorburger T.V, Teague E.C. 1981). Similar techniques have also been researched by (Stout K. J. 1984; Church E. L. 1979).

Other on-line processes use fibre optic bundles to assess the light reflected from relatively smooth surfaces (Inasaki I 1982). **Figure 2.25a** shows the experimental arrangement required for measuring the reflection distribution using optical fibres. The particular system contains 675 incident and detecting 50μm diameter optical fibres randomly bound into a 3mm cluster. The experimental results obtained are illustrated, **Figure 2.25b**, when the reflection intensity was monitored on austentic stainless steel (Takeyama H. et al 1976).

The surface measurement methods described all have undesirable limitations, from a manufacturers point of view. The contact systems present either subjective results or they operate in a post process environment. The optical profilometers improve on the stylus based instruments, in that they prevent surface damage on the component, but again have relatively slow operating times. The in-process systems described are expensive or are only suitable using highly reflective surfaces, where the surface roughness average is much less than the wavelength of illuminating light. The features illustrated make these systems unsuitable for in-process measurement of a diffuse material such a wood.

3. SYSTEM CONCEPTS AND DEVELOPMENT

3.1 System Strategies

3.1.1 Overall Project Strategy

Low utilisation figures of expensive moulding machines have detrimental effects on profitability. A basis for improving this could involve computer integration and control. CNC moulding machines have previously been presented (**Timber Trades Journal 1986**) which partially improve efficiency by reducing machine head setting times (automatic movement of cutter head spindles). However, the area automated by the above solutions only account for approximately 10 to 15% of the total down time cycle of the machine. It is therefore necessary for another more rigorous and integrated approach to be investigated.

A carefully planned custom, but low cost and reliable CIM system could provide the foundation for reducing planing and moulding machine down time cycles (Figure 3.1). Primarily a simple CAD package would be required for the design and storage of the two dimensional component sections. In addition, for effective information dissemination, it would be important for the CAD system to manage other information such as timber data (created from the CAD component section files), cutter block identification and cutter profile data. Combining CAD objectives with efficient and compatible communication between the drawing office, tool room and manufacturing floor, in the form of an interactive data base, quick information interchange would become possible.

With cutter block and timber data information centrally located within the data base, calculation of the machine's associated spindle offsets would be possible. Obtaining the spindle offset values however, involves measuring each of the machines cutter block profile knife sets (measured as a complete block and arbor assembly). The subsequent measurements and calculations, between timber and cutter block data, to obtain the machine's offset values will require the design and development of a new economic computer aided setting system (CASS).

With valid ,collated, manufacturing data available within the data base (via the CASS unit) an intelligent control unit would be required on the machines to aid in the reduction of down time cycles. The Reduced Down Time (RDT) unit, to decrease cycle idle times, would have to be capable of receiving and transmitting machine data. A prerequisite of the unit will be manufacturing information analysis facilities, enabling the initialisation of automatic or manually assisted machine setting. Computer aided control of the planing and moulding process with the conjugation of effective data transmission, it is deemed, could result in dramatically alleviated machine down times and hence greater profitability.

It is envisaged that the progression of computer aided control will increase machine efficiency but, from its own development, problems of sub standard material quality will arise. With shorter machine idle time periods and reduced operator intervention the advent of multiple machine supervision will become the norm (within this sector of the industry). With the supervision of several machines, visual post process assessment of product quality, by the operators, will no longer be feasible. As moulding machines have high material feed rates, large quantities of product could be potentially ruined when machines develop a typical fault such as an out of balance cutter block assembly. As raw material is expensive, high volumes of waste resulting from undetected machine faults would have to be reduced automatically. Improved quality control levels of the product could be achieved by the design, development and integration of an in-process surface characterisation system.

The overall project strategy, in the main, is then to improve machine utilisation by increased machine operation times and reduced direct labour costs. As the woodworking industry is very cost conscious, careful system consideration would lead to modular design concepts. This approach would allow woodworking manufacturers purchasing flexibility. However for a smooth transition to computer aided control, within the planing and moulding area of the industry, several custom constituent parts of the CIM system (the CASS, RDT and laser surface characterisation system) require further design strategy investigation.

3.1.2 Computer Aided Setting System Strategy

The purpose of the CASS system is to manage information flow. The functions of the module are:-

1) Hold timber information - coordinates of feature data (for each face) from data positions.

2) Hold data of each cutter regarding radius and length departure positions - from spindle arbor datum

This system, in addition to the functions above, requires the capability of exporting the information by hardwire link or memory storage cards in a condensed form required for a single job or task.

For penetration of the established market sector the CASS system would have to be operator tolerant, reliable and of low production costs. Accurate offset calculations of the cutter block knife profile features (from measurement and calibration) would be achieved using integrated circuit counter and signal conditioning circuitry, microprocessor architecture and suitable transducer/readout interfaces. Measurement of the cutter head profile knives would be undertaken on an existing measuring stand (Figure 1.12b). As Spherosyn (trade mark of Turner Newall Ltd) inductive transducers (see **Appendix A**) are an integral part of the stand, compatible signal conditioning circuitry and interface design considerations would be necessary in supplying the transducers with correct drive signals (Parkin R 1988[2]). Extensive software program design, providing a structured operating system, would also be necessary to provide integrated data transfer, manipulation and storage.

The bulk of the CASS unit development was undertaken by Sanusi T (Sanusi T. 1989). However the design and development for the CASS system's spherosyn transducer counter circuitry was investigated and resolved by the author. The results of this work are presented in **Appendix B**. To obtain greater integration benefits, between the CASS and the RDT units, any system development arising due to future needs must be carried out in parellel.

3.1.3 Reduced down time strategy

The purpose of the RDT system is to reduce the idle time of the moulding machines. It accomplishes this by accepting data for a single machining task (transferred from the CASS system). By effectively presenting machine data (using visual display aids) the operator can quickly and accurately set the head offsets, of the machine, that are required for product manufacture to the required dimensions.

To achieve system flexibility and market competitiveness the hardware concepts, of the RDT unit, would need to incorporate designs at integrated circuit level. Using this technological foundation design considerations, essential in part for greater acceptance and system success, in areas such as the working environment and data transfer would need methodically establishing in conjunction with the collaborating industrialists.

The initial objectives of the RDT unit would be to absorb, directly or indirectly, machine cutter head identification and positional information generated by the CASS system. It was deemed that this approach will benefit both the operators and the manufacturers as data transfer, between the CASS and the RDT units, may be achieved using direct wire links or indirect storage mediums. However, with the planing and moulding working environment being harsh (relatively high dust, vibration and noise levels) special examination of these mechanisms is required.

Irrespective of the data interchange approach chosen, the standard files created by the CASS system contain information other than identification values and machine setting coordinates. Consequently RDT software aims need to incorporate structured validation, format and storage procedures.

On completion of data interchange between, and within, the two systems it would be necessary for subsequent strategies to functionally integrate the process and its control mechanisms. Typically a surveillance scanning strategy would be necessary, employing both hardware and software designs, to encompass each set of the machines cutter head direction controls. This action would obtain prompt, simple and accurate spindle positioning. It is probable that this could be undertaken using intelligent interface electronics, microprocessor control and optical visual aids.

Reduced machine setting times and direct operator supervision levels would be promoted using compatible data structures and system integration. Ultimately this could be achieved with the design of a low cost, compact, reliable and efficient data exchange system. However the scenario of computer control would, nevertheless, create a process monitoring requirement.

3.1.4 Surface Characterisation Strategy

Woodworking manufacturers can no longer financially absorb the costs incurred when large quantities of expensive sub standard (poor surface quality) artifacts are produced on machines which exhibit operational faults (e.g. blunt cutter block knives). With machine operator supervision levels declining, as a consequence of growing computer control, automatic product monitoring will become essential. The philosophy thus adopted, to develop a suitable monitoring and control system, requires careful consideration due to inherent operation features within the planing and moulding process (e.g. high material throughput rates and harsh local environments).

From this the monitoring system would have to be designed in such a way as to allow in-process surface characterisation measurement of wooden components. The measurement system, due to production speeds and the characteristics of the material machined will, it is envisaged, have to operate in a non-contact nature and match the monitoring operations to the process.

Several characteristic methods (visual and tactile techniques) employed, by the woodworking manufacturers, exploit aesthetic evaluation. Due to this it is envisaged that the surface monitoring system's development will incorporate optical techniques. In addition to complement existing industrial approaches, periodic assessment of surface waveforms would be attractive.

The CASS unit is discussed in **Appendix B** and the surface characterisation system in subsequent chapters. A detailed examination of the RDT unit directly follows.

3.2 RDT Hardware Design

3.2.1 The Microprocessor

The RDT unit is illustrated in **Figure 3.2.** The Mitsubishi 50734SP microprocessor (circuit schematics and description shown in Appendix C), used within the unit, was primarily selected for its programmable Input and Output (I/O) capability. Choice of a processor supporting high levels of I/O capacity conveniently allowed system expansion, when the accommodation of future manufacturing developments were required.

Figure 3.3a schematically shows the RDT unit's hardware arrangement. The processor architecture (Figure 3.3b) consists of a 7.37280Mhz crystal circuit driving the processor, 8K bytes of Random Access Memory (RAM) and 8K bytes of Read Only Memory (ROM). The RAM and ROM integrated cir cuits are shown as IC3 and IC4 respectively. As the lower 8 bits of the processor data bus are shared with the lower 8 bits of the address bus, an octal D-type latch (IC No 2) is used to separate memory addresses from data. This is synchronised using the address latch enable output signal from the processor.

A 74LS02 NOR gate was required between the Direct Memory Enable (DME) output pin of the processor, the memory card and the multiplexer (IC Nos 5&6). This was necessary to "enable" the system's internal RAM, ROM or chip selects, via the multiplexer, while the external memory card was disabled (by programming the DME pin high).

However, if the DME pin of the processor was programmed low the system's external memory was subsequently enabled for data reading or writing operations. Consequently the internal memory and chip selects were disabled.

Other pins of the microprocessor were reserved for the RS232 hard wire link communications port (connections between IC1 and 1C7). **Figure 3.3** also shows the microprocessor connections which are used to control the light emitting diode display (Figure 3.4 (drawing 2)), the liquid crystal display (Figure 3.5, (drawing 3)), the switch control (Figure 3.6 ,(drawing 4)) and the memory storage card holder (Figure 3.7, (drawing 5)).

3.2.2 Visual Aids

Light Emitting Diode Hardware Suitable display mediums vital in allowing essential information interchange, between the RDT unit and the machine's operator, were reviewed. Eight seven segment high efficiency, common anode, Light Emitting Diodes (LED) were used. Four were used for the cutter identification numbers and another four for cutter head position data. These are shown diagrammatically with their associated hardware in **Figures 3.4 and Figure 3.8** respectively.

Port zero of the processor was programmed to mask the 3 line address of the decoder/multiplexer (Figure 3.4,IC No 8 , (drawing 2)). The mask provided a logic low on each SN7407 hex buffer output line sequentially (IC Nos 9&10). This procedure effectively scanned a logic low to the base resistor of each transistor in turn. The transistors driving the LED's, being PNP devices, were thus provided with the capability of supplying their load (T_1 to T_8).

The data, required for display, was then loaded to port one of the processor. This action determined the status of the darlington driver's output lines (IC No 11). Thus with the multiplexer scanning the PNP transistors, via the hex buffers, and the appropriate darlington driver output lines set correctly, the display of data was achieved.

Liquid Crystal Display Hardware Beneficial optical information interfaces were used to enhance data transfer within the production environment. This resulted in a Densitron Liquid Crystal Display being used which is illustrated in **Appendix D.** The alphanumeric, dot matrix module incorporated a CMOS microprocessor and LCD display drivers. The unit utilises a 5x7 dot matrix format and is capable of displaying the full American Standard Code for Information Interchange (ASCII) character set plus eight user programmable symbols.

The hardware configuration is shown in **Figure 3.5; (Drawing No 3)**. It comprises of a 6522 Versatile Interface Adapter (VIA) preceding the LCD unit. The control of peripheral devices from the VIA was handled primarily through two 8 bit bidirectional ports (only port A shown as it was used to control the LCD module). Using these ports It was possible for the lines to be programmed as either outputs or inputs. An R-C and Nor gate circuit was required at the VIA clock input (pin No 25) to synchronise the data Read and Write signals between the processor and the VIA, thus allowing valid data transfer.

3.2.3 Data Transfer

Figure 3.9 shows the type of memory storage card (Fujisoku$^{(tm)}$) and holder used. The cards were highly reliable and resistant to static electricity. The storage card holder and it's direct connections are shown in **Figure 3.7.** Each card was programmed directly via the system data bus. Programming the external cards required memory initialisation using the DME facility of the processor and subsequent data read/write operations

Switch Input Control Hardware The switch inputs, when activated, initialised data transfer, from the processor's data buffer to the LED unit. The wiring arrangements for the switches are shown in **Figure 3.10.** The switches are pulled up to a 12V level using convenient resistance values (Figure 3.6). For system compatibility the 12V input levels, of the switches, are converted to 5V using 4050B non-inverting buffer chips. All outputs of the four buffers were monitored by three eight channel analogue multiplexer/demultiplexers (4051B chips). With the processor sequentially scanning the multiplexer's address and enable lines, with the single output of each 4051B common, any switch triggered was sensed.

3.3 Software Development

The software required to control the RDT unit, is schematically detailed in **Appendix E**. The programs general operation principles are however outlined and commence with the system's instruction and variable module.

3.3.1 System Instructions and Variables

740 Module. Initially the 740 file was created to contain all the non standard 6502 language instructions. The file was an important integrative bridge between the standard 6502 assembler and the 50734SP microprocessor (an enhanced 6502 device). Within this module each enhanced instruction was equated to the machine code value handled by the processor.

VariesC module. The module "variesC" was designed to allocate specific memory locations (addresses) to labelled variables. For convenience there were memory look up tables created for the LED number codes and the LCD message buffers, enabling simplified device programming. RAM memory buffers were also specified for later storage and manipulation of card information.

VarX. The "VarX" module was also created to assign variables to specific memory addresses. However, memory card information rather than program information was held within this module's variables. Examples of the type of data held is the maximum number of cutter heads used for a particular job or individual job data file lengths.

3.3.2 Initialisation

Initc. This module of the software initially cleared the processor's D,T and V status flags. The D (or decimal) flag was cleared so the device operated in a binary mode. The T and V flags were also set to zero. This allowed operation results, between two memory locations, to be stored in the accumulator of the processor for data manipulation convenience. As these types of instructions were enhanced codes they needed to be byte equated. This was achieved using an "equb" statement within the assembler package. Thus the actual machine codes value were inserted into the system's memory on assembly completion. Selective variables such as "gotcard" and "end" were then equated to zero before the processor's operating status was set up, but after its interrupt capabilities were halted.

Processor data bits two to five of port zero were then set up as outputs followed by the first seven and six bits of ports one and three respectively. These ports were program selected as outputs for the LED's, machine switch enable and address lines, in addition to the external memory requirements.

The maximum switch value constant was then set (having a value of 24 on the RDT system). Several program variables such as "multi", "single" and "button" were also set at this time (ie "multi" being a labelled variable containing a predetermined value to identify whether multiple characters were to be displayed on the LCD).

Important card memory address information was then stored as the contents of address labels before specific card data buffers were created. A memory allocation was designated for these buffers to enable storage and manipulation of machine data. Four data buffers were created, two for the LCD device and two for the LED'S. The buffer's positions in memory were determined by inserting their start addresses as the contents of 2 byte buffer variable labels.

Information was placed or withdrawn from the buffers using the determined base addresses (contents of the buffer's variable label) in conjunction with a selected pointer value, from either of the processor's X or Y registers. Four data buffers were required to prevent data corruption (data corruption discussed in section 3.3.4). All of the buffers were then preset with termination bytes (equalling a value of &FF). This was carried out to prevent information being displayed on the LED's (a &FF transmitted to a LED, with this system configuration, blanks the device) before the insertion of a memory card into the system.

Subsequently the "setup" subroutine was used to organise portions of the processor's zero page RAM memory to improve data transfer efficiency. This block of code then initialised the 6522 Versatile Interface Adapter (VIA) CHIP. VIA initialisation included programming the reset, enable and read/write I/O lines of the LCD display.

The "lcdmd" subroutine was then used to instate the LCD and display the machine's start up message (ie Wadkin Woodworking Division Version 2.0). This sequence of operations was then followed by the establishment of the processor's timer interrupt vectors. These vectors were created to enable correct processor timed interrupts. The first timer of the device was then preset and loaded. The preset operation was required before the interrupt capabilities of the device could be utilised.

3.3.3 Foreground Scanning

The foreground programme module (Buttc) was used to continually scan the machine's button inputs (machine button input hardware shown in Figure 3.6). Initially the multiplexer's count value (count value = &02) was stored along with its software enable and address masks (labelled "Mmask" and "Adcnt"). The first multiplexer was enabled and its address set to zero using the masks. These operations also disabled the 2nd and 3rd multiplexers.

The common outputs of the three mulitplexers were then monitored to determine whether the first button of the machine had been initialised. If this button had not been depressed the software looped (up to seven times) to scan all the other inputs of the first multiplexer (first 8 buttons of the machine). This was achieved by incrementing the "Adcnt" address mask which set a new multiplexer address in each software loop. If no button had been operated the software multiplexer enable mask was rotated by one bit to enable the second multiplexer (thus disabling the 1st and 3rd multiplexers).

The Multiplexer count value was then subtracted by one and the address scanning loop for the second multiplexer commenced. Again the common output of the multiplexers was examined to determine if one of the eight button inputs had been operated (inputs now generated from the second block of 8 buttons on the machine).

If none of these buttons (buttons No 1-16) had been operated then the software enabled the 3rd multiplexer and consequently examined its eight button inputs (every time a new multiplexer was scanned the "Mcount" variable's content value was reduced by a value of one). If none of the twenty four machine inputs, on examination, had been operated a dummy value (value = &18) was stored in the software variable "button".

If a machine button had been pressed during the "ButtC" software routine scanning, its corresponding stored value (buttons No 1-24) required calculating. Calculation of the pressed machine button value was achieved using the variable "adjust" (set originally to sixteen (&10), and the variable "Mcount" which initially equalled two (&02)). The

"Mcount" variable contents, for this calculation routine, was required purely as a terminating loop count.

The contents of the variable adjust, to achieve the correct button value, was conveniently stored in the processor's accumulator. If after button scanning the "Mcount" variable contents equalled zero the resultant button number equalled a value of sixteen plus the local address count (adcnt) of the 3rd multiplexer (as three 8 bit multiplexers had been sequentially enabled).

If the variable Mcount contents equalled 1 then the content value of the adjust variable was rotated one bit right. From this the resultant buttons number equalled a value of eight plus the local address count of the second multiplexer (as only two 8 bit multiplexers had been enabled during the scanning process). finally if the variable "Mcount" contents equalled 2, at completion of the button scanning routine, then the button value was determined purely by the local address count of the first multiplexer. On completion of the button calculation software loops, the actual machine button value was stored in the variable named "button" (for future use).

The remainder of the (Buttc) module code was designed for memory card data collection and transfer. This block of code examined the memory card holder to check if a memory card was present (using the card detect facility). If no card had been inserted, the processor's RAM data buffer values were unaltered and the software returned to the beginning of the continuous foreground program.

If a memory card had been inserted into the card holder, it was then checked (using software flags) to identify whether that particular card had been interrogated previously. If the machine data, of the card within the card holder, was identical to the processor's RAM data buffers the card was not read again (each card interrogated only once within the system). The software again then returned to the beginning of the foreground program with the processor's data buffer contents unaffected.

If a memory card which had not previously been interrogated had been inserted into the card holder, its data was examined and transferred to the processor's RAM. This operation was accomplished using the subroutine "recCHD" and its associated nested software routines.

3.3.4 Data Transfer

The module "recCHD" was designed to transfer data from the external memory cards to the random access memory buffers of the processor. The related subroutines of recCHD initially checked the status of the inserted card. The card status check identified whether the card was powered correctly and that it was in fact a transfer card and not a storage card (transfer and storage cards are not exchangeable as they contain different information although they are physically the same). If for any reason the card was not powered correctly, or it was a tool room storage card, the appropriate error message was displayed on the liquid crystal display.

By monitoring card status, only valid machine configuration data was transferred to the processor's memory map. Three types of machine related data files were transferred from any one external transfer memory card. Two of the three files extracted were used to aid the machine set up procedures. The important data files transferred were the Component File (CFile) and the Head File (HFile) which provided all of the information to set the machine. These files however, were arranged in a format which was not compatible with the machines display hardware (raw data format of both Cfile and Hfile are shown in **Figure 3.11**). An extra subroutine module "reader" required development to manipulate the raw data extracted from the external storage medium. Once the correct data had been removed it was then transferred to specific receive and display random access buffers, which later allowed easy data collection and hard ware programming. If during the card reading procedure, any software flag errors were encountered the card was read again (for a set number of retries). If the set number of retries was exceeded or an incorrect card had been inserted into the system the operator was instructed to remove the present card and replace it with another (for reasons given by the error message displayed on the LCD).

Once the correct card had been successfully interrogated the "reader" module reformatted and redirected the machine set up data to the prescribed, memory, receive and display buffers. On entering the reader module several of the processor's registers were preserved (pointer addresses for the processor on return of subroutine as this module operated under interrupt control). The first 8 characters of the CFile data buffer were then directed to the LCD receive buffer using indirect indexed Y register programming techniques (Figure 3.12).

The memory block transfer operation was then succeeded with a machine head number calculation. The calculation was required to ascertain the number of head files present in the data file. The calculation consisted of a simple subtraction of the variables "firsthead" and "lasthead" contents. The result of the calculation was then stored in a variable called "Nohead" (the number of heads).

A termination byte (equalling &FF) was then stored at the end of the LCD received buffer for display purposes. The base address of the LCD receive and display buffers were then swapped using a "Gabowski" routine to ensure that only uncorrupted data was displayed on the machine. The "Gabowski" routine consisted of filling the receive buffer with data and checking its validity status. If this buffer contained authentic data its base address was swapped with that of the display buffers. This procedure ensured that the new display buffer contained valid data to be displayed on the machine, while the new receive buffer was ready to receive data. Using this routine the problem of corrupted display data was eliminated.

Every LED data byte that was collected from the RAM buffer (HFile) was compared with a value of &20. If the byte equalled &20 it was replaced with a value of &FF (any ASCII &20 spaces in the file were changed to a &FF to display a blank on the LED). An address pointer was then constructed to increment every data byte transfer. This pointer was necessary to identify the programs present position within the data file.

The first four cutter head identification characters were then directed from the HFile buffer to the receive RAM buffer. The next two data bytes, which were not required, were then skipped by the programme before the corresponding cutter head's X coordinate data bytes were transferred.

The program was then required to loop and collect the first four bytes of cutter head identification. This duplication was needed because for each cutter head, a X coordinate plus a Y coordinate was required. After collection of the duplicate cutter head identification information the four byte Y coordinate information was redirected to the receive buffer (Figure 3.13). Once the information of a single cutter head had been redirected, to the receive buffer, the program then looped to the start of the data collection routine. The program continued to loop until the data for the total number of heads present, for the particular job, had been collected.

The base address for the LED receive and display buffers were then swapped enabling, as described previously, uncorrupted data to be displayed. The processor's registers were then restored before the program returned to the (Buttc) scanning module from where it had originated. The correct job information name was then subsequently displayed on the LCD and the button scanning routine repeated.

The processor was interrupted every millisecond using it's first timer and timer interrupt vectors. When an interrupt occurred the processor's program counter was directed to the start of the interrupt code (the address of this code being located in the two byte variable "Timlint").

The interrupt unit of the program, after resetting the interrupt request bit and stacking (a term used to preserve the processor's register values) the processor's registers, multiplied the machine button values (value of 0-24 obtained in the Buttc module) by eight. This multiplication was necessary due to each machine button requiring 8 related LED display characters. The new button value calculated was then transferred to the (Y) register for later indirect indexed data collection. The LED display was blanked out using the LS139 multiplexer's G2A control line. This was achieved by setting the subsequent G2A line (Figure 3.4) high via port zero, which set all the multiplexer's outputs high.

With the LED disabled the multiplexer's address was arithmetically shifted left by 2 bits (multiplexer port line allocation offset by 2 bits) before it was temporarily stored in the variable "AD1". Port zero was then examined and the multiplexer's address and control lines were set low, before they were logically ORED with the correct character and enable addresses. With the correct address stored back on the multiplexer's port, character display potential was created via the hex open-collector high voltage buffers. The common anode of the LED character was thus programmed but no illumination occurred until subsequent character information was loaded on to the LED'S cathode port (port 1).

The cathodes of the LED character were then programmed using port 1 of the processor. The correct character from the processor's random access memory buffer was loaded using the modified button value as an indexed pointer. Once the character had been collected it was checked to establish whether a blank or a valid numeric was to be displayed. A blank was displayed using a segment code which would turn off all the elements of the LED character (a &FF character used).

If a numeric was to be displayed the ASCII offset of the character (&30) was stripped and the resulting value (value from 0-9) was stored in the processor's (X) register. The data stored was used as an index pointer in the LED data buffer (Figure 3.14). Relevant port 1 data bits were then set and the correct character was thus illuminated. The multiplexer's address was then incremented to the next LED character before the processor's interrupt request bit was cleared. The registers of the processor were then restored (to the state prior of system interrupt) before the program returned to the foreground program. Every interrupt initialised by the timer enabled another LED character to be illuminated or blanked accordingly.

With machine set up times reduced by the development and installation of the CASS and RDT systems, the production aims subsequently focused on component and process quality. The quality is related to the machining parameters used (ie the cutter head spindle speed, the number of knives in a cutter block etc), the type of material machined and the condition of the manufacturing process.

The new production objectives fundamentally guided an investigation to mathematically model the machining process. The products of this development, it was deemed, would generate quantitative process and component quality prediction information. The data obtained would prove valuable as correlation between the results from the surface characterisation system and the model would be possible.

4. SURFACE MODELS

Page #

4.1 Surface Characterisation

4.1.1 Mathematical Modelling

Theoretical and scientific study of a situation often centres around a mathematical model which simulates relevant features of a system. A mathematical model can be described as "an abstract, simplified, mathematical construct related to a part of reality and created for a particular purpose" (Bender E. A 1978).

Events are modelled for various purposes. Among these is the necessity to predict new results or features which are physically practicable and which categorise a specific entity. However as individual models incorporate various simplifying assumptions there is usually no single model for describing a situation.

The creation of a mathematical model requires identification of a system's real problem. In addition the entity to be modelled rarely appears as a well defined statement and usually needs to be derived from an embedded environment. Subsequent processes are then necessary to clarify and organise the simplification of a model's construction from its surroundings.

Within physical situations in particular, the simplification process is a crucial formulation stage of the model's creation. This idealisation process is essential as it resolves significant and irrelevant features from general modelling problems that involve many events which are usually complex.

With the identification of vital event features the following stage is to translate them into mathematical entities and postulate individual relationships (Clements R.R. 1989). This is generally the most difficult modelling phase.

Once a model has been constructed it needs to be validated. Usually some form of validation is carried out throughout the formulation of the model. This is achieved by inspecting the equations or other mathematical relationships set up, with initial conditions (Figure 4.1). However, a model's validity rests in its ability to represent the situation initially described. (McLone R.R, Andrews J.G. 1976)

It is important that too much time is not wasted in refining a solution of a model to an extent that is not justified by the formulation of the problem itself. In addition one must always realise that a model may have to represent reality but it is not itself reality, only an analytical instrument.

Mathematical model development for the planing and moulding process initially starts, for simplicity, with the difference of centres theory adaptation.

4.1.2 Difference of Centres Theory

Horizontal displacement of the planing and moulding machine's cutter head spindle, in relation to material traverse, can be iteratively simulated using the Difference of Centres Theory (Jackson M 1988). **Figure 4.2** represents a surface profile, generated using this approach, which consists of knife traces (arcs), detailed A_1 to A_n, with corresponding arc radii being R_1 to R_n. The origin of each arc radius is separated by a pitch distance (p) being the theoretical feed distance per knife. With the centre C_1 of arc A_1 being set on the X/Y axis, the equation relating the circle that A_1 is a section of, is defined as:-

$$x^2 + y^2 = R_1^2 \qquad \text{---(3)}$$

Arc A_2:

$$(x - p)^2 + y^2 = R_2^2 \qquad \text{---(4)}$$

Arc A_3:

$$(x - 2p)^2 + y^2 = R_3^2 \qquad \text{---(5)}$$

This general type of relationship is true for all arcs A_1 to A_n (equations representing arc A_2 are shown in Figure 4.3). By employing this method manufactured surfaces can be simplistically simulated. However, the machining conditions, for this approach, need to be known and considered ideal.

4.2 Circular Arc Modelling

4.2.1 Ideal Machining Conditions

Individual surface waveform information can be established, for ideal machining conditions, using the theory of circular arcs in conjunction with the basic surface equations previously created, using the Difference of Centres Theory (equation No's 3,4 and 5 (Jackson M. 1986)). Using equations (3 & 4) at the intersection of the two corresponding surface arcs, shown in **Figure 4.4 at point (a)**, the following surface waveform boundary equations can be obtained:-

$$y^2 = R^2 - x^2 \qquad \text{---(3a)}$$

$$y^2 = R^2 - (x - p)^2 \qquad \text{---(4a)}$$

$$R^2 - x^2 = R^2 - (x - p)^2 \qquad \text{---(6)}$$

$$R^2 - x^2 = R^2 - x^2 + 2xp - p^2$$

$$2xp = p^2 \qquad R_1 = R_2 = R_3 = R$$

$$x_{12} = p/2$$

Using equations (4 & 5) at ,point (b), the intersection of the two corresponding surface arcs we obtain;

$$y^2 = R^2 - (x - p)^2 \qquad \text{---(4a)}$$

$$y^2 = R^2 - (x - 2p)^2 \qquad \text{---(5a)}$$

$$R^2 - (x - p)^2 = R^2 - (x - 2p)^2 \qquad \text{---(7)}$$

$$R^2 - (x^2 - 2xp + p^2) = R^2 - (x^2 - 4px + 4p^2)$$

$$2xp = 3p^2 \qquad ** \; R_1 = R_2 = R_3 = R$$

$$x_{23} = 3p/2$$

By solving the simultaneous equations for x (at the intersection of the surface arcs shown in Figure 4.4) one is able to determine the width of individual wave marks. The results of which are shown as:-

$$W_1 = x_{12} - 0 = p/2 \qquad \text{---(8)}$$

$$W_2 = x_{23} - x_{12} = 3p/2 - p/2 = p \qquad \text{---(9)}$$

Additional examination of succeeding arcs, on the ideal surface, show that the pitch of these wave marks would also equal (p).

The models created, this far, have only been used to establish widths, pitches and heights of ideal surface waveforms. In practice, however, the moulders used to manufacture components regularly develop operational faults.

There are a variety of faults that can occur on individual machines, such as worn cutter head spindle bearings, generated revolution effects from motor pulley and cutter head drive ratios as well as the more common fault such as an out of balance cutter head caused by the jointing process or a proud knife.

These types of faults usually cause a cutter head vibration, which in turn contributes to an uneven set of cutter markings across the manufactured specimen. Work carried out (Jackson M. 1986) simulates the vibration effects ,caused by out of balances, by resolving them as vertical displacements. These displacements are measured from the ideal centre of the cutter head spindle.

The resulting surface wave widths are thus determined using a modified approach to the fundamental circular arc theory. Using this adaptation a common machine vibration, incorporating a twice per revolution effect, will be illustrated.

4.2.2 A Superimposed Once Every Two Revolutions Displacement of a Cutter Head

A once every two revolution displacement of a cutter head could be generated if an out of balance drive motor pulley is run at half the angular velocity of the cutter head spindle (2:1 pulley ratio). Amplification of the drive motor pulley imbalance, due to structural resonance, could create significant cutter head displacement.

Figure 4.5 shows the resultant surface profile obtained when a single knife cutter block, exhibiting an once every two revolution effect, is used during machining. If the vertical displacement $+\delta \mathrm{Cos}\,(w/2)t$ is aligned at the origin (as in Figure 4.5) Equation (3), that was established using ideal cutting conditions, can be modified to incorporate the vibration as shown.

$$x^2 + y^2 = (R_1 - \delta)^2 \qquad \text{---(10)}$$

It follows that arc A_2 of the surface profile will also exhibit the displacement characteristic in conjunction with an additional material feed displacement. Arc A_2 geometry can then be described as:

$$(x - p)^2 + y^2 = (R_2 + \delta)^2 \qquad \text{---(11)}$$

Subsequent arc equations for this type of surface will incorporate a translation variable (in the x direction) and a sign change for δ, which relates to the revolution effect.

Arc A_3 geometry can thus be described as:-

$$(x - 2p)^2 + y^2 = (R_3 - \delta)^2 \qquad \text{---(12)}$$

Arc A_4 geometry can thus be described as:-

$$(x - 3p)^2 + y^2 = (R_4 + \delta)^2 \qquad ---(13)$$

Examination of **Figure 4.6** shows the difference of curvature, for this type of surface profile, to be small as $\pm\delta$ is small (typically 10μm). This assumption permits $\theta_2 \approx \theta_3 \approx 0$. From this it is considered that the radii at point B equal (R). Displacement (x) shown in **Figure 4.7**, from the X/Y origin, to each wave peak can then be determined by evaluating joining surface arc equations. Using equations (10 & 11) at, **point (a) in Figure 4.7**, the intersections of the two corresponding surface arcs, we obtain:-

When $R_1=R_2=R_3=R_4=R$;

$$y^2 = (R - \delta)^2 - x^2 \qquad ---(10a)$$

$$y^2 = (R + \delta)^2 - (x - p)^2 \qquad ---(11a)$$

$$(R - \delta)^2 - x^2 = (R + \delta)^2 - (x - p)^2 \qquad ---(14)$$

$$-2R\delta = 2\delta R + 2xp - p^2$$

$x_{12} = p/2 - 2\delta R/p$ (illustrated in Figure 4.7).

Using equations (11 & 12) at, **point (b)**, the intersection of the two corresponding surface arcs, we obtain:-

$$y^2 = (R + \delta)^2 - (x - p)^2 \quad \text{---(11a)}$$
$$y^2 = (R - \delta)^2 - (x - 2p)^2 \quad \text{---(12a)}$$

$$(R + \delta)^2 - (x - p)^2 = (R - \delta)^2 - (x - 2p)^2 \quad \text{---(15)}$$
$$2R\delta + 2xp - p^2 = -2R\delta + 4xp - 4p^2$$

$$x_{23} = 3p/2 + 2R\delta/p \text{ (illustrated in Figure 4.7)}$$

Using equations (12 & 13) at, point (c), the intersection of the corresponding surface arcs, we obtain;

$$y^2 = (R - \delta)^2 - (x - 2p)^2 \quad \text{---(12a)}$$
$$y^2 = (R + \delta)^2 - (x - 3p)^2 \quad \text{---(13a)}$$

$$-2R\delta + 4xp - 4p^2 = 2R\delta + 6xp - 9p^2$$

$$x_{34} = (5p^2 - 4R\delta)/2p$$
$$x_{34} = 5p/2 - 2R\delta/p \text{ (illustrated in Figure 4.7)}$$

From these results individual wave widths (W) can be defined as shown:-

$$W_2 = x_{23} - x_{12}$$
$$W_3 = x_{34} - x_{23}$$

$$W_2 = p + 4R\delta/p \quad \text{---(16)}$$
$$W_3 = p - 4R\delta/p \quad \text{---(17)}$$

The circular arc theory, as shown, can be adapted to mathematically model typical machine operating conditions. This is achieved using the assumption that cutter tip paths, in relation to the workpiece, are circular.

This theory also assumes that a cutter head spindle exhibiting a displacement of (δ) has an effective cutting radius, at the intersection of surface arcs, that is equal to that of the cutter block's knife radii. Because the model assumes circular cutting arcs, the translatory motion of the material is not incorporated when the surface's boundary conditions are established. The translatory movement, of the material, in practice creates an effective cutter tip loci which is not circular but in fact trochiodal.

Due to the geometric relationship of this particular action, greater accuracy can be generated if the loci patterns of each cutter tip is expressed parametrically.

4.3 Curtate Trochoidal Modelling

4.3.1 Parametric Modelling

The limited period of engagement of each cutter, during the planing and moulding process, results from the combination of the translatory and rotary motion of the workpiece and cutter block respectively. Hence the direction of motion of each knife point is constantly changing with respect to the direction of motion of the workpiece. The resulting paths of the cutter tips are not circular but of a type which is properly described as trochoidal

For analytical simplicity the planing and moulding process can be represented by considering a stationary workpiece, while the spindle of the cutter block rotates and translates along a predetermined datum (the principle of which is shown in Figure 4.8). This analogy of the actual system, simulates the curtate trochoidal paths that are generated by the cutter tips (This phenomenon is shown in Figure 4.9). An investigation for a similar geometric process (ie up cut milling) was undertaken by Martellotti M.E. in 1941.

Upon spindle rotation the cutters are introduced to the workpiece in a direction which simulates the action of ordinary planing or moulding. As the spindle is translated at a rate corresponding to the feed of the work, the pitch radius (r) of the spindle may be determined by the following equation:-

$$F = 2\pi rn \qquad \text{---(18)}$$

Where;

F = feed rate (m/min)
n = rev/min of cutter and spindle
r = pitch radius of spindle (m)

If the cutter block, shown in **Figure 4.10**, is rotated through an angle α in the direction (M) and from a starting point of (O) then the parametric equations that follow can be established:-

$$X = r\alpha + R\mathrm{Sin}\alpha \qquad \text{---(19)}$$

$$Y = R(1 - \mathrm{Cos}\alpha) \qquad \text{---(20)}$$

The relationship of these equations are shown in **Figures (4.11 & 4.12)** respectively. If a quantity of 2π is added to the angle (α) the result is a translation of a given cutter path, in the direction of the feed, by an amount equal to the feed distance per revolution. Thus a more general system of parametric equations, of a cutter's path, can be shown:-

$$X = (2\pi K + \alpha)r + R\mathrm{Sin}(2\pi K + \alpha) \qquad \text{---(21)}$$

$$Y = R\{1 - \mathrm{Cos}(2K\pi + \alpha)\} \qquad \text{---(22)}$$

Where (K) is an integer number

Parametric modelling which incorporates cutter head rotation and material displacement provides a more accurate representation of the planing process when compared to ideal circular arc development. However, the model presented only provides instantaneous positions for, vertical and horizontal, displacement of cutter tips. In addition the model does not incorporate any operation effects that are frequently superimposed onto the workpiece, during cutter engagement.

Thus to simulate the surface topography of artifacts that are manufactured in practice, inherent aspects of the planing process (such as the effect of material velocity and the duration of cutter engagement) required investigating (Maycock K.M. 1987). Utilising these developments the curtate trochiodal locus action of individual cutter tips, and the resultant surface topography of the material was mathematically modelled. The model developed, which more accurately represents the planing and moulding process, will now be presented.

4.3.2 Trochoidal Development

Figure 4.13 illustrates the cutting action of the planing and moulding process. The total angle of contact, between the cutter knives and the material is represented by:-

$$\theta = 2.\mathrm{Cos}^{-1} \frac{(R - d)}{R} \qquad ---(23)$$

The general angle of lag between the 1st and the Ith cutter, of the cutter block, can be determined using the following equations:-

$$L_b = \frac{(2.\pi)}{N} \quad ---(24)$$

Where;
L_b = angle between cutters
N = number of cutters.

$$L = (I - 1).L_b \quad ---(25)$$

Where;
L = angle of lag between the 1st and the Ith cutter.
I = Ith cutter number

Displacement in the (x) plane for the Ith knife , of the cutter block, relative to the position of the point of 1st contact may be determined by:-

x = cutter traverse during $\delta\theta$ + wood traverse during $(L+\delta\theta)$

$$x = R\{Cos(\phi+\delta\theta) - Cos\phi\} + V.\{\frac{(L+\delta\theta)}{w}\} \quad ---(26)$$

Where;
w = angular velocity of the cutter spindle
V = the linear velocity of the wood

By relating $\delta\theta$ to the basic unit of time, using $\theta = w.t$, we obtain:-

$$\delta\theta = w.\delta t \qquad \text{---(27)}$$

Using $\text{Cos}(\phi+\delta\theta) = (\text{Cos}\phi\text{Cos}\delta\theta - \text{Sin}\phi\text{Sin}\delta\theta)$ equation (26) becomes:-

$$x = R\{(\text{Cos}\phi\text{Cos}\delta\theta - \text{Sin}\phi\text{Sin}\delta\theta) - \text{Cos}\phi\} + V.\{\frac{(L+\delta\theta)}{w}\} \qquad \text{---(28)}$$

By substituting equation (27) into (28) and expanding equation 29 is established:-

$$x = R.\text{Cos}\phi\text{Cos}w\delta t - R.\text{Sin}\phi\text{Sin}w\delta t - R.\text{Cos}\phi + \frac{(V.L)}{w} + \ldots$$

$$\ldots V.\delta t \qquad \text{---(29)}$$

To separate the time variable (δt), in equation (29), the terms $Cosw\delta t$ and $Sinw\delta t$ require expanding. This was achieved using the significant terms of:-

$$Cos(w.\delta t) = 1 - \frac{(1)}{2!}.(w.\delta t)^2 + \frac{(1)}{4!}.(w.\delta t)^4 + \frac{(1)}{n!}.(w.\delta t)^n$$

$$Sin(w.\delta t) = (w.\delta t) - \frac{(1)}{3!}.(w.\delta t)^3 + \frac{(1)}{5!}.(w.\delta t)^5 + \ldots$$

$$\ldots \frac{(1)}{n!}.(w.\delta t)^n$$

Equation (29) thus becomes:-

$$x = R.Cos\phi\{(1 - \frac{w^2.\delta t^2}{2}) - 1\} - R.Sin\phi.(w.\delta t) + \ldots$$

$$\ldots \frac{(V.L)}{w} + V.\delta t \qquad ---(30)$$

By multiplying equation (30) with a value of 2 and a rearranging, a quadratic form is established which separates the real roots of the independent time variable δt. From this equation (30) becomes:-

$$2x = -R.\cos\phi.(w^2.\delta t^2) - 2.w.R.\sin\phi.\delta t + 2.\frac{(V.L)}{w} + 2.V.\delta t$$

$$2x = -w^2.R.\cos\phi.(\delta t^2) + 2(V - w.R.\sin\phi).\delta t + 2.\frac{(V.L)}{w}$$

$$w^2.R.\cos\phi.(\delta t^2) + 2(w.R.\sin\phi - V).\delta t + 2(x - \frac{(V.L)}{w}) = 0$$

From this:-

$$\delta t = \frac{-b \pm \sqrt{(b^2 - 4ac)}}{2a}$$

Where;

$$a = w^2.R.\cos\phi.$$

$$b = 2.(w.R.\sin\phi - V)$$

$$c = 2.(x - \frac{(V.L)}{w})$$

$$\delta t = \frac{-2.(w.R.\sin\phi - V)}{2.w^2.R.\cos\phi} \pm \frac{\sqrt{4.(w.R.\sin\phi - V)^2 - 4.w^2.R.\cos\phi.2.(x - \frac{(V.L)}{(w)})}}{2.w^2.R.\cos\phi}$$

---(Eq. (31))

For a given value of x, δt can be calculated. Using this result the displacement of the cutter, in the Y plane, can be represented as:-

$$Y = H + R\sin(\phi + w\delta t) \qquad \text{---(32)}$$

Equations (31) and (32) in conjunction with the knife angle equations may be utilised to accurately mathematically model surface waveforms, generated during ideal cutting conditions.

The development presented incorporate the looped or curtate trochoidal paths of cutter tips (Cutri F.A. et al 1990). In practice, however, interference is generated that would possibly cause a departure from this ideal situation.

Further examination is thus required to determine the vibration effects that are typically found on actual systems. General interference patterns created, by these types of machines, were then investigated and are discussed in the following chapter.

5. MACHINE INVESTIGATION

Page #

5.1 System Vibration

5.1.1 The Planer Moulder

The woodworking industry is becoming increasingly automated with the aid of complex computers to control production. These devices are used, ever more, to control production machinery and processes (Rakowoski L. R. 1987). However, irrespective of the system's enhanced control sophistication, the planing and moulding process still propagates functional vibrations to the components that are manufactured.

The period and energy content of these inherent cyclic undulations, when analysed, build up a frequency signature which represents the characteristic operation conditions of the process. The amplitude and repetition of the vibrations, due to their origins, are usually unique to individual machines.

Typical mechanisms that generate vibration, on planing and moulding machines include, spindle drive pulley assemblies, out of balance cutter blocks, interference between independent cutter heads and the Carden feed motor drive gearbox.

These undesirable machine deflections, using a frequency signature analysis approach, could aid in the identification of specific vibration origins. This would enable general machine condition to be monitored. Transitions of frequency patterns between initially "healthy" and eventually "worn" or failed machines could then be statistically recorded (Catlin J. B. 1985).

As the operation time of machines increase, and their frequency spectra alter, statistical threshold levels could be established for acceptable machining conditions. The thresholds imposed could be used to initialise fast and effective, planned, preventative maintenance work. Such remedial activity could be undertaken before eventual catastrophic machine failure occurred.

5.1.2 Vibration Origins

A schematic diagram representation of a planing machine and the resultant frequency signature is shown in **Figure 5.1.** The name "signature" usually designates signal patterns which characterise specific properties of machinery (Braun S. 1984). Point (A) on the spectrum identifies a spectral peak produced by an out of balance. The apex, of this peak, appears at a frequency related to the corresponding shaft's angular velocity.

The crest at point (B) illustrates the frequency at which gear teeth mesh. This frequency corresponds to the angular velocity related value of the gear wheel shaft multiplied by the sum of the teeth located on the wheel. However in conjunction with this dominant meshing frequency higher harmonics are also generated. These higher harmonics are generated as a result of loading and deflection variations or imperfect rolling action, that occurs on worn gears (Figure 5.2).

If a local incipient fault such as a cracked (but not fully broken) tooth develops it affects the meshing and higher harmonic frequencies (Martin A. 1987). The damaged tooth deflects more during meshing thus altering the normal operation vibration characteristic as shown in **Figure 5.3a.** The effect of a single cracked tooth in the time domain signal is that of a healthy, or maybe worn, mesh signal which has a series of superimposed pulses upon it. This type of local fault generates low level side bands in the frequency domain spectrum (Figure 5.3b).

As this type of fault propagates (i.e. several faulty teeth develop in the mesh) the periodic characteristics alter (Figure 5.4a) to that of an amplitude modulated time domain signal. The effect of this change in the frequency domain is represented by an increase in the sideband amplitudes (Figure 5.4b).

Point C of **Figure 5.1** represents a frequency generated from defective rolling element bearings. It is possible for several defects to develop within rolling element bearings (Hundal M.S. 1983). Faults such as cracks or corrosion pits (commonly known as blemishes) can develop on either of the bearing races or even on the rolling elements themselves (Figure 5.5a). If a fault occurs on the surface of the outer race (with the outer race fixed) then small amplitude impulses arise every time a rolling element passes over the affected area. The amplitude and frequency rate of these impulses are constant (Figures 5.5b & 5.6). If an imperfection arises on the surface of the inner race (the rotating race in this example), then the resultant energy impulses vary in amplitude with the changes in rolling element load (Figure 5.5c). However, in both cases the energy impulses are transmitted to the bearing housing, which in turn vibrates at its natural frequency.

These types of effects require monitoring and evaluating. The information obtained could be used as the foundation for improving quality control and preventing unscheduled machine failures. In addition vibration origins, amplitudes and frequency need monitoring as their effects can superimpose unwanted structural deflections onto the machined components.

5.1.3 Monitoring Vibration

The increasing costs of maintenance, labour, replacement parts and inventories are causing machine down time penalties to increase. As a result operation and maintenance engineers are acquiring advanced technology that aids in reducing undesirable and unscheduled machine vibration or failure (Smiley R. G. 1983).

Vibration levels are often a direct indicator of a rotating machine's condition. High vibration amplitudes or changing vibration amplitude patterns can be a sign of impending equipment failure. In many cases these patterns can provide important information to the cause of a machines deterioration.

Vibration measuring equipment is commonly employed on rotating machinery to identify characteristic vibration levels and trends. From this, for the instrumentation to provide useful information, it must measure amplitudes and frequencies that are truly indicative of the machinery's condition (Lifson A. et al 1987).

To detect variations in vibration levels, before mechanical problems occur, it is necessary to use a suitable monitoring system. However, since each system has its own merits and disadvantages, no single type can be relied upon to meet all the requirements of every application.

Individual systems generate vibration variations. Thus system operating limits have to be based on statistical or empirical vibration and machine failure data. This information, for it to be beneficial, requires collating from a number of operating units over a period of time (Buehler M.W., Bertin C.D. 1983). Consequently however, there are no absolute or definite upper limits which, if abided by, will ensure long term system operation or prevent invariable machine failure.

However, to determine the fundamental operating characteristics, of typical planer moulders, an investigation of a specific application was undertaken.

5.2 System Investigation

5.2.1 Cutter Head Balancing

Objective The objectives of the investigation were to determine local amplitude displacements caused as a result of:-

1) The rotation of a single cutter block
2) Interference caused as a result of simultaneous operation of multiple cutter heads.
3) Feedwork Interference.

The apparatus required during the investigation included:-

GD Moulding Machine
Model 3655E Yokogawa Recorder (Serial No 205V3109)
Wayne Kerr Feedback Amplifiers
Inductive Transducers (Type GE 35003C29)
Drive Motor (Serial No BG 21321701)
Precision Spindle (Type P5)
Dial Test Indicator
Bridge Arrangement and Micro-switch
Concrete Mounting and Steel Bedplate
Two Knife Cutter Block and Reference Disc
Tachogenerator
Optical Tachogenerator (Plus Reflective Tape)
Dust Extraction Equipment
Inverter

Procedure The experimental set up, to reduce out of balance forces generated by the machine's cutter block and spindle assembly, is shown in **Figure 5.7**.

A steel disc (required as a reference for the monitoring equipment) was secured on to the machine's top cutter head assembly, by locking it on to the precision spindle's thread. The resultant out of balance caused, as a result of the additional mass, required quantifying.

The static run out, of the disc, due to its fixing mechanism, was recorded using a Dial Test Indicator (DTI). Any positive run out readings, obtained during manual rotation, were monitored and subsequently impact alleviated. Iterations of this procedure were carried out until a static run out of 12μm or below was achieved.

Dynamic Balancing, of the assembly, was then carried out using a Yokogawa Waveform Analyser/Recorder and a bridge arrangement that is shown in **Figure 5.8**. A software program called "MICRON2" was run, within the analyser, which converted the output voltage of the bridge transducers to a related displacement (displacement quantified in microns). To create compatibility between the transducer's output and the waveform analyser's input signals, amplification was required (Figure 5.9). With the bridge arrangement, waveform analyser and the transducers set up the drive system was rotated at a rate of 6000 rev/min.

Results of the reference disc's vertical displacement, in relation to transducer (TB), is shown in **Figure 5.10**. The vertical displacement shows a minimum occurring at approximately 50° past the lower marker pulse (a marker pulse was generated with each 360° of rotation of the reference disk). A relative peak to peak amplitude of the displacement is in the order of 70μm. With this information obtained, concerning the initial out of balance conditions, the system was stopped.

A 12mm long, 6mm diameter grub screw was then secured into an appropriately positioned balancing hole (one which was located at a position opposite the run out minimum (ie 225° from the marker pulse)). The system was then once again operated at 6,000 rev/min.

Figure 5.11 shows the final out of balance profile obtained for the precision (P5) spindle arrangement. The resultant out of balance effect is situated approximately at the marker pulse. With the counter balance mass added (the grub screw) the peak to peak amplitude, obtained during initial balancing, was reduced to 42μm but higher frequency harmonics were generated.

The overall dynamic out of balance was reduced by 28μm. It was considered that the new amplitude values obtained would be difficult to improve, thus the spindle was transferred to the GD moulding machine.

However, before application monitoring could commence the operation techniques of the monitoring system, which was to be used to record simulated production displacements, required familiarisation.

5.2.2 Measurement of Cutter Head displacement using the Yokogawa Waveform analyser.

Monitoring the planer moulder's cutter head displacement was undertaken using inductive transducers and a Yokogawa waveform analyser. In order to record appropriate transducer output signals, while using the analyser, sampling theory considerations in areas such as aliasing and signal filtering were required.

Aliasing Aliasing considerations need to be applied when a continuous wave signal is sampled at a designated sampling frequency (fs). If the signal frequency becomes larger than one half of the sampling frequency (fs/2), an imaginary and spurious wave is generated from the sampled data. This effect is known as the aliasing phenomenon.

If for example a sampling frequency of 800Hz is chosen, then only a signal frequency of 400Hz or less can be accurately represented. If, however, the signal frequency is increased above (400Hz) then the sampled signal will represent a continuous wave exhibiting a lower signal frequency. An example of this phenomenon, using a signal frequency of 700Hz and a sample frequency of 800Hz, is illustrated in **Figure 5.12a.**

The waveform analyser overcomes this phenomenon with the use of an anti-aliasing filter. The filter removes any signal components over (fs/2) before analogue to digital conversion is carried out (Figure 5.12b).

The anti-aliasing filter used is of a "low pass" type. A variable break frequency filtering point is automatically selected when the sampling rate, for the analyser, is chosen. As the filtering point is automatically set to omit signal frequency components over (fs/2) then aliasing is not permitted. With the signal frequency and the sampling rate of the analyser considered and correctly selected, process monitoring of the system could proceed.

5.2.3 Condition Monitoring (unloaded condition)

The Top Head Initially each of the planer moulder's, cutter head, spindle speeds were recorded. Each spindle was driven by an independent 3,000 rev/min electric motor in conjunction with a 2:1 pulley arrangement. The nominal speed of each spindle was thus 6,000 rev/min. However, measurement of each cutter head spindle, using an optical tachogenerator, highlighted speed variations. The range of the variations obtained are graphically represented in **Figure 5.13.**

The top head of the machine was then run independently and the resulting displacements, between the reference disc and transducer (TB), are shown in **Figure 5.14.** The nature of travel, with respect to time, reflects the results obtained when dynamic balancing (Figure 5.11). However the higher frequencies, that had previously existed were dampened by the machine structure.

Further investigation of the spindles movement was undertaken by increasing the time base value of the monitoring system. The spindle displacement, when analysed on the concrete balancing platform, produced a regular disturbance as shown in **Figure 5.15**. The displacement, while the rotating spindle was analysed on the machine however, reproduced an amplitude modulated effect (Figure 5.16).

Earlier investigations for the FDB moulder identified no resonance spectral peaks that interfered with the cutter head's spindle frequency, as a result of the machines structure (Beeson H. 1973). The origin of the amplitude interference effect, it was deemed, originated from some feature of the spindle's drive pulley arrangement. This effect, at a later stage, will then be investigated further.

The Top and First bottom head The first bottom head of the machine was run in conjunction with the top head (The physical relationship between these and other machine heads is shown in Figure 5.17). "Snapshot" frames of the resulting displacement profiles obtained are shown in **Figure 5.18** and **Figure 5.19** respectively. Investigations of cutter head angular velocities, with respect to time, revealed speed variations in the order of 6 to 22 rev/min between the two heads.

The difference in speed created a superimposed, large but low frequency amplitude beat onto the top cutter head's original displacement pattern (this displacement is illustrated in Figure 5.16). The resulting effect of this phenomenon is shown in **Figure 5.20** and is discussed later within the "influence of second heads" section.

The top head and 2nd bottom head The second bottom head of the machine was run simultaneously with the top head. Instantaneous frames of displacement were again taken and the results are shown in **Figures 5.21** and **Figure 5.22** respectively.

The difference in spindle speeds between the top and 2nd bottom head was found to be greater than that observed for the top and 1st bottom head. The order of difference for this combination of machine heads ranged between 80 and 91 rev/min. As a result of the higher speed variation an erratic displacement profile was generated, which is shown in **Figure 5.23**.

Top, Fence and Near heads Vibration interference occurred between the top and other cutting heads, when their planes of vibration were directionally identical. The different interference patterns obtained when the fence or near heads were run independently, but in conjunction with the top head, are shown in **Figures 5.24** and **Figure 5.25** respectively.

As the vibration plane of these heads are perpendicular to the top heads, limited interference occurred. The expanded time base profiles, of the resultant displacement, for both situations, are shown in **Figure 5.26** and **Figure 5.27** respectively.

The results illustrate a similar effect observed when the single top head was run in isolation. The small amplitude beat effect seen in **Figure 5.26** is a result of a large speed variation. The variation, between the fence and top head, ranges from 137 - 149 rev/min while between the near and top head the range limits lie between zero to 6 rev/min.

Further system investigation included simultaneous operation of :-

1) The top, 1st and 2nd bottom heads
2) All of the heads and the machines feedworks.

The results of these situations are presented in **Figures 5.28, 5.29** and **5.30** respectively. These results contain a combination of the effects, that were determined individually, in a single frame.

Unloaded machine conditions were recorded to establish the origins and interference effects generated by different features of the system. However, to aid development of extended mathematical modelling, it was necessary to identify whether these types of interference patterns remained during actual planing conditions.

5.2.4 Condition Monitoring (Loaded Condition)

Top head Five timber specimens were machined in order to obtain information relating the machine's cutting depths against material feed rates. Cuts were made at depths ranging from 1 - 5 mm on individual specimens while the material feedrate, of the machine, was held at predetermined values.

For all of the feedrates used the spindle speed of the top head reduced, as the depth of cut increased (Figure 5.31). However the gradient relating the spindle speed and cutting depth was non-linear. It is concluded that this phenomenon occurred as a result of the initial, unloaded spindle speed variations (variations shown in Figure 5.13). In addition, irrespective of cutting depth, the spindle speeds are not directly related to the material feed rates being used. A possible reason for this effect being, the discontinuity of material properties found in individual timber specimens and the variation in "initial" machine feed rates (Figure 5.32).

Machining was carried on a number of Scot Pine specimens which exhibited a moisture content of 13.25%. With the top head running in isolation, a 2mm depth of cut was made at three different feed rates on individual specimens.

During this machining period displacement profiles were captured at a predetermined position on the timber specimen, using a microswitch as an external trigger for the waveform analyser (Figure 5.33). The profiles obtained at feedrates of 9m/min, 18m/min and 27m/min are illustrated in **Figures 5.34** to **5.36**.

If point (1) on the displacement profile of **Figure 5.34**, which was obtained with a feedrate of 9m/min, is aligned with point (1) in **Figure 5.14** (the unloaded condition) good correlation between the displacements shape and frequency can be made using superposition and visual means (a light box). However the profiles amplitude, shown in **Figure 5.34** for the loaded condition, has been attenuated by 3.06 microns.

If points (2) and (3) on the displacement profiles of **Figure 5.35** and **5.36**, which were obtained using feedrates of 18m/min and 27m/min respectively, are aligned with point (1) on **Figure 5.14** (the unloaded condition) again good correlation between displacement shape and frequency can be established (as described above). The difference of peak to peak amplitude, between **Figures 5.35** and **5.36** results as each trace was captured at different points in time. In respect these amplitudes result as each trace is an integral part of the inherent low frequency beat (The underlying low frequency beat effect illustrated in Figure 5.16).

Machining was then carried out with the top and 1st bottom heads running (with the bottom head also cutting at a depth of 2mm). The displacement profile of this particular situation is shown in **Figure 5.37**. If point (5) on the displacement profile in **Figure 5.37** is aligned with point 4 in **Figure 5.19** (the unloaded condition) a good frequency correlation can be made. However, the displacement profile shown in **Figure 5.37** illustrates a marked reduction in peak to peak amplitude and the attenuation of alternate wave displacements.

Finally machining was carried out with the 1st and 2nd bottom heads running in conjunction with the top head. The result of which is shown in **Figure 5.38**. If point (7) in **Figure 5.38** is aligned with point (6) in **Figure 5.28**, good correlation is obtained.

The results obtained during loaded and unloaded machine conditions when analysed compare, in the main, accurately. No further results for the fence or near heads were obtained as limited interference occurred between perpendicular cutting spindles.

There are some amplitude variations apparent in several of the results but the vibration trends first identified, are generally unaltered. Interference patterns, thought to be generated by the spindles drive pulley arrangement and non synchronised cutter head velocities, which remained apparent through machining, will therefore be discussed in more detail.

5.3 Interference Model Development

5.3.1 Influence of the First Top Head

The basis of a theoretical model was described previously. The model incorporated the trochoidal loci of the planing process's cutter tips. However it did not encompass any of the disturbances that are commonly generated during actual machining.

Initially primary disturbances, such as a once per revolution displacement effect, are frequently observed when a single cutter block and spindle assembly rotates. This effect usually originates from the jointing process (This results because the jointing process is carried out at one half of the machines nominal spindle speed).

A secondary effect, which is also monitored on a single cutting head, is created as a consequence of structural displacements which can be excited by electric motor imbalance forces. When these forces are amplified by, structural resonances, sufficient cutter head spindle displacements can be created, at the motor's frequency.

The effects described create an interference displacement of the form $\delta \text{Cos}wt$ (this compares with Jackson's simplistic displacement model that was established using a single spindle test machine in section 4.2.2).

The resulting effect created by these anomalies, result in either an increased head displacement amplitude (which occurs at the spindles original frequency) or a modified cutter head displacement.

The modified displacement frequency, caused as result of motor imbalance forces, is dependent on the motor and spindle speed characteristics. The form of these displacements can be embodied within a computer simulation program, and used as the cutter heads centre displacement reference (the displacement from the ideal).

Other more complex vibration phenomenons are however, generated as a result of interfering system frequencies (the amplitude modulated effect observed on the single cutter head spindle). It was envisaged that the origins of this type of effect, on a single cutter head, originated from the machine's pulley drive arrangement.

5.3.2 The Pulley System Effect

The geometry of the machine's belt drive arrangement is shown in **Figure 5.39**. Detail designs for the system's spindle pulley are shown in **Figure 5.40**. This pulley was manufactured from spun cast iron (grade 14) and balanced to run at 6,000 rev/min when driven by three "V" belts.

To produce a speed ratio of 2:1 between the system's pulley centre distance of 233mm, using spindle and motor pulley diameters of 80mm and 160mm respectively, the belt needed to be 850mm in length. In addition to provide adequate power capabilities SPZ type belts were originally chosen. The dimensions of such belts and their power characteristics are shown in **Figure 5.41.**

Interference effects were superimposed onto the top head's spindle, it was thought, as a result of pulley belt agitation. This type of excitation is illustrated in **Figure 5.42.** To determine whether the frequency of this type of disturbance interfered with that of the spindles a more detailed examination, of the pulley system, was undertaken

Initially system factors which remained constant throughout the investigation carried out on the machine needed to be determined. These factors were required before further mathematical analysis of the system could be carried out. The following system relationships were then determined for:-

1) The initial tension between the pulleys.
2) The coefficient of friction between the belt and the pulley.

The experimental procedures, used to obtain these values (initial tension = 1.35KN, coefficient of friction = 0.441), and the results are detailed in **Appendix F.**

With the frictional coefficient and tension value determined further mathematical analysis was undertaken. This was carried out to establish the frequency at which transverse vibrations developed along individual pulley belt strands.

Transverse Vibrations of Belts

Under certain conditions the strands of the driving belt can execute serious flapping vibrations. The following analysis, characterising this phenomenon, assumes that the flexural rigidity of the belt is small. Thus the natural frequency of the stands are determined by the belts tension alone.

Assuming the belt of the system is perfectly elastic the initial tension ($2T_o$) applied between the pulleys, which is shown in **Figure 5.43**, equals :-

$$2T_o = T_1 + T_2 \qquad \text{---(33)}$$

By substituting the tension ratio, expressed as equation (F1), into equation (33) the slack and tight side tensions, of the belt can be established as follows:-

$$2T_o = T_1 + \frac{T_1}{e^{(\mu\Phi/\sin\beta)}}$$

$$T_1 = \frac{2T_o . e^{(\mu\Phi/\sin\beta)}}{1 + e^{(\mu\Phi/\sin\beta)}} \qquad \text{---(34)}$$

It also follows that:-

$$2T_o = T_2 . e^{(\mu\Phi/\sin\beta)} + T_2$$

$$T_2 = \frac{2T_o}{1 + e^{(\mu\Phi/\sin\beta)}} \qquad \text{---(35)}$$

In addition to the slack and tight side tension another tension, known as centrifugal tension, is generated in the system when the belt rotates. This effect increases the total tension in each strand of the belt, by an amount that can be expressed as :-

$$T_c = K.\rho.A.v^2 \qquad \text{---(36)}$$

Where;

K = a constant.
ρ = the specific mass of the belt.
A = the cross section area of the belt.
v = the linear velocity of the belt.

By combining the tension effects, that are generated in each strand, with the physical characteristics of the belt (ie the belts cross section area and its specific mass) the velocity of propagation of disturbances along an individual stand can be expressed as:-

$$u = \sqrt{\Sigma T.g/(\rho.A)} \qquad ---(36)$$

Where;

u = the velocity of propagation of disturbance along a strand
g = $9.81 m/s^2$

From Figure 5.43 the time taken for a disturbance to travel from (x) to (y), ie in the direction of motion of the belt, is $(L_s/(u+v))$. Also the time taken to travel from (y) back to (x) against the motion of the belt is $(L_s/(u-v))$ where $v = 2\pi.R.N_R/60$. Since one belt cycle is completed during the time taken by the disturbance to go from (x) to (y) and back again, its periodic time can be represented by:-

$$t = \frac{L_s}{u + v} + \frac{L_s}{u - v} \qquad ---(37)$$

(Wilson W.K. 1956)

From equation (37) the frequency of belt agitation can be determined.

In conjunction with the vibrations generated by a single machine spindle, other system interference occurs. The origins of these types of disturbances were isolated to a number of machine spindles operating simultaneously.

5.3.3 The Influence of Second Heads

When more than one head was simultaneously run on the GD planing and moulding machine, complex interference displacements developed at the point of measurement. These disturbances resulted from unsynchronised cutter head spindle velocities (these results are shown in Figure 5.13).

Imbalances, present on each spindle assembly, generated interfering structural displacements at a frequency characterised by the difference of angular speeds. Initially the vertical displacement of a single cutter head spindle can be represented, using the superposition principle of linear waves, by:-

$$y = (\delta_1 \text{Sin} w_1 t + \delta_2 \text{Sin} w_2 t) \qquad ---(38)$$

Where δ_1 and δ_2 are the displacement amplitudes generated as a result of out of balances and revolution effects. In conjunction w_1 and w_2 represent the spindle and motor angular velocities respectively.

Combining the displacement generated by a the single spindle with belt agitation and imbalance effects, of a second spindle, an algebraic interference pattern is created of the form:-

$$y = (\delta_1 \text{Sin} w_1 t + \delta_2 \text{Sin} w_2 t) + \delta_3 \text{Sin} w_3 t + \ldots$$
$$\ldots \delta_4 \text{Sin} w_4 t \qquad ---(39)$$

Where δ_3 and δ_4 are the displacement amplitudes generated as a result of belt agitation and a second spindle's imbalance. In conjunction w_3 and w_4 represent the belt's agitation frequency and the second spindle's angular velocity of imbalance.

Typical interference patterns generated, as a result of these effects on the GD moulder, are illustrated in **Figure 5.20** and **Figure 5.23**. The results highlight the transition in interference that occurs as a result of spindle velocity variations.

From the investigation it is evident that inherent machine vibrations remain during machining. The origins of such disturbances are generated by single or multiple spindles, during normal operation. The vibration results obtained illustrate the type of amplitude variations, as a result of cutter block spindle deflections, that are transferred to manufactured components. From this it is apparent that a system capable of monitoring surface quality is required. The system thus developed, to monitor surface quality, will now be discussed.

6. SURFACE MEASUREMENT

Page #

6.1 The Laser Measurement System

6.1.1 Operation Objectives

Successful design and development of the monitoring system centred around directed production objectives. These aims were formulated as a result of computer automation, of standard equipment, in conjunction with the present absence of process control and product measurement systems.

Developing the overall measurement system required an understanding in areas such as design philosophies, electronics, mechanical engineering and system integration. As a result it was important to develop and consolidate the concepts of the system, using a Mechatronics approach.

Due to the material feedspeeds exhibited by the planing process and the nature of the cutting action, it was deemed that the characterisation system would operate in-process. In addition, as a consequence of inherently high vibration interference levels, it was also necessary for the system to operate in a non-contact mode.

The action of the production process, as discussed previously, generates cutter marks (known as cusps) on the surface of artifacts manufactured. The geometric shape, of the resulting surface finishes, thus required quantifying. Post process visual inspection, that is currently undertaken features manual, periodic surface assessment that is very subjective. Utilising the visual inspection concept, a measurement system combining laser illumination and optical detection was developed. The measurement of artifact surface finish, using this system, removed the sujectivity of the manual process. The automatic system employed several coherent laser light sources and a photoelectronic detector.

6.1.2 Design Concepts

Broad laser beams were used to illuminate the machined surface at grazing incidence (an angle of incidence of $\theta<1.5°$) as in **Figure 6.1.** Illumination emanated at an acute angle to that of the traversing workpiece. This configuration gave prominence to the slope faces of the machined cusps that were present on the artifact's surface. The illumination arrangement generated a fringe pattern of bright and dark regions along the product which represented the material's instantaneous surface slope.

A single element silicon photo diode was used to detect the variations in diffusely reflected laser light, as the timber passed from the machine. Gain control and signal conditioning circuitry was necessary to amplify and filter the output voltage of the photo diode. These circuits were used to generated an analogue signal that was suitable for digitisation. The analogue output signal, of the photo diode, was sampled and digitised using the output signal of a rotary position encoder as a reference for synchronising data conversions. Digitisation was necessary as data evaluation and manipulation was undertaken within a digital computer system.

The data captured was not prone to distortion as a result of vibrations, as the plane of vibration was almost perpendicular to the illumination. Because the laser beams used were broad, and of grazing incidence to the surface, the vibration levels did not exceed the outer limits of the beam. This only occurred because diffuse and not specular reflection was monitored.

6.2 Hardware Designs

6.2.1 Mechanical Designs

A diagram of the measurement system is illustrated in **Figure 6.2.** The development apparatus consisted of a base plate and fence, several adjustable laser holders, a measuring head unit with carriage and a variable speed drive system.

The variable speed drive system provided material traverse, using a pneumatically loaded feed roller, at rates ranging between 6 and 30m/min. The material to ensure its contact along the bed plate, was also pressurised using a second roller arrangement (this roller was spring loaded).

The laser holders are shown, on the apparatus, in **Figure 6.3.** They were designed to provide movement in an arcuate sweep. This allowed any position on the surface of the sample, across its width, to be illuminated. In addition a spring loaded tilt action and locking mechanism was incorporated which provided permanent setting facilities. Using the height adjustment and the tilt action, the lasers could be set at an angle and height which provided illumination, for any thickness of sample, at an angle of grazing incidence.

A carriage assembly was constructed above and across the bedplate, leaving a clearance distance which permitted timber to traverse freely beneath. A measuring head unit, carrying the photo detector and amplifier circuitry, was designed and fitted to the carriage. The unit is shown in **Figure 6.4.** The unit was suspended from a frame which allowed variable height adjustment. The aperture of the photodiode was enclosed by a 1/8th of a millimetre slot, to create a sampling window. Mounted to the unit was a 12v solenoid assembly carrying an ink tip which was used to mark individual samples, at the position measurements were taken.

6.2.2 Electronic Design

Figure 6.5a shows the system architecture. Electronic design of the laser measurement system, including the optical detection circuitry is shown in **Figure 6.5b.** The illumination circuitry is detailed in **Figure 6.6.** Measurements were initialised by a start pulse generated by the start circuitry, that was programmed from the computer system.

The analogue output signal of the photo diode was sampled and digitised during measurement periods. Sampling points were determined, using the output signal of the rotary encoder as the clocking input signal for the analogue to digital convertor. Once digitised the data was transferred to the RAM.

Data transfer from the Analogue to Digital Convertor (ADC) to the RAM and from the RAM to the computer's memory was achieved with the generation of correctly timed logic signals. These signals were generated from the 74HC74 blank out flip flop, the start circuitry, the "BBC.CK" clock signal (this signal is shown in Figure 6.5) and the rotary encoder. Efficient storage to the RAM, of the data produced, was controlled using three 74LS191 synchronous up/down counters.

6.2.3 Measurement Start and Counter Control Circuitry

A logic high start pulse used in conjunction with other system signals, to initiate measurements, was generated using a 74HC74 D type flip flop (Figure 6.7). The start pulse was initialised using a programmed pulse from pin CB2 of the computer system. The resulting signal, shown in relation to the clock waveform produced by the encoder, is illustrated in **Figure 6.8a.**

Before any measurements were taken the counters, which controlled the data address locations of the RAM, required presetting to their start value. This was achieved by supplying an inverted start signal to the load pin (pin 11) of the counters. With these pins programmed low and all the data inputs, of each device, set high a count value of 1023 was initially set. The timing diagram for this operation is illustrated in **Figure 6.8b.**

1024 data bytes, for data analysis purposes required storage during a measurement period. A blank out signal was therefore used, in conjunction with the synchronous counters, to control the direction and amount of data storage within the RAM. The circuitry used to generate the blank out signal is detailed in **Figure 6.9**. The associated timing diagram, illustrated during the preset mode of the counters, shows the blank out signal as a logic low level. Using this signal as the up/down control level, for the counters, a "count up" mode was selected.

The timing diagram for a complete measurement cycle is shown in **Figure 6.10**. The counters were initially set, to a value of 1023, when the inverted start pulse was generated. Following this pulse, at the first rising edge of the encoder clock, the address of the counters rolled over and a sampled data byte was stored in location zero of the RAM.

Subsequent data was stored, when a rising edge of the encoder's output signal occurred. After 1024 bytes of data had been stored in the RAM the logic level of address line A10 changed. This action reverted the logic of the blank out signal which subsequently completed the data capture cycle.

The change in status of the blank out signal was also used to interrupt the processor of the computer system and change the counter's count direction to that of the count down mode. Stored data was then sequentially transferred from the RAM to the computer's memory under software control using the "BBC CLK" signal.

6.2.4 The Photodiode Detector

The circuit diagram for the IPL 10500ADL photodetector used is shown in **Figure 6.11.** The hybrid circuit consists of a photodiode and an amplifier, with a feedback circuit which is mounted onto a ceramic substrate. The detector used provided an output voltage that was proportional to the incident light level.

The device was encapsulated in a four lead T05 package and was supplied from a dual supply. The glass window of the device was replaced by a lens which increased the signal to noise ratio by a value of approximately ten.

The detector was selected due to the frequency response of its feedback network (the -3dB frequency break point of the network appeared at 65 KHz) and its relative spectral response (Figure 6.12). Another beneficial attribute of the device was its suitability to be used within electronically noisy environments, since both the amplifier and the detector are situated close together within a screened CAN.

To reduce undesirable noise effects that appeared on the supply rails of the diode and amplifier, which were invariably superimposed onto the output signal of the device, a tracking power supply was designed. Using a potentiometer and power amplifier to produce a relative zero volts reference for the photodiode, between the supply rails, noise effects were reduced. The circuit design for this power supply is shown in **Figure 6.13.**

6.2.5 Signal Conditioning Circuitry

Under certain conditions, within the planing and moulding industry, material feedrates tending towards 180m/min (max) are being achieved. Using this upper value as a production bench mark, the signal conditioning circuitry, of the laser measurement system, presently need to manage a 3KHz data signal. However to extend the systems capabilities conditioning circuitry, capable of monitoring a 5KHz (300m/min) data signal, was designed in. This approach would allow the absorption of progressive technology without limiting the system's monitoring performance.

On an actual machine, the photodiode detector would be situated some distance from the control circuitry. To minimise electrical interference, on the data signal, a twisted pair configuration was employed between the measuring head and the conditioning electronics.

The first stage of the conditioning circuitry consisted of a precision feedback INA105KP differential amplifier. This integrated circuit is shown in **Figure 6.14.** Any interference superimposed on the data signal that was not cancelled using the twisted pair was removed using this unity gain amplifier.

The remaining conditioning circuitry is shown in **Figure 6.15.** The filter and first CA 3140E amplifier were used to separate the high frequency components of the signal which had not been removed by the tracking amplifier and which could not be removed using the twisted pair or initial differential amplifier.

The separated high frequency components and the original signal were then used as the input to the differential amplifier in the 2nd stage. The resulting signal to noise ratio was improved, using this configuration, as the output signal from this amplifier did not contain high frequency noise.

With a clean data signal, amplification and filtering was carried out with the remaining amplifier stages. The filters used on the final amplifier exhibited a break frequency of 50KHz as shown in **Figure 6.16.** This value of break frequency was chosen to prevent any amplitude attenuation or phase changes occurring on the data signal.

6.2.5 Control Counters

The LS191 synchronous counters used were reversible up/down 4 bit binary counters. Synchronous operation was provided as all the internal flip flops clocked simultaneously. This action produced output changes, which were coincident with each other. The mode of operation utilised eliminated the output counting spikes that are normally associated with asynchronous (ripple clock) counters.

The outputs of the four flip flops were triggered on a low to high transition of the clock input, if the enable line level was set low (pin 4 on the counters). However a high on this pin prohibited counting to be carried out. The direction of counting was determined purely by the level of the down/up input (pin 5 on the counter).

The counters were used in the fully programmable mode; that is, the outputs were preset by placing a low on the load input (pin 11) and entering the desired data at the data inputs. The outputs of the counters changed to agree with the data inputs irrespective of the clock input level.

The counters were easily cascaded by feeding the ripple clock (pin 13) output to the enable input (pin 4) of the following counter. The ripple clock output was used to enable the next counter as it produced a low level output pulse, equal in width to the low level portion of the clock input, when an overflow or underflow condition existed.

6.2.7 The Analogue To Digital Convertor

The analogue output signal from the conditioning circuitry required digitising. Digitisation enabled data manipulation, within the computer system to be carried out. The ADC 3300 incorporated 64 parallel auto-balanced, voltage comparators. These comparators compared the analogue input voltage against the ADC's reference voltage, to produce a parallel bit output.

One complete conversion cycle can be traced through the 3300 with the aid of the timing diagram shown in **Figure 6.17.** At the rising edge of the clock all of the 64 comparator outputs are stored by the internal latches that are shown in **Figure 6.18.** During the high period of the clock cycle, with the phase control pin (pin 8) set to low, the auto balance phase occurs. Within this phase the digital count value, corresponding to the analogue input signal is established. The digital value that is subsequently generated is related to the reference input voltage to the convertor.

At the falling edge of the clock signal the data is shifted into the output registers of the device. With the 6 bit device used, and limiting case signals considered, it was found that no sample and hold facilities were required. Thus continuous conversions were carried out to obtain 1024 signal data bytes during each measurement period.

6.2.8 The Rotary Encoder

The analogue output signal of the photo diode was sampled and digitised using the output signal of the rotary encoder as the ADC clock input. The encoder used generated 500 pulses for every complete revolution. As 1024 data points were required within a 128mm sample length, which were necessary for data analysis requirements, a contact wheel with a diameter of 19.89mm was used. This size wheel provided 2.048 revolutions for every 128mm of timber travel. Thus the correct number of sample points were provided during each measurement.

The wheel of the encoder made direct rolling contact with the timber. This arrangement was used instead of direct contact onto the rubber feedroller, as the feedroller's effective diameter altered with pressure variations (Figure 6.19)

6.3 Software Procedure Philosophy

6.3.1 System Initialisation

The program used to establish intensity measurements of diffusely reflected laser light is schematically detailed in **Appendix G.**

Within the initialisation procedure, of the laser measurement program, variables were set to their prescribed values. System addresses for registers controlling data direction, interrupts and auxiliary control were also established. The contents of the interrupt vector were set using an assembly code subroutine labelled "unit". This subroutine was called from within the initialisation module.

The "Init" routine immediately disabled all of the system's interrupt facilities. Prior to this program sequence, if no interrupt had been initiated the contents of the original interrupt vector were stored. The programs interrupt code address was then loaded as the contents of this vector. This action enabled the program interrupt code to service any subsequent interrupts that were generated. After completion of the initialisation procedure the main program procedure began.

6.3.2 Laser Measurement

For laser measurements the procedure "laser" was called. This procedure immediately called the "start" assembly code sub routine. Within this block of code the status for the "measurement complete" interrupt pin (pin CB1) and the programmed "Start pulse" pin (pin CB2) were configured. The data bus pins, at this point, were set to be received as inputs, on port B of the user port facility.

With all of the necessary I/O pins programmed, the software looped until the hardware "start measurement" microswitch was activated. The start measurement microswitch signal was immediately followed by a start pulse which initialised data sampling, digitisation and storage.

Sampling was carried out (as discussed earlier) on 1024 data points before the blank out signal caused an interrupt condition (a positive rising edge) on pin CB1. The interrupt condition that occurred, triggered the start of the interrupt code.

Data which had been stored in the RAM using hardware logic signals, generated from an initial start pulse, were transferred into the computer system using the interrupt code. The code first ensured that it was, in fact, the blank out signal (the end of data transfer signal) which had caused the interrupt. If this signal had caused the interrupt the address for the beginning of the computer's memory, where the data was to be stored, was established.

Along with this data, for efficient data storage, associated variables for the memory's page boundaries and line pointers were also determined. These variables were used to index the data transfer.

With memory space now allocated, the data that was stored ,within the RAM, was clocked into the computer system by strobing the "BBC CLK" pin of the user port. As there were only 6 Bits of data in each data byte transferred (Because a 6 Bit ADC was used for conversions) the two non-data bits were stripped before relocation.

Finally the value of the first data byte was stored at the address of the last byte. This operation was carried out to ensure a periodic data window during subsequent Fourier analysis. The intensity plot of the artifact's surface was then displayed before continuing to the Fast Fourier Transform algorithm procedure.

6.3.3 The Fast Fourier Transform

A mathematical technique used, for the evaluation of continuous analogue signals is known as the Discrete Fourier Transform (DFT). A transform, in mathematical terms, is a device (often an integral or a series) which changes equations from one form to another (O'Neil P.V. 1986). The DFT performs the transformation of a time series of samples to a series of frequency samples. As the name implies the DFT operates on finite sets of data with each point discretely and evenly spaced in time.

The transform, dependent on the application evaluated, performs a proportional number of computations. For example, 32^2 major operations are required when executing a 32 point DFT. However, to represent typical applications which require this type of analysis, the number of samples described is not normally sufficient. The required number of samples, necessary to define many real life functions, frequently run into the hundreds or sometimes a thousand or more (Ramirez R.W. 1985). From this it is not difficult to understand why, in the past, this processing approach has been generally avoided.

To alleviate the processing, and thus time, limitations of the DFT an efficient algorithm, in conjunction with digital computers, is utilised. This algorithm is known as the Fast Fourier Transform (FFT).

The FFT by recognising certain symmetries and periodicities, during the calculation of the DFT, reduces computational evaluation from N^2 to $N.\log_2 N$ operations (where N is equal to the number of samples used). This significant saving of $N.\log_2 N$ versus N^2 operations is shown in Figure 6.20.

An FFT algorithm, used for frequency analysis, assumes periodic data within the sampling period selected. Periodic data eliminates discontinuities, at the sample length's boundaries, which would otherwise generate spectral leakage in the resulting frequency domain (Harris F.J. 1978).

Real signal data is thus windowed (a term used when applying a weighting function to the signal data) to ensure that this essential analysis criterion is maintained (Omer W. 1986). Whilst the choice of window effects the results obtained the use of a rectangular window (used during data analysis) is omissible as all results are comparative.

A FFT algorithm program (Maycock K.M. 1987) was incorporated within the laser measurement system's operating software. This routine converted real time intensity sample levels, that had been captured, digitised and stored into frequency domain harmonic samples.

This algorithm was extensively tested before implementation to determine its accuracy. **Figure 6.21** to **Figure 6.25** show a number of typical input signals that were generated to evaluate the algorithm. Also illustrated in these figures are the harmonic spectra that resulted.

Figure 6.21a and **Figure 6.22a** show pure sine waves which exhibit frequencies of one and sixteen cycles, within the sample length shown, respectively. The harmonic spectra produced represent these time domain signals as single harmonics in the frequency domain. **Figure 6.21b** shows a corresponding harmonic value that is equal to one (ie one complete cycle generated during the sample length). **Figure 6.22** shows a harmonic value that is equal to sixteen. The corresponding amplitudes, of the harmonics, are related to the time domains signal's magnitude.

Figure 6.23a incorporates the combination of two sine waves which exhibit different amplitudes and frequencies. The two sine waves illustrate an amplitude ratio that is equal to 2:1. In addition the relationship between the frequencies, within the sample length, is 4:1. The resulting frequency harmonic spectrum shows the harmonics of the separated sine waves (Figure 6.23b). Each harmonic appears exhibiting correct amplitude proportion. In conjunction the original frequencies of the time domain signal, within the sample length, are generated.

Figure 6.24a and **Figure 6.25a** show more complex sinusoids that exhibit varying amplitudes and frequencies. Again for all cases, as shown in **Figure 6.24b** and **Figure 6.25b**, the harmonics generated represent the original signals, in amplitude and frequency.

The monitoring system developed was used to measure timber specimens, that were generated under typical manufacturing conditions. The results obtained are detailed in the next chapter.

7. INVESTIGATION RESULTS

Page #

7.1 Laser Measurement

7.1.1 Experimental Procedure

With the traversing material's speed effectively transparent to the monitoring system an arbitrary feedspeed, when taking intensity measurements, was selected using the variable drive system. The laser's tilt mechanisms were adjusted to generate a beam at grazing incidence across the timber sample selected.

Using two illumination sources a beam cross over point, on the surface of the sample, was obtained. By adjusting the laser's sweep angle, while monitoring the maximum voltage output of the photodiode, this point was positioned directly beneath the measuring units aperture. The "start measurement" microswitch, that was positioned beneath the measuring unit, was then adjusted to activate at the required position along each sample.

The rotary encoder carriage was adjusted to give rotary contact of the encoder's wheel on the machined side of the samples. The ratio of the wheel's circumference in relation to its output signal generated the correct sampling intervals that were required during individual measurements.

The independent, spring loaded, pressure roller was set to give an adequate downward force on each of the samples during monitoring. This roller ensured constant contact between the samples and the bedplate. With the system configured the covers were positioned to guard against laser radiation leakage. The interlock facility of each laser was then deactivated and the system's power instated.

Before sample surfaces were measured, however, an intensity reflection investigation was undertaken, using the system. This investigation was carried out to ensure that no adverse diffuse reflection levels occurred, at the apex of individual surface cusps, as a result of the in-process bidirectional illumination technique used.

7.1.2 RESULTS

Single Illumination Initially several timber sample surfaces were monitored using the measuring unit in conjunction with a single coherent light source (Figure 7.1). The intensity levels obtained along the samples, using this arrangement, were recorded. The same samples were again measured and recorded, while using a second illuminating source. This laser beam, however, emanated from the opposite side of the measuring unit (Figure 7.2).

The intensity levels obtained, for both of the measurements, were analytically combined to generate simulated intensity profiles. These calculated profiles were then compared with measured light levels, acquired using bidirectional illumination, on the same specimens.

Figures 7.3, 7.4 and 7.5 show calculated intensity profiles and associated harmonic spectra for three separate timber specimens. The intensity levels of these samples were measured, as described, using the single illumination procedure.

Figures 7.6, 7.7 and 7.8 illustrate the intensity levels that were recorded and the harmonic spectra obtained, from the same three timber samples, when measured using bidirectional illuminating sources. As these results were recorded using this type of illumination, no intermediate intensity calculations were necessary.

The attenuation in amplitude, exhibited by the calculated intensity profiles was due to independent illumination of each light source. However, the shape and frequency of the profiles, and their associated harmonic spectra, compare excellently (using superposition visual inspection).

As no adverse intensity effects were identified, from these results, measurements of timber samples using a bidirectional illumination technique were undertaken

Bidirectional Illumination Initially the procedure used to obtain intensity results, was that described in sub section 7.1.1. The first set of samples measured were those generated during the machine investigation. This investigation is outlined in sub section 5.2.4 called "Condition Monitoring (Loaded Condition)".

The results obtained, from samples generated by the machine's top head, are shown in **Figure 7.9** to **Figure 7.11**. In conjunction material feedspeeds used, while producing these samples, were **9, 18** and **27m/min** respectively.

Other results were also obtained, from samples generated using a combination of the machine's top, 1st and 2nd bottom heads. Material feedrates of 21 and 24m/min were employed to produce these samples. The resulting profiles and harmonic spectra, that were measured, are shown in **Figure 7.12** and **Figure 7.13**.

In addition to the samples generated, during the machine investigation, other specimens were produced using an out of balance top cutter assembly. This out of balance was generated by securing a single, 12mm x 6mm diameter, grub screw into the reference disk of the cutter block at the marker pulse position. The results obtained, from samples manufactured at material feedrates of **9, 18** and **27m/min**, are shown in **Figure 7.14** to **Figure 7.16**.

A number of samples were also generated on a high speed machine. One of the samples that was produced using a single top head, in conjunction with a material feedrate of 100m/min, is illustrated in **Figure 7.17**.

Each specimen, was also measured using a Talyrond 200 surface measurement instrument. This second set of measurements was undertaken as a comparison between the results obtained, from the laser system, with those produced by a classic contact profilometer.

The Talyrond 200 system was used to measure individual specimens because of its excellent traverse length. The procedure carried out to perform surface measurements, using this system, is thus outlined.

7.2 Talyrond Measurement

7.2.1 Experimental Procedure

The apparatus used to perform post process, contact measurements is shown in **Figure 7.18.** The system comprises of the Talyrond 200 system, a 10 Bit ADC and a standard BBC Master computer.

The Tayrond 200 system consists of a Base unit, turntable, electronic unit, polar recorder, drive unit and column. The column's bearing faces form the vertical straightness datum for the pick-up mounting bracket, as it is driven up and down.

A motor and three speed gearbox provides both setting and recording drive speeds for the pick-up unit. The pickup unit carries an interchangeable stylus arm, which contacts the surface of the specimen under measurement. The pick-up unit is electrically connected to the electronic unit which contains the amplifiers, filters and the power supply for the system.

Measurements were undertaken by positioning and securing the timber samples against a face plate, which was situated on the turntable. The arm carrying the pick-up unit and stylus arm was adjusted to obtain a null reading, on the centring unit of the polar recorder. With the stylus displacement centred, the drive mechanism was initialised. The subsequent traverse of the pick-up unit and stylus, along the sample, triggered the "start measurement" control signal to the computer system.

Instantaneous displacement values generated during the measurement period were digitised and sequentially recorded. The circuit diagram and the calibration curve for the 10 Bit ADC, used during measurements, is shown in **Figure 7.19** and **Figure 7.20**. Digitisation and data collection was controlled using interval timed data capture software. This program was incorporated within the laser illumination program and is schematically detailed in **Appendix G.**

7.2.2 Results

The surface profiles obtained, using the Talyrond system, from samples previously measured using the laser arrangement are shown in **Figure 7.21** to **Figure 7.26**. Also shown ,in these figures, are the associated resultant harmonic spectra.

In addition the results obtained from the specimens produced while the top cutter head exhibited an out of balance are shown in **Figure 7.27** to **Figure 7,29.**

7.3 Surface Assessment

7.3.1 Measurement of Fabricated Specimens

With the surfaces of the Scot pine samples inherently soft, metal specimens were created to aid in the comparative assessment of each measuring system.

The samples were manufactured, to specific forms, and measured using both of the systems described. Prior to measurements the samples were sand blasted to produce a diffusely reflective surface.

Figure 7.30 shows the parameters of typical specimens manufactured and measured. The intensity, amplitude and harmonic results obtained, from the laser and Talyrond systems, are shown in **Figure 7.31** to **Figure 7.36** respectively.

7.4 Computer Simulation

7.4.1 Surface Generation

A computer simulation program incorporating the combined effects associated with ideal knife tip displacements (which were presented in chapter 4) and simple spindle perturbations was developed. Typical anomalies, which were identified during machining conditions, were also mathematically simulated within the program.

The results obtained when simulating the GD moulding machine's effects, which included pulley belt agitation, out of balances and structural interferences (the interferences generated from simultaneously operating cutting heads) are shown in **Figure 7.37** to **Figure 7.41**.

Several simplistic sinusoidal displacement signatures were postulated (from the machining effects that were identified in section 5) and used to obtain these results. These interference models are illustrated in **Figure 7.42** to **Figure 7.45**.

Additional surface simulation was undertaken on different samples that exhibited similar surface effects, however, these samples were generated on a different machine. The results of this investigation are shown in **Appendix H**.

8. DISCUSSIONS

Page #

8.1 Computer Integrated Manufacture

A computer integrated manufacturing strategy was initialised to consolidate significant manufacturing regions of the planing and moulding industry. The general procedure that was developed created efficient and fast information interchange between individual departments. The perceived structure of the CIM system, when fully implemented was also designed to provide centrally located, on-line, information for use by peripheral and adjacent facilities.

Extensive considerations were given during the design stage of the CIM system, to a number of operational aspects within areas such as the market environment, customer acceptance, long term objectives of main competitors and progressive system development. This examination provided the basis for enhancing the companies competitiveness through increased quality, flexibility and improved responsiveness to shifting market conditions.

For the successful development of the CIM concepts, however, top down design and bottom up implementation was essential. The bottom up implementation involved the design and development of a number of local control, measurement, monitoring and interface sub systems. This type of automation, in conjunction with compatible electronic data interchange, initially generated effective and fast integrated communication between a number of manufacturing areas.

The inherent nature of each manufacturing element (the planing and moulding machine) to be controlled, coupled with the complex supervision requirements of each local constituent CIM module, dictated a mechatronic design approach.

Initially, while employing a mechatronic's approach, the general operation outlines of each sub system were delineated. Several system alternatives, which attained individual local requisites, were investigated. Feasible alternative configurations were then subsequently reviewed during a conceptual design phase, until the more suitable system structures were finally selected.

Considerations concerning machinery options, that are available from manufacturers, and the size variations (the number and types of machines) exhibited by typical woodworking mills influenced a modular design philosophy. This philosophy provided positive manufacturing benefits for individual customers in terms of their production efficiency, purchasing flexibility and technological progression.

8.2 The Reduced Down Time Unit

The RDT unit utilised cutter head identification and position information that was received, directly or indirectly from the CASS system. Electronic data storage and interchange benefited the operators and manufacturers as the approach generated fast and accurate information transfer.

The RDT system's design and development was completed in the second quarter of 1989. Its commercial presentation was carried out during the Ligna Hannover Woodworking Machinery Exhibition, in May of that year. Since its introduction the unit has been batch manufactured and has retailed well, with only minor modifications required for system improvement.

This type of system is typically fitted to new machinery during factory assembly. However, the original version was also designed for retrofitting onto older machines, that were already situated within woodworking mills.

A retrofit system is reported to have been implemented in Australia. With such long lines of support the system's inherent simplicity, reliability and low cost, that were attained by employing a mechatronic design approach, were of paramount importance for this type of situation.

The machines that have been fitted with the RDT system have exhibited large increases in production usage time. This has been achieved using optimised but interactive data communications.

The present recession however has suppressed a considerable number of enquiries, from potential customers, for the unit. Subsequently an unproductive industrial period has developed. Thus as a future counter measure a machine automation programme has now been initiated. The hardware results of this programme will be used to penetrate the competitive market sector during the economic recovery period.

The automation programme (Hubbard B.W, Parkin R. 1990) aims to extend the setting aids of the existing RDT system. The work which is presently under development, will enable automatic setting of individual cutter head spindle off-sets, using independent DC drive motors. The information procedures generated (the procedures used to select correct spindle offset values) and the Architecture design of the original RDT unit will, however, be modularly incorporated within the new system.

The design aspect of the individual CIM constituents has promoted various levels of system sophistication and integration. Upgrading existing configurations does no longer generate any major production problems as compatible stand alone units can now be introduced as, and when, they are required by the woodworking manufacturers.

8.3 Vibration Effects

There are many possible combinations of cutting conditions and interfering frequencies that may occur on moulding machines. A number of these effects were identified within Chapter 5. It was found during this investigation that ideal cutting conditions did not occur. This resulted from a number of interference displacements that were superimposed onto the cutter head's ideal spindle position, during machine operation.

The isolated final out of balance, for the machines top head, is shown in **Figure 5.11.** This effect was generated by the reference disc used during the measurement period. However, this type of effect is easily produced by a proud knife of the cutter block.

During machine operation a cutter head displacement signature variation (a variation from the displacement observed on the balancing set up) was identified (Figure 5.16). This difference in displacement signatures, between the two systems, was created by environmental changes which included the new system structure and drive characteristics.

To generate the displacement pattern shown in **Figure 5.16** an interference displacement, at a frequency similar to that of the top head's spindle frequency, would be required. An investigation that was undertaken by **Beeson H. 1973,** on a similar moulding machine, identified no such structural resonance response peaks that interfered near the cutter head's spindle frequency. As a result the pulley drive system characteristics, were investigated.

To generate the displacement pattern shown for the single top head while considering an average cutter head spindle angular velocity of 5955 rev/min (this value was obtained from the machining data used to generate Figure 5.13), a spindle interference displacement angular velocity of 5872 rev/min would be necessary. A generated pattern, using a pure sine wave approximation exhibiting these frequencies, is shown in **Figure 7.42.**

To establish this frequency value an investigation of the drive pulley system, for the cutter head spindle, was undertaken. During this work transverse vibrations of the driving belts were investigated. This analysis assumed the flexural rigidity of the driving belts to be small. Using this assumption the natural frequency of belt vibrations was determined using system tension values alone.

Three tension quantities were considered within individual belt strands. A tight and slack side tension was generated as a result of the system's configuration. In addition, due to the belts rotation during operation, a centrifugal tension was also induced.

The experimental procedure and analysis, detailed in chapter 5 and **Appendix F**, was used to determine the system's tension values and the coefficient of friction that existed between the belts and drive pulley.

The fundamental displacement frequency, that was generated by individual pulley belts, on the GD moulder was calculated between 7 and 8 Hz. This frequency of vibration clearly did not interfere with the cutter head's spindle frequency to produce the effects shown in Figure 5.16 (the resulting displacement effect using the spindle and calculated pulley belt vibration frequency is thus shown in Figure 7.43). Further investigations, as a result of this work, are thus required to isolate the phenomenon discussed.

Because this displacement effect occurs during the operation of a single cutter head spindle, a further investigation incorporating the mounting arrangements of the drive pulley and AC motor is required (these arrangements are shown in Appendix F, Figure F1).

Further variations in the top head's spindle displacement signature were identified. This interference displacement was generated from additional, simultaneously operating, cutter head spindles which exhibited imbalance effects. The angular velocity of these spindles it was found did not match the top heads as shown in **Figure 5.13**.

Unsynchronised spindle frequency effects were thus attributed to the independent AC motors that were used to drive individual cutter head spindles.

The basic displacement pattern (the pattern illustrated for the single spindle) was generated and an interference displacement, which exhibited the average period of the 1st bottom head's frequency was added. The simulated result that is shown in **Figure 7.44** transpired. The beat of the simulated result compared reasonably with the monitored result, that is shown in **Figure 5.20**.

The overall displacement patterns, that were monitored during the machine investigation, vary considerably as a result of changes in the synchronisation frequency. This phenomenon is shown in the simulated effect that illustrates the top and second bottom heads interference (Figure 7.45). The simulated effect is comparable to the effect generated on the machine as shown in **Figure 5.23** but further investigations are required to establish a more accurate mathematical representation of this event.

Other interference results shown in chapter 5, for multiple cutting heads and the feedworks were not simulated as a result of the deviation in vibration patterns observed between the actual system (Figure 5.23) and the model approximation (Figure 7.45).

Results shown in **Figure 5.29** when compared to those illustrated in **Figure 5.30** show that the feedwork drive arrangement, in fact, only generates a small displacement effect on the overall vibration signature. This effect results from the drive system's much slower operation speed.

The simplistic simulated results, however, have strongly indicated that the interference patterns generated and re corded, from the top head's reference disc transducer, are generated from vibration interference that originates from different independent cutter head spindles. These interference effects were monitored and classified using the newly developed laser measurement system.

8.4 The Laser Measurement System

A measurement system, combining laser illumination and opto-electronic detection was developed to monitor the surface finish of planed and moulded timber products. As a result of inherent manufacturing features, such as the harsh local environment, material throughput speeds and the nature of the raw material machined, extensive control and signal conditioning circuitry was designed specifically for this application.

Initially an illumination feasibly study was required and subsequently undertaken using a gas filled helium neon laser source. This study investigated the reflection characteristics of typical manufactured surfaces. The diffusely reflected light levels that were captured from the timber samples were found to be insufficient for signal processing, unless large amplification of the signal was carried out.

The intensity problem was partially resolved using increased power output solid state laser diode modules. However, small sampled signal levels were still prominent while utilising enhanced powered illumination sources, such as the 3mW Imatronic diodes. This effect, combined with high signal to noise ratio's, necessitated the design of precision operational amplifiers, tracking power supplies and filtering networks for the data signal.

Other system considerations were also required during the consolidation phase of the electronic circuitry designs. These considerations involved the frequency and amplitude limiting characteristics of the data signal that was to be monitored.

In addition to these, process parameters such as the sample length (that was to be used during measurements) and the resultant machining characteristics (that required monitoring within a measurement frame) consequently influenced overall system designs.

The initial investigations undertaken emphasised the general outlines of the monitoring system's requirements. Thus by utilising the mechatronic design approach the development objectives and potential design complications, of the system, were quickly and effectively resolved.

The system and process aspects finally identified and outlined, using this approach, were critically reviewed during a task setting and conceptual design phase of the project. Subsequent implementation, of these designs, was then carried out during the programmes development stage.

A number of results were recorded using the measurement system. These results provided information relating the set up and operation conditions of the process. The validity of this data was established by comparing like results, that were obtained using the Talyrond stylus instrument.

8.5 Results

As the majority of results were obtained during actual machining conditions, a comparison between the measured effects obtained from both the laser and Talyrond systems will be discussed. This approach was taken as the surface models that were reviewed to establish ideal surface heights and pitch distances are no longer accurate for these conditions.

The results shown in **Figure 7.9** to **Figure 7.11** were captured using the laser measurement system, from samples manufactured by a single top head at material feedrates of 9m/min, 18m/min and 27m/min. The dominant harmonics generated from the resulting surface profiles compare with those measured using the Talyrond 200 system. These are illustrated in **Figure 7.21** to **Figure 7.23**.

The low frequency harmonics, that occur in these results, are attributed to the low frequency beat that is associated with the spindle displacement of the single top head. This displacement is shown in **Figure 5.16**. A proportion of this beat occurs during each of the 128mm sample lengths.

Each system, in addition to this low frequency harmonic, also identified dominant knife cusp harmonics from the samples manufactured at feedrates of 18m/min and 27m/min. The harmonics generated (harmonic numbers 44 & 30) as a result of the feed speeds utilised, represent an occurrence of consecutive 2.9mm and 4.26mm wavelengths on each sample's surface respectively. These harmonics are illustrated in **Figure 7.10** and **Figure 7.11** for the laser system and **Figure 7.22** and **Figure 7.23** for the Talyrond system.

The dominant harmonics correlate well between the laser and classic stylus instrument. The harmonic spectra information that was produced from the captured data of each system, is not however identical. This is due to the inherent surface characteristics of the type of material measured and the difference of approaches employed by both systems. These results also show that the Talyrond 200 system is more sensitive to the low frequency signature information, that is present on each sample surface, as a result of the absolute displacement technique employed.

A sample generated, by the top and simultaneously operating 1st bottom head, at a material feedrate of 21m/min was measured using both systems. The results obtained are shown in **Figure 7.12** and **Figure 7.24**. Within this measured sample length a good correlation of surface knife cusp markings and other dominant harmonics can be made. However the laser system, due to is grazing incident illumination technique, did not significantly identify the shallow low frequency beat that was highlighted by the stylus instrument.

A sample generated, by the top and simultaneously operating 2nd bottom head, at a material feedrate of 24m/min was measured again using each system. The knife mark harmonics that were obtained from both of the measurement systems, were identical. These effects are shown in **Figure 7.13** for the laser system's results and **Figure 7.25** for the Talyrond system's results. The dominant knife harmonic identified on the surface of this sample represents the generation of 34, 3.76mm, knife cusps.

A low frequency profile displacement and harmonic discrepancy was however generated between individual measurements on this sample, as a result of a measurement period delay. This delay, of several weeks, was caused by the failure of the laser monitoring system's illumination sources. During this delay period the specimen warped. The low frequency beat is not shown in the results of the laser measurement as the spring loaded roller deformed the sample to the material feed bedplate, which subsequently produced a straightening effect.

As the sample was only lightly secured against a faceplate during the Talyrond measurement, the warp remained and its low frequency beat was recorded. This type of error would not, however, occur during on-line measurements.

The harmonic results of the samples created at feedspeeds of 9m/min, 18m/min and 27m/min, while the top head exhibited an out of balance, are shown in **Figure 7.14** to **Figure 7.16** for the laser measurement system and **Figure 7.27** to **Figure 7.29** for the Talyrond system.

The out of balance effect created a greater variation of spindle displacement during machining, which in turn generated larger surface cusp heights. The larger cusps are reflected in the amplitudes of the harmonics illustrated. When these results were compared against the results obtained from samples generated using a balanced top head, at corresponding material feedrates, significant amplitude increases were observed.

A good match of surface profile wavelengths and dominant harmonic numbers is observed, from each specimen, when the results obtained from both machining conditions are analysed.

However, a discrepancy of a single knife cusp harmonic value is apparent when the results for the unbalanced and balanced conditions, for the sample produced using a feedrate of 18m/min, are analysed. This error relates to the suppression of only a single 2.9mm surface cusp within the 128mm wave length.

High speed manufacture The samples discussed, up to this point, were all manufactured using material feedrates of 27m/min or less. Therefore to characterise high speed production a second moulding machine was set up to generate a surface that is typically produced when a material feedrate of 100m/min is utilised.

The resulting surface cusp heights produced, using a balanced top head, obtained much greater amplitude values in conjunction with reduced material texture effects. The results obtained from both measurement systems, for this sample, are shown in **Figure 7.17** and **Figure 7.26.**

An excellent match between the harmonic spectra has been obtained for the knife cusp markings. However, even for this prominent surface, low and intermediate frequency discrepancies, between the measurement systems, have emerged.

To investigate these effects a number of metal samples were fabricated to known forms. The samples were manufactured from metal in an attempt to reduce specimen damage that was caused by the stylus of the Talyrond system. In addition the metal surfaces manufactured exhibited a finer and more uniform surface structure than those manufactured in timber.

8.6 Fabricated Surface Profiles

Results, using both measurement systems, were obtained from the samples illustrated in **Figure 7.30**. **Figure 7.31** and **Figure 7.34** show the surface profiles and harmonic spectra that were obtained from the first fabricated sample using the laser and Talyrond systems respectively.

This sample consisted of 30 uniform, 4.266mm wavelength, surface cusps within a 128mm sample length. This sample was similar to those produced on the moulding machine at a feedrate of 27m/min. The cusp heights of the fabricated sample were however larger as a smaller radius cutter was utilised during manufacture. This physical parameter is illustrated by much larger amplitude knife cusp harmonics exhibited within the fabricated sample's frequency spectrum results.

The 30 cusps present, on the sample, are represented by the dominant knife mark harmonic number (harmonic number 30) that is evident in the results. However, other wavelengths were identified on the surface of this sample, during measurements, which originate from the operation characteristics of the machine used to manufacture the profile.

The low frequency beat of these errors was not recognised by the laser system. This is evident by the absence of the lower harmonics in the results, but which are clearly displayed in the results obtained from the Talyrond system.

This difference again resulted from a system sensitivity variation.

The second fabricated specimen was produced on a CNC lathe to obtain the necessary step resolution that was required for sample manufacture. This sample consisted of 36 uniform, 3.56mm, surface cusps within a 128mm sample length. Again this sample, when measured, exhibited operations errors.

The results obtained for this specimen are shown in **Figure 7.32** for the laser system and **Figure 7.35** for the Talyrond system. Both systems again identified the correct knife cusp harmonic (harmonic number 36). However a sensitivity variation, that has become evident between the two systems, emphasised different surface components.

The results obtained using the laser system show a dominant low, knife cusp and multiple knife component frequency. The Talyrond system however, while identifying a lower amplitude knife cusp frequency, portrays a much larger low frequency surface component.

This sensitivity phenomenon was investigated further by manufacturing a sample which exhibited a known low frequency deformation, in addition to the knife cusp profile. The sample manufactured (sample No. 3) is shown in **Figure 7.30**. For this specimen 36 uniform, 3.56mm, surface cusps were produced on a single low frequency beat within a 128mm sample length.

The results obtained from this sample are shown in **Figure 7.33** for the laser system and **Figure 7.36** for the Talyrond system. It can be seen that the results obtained from the Talyrond exhibit a larger amplitude low frequency beat, than that observed from the laser system. The results also identify the laser systems enhanced sensitivity for the higher surface component frequencies. This is shown when the two results are compared, by a larger amplitude knife cusp's harmonic.

Both systems, however, identified a correct knife harmonic value, for the sample measured (ie 36 uniform, 3.56mm wavelengths within the sample length measured).

For all samples measured the harmonics produced, from surface knife cusps compare excellently. However, the amplitude distribution of these harmonics vary as a result of the approaches employed by each measurement system. A good example of this phenomenon is illustrated in the results obtained from the 3rd fabricated sample. These results are shown in **Figure 7.33** for the laser measurement system and **Figure 7.36** for the Talyrond system.

The 32μm low frequency beat, inherent on this sample, has clearly been identified by both systems. The laser system's spectrum amplitude result value, for this low harmonic, is only 68.5% of that recorded by the Talyrond system.

However, the dominant knife cusp harmonic amplitude, for the laser system, emerged with a value of 48% above the value identified by the Talyrond system. The results show that the laser measurement system is more sensitive to the higher frequency surface wavelengths measured.

Further examination of recorded results also show that the low frequency sensitivity, of the laser measurement system, is, however, sufficient to identify low frequency beats that exhibit smaller peak to peak amplitudes.

A low frequency beat amplitude, of the order of 10μm, was produced on the surface that was generated using a single top head at a material feedrate of 9m/min. The laser system identified this effect as a dominate frequency within the resulting frequency spectrum produced for the surface (Figure 7.9).

This result, in addition to other recorded events, indicates that the monitoring system's attenuated sensitivity is still of a sufficient capacity to identify typical low frequency surface amplitude variations, that occur during machine operation.

8.7 Simulated Effects

Simulated surface effects were produced by accommodating machine interference frequency characteristics, that were observed during sample manufacture, within a trochoidal model.

However, analytical development established the single spindle effect, that is shown in **Figure 5.16**, was not generated as a result of pulley belt agitation. Investigative results, that are shown in **Figure 7.44** and **Figure 7.45**, did however indicate the generation of low frequency interference displacements that are created by second spindles.

From these results, multiple spindle interference and calculated belt agitation frequencies were utilised during simulated surface generation. Combining these displacement signatures with equipment parameters, that were set during the machine investigation, within the model the results that are shown in **Figure 7.37** to **Figure 7.41** were obtained.

The results (excluding those shown in Figure 7.37) calculated from the simulated knife cusp profiles follow the same harmonic translation that is apparent in the results obtained from similarly manufactured specimens. However discrepancies occur as a result of spindle displacement variation.

A spectrum error was created within the low frequency harmonics, of these results, as a direct effect of the higher frequency belt agitation displacement employed. In addition as the interference displacements, that were incorporated within the model, simulated pure sine wave approximations, knife harmonic anomalies consequently emerged.

The simulated effect generated at a material rate of 9m/min, for a sample generated using the top head, identified a dominant knife cusp harmonic. This effect cannot be seen in the corresponding results for the manufactured specimen (Figure 7.9) as a result of the inherently fine surface finish produced and subsequent elevated material surface fibres.

9. CONCLUSIONS

Page #

9.1 Present Investigation

9.1.1 Process Automation

The present investigation has involved a substantial automation design and development programme in conjunction with the mathematical development of typical operation characteristics, which are exhibited by the planing and moulding process.

The process control programme proceeded through several stages of development, as detailed in chapter 2, chapter 3 and chapter 6.

The initial aim of the project was to create a computer integrated manufacturing environment for the planing and moulding process. To this end an extensive design and development programme was undertaken concerning the local but modular automation points of the CIM strategy. The conclusions that can be drawn from this work are :

1) Efficient and accurate data transfer, between the tool room (using the CASS system) and the factory floor (using the RDT system), has been achieved.

2) By employing the RDT system, machine down time cycles have been greatly alleviated as a result of the fast interactive data facilities utilised.

3) Typical production characteristics, generated by planing and moulding machines, have been identified using the experimental in-process surface measurement system that is detailed in chapter 6.

4) The quantity of sub standard surface finish timber could be reduced with the introduction of the in-process surface measurement system.

However some work remains to be carried out on the system before it can be successfully implemented within the planing and moulding production environment.

9.1.2 Process Characteristics

Spindle vibration characteristics, of a typical planing and moulding machine, were identified using data acquisition instrumentation. An array of machine conditions were monitored and from these the following conclusions can be made :

1) The low frequency interference displacement beats, that were superimposed onto the top head's spindle, resulted from unsynchronised simultaneously operating cutter heads.

It was also identified that significant displacement amplitude variations were only observed from cutter heads that operated in identical vibration planes.

Negligible variation in the top head's displacement signature resulted from the slower operating feedworks and the operation of perpendicular fence or near heads.

2) After an analytical investigation it was established that the significant single spindle displacement signature identified was not generated as a result of pulley drive belt agitation. A further programme of work concerning the drive system mounting arrangements is thus required to establish the origins of this effect.

9.1.3 Theoretical Characterisation

A computer simulation program was developed which incorporated the trochoidal development detailed in chapter 4 and the simplistic interference displacements discussed in chapter 5. This program was used when comparing theoretically generated surfaces with surface profiles that had been manufactured under typical production conditions.

Discrepancies were identified between manufactured and theoretical surfaces as a result of the variation in displacement signatures employed (the sine wave approximations), in conjunction with the absence of surface texture compensation within the theoretical model. However, a good correlation of knife cusp harmonic positions was established for individual surfaces.

9.2 Suggestions For Future Work

9.2.1 Experimental work

1) The development of an interactive data base, which is required to consolidate the locally developed process modules. The creation of such a structure would have to be designed specially for this area of the woodworking industry, for the reasons discussed in chapter 2

2) The completion of a fully automatic RDT cutter head setting system, which would further reduce machine setting times.
NB This work is currently under development.

3) A more detailed investigation of the inherent vibration characteristics exhibited by typical planing and moulding machines is required. Thorough consideration should be given to the area of the pulley drive system mounting arrangement.

4) The experimental laser surface measurement system should be further developed. The sample length monitored during measurements requires expanding to facilitate very low frequency beats that are generated by interfering cutter heads. In addition a production version of the system, incorpo-

rating automatic signal gain control circuitry, real time FFT processing hardware architecture and a scanning measurement head is required. This latter feature would prove beneficial during planing operations.

9.2.2 Theoretical Work

1) Further vibration and computer simulation development is required for the prediction of characteristic surface parameters that are produced on samples, during typical manufacturing conditions. Considerations should be given to the surface texture of the material measured, when analysing fine surface finishes.

2) The theoretical work requires integrating with the local measurement system's control structure. This development if combined with machine trend statistical procedures could produce important manufacturing threshold level and process status feedback information.

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Surface Measurement of Planed and Moulded Timber Products

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A Typical Planer Moulder

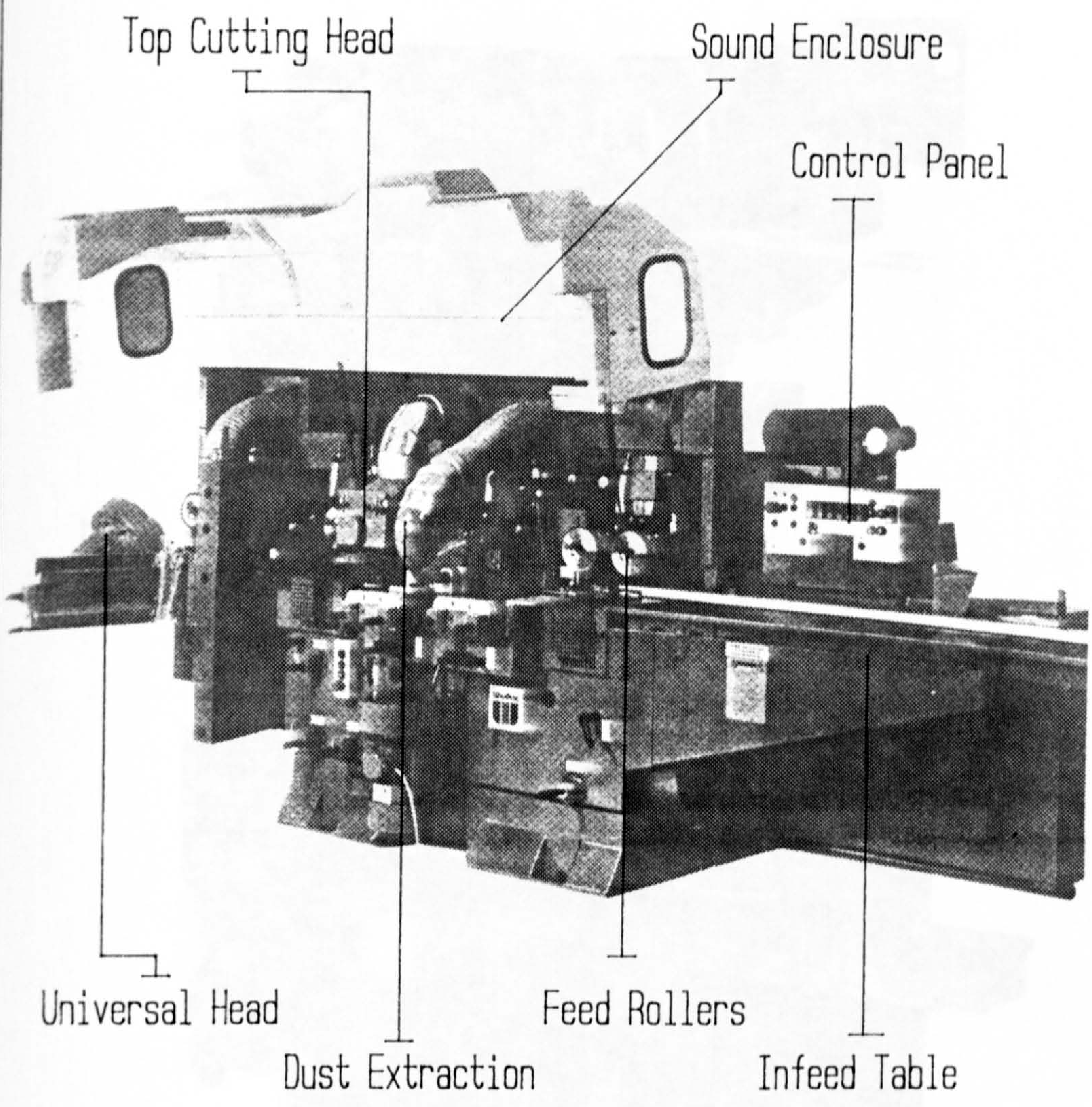
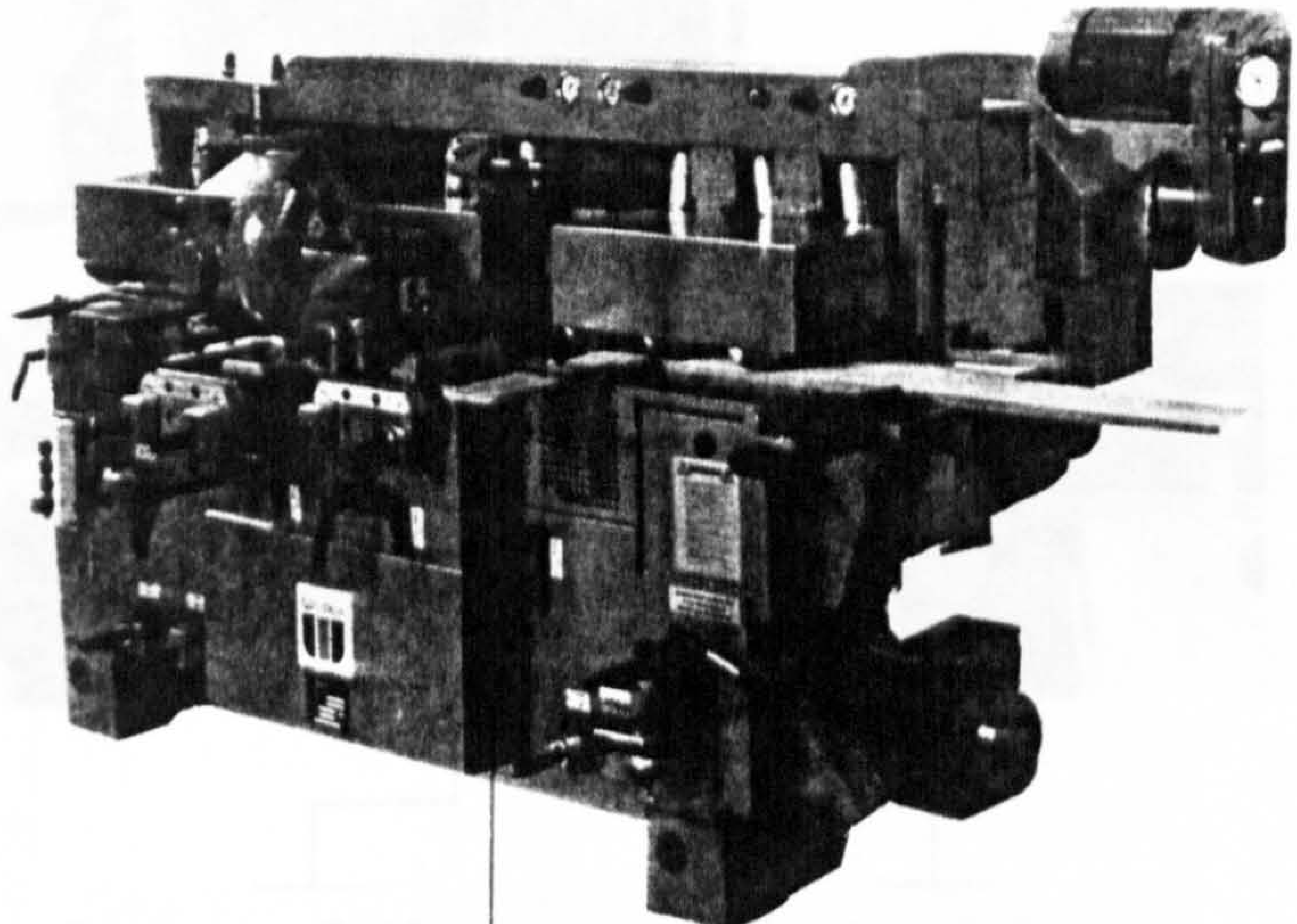


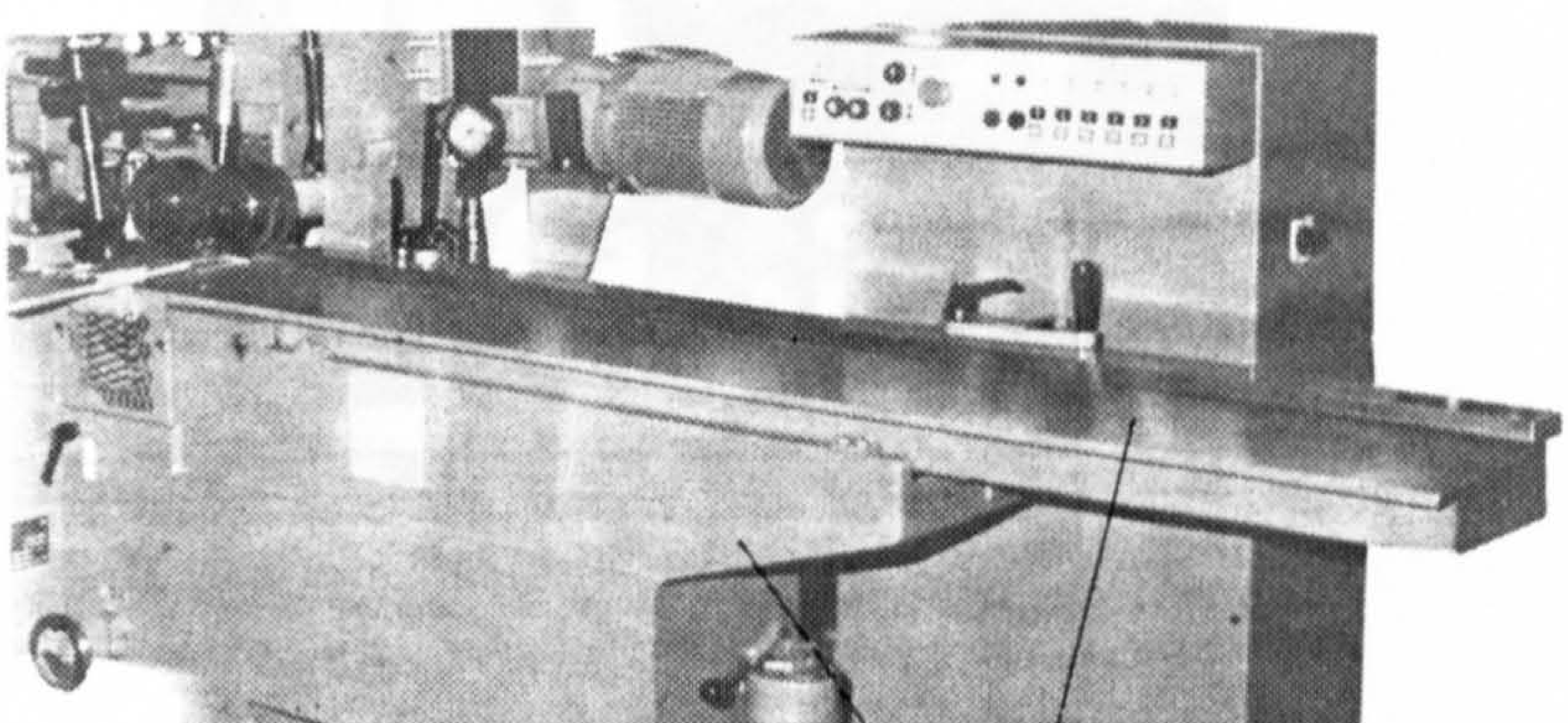
Figure 1.1

Moulder Structural Features



1.2a

Cast Iron Machine Base Structure



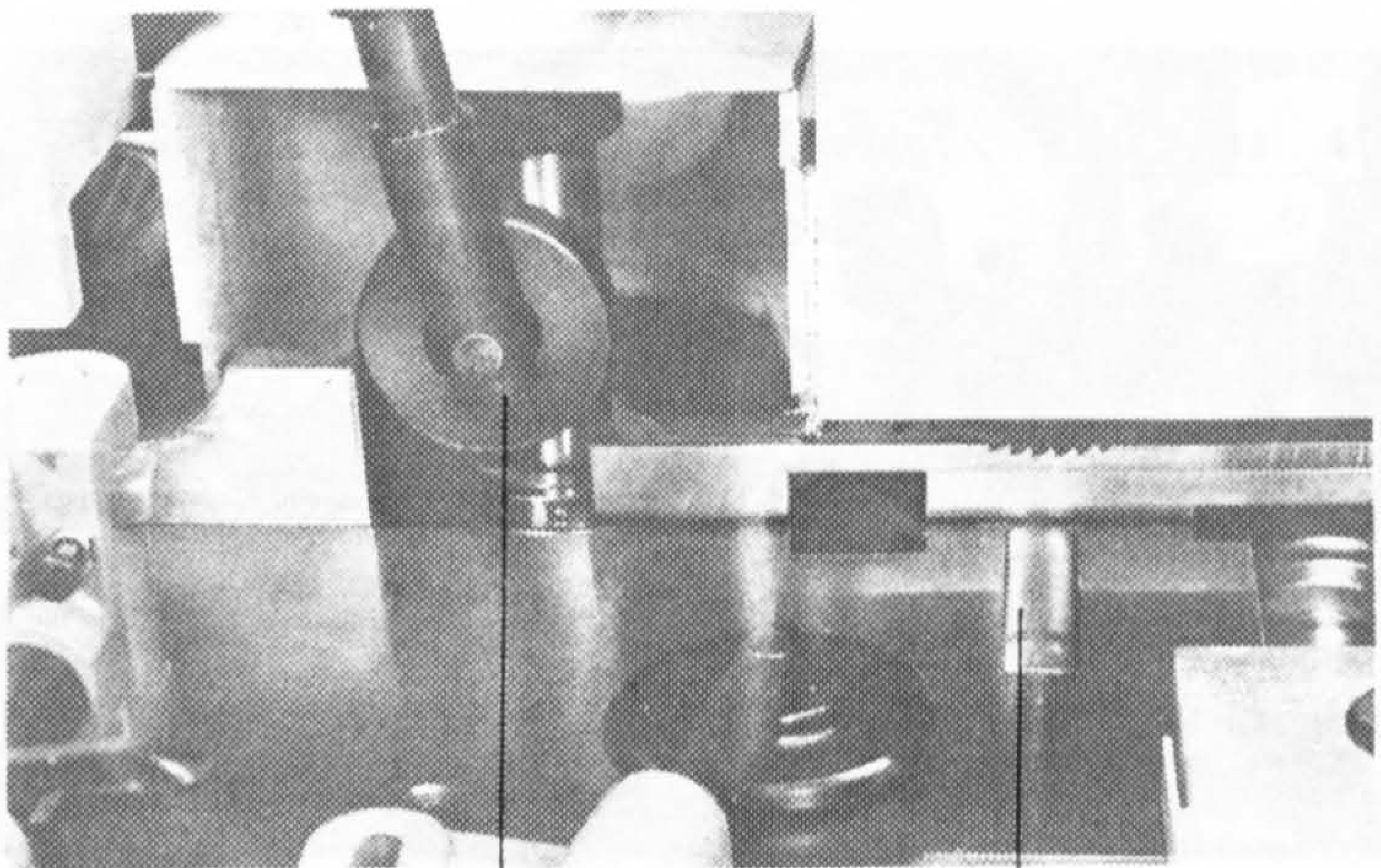
1.2b

Infeed Straightening Table and Oil Lubricated Bed and Fence

Figure 1.2

Idle Bed Rollers and Cutter Head Assemblies

1.3a



1.3b

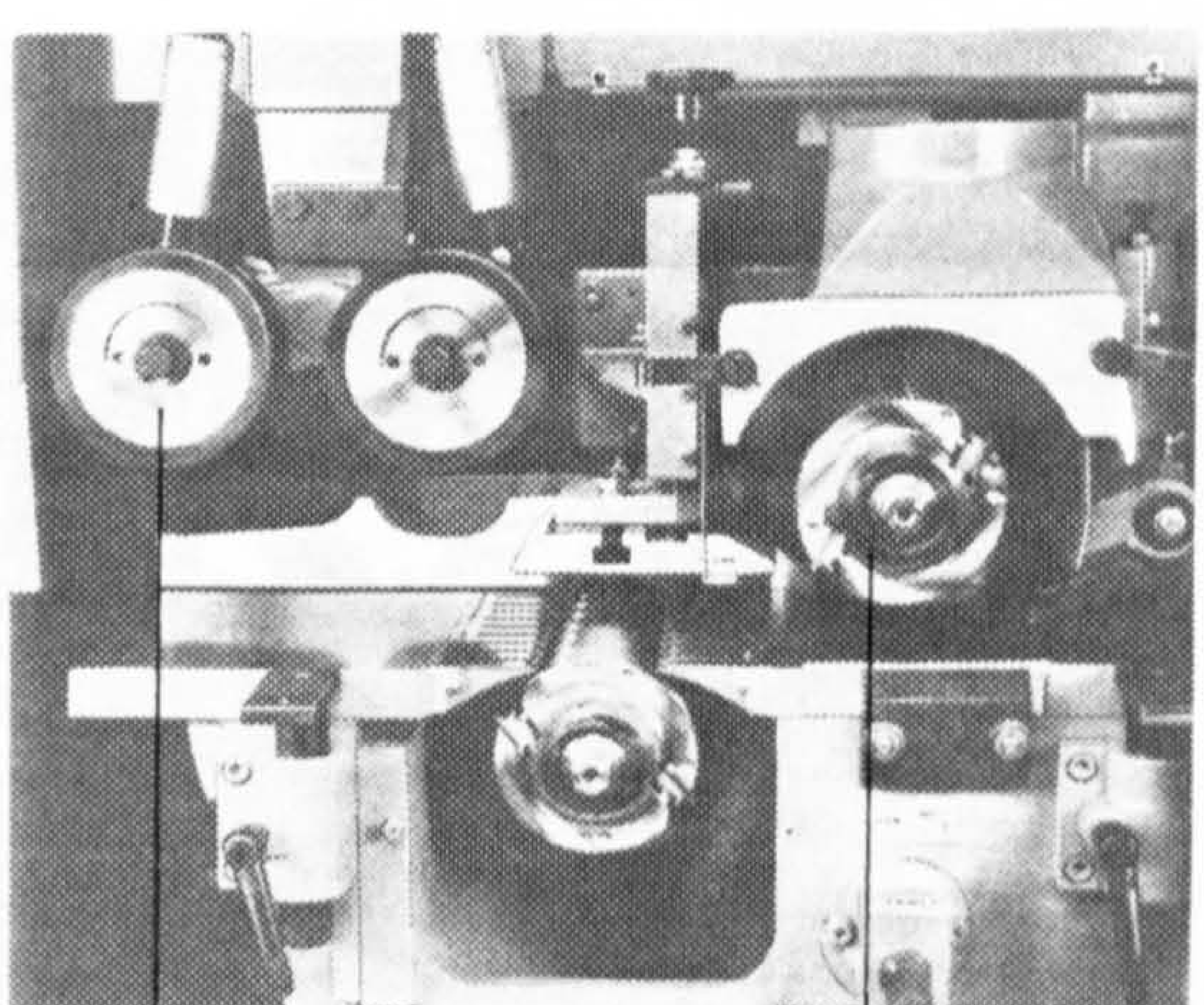


Figure 1.3

Pneumatically Loaded Feed Rollers and Pressure Pads

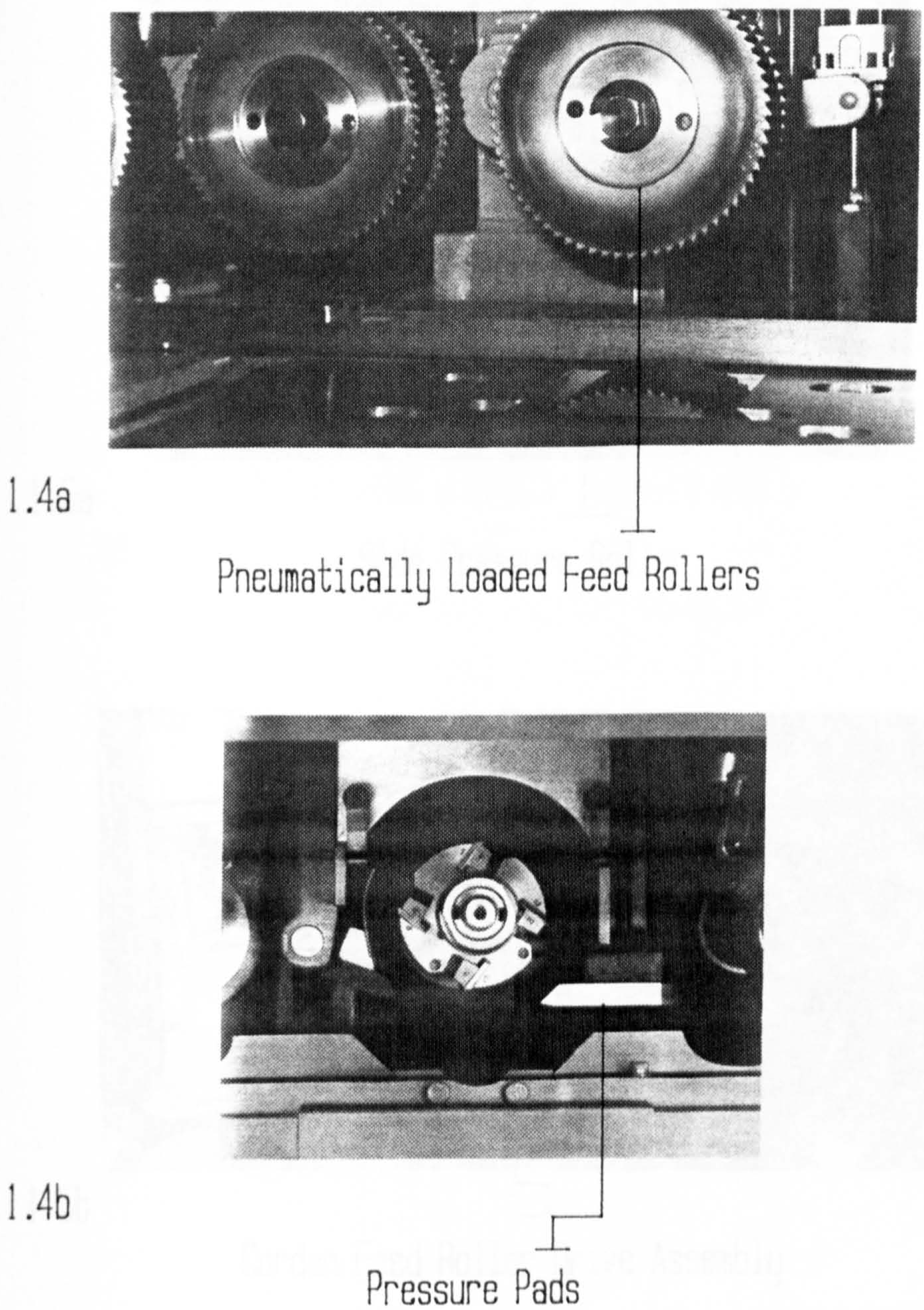
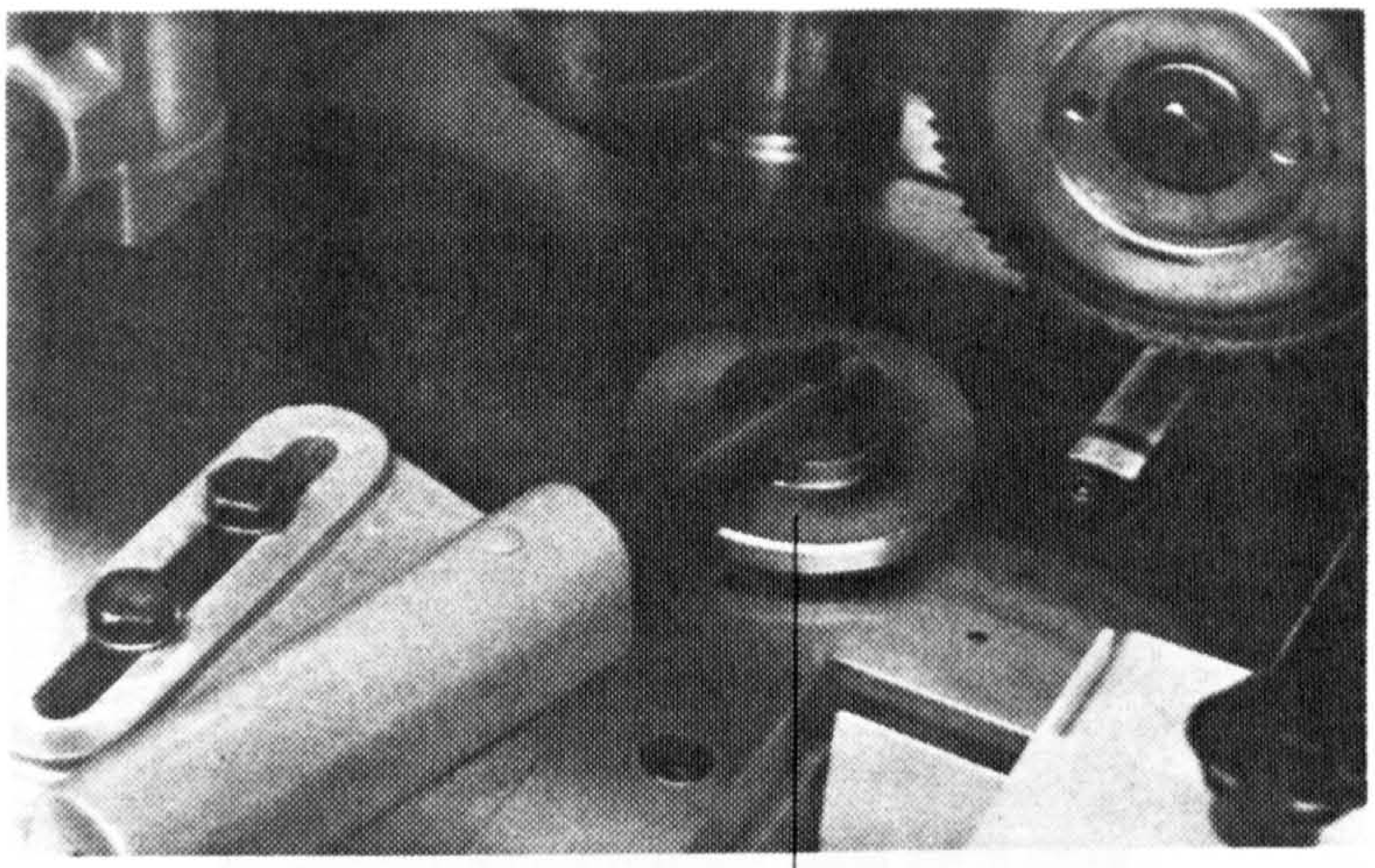


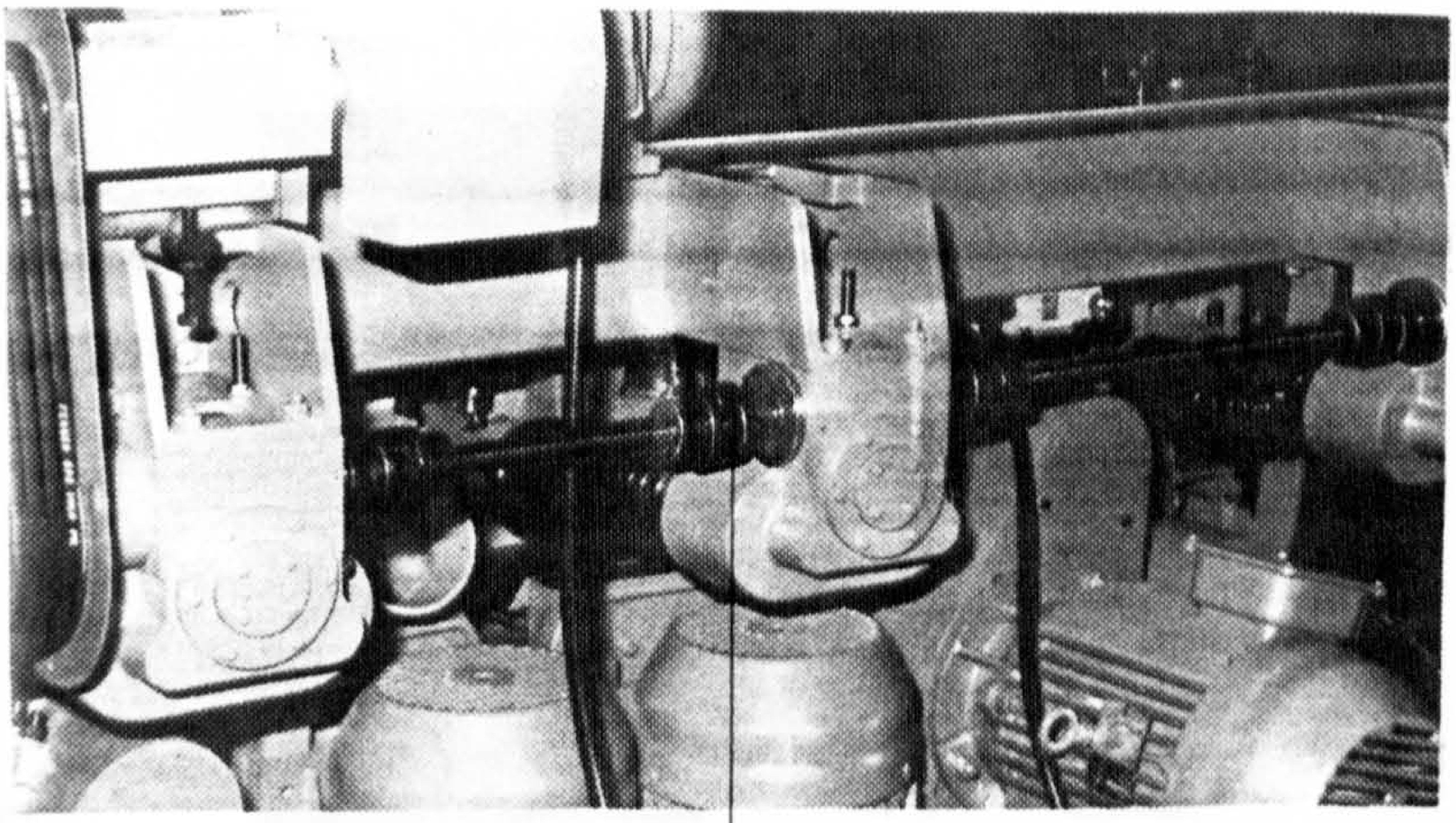
Figure 1.4

Side Pressure Rollers and The Carden Drive



1.5a

Side Pressure Roller

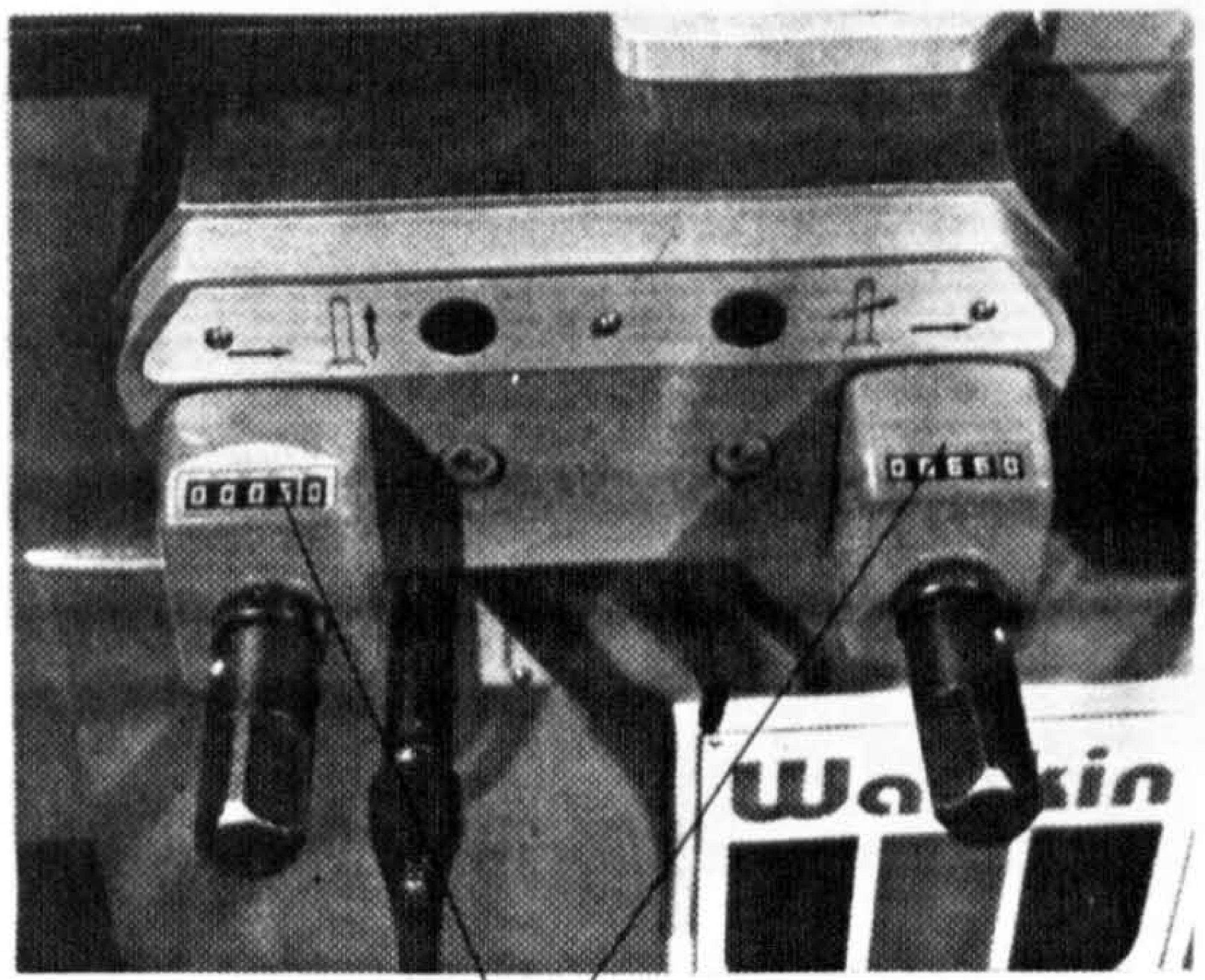


1.5b

Carden Feed Roller Drive Assembly

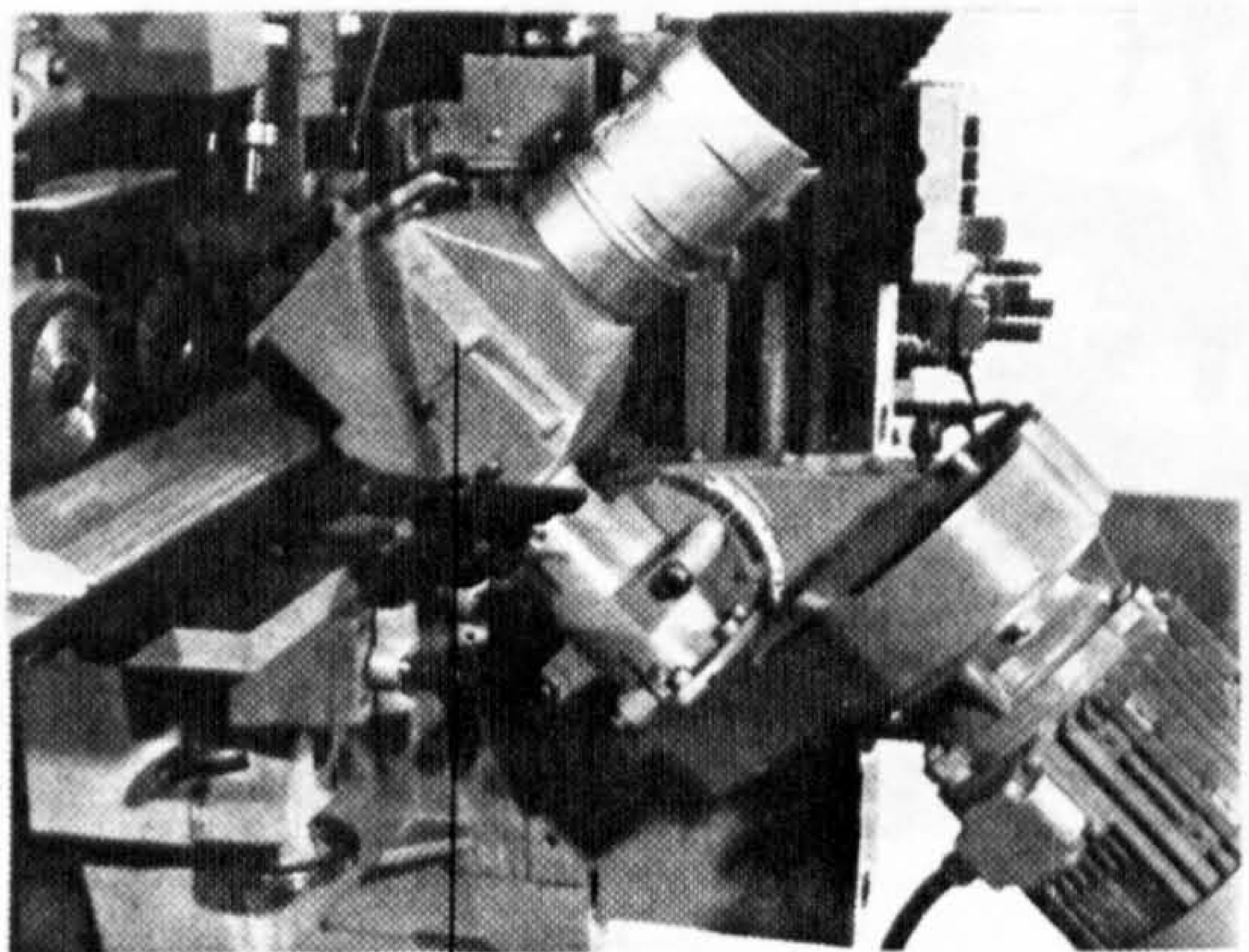
Figure 1.5

Mechanical Digital Readouts and the Universal Head



1.6a

Mechanical Digital Readouts

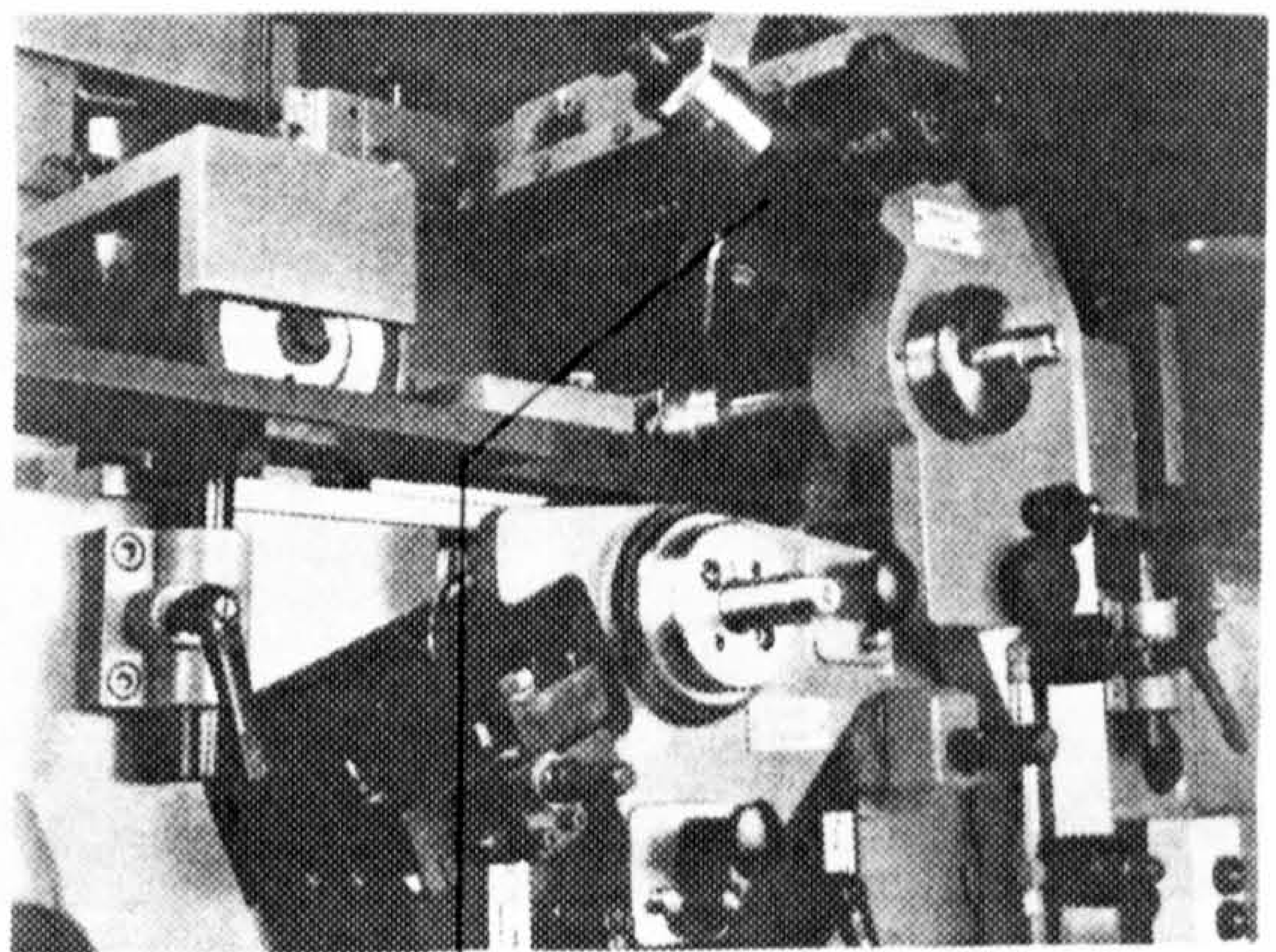


1.6b

3 or 4 Position Universal Head

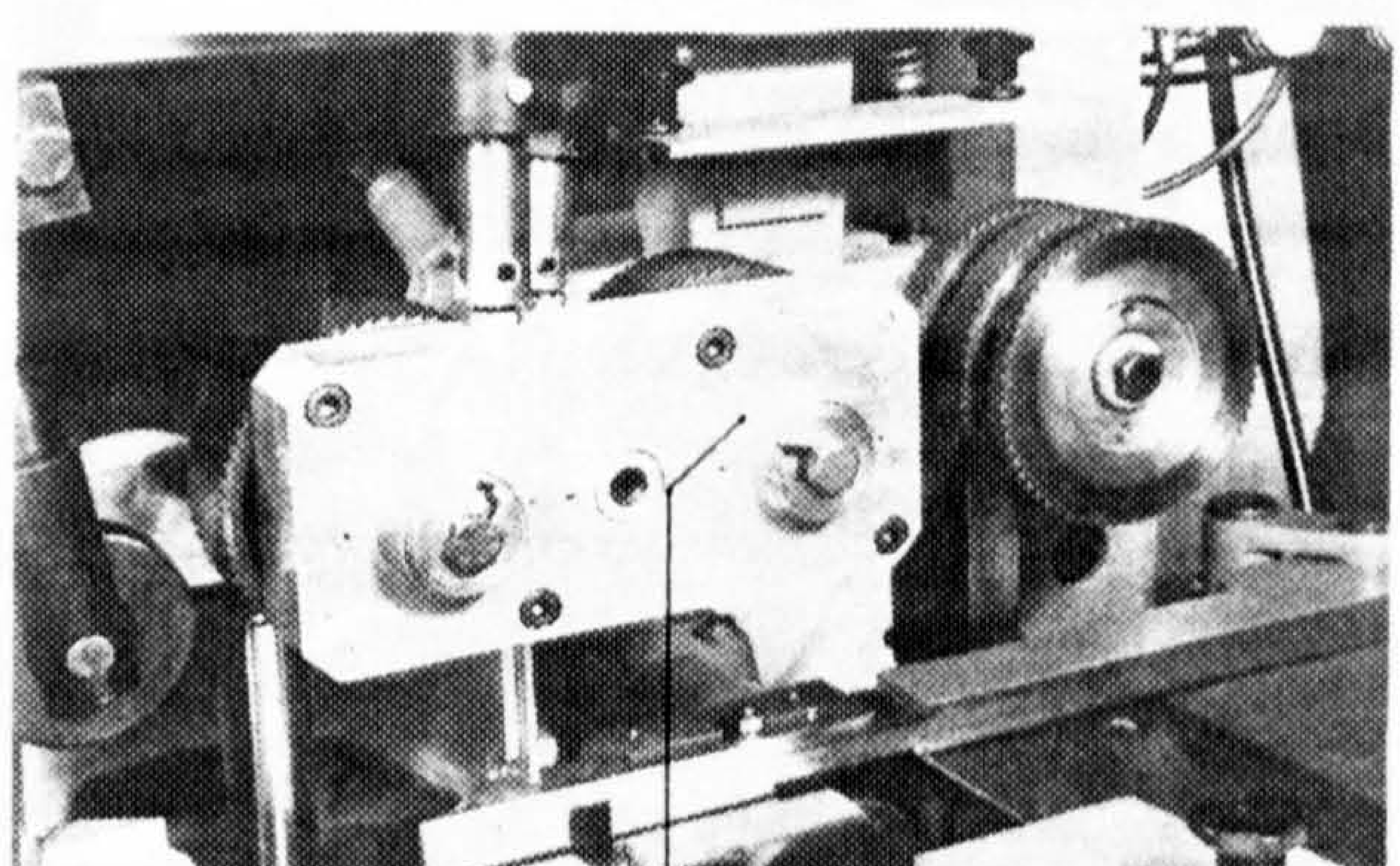
Figure 1.6

Jointer Cartridge and Intermediate Feed Rollers



1.7a

Jointer Cartridge

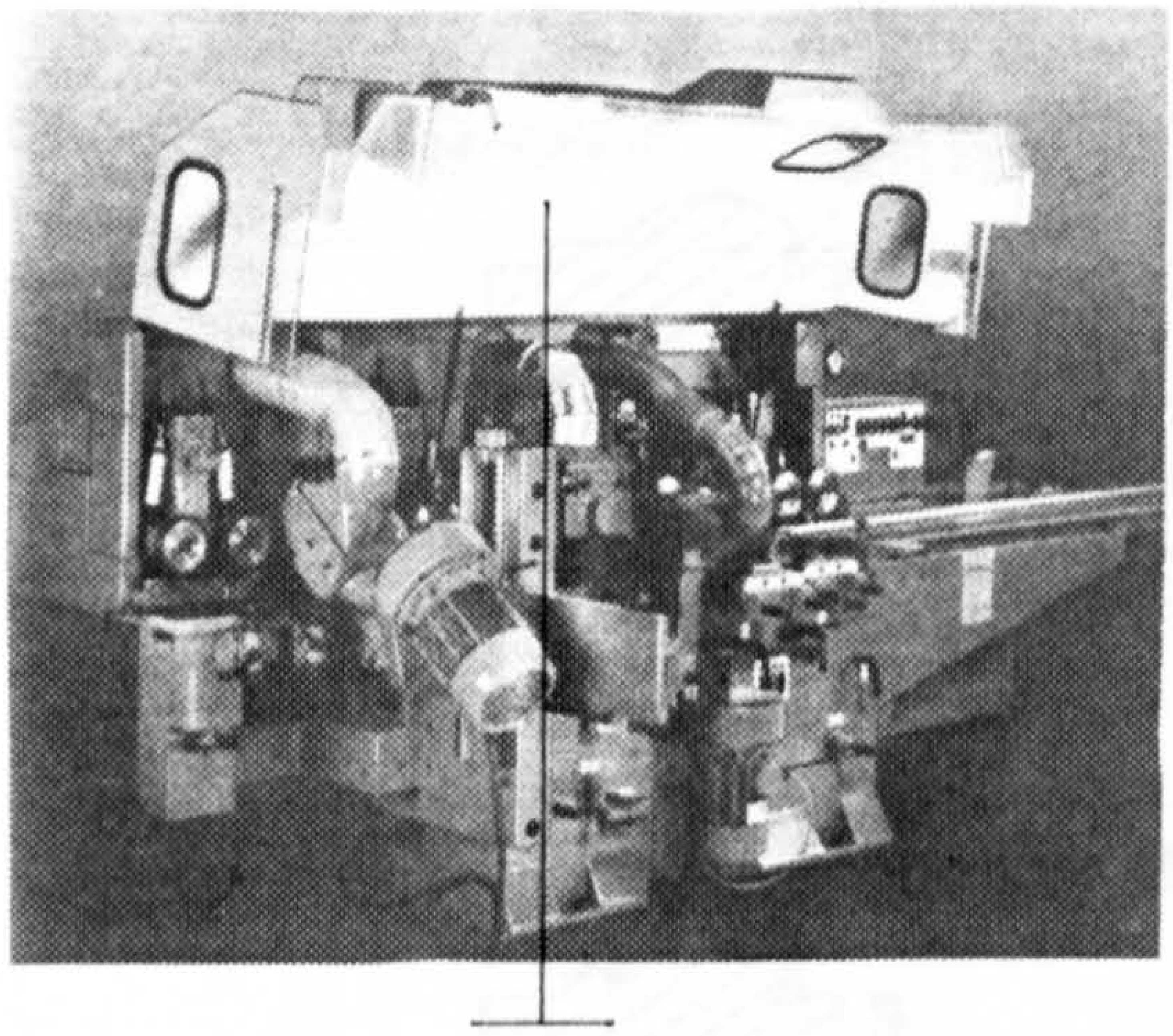


1.7b

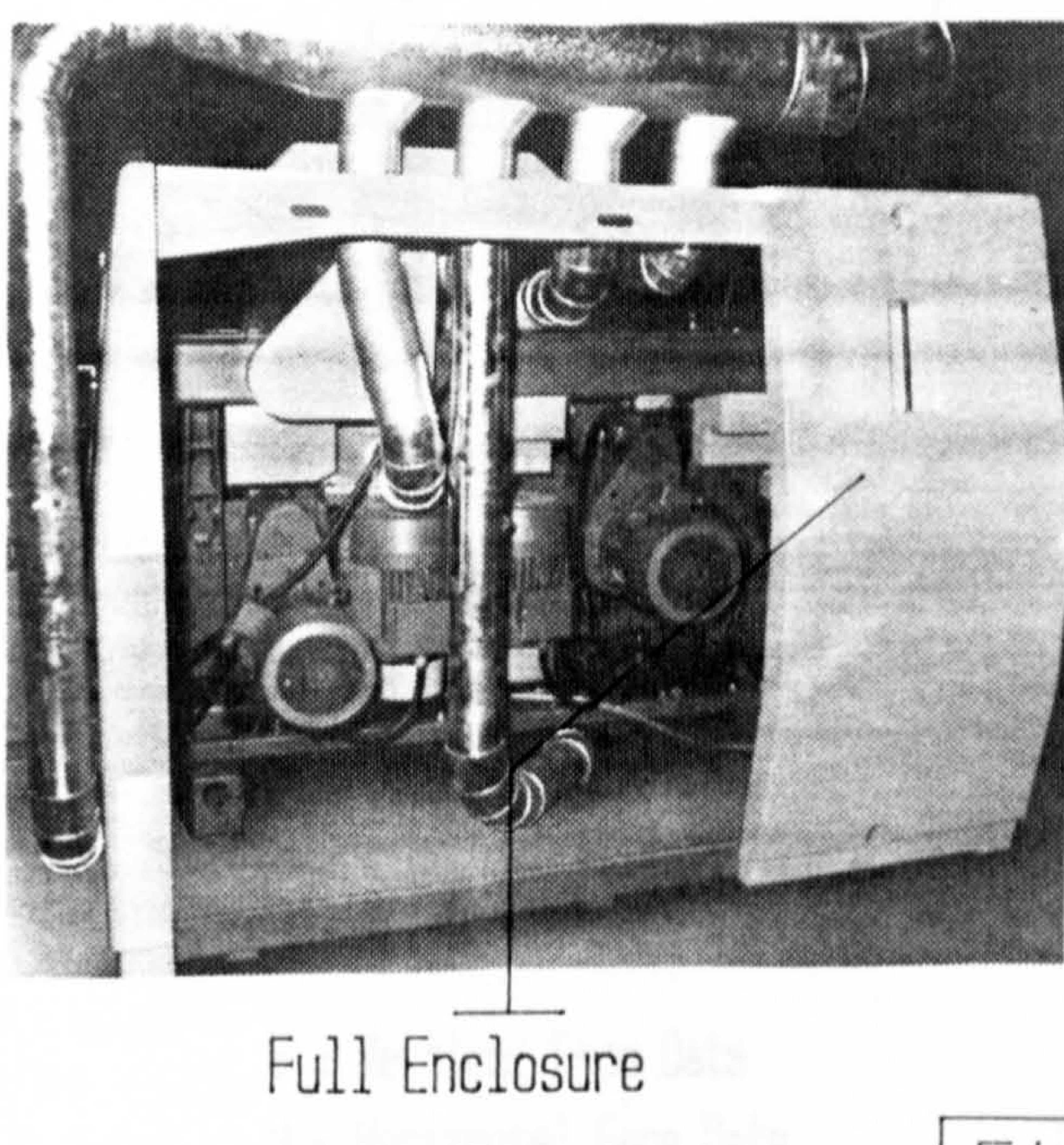
Intermediate Feed Roller Assembly

Figure 1.7

Sound Enclosures



Hood Enclosure



Full Enclosure

Figure 1.8

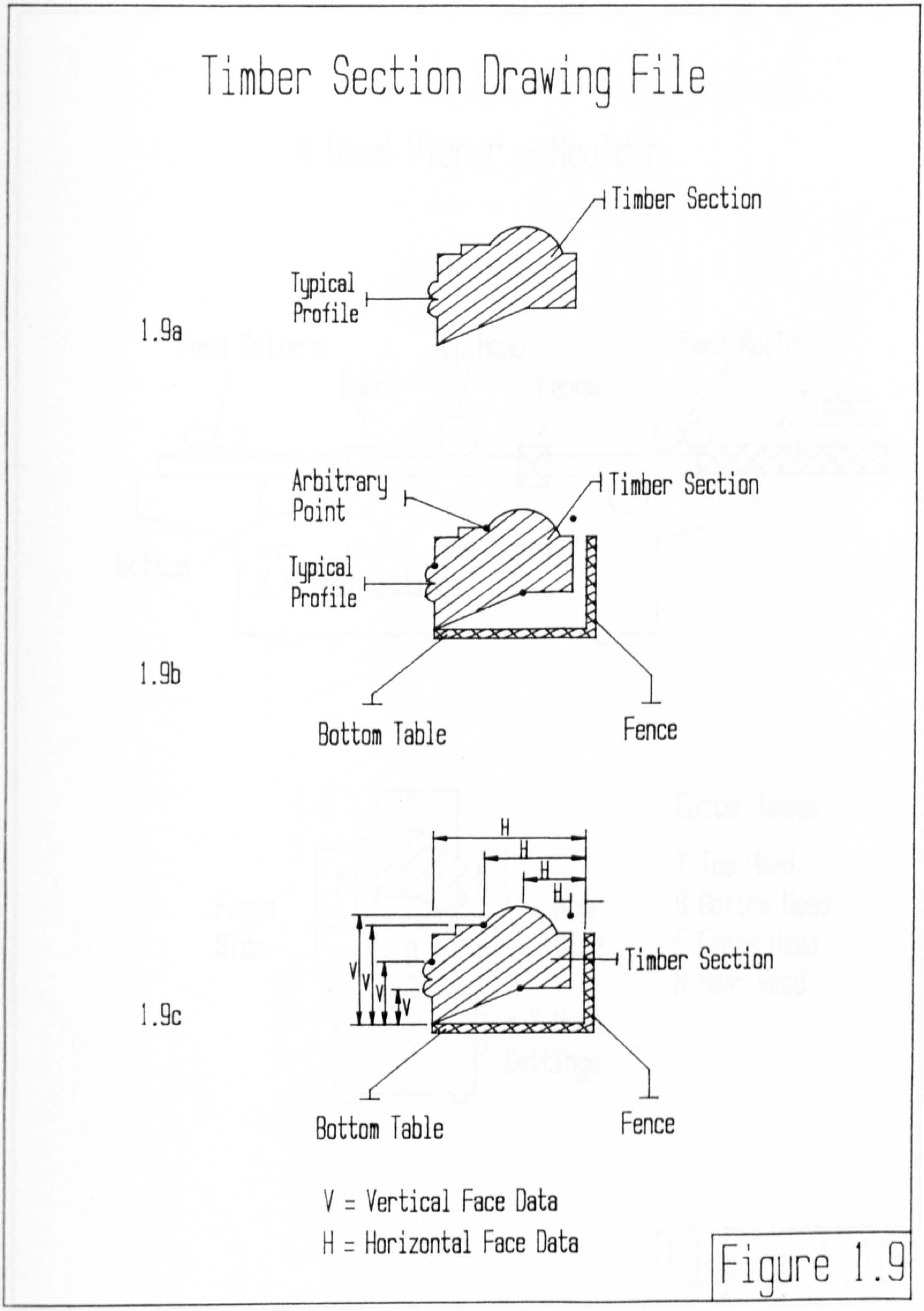

Timber Section Drawing File
Timber Section
Typical Profile
1.9a
Arbitrary Point
Timber Section
Typical Profile
1.9b
Bottom Table
Fence
H
H
H
H
V
V
V
V
Timber Section
1.9c
Bottom Table
Fence
V = Vertical Face Data
H = Horizontal Face Data

Figure 1.9

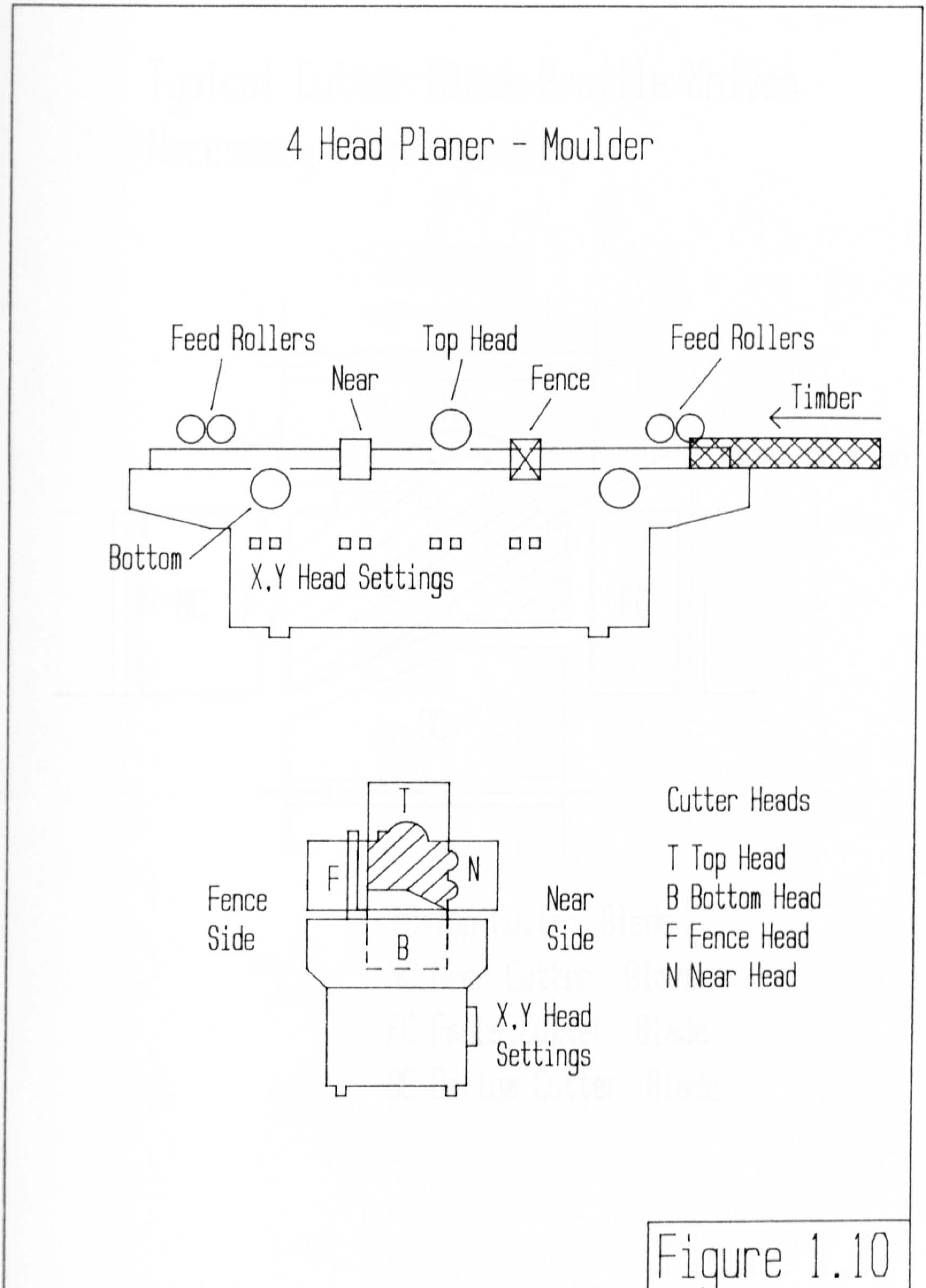
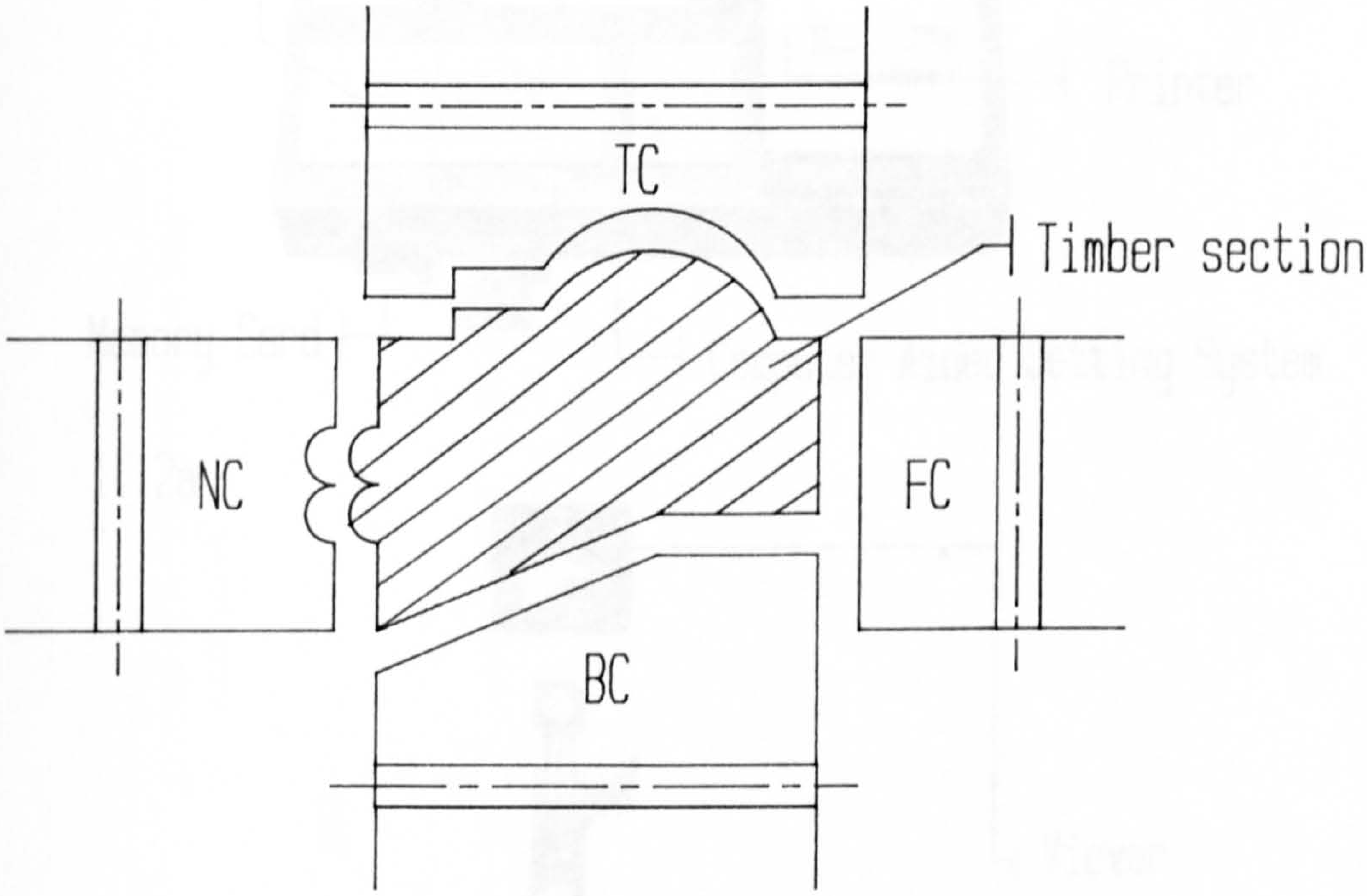

4 Head Planer - Moulder
Feed Rollers
Near
Top Head
Fence
Feed Rollers
Timber
Bottom
X,Y Head Settings
T
F
N
B
Fence Side
Near Side
X,Y Head Settings
Cutter Heads
T Top Head
B Bottom Head
F Fence Head
N Near Head

Figure 1.10

Typical Cutter Block Profile Knives Necessary When Moulding



TC Top Cutter Blade
NC Near Cutter Blade
FC Fence Cutter Blade
BC Bottom Cutter Blade

Figure 1.11

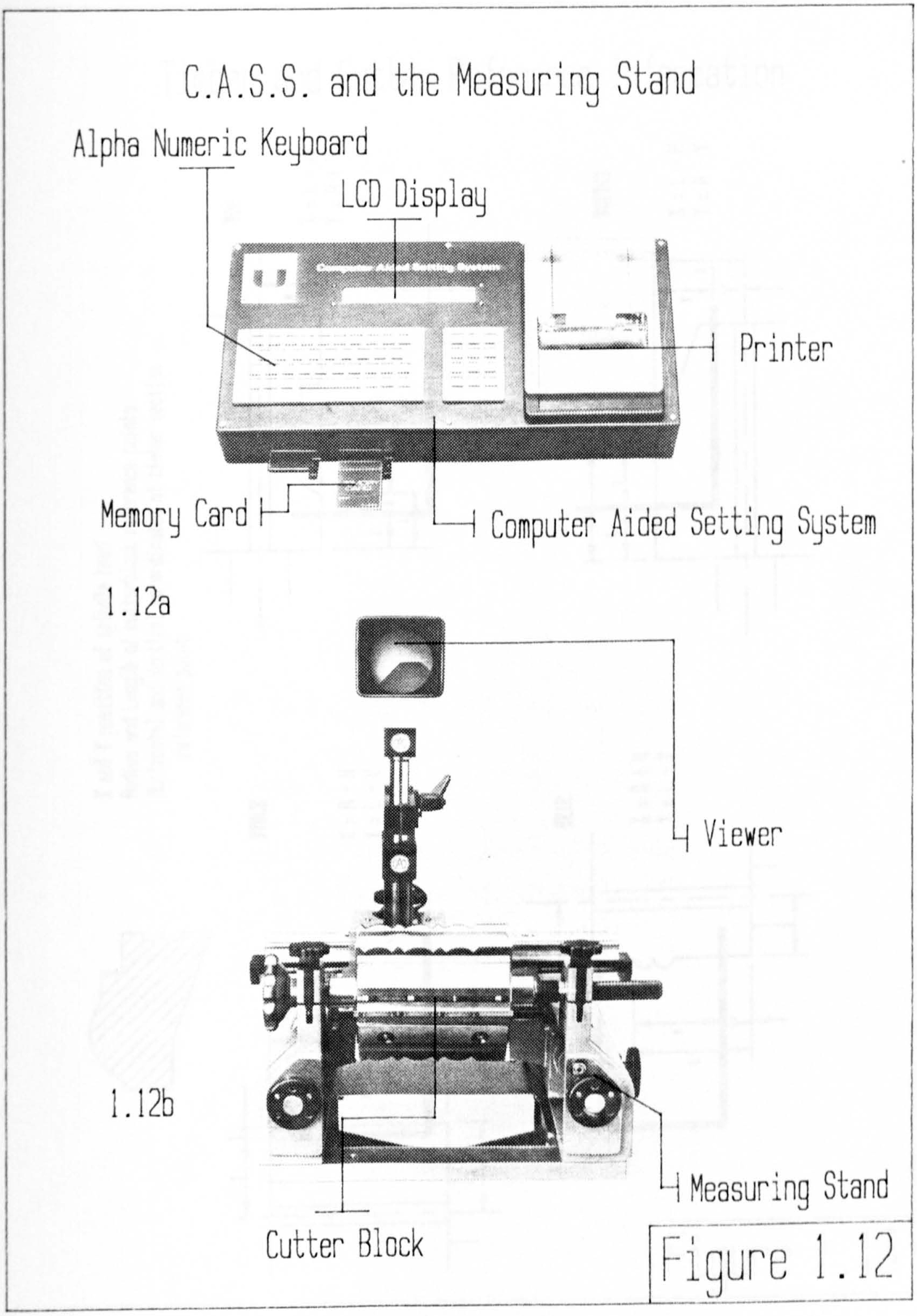

C.A.S.S. and the Measuring Stand
Alpha Numeric Keyboard
LCD Display
Printer
Memory Card
Computer Aided Setting System
1.12a
Viewer
1.12b
Measuring Stand
Cutter Block

Figure 1.12

Timber and Cutter Reference Information

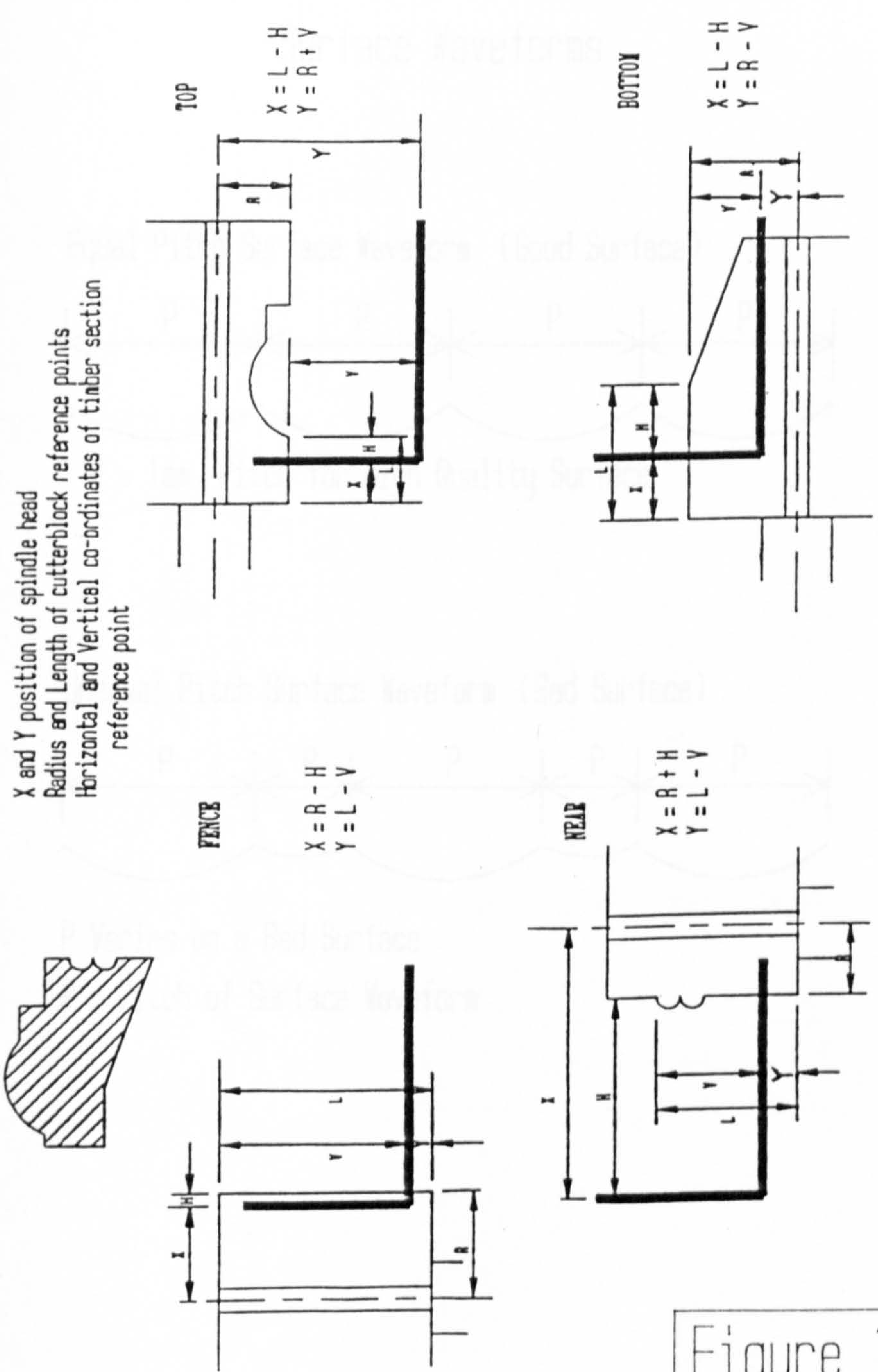


Figure 1.13

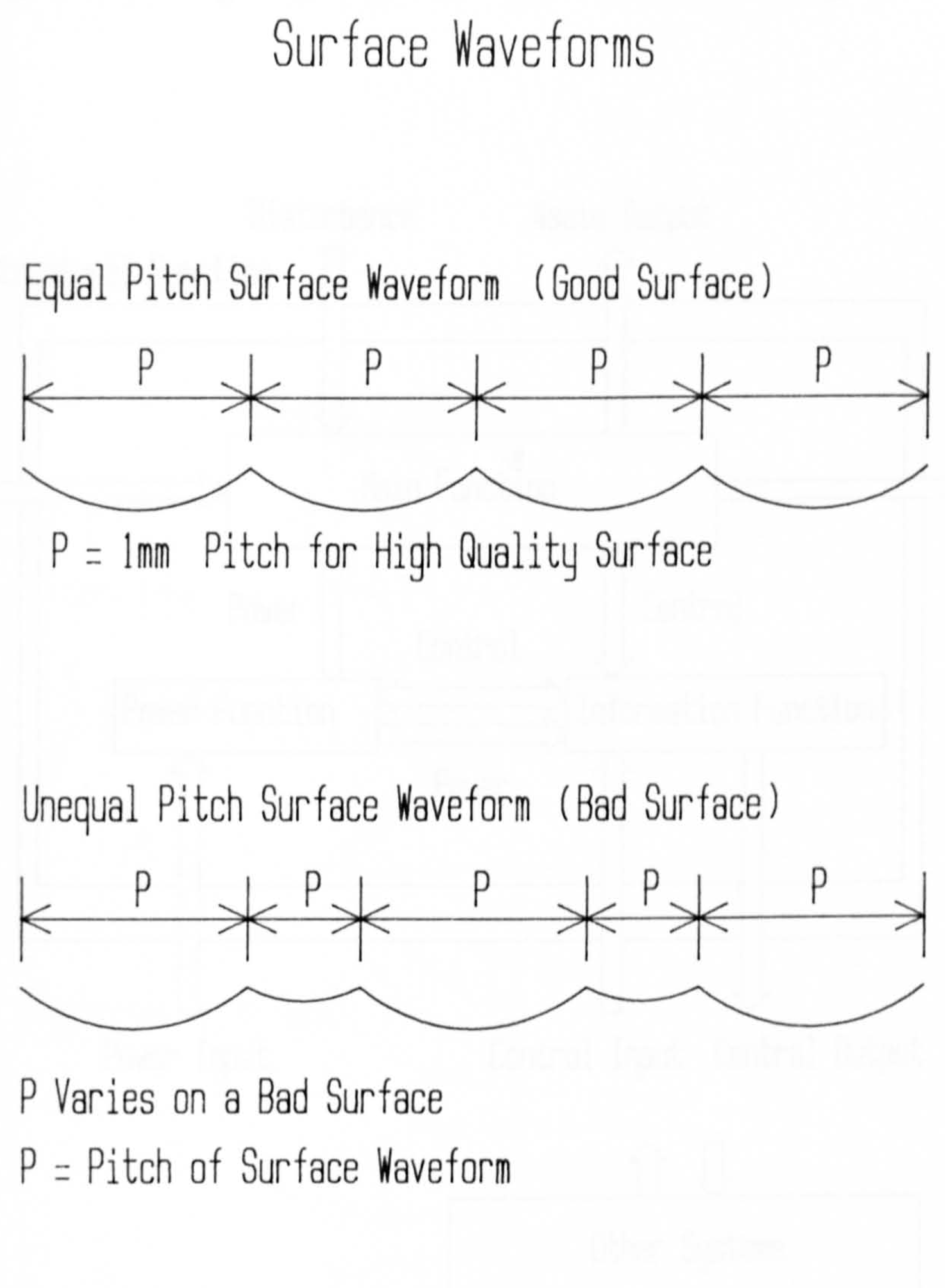

Surface Waveforms
Equal Pitch Surface Waveform (Good Surface)
P
P
P
P
P = 1mm Pitch for High Quality Surface
Unequal Pitch Surface Waveform (Bad Surface)
P
P
P
P
P
P Varies on a Bad Surface
P = Pitch of Surface Waveform

Figure 1.14

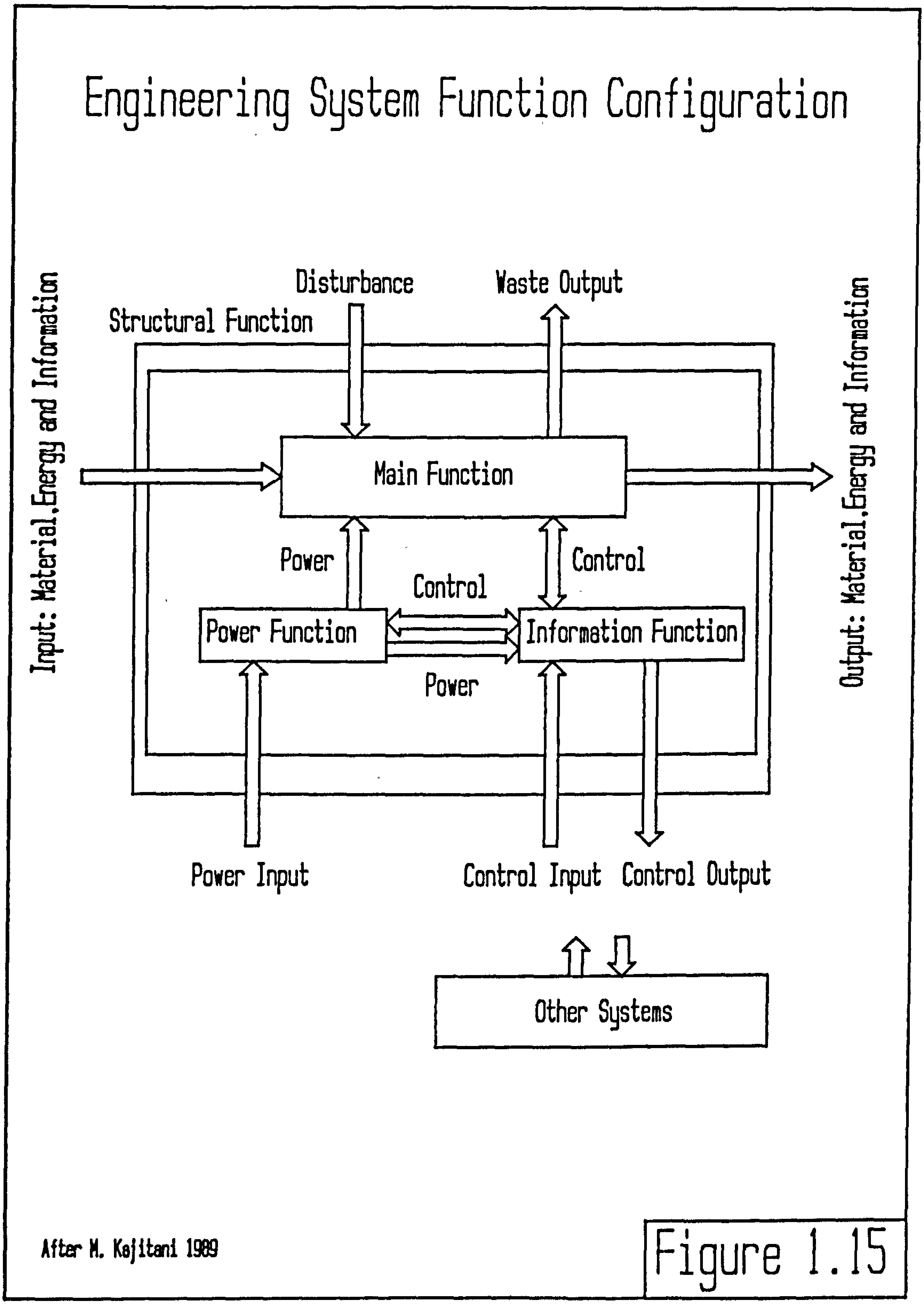

Engineering System Function Configuration
Input: Material,Energy and Information
Structural Function
Disturbance
Waste Output
Main Function
Output: Material,Energy and Information
Power
Control
Control
Power Function
Information Function
Power
Power Input
Control Input
Control Output
Other Systems
After M. Kajitani 1989

Figure 1.15

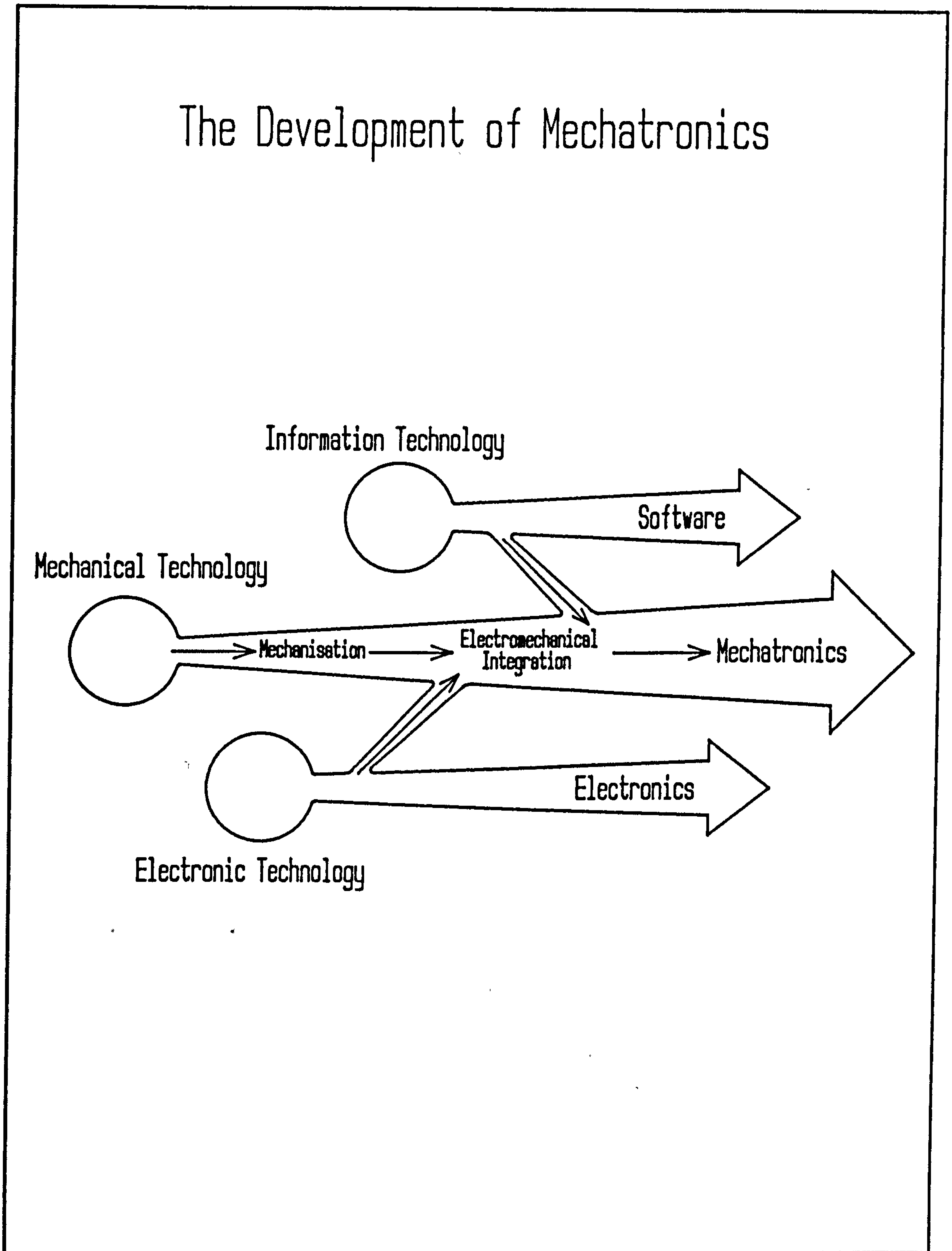
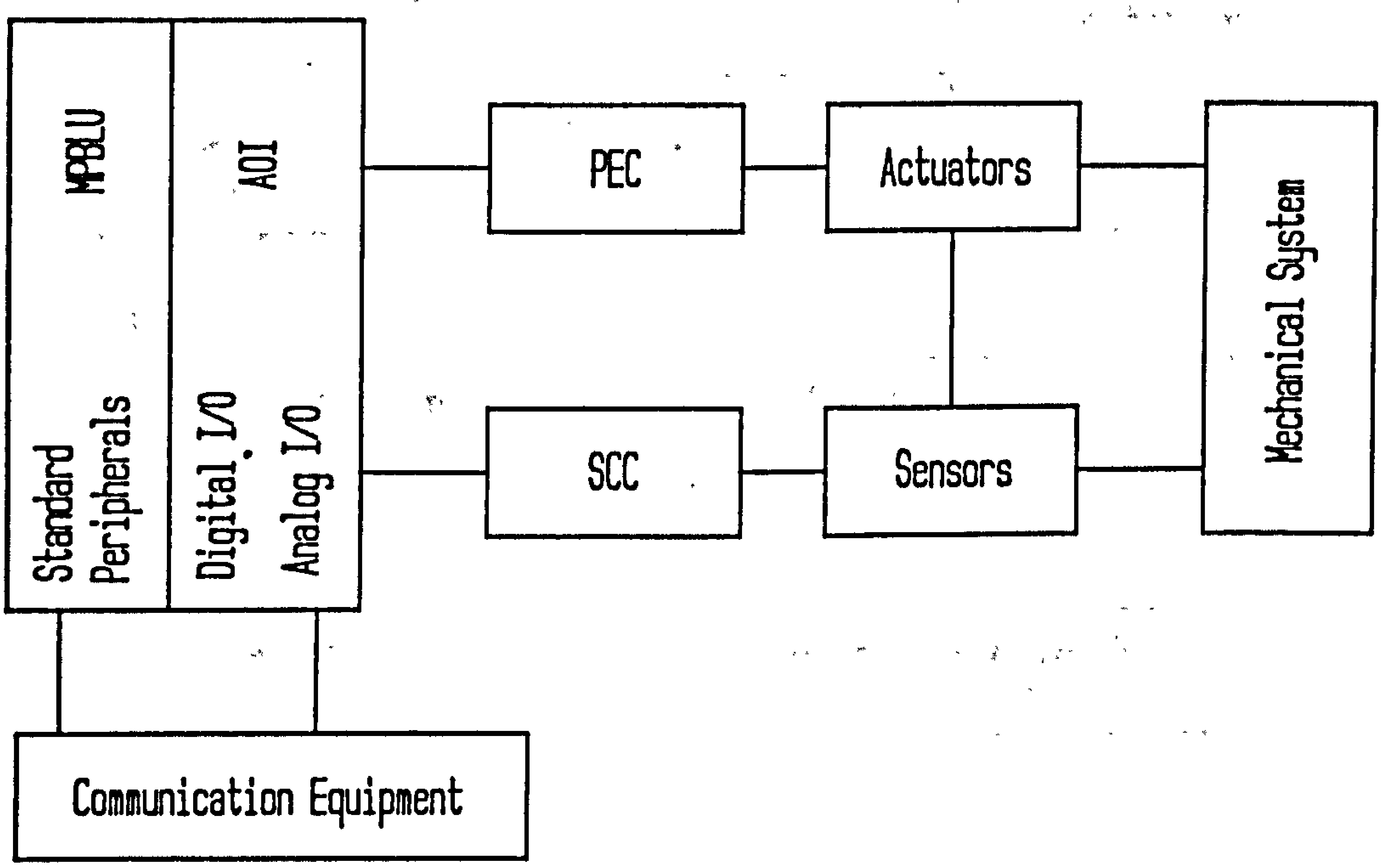

The Development of Mechatronics
Information Technology
Software
Mechanical Technology
Mechanisation
Electromechanical Integration
Mechatronics
Electronics
Electronic Technology
After M. Kajitani 1989

Figure 1.16

General Model of a Mechatronic System



PEC: Power Electronic Circuit
SCC: Signal Conditioning Circuit
AOI: Application Oriented Interfaces
MPBLU: Microprocessor Based Logic Unit

After J. Dinsdale 1989

Figure 1.17

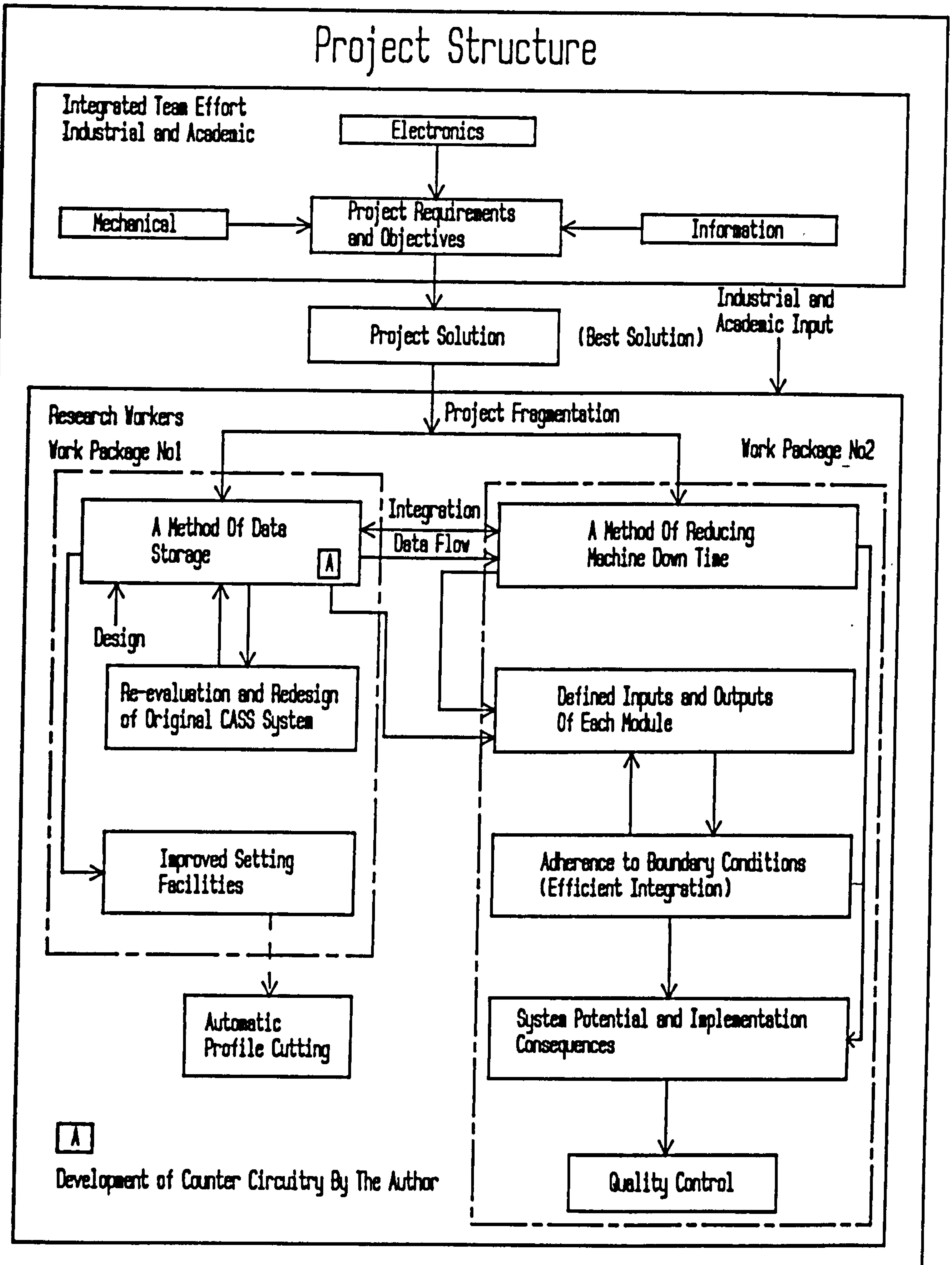

Project Structure
Integrated Team Effort
Industrial and Academic
Electronics
Mechanical
Project Requirements and Objectives
Information
Industrial and Academic Input
Project Solution
(Best Solution)
Research Workers
Project Fragmentation
Work Package No1
Work Package No2
Integration
Data Flow
A Method Of Data Storage
A
A Method Of Reducing Machine Down Time
Design
Re-evaluation and Redesign of Original CASS System
Defined Inputs and Outputs Of Each Module
Improved Setting Facilities
Adherence to Boundary Conditions (Efficient Integration)
Automatic Profile Cutting
System Potential and Implementation Consequences
A
Development of Counter Circuitry By The Author
Quality Control

Figure 1.18

G Codes

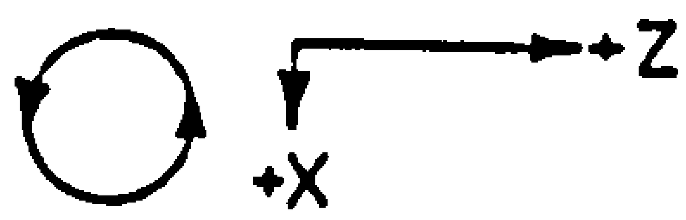
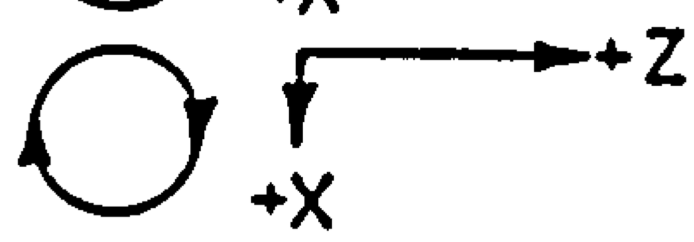
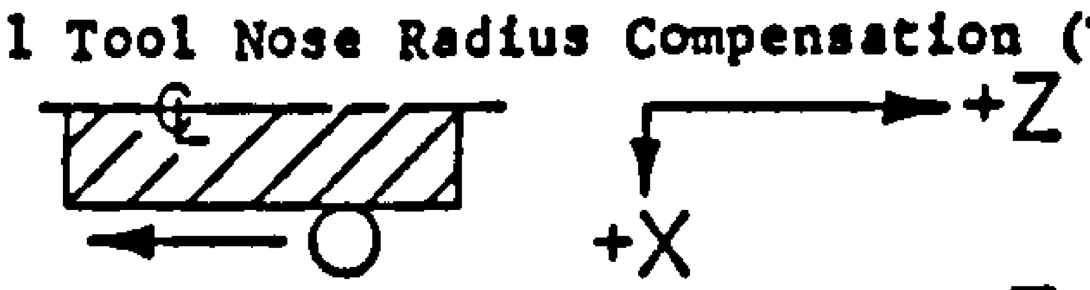
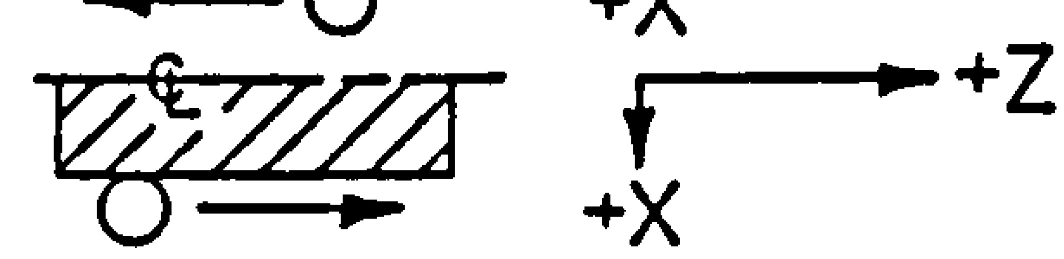
CODE	GROUP	DESCRIPTION
G00	1	Positioning Mode at Traverse Rate
*G01	1	Linear Interpolation
G02	1	Circular Interpolation 
G03	1	Circular Interpolation 
G04	0	Dwell-Seconds or Revolutions
G24	0	Program Variables
G25	0	Call Subroutine
G27	0	Tool Data File Programming
G33	1	Single Block Threadcutting
*G40	2	Cancel Tool Nose Radius Compensation (TNRC)
G41	2	TNRC 
G42	2	TNRC 
G53	0	Cancel Position Offset
G54	3	Position Offset No. 1
G55	3	Position Offset No. 2
G63	0	Chamfer at End of Cut
G64	0	Arc at End of Cut
G65	0	Combined Linear Moves With Arcs
G66	0	Z-Axis Contour Cycle Generator
G67	0	X-Axis Contour Cycle Generator
G68	0	Z-Axis Roughing Cycle Generator
G69	0	X-Axis Roughing Cycle Generator
* *G70	4	Inch Data Input
*G71	4	Metric Data Input
G80	0	MSD Parameter Override
G81	0	Automatic Turning Cycle
G82	0	Automatic Facing Cycle
G83	0	Automatic Drilling Cycle
G84	0	Auto Threading Cycle - Longitudinal Plunge
G85	0	Auto Threading Cycle - Face Plunge
G86	0	Auto Threading Cycle - Longitudinal Compound
G87	0	Auto Threading Cycle - Face Compound
G88	0	Automatic Shaft Grooving Cycle
G89	0	Automatic Face Grooving Cycle
G92	0	Preset the Position Registers

Figure 2.1

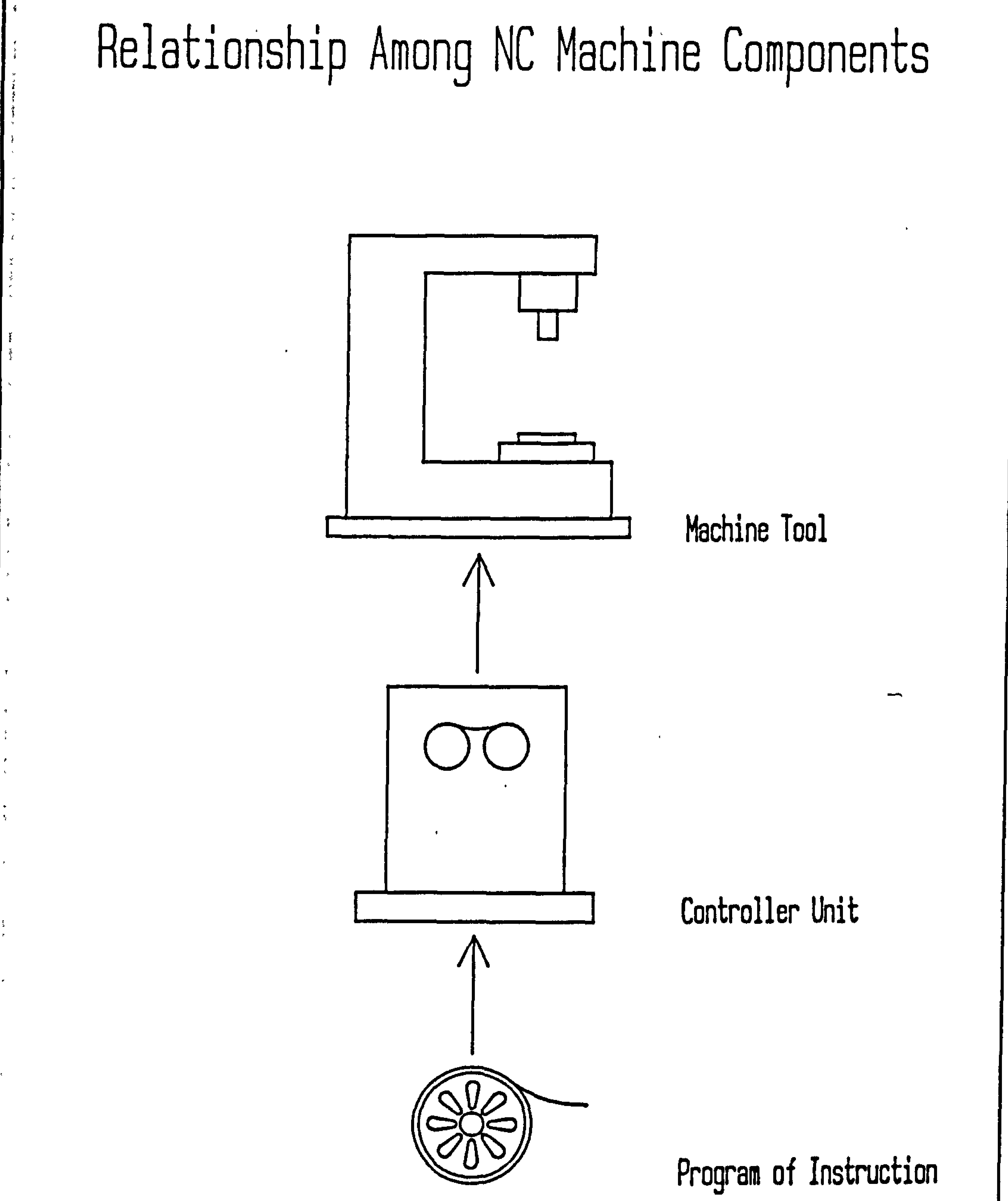

Relationship Among NC Machine Components
Machine Tool
Controller Unit
Program of Instruction

Figure 2.2

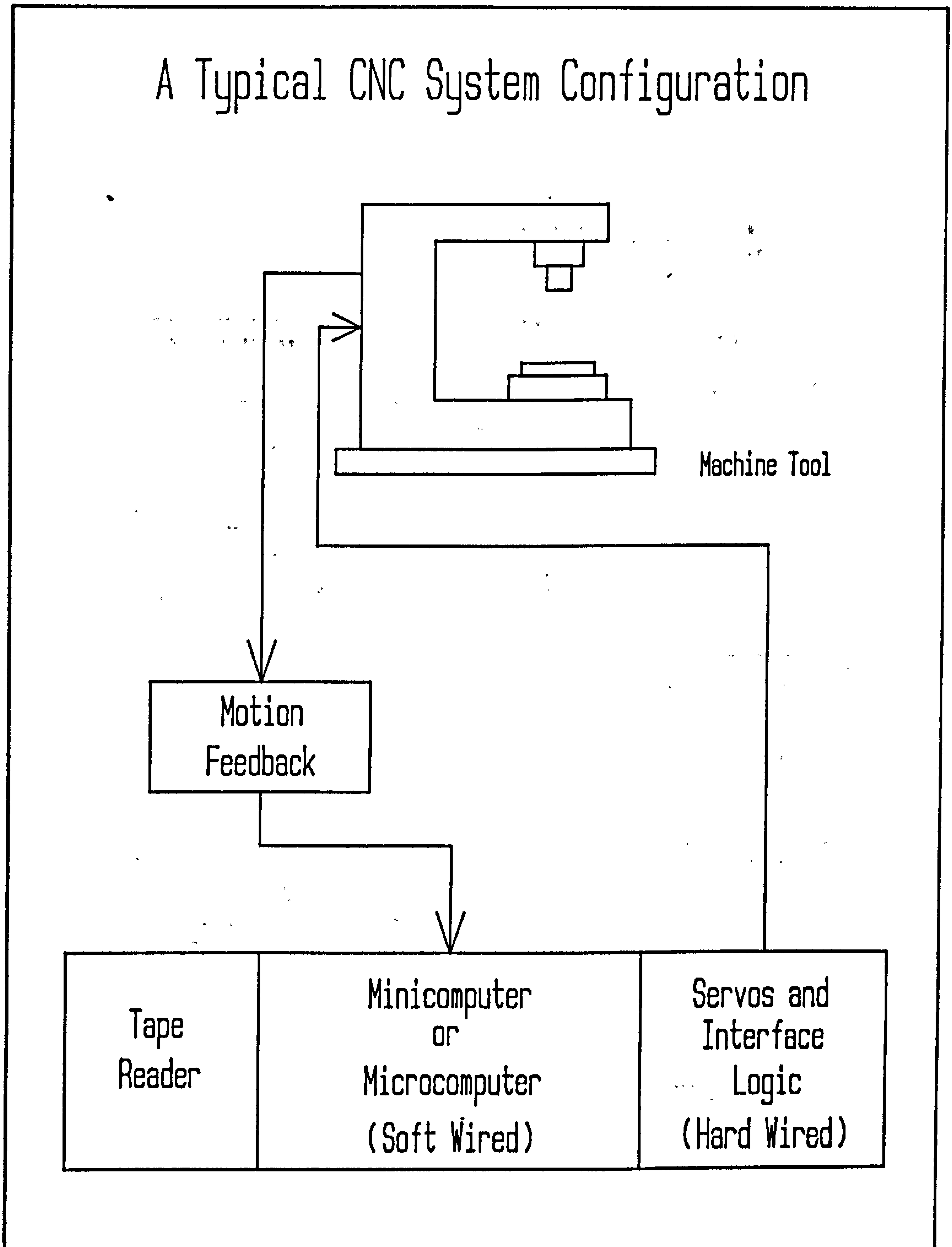

A Typical CNC System Configuration
Machine Tool
Motion Feedback
Tape Reader
Minicomputer or Microcomputer (Soft Wired)
Servos and Interface Logic (Hard Wired)

Figure 2.3

Schematic Layout of an FMS System

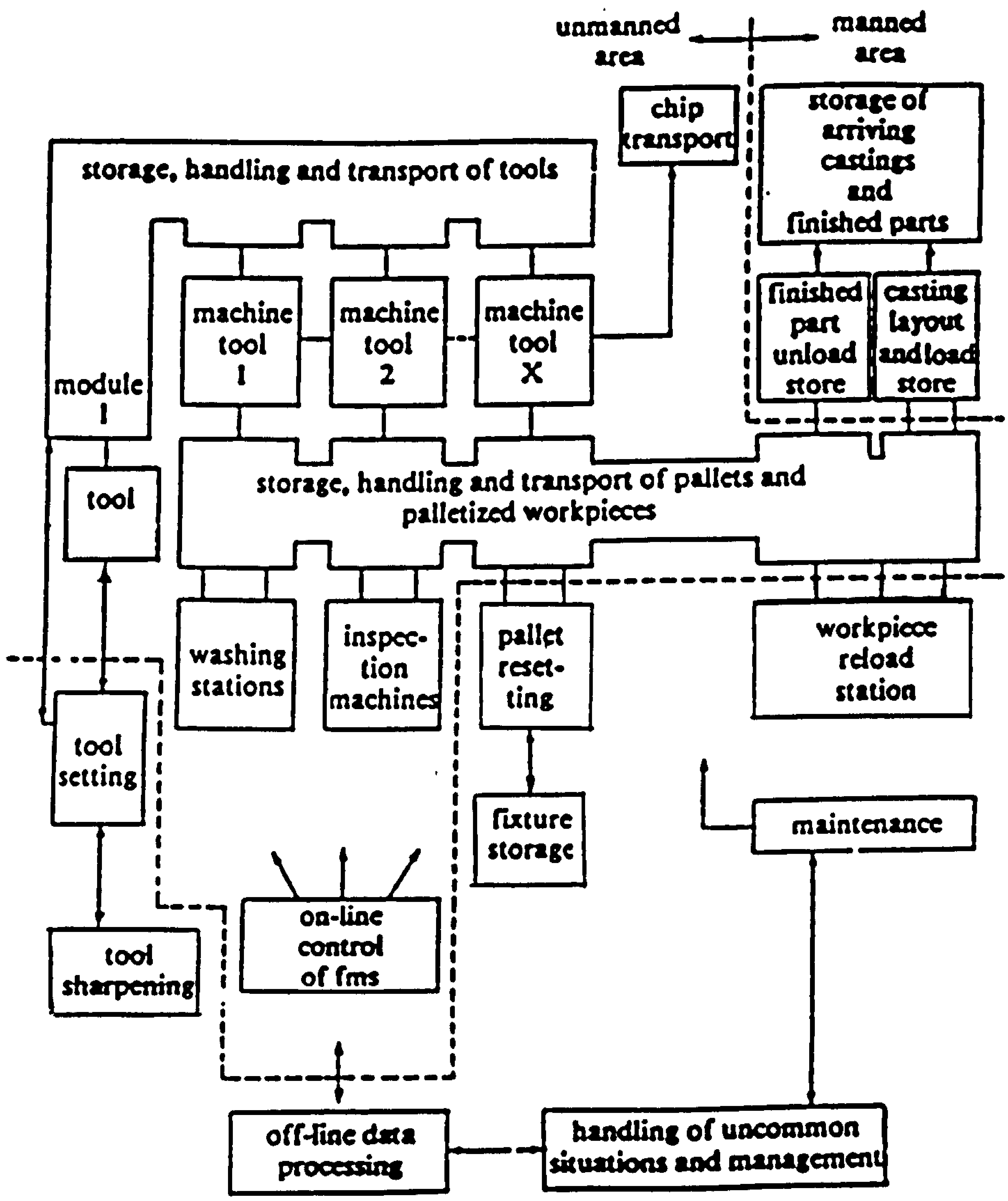
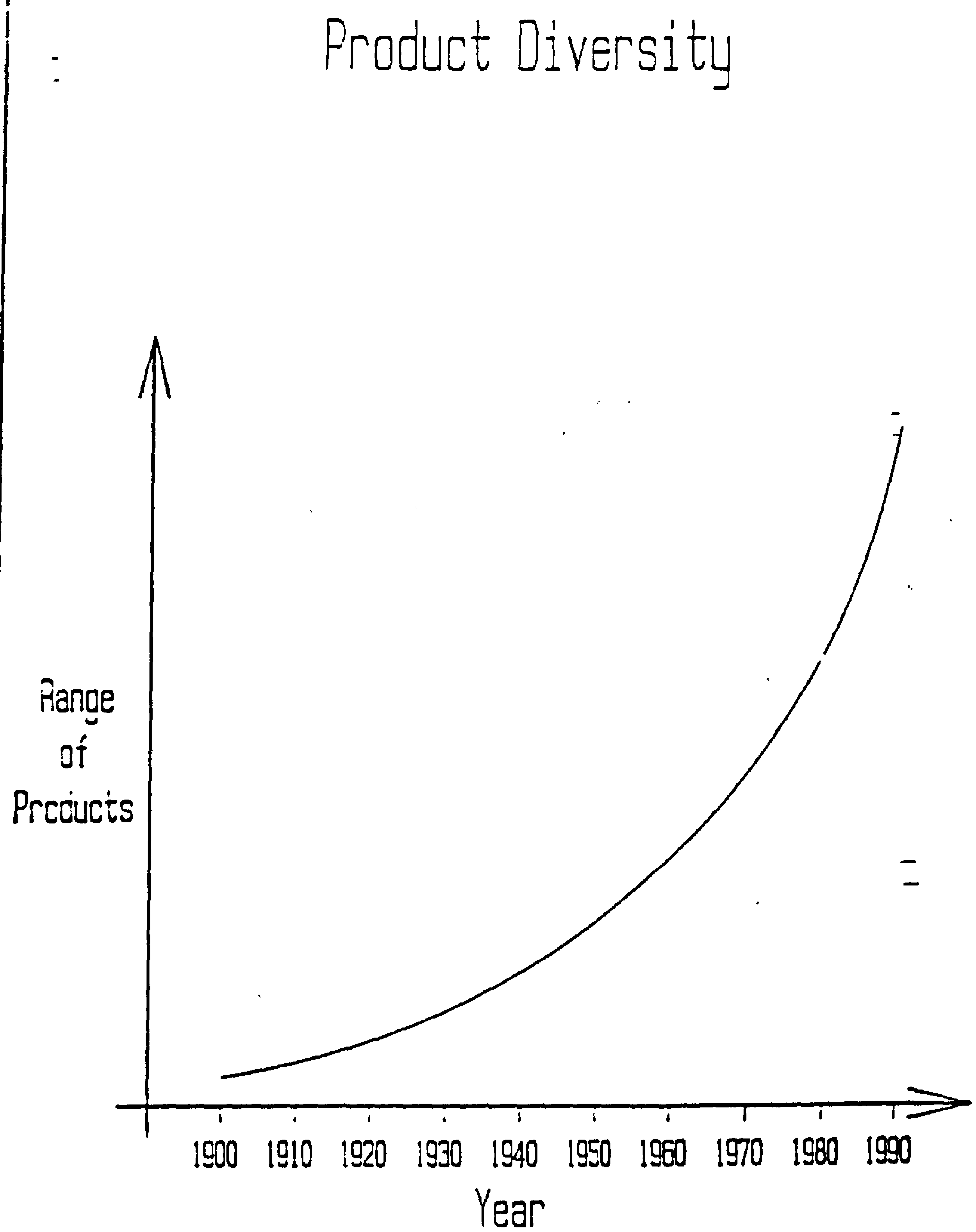


Figure 2.4



After Brown J. et al 1988

Figure 2.5

Computer Integrated Manufacturing Concept

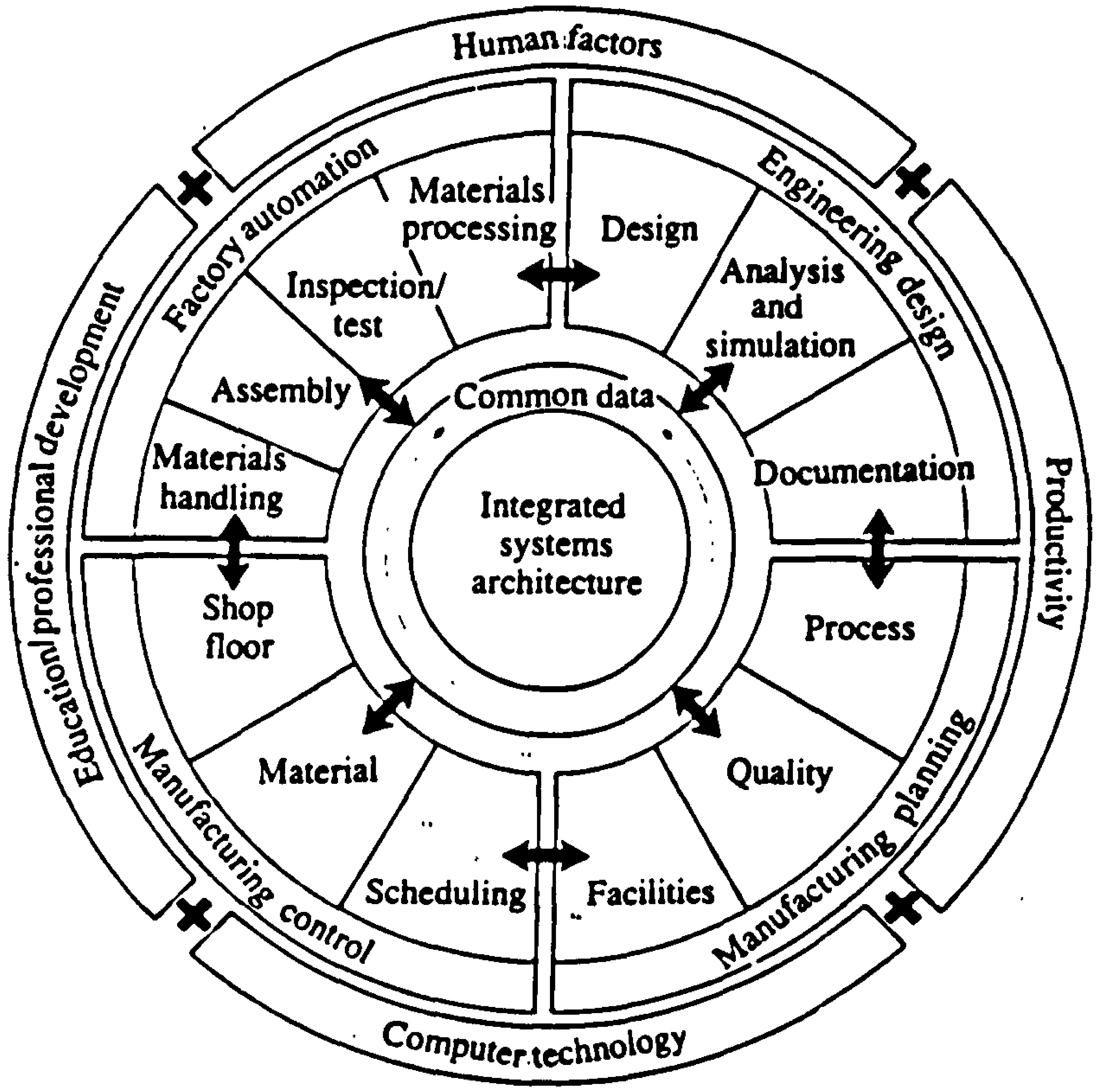
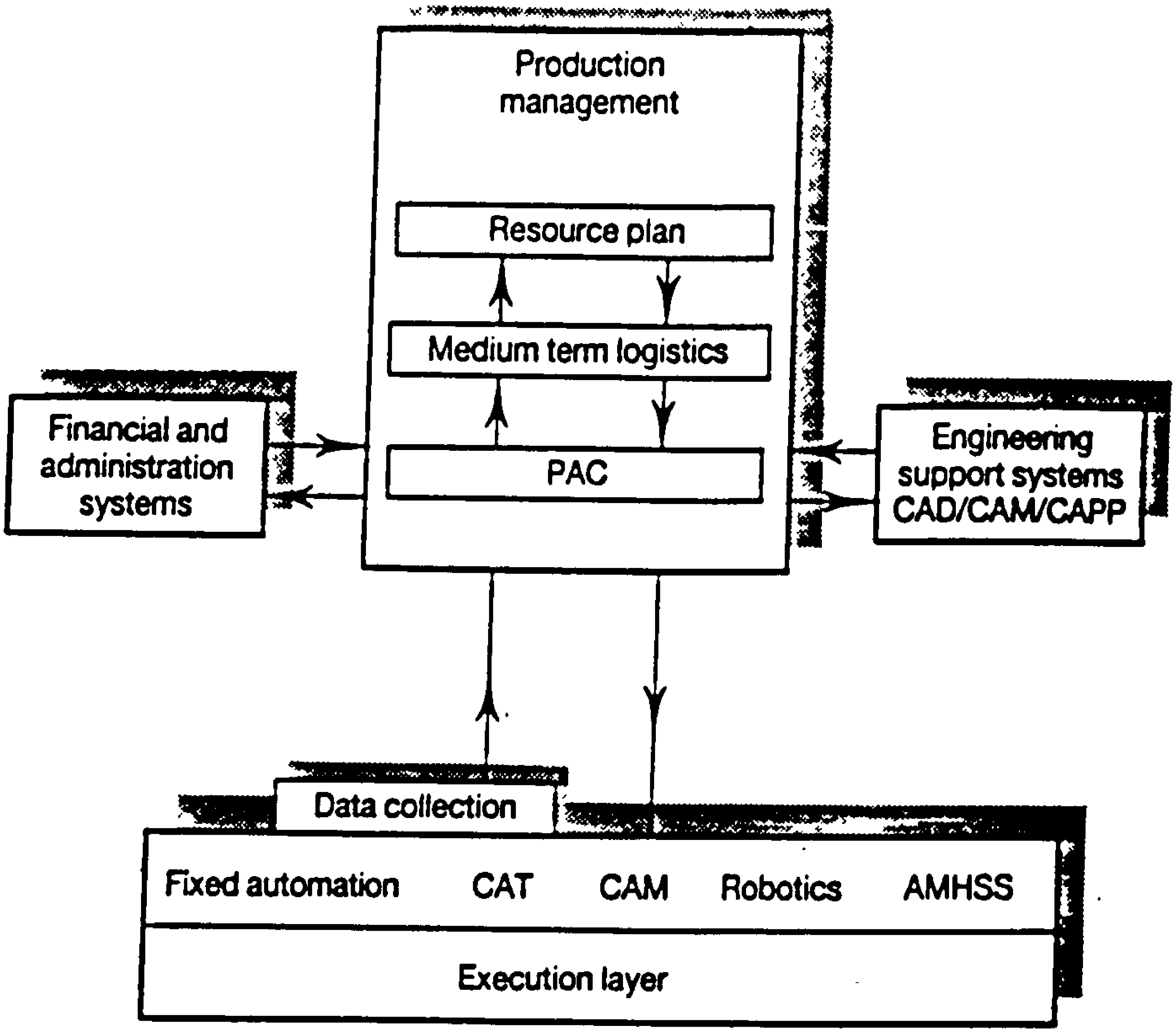


Figure 2.6

A Unified View of CIM



PAC Production Activity Control

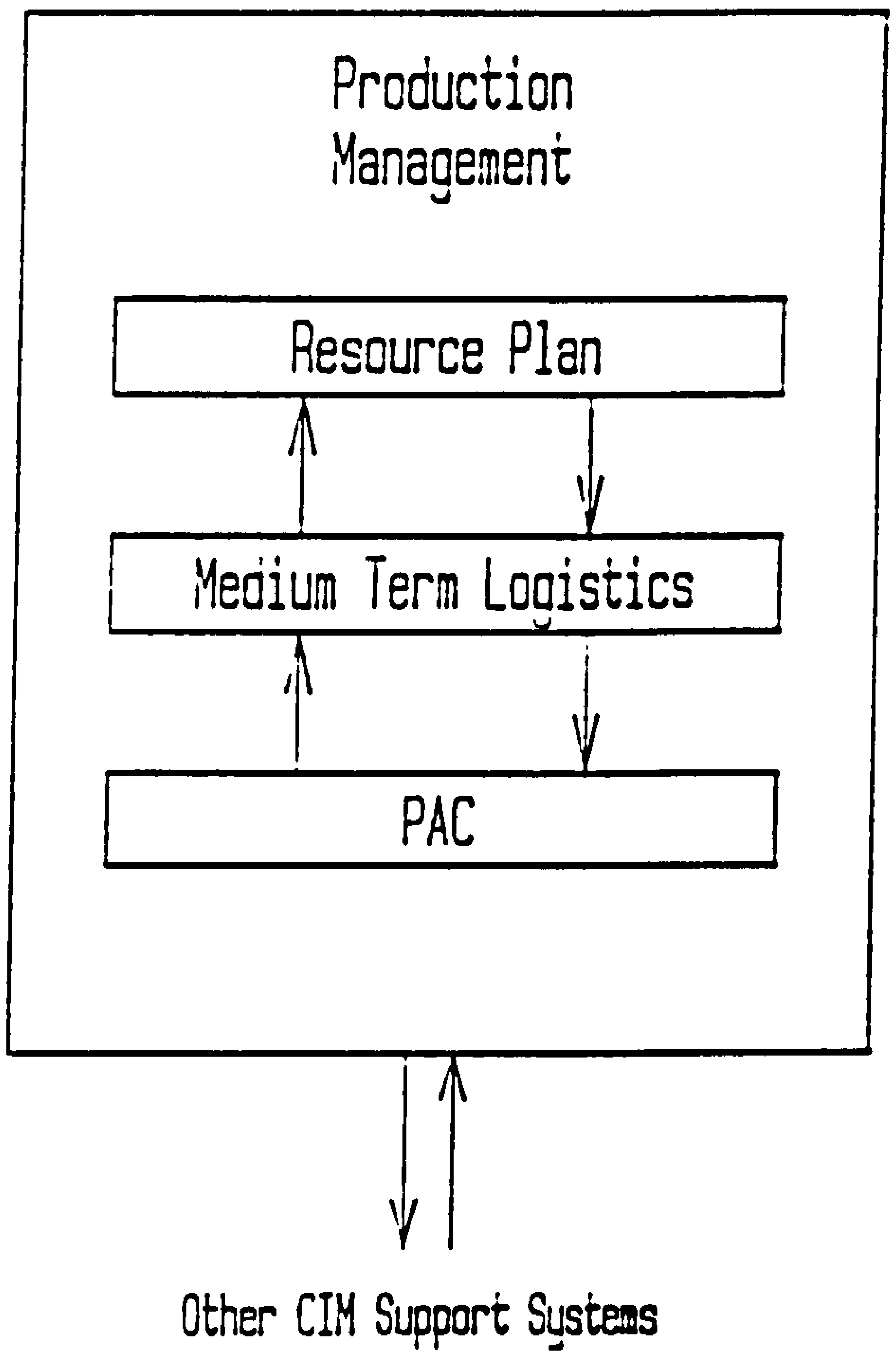
CAT Computer Aided Test

AMHSS Automatic Materials Handling and Storage Systems

After Brown J. et al 1988

Figure 2.7

Production Management Function



After Brown J. et al 1988

PAC Production Activity Control

Figure 2.8

Cutting Characteristics

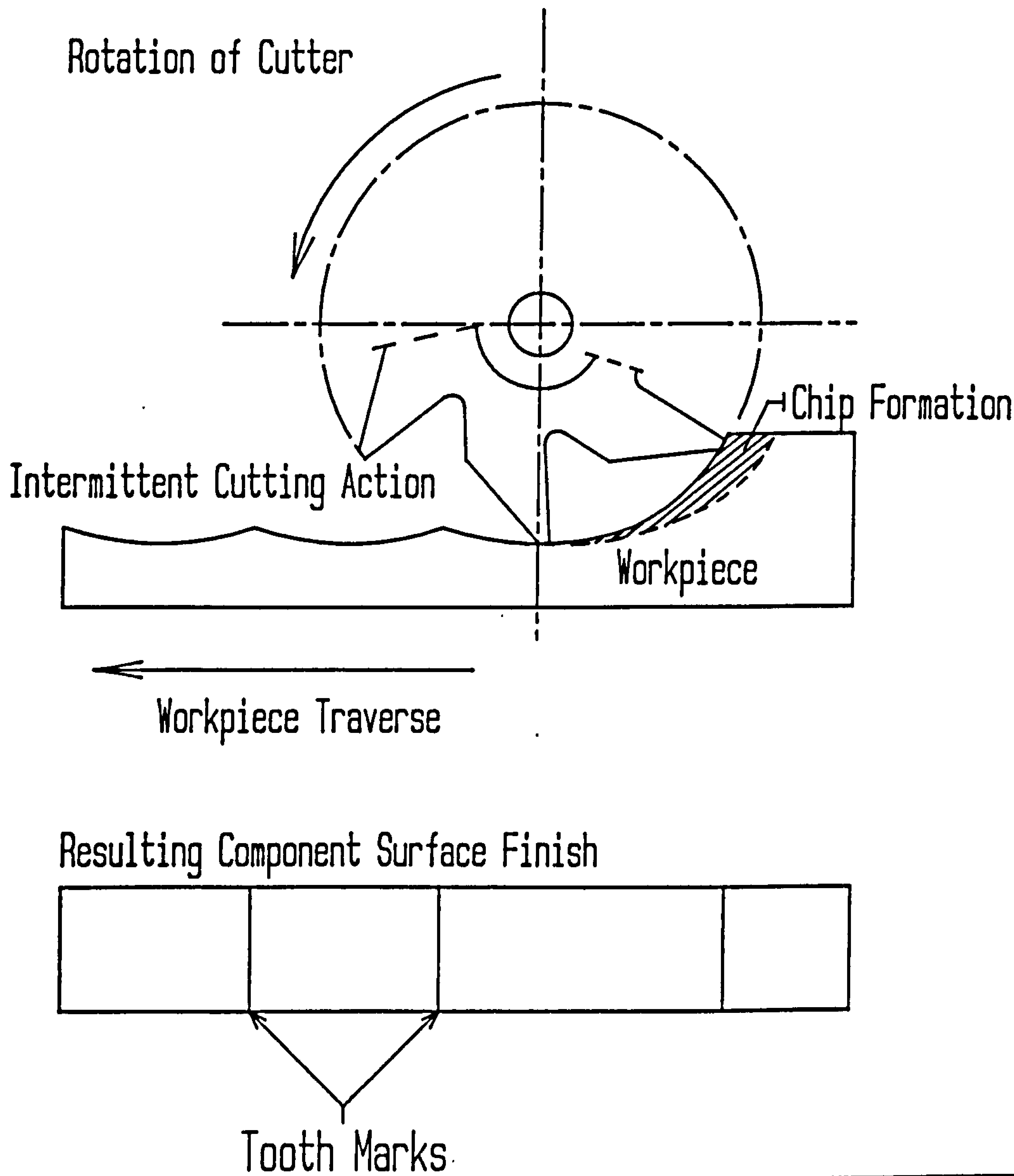
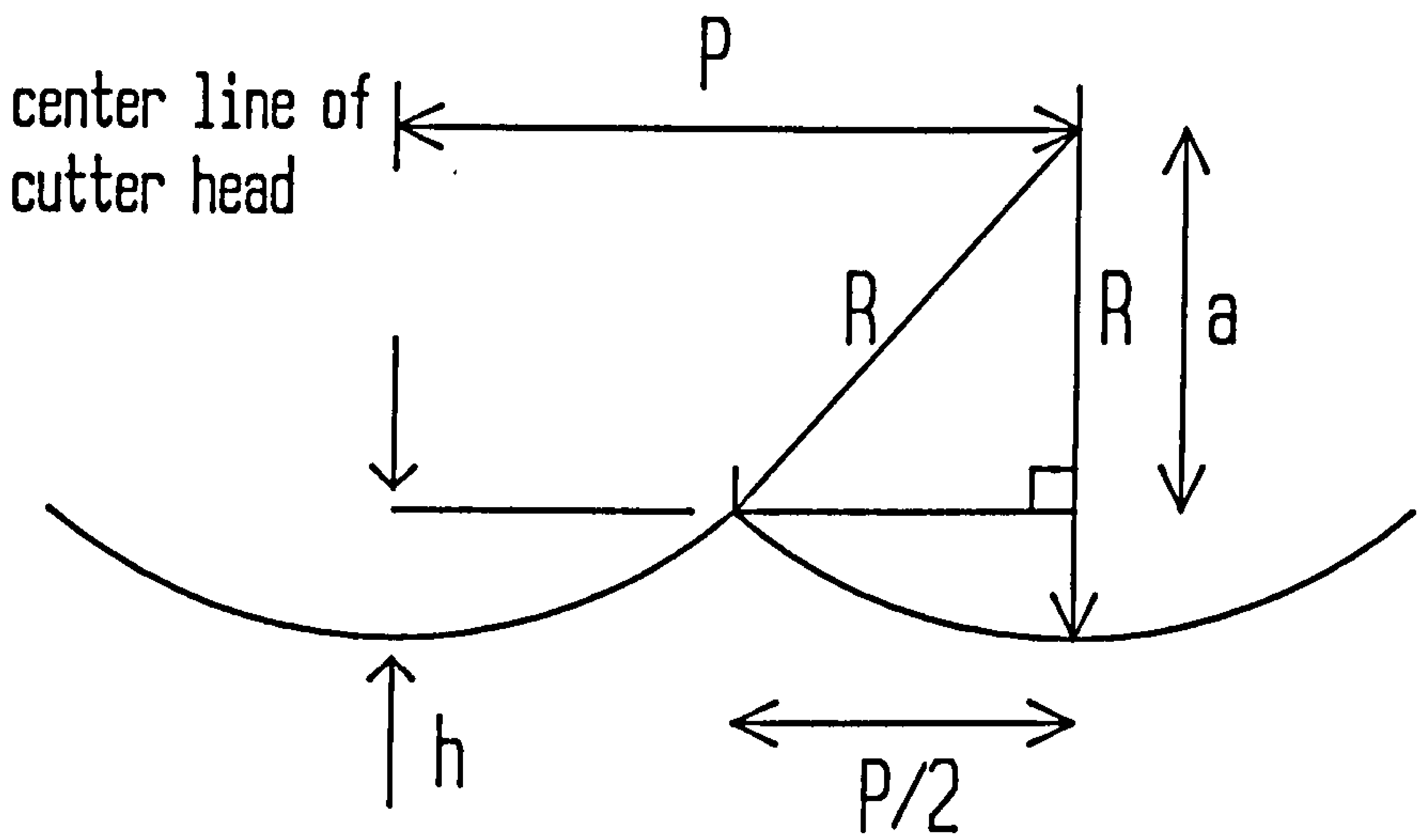


Figure 2.9

Surface Profile Height and Pitch



$$a = R - h$$

$$a^2 = R^2 - \{P/2\}^2$$

$$a = \{R^2 - (P/2)^2\}^{0.5}$$

$$h = R - a$$

$$h = R - \{R^2 - P^2/4\}^{0.5}$$

$$P = (f*10^3)/n*N$$

P = Pitch of the knife marking.
f = Feed speed of the workpiece (metre/min).
n = Cutter head rotational speed (rev/min).
N = Number of knives in the cutter head producing a wave on the workpiece.

Figure 2.10

Schematic Diagram Of The Talysurf 10 Instrument

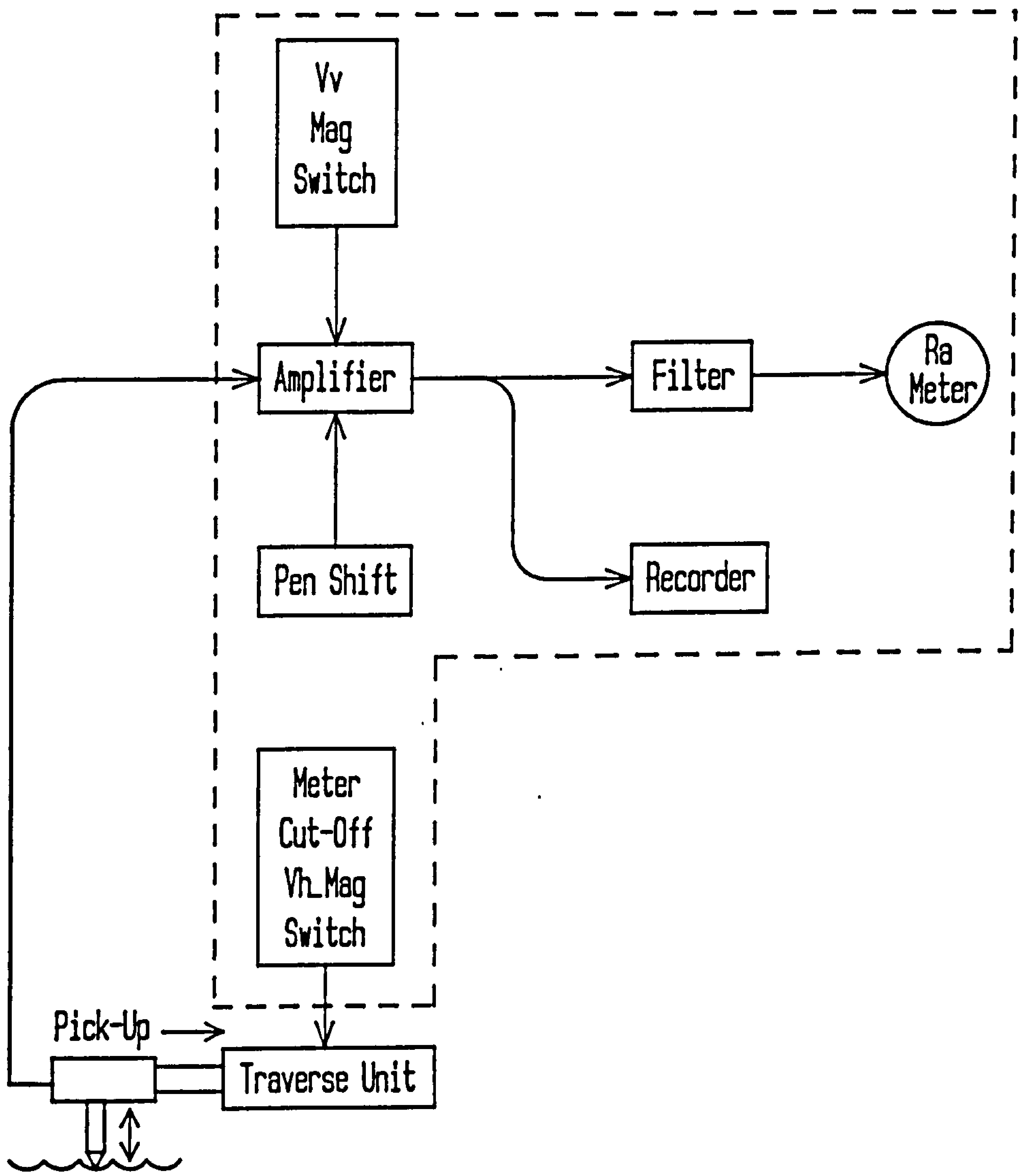


Figure 2.11

The Talysurf 10 Instrument

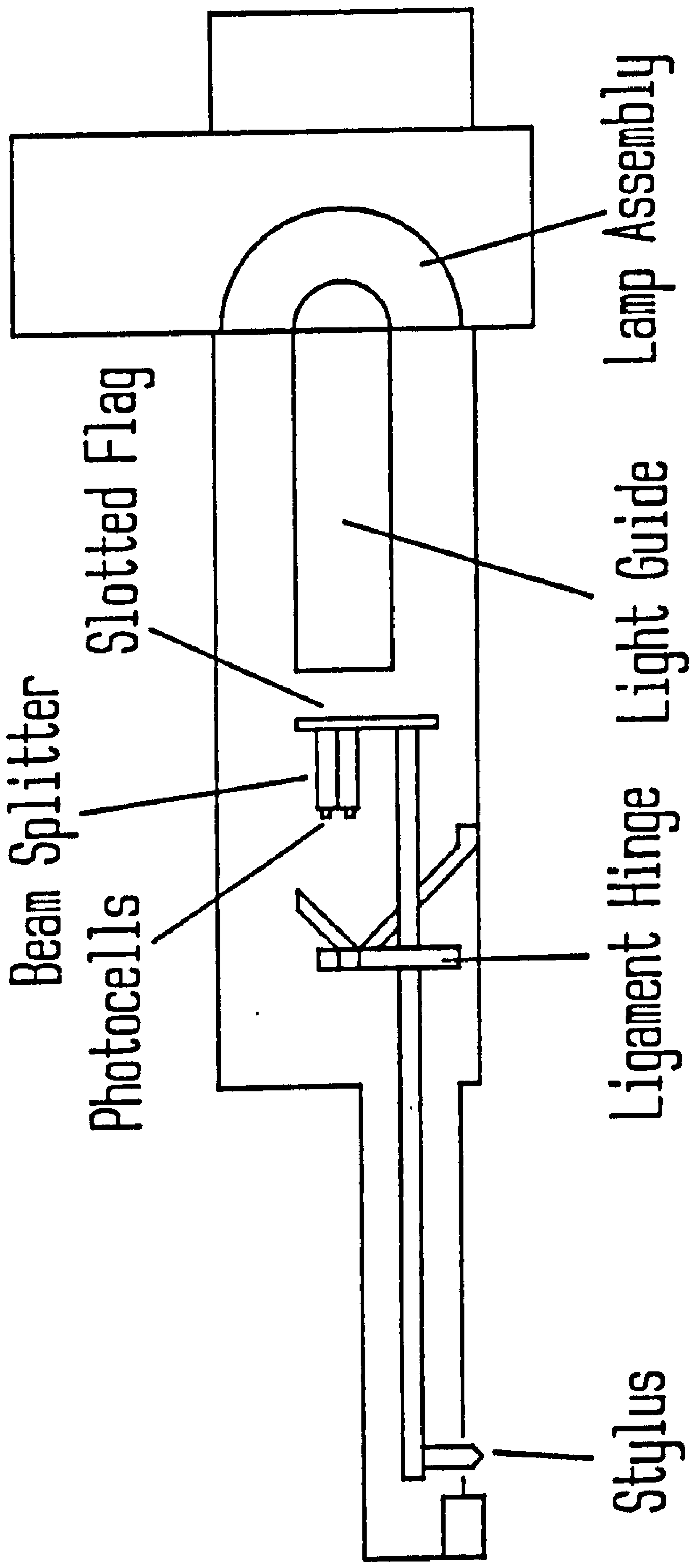
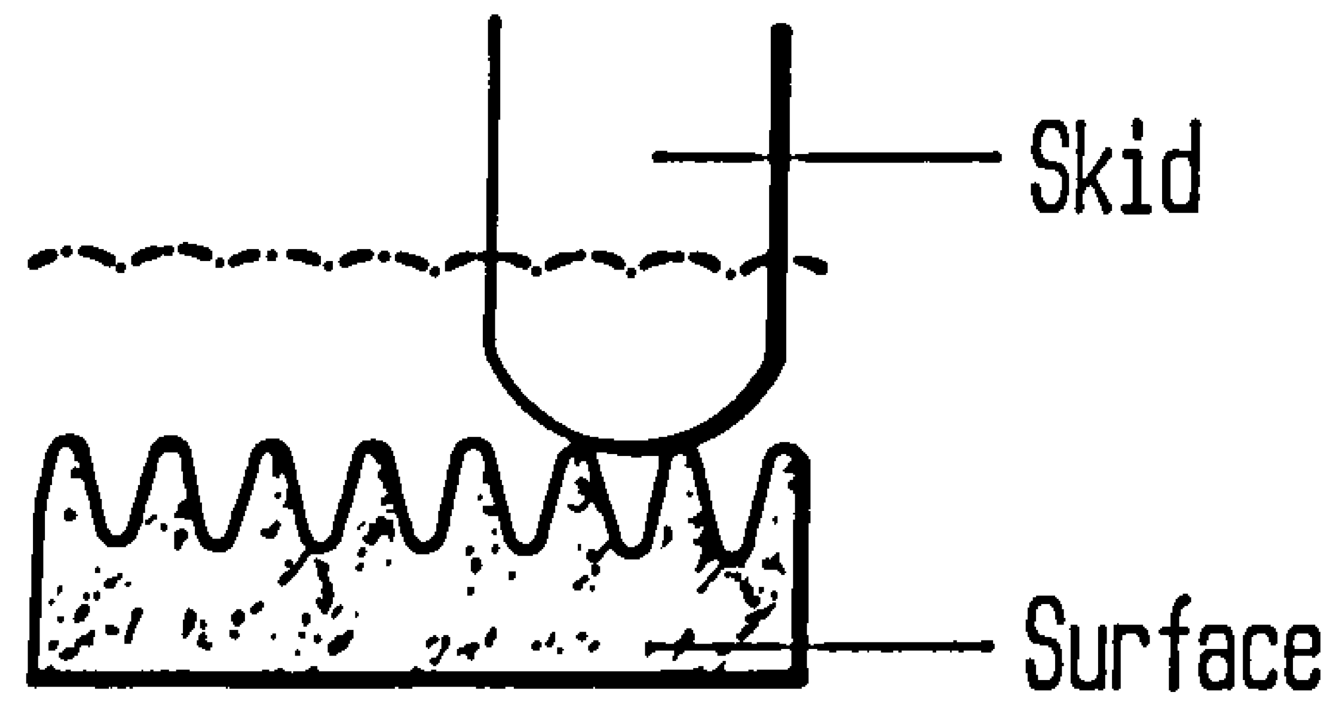


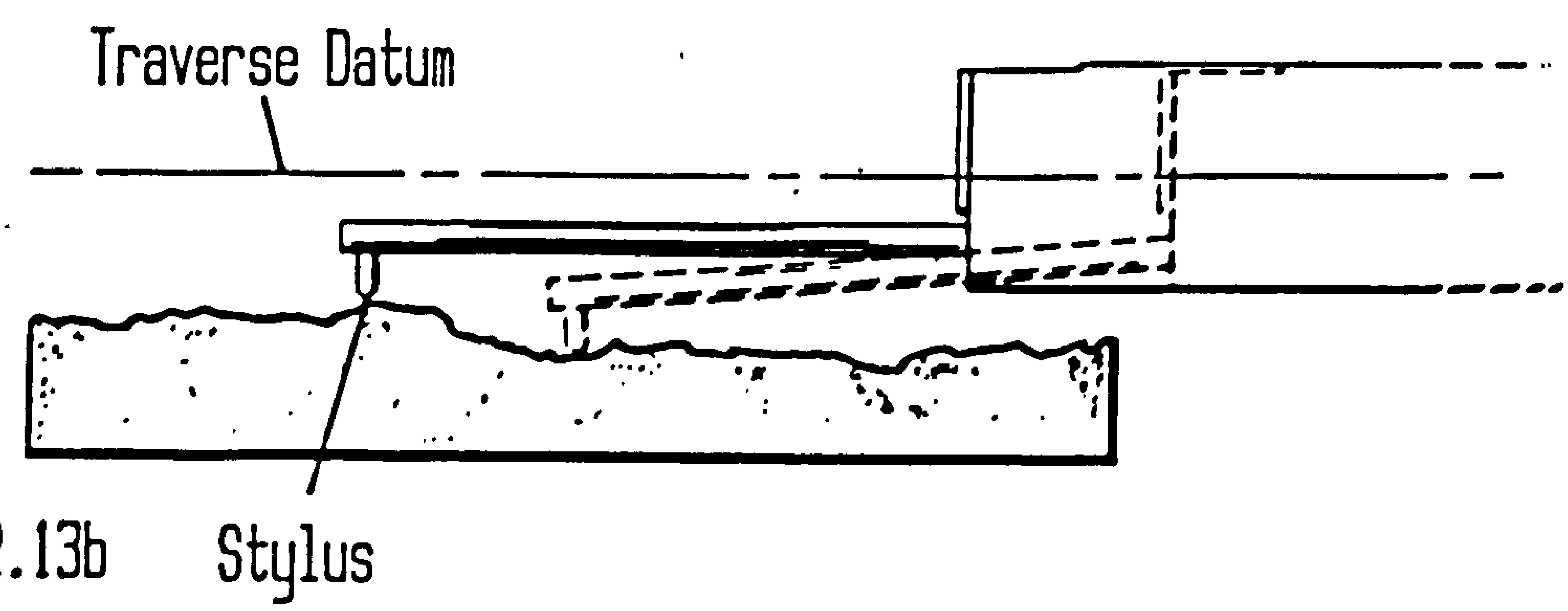
Figure 2.12

Talysurf 10 Datums

2.13a



A Skid Supporting The Pick-up Gives An Almost Straight Line Movement Across The Surface

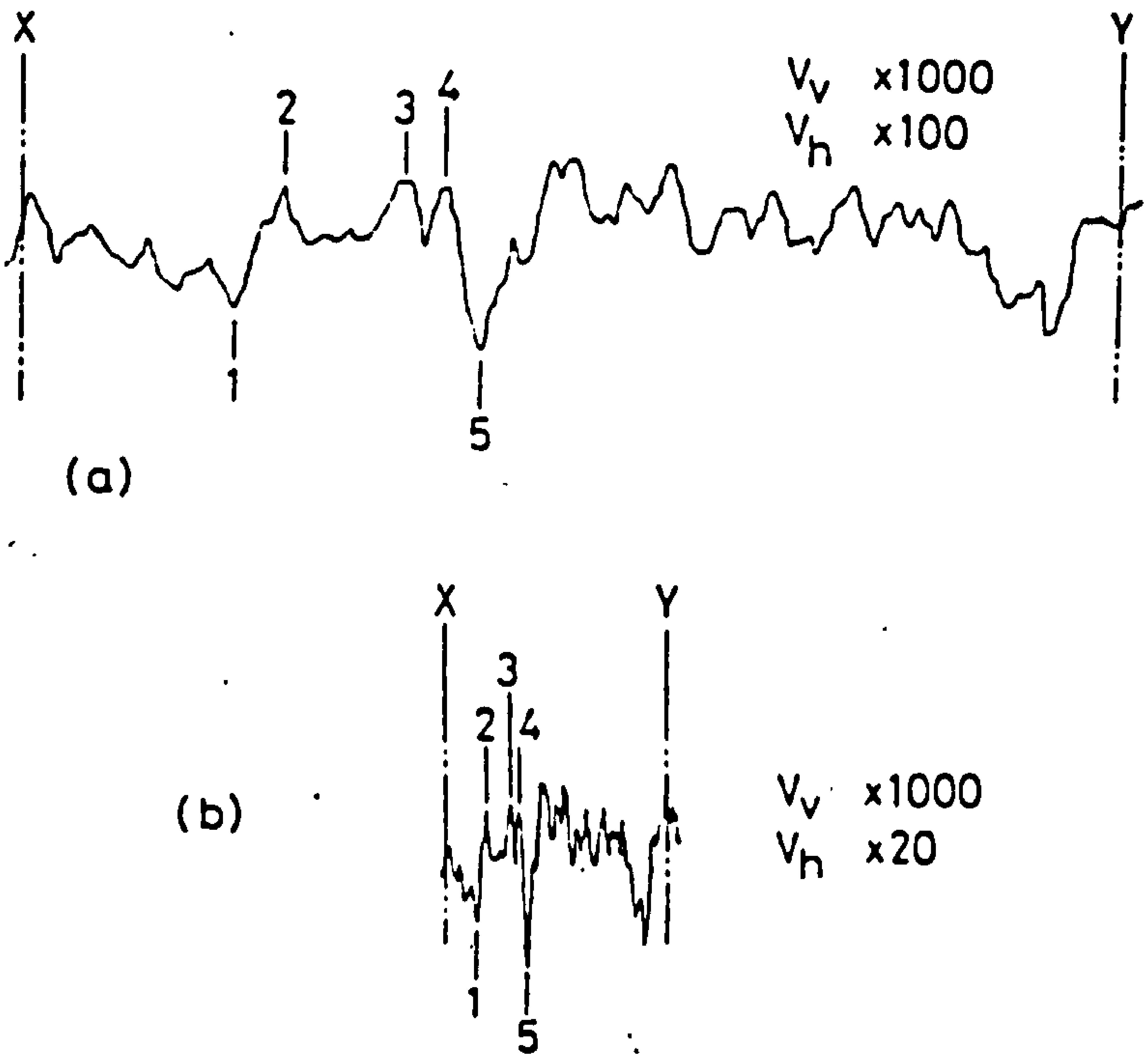


2.13b

The Traverse Datum Shaft Provides A Straight Reference Datum For The Pick-Up

Figure 2.13

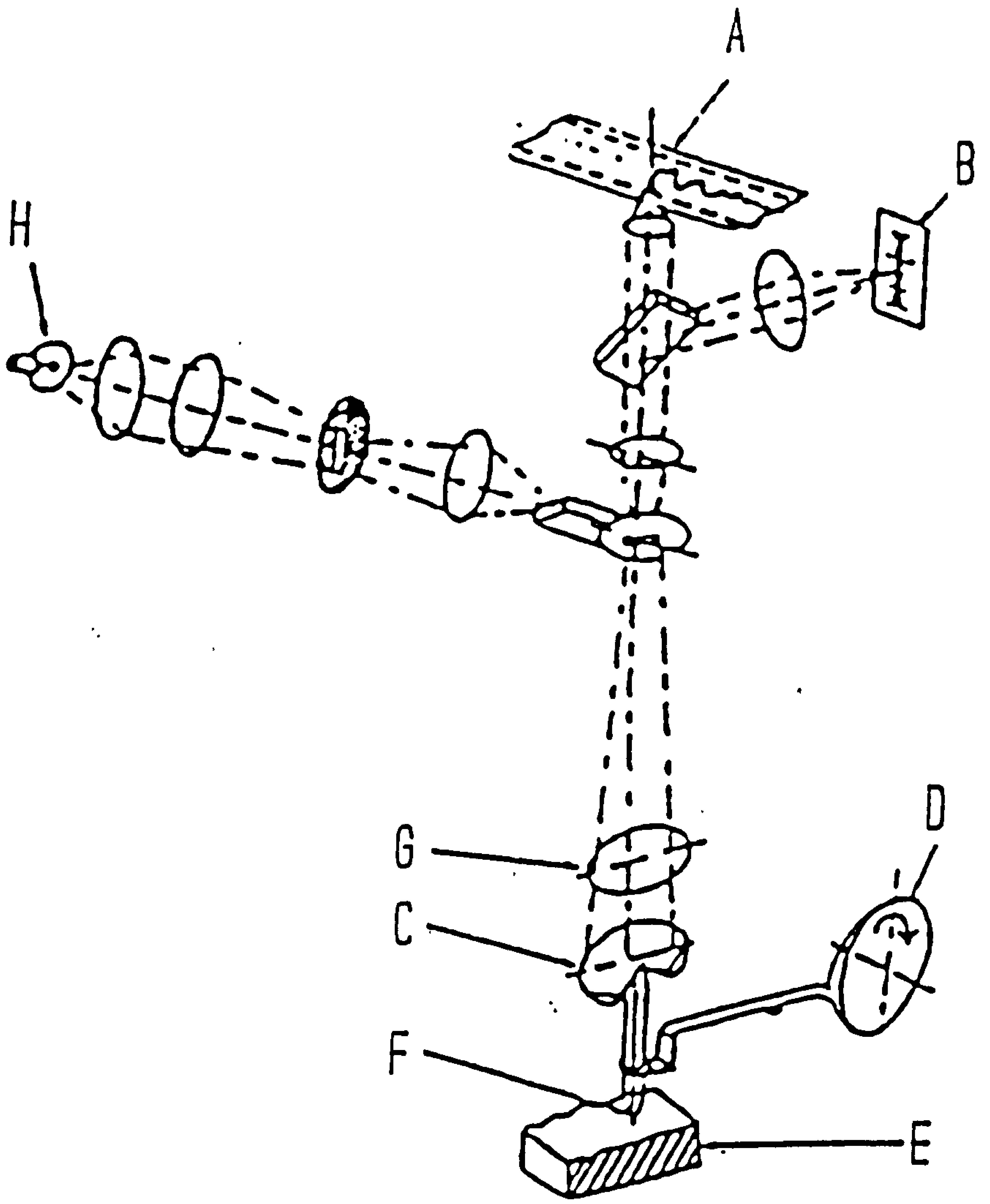
Effect Of Horizontal Magnification on Graphical Recording



The Effect Shows The Movement Of Points As The Profile is Magnified

Figure 2.14

Operation Principle Of The Forster Apparatus



A, Film; B, Ground Glass Viewer; C, Tilting Mirror
D, Oscillating Mechanism; E, Test Specimen; F, Stylus
G, Lens; H, Light Source

Figure 2.15

Principle Of Optical Sectioning

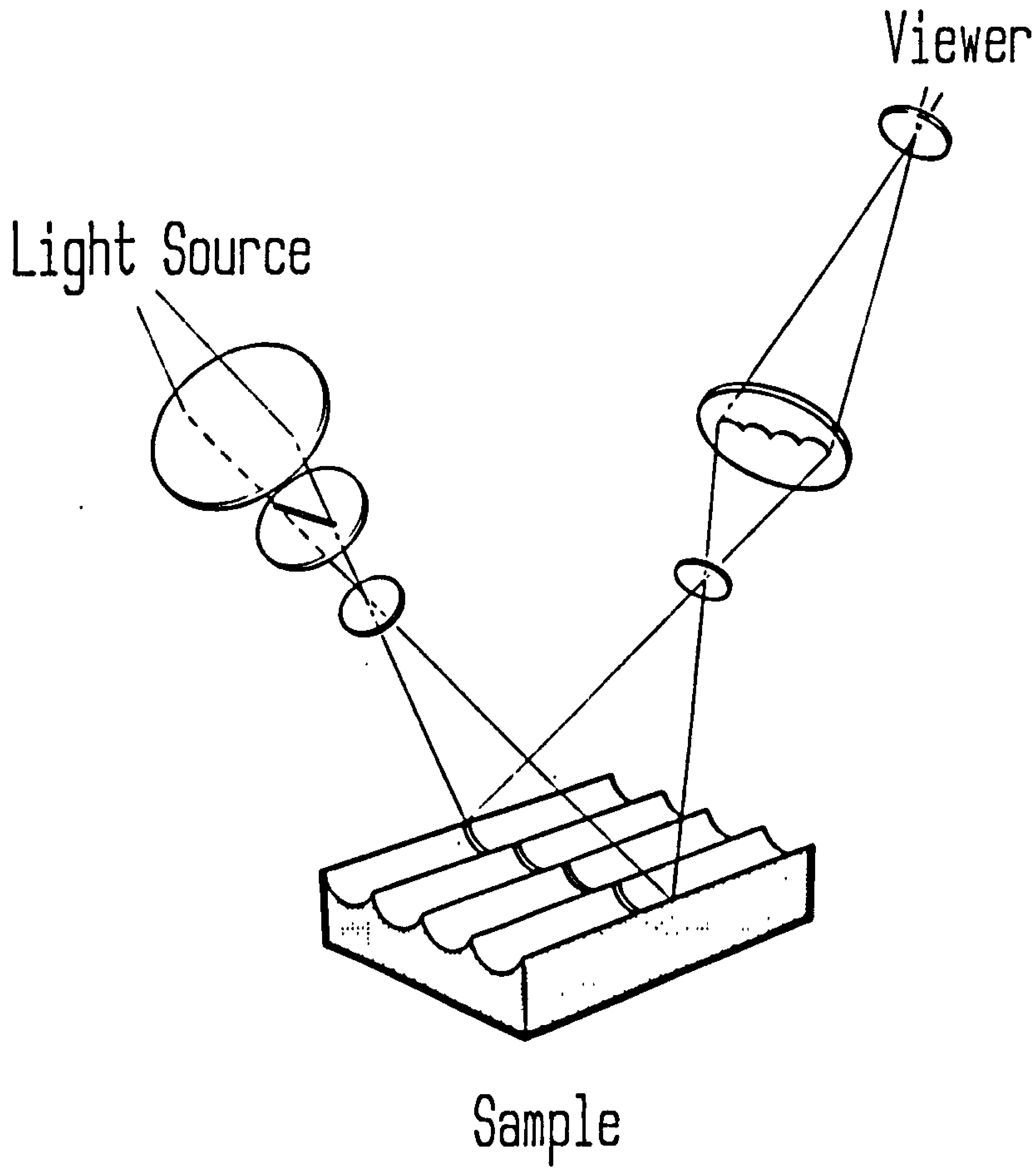


Figure 2.16

Foucault's Principle

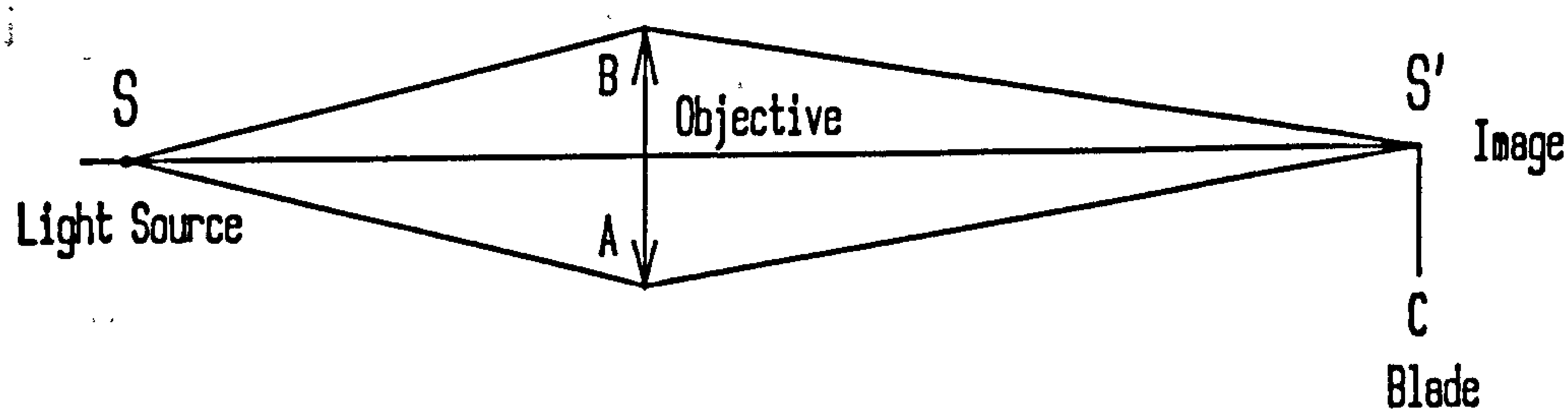


Figure 2.17

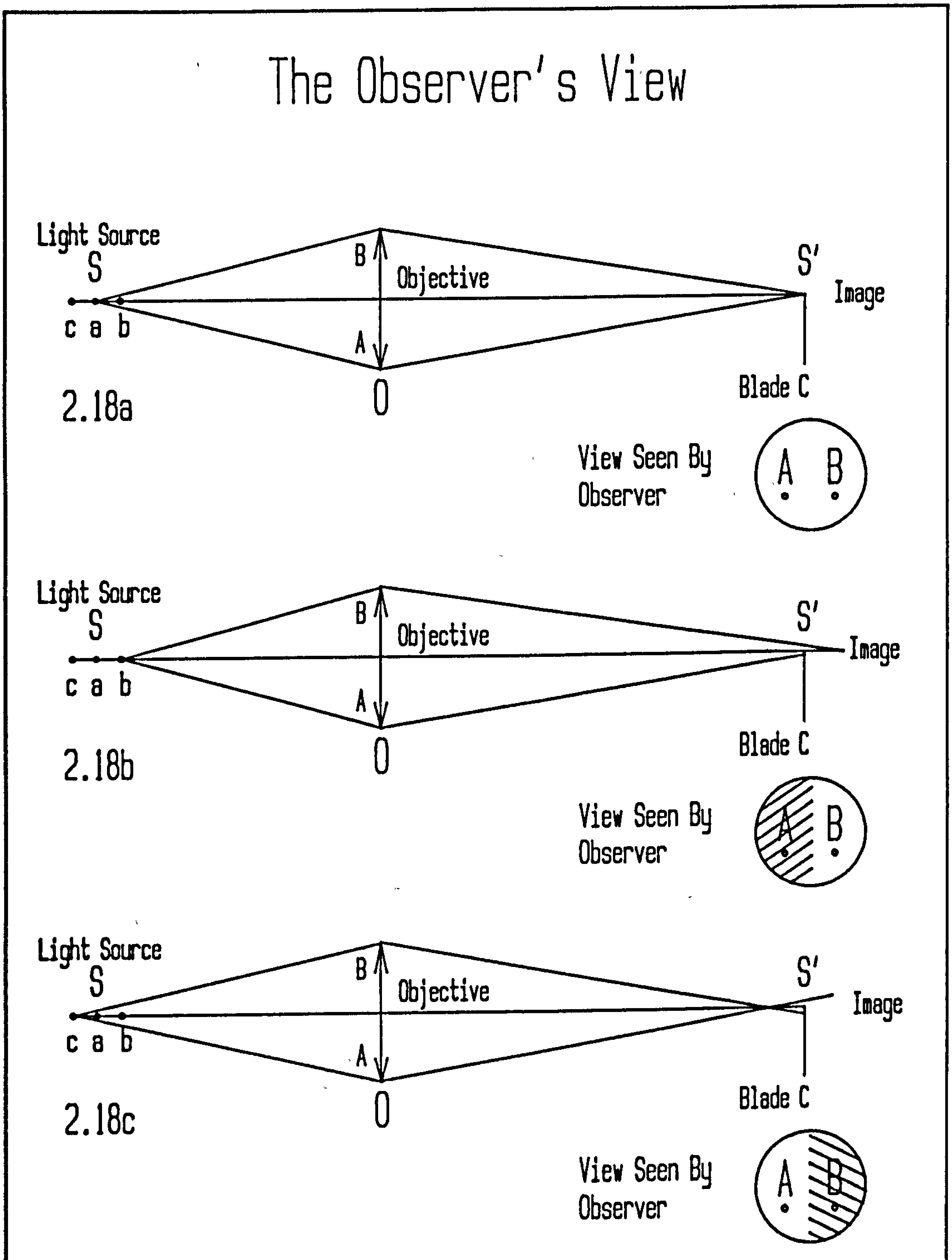

The Observer's View
Light Source
S
B
Objective
S'
Image
c a b
A
2.18a
O
Blade C
View Seen By
Observer
A B
Light Source
S
B
Objective
S'
Image
c a b
A
2.18b
O
Blade C
View Seen By
Observer
A B
Light Source
S
B
Objective
S'
Image
c a b
A
2.18c
O
Blade C
View Seen By
Observer
A B

Figure 2.18

Foucault Knife Probe

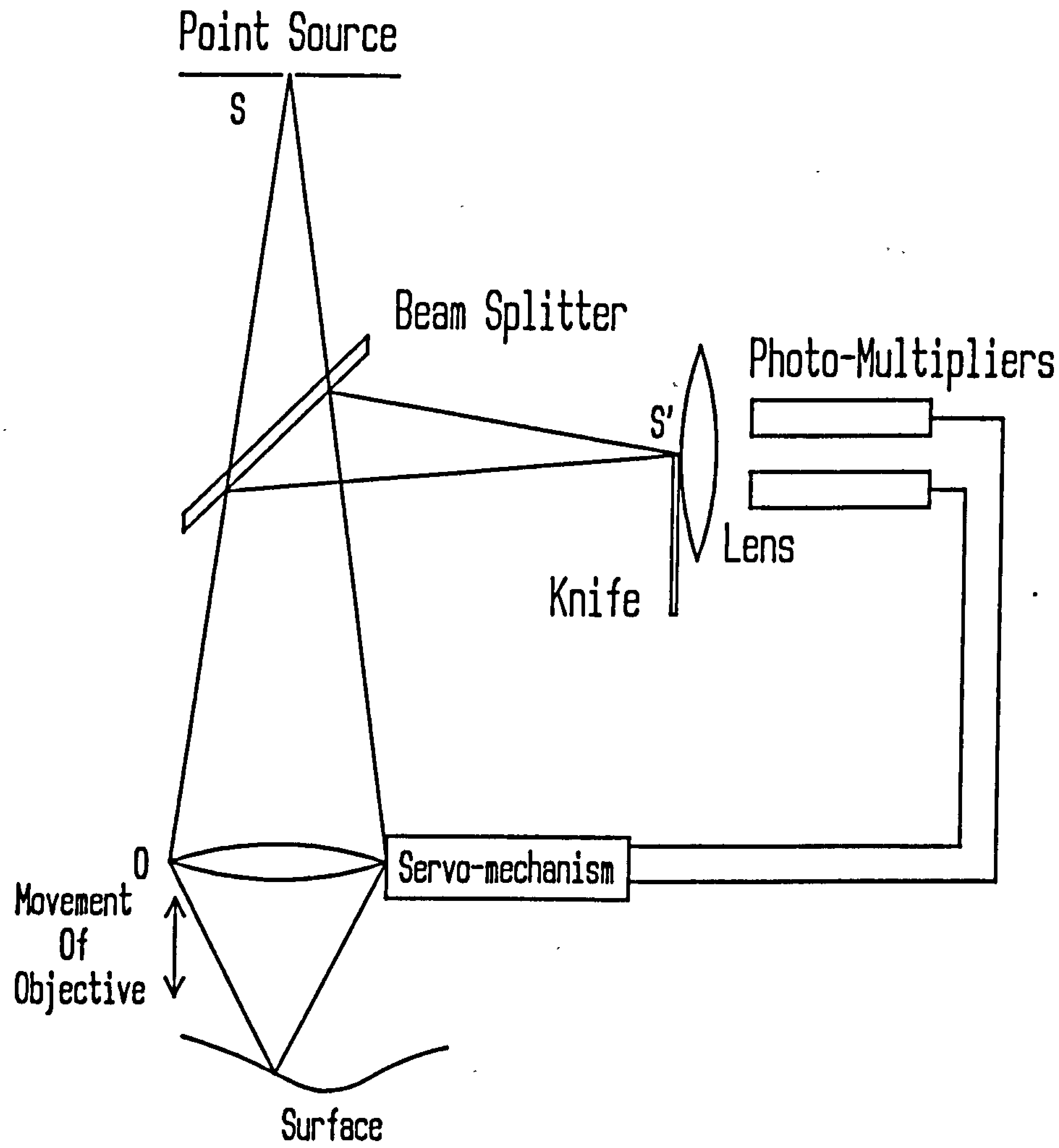


Figure 2.19

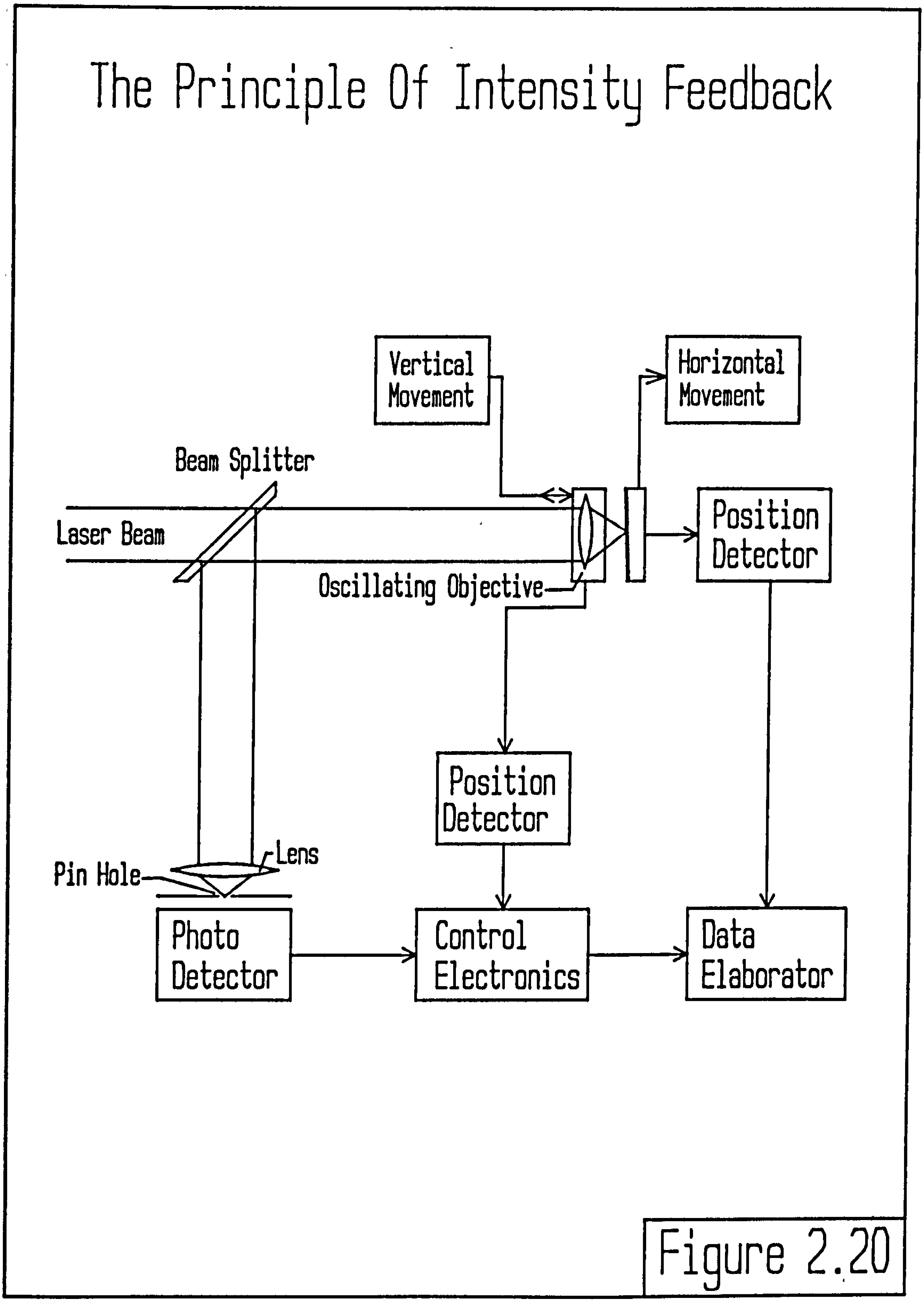

The Principle Of Intensity Feedback
Vertical Movement
Horizontal Movement
Beam Splitter
Laser Beam
Position Detector
Oscillating Objective
Position Detector
Lens
Pin Hole
Photo Detector
Control Electronics
Data Elaborator

Figure 2.20

Reflected Light Position Detection

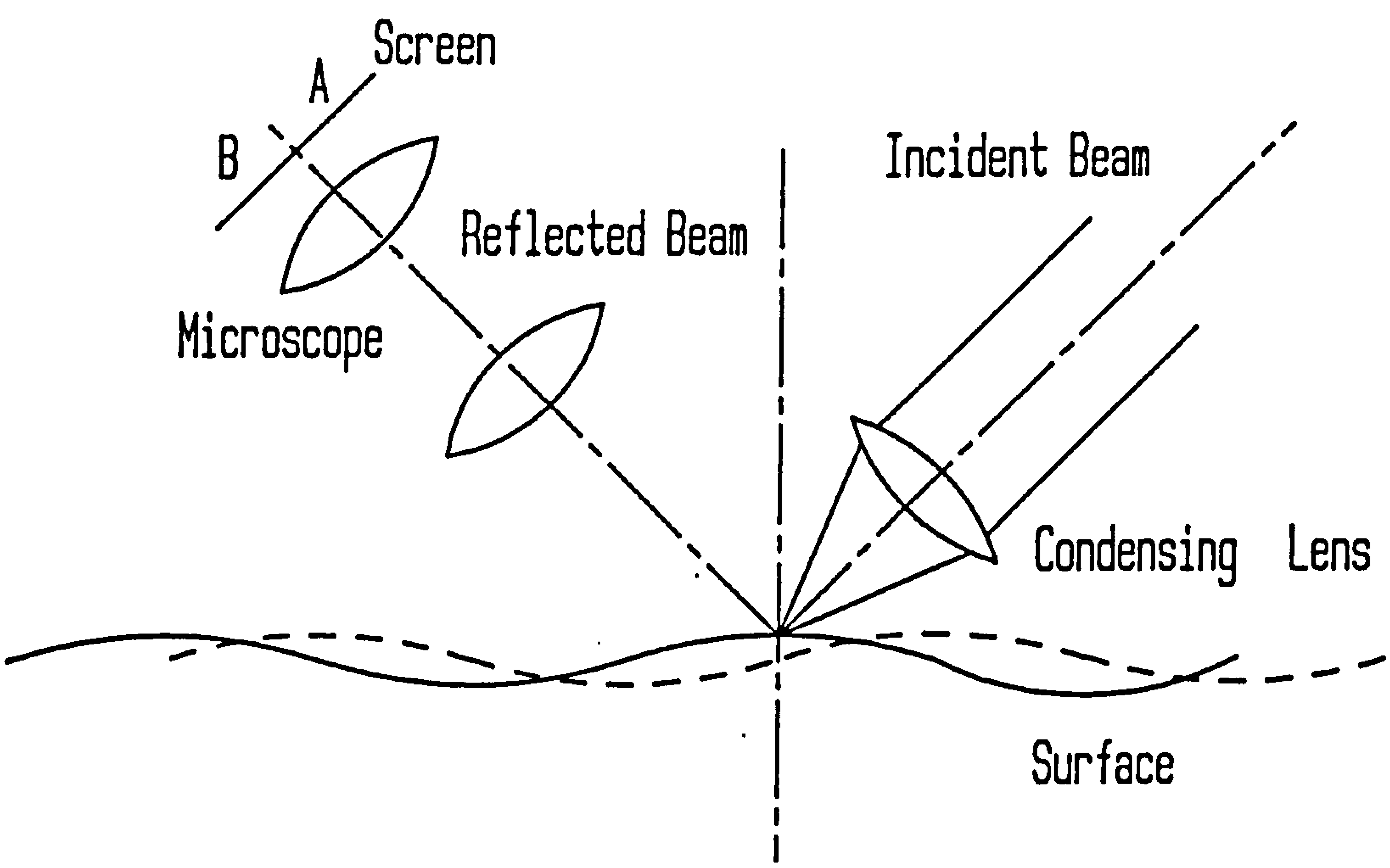


Figure 2.21

Light Reflection

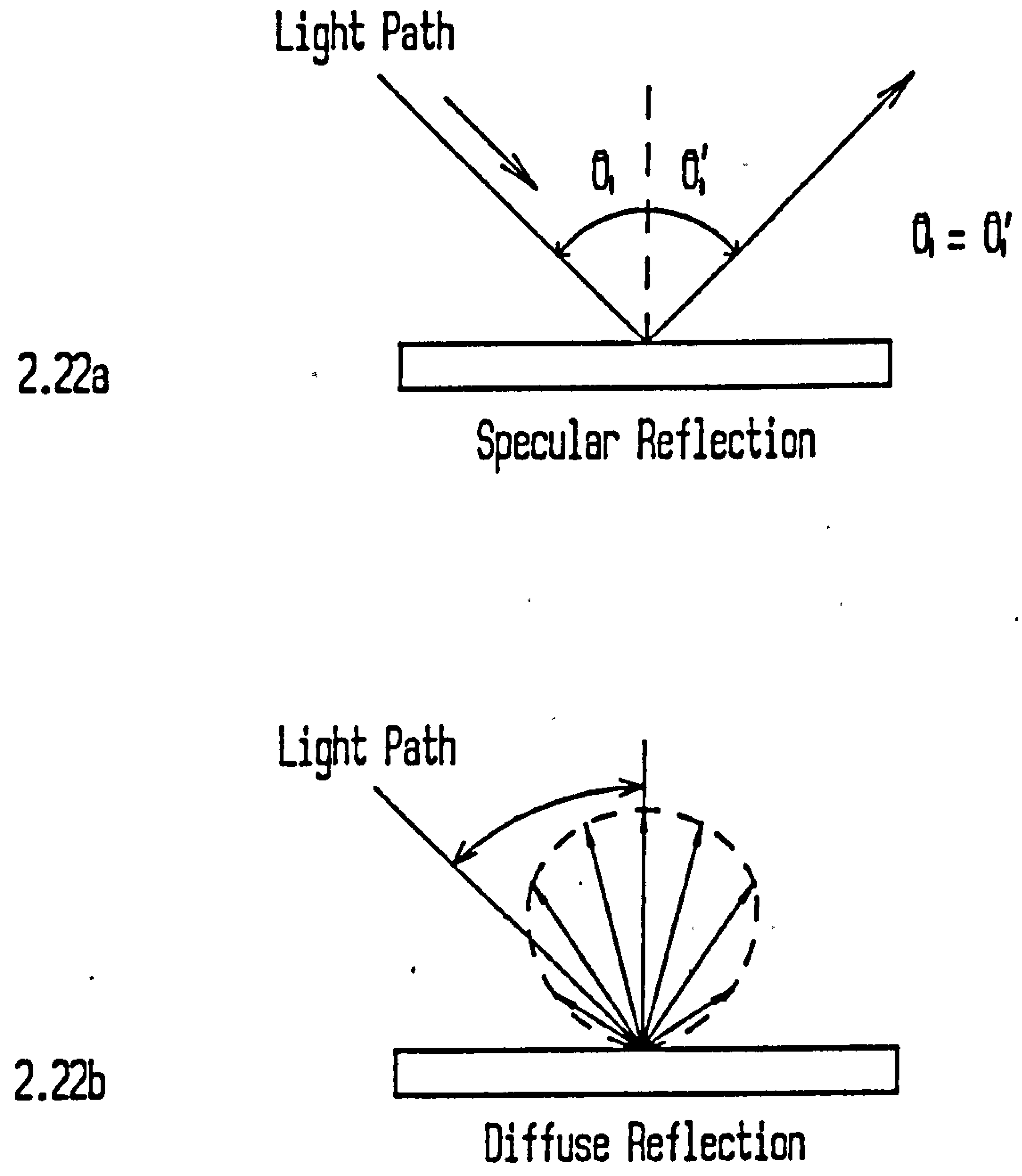
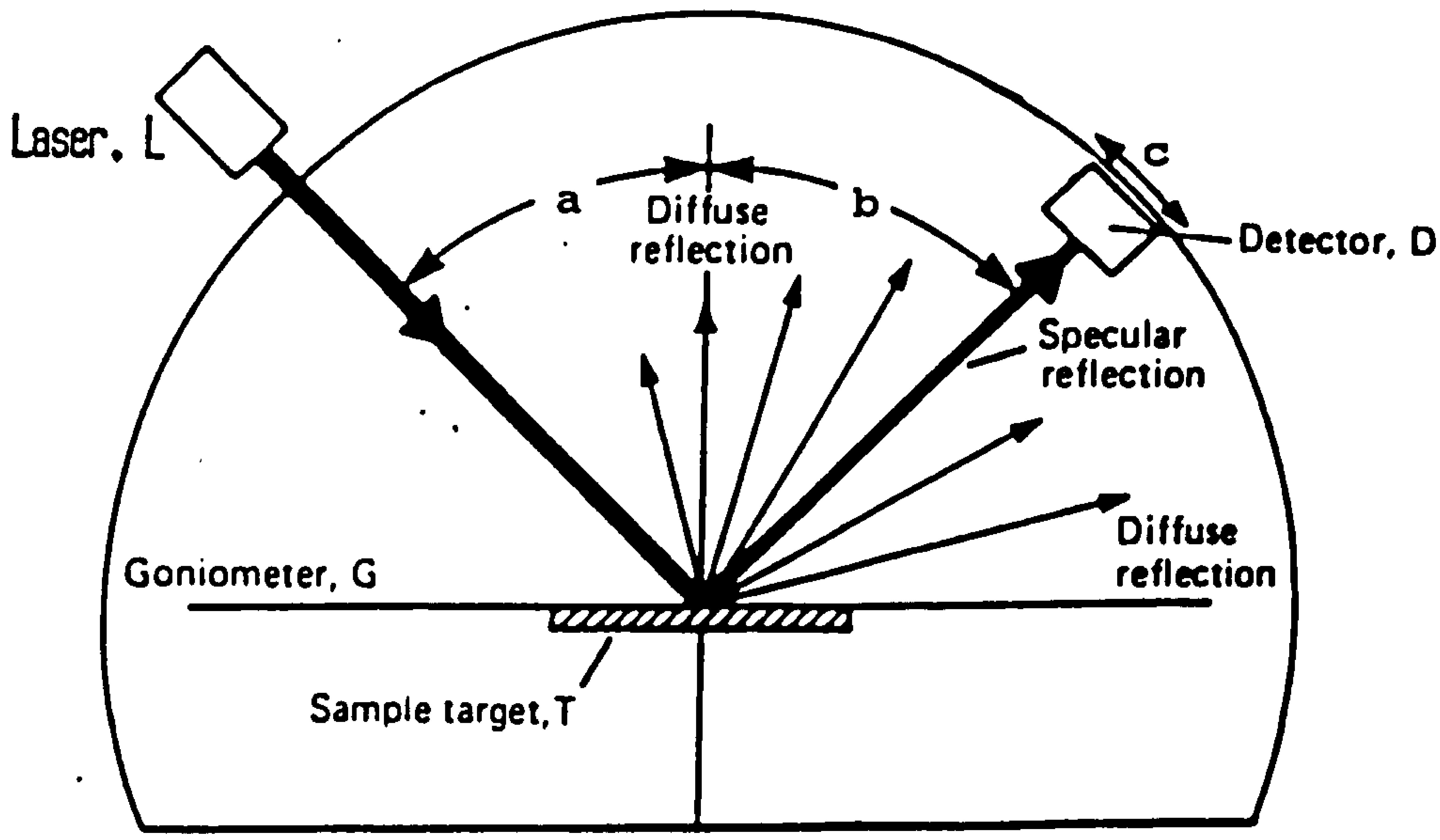


Figure 2.22

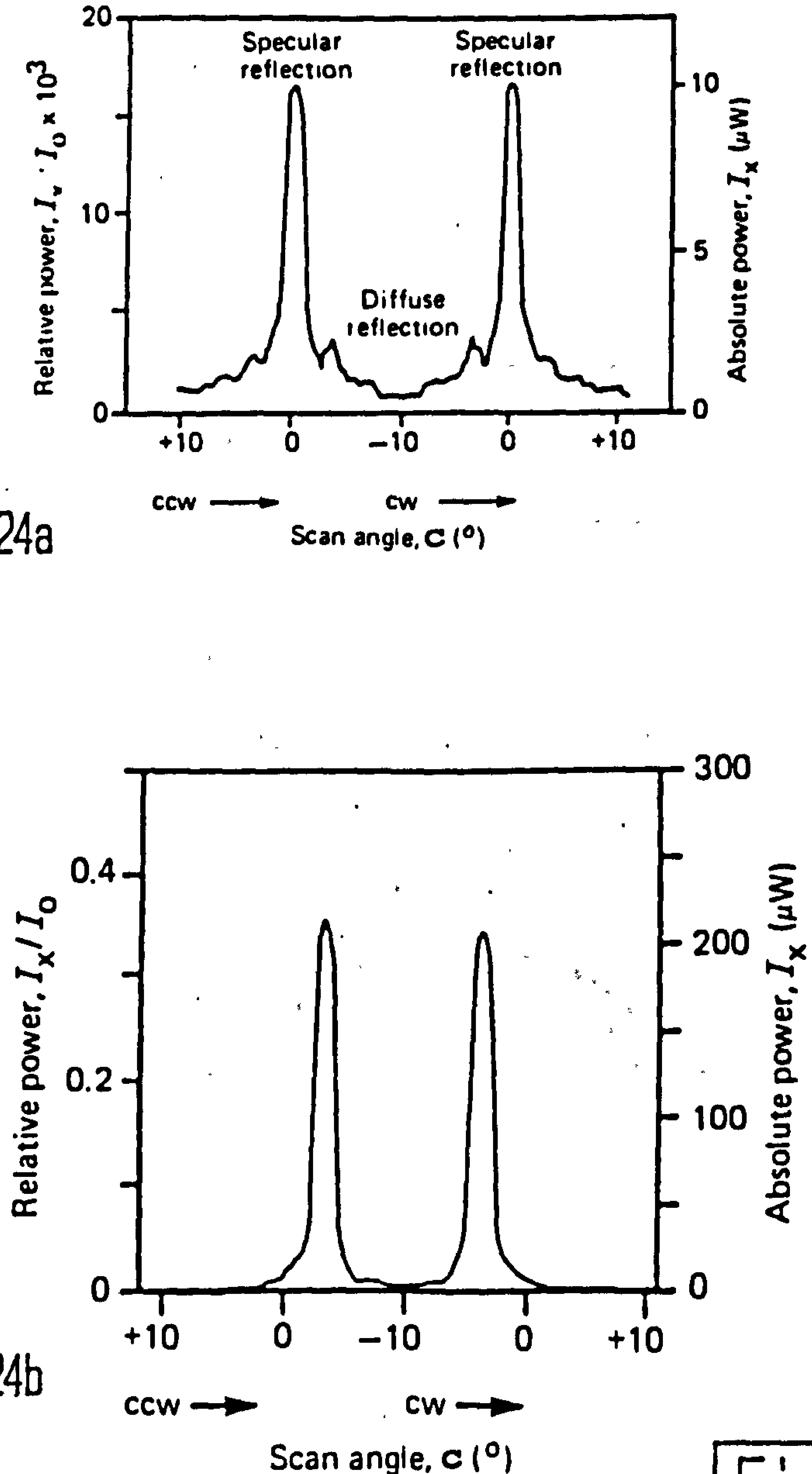
The Laser Scattering Instrument



After Whitley J.Q. et al 1987

Figure 2.23

Power Spectra Results



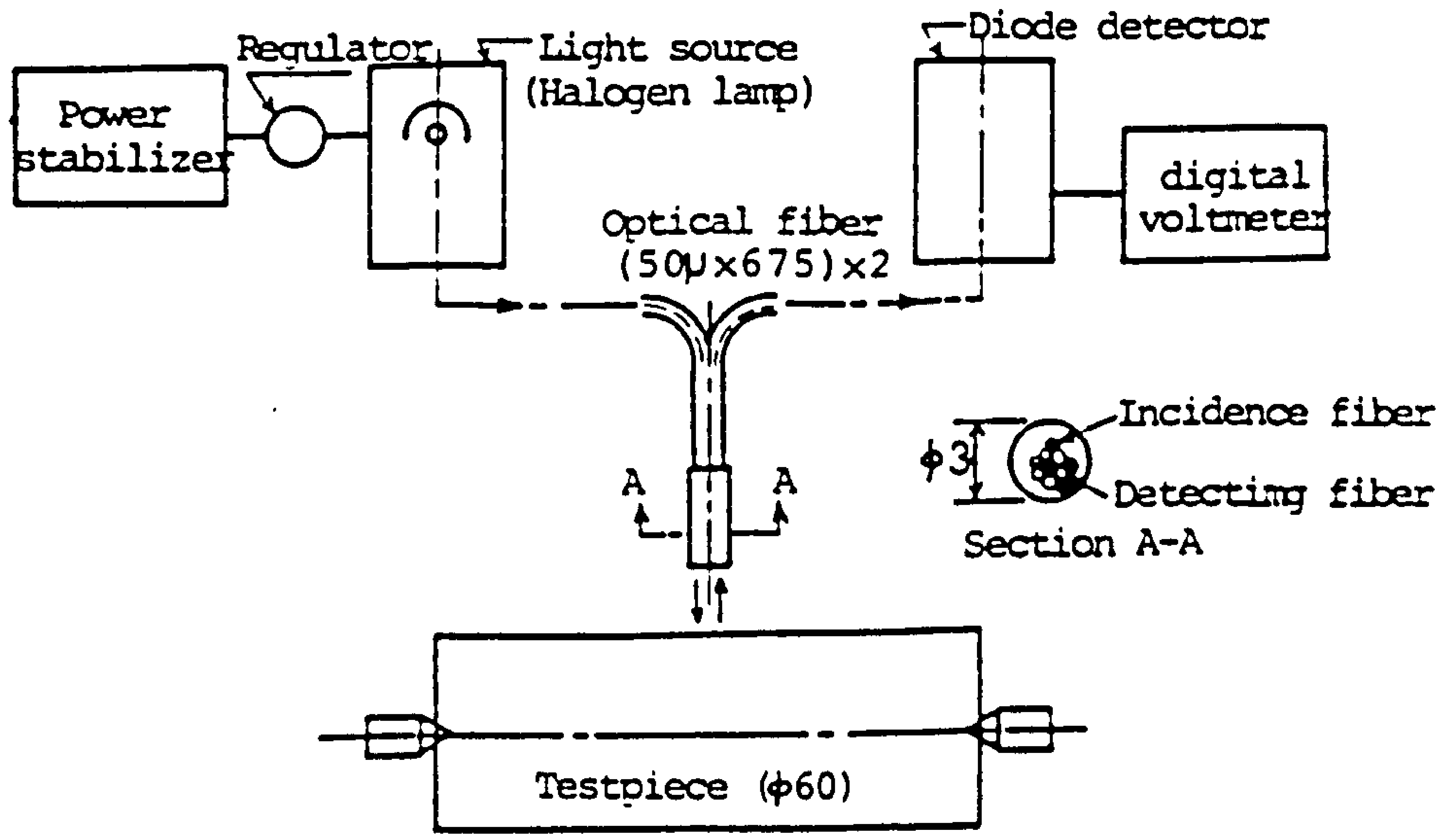
2.24a

2.24b

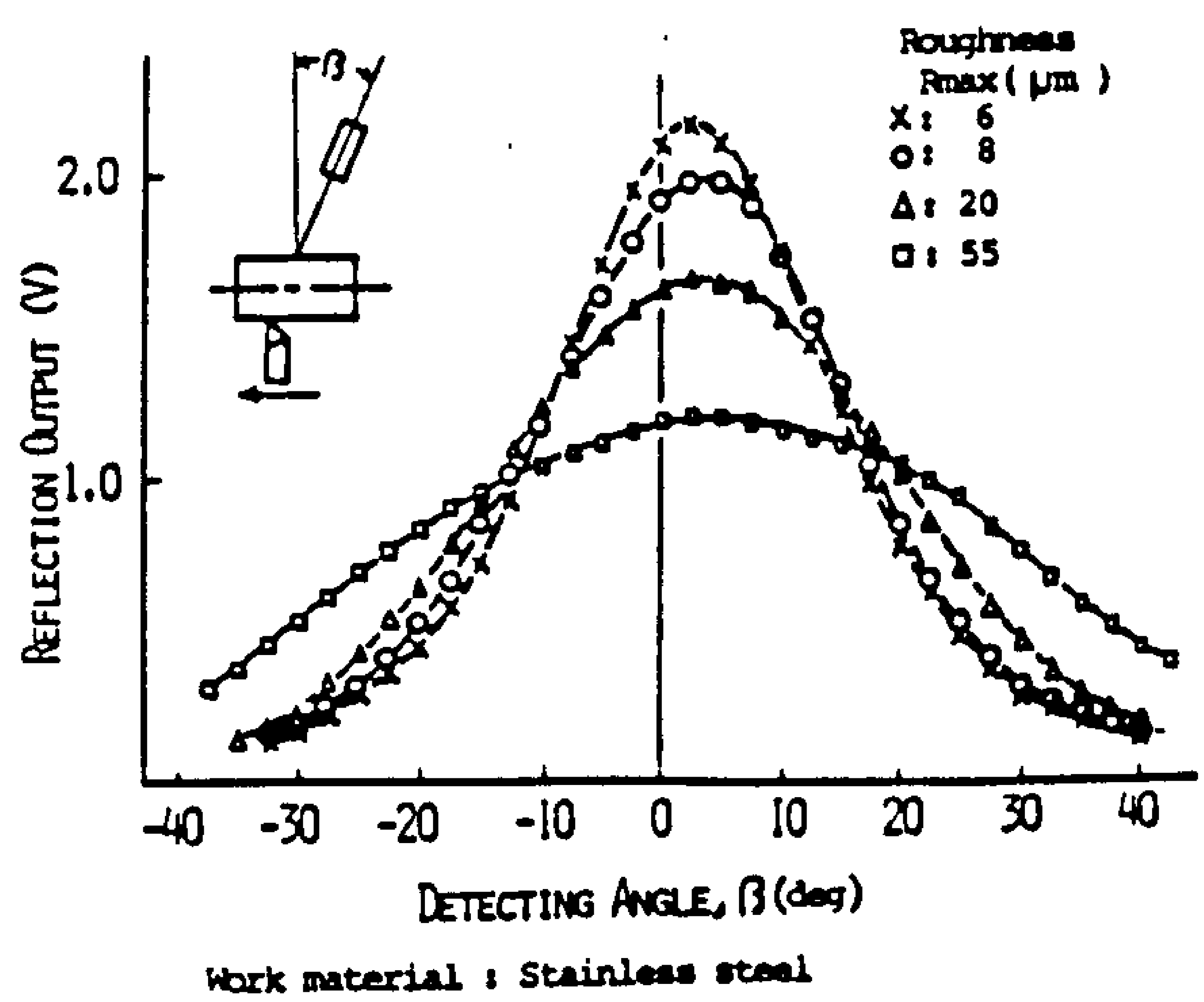
After Whitley J.Q. et al 1987

Figure 2.24

Light Reflection Distribution



2.25a Optical Fiber System



2.25b Reflection Distribution (Stainless Steel)

After Takeyama H. et al 1976

Figure 2.25

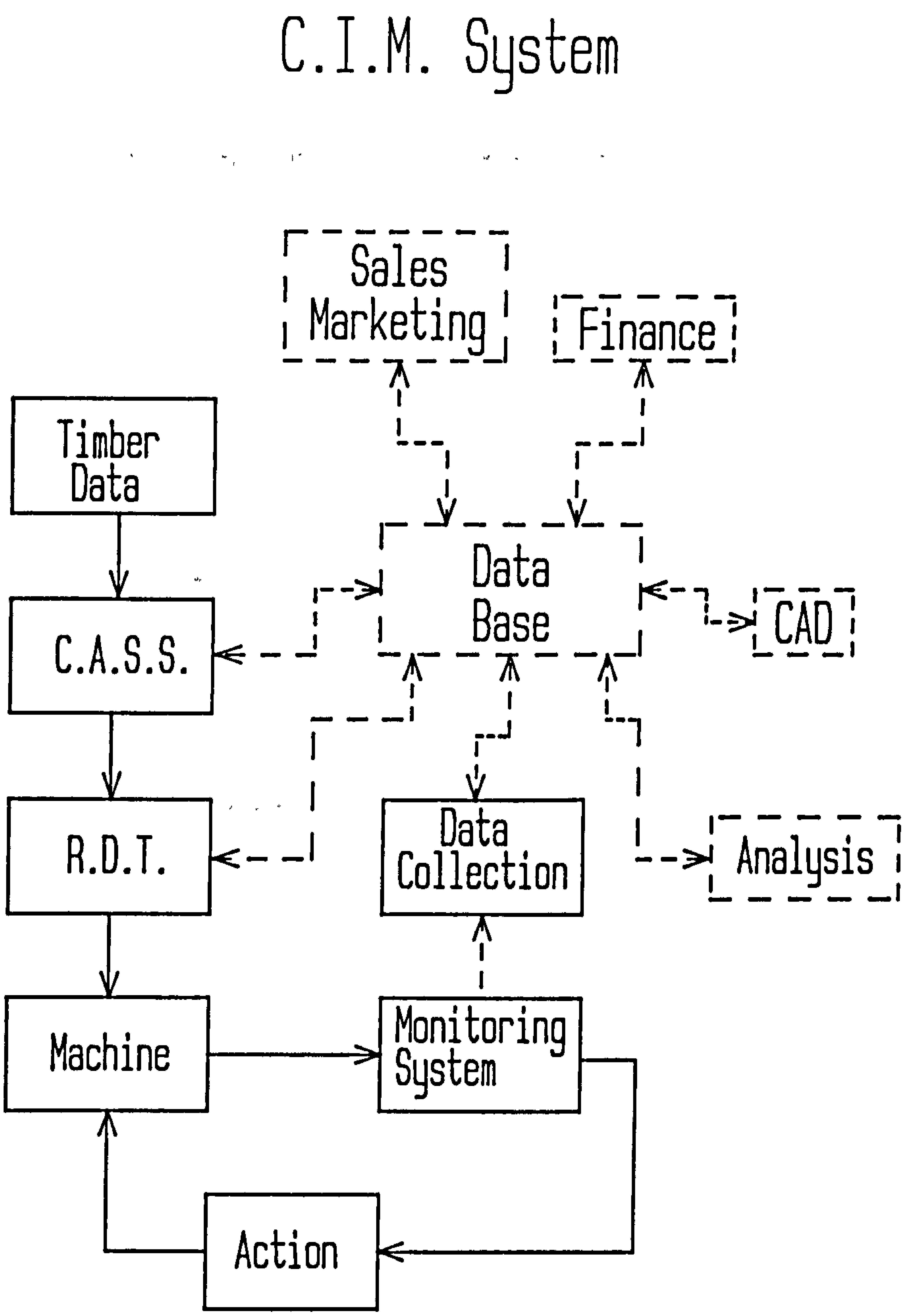
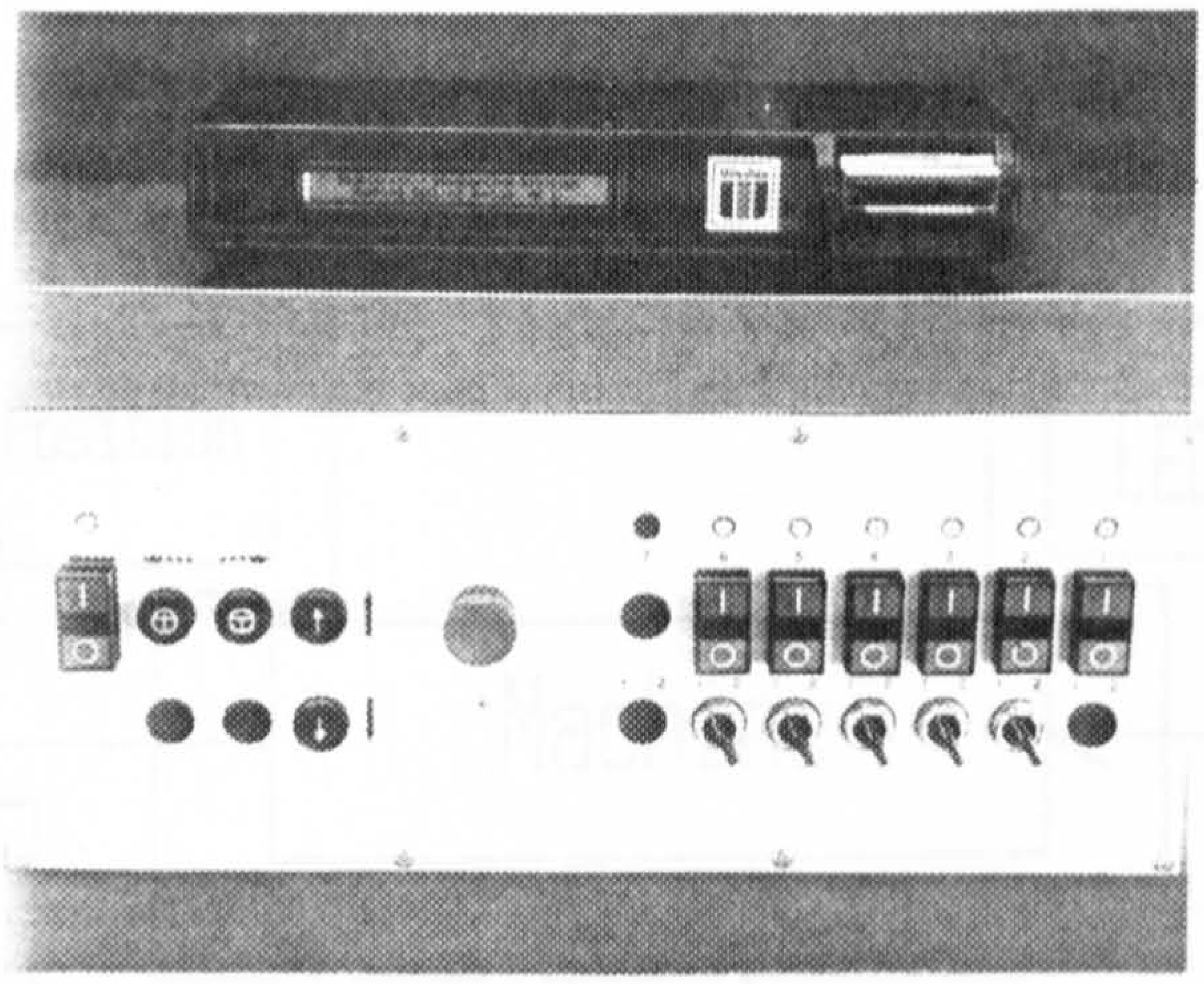

C.I.M. System
Sales Marketing
Finance
Timber Data
Data Base
C.A.S.S.
CAD
R.D.T.
Data Collection
Analysis
Machine
Monitoring System
Action

Figure 3.1

Reduced Down Time Unit (RDT)



RDT LED Unit on Moulder

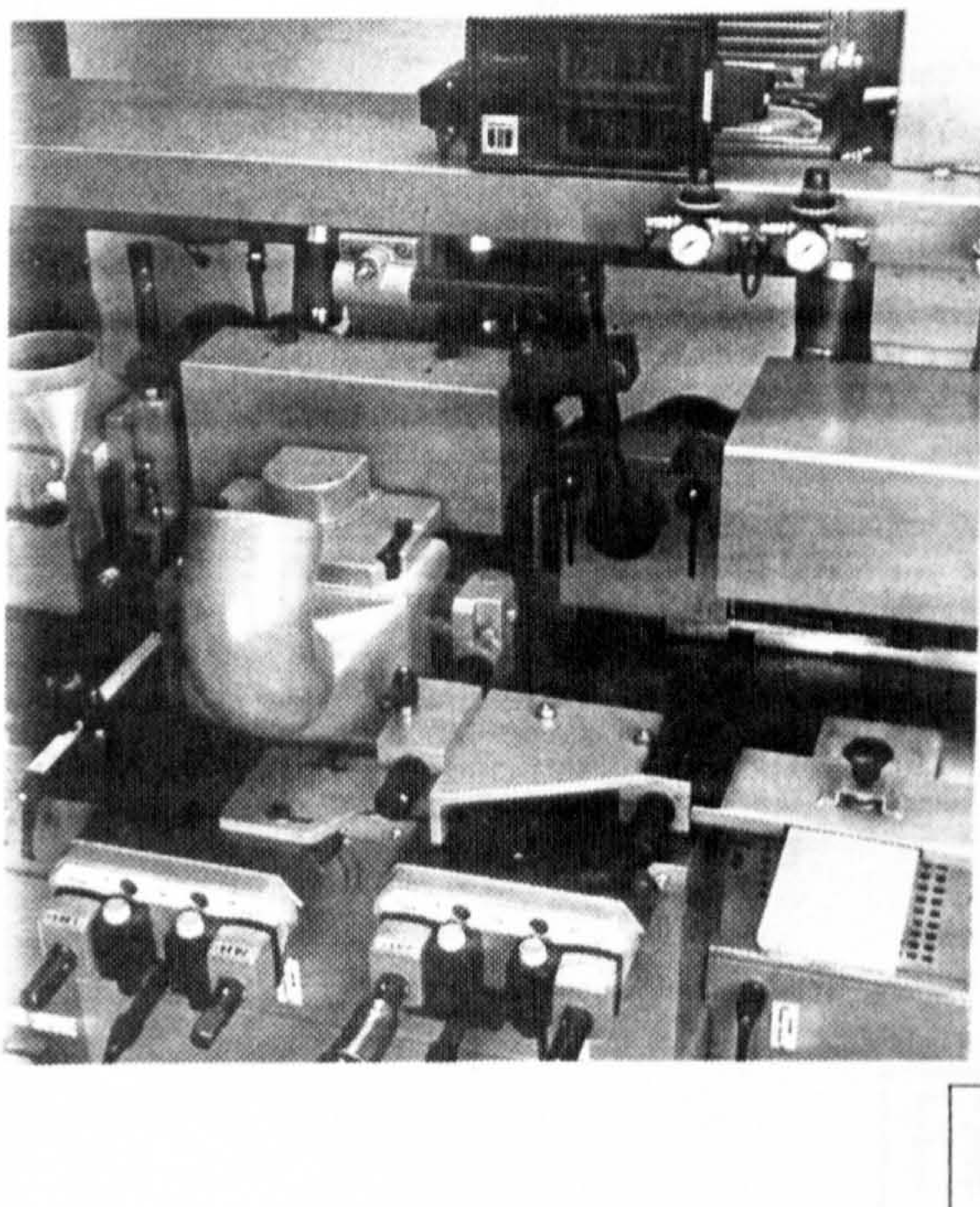


Figure 3.2

RDT System Architecture

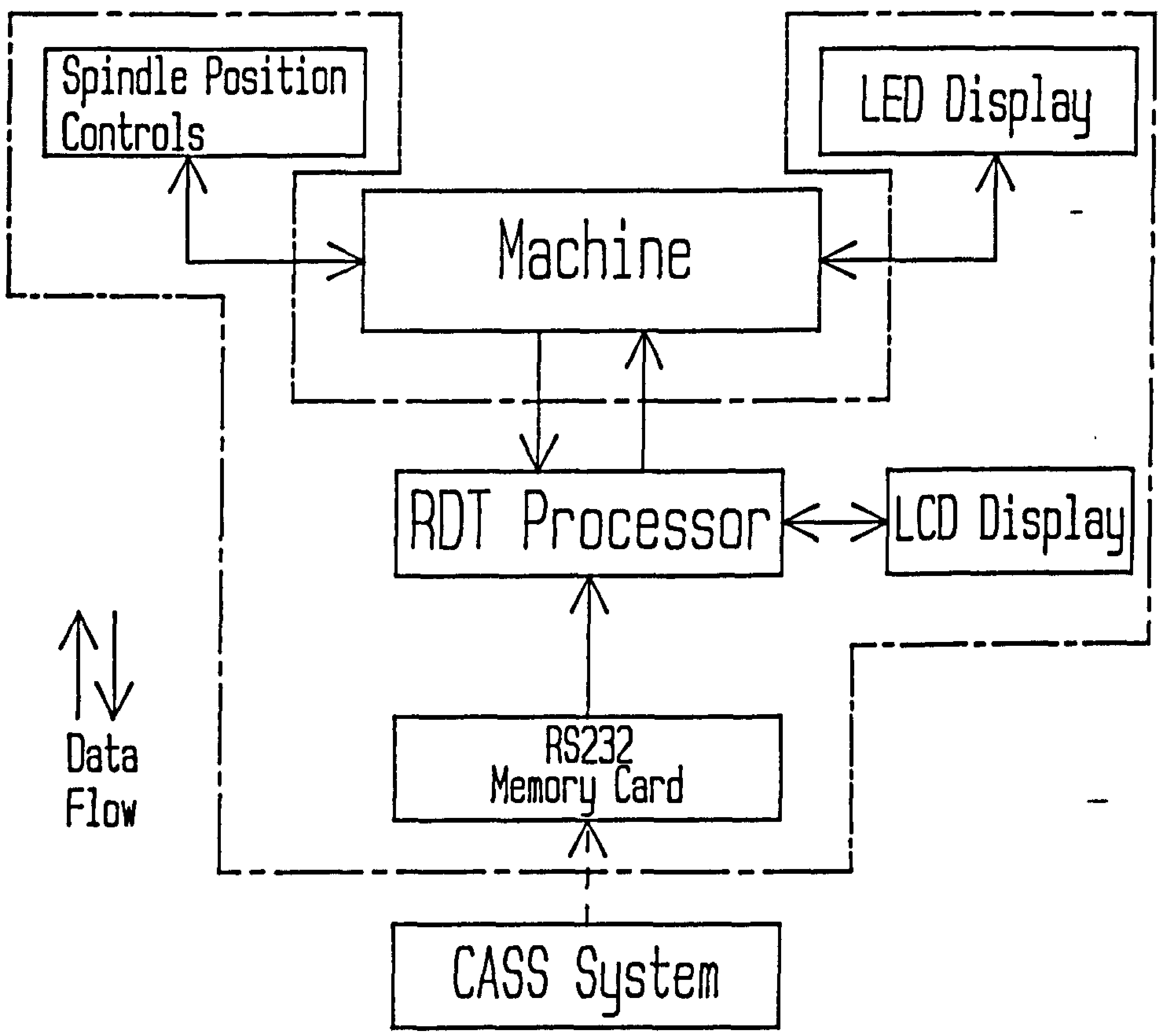


Figure 3.3a

Figure 3.3b

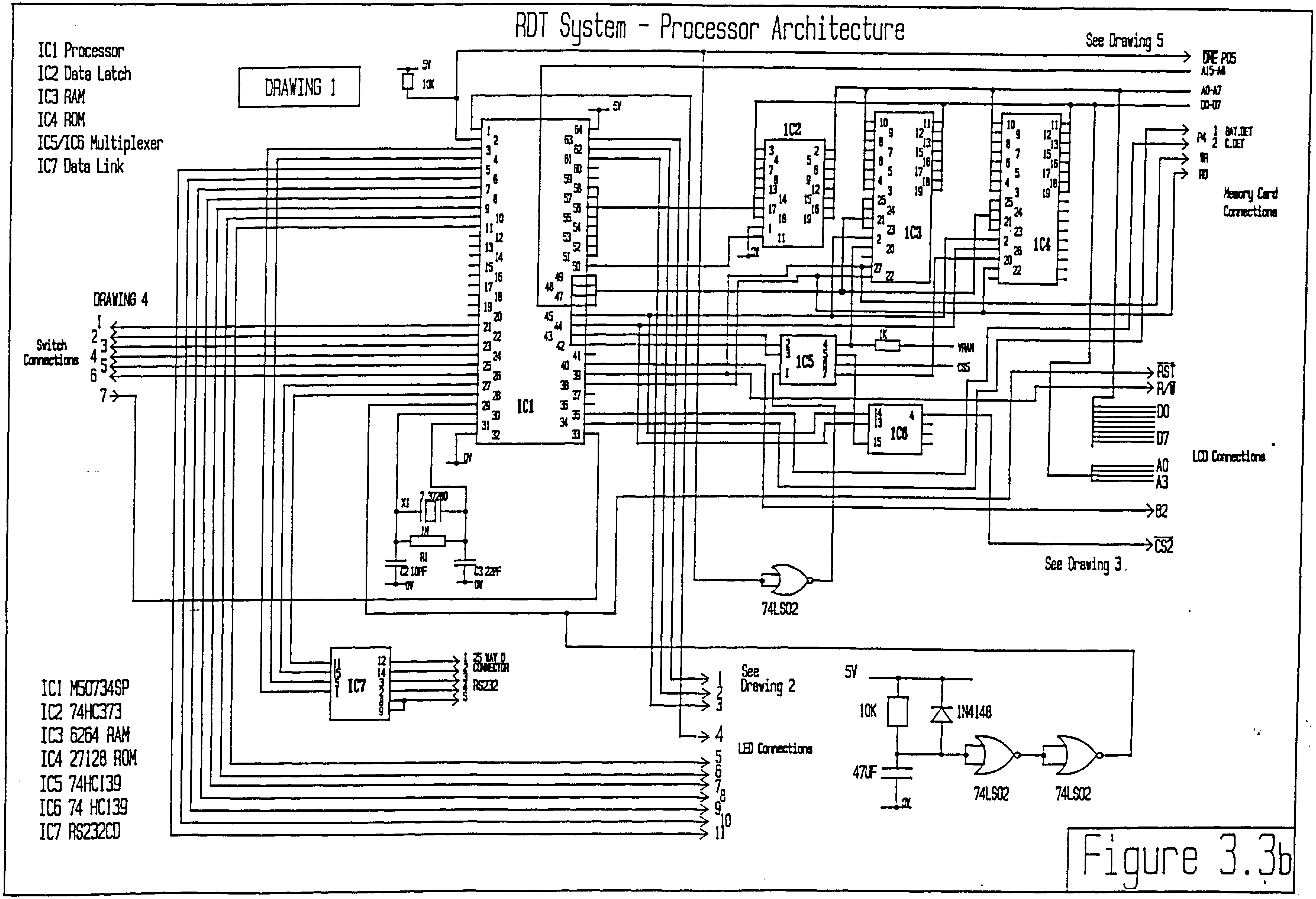
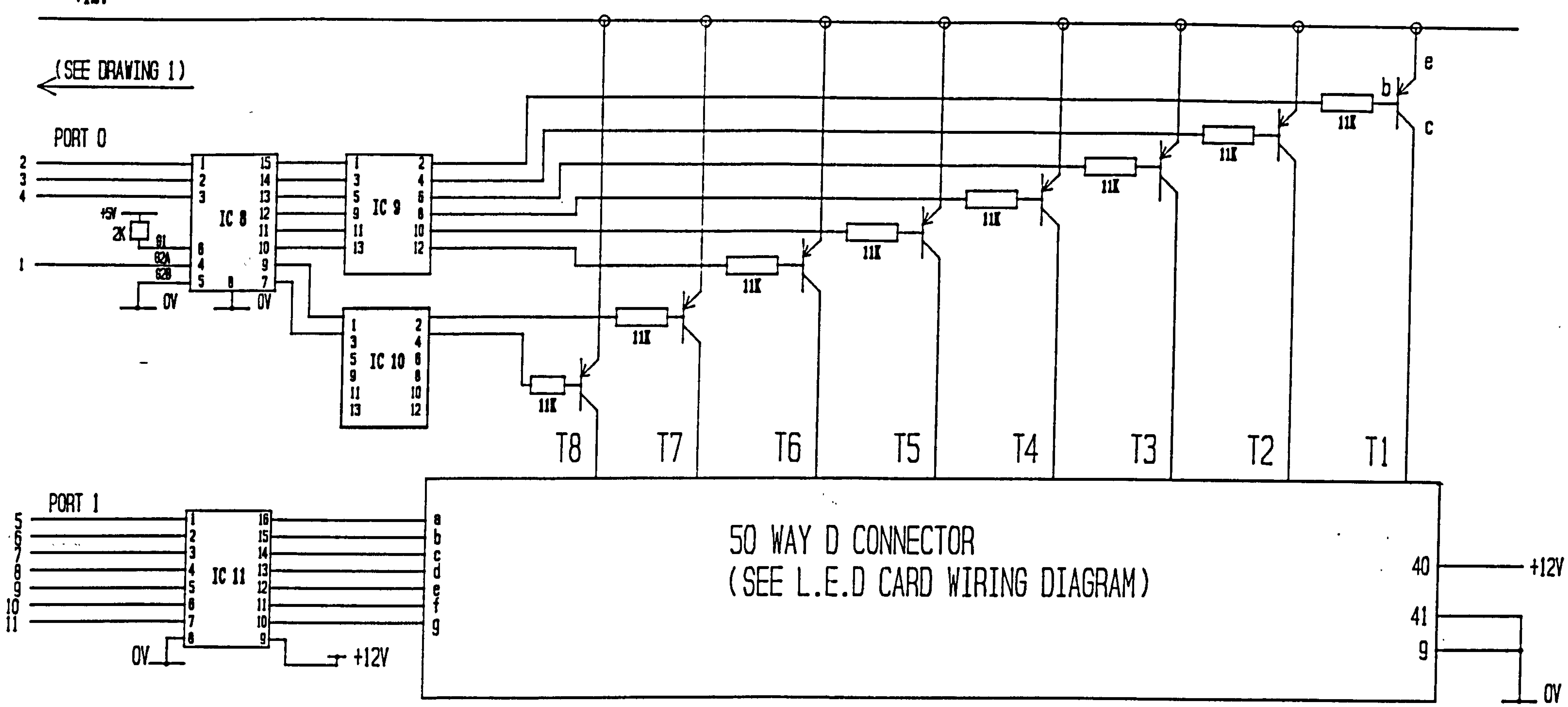

RDT System - Processor Architecture
DRAWING 1
IC1 Processor
IC2 Data Latch
IC3 RAM
IC4 ROM
IC5/IC6 Multiplexer
IC7 Data Link
See Drawing 5
A15-A8
A0-A7
D0-D7
BAT.DET
C.DET
WR
RD
Memory Card Connections
DRAWING 4
Switch Connections
IC1
IC2
IC3
IC4
IC5
IC6
IC7
VRAM
CS5
RST
R/W
D0
D7
LCD Connections
A0
A3
Ø2
CS2
See Drawing 3.
74LS02
25 WAY D CONNECTOR
RS232
See Drawing 2
LED Connections
5V
10K
IN4148
47UF
0V
1M
R1
C2 10PF
C3 22PF
X1
IC1 M50734SP
IC2 74HC373
IC3 6264 RAM
IC4 27128 ROM
IC5 74HC139
IC6 74 HC139
IC7 RS232CD

Figure 3.3b

Figure 3.4

Light Emmitting Diode Hardware



	5V	0V	
PIN No	16	8	8. 74LS138 - DECODER/MUX
	14	7	9. SN7407 - HEX BUFFER DRIVERS (HiV, o.c.)
	14	7	10. SN7407 - HEX BUFFER
	*	8	11. 2003A - DARLINGTON DRIVER

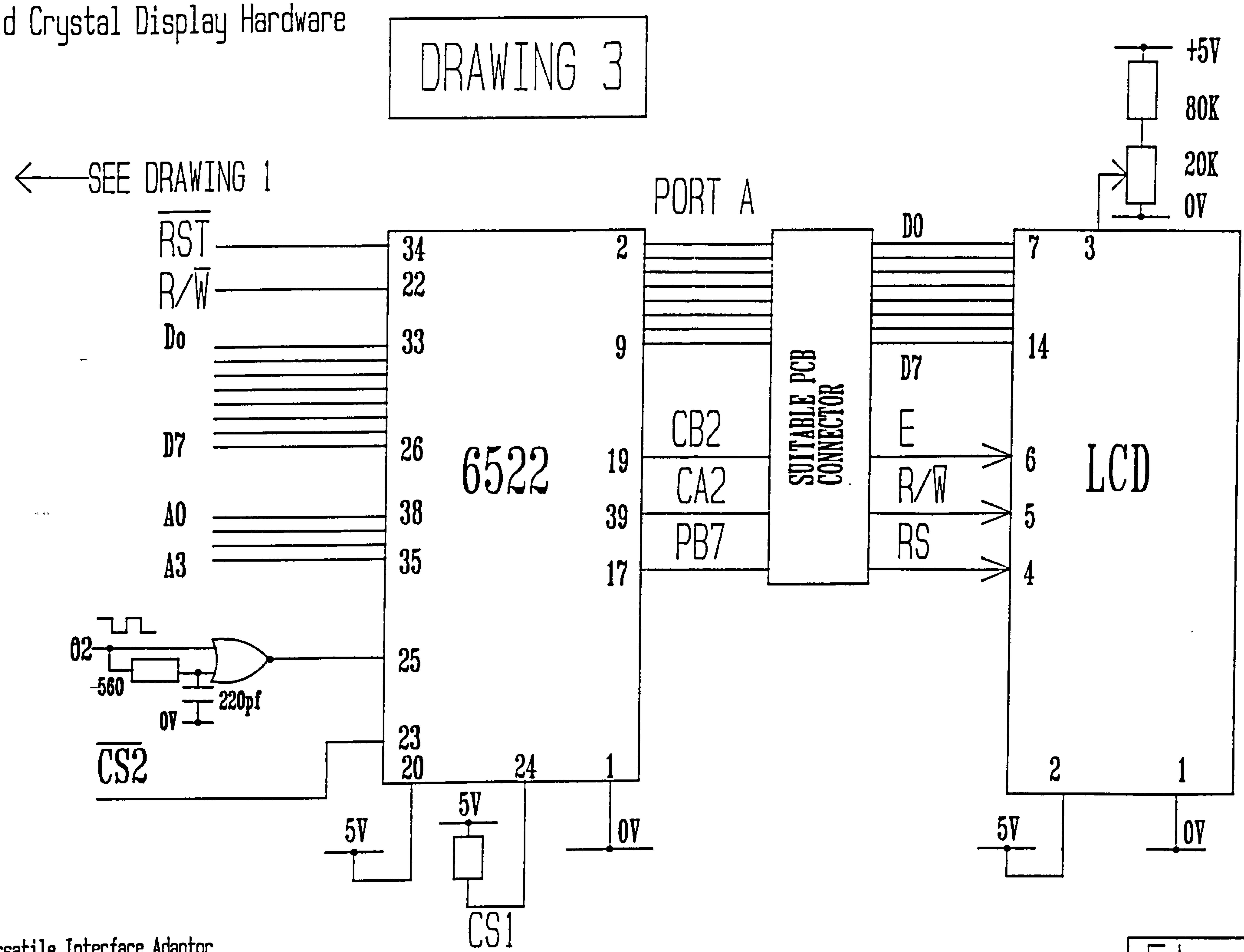
DRAWING 2

* PIN 9 CONNECTED TO +12V   transistors - BD680

Figure 3.4

Figure 3.5

Liquid Crystal Display Hardware

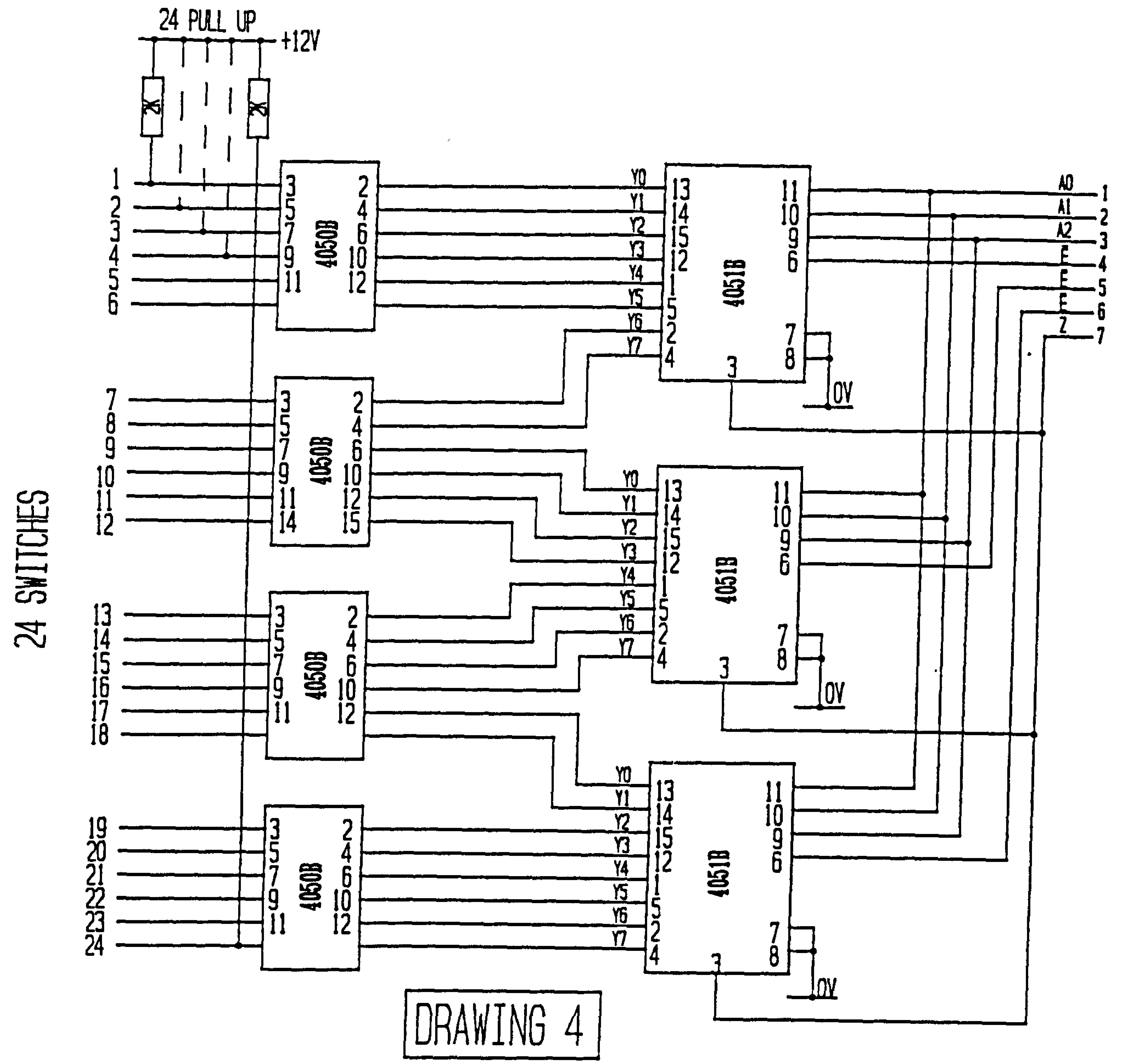


6522 Versatile Interface Adaptor
LCD Liquid Crystal Display

Figure 3.5

Figure 3.6

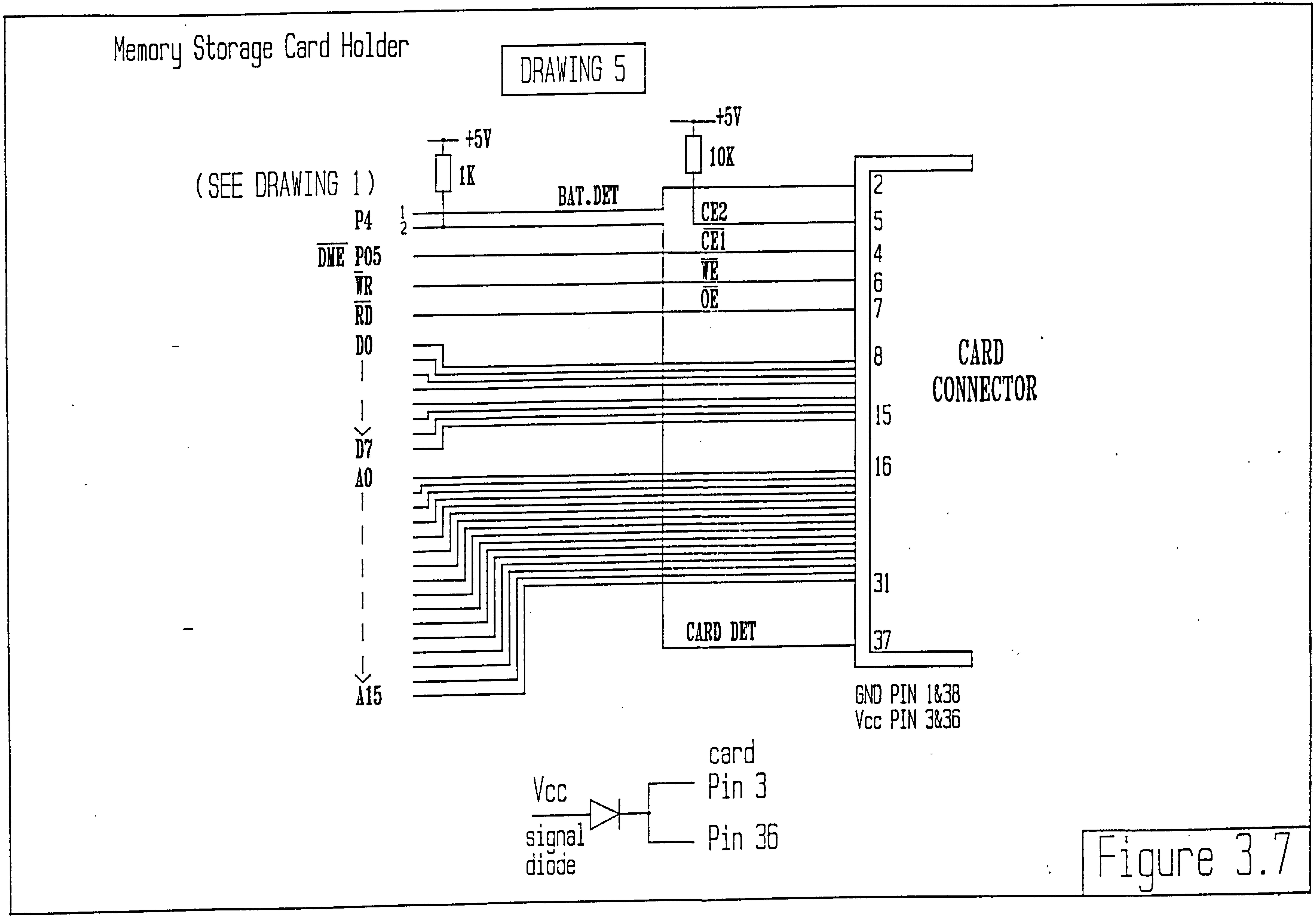
Switch Input Control Hardware



4051B Decoder
4050B Buffer

Figure 3.6

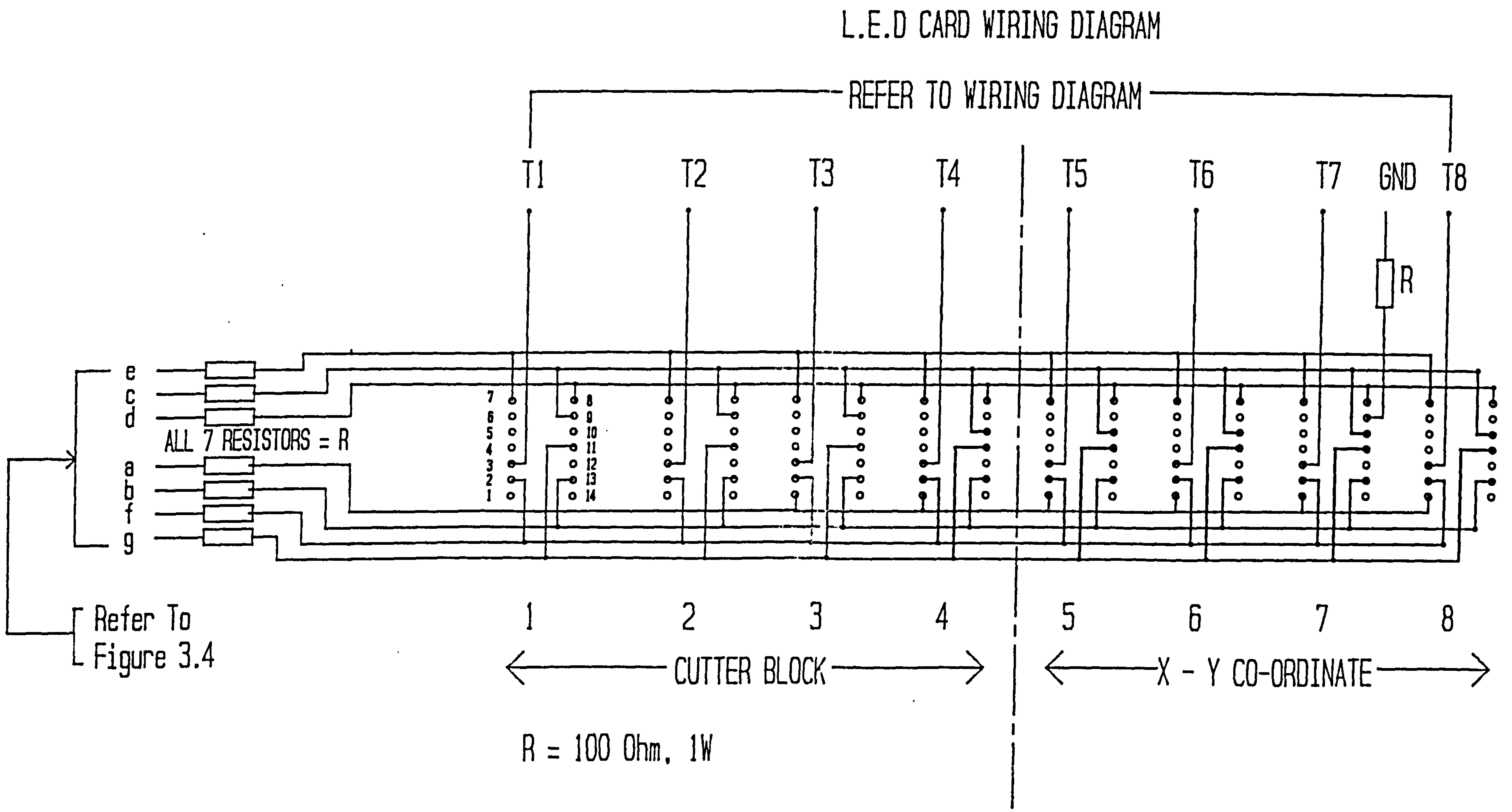
Figure 3.7



Memory Storage Card Holder
DRAWING 5
(SEE DRAWING 1)
+5V
1K
+5V
10K
BAT.DET
P4
1
2
CE2
$\overline{CE1}$
$\overline{WE}$
$\overline{OE}$
$\overline{DME}$ P05
$\overline{WR}$
$\overline{RD}$
D0
D7
A0
A15
2
5
4
6
7
8
15
16
31
37
CARD DET
CARD CONNECTOR
GND PIN 1&38
Vcc PIN 3&36
Vcc
signal diode
card
Pin 3
Pin 36

Figure 3.7

Figure 3.8



L.E.D CARD WIRING DIAGRAM
REFER TO WIRING DIAGRAM
T1
T2
T3
T4
T5
T6
T7
GND
T8
R
e
c
d
ALL 7 RESISTORS = R
a
b
f
g
Refer To Figure 3.4
1
2
3
4
5
6
7
8
CUTTER BLOCK
X - Y CO-ORDINATE
R = 100 Ohm, 1W

Figure 3.8

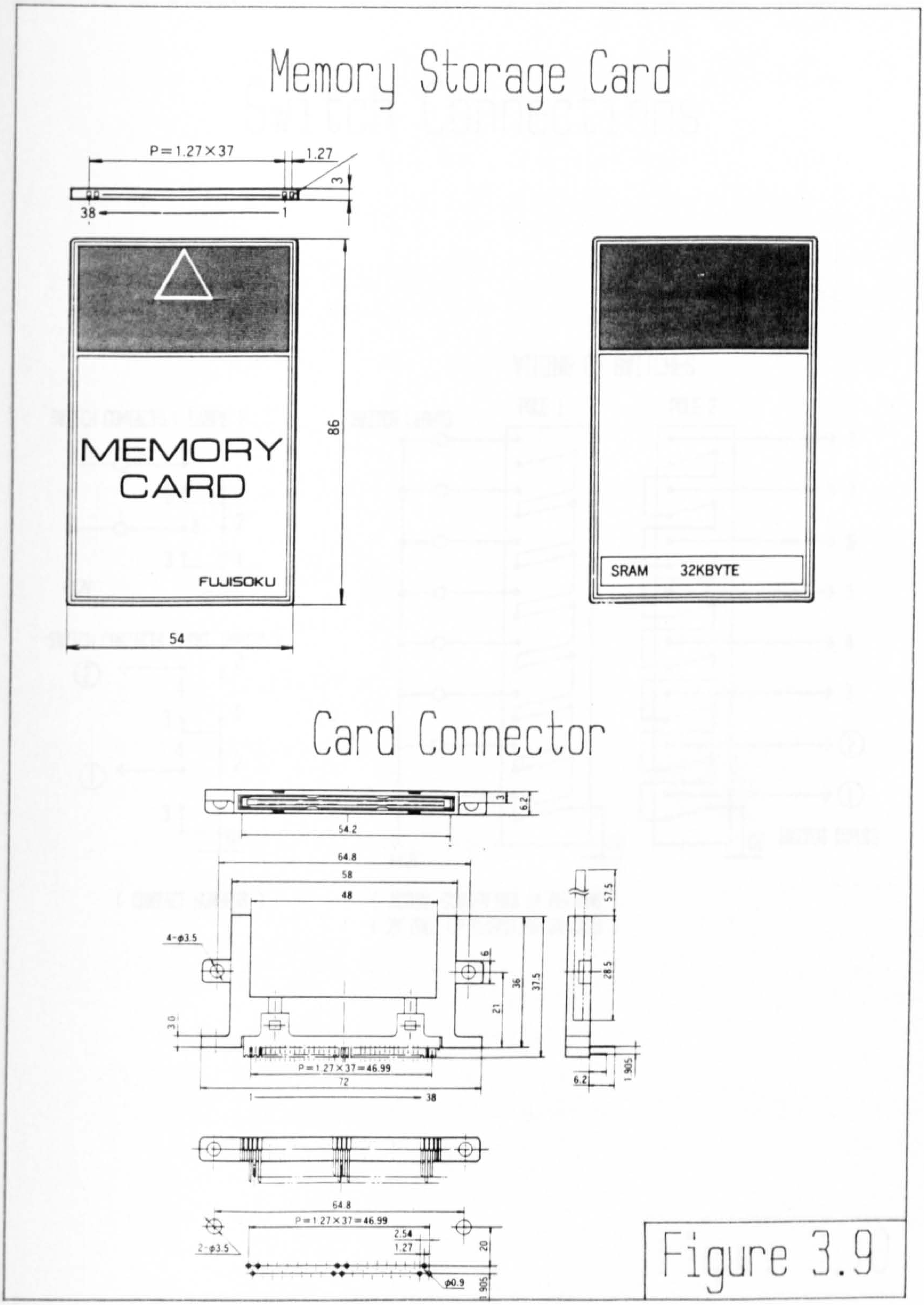

Memory Storage Card
P=1.27×37
1.27
3
38
1
86
54
MEMORY
CARD
FUJISOKU
SRAM 32KBYTE
Card Connector
54.2
3
6.2
64.8
58
48
4-φ3.5
6
36
37.5
21
3.0
P=1.27×37=46.99
72
1
38
57.5
28.5
6.2
1.905
64.8
P=1.27×37=46.99
2.54
1.27
2-φ3.5
20
φ0.9
1.905

Figure 3.9

Switch Connections

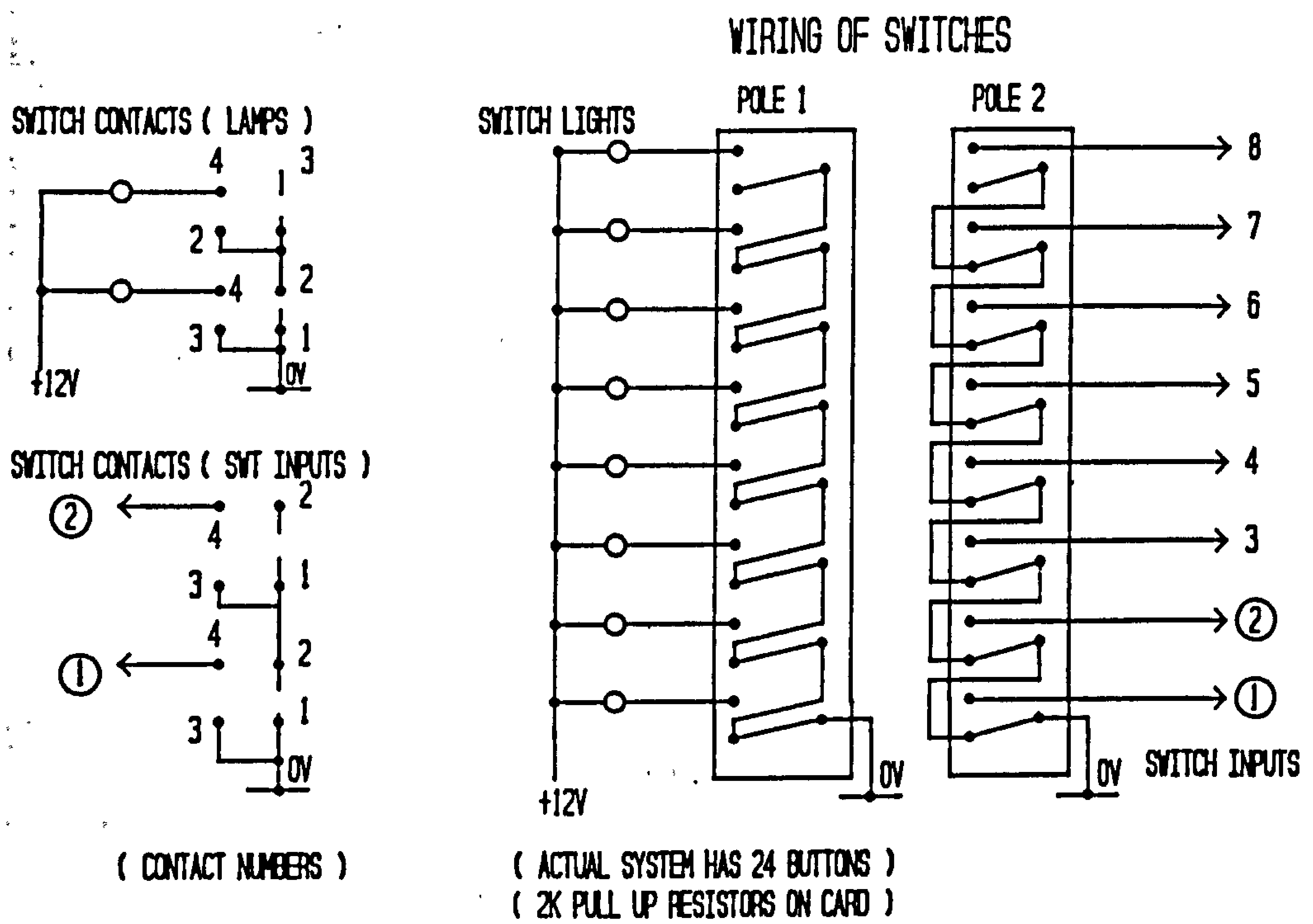


Figure 3.10

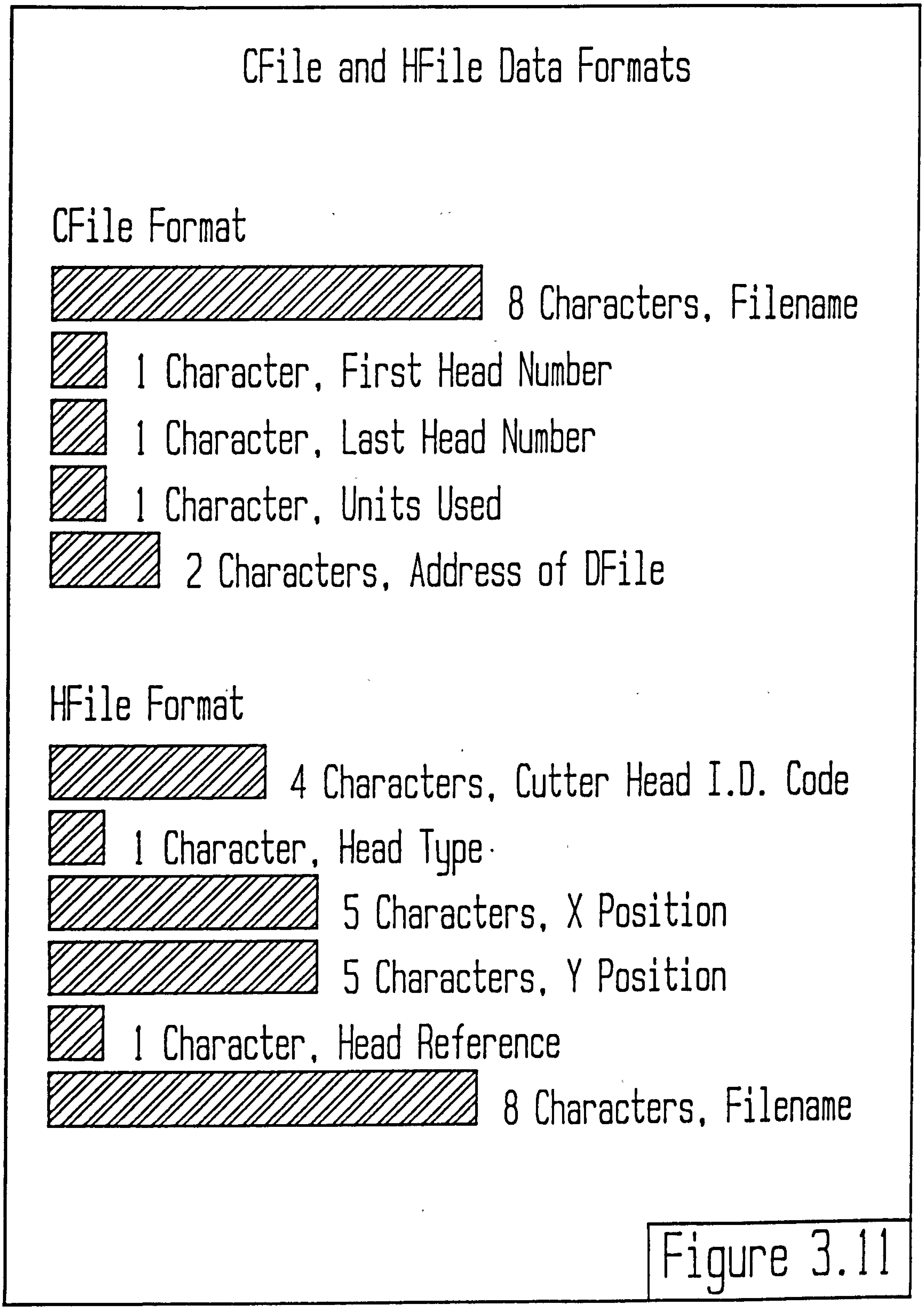
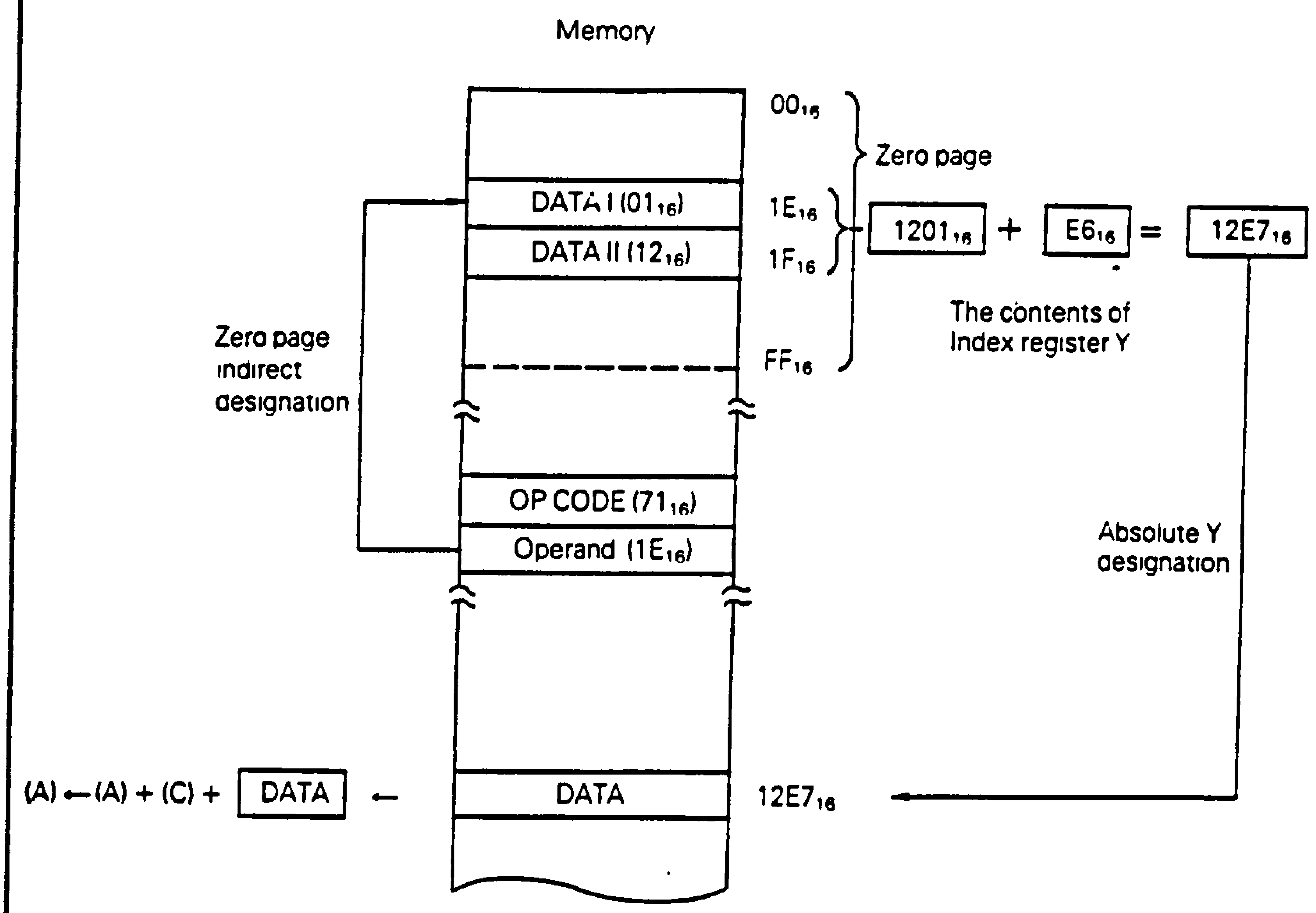

CFile and HFile Data Formats
CFile Format
8 Characters, Filename
1 Character, First Head Number
1 Character, Last Head Number
1 Character, Units Used
2 Characters, Address of DFile
HFile Format
4 Characters, Cutter Head I.D. Code
1 Character, Head Type
5 Characters, X Position
5 Characters, Y Position
1 Character, Head Reference
8 Characters, Filename

Figure 3.11

Indirect Indexed Y Register Programming



In this example, 01_{16} for data I and 12_{16} for data II are stored beforehand.

Address Mode Indirect Y Takes the memory Content Appointed By The Added Value Of The Index Register and The Contents Of The 2 Byte Zero Page Memory Location Appointed By The Program Operand

Figure 3.12

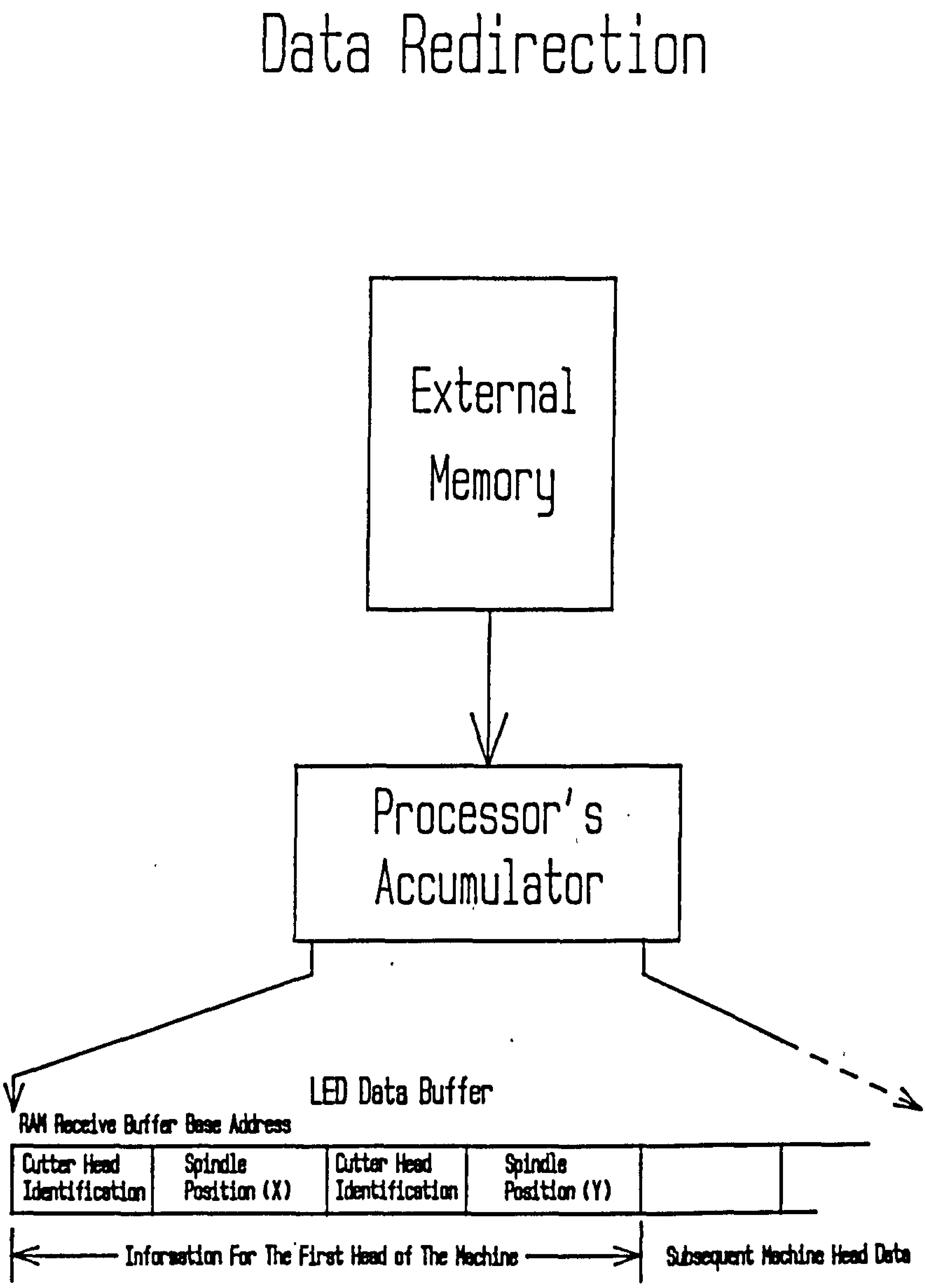

Data Redirection
External Memory
Processor's Accumulator
LED Data Buffer
RAM Receive Buffer Base Address
Cutter Head Identification
Spindle Position (X)
Cutter Head Identification
Spindle Position (Y)
Information For The First Head of The Machine
Subsequent Machine Head Data

Figure 3.13

LED Character Data Retrieved Using Indexed Pointers

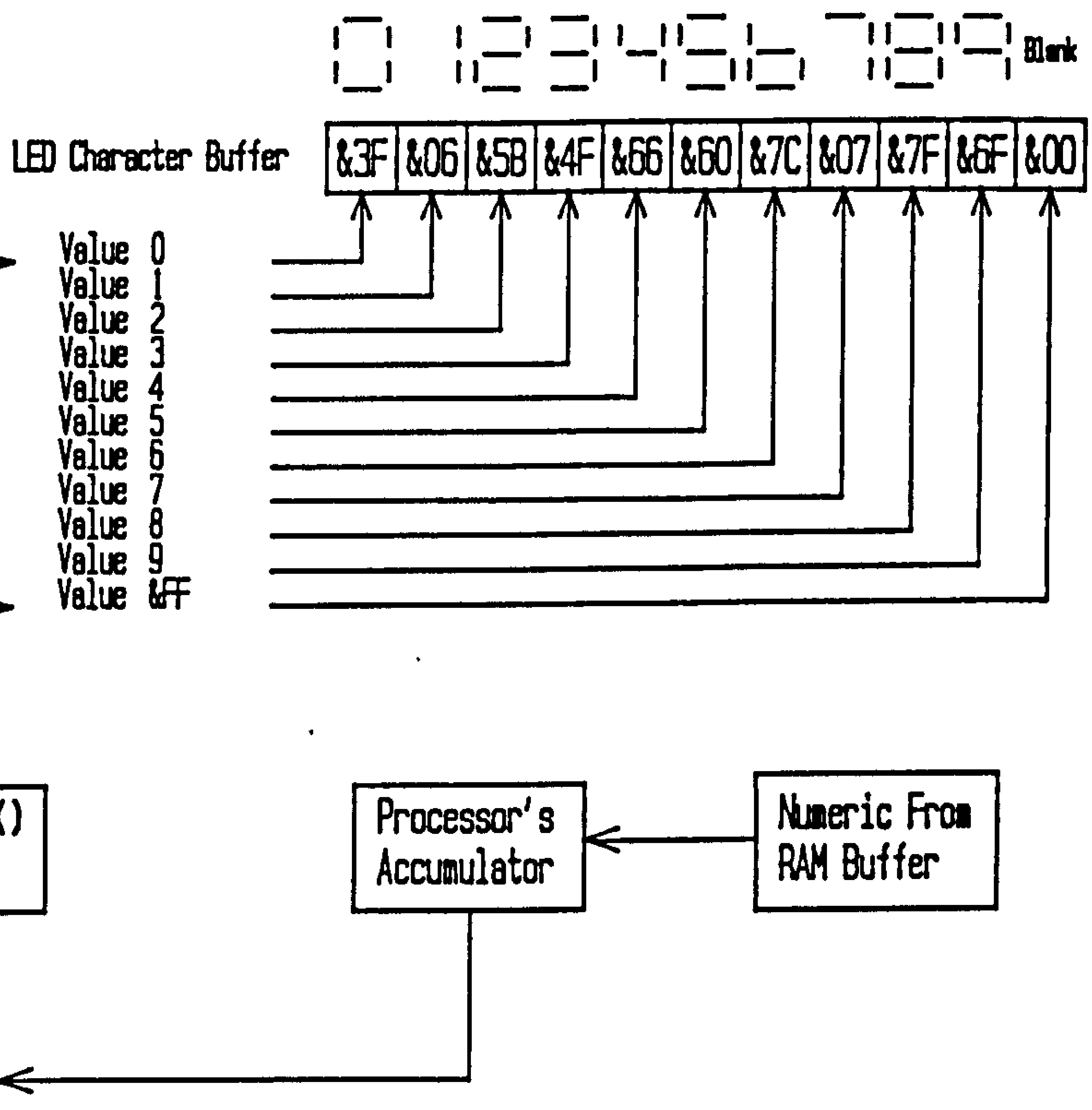


Figure 3.14

Model Validation

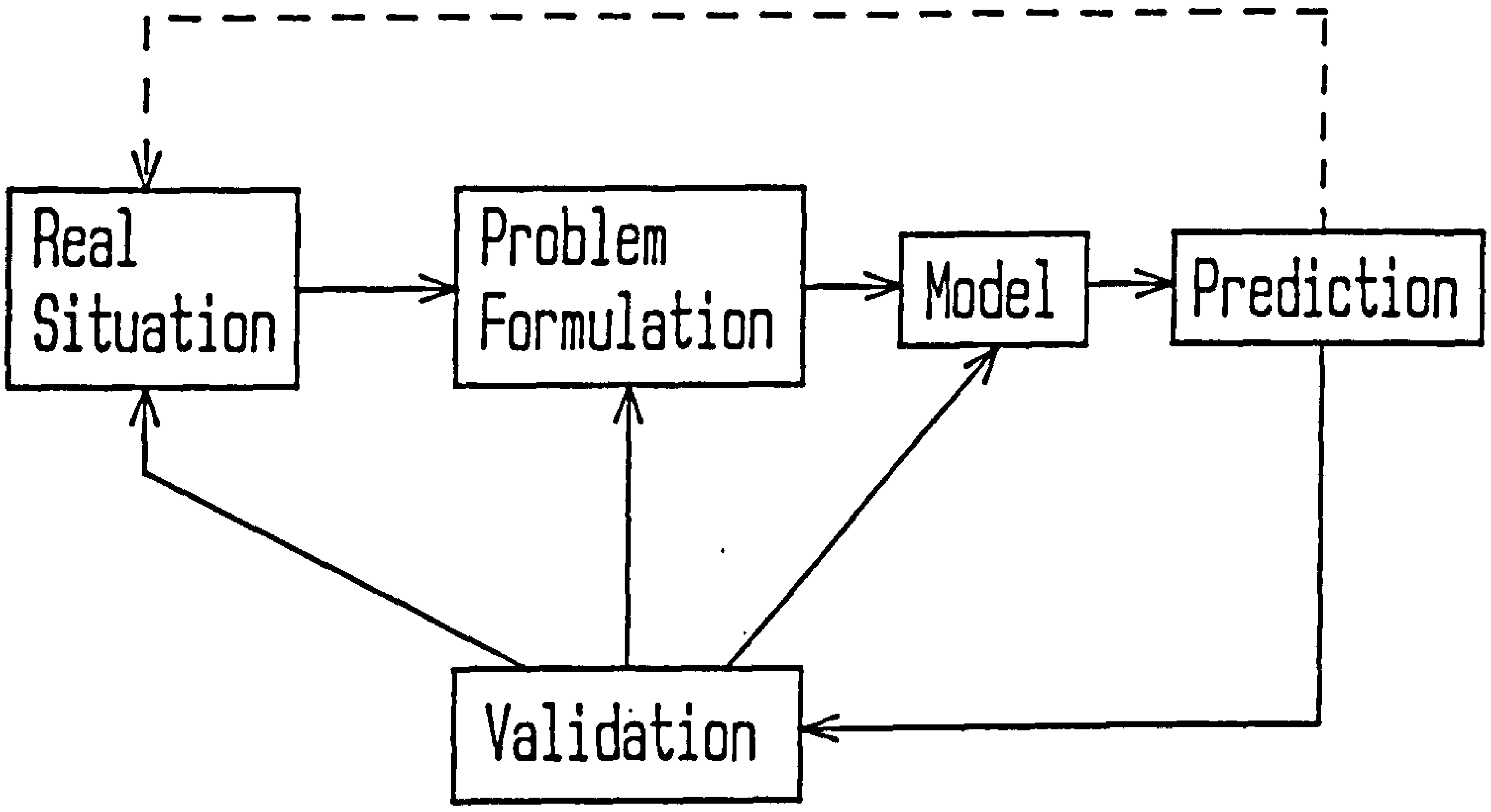


Figure 4.1

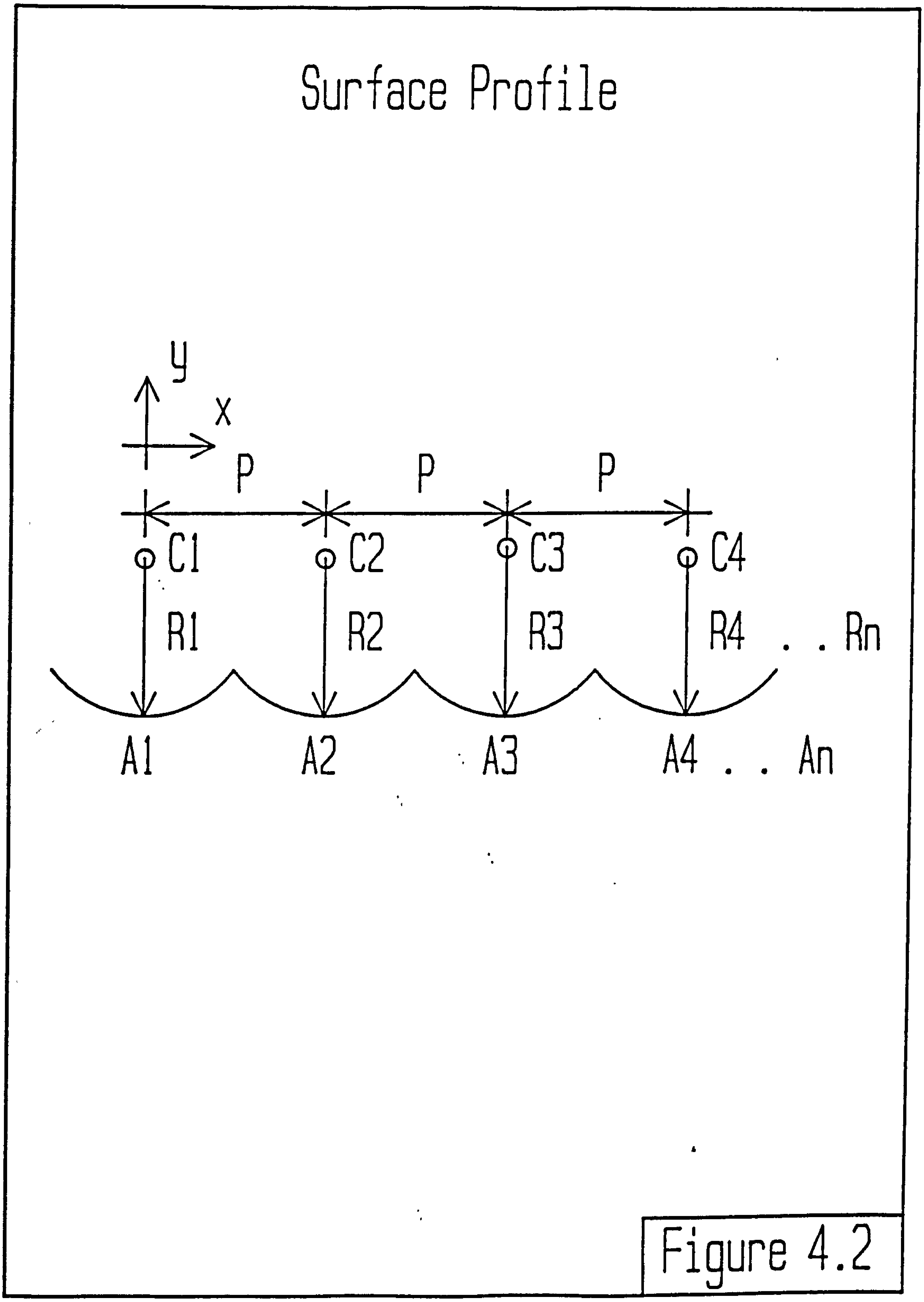
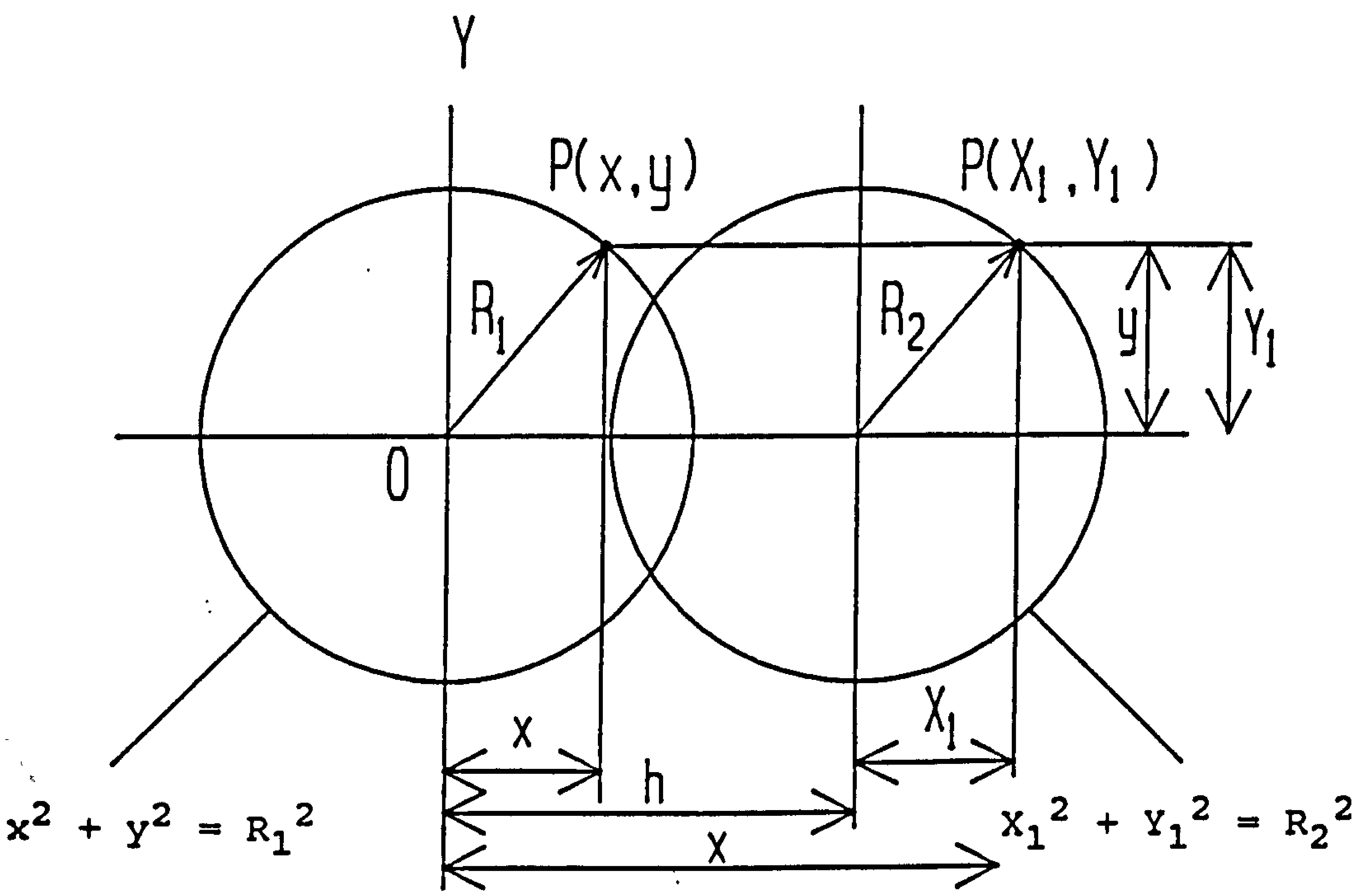


Figure 4.2

Difference of Centres Theory



$X_1^2 + Y_1^2 = R_2^2$ $\quad :Y_1 = (y - K)$

$X_1 = (x - h): \Rightarrow \quad (x - h)^2 + y^2 = R_2^2$ $\quad :K = 0$

let $h = p$ $\quad :Y_1 = y$

$R_2^2 = (x - p)^2 + y^2$

Figure 4.3

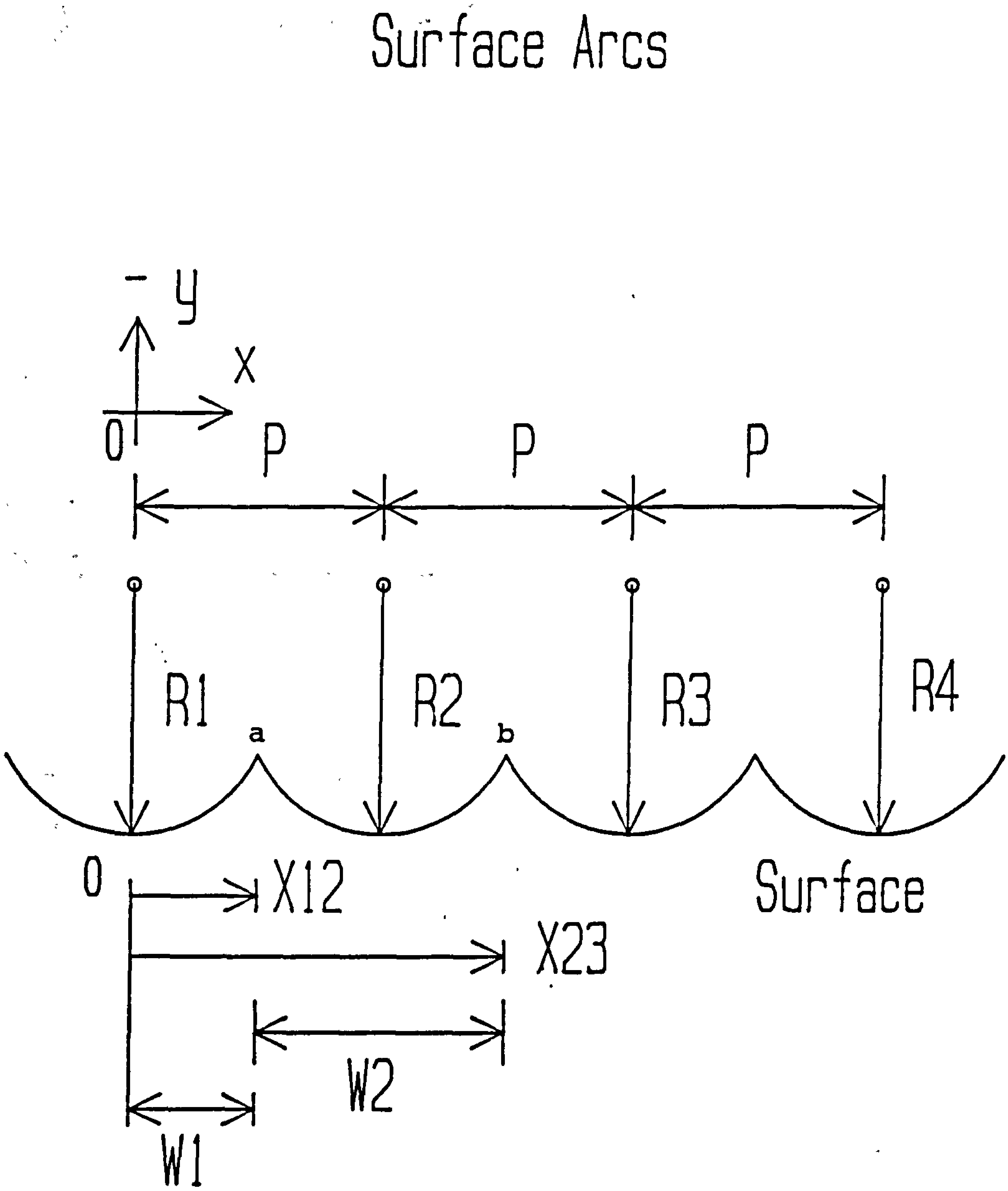


Figure 4.4

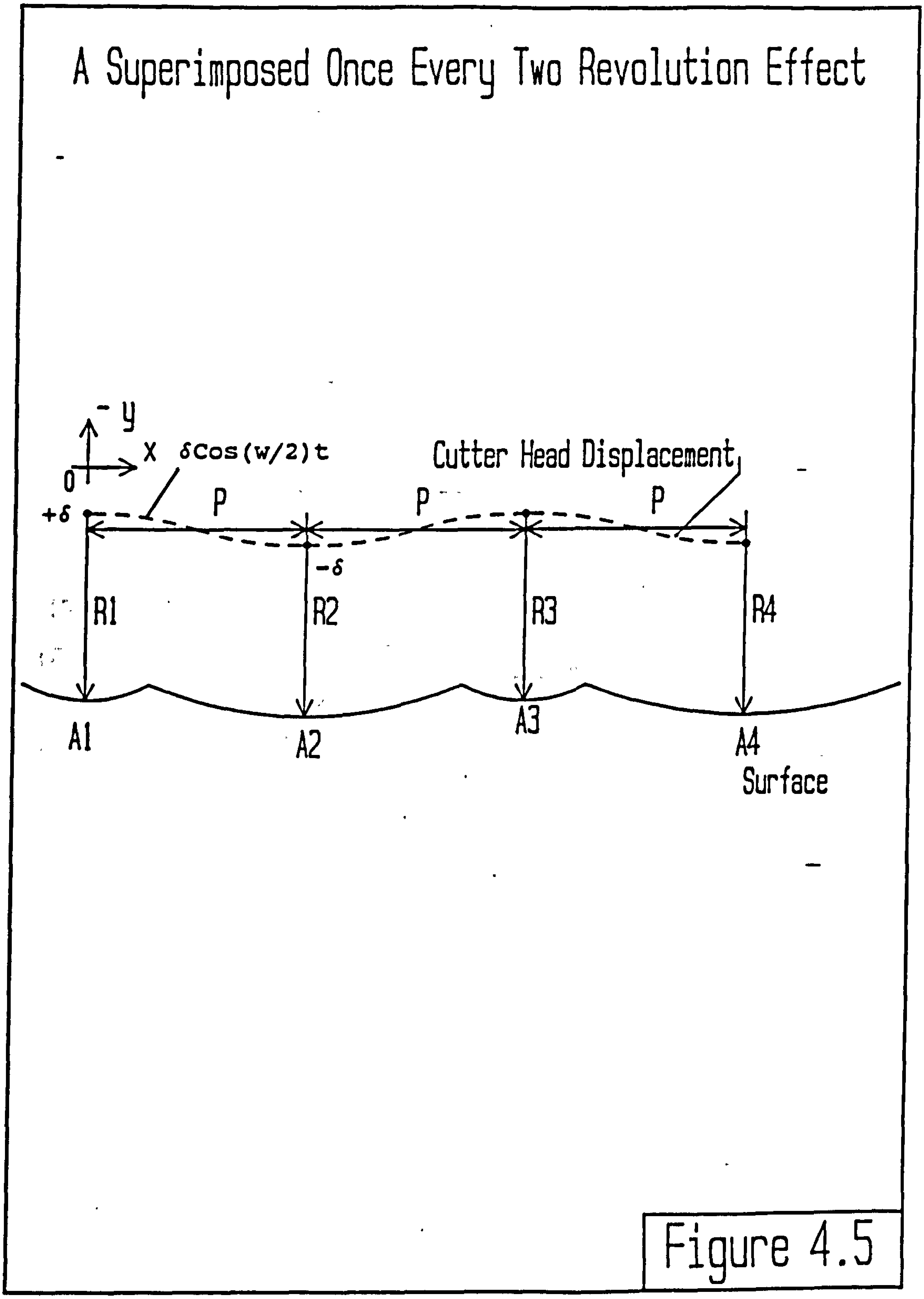

A Superimposed Once Every Two Revolution Effect
- y
X
0
δCos(w/2)t
Cutter Head Displacement
+δ
P
P
P
-δ
R1
R2
R3
R4
A1
A2
A3
A4
Surface

Figure 4.5

Difference of Curvature

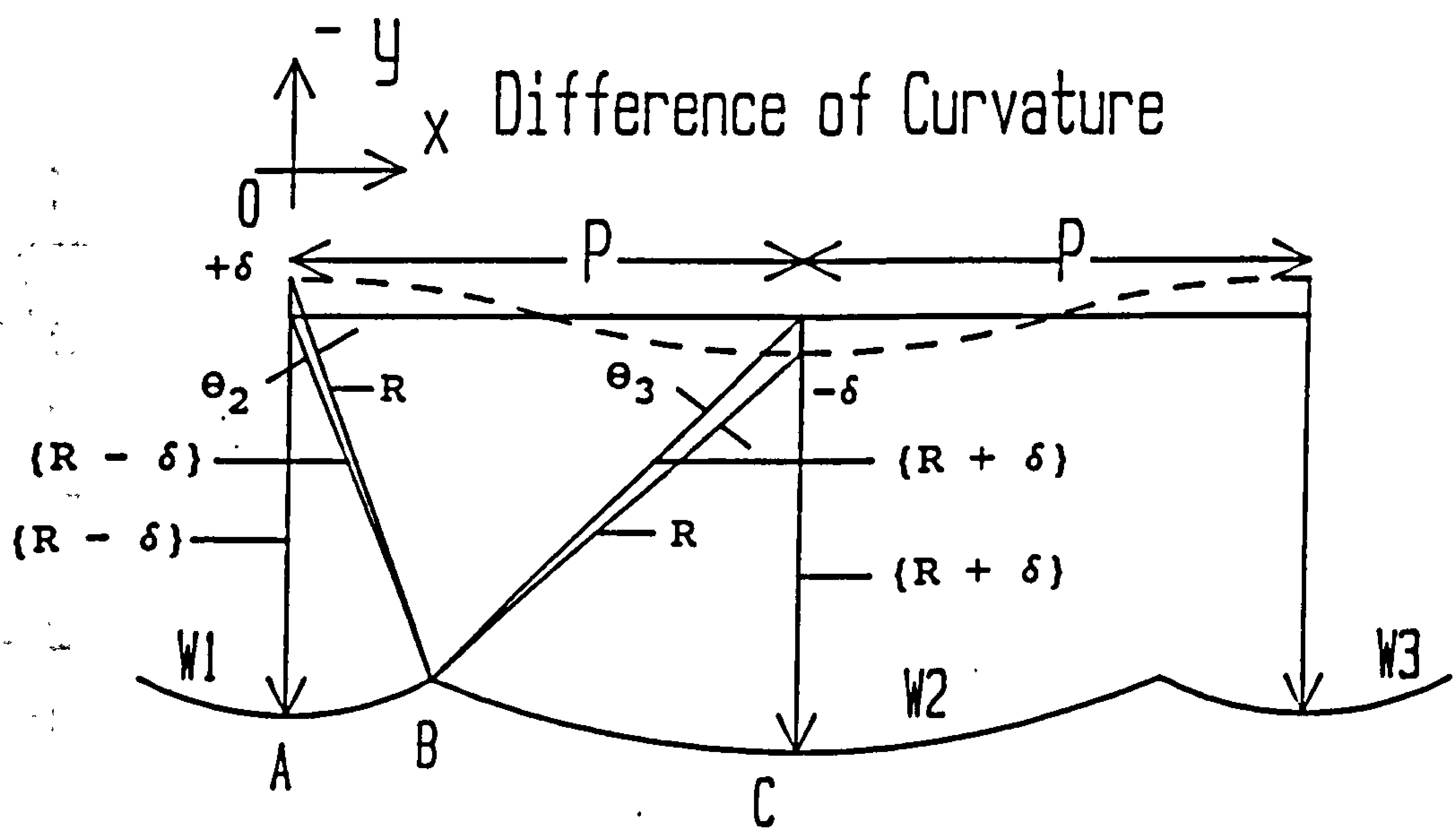


Figure 4.6

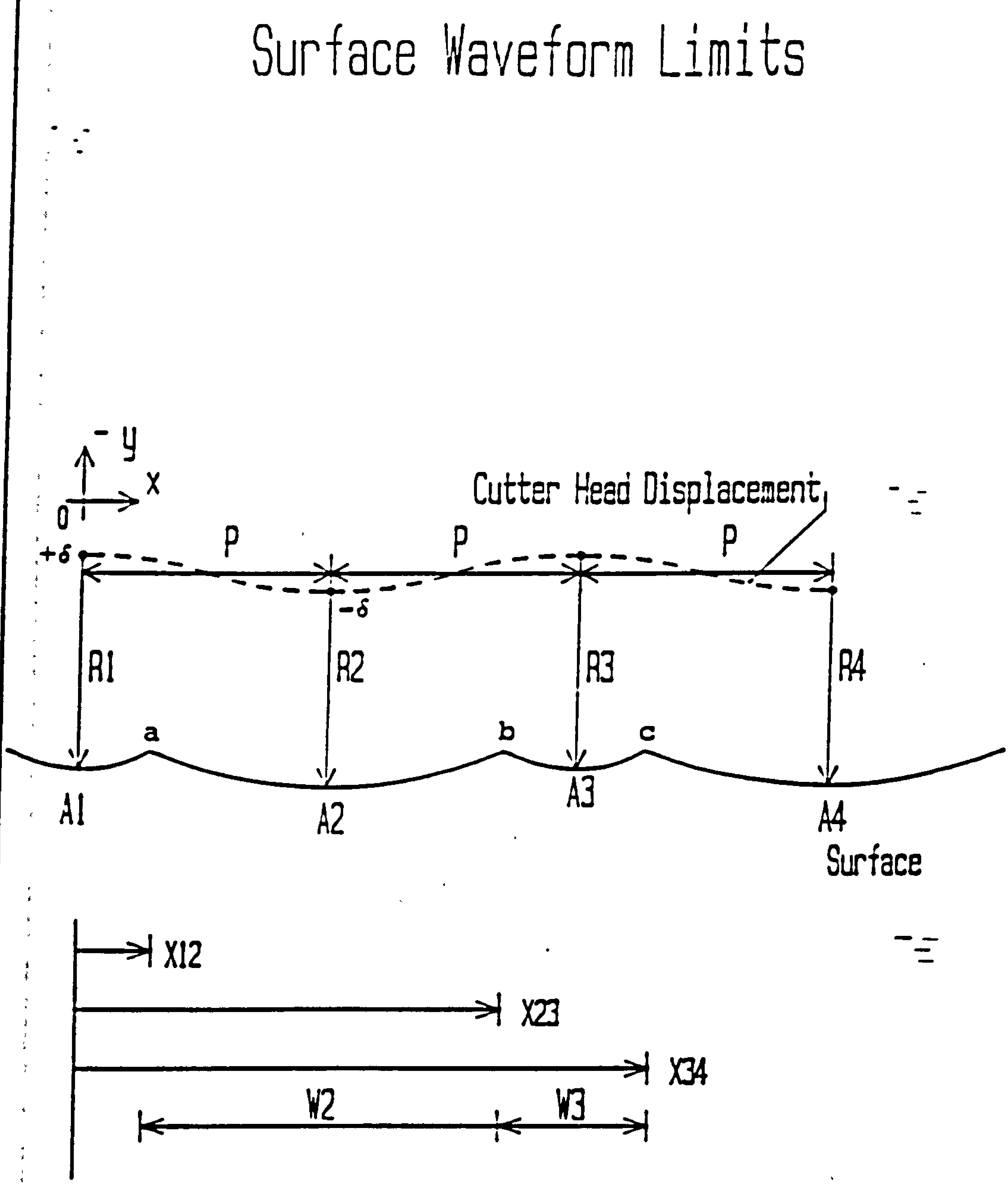

Surface Waveform Limits
-y
x
0
+δ
P
P
P
Cutter Head Displacement
-δ
R1
R2
R3
R4
a
b
c
A1
A2
A3
A4
Surface
X12
X23
X34
W2
W3

Figure 4.7

Cutter Block Assembly Motion

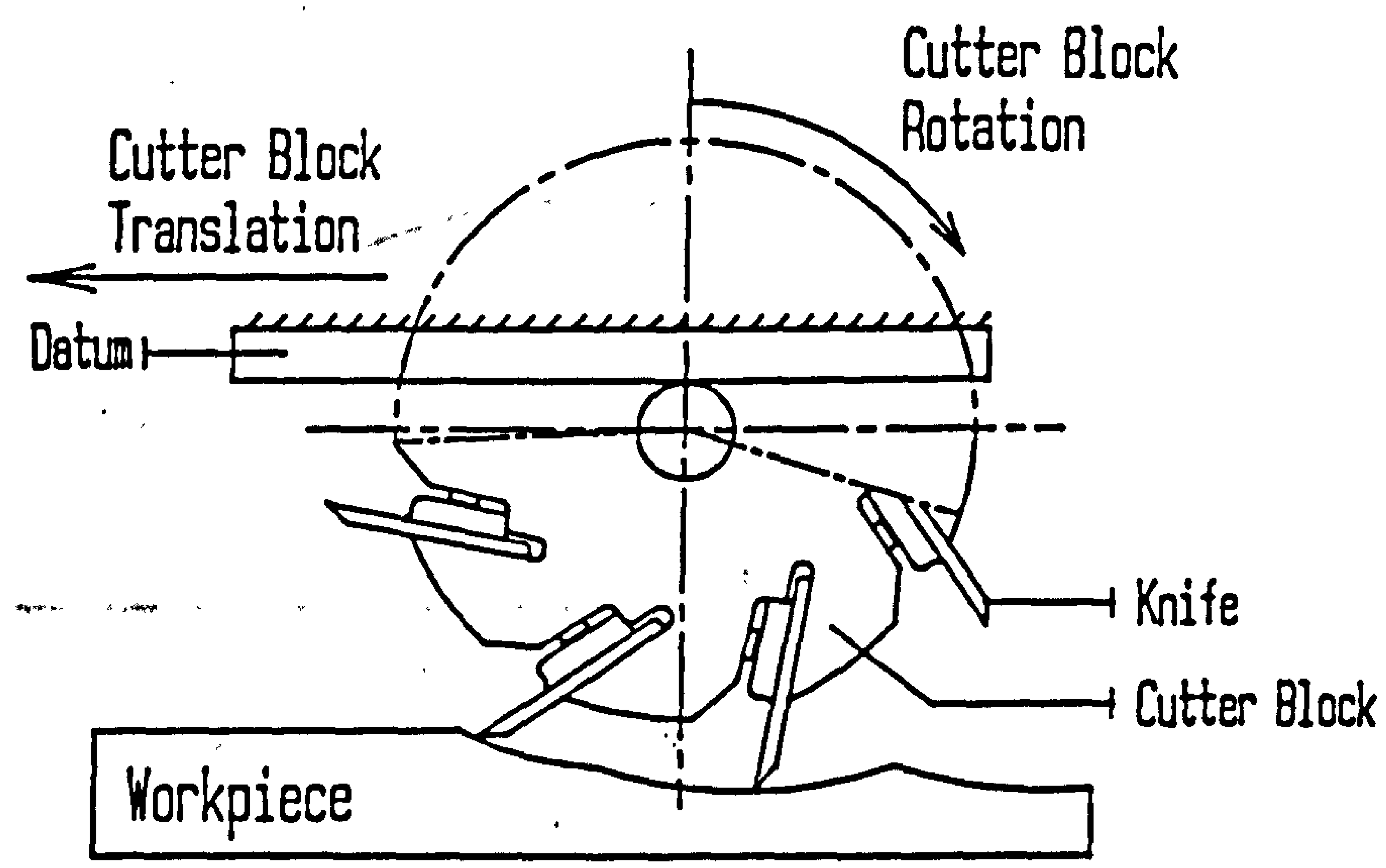
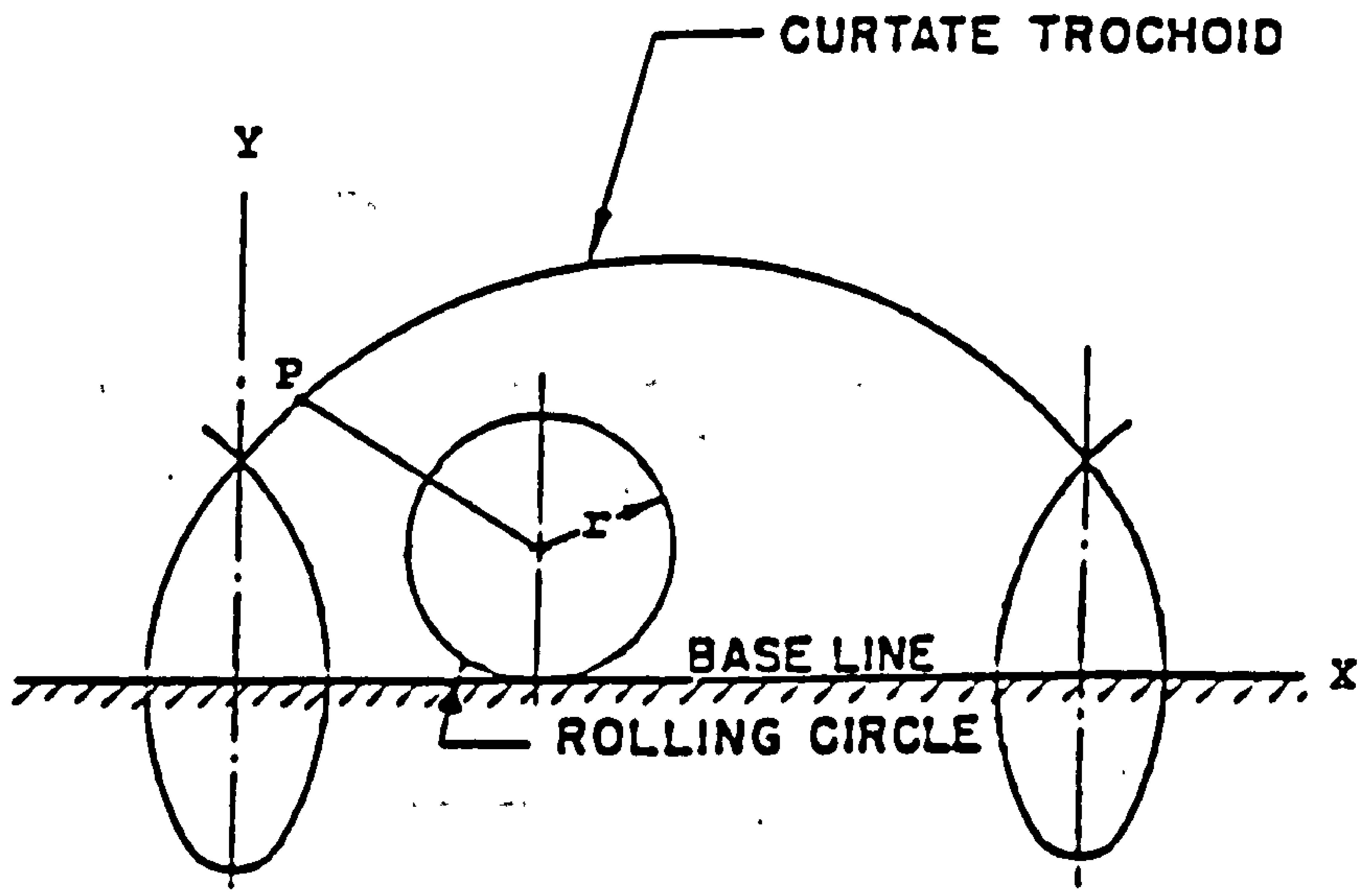


Figure 4.8

Cutter Tip Trochoidal Path



r = Radius of Rolling Circle
P = Instantaneous Cutter Tip Position

After Martellotti M.E. 1941

Figure 4.9

Cutter Block Rotation

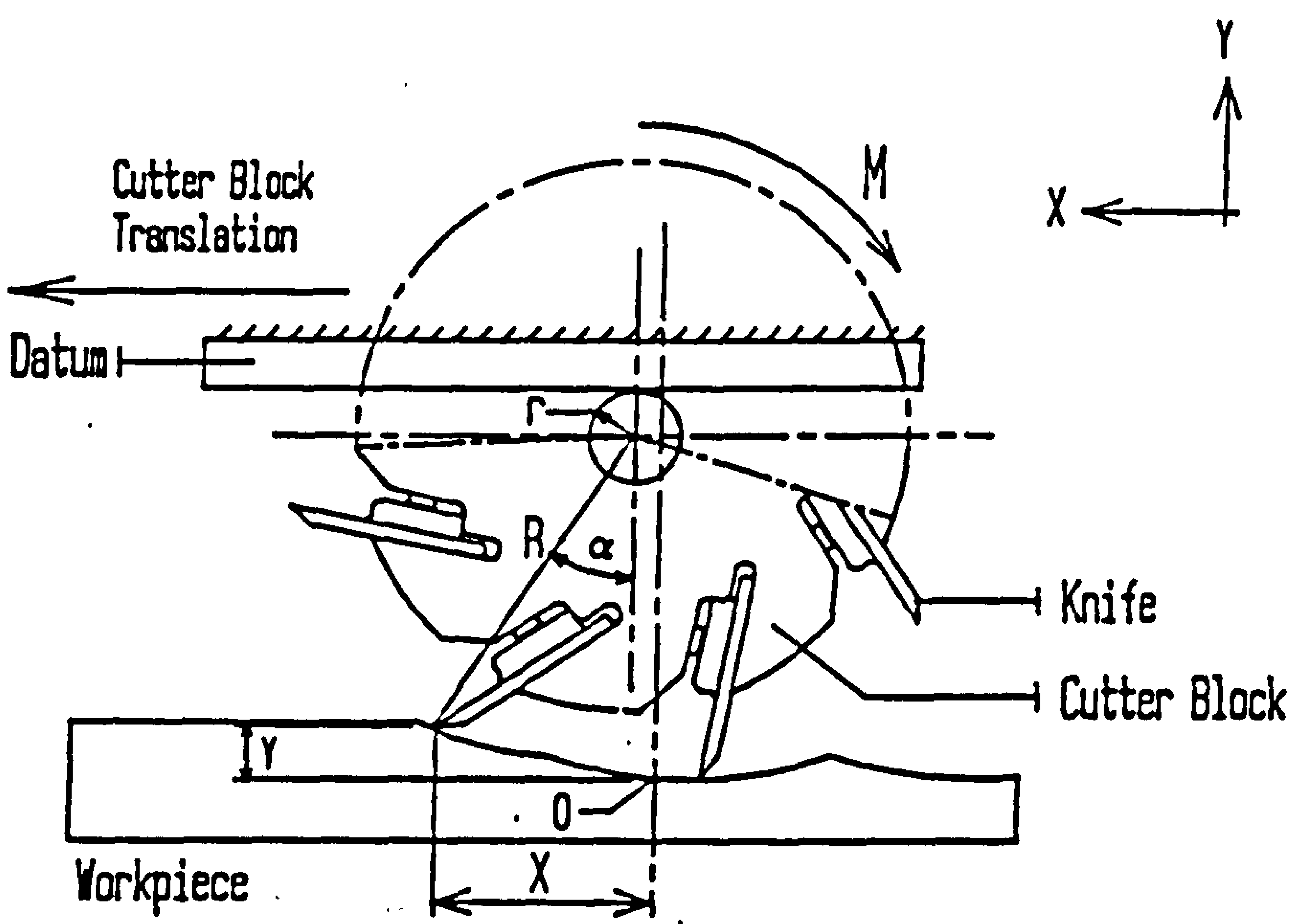
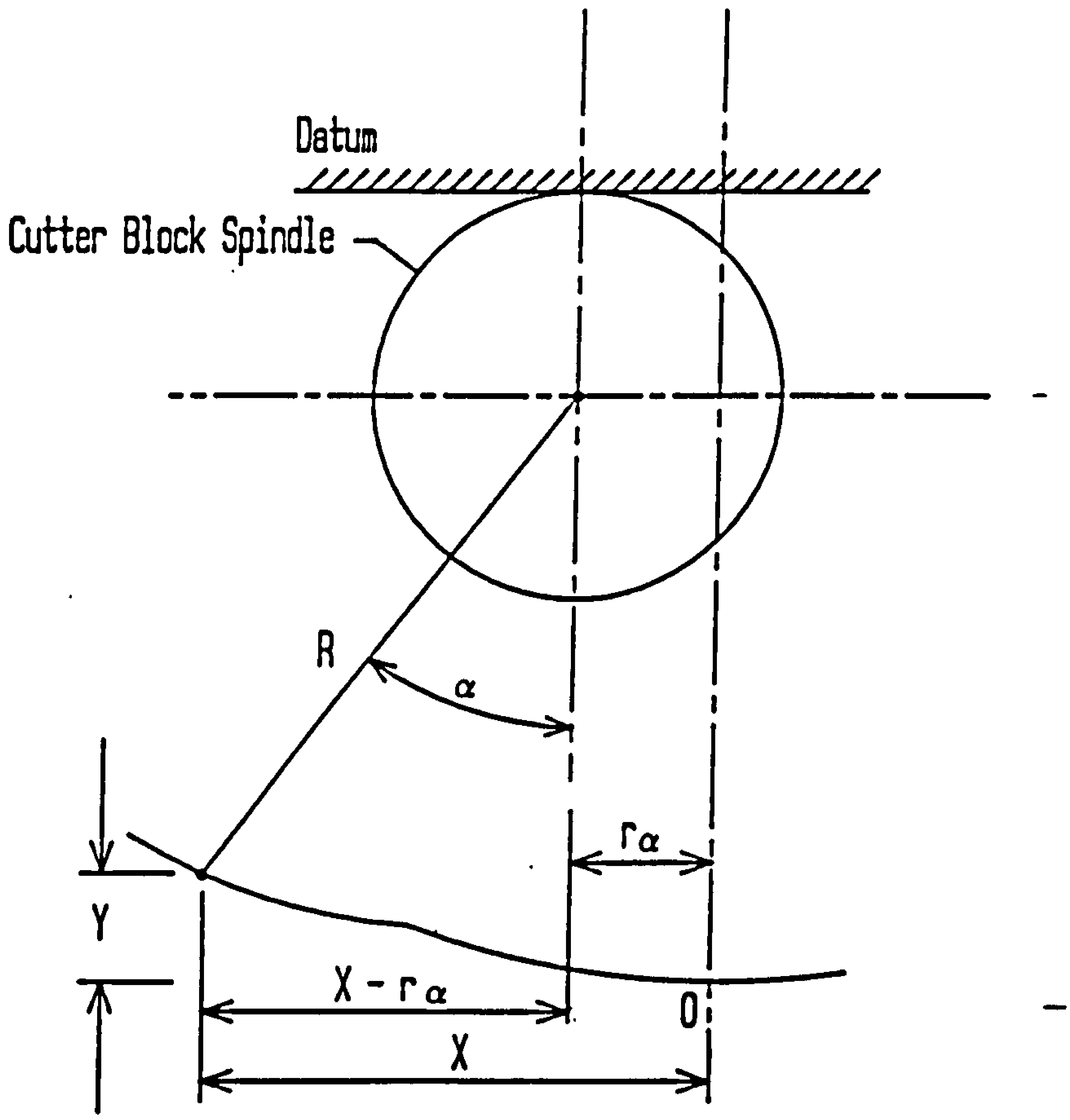


Figure 4.10

Rotation Analysis

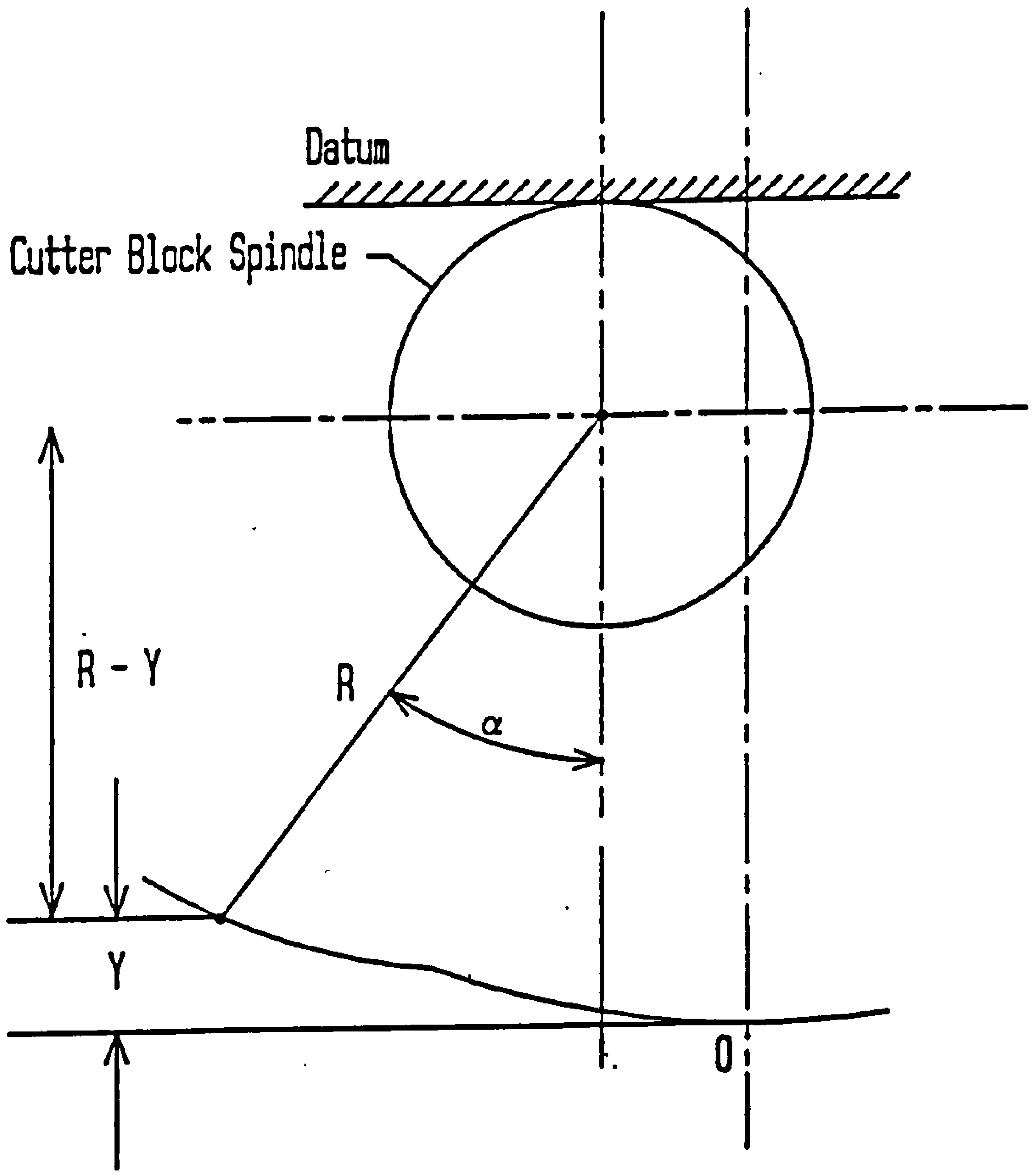


Sinα = (X - rα)/R X = RSinα + rα

The spindle's circumference length subtended by the angle α is equal to rα.

Figure 4.11

Rotation Analysis

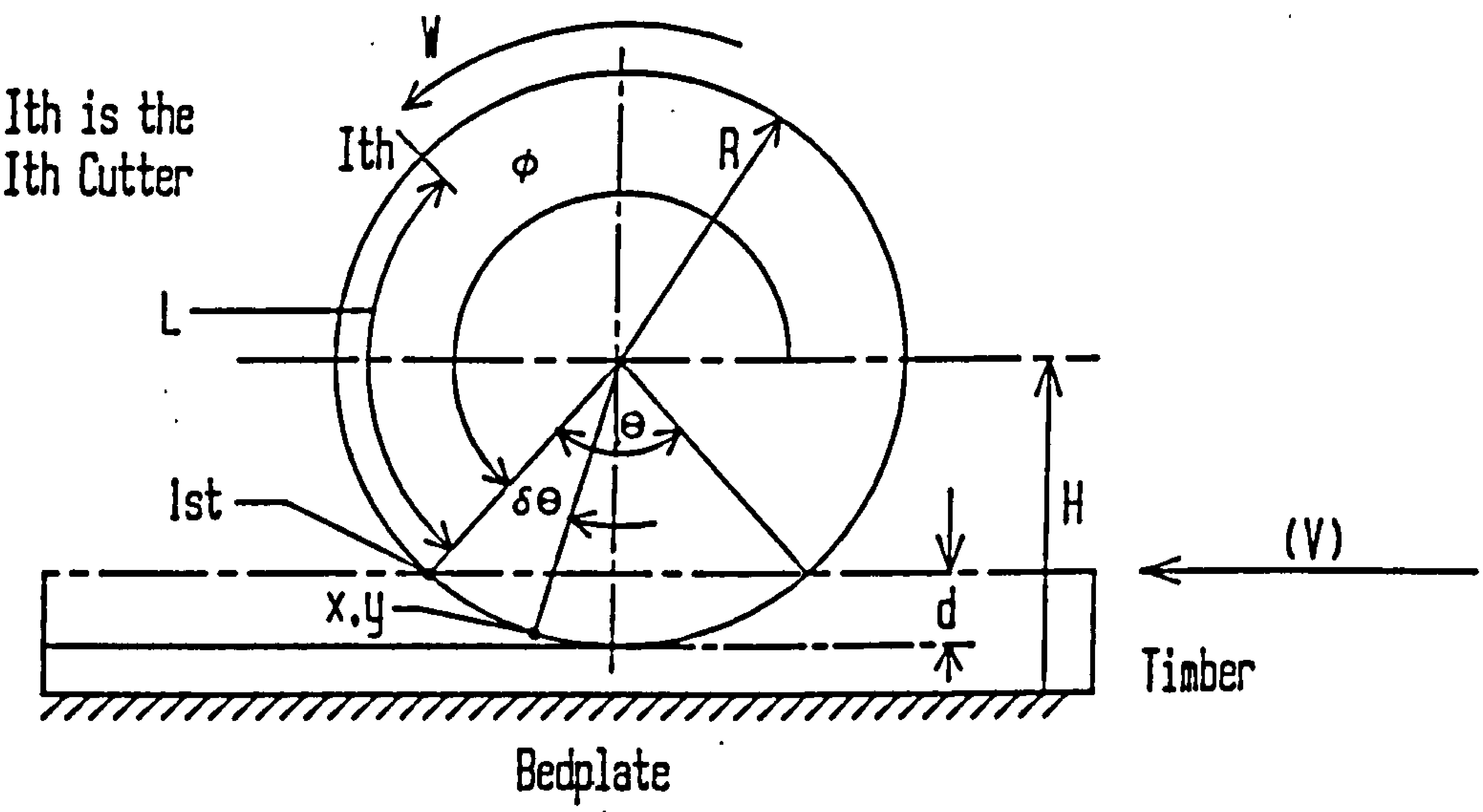


$$\cos\alpha = (R - Y)/R \qquad Y = R - R\cos\alpha$$

$$Y = R(1 - \cos\alpha)$$

Figure 4.12

Trochoidal Analysis



L is equal to the general angle of lag
Lb is equal to the angle between knives

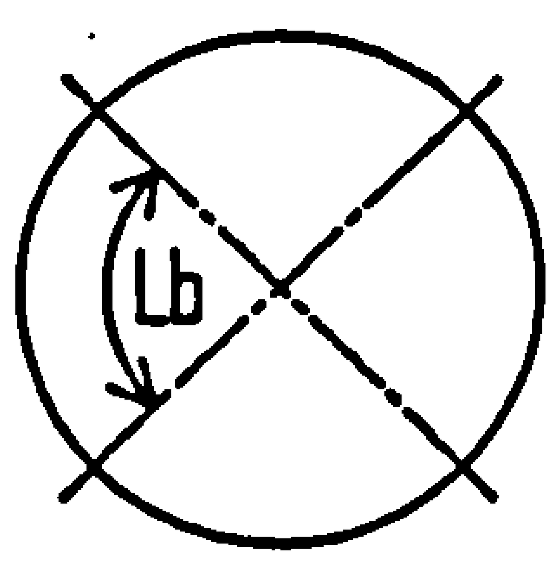


Figure 4.13

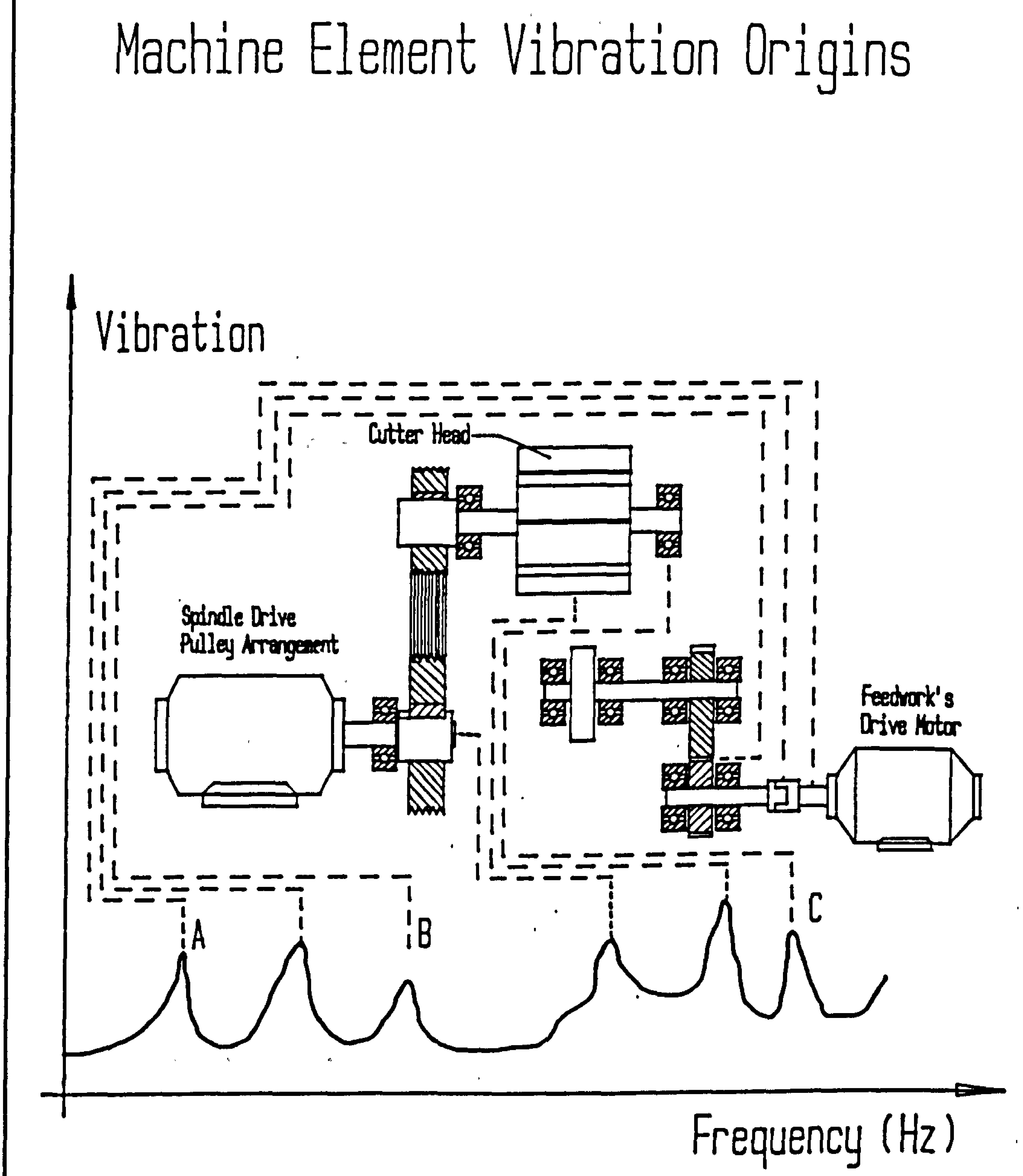

Machine Element Vibration Origins
Vibration
Cutter Head
Spindle Drive
Pulley Arrangement
Feedwork's
Drive Motor
A
B
C
Frequency (Hz)

Figure 5.1

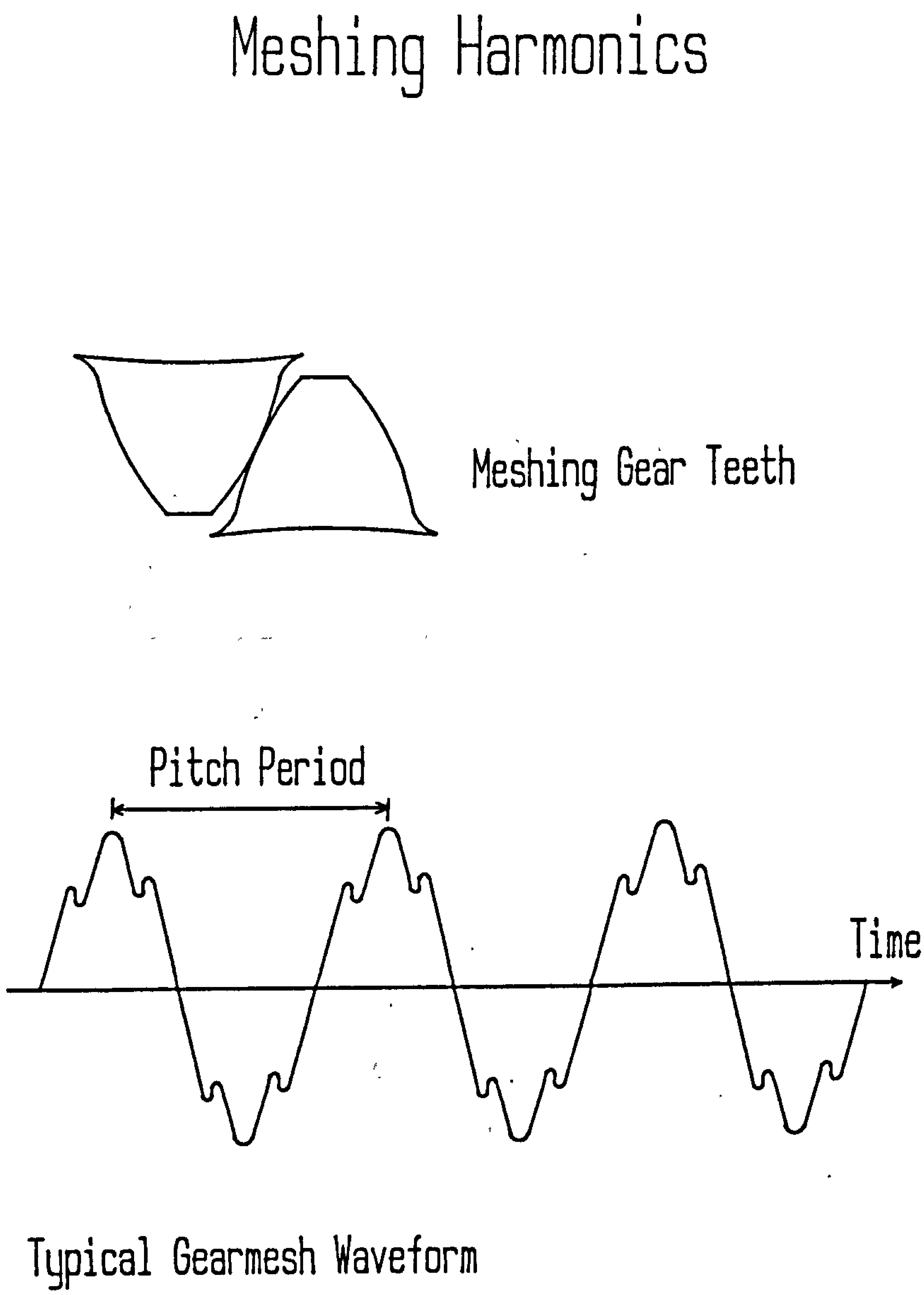

Meshing Harmonics
Meshing Gear Teeth
Pitch Period
Time
Typical Gearmesh Waveform

Figure 5.2

Vibration Characteristic

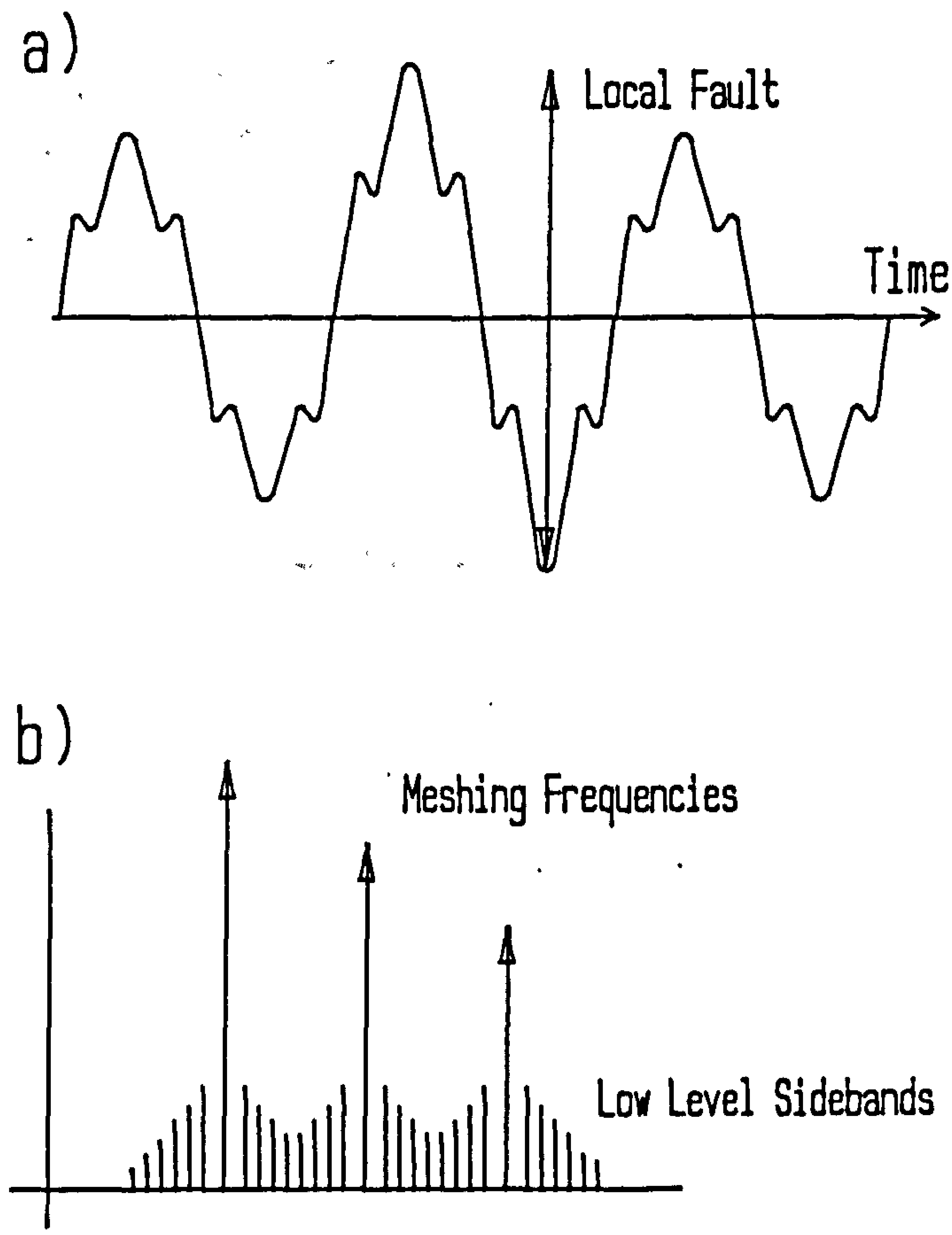


Figure 5.3

The Effect of Fault Propagation

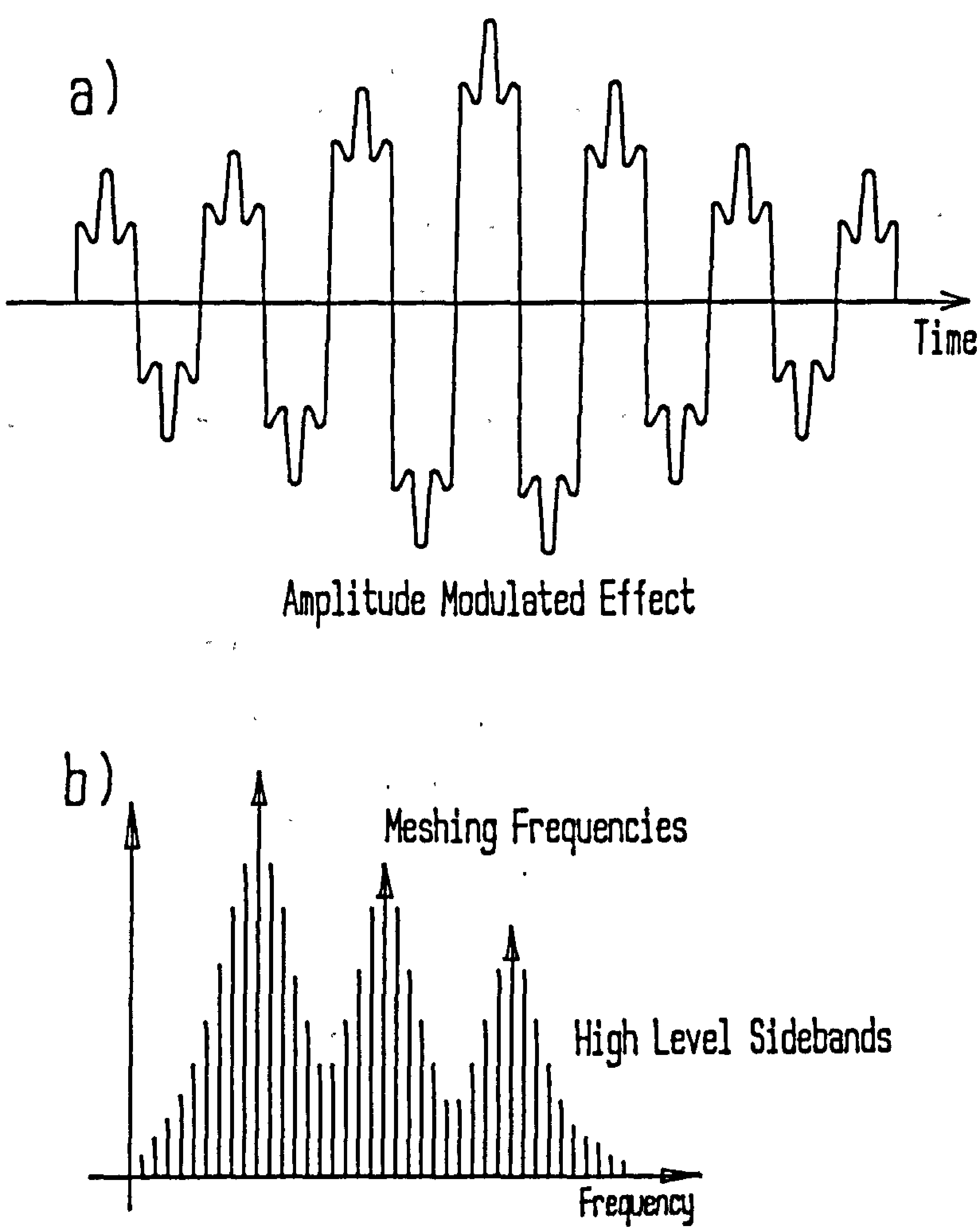


Figure 5.4

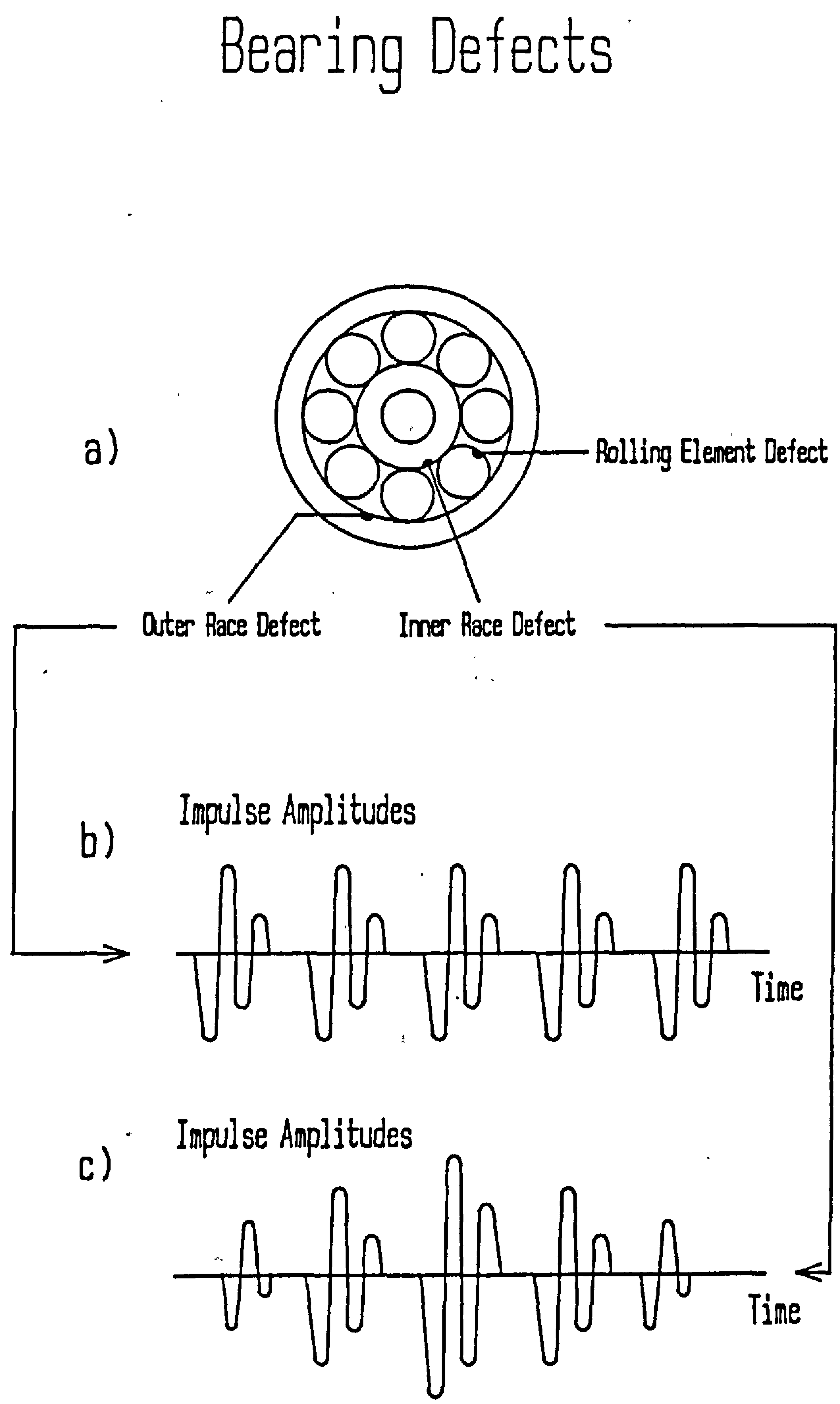
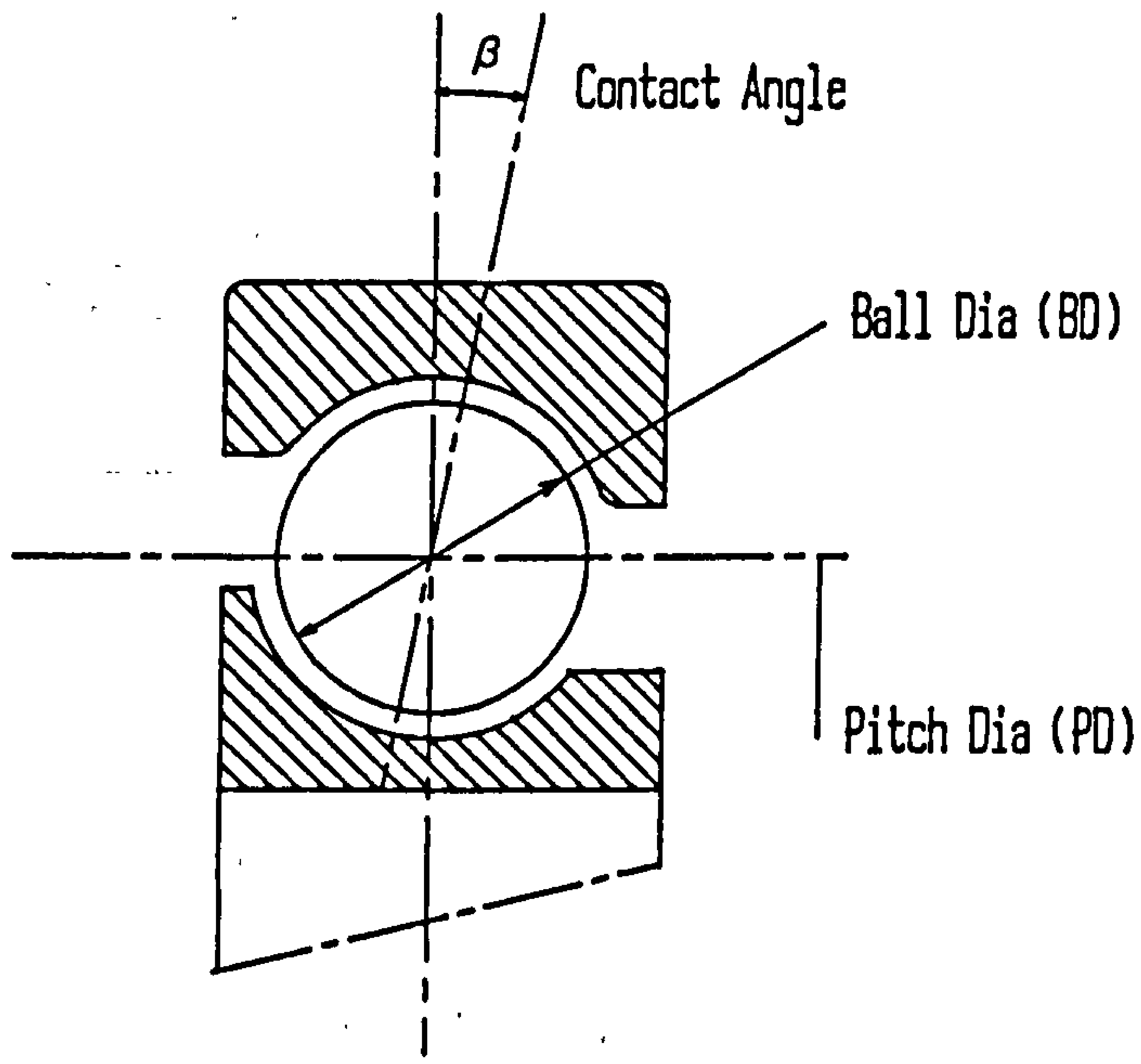

Bearing Defects
a)
Rolling Element Defect
Outer Race Defect
Inner Race Defect
b)
Impulse Amplitudes
Time
c)
Impulse Amplitudes
Time

Figure 5.5

Rolling Element Bearing Impulse Frequency Rates



N = Number of Balls or Rollers

1 = Relative rev/s Between Inner and Outer Races

Impact Rates f(Hz) (assuming pure rolling motion)

For Outer Race Defect: $f(Hz) = N/2 \; 1(1-(BD/PD)\cos\beta)$

For Inner Race Defect: $f(Hz) = N/2 \; 1(1+(BD/PD)\cos\beta)$

For Ball Defect: $f(Hz) = (PD/BD) \; 1(1-((PD/BD)\cos\beta))$

Figure 5.6

Cutter Head Balancing Apparatus

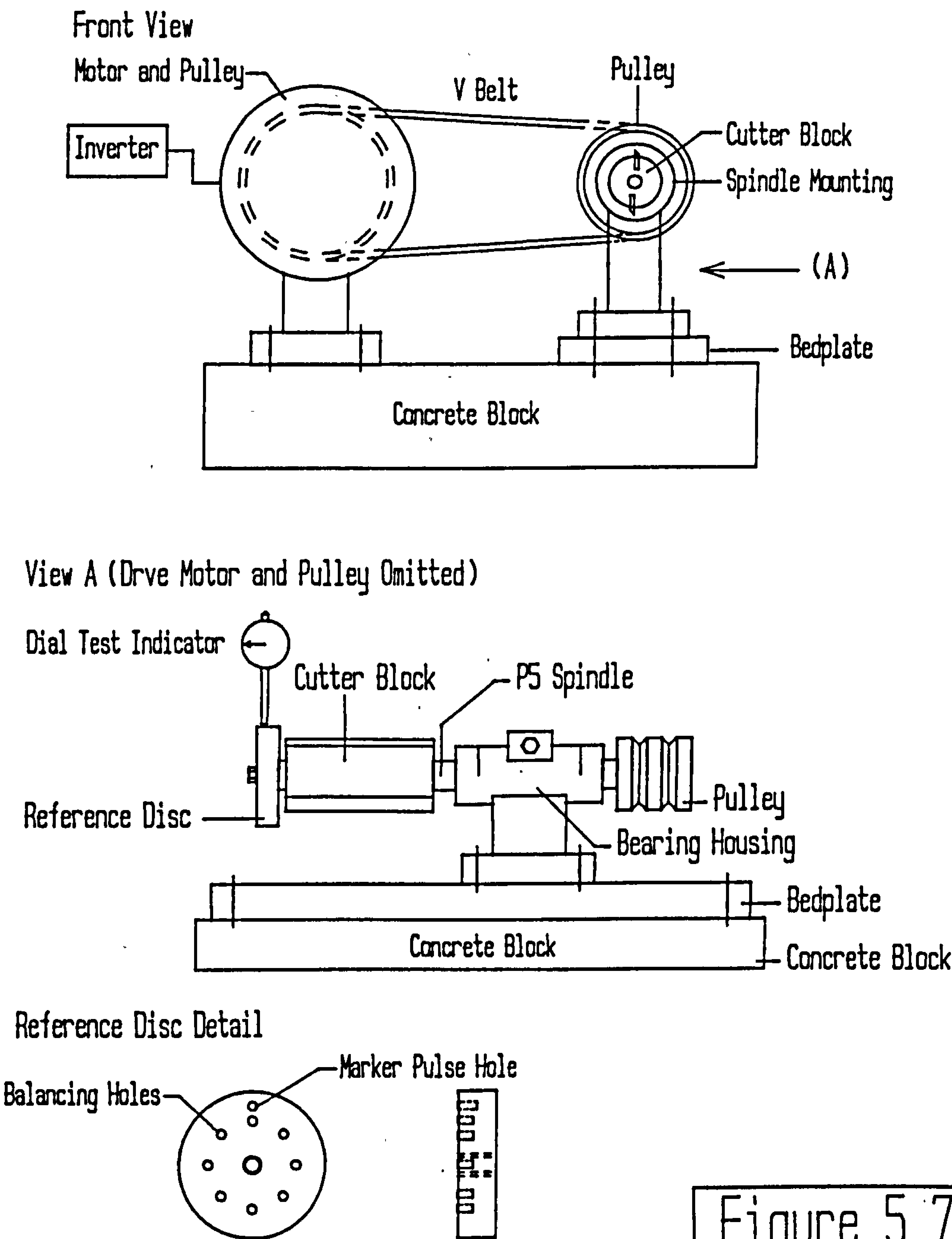


Figure 5.7

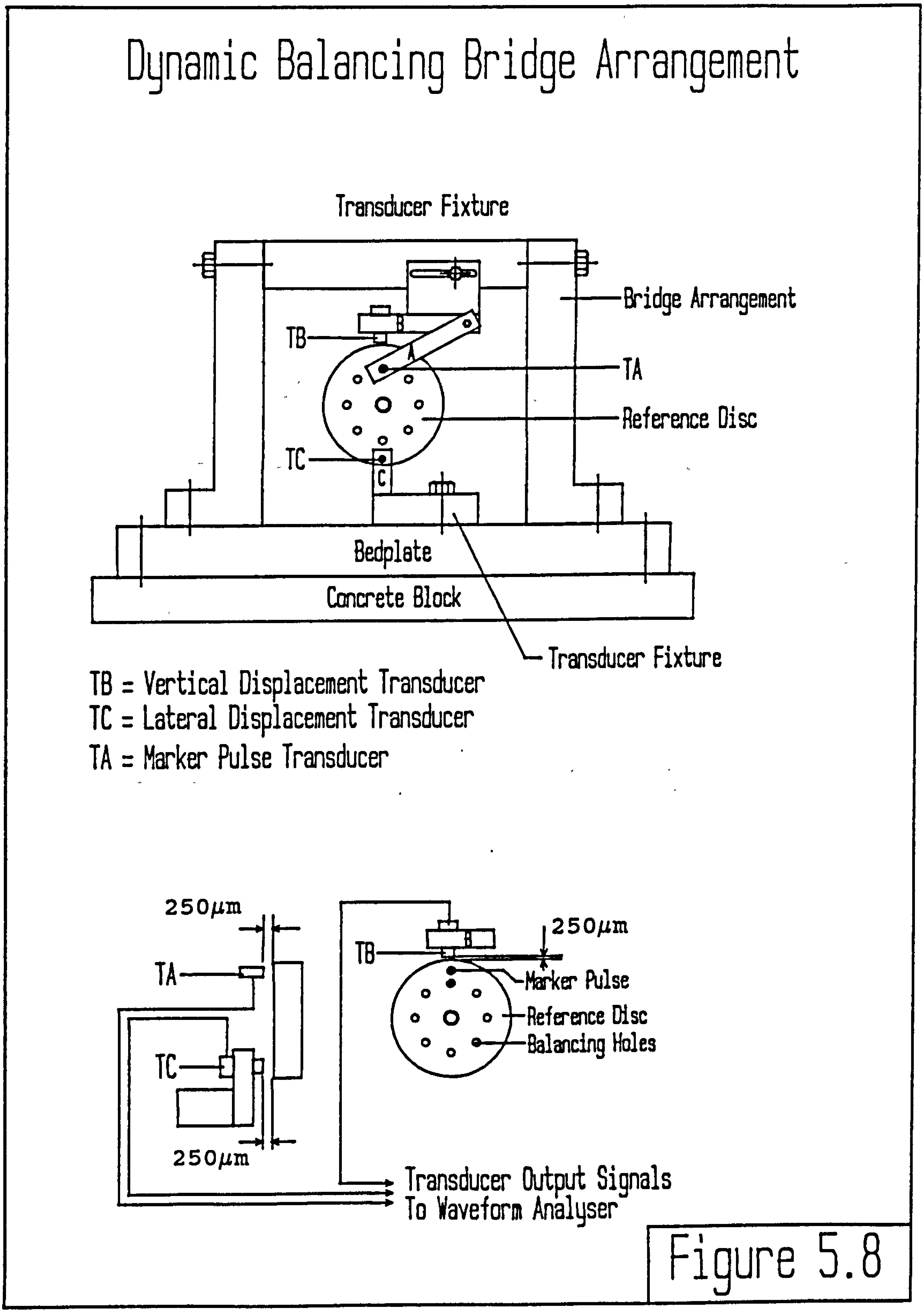

Dynamic Balancing Bridge Arrangement
Transducer Fixture
Bridge Arrangement
TB
TA
Reference Disc
TC
Bedplate
Concrete Block
Transducer Fixture
TB = Vertical Displacement Transducer
TC = Lateral Displacement Transducer
TA = Marker Pulse Transducer
250μm
TA
TC
250μm
TB
250μm
Marker Pulse
Reference Disc
Balancing Holes
Transducer Output Signals
To Waveform Analyser

Figure 5.8

Signal Conditioning

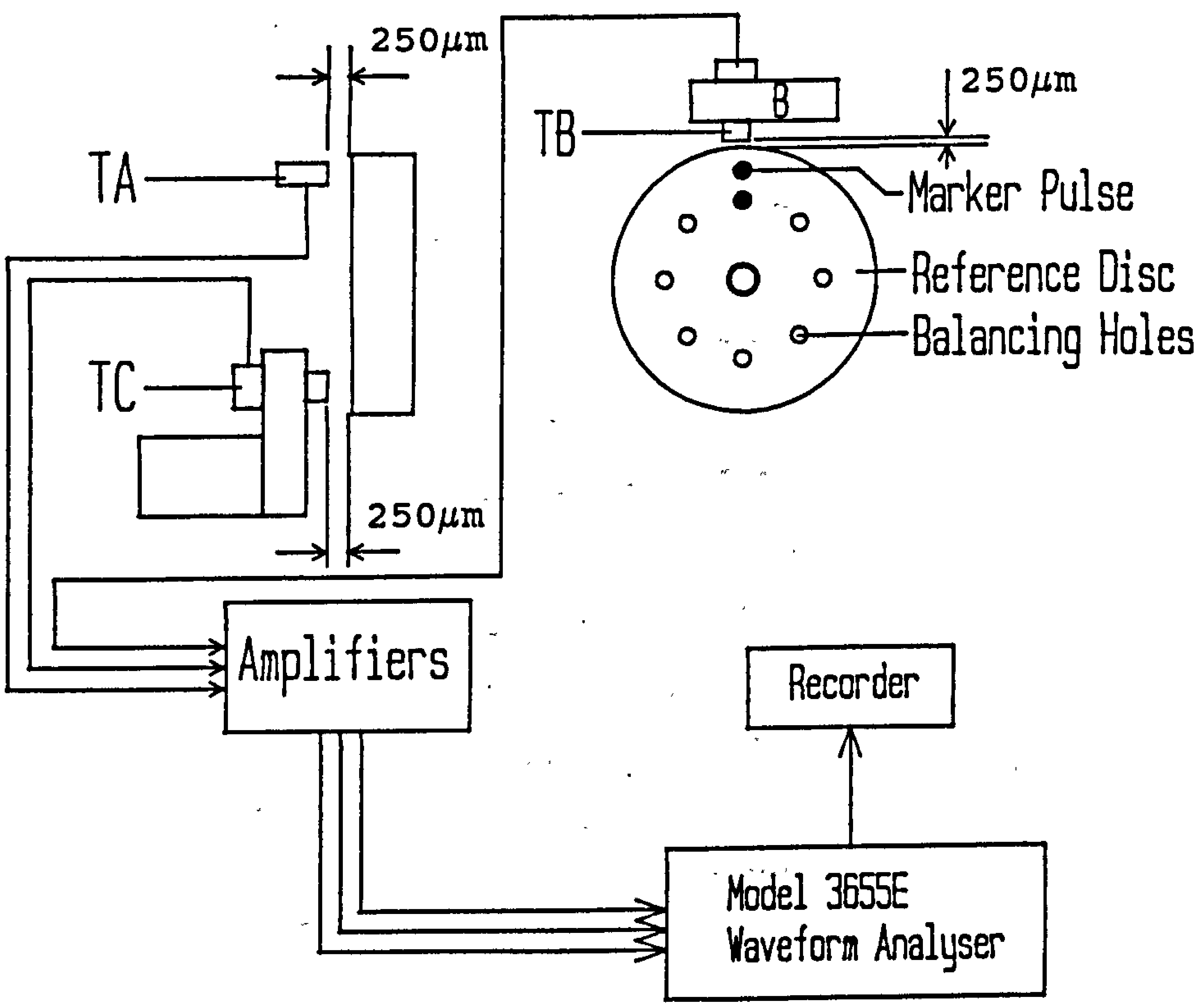


Figure 5.9

Reference Disc's Initial Displacement

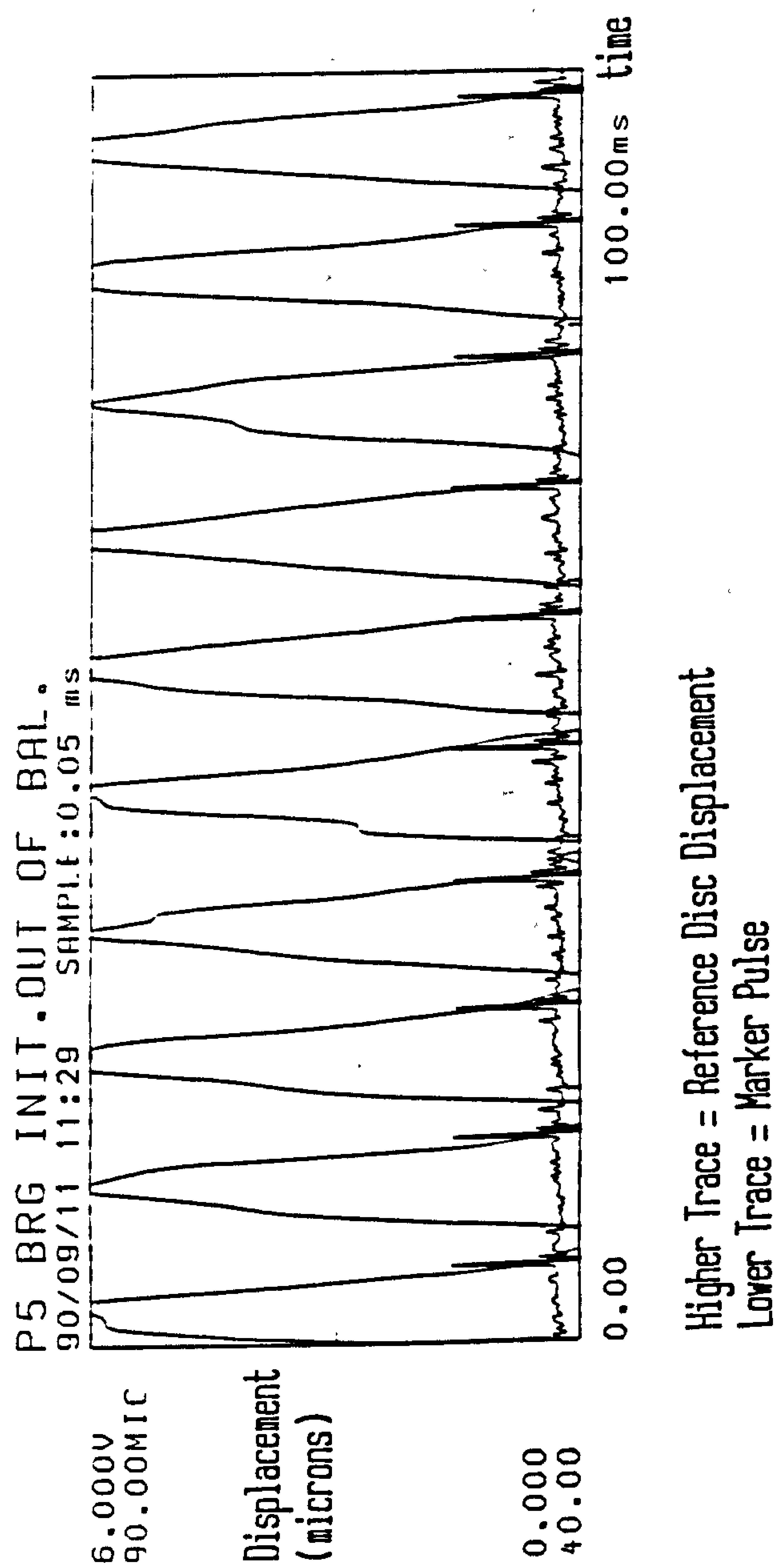


Figure 5.10

Reference Disc's Final Displacement

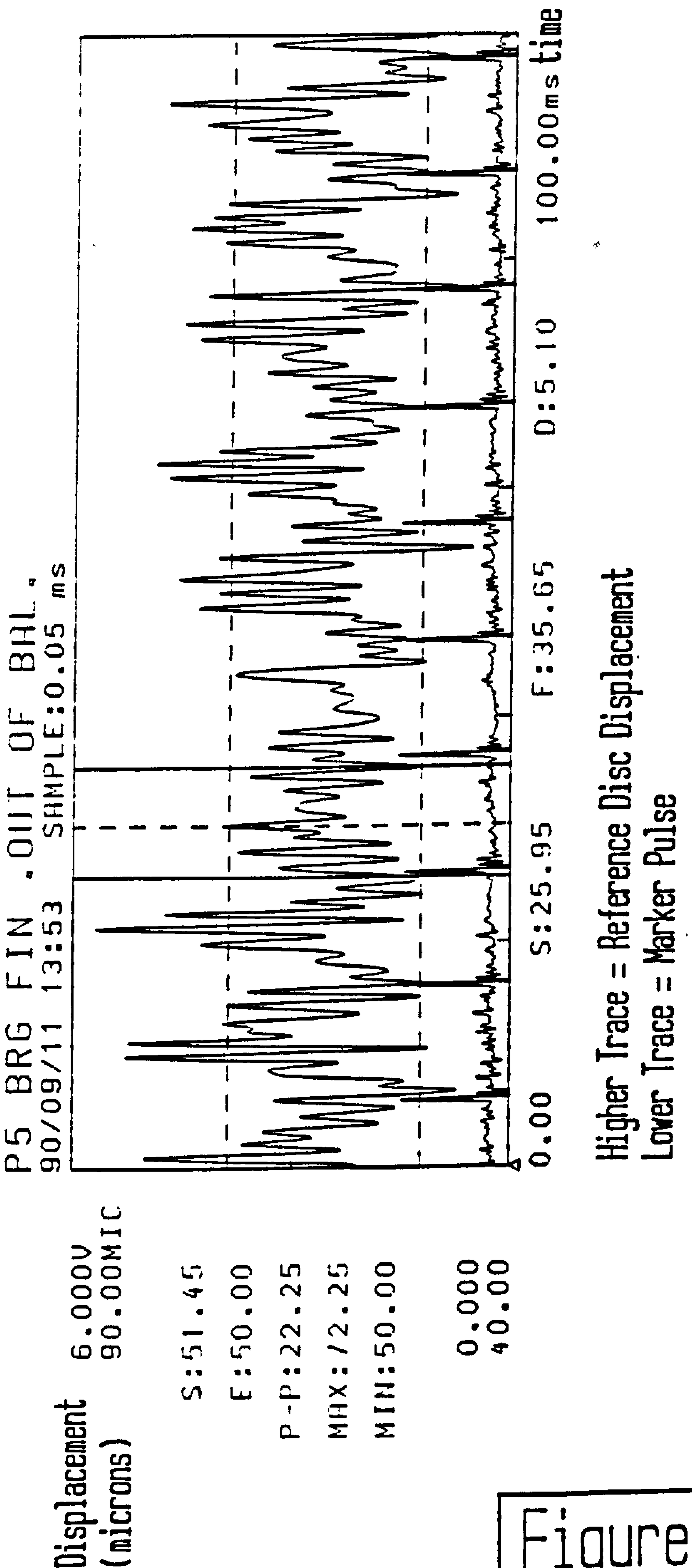


Figure 5.11

Aliasing

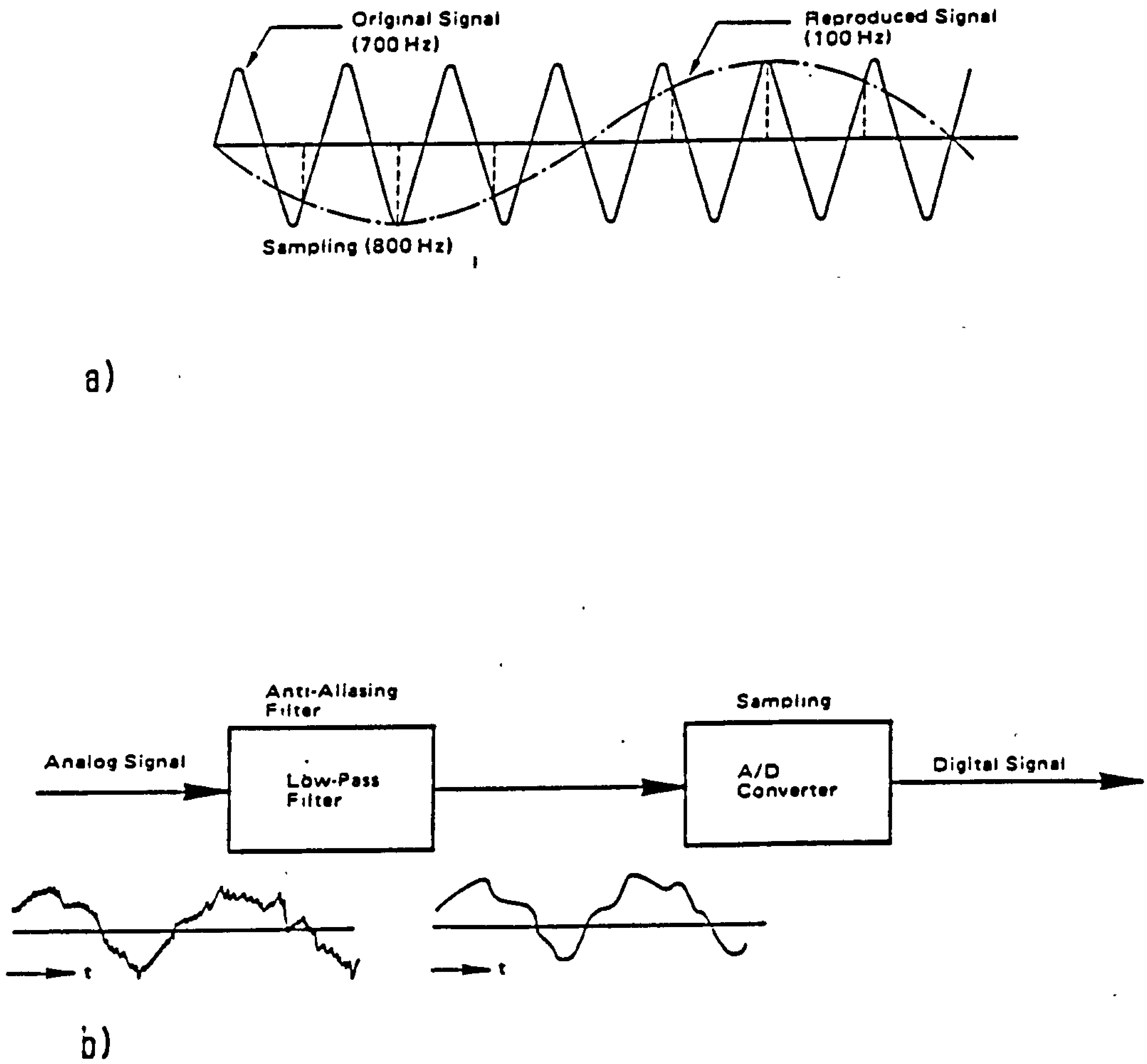


Figure 5.12

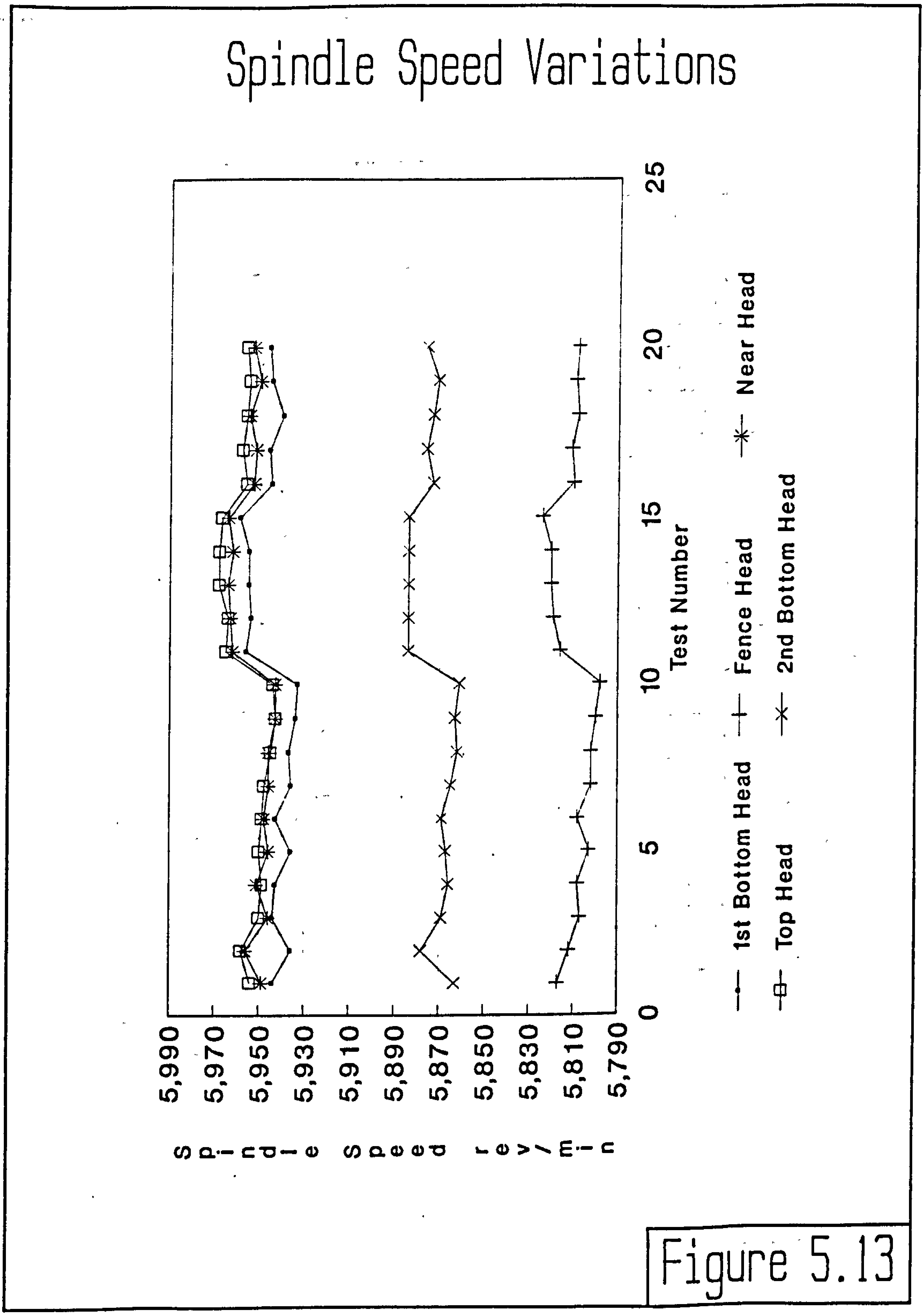

Spindle Speed Variations
Spindle Speed rev/min
5,990
5,970
5,950
5,930
5,910
5,890
5,870
5,850
5,830
5,810
5,790
0
5
10
15
20
25
Test Number
1st Bottom Head
Fence Head
Near Head
Top Head
2nd Bottom Head

Figure 5.13

Top Head Running Only

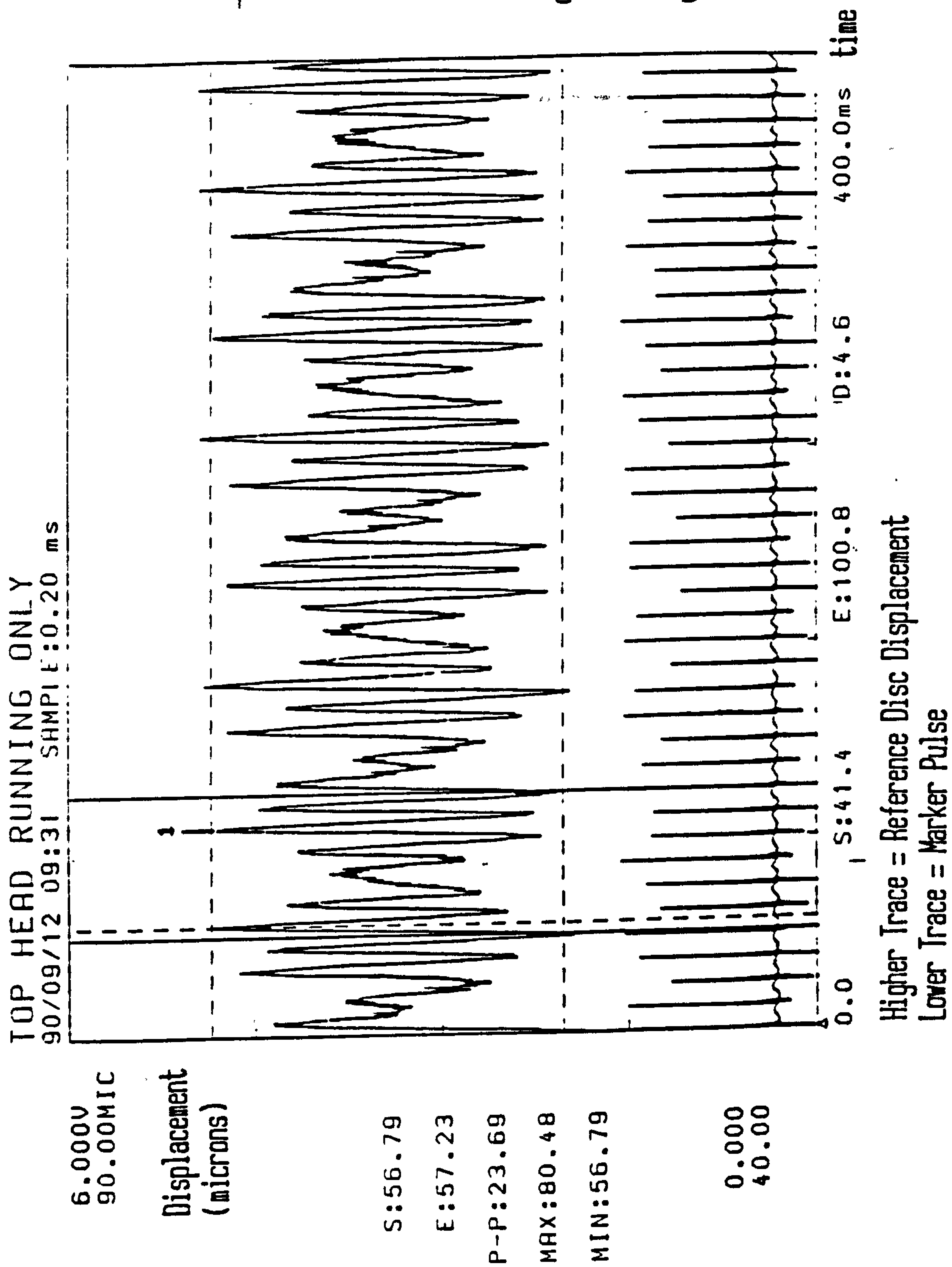


Figure 5.14

Top Head Running Only (Concrete Block)

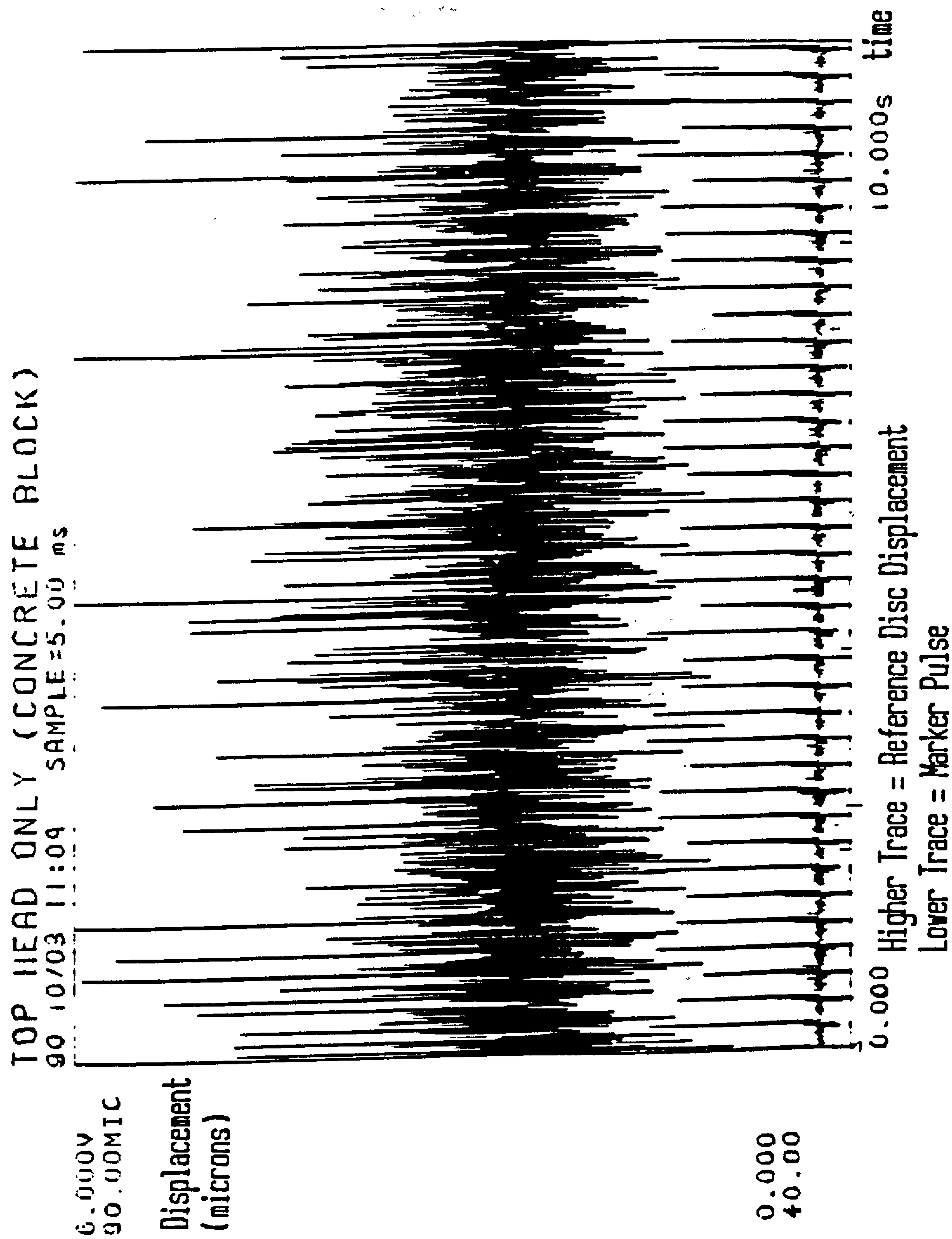


Figure 5.15

Top Head Running Only (Machine)

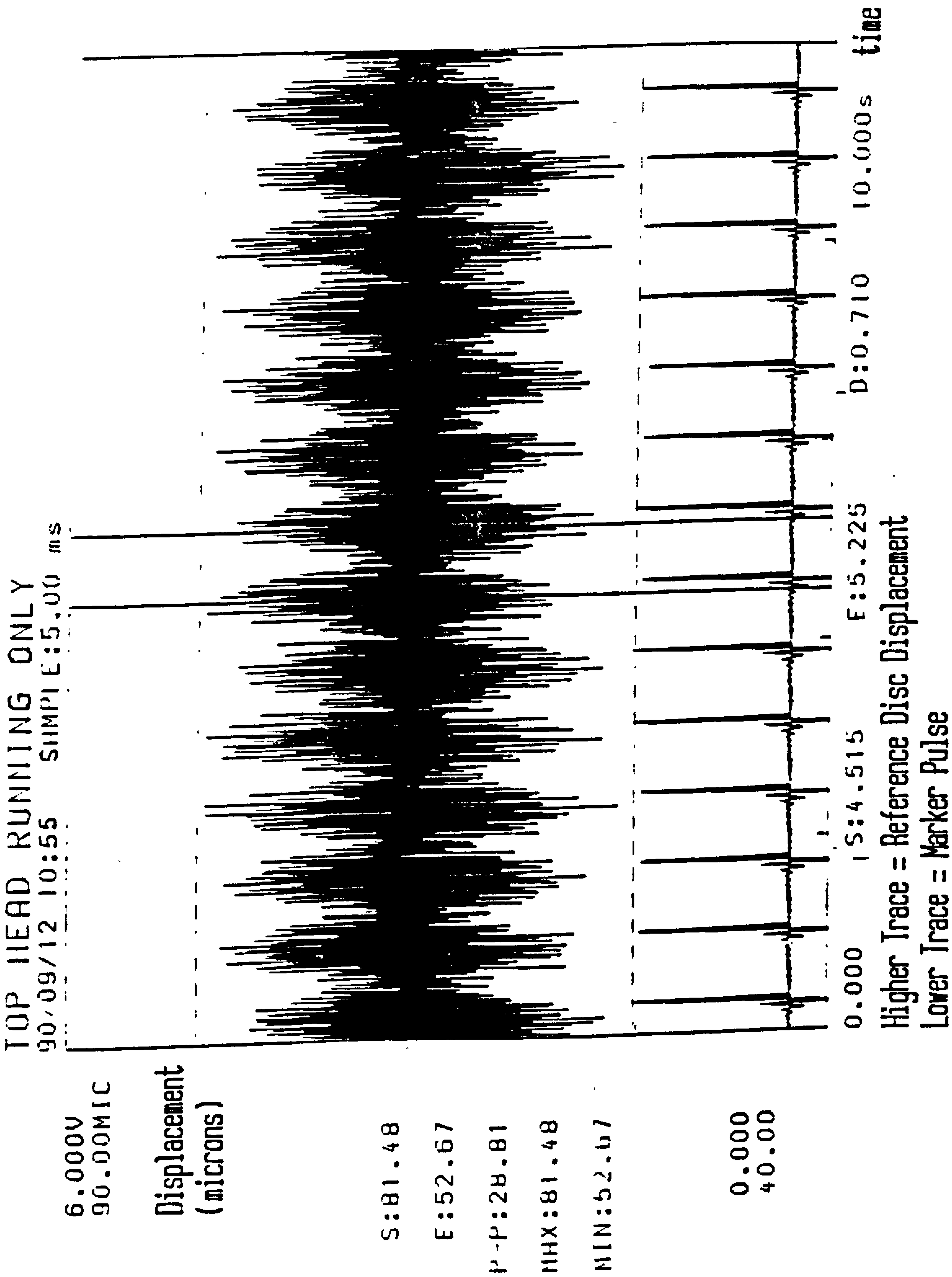


Figure 5.16

Machine Cutter Head Relationship

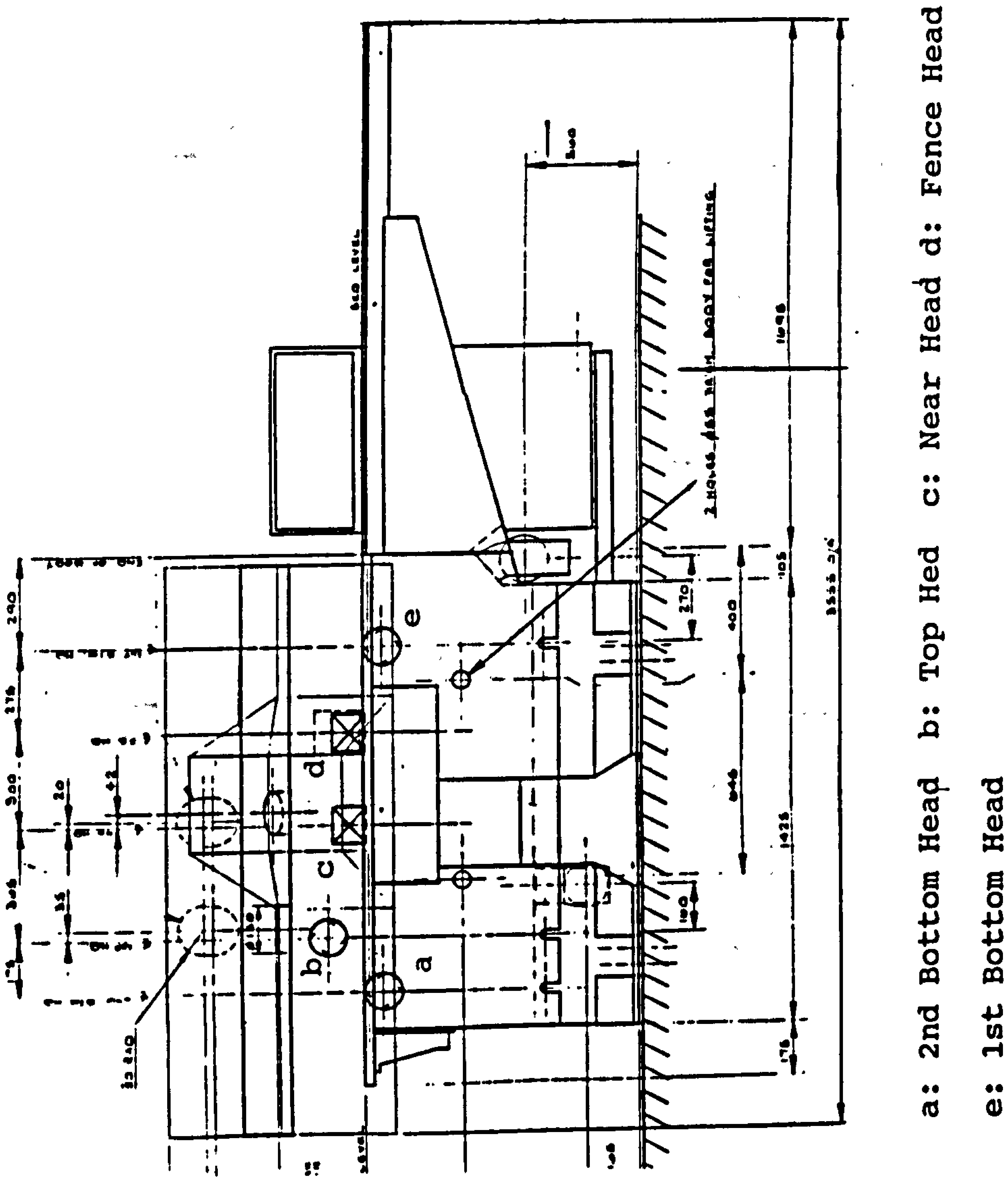


Figure 5.17

Top Head Running With 1st Bottom Head

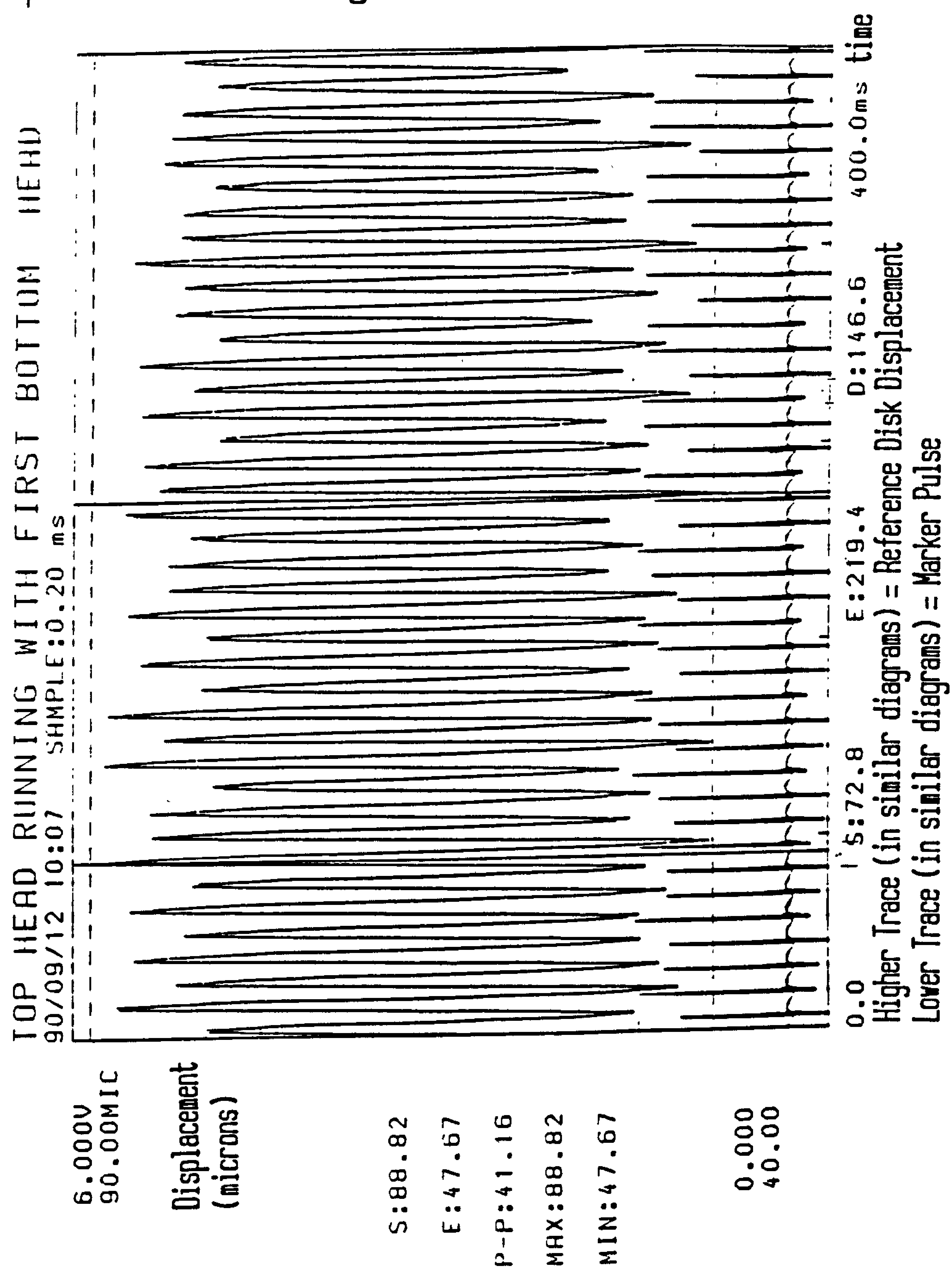


Figure 5.18

Top Head Running With 1st Bottom Head

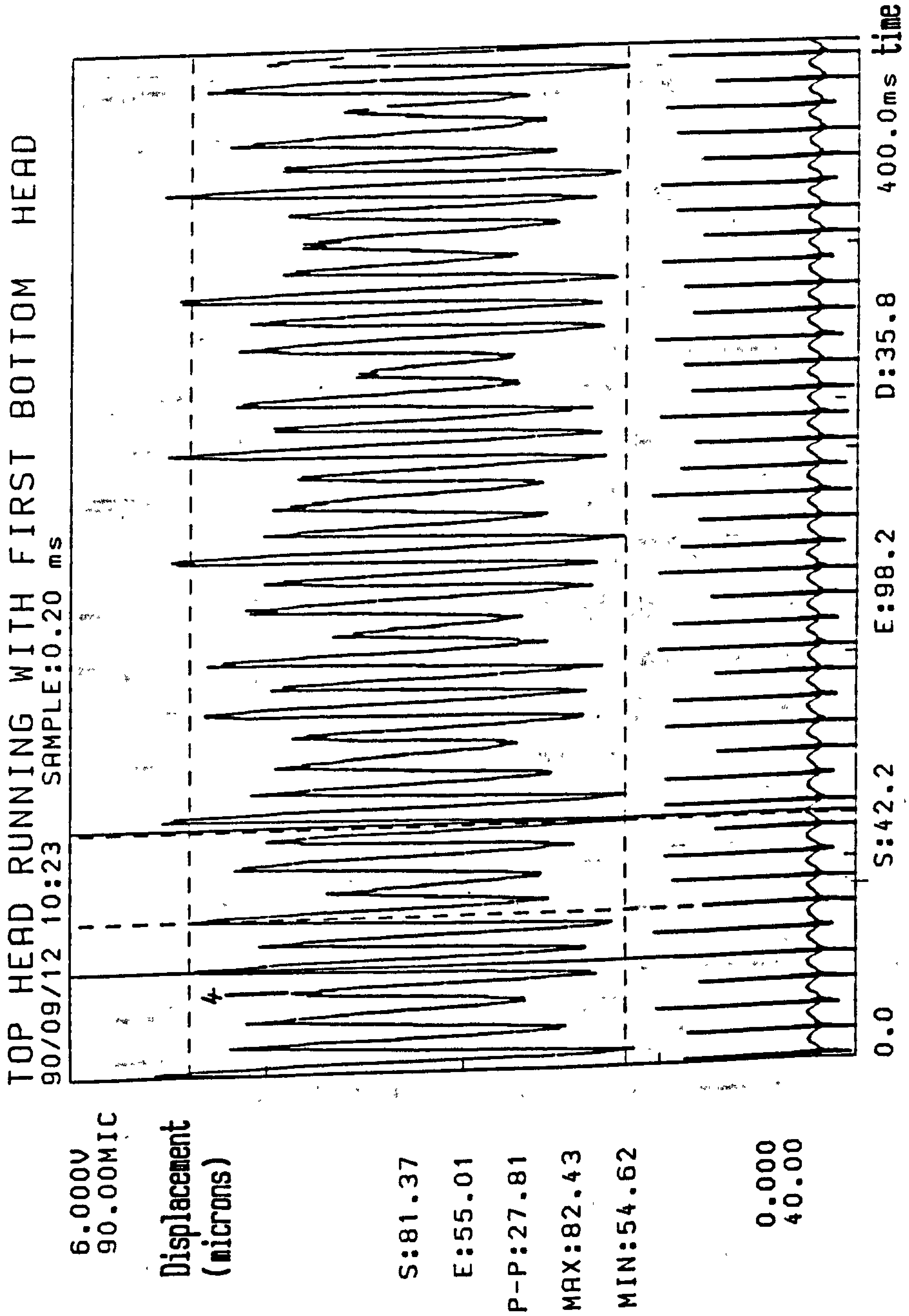


Figure 5.19

Top Head Running With 1st Bottom Head

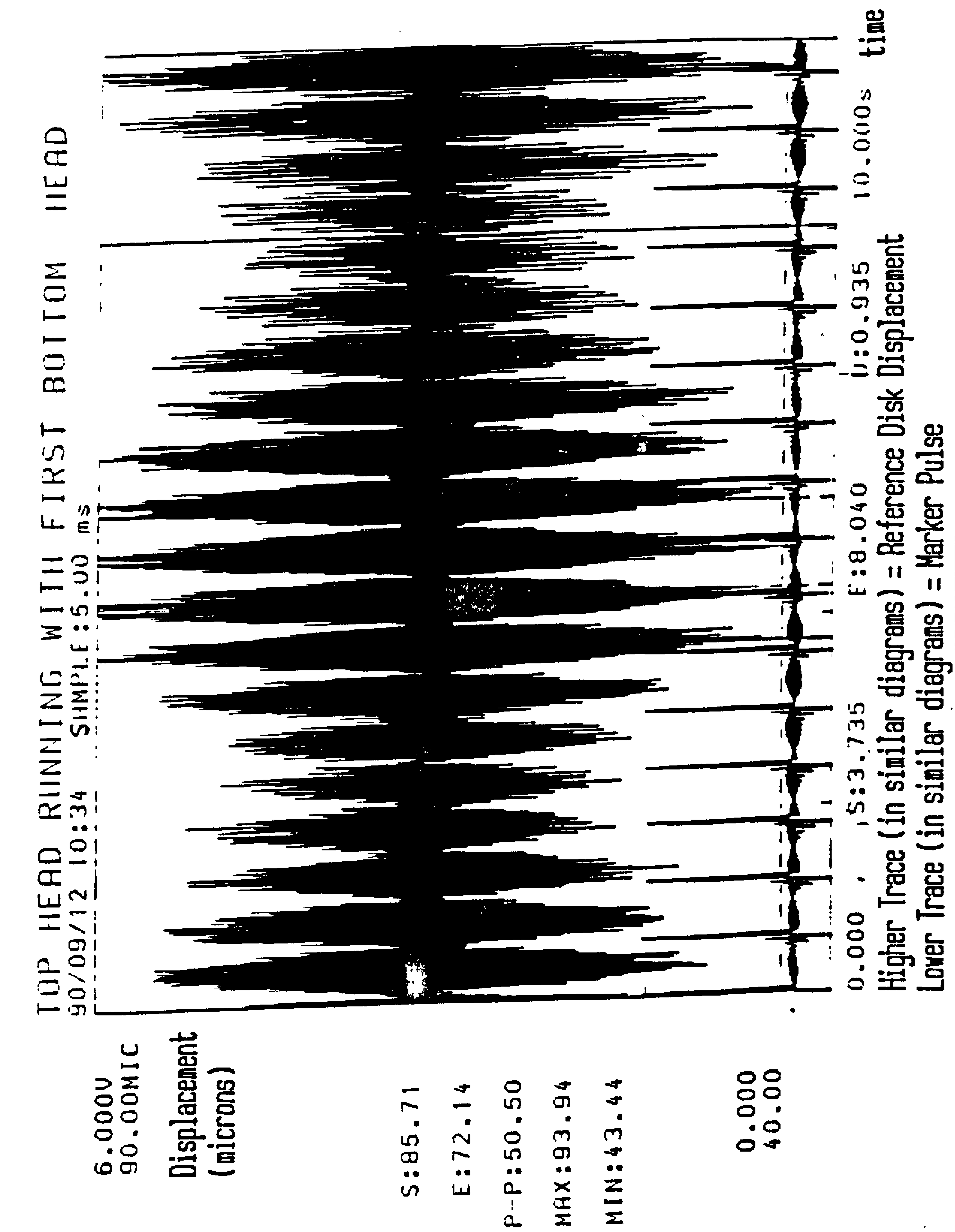


Figure 5.20

Top Head Running With 2nd Bottom Head

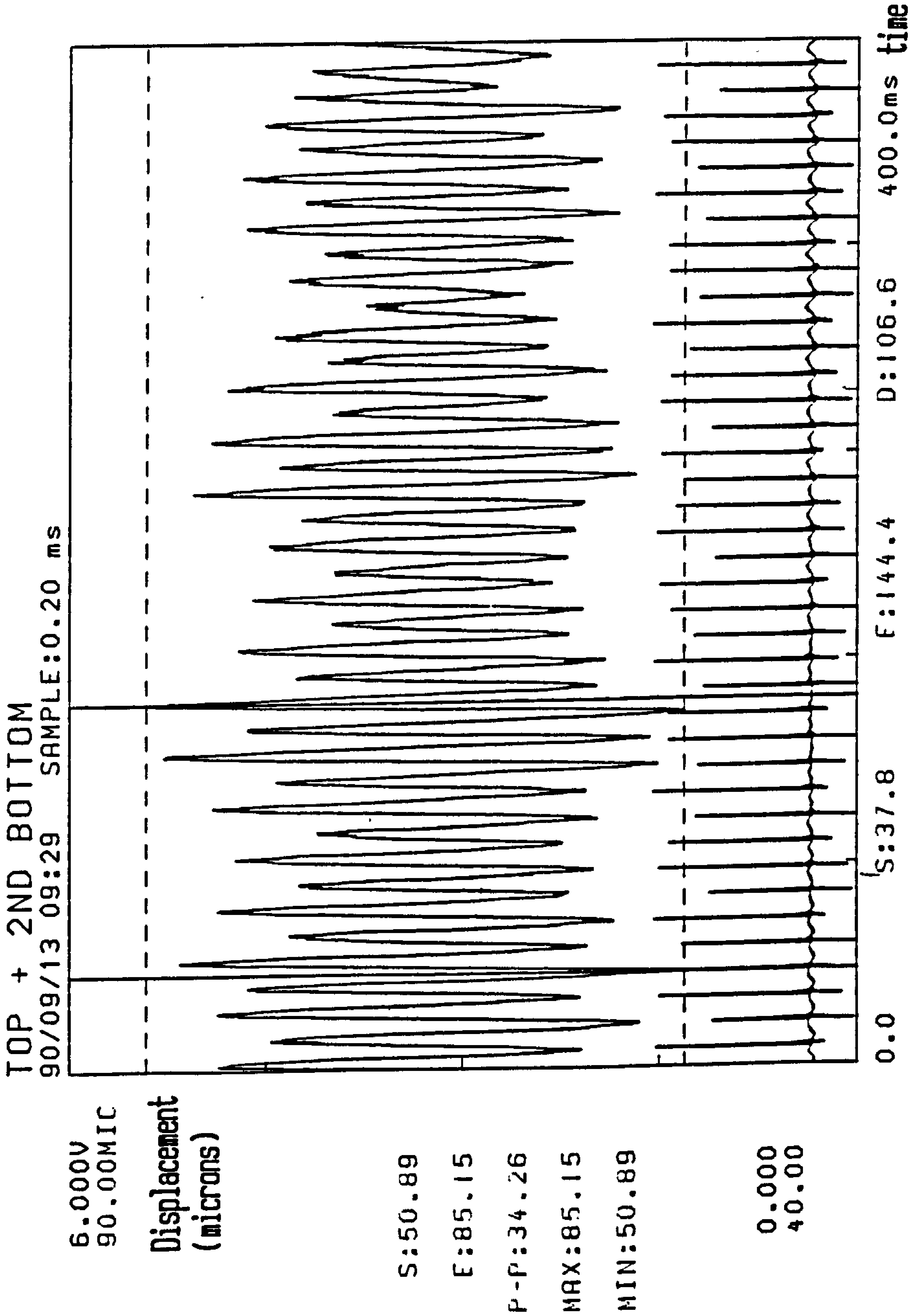


Figure 5.21

Top Head Running With 2nd Bottom Head

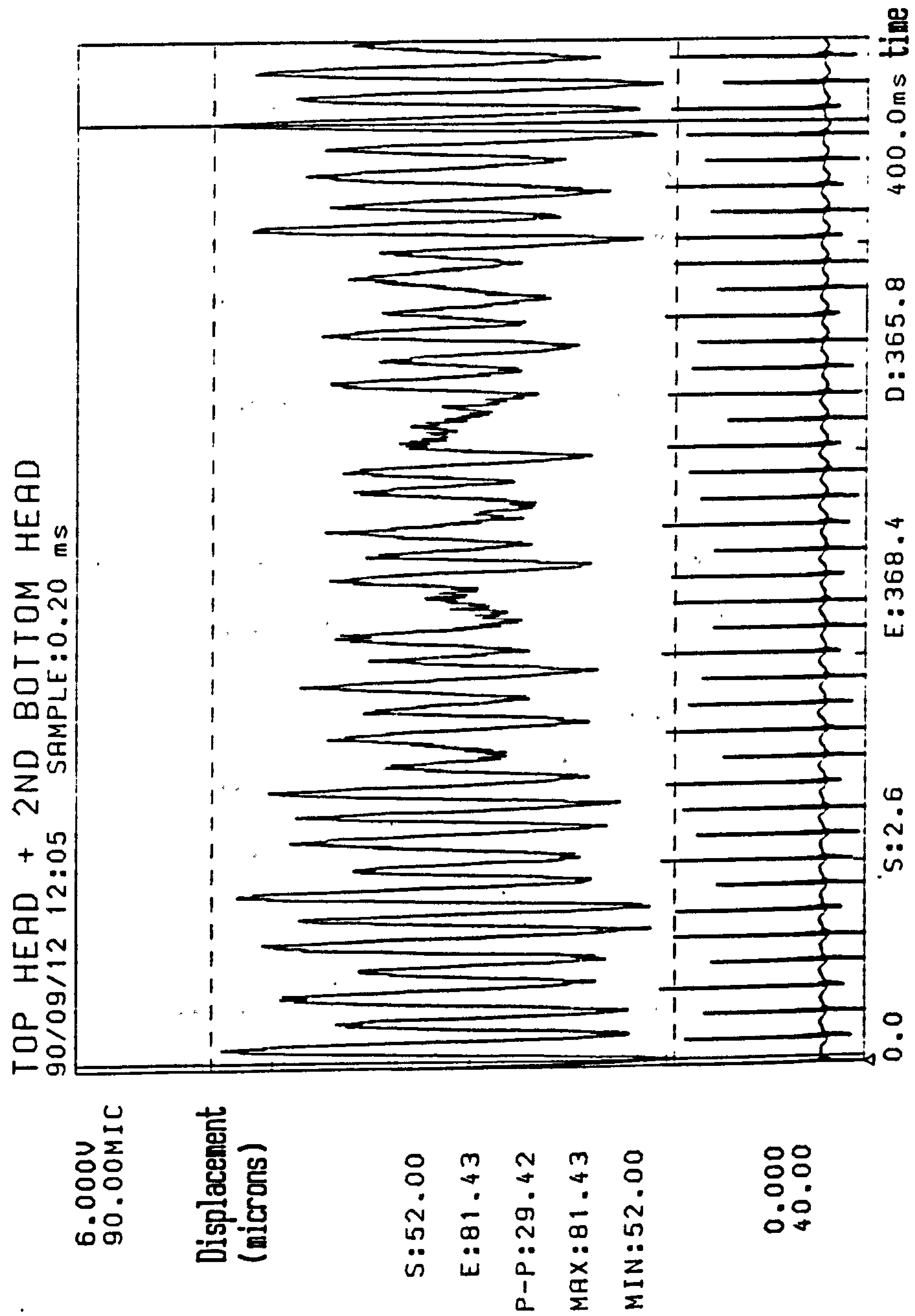


Figure 5.22

Top Head Running With 2nd Bottom Head

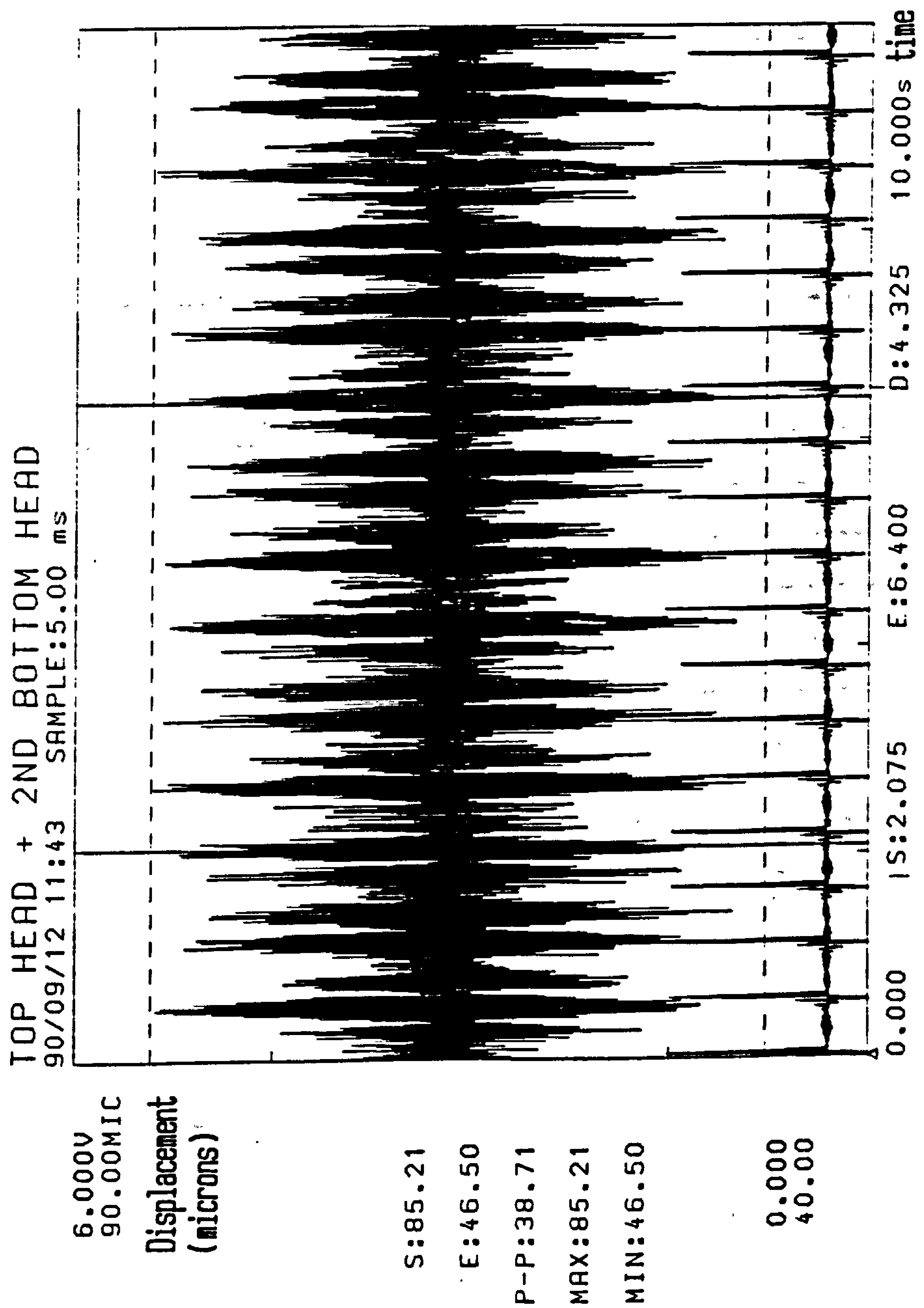


Figure 5.23

Top Head Running With The Fence Head

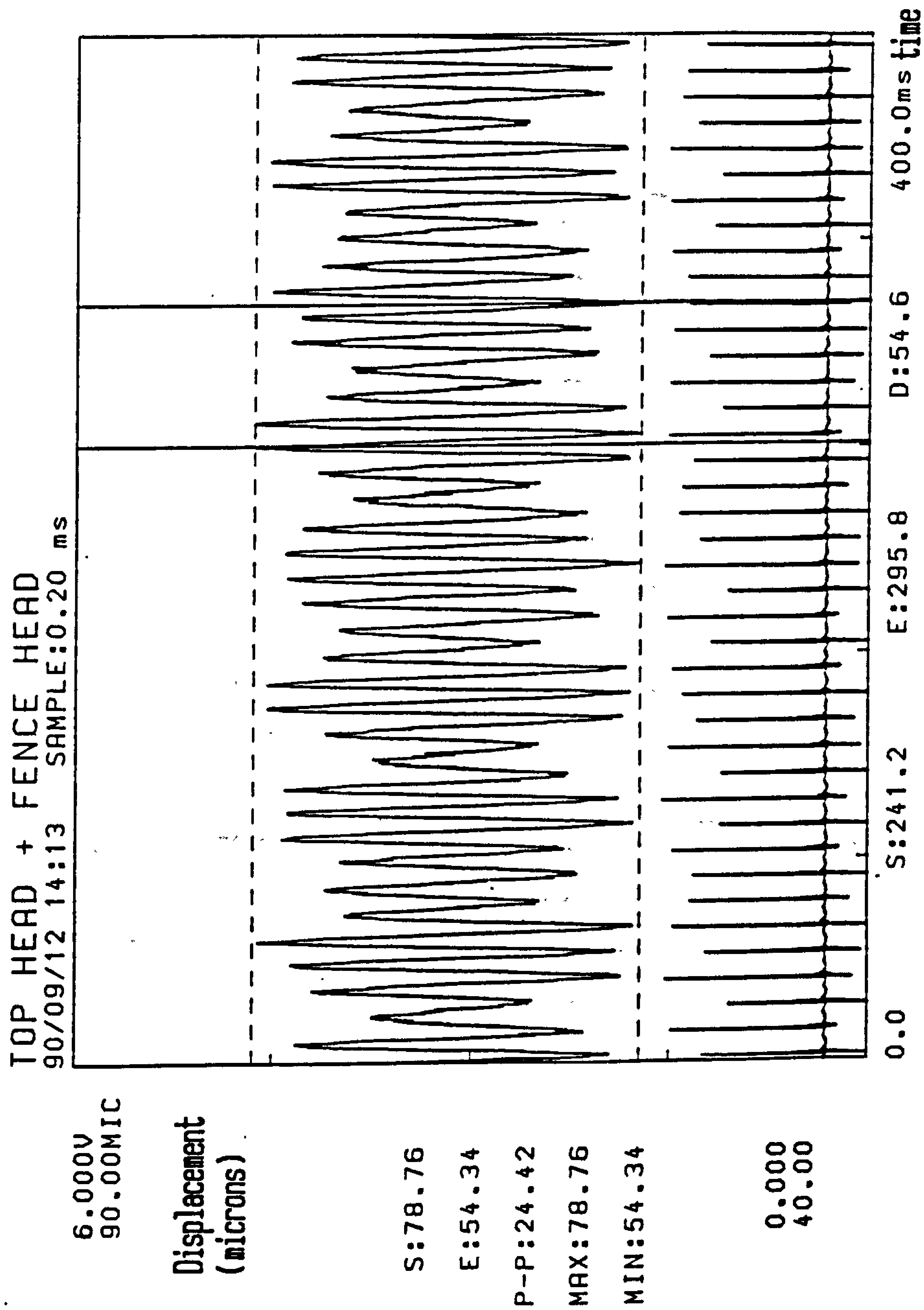


Figure 5.24

Top Head Running With The Near Head

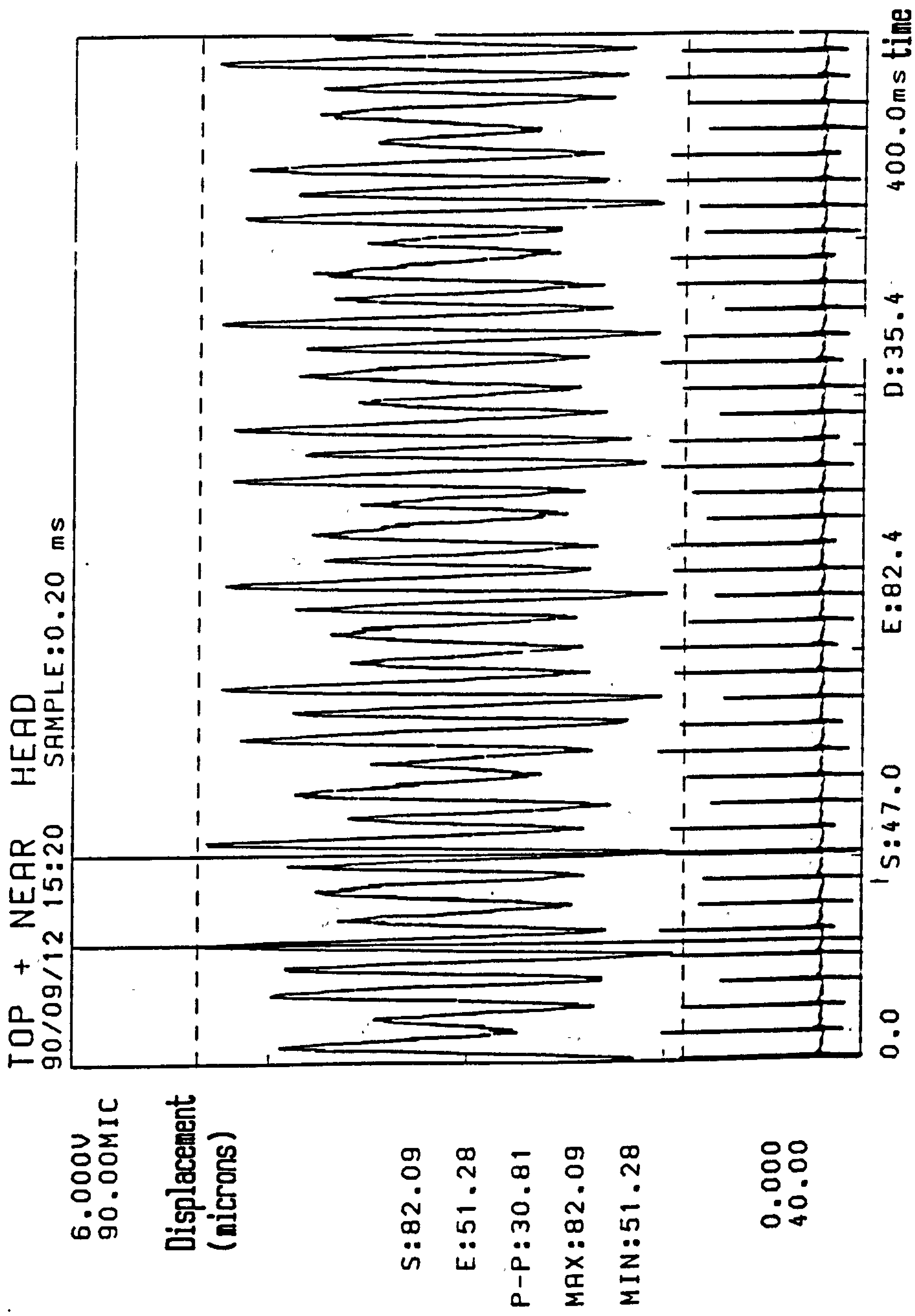


Figure 5.25

Top Head Running With The Fence Head

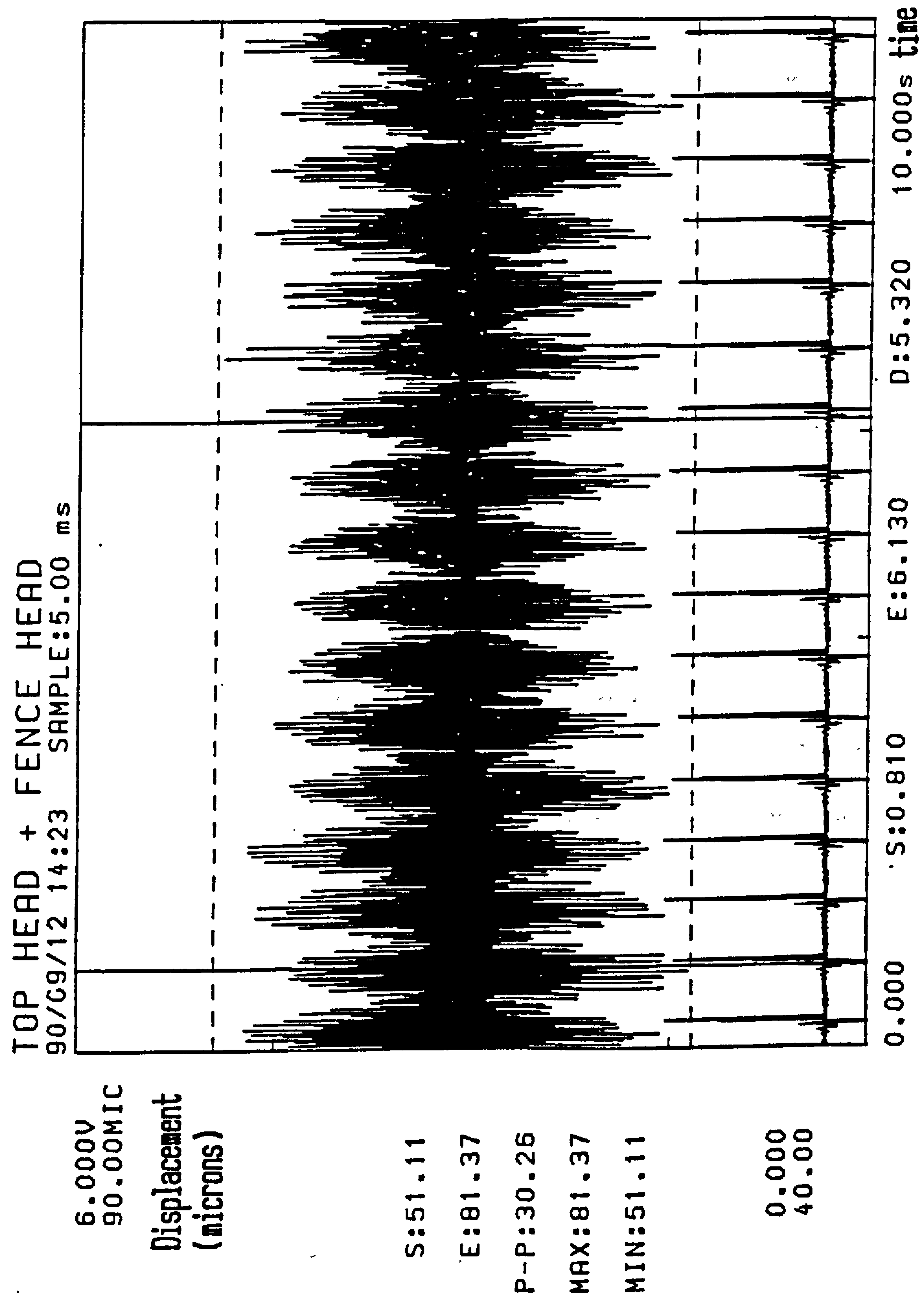


Figure 5.26

Top Head Running With The Near Head

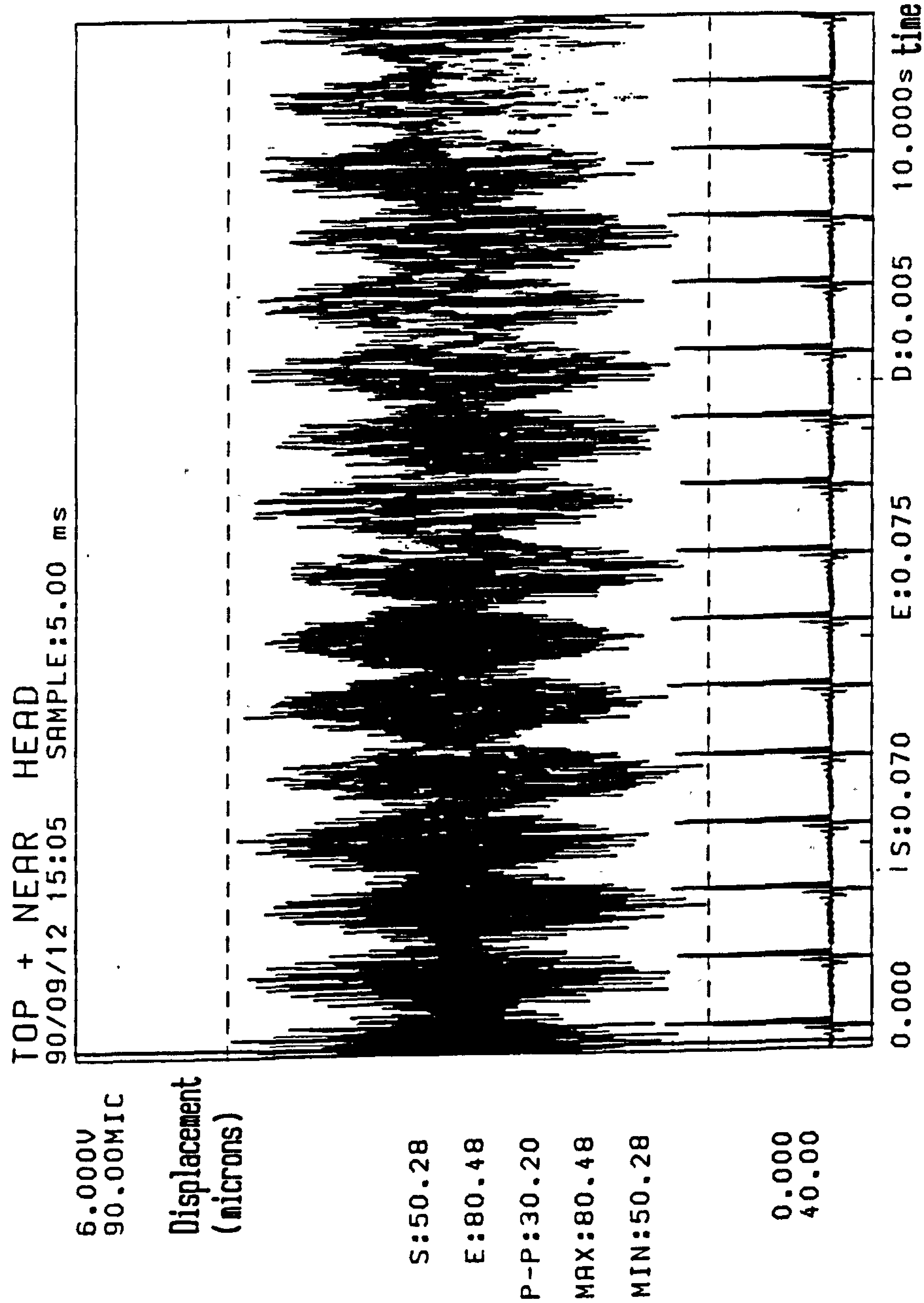


Figure 5.27

Top Head Running With The 1st and 2nd Bottom Heads

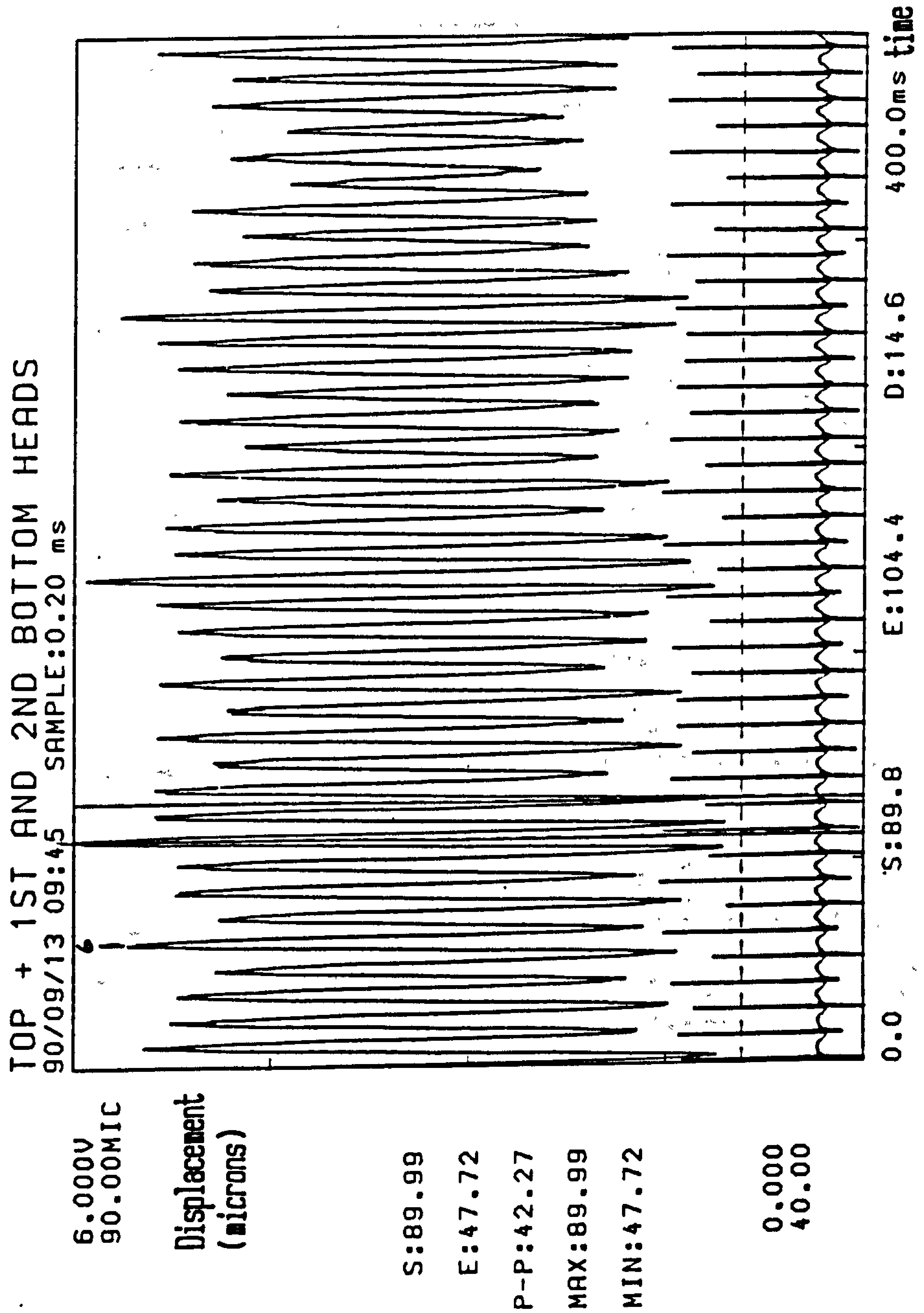


Figure 5.28

Top Head Running With The 1st and 2nd Bottom Heads

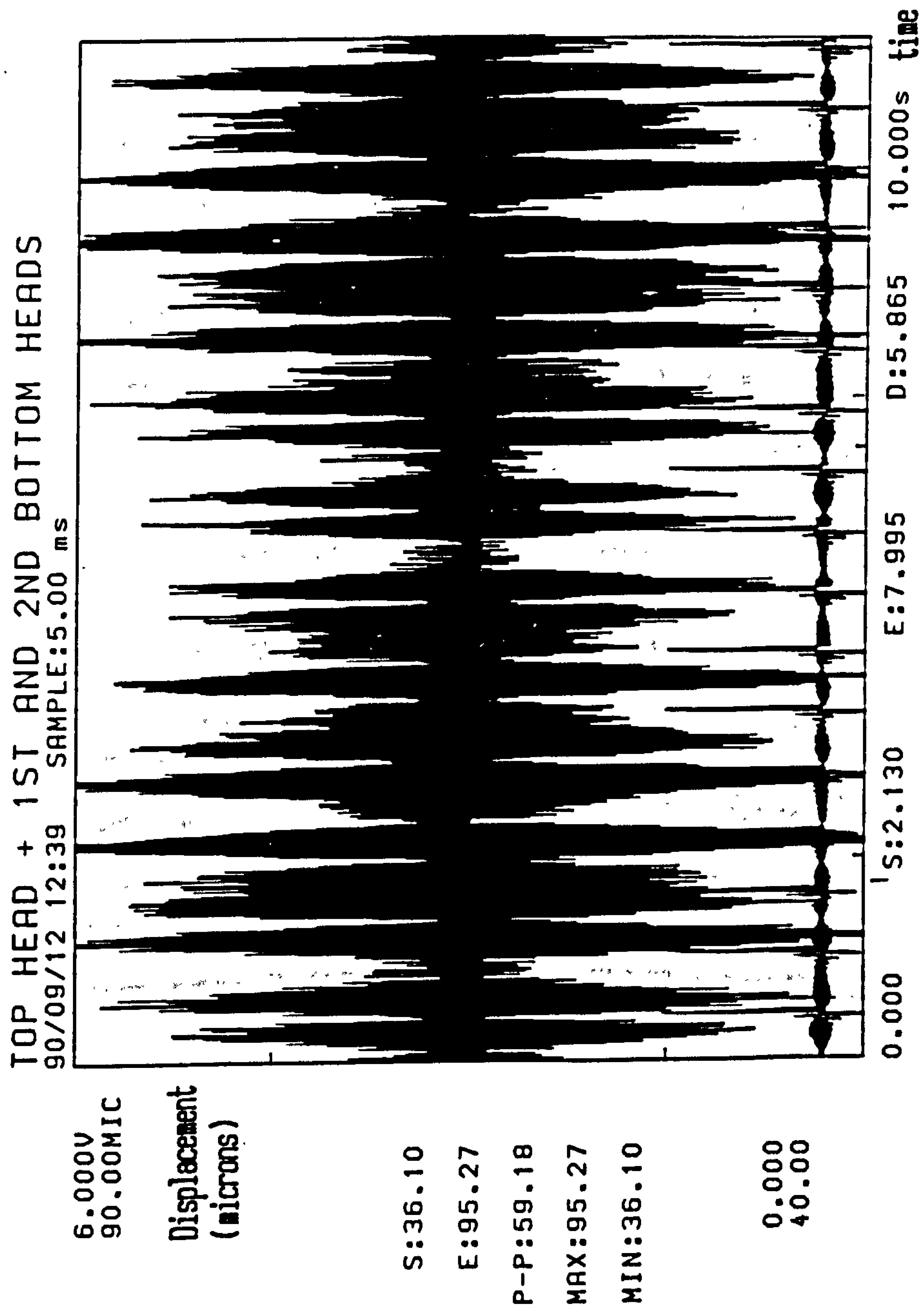


Figure 5.29

All Heads Running With The Feedworks

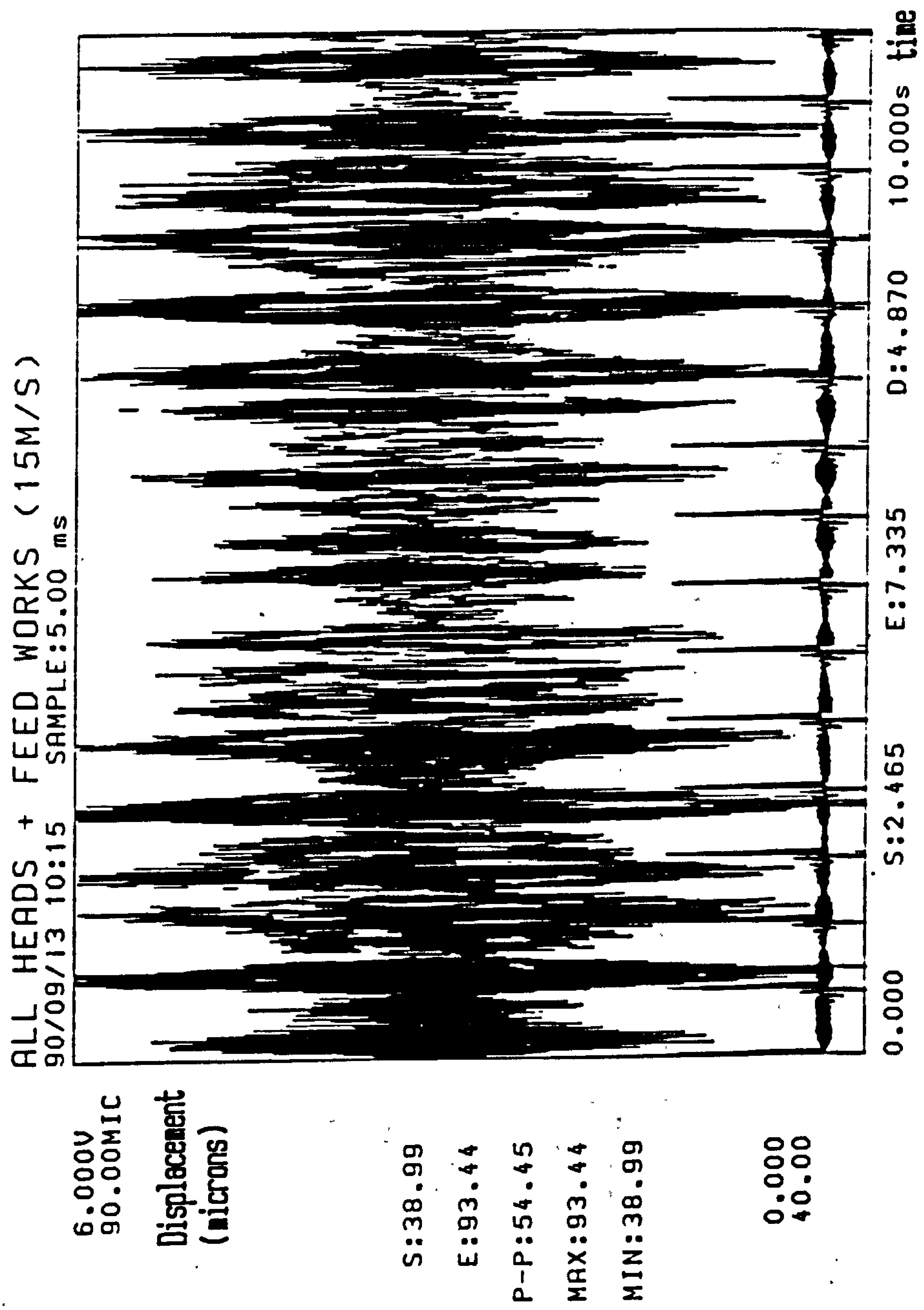


Figure 5.30

Spindle Speed Versus Cutting Depth

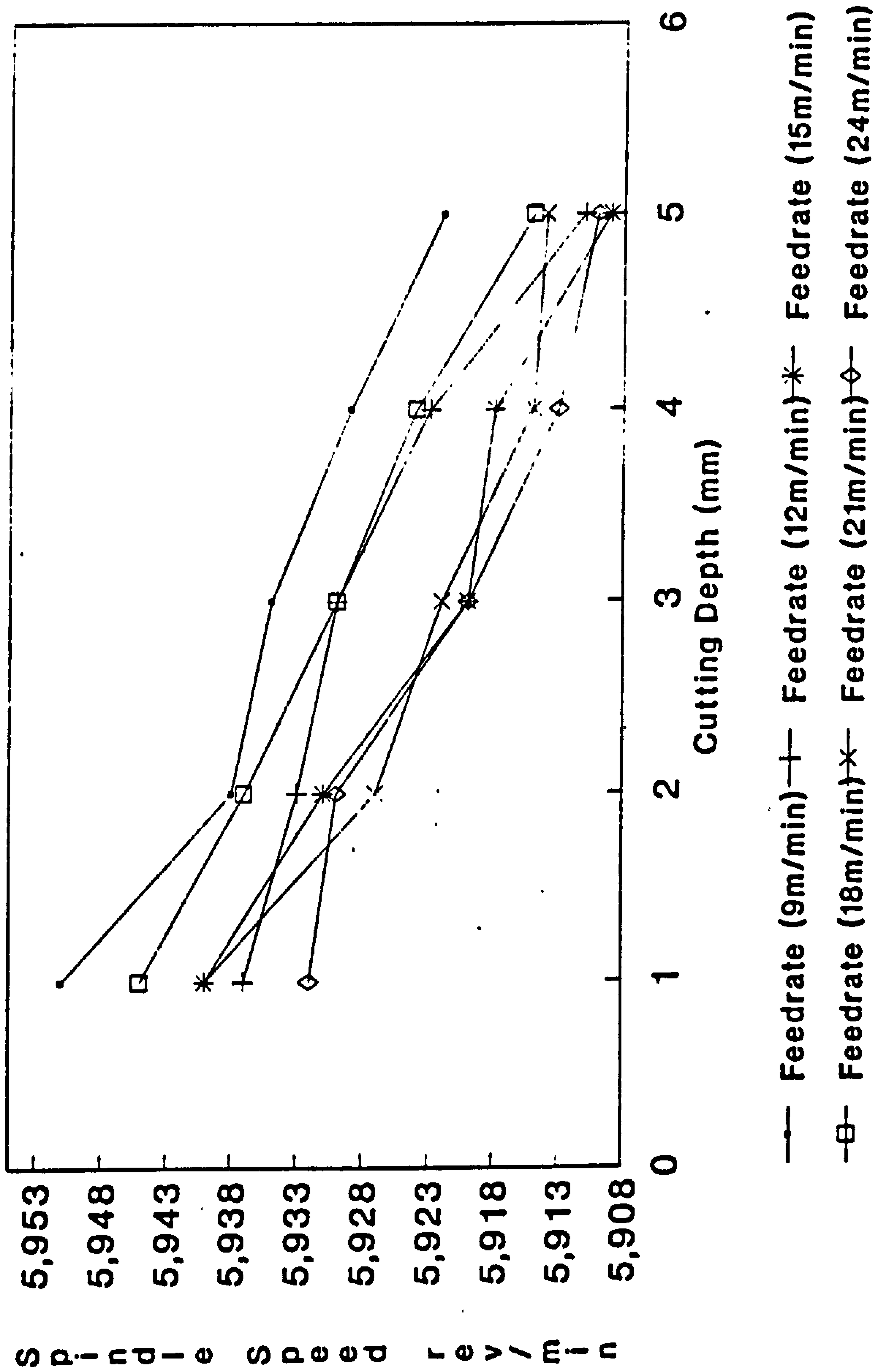


Figure 5.31

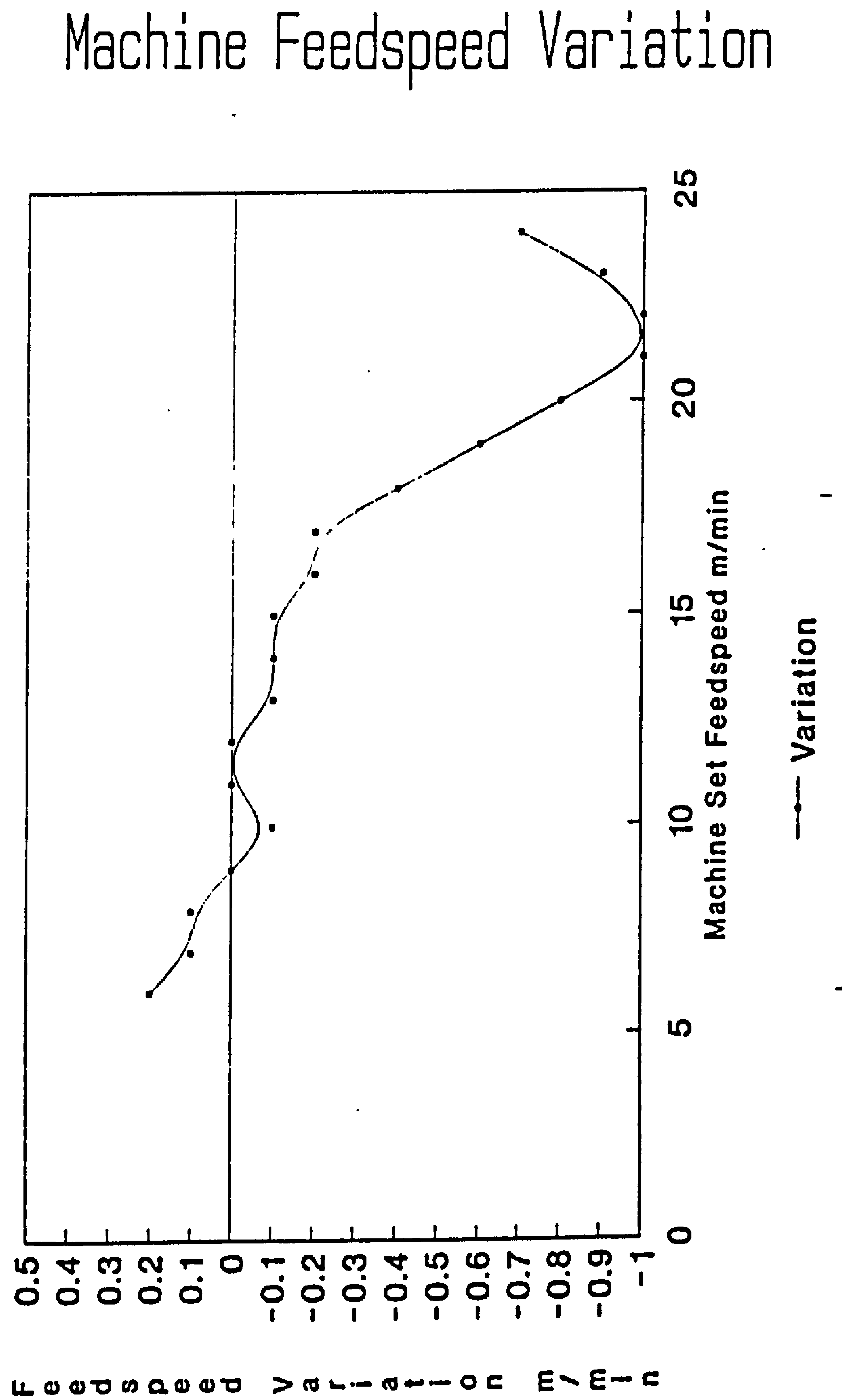

Machine Feedspeed Variation
0 5 10 15 20 25
Machine Set Feedspeed m/min
0.5 0.4 0.3 0.2 0.1 0 -0.1 -0.2 -0.3 -0.4 -0.5 -0.6 -0.7 -0.8 -0.9 -1
Feedspeed Variation m/min
Variation

Figure 5.32

External Triggering

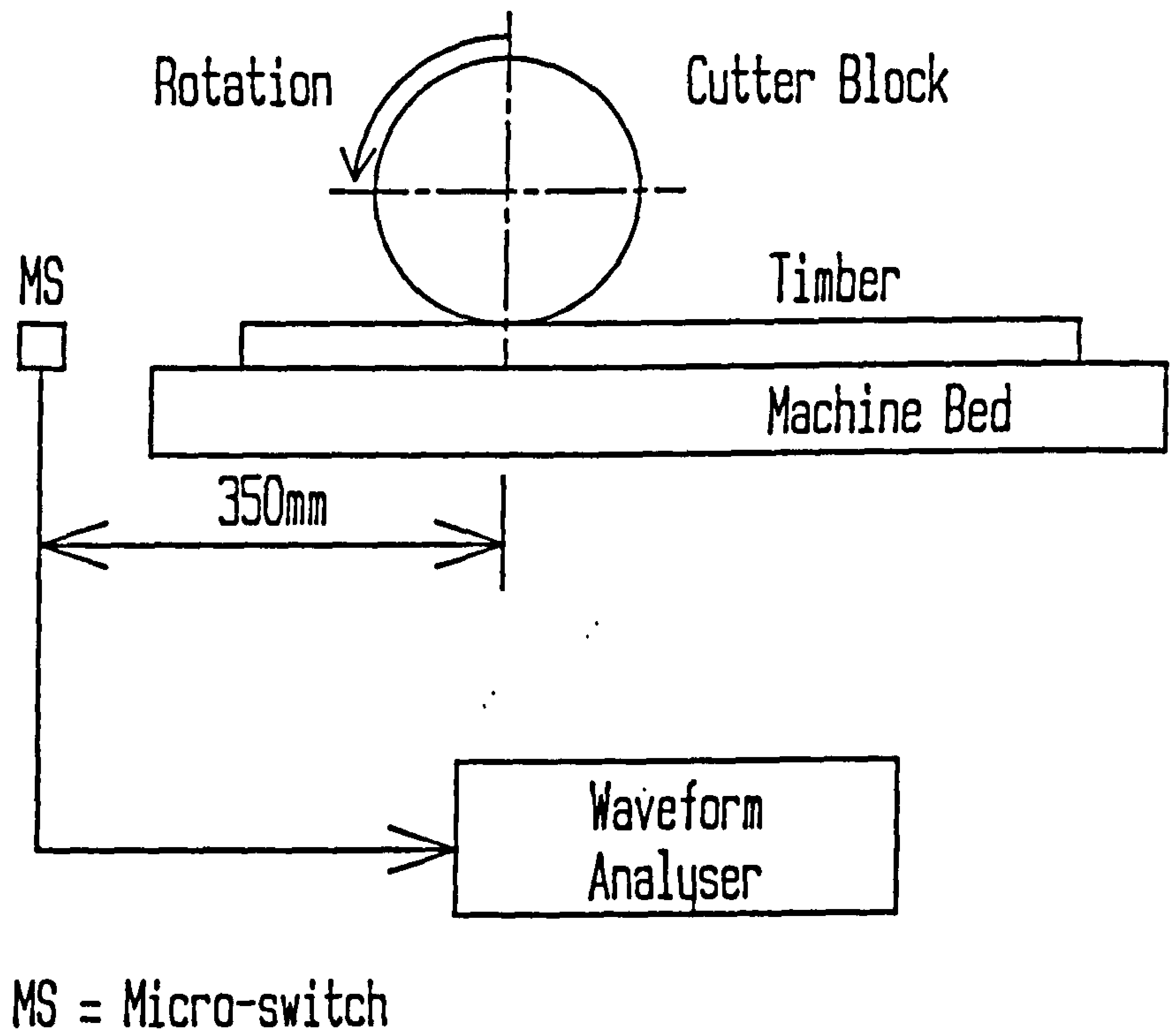


Figure 5.33

Top Head Only (9m/min)

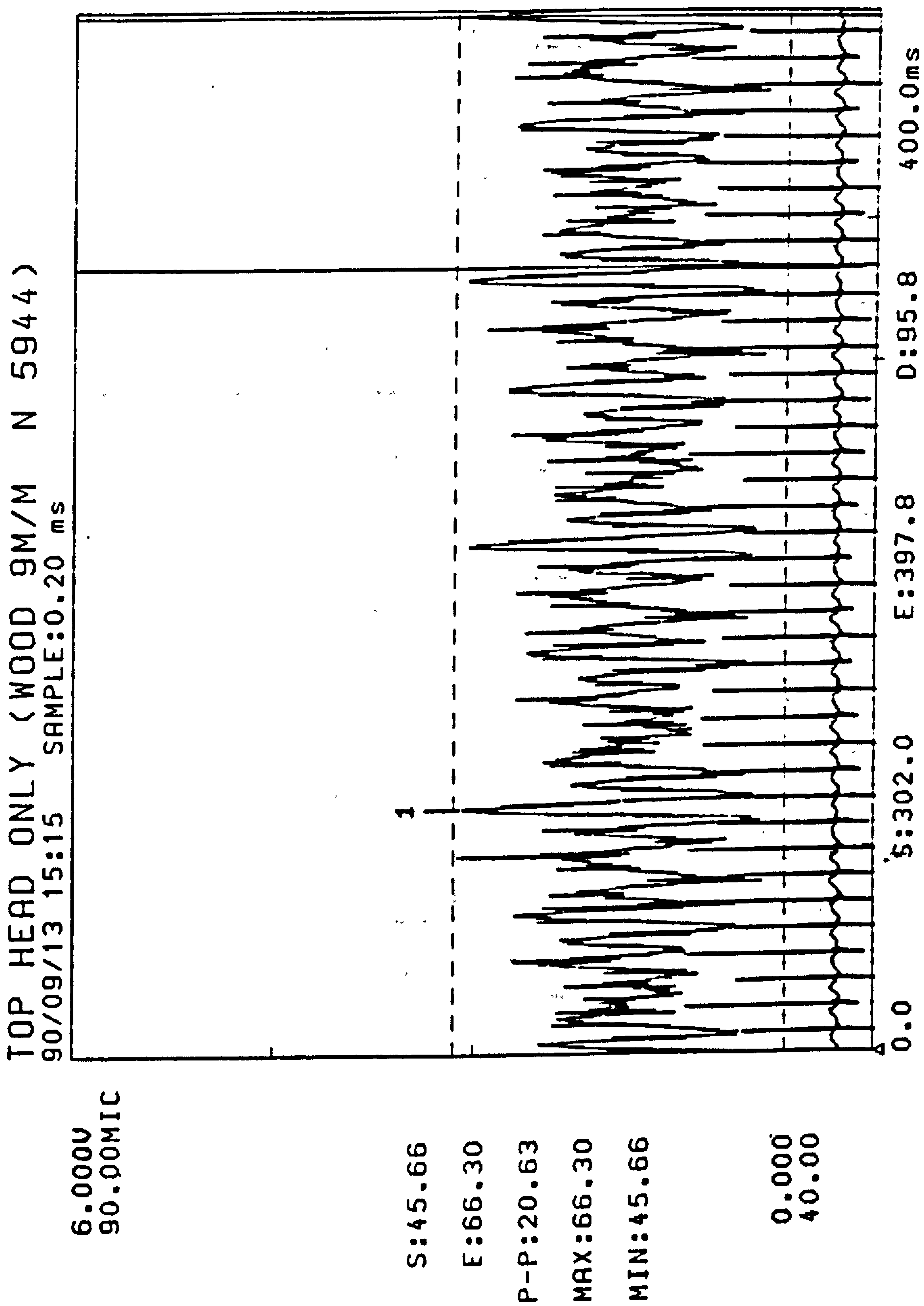


Figure 5.34

Top Head Only (18m/min)

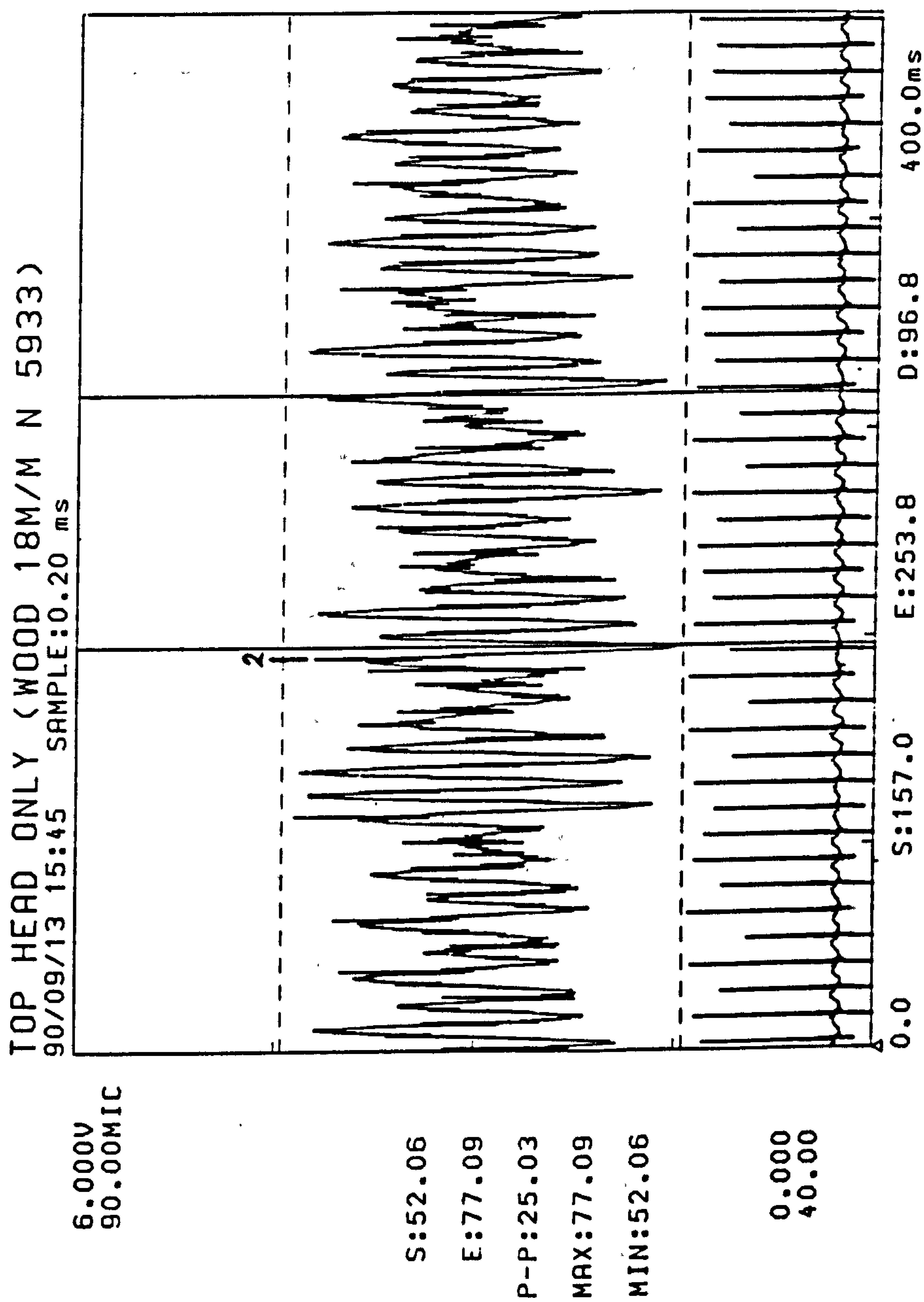


Figure 5.35

Top Head Only (27m/min)

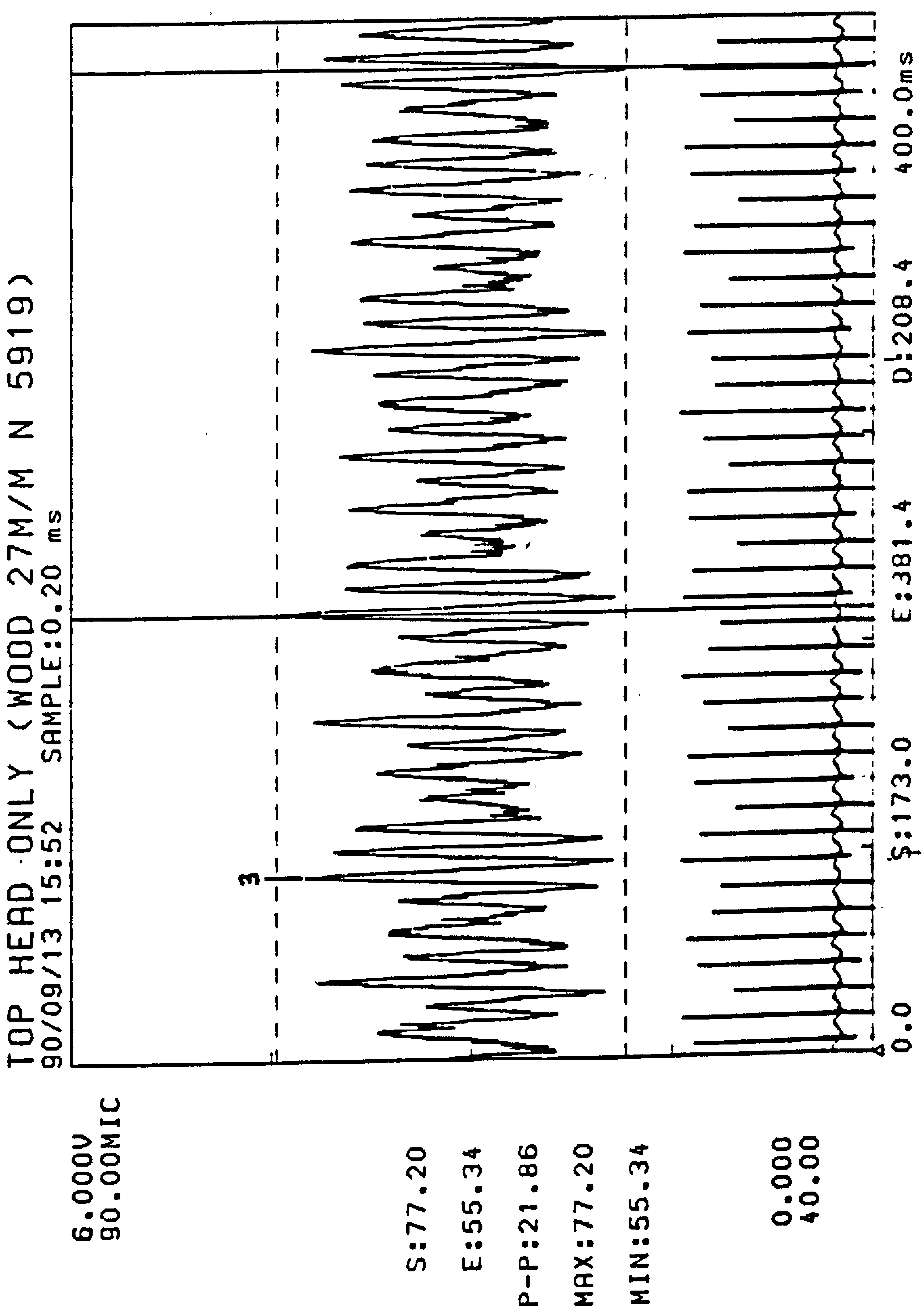


Figure 5.36

Top Head and 1st Bottom Head (21m/min)

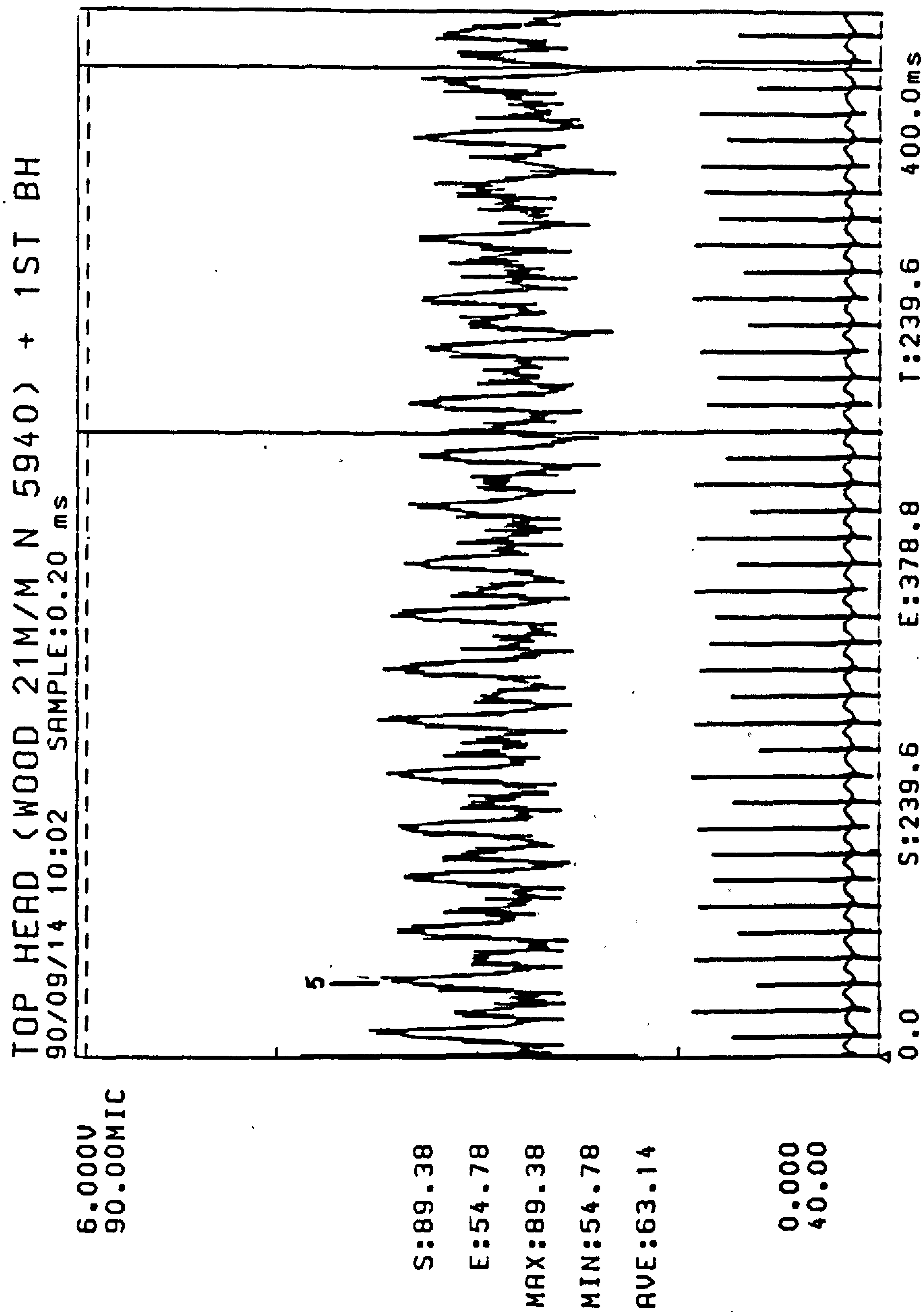


Figure 5.37

Top Head, 1st and 2nd Bottom Heads (24m/min)

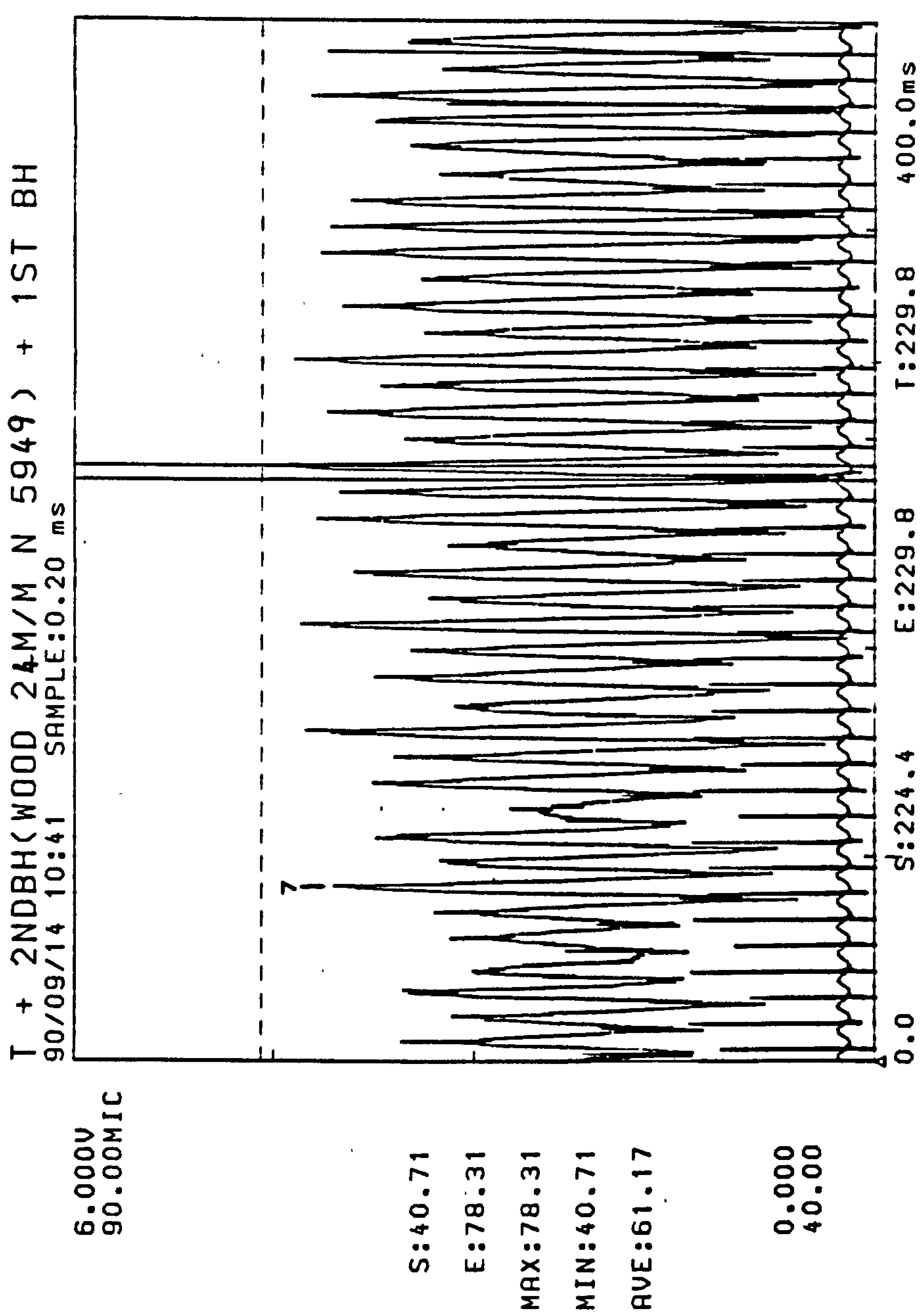
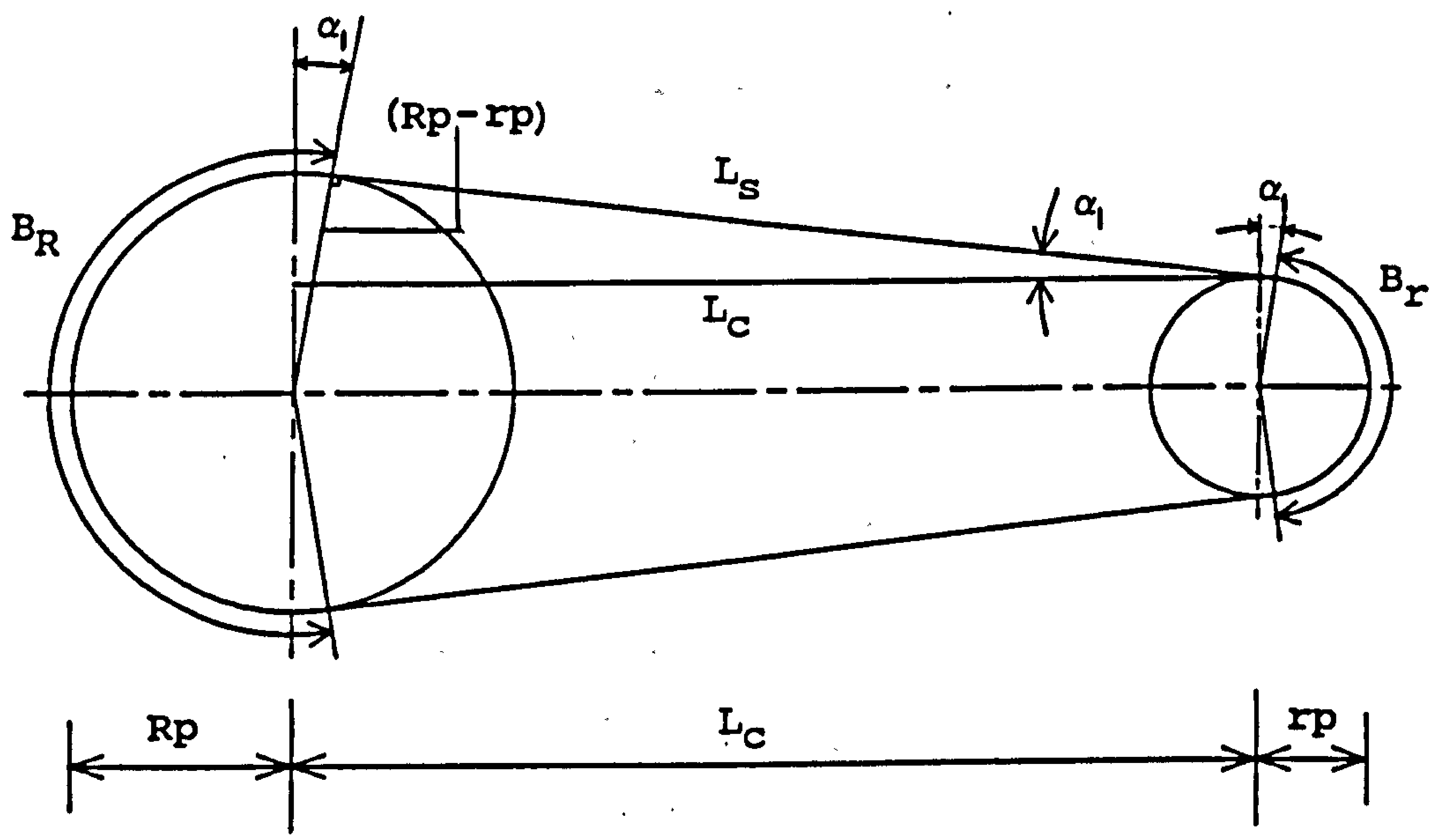


Figure 5.38

Belt Drive Geometry



$$L_s = \sqrt{L_c^2 - (Rp - rp)^2}$$

$$B_R = (\pi + 2\alpha_1)$$

$$B_r = (\pi - 2\alpha_1)$$

$$\sin\alpha_1 = (Rp - rp)/L_c$$

Figure 5.39

Pulley Design

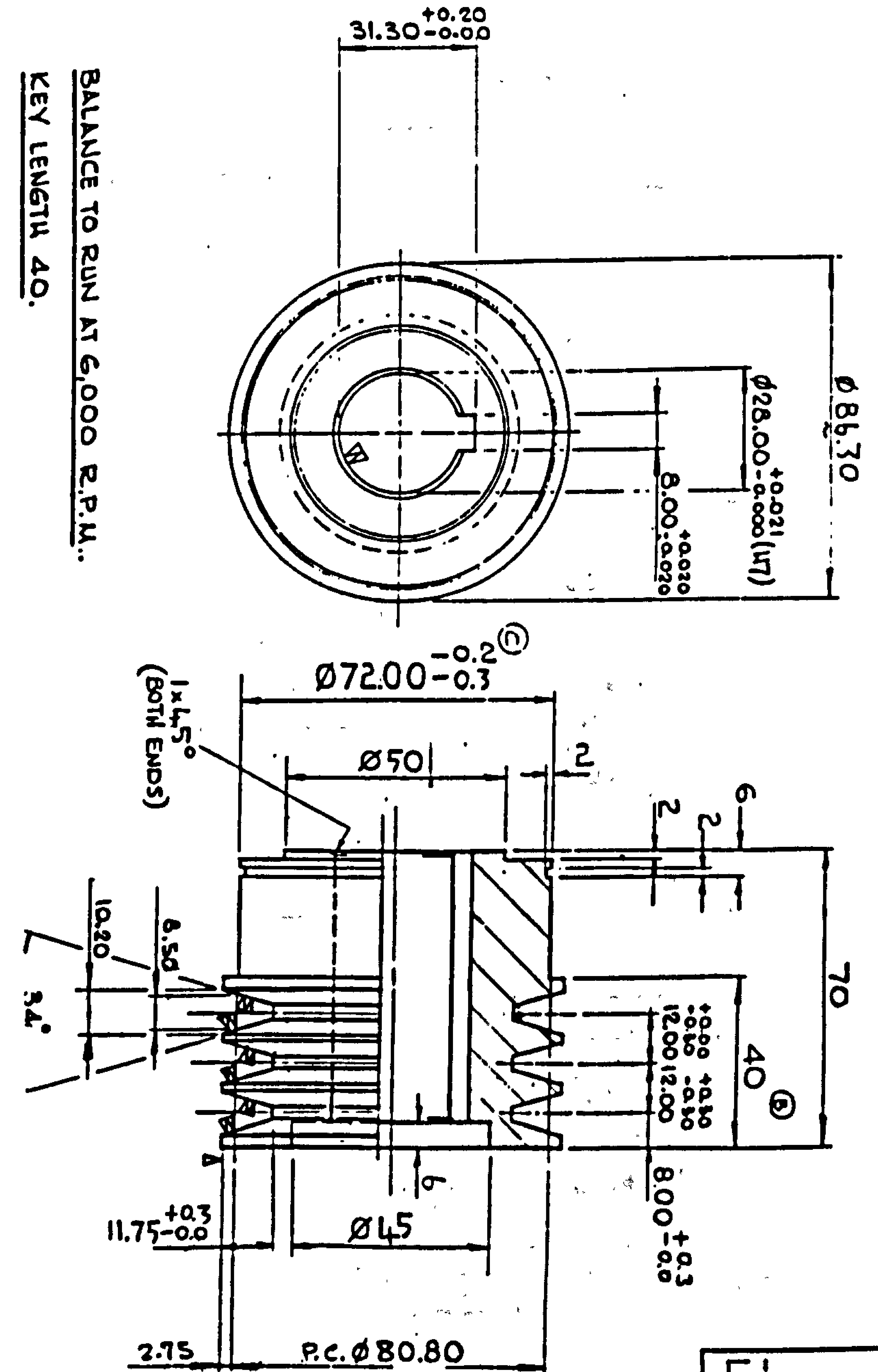


Figure 5.40

Belt Characteristics

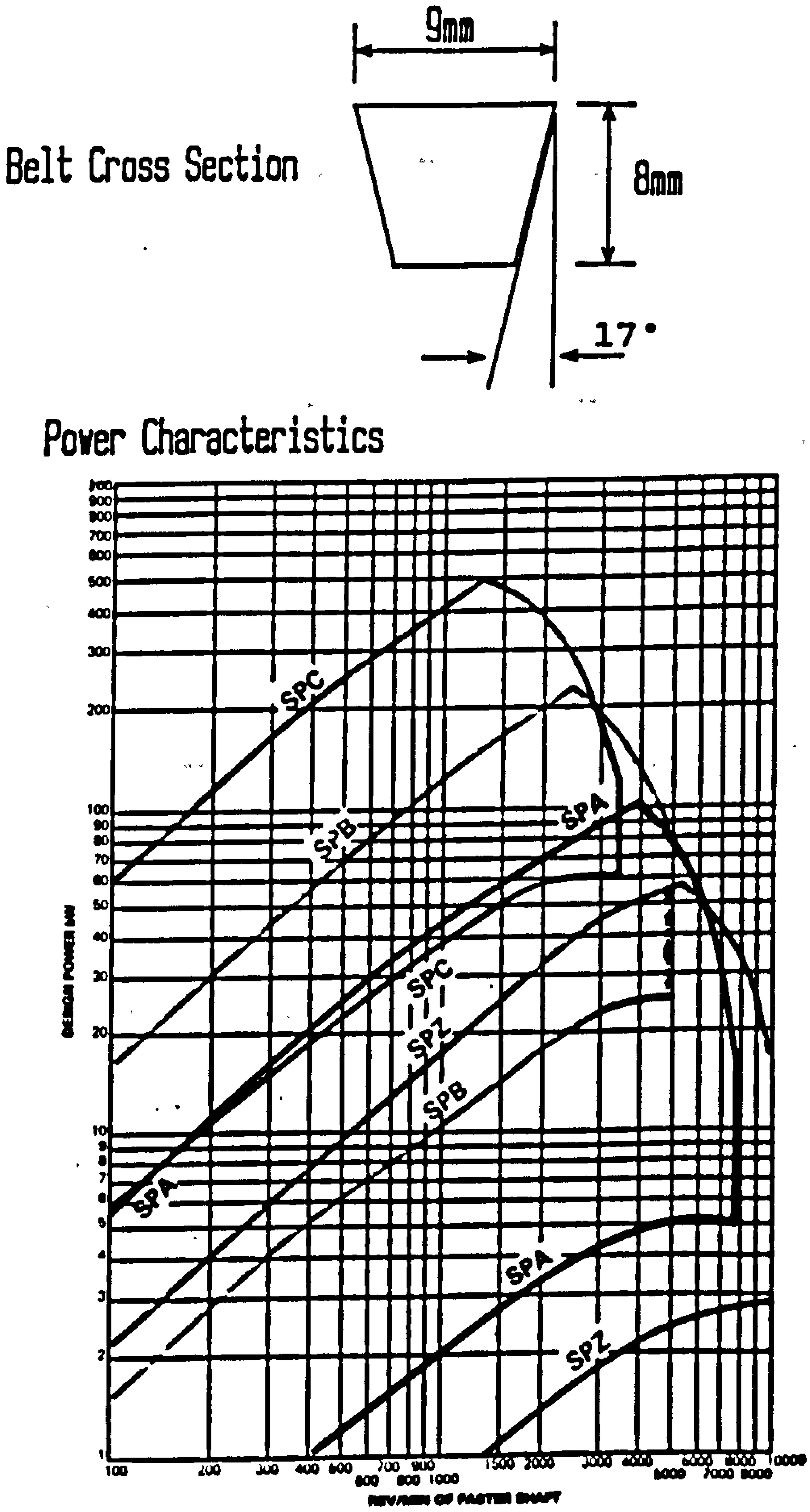


Figure 5.41

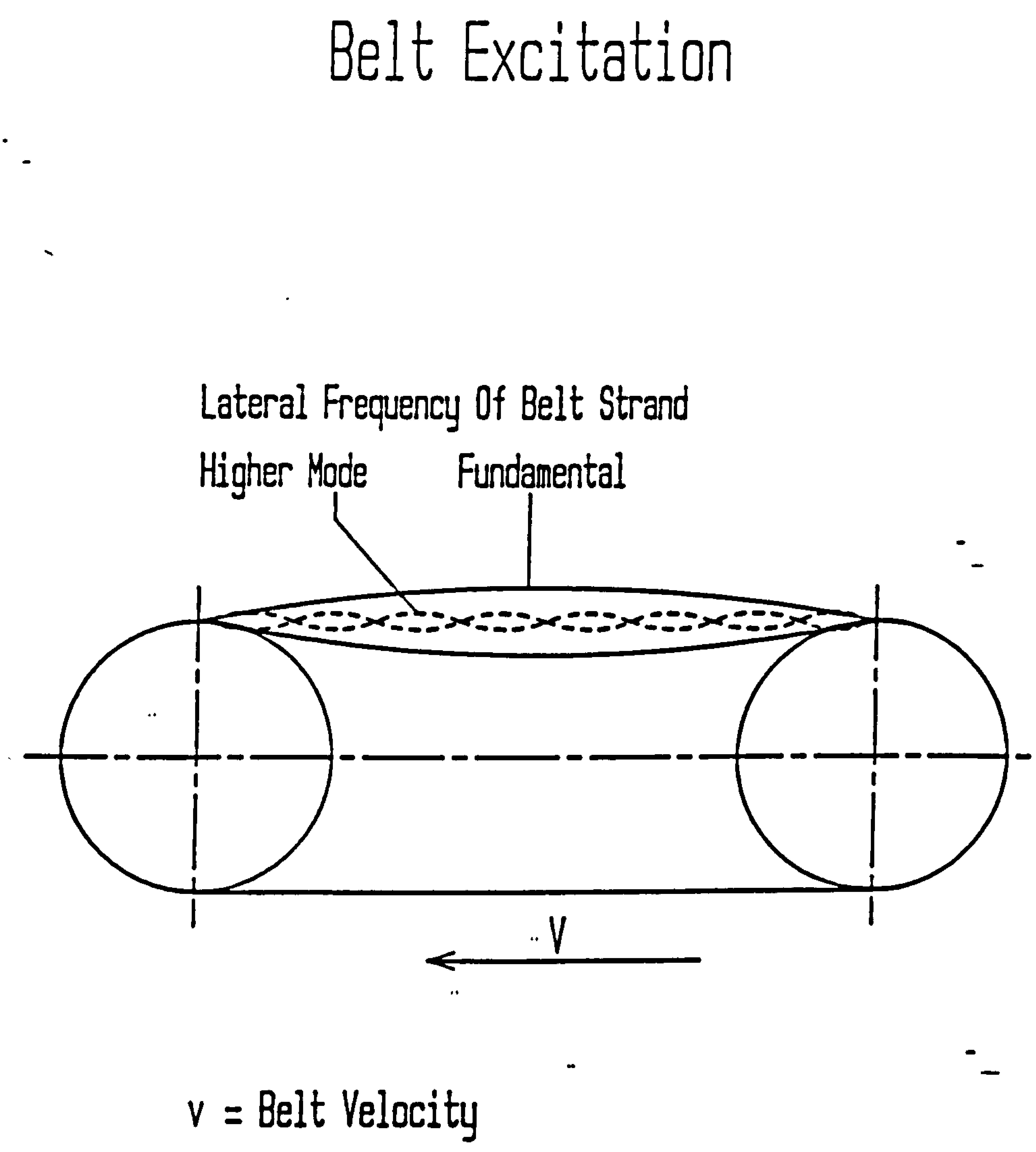
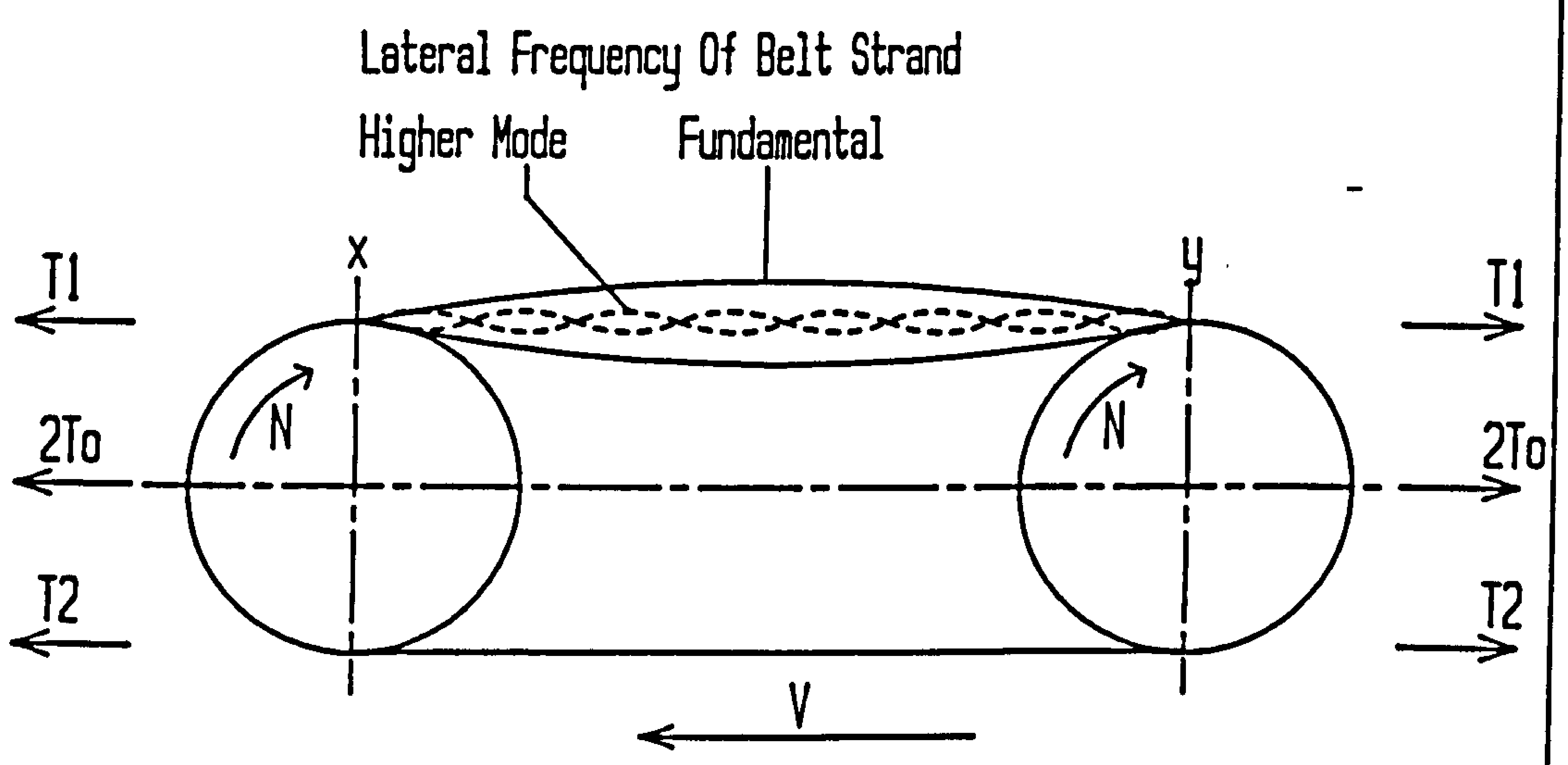

Belt Excitation
Lateral Frequency Of Belt Strand
Higher Mode
Fundamental
V
v = Belt Velocity

Figure 5.42

Vibration Travel



v = Belt Velocity
n = Pulley Speed (rev/min)

Figure 5.43

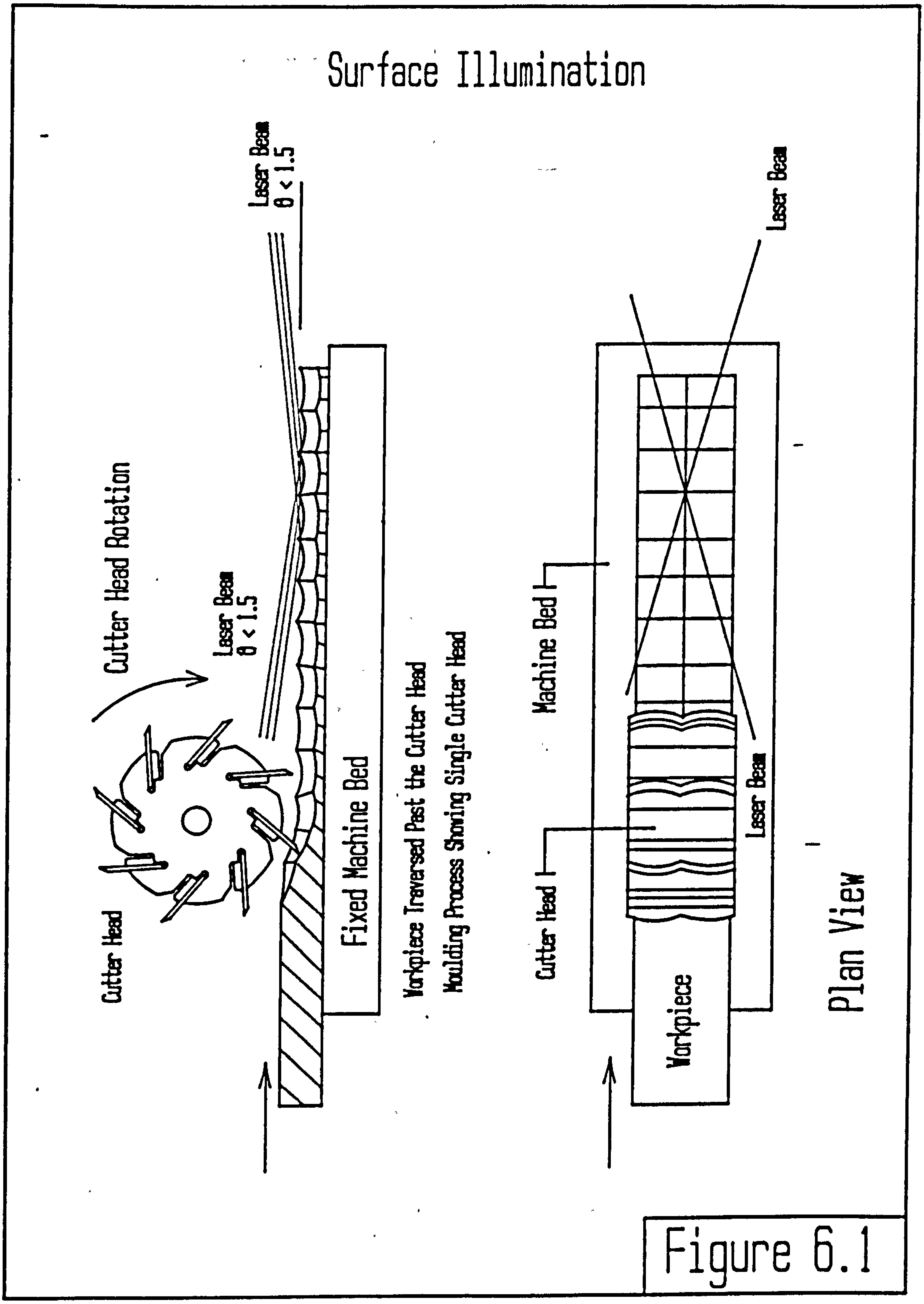

Surface Illumination
Laser Beam
θ < 1.5
Cutter Head Rotation
Laser Beam
θ < 1.5
Cutter Head
Fixed Machine Bed
Workpiece Traversed Past the Cutter Head
Moulding Process Showing Single Cutter Head
Laser Beam
Machine Bed
Laser Beam
Cutter Head
Workpiece
Plan View

Figure 6.1

Arrangement of Measurement System

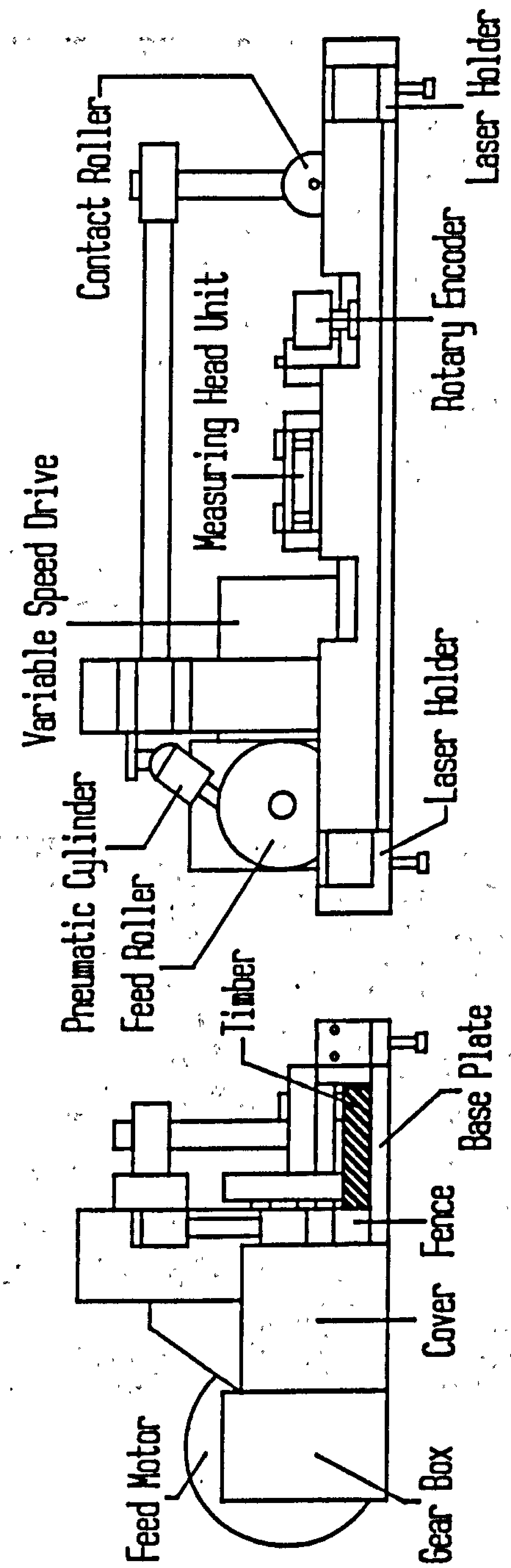
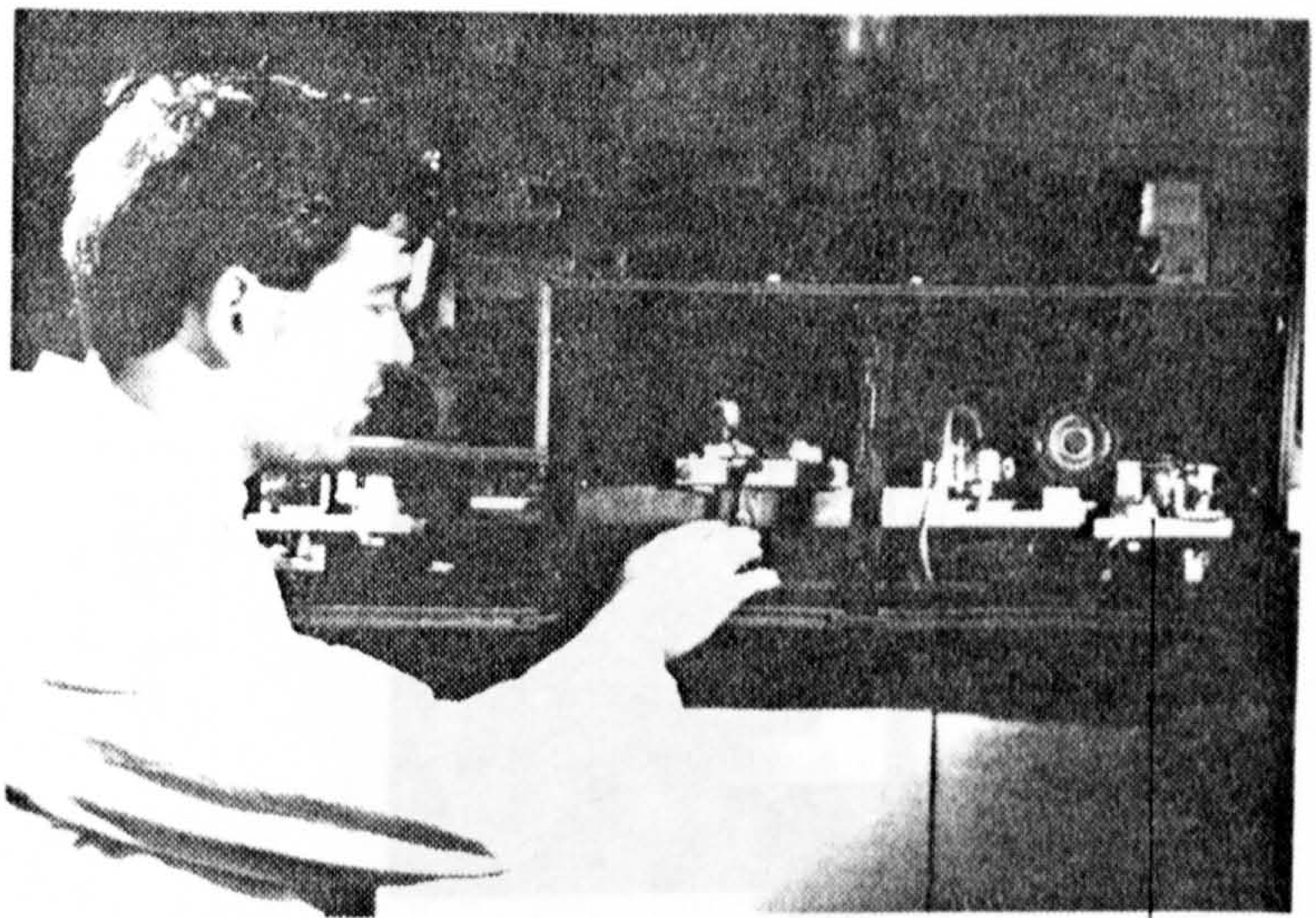
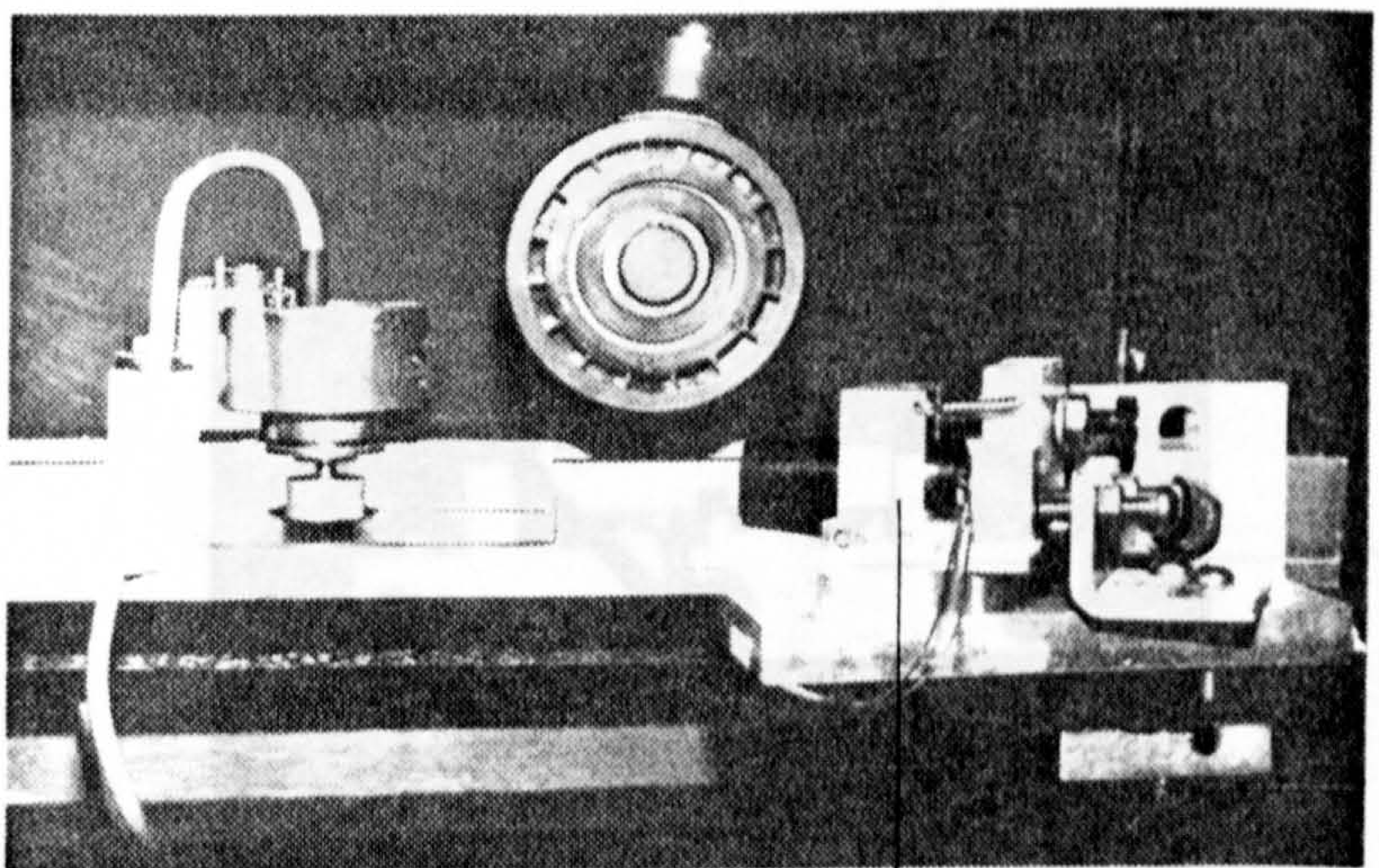


Figure 6.2

Laser Holders



Laser Holder



Laser Holder

Figure 6.3

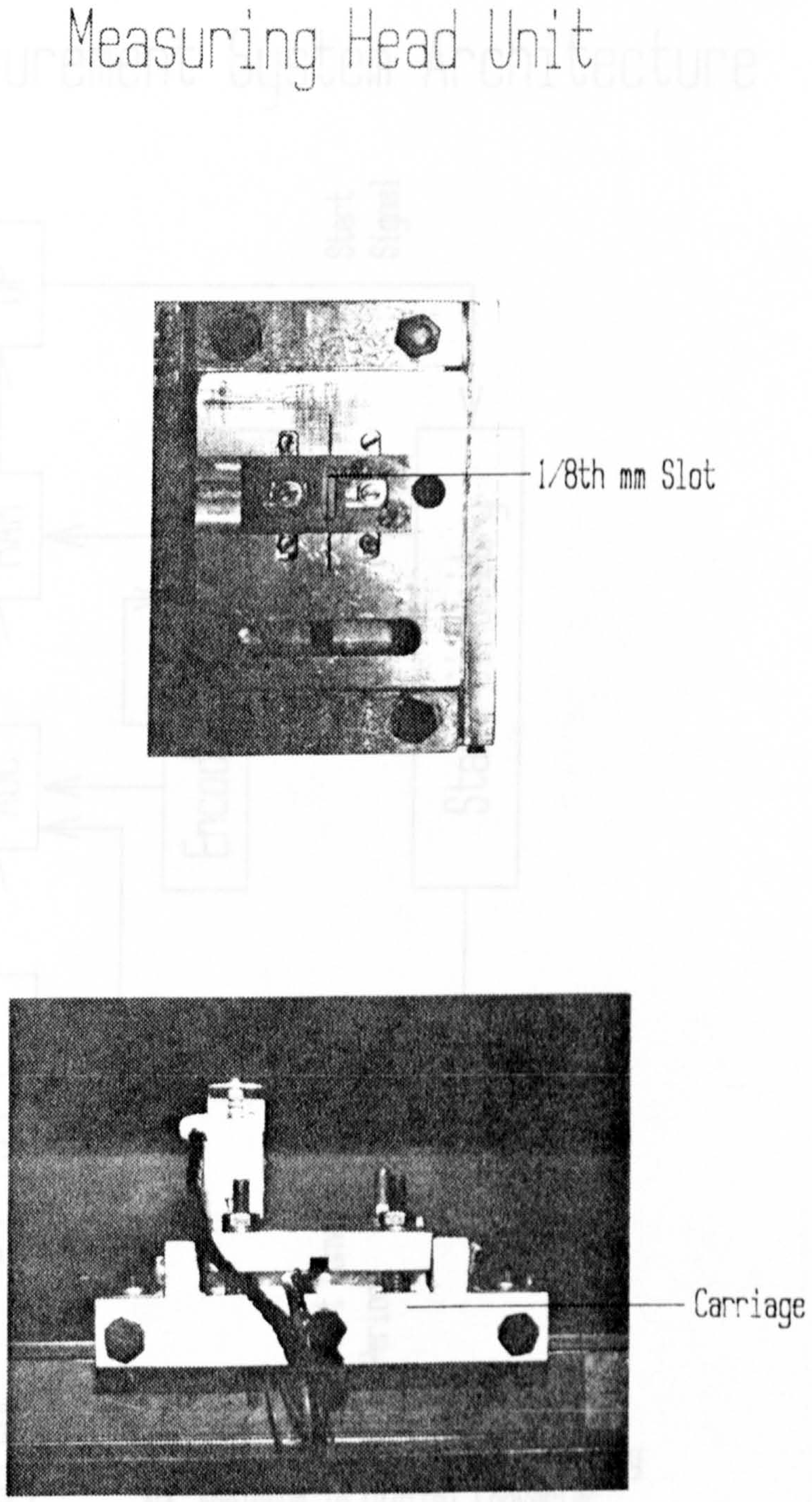
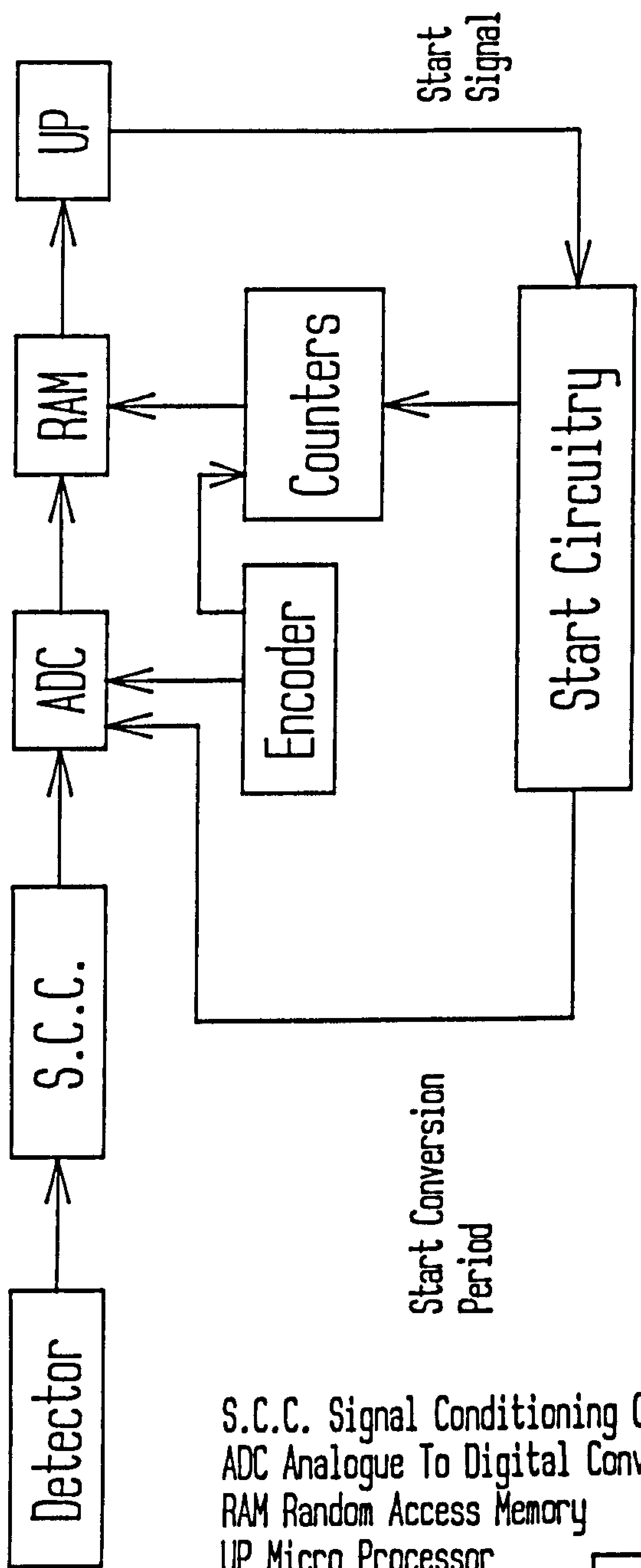


Figure 6.4

Laser Measurement System Architecture



S.C.C. Signal Conditioning Circuitry
ADC Analogue To Digital Converter
RAM Random Access Memory
UP Micro Processor

Figure 6.5a

Figure 6.5b

Laser Measurement System Architecture

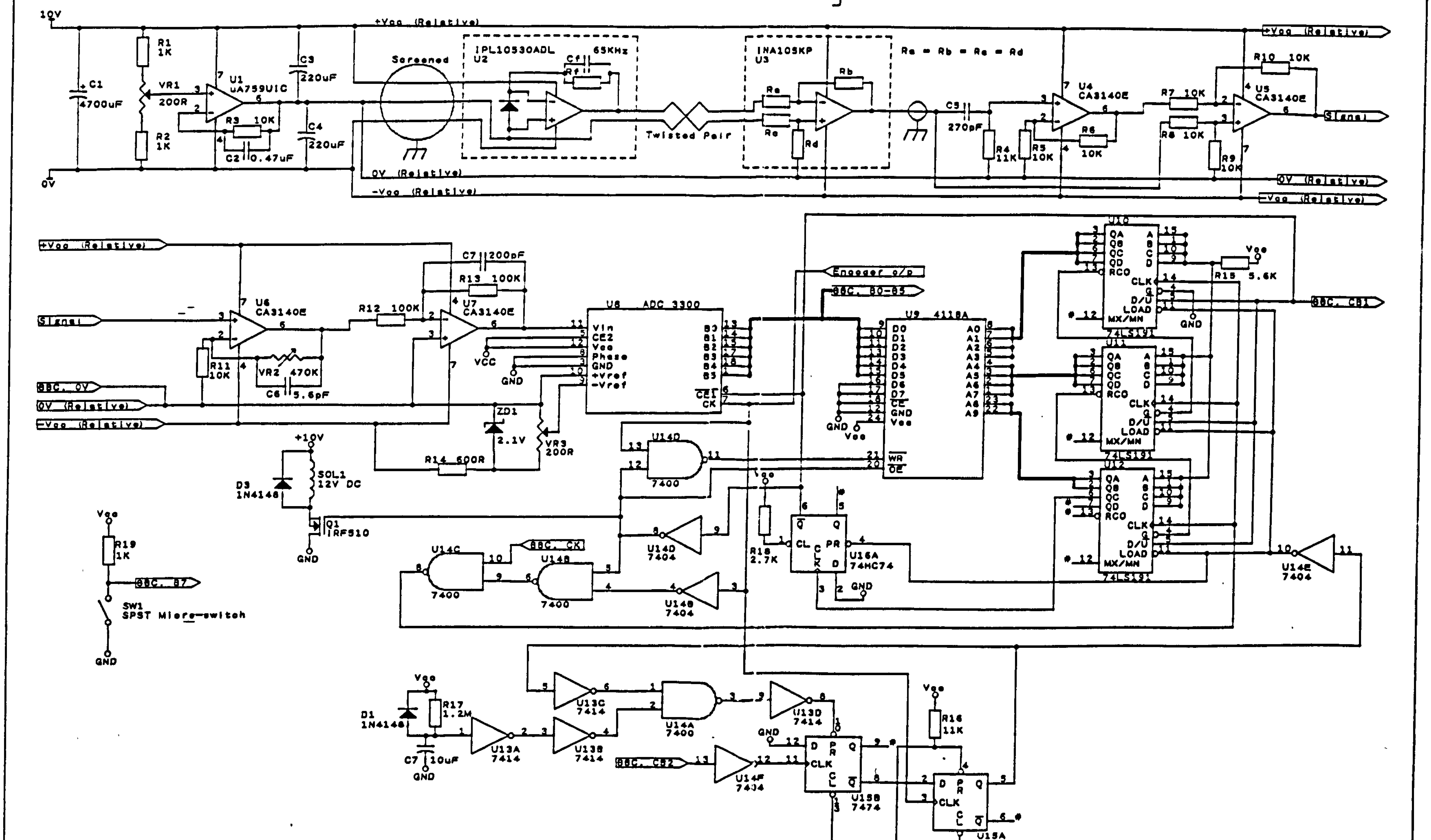
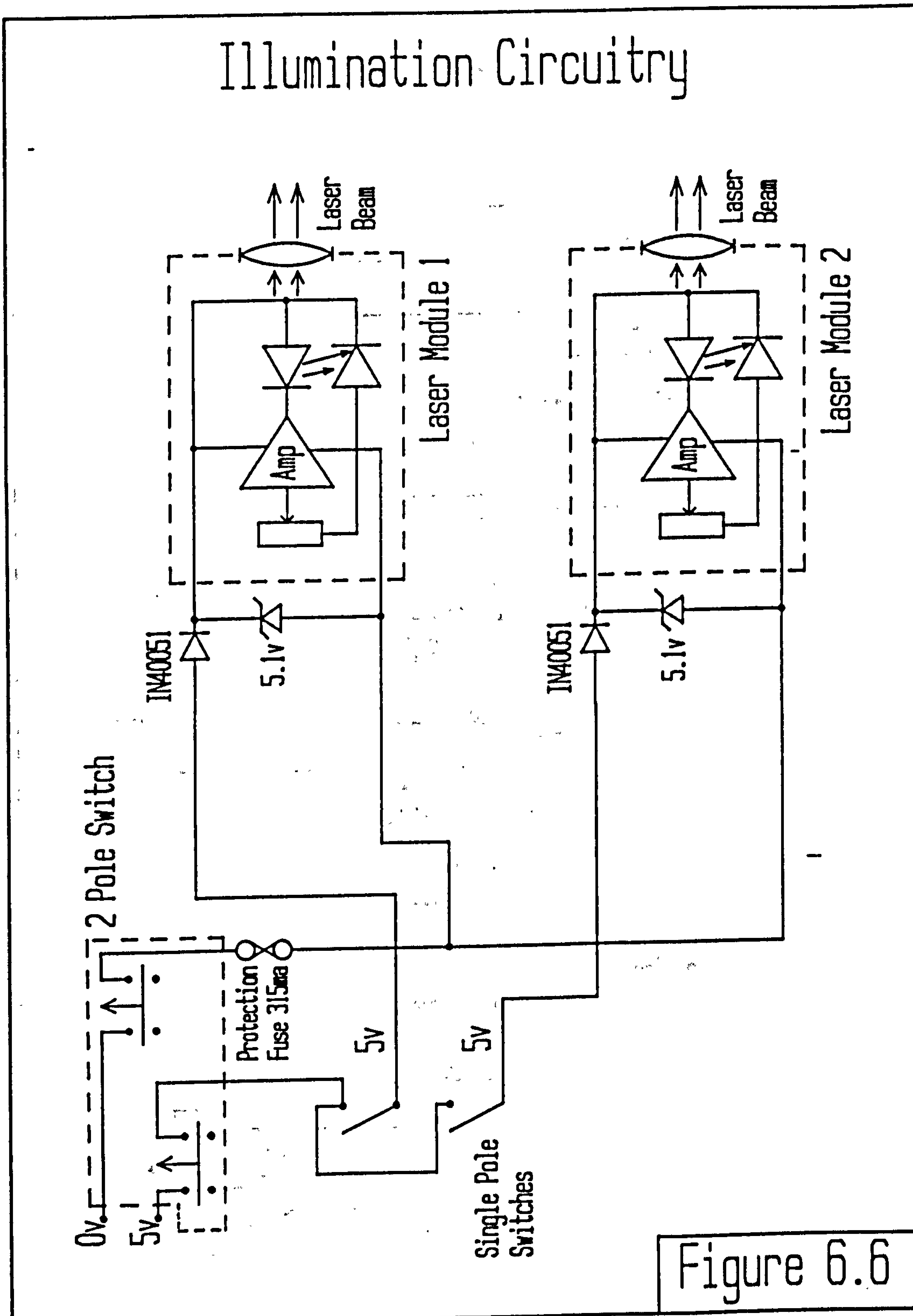


Figure 6.5b



Illumination Circuitry
Laser Beam
Laser Beam
Laser Module 1
Laser Module 2
Amp
Amp
IN4005I
IN4005I
5.1v
5.1v
2 Pole Switch
Protection Fuse 315ma
5v
5v
0v
5v
Single Pole Switches

Figure 6.6

Start Circuitry

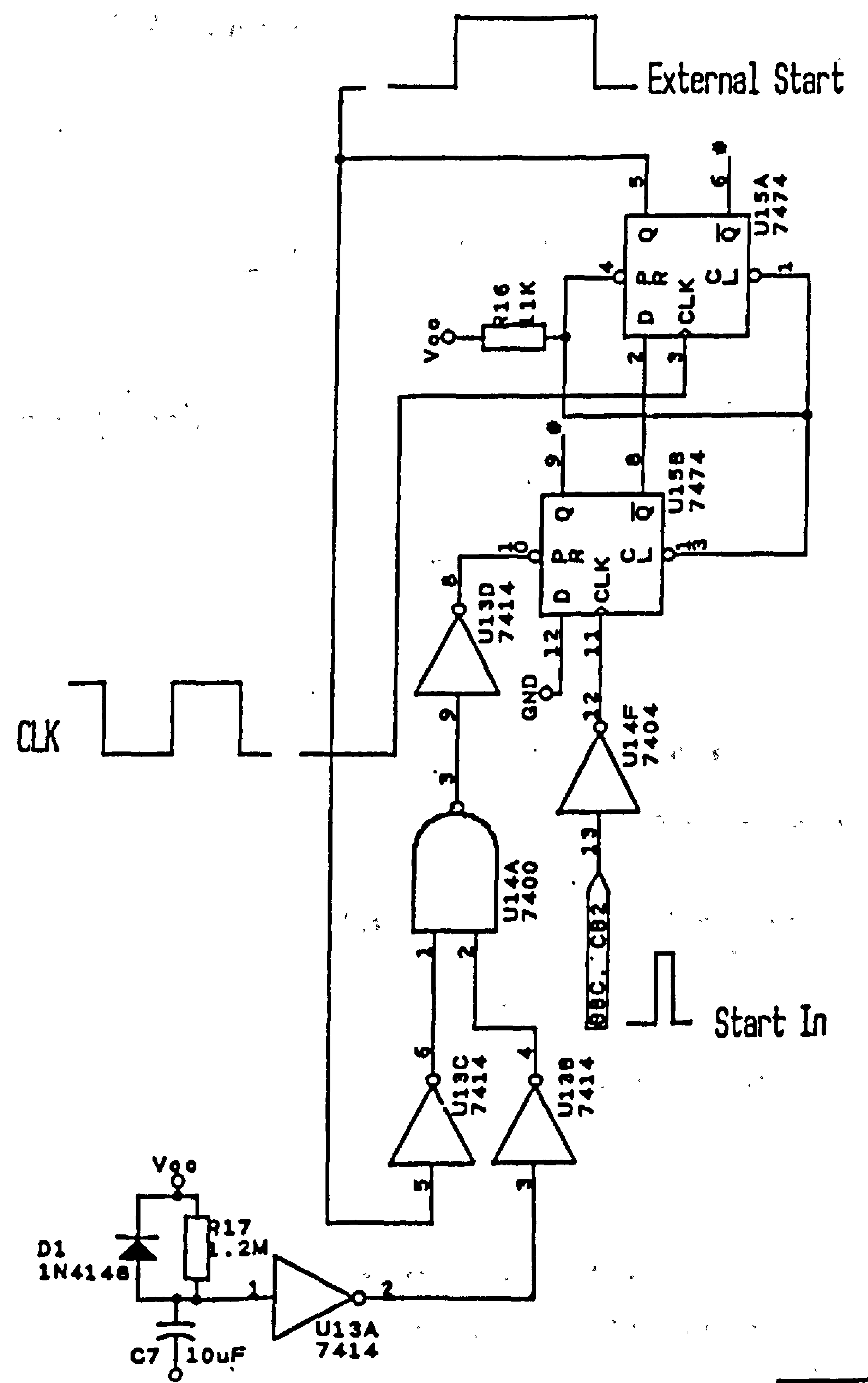
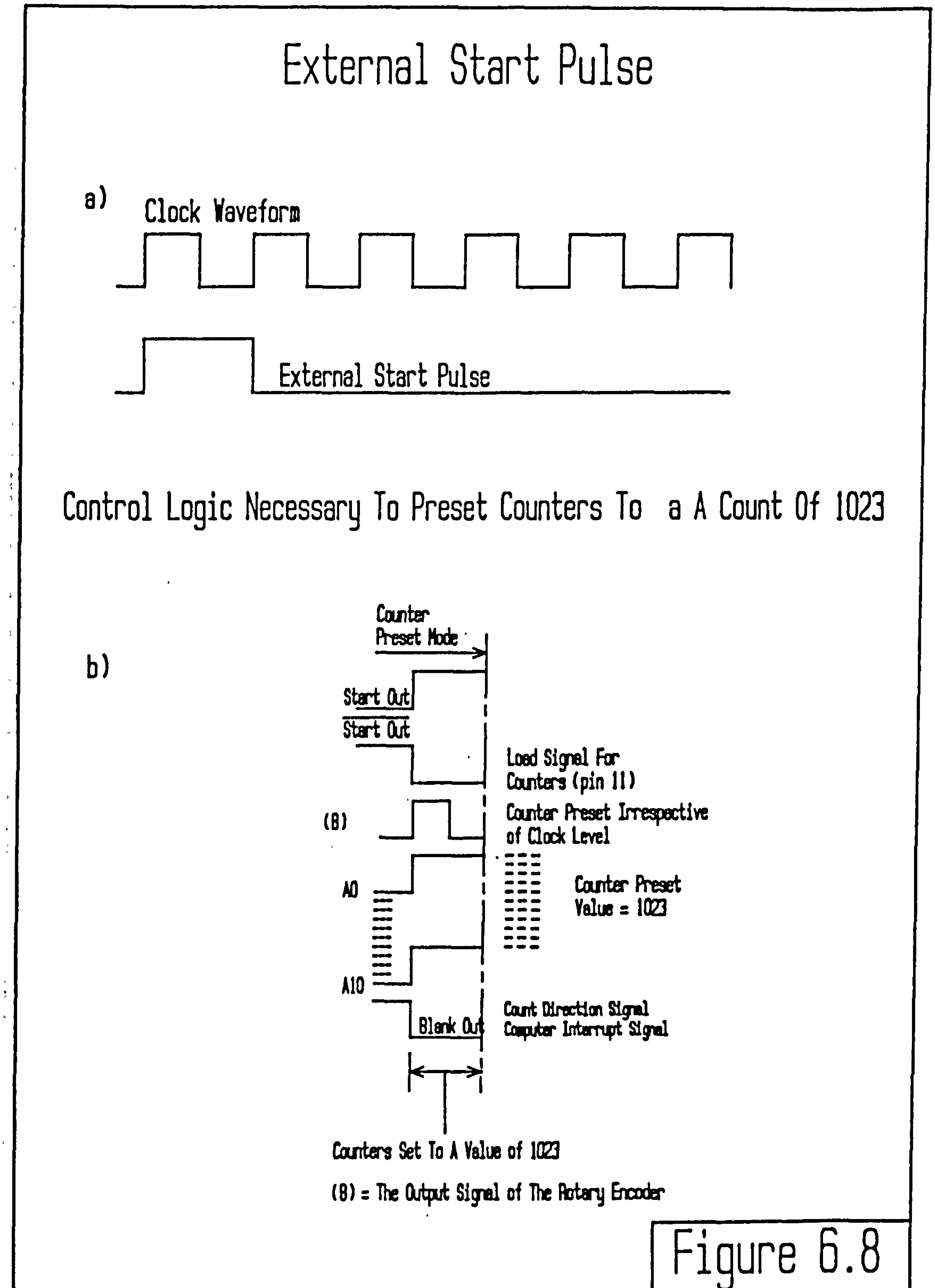


Figure 6.7


External Start Pulse
a)
Clock Waveform
External Start Pulse
Control Logic Necessary To Preset Counters To a A Count Of 1023
b)
Counter
Preset Mode
Start Out
Start Out
Load Signal For
Counters (pin 11)
(B)
Counter Preset Irrespective
of Clock Level
A0
Counter Preset
Value = 1023
A10
Blank Out
Count Direction Signal
Computer Interrupt Signal
Counters Set To A Value of 1023
(B) = The Output Signal of The Rotary Encoder
Figure 6.8

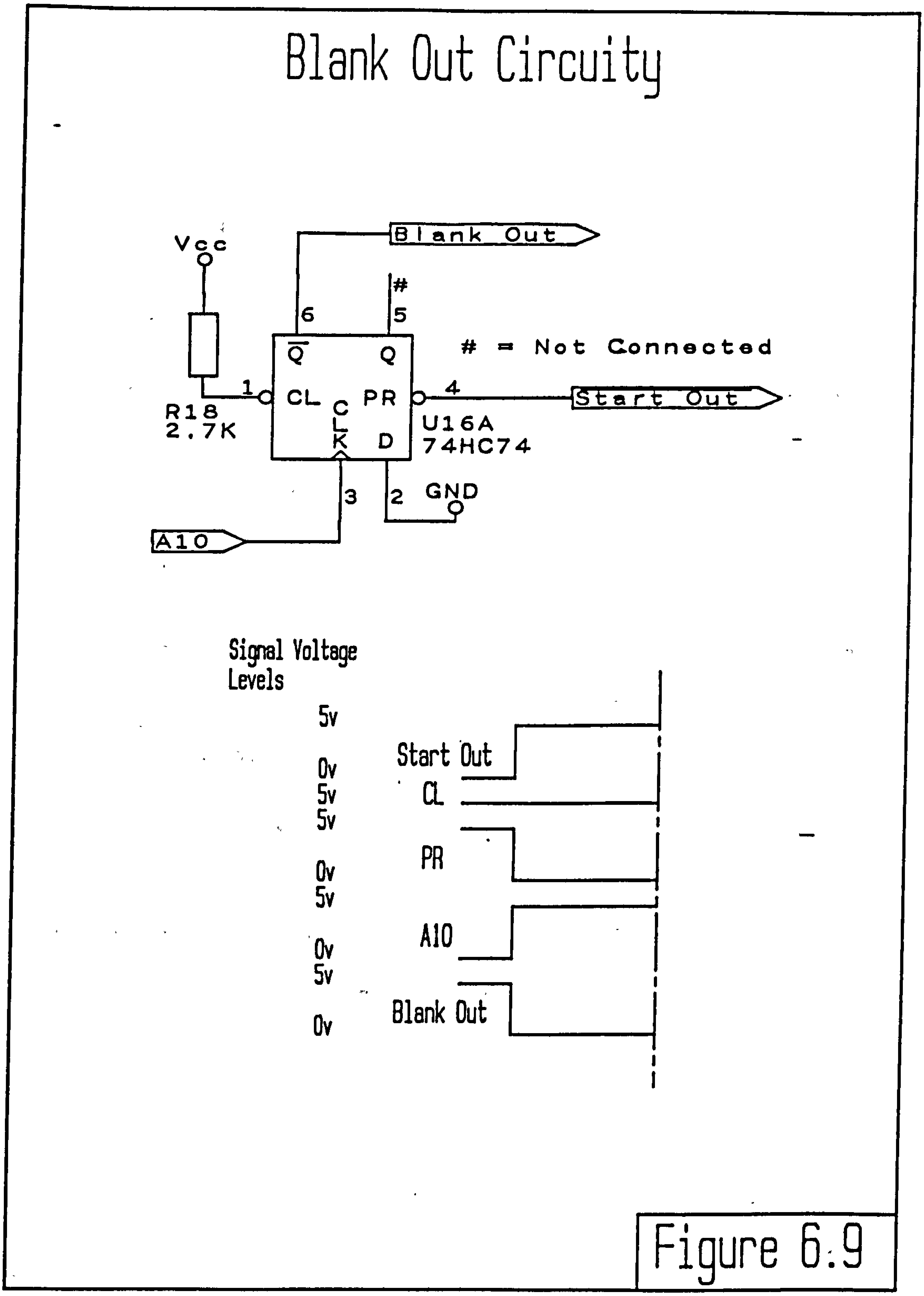

Blank Out Circuity
Vcc
R18
2.7K
Blank Out
#
6
5
Q̄
Q
= Not Connected
1
CL
PR
4
Start Out
CLK
D
U16A
74HC74
3
2
GND
A10
Signal Voltage Levels
5v
0v
5v
5v
0v
5v
0v
5v
0v
Start Out
CL
PR
A10
Blank Out

Figure 6.9

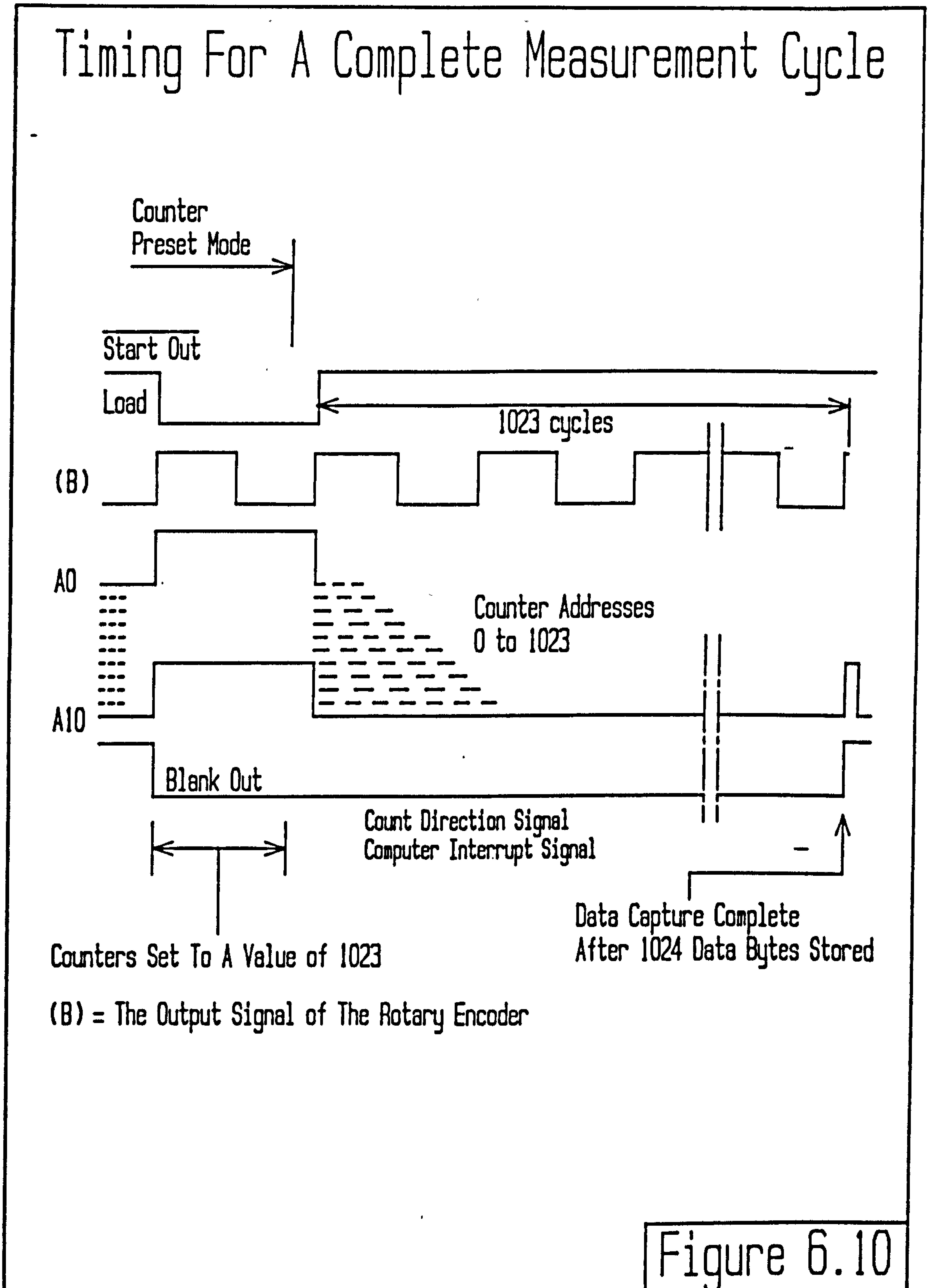

Timing For A Complete Measurement Cycle
Counter
Preset Mode
Start Out
Load
1023 cycles
(B)
A0
Counter Addresses
0 to 1023
A10
Blank Out
Count Direction Signal
Computer Interrupt Signal
Data Capture Complete
After 1024 Data Bytes Stored
Counters Set To A Value of 1023
(B) = The Output Signal of The Rotary Encoder

Figure 6.10

The Photo-Detector

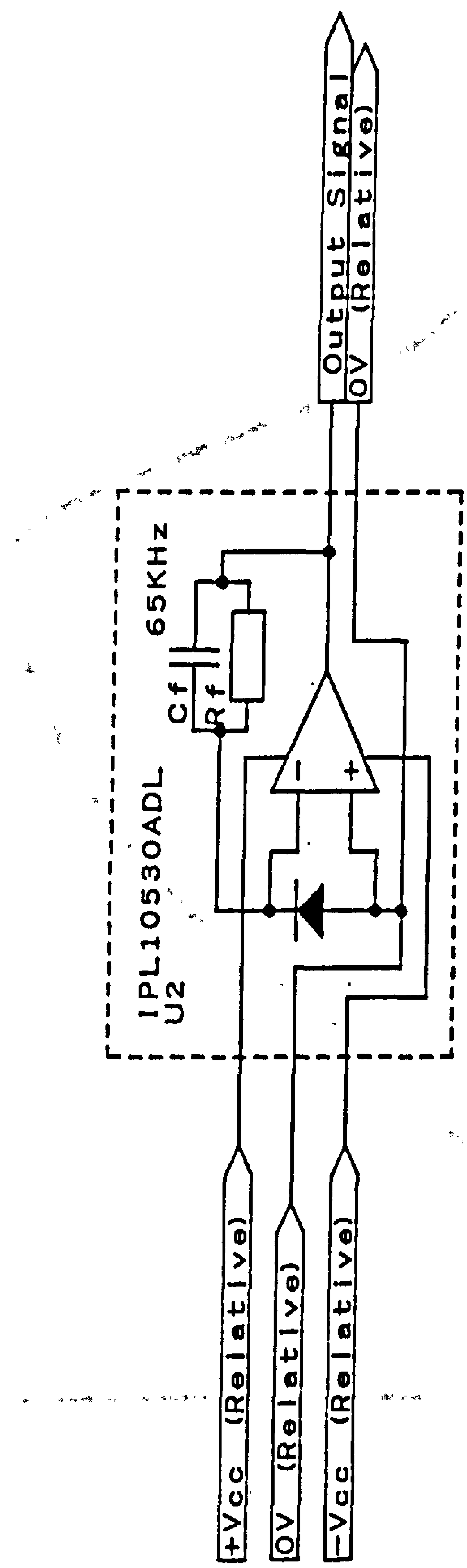


Figure 6.11

Relative Spectral Response

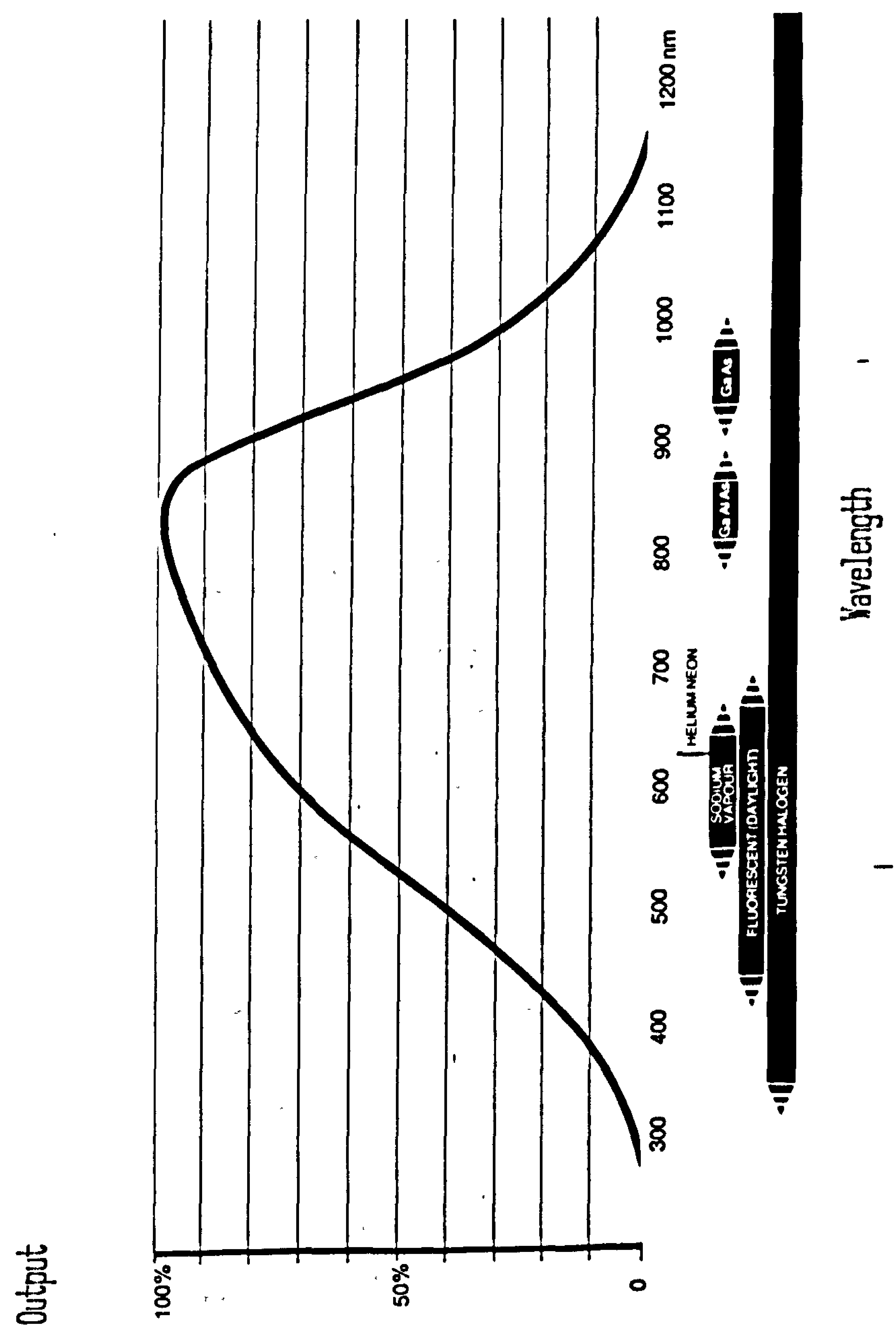


Figure 6.12

Power Supply Design

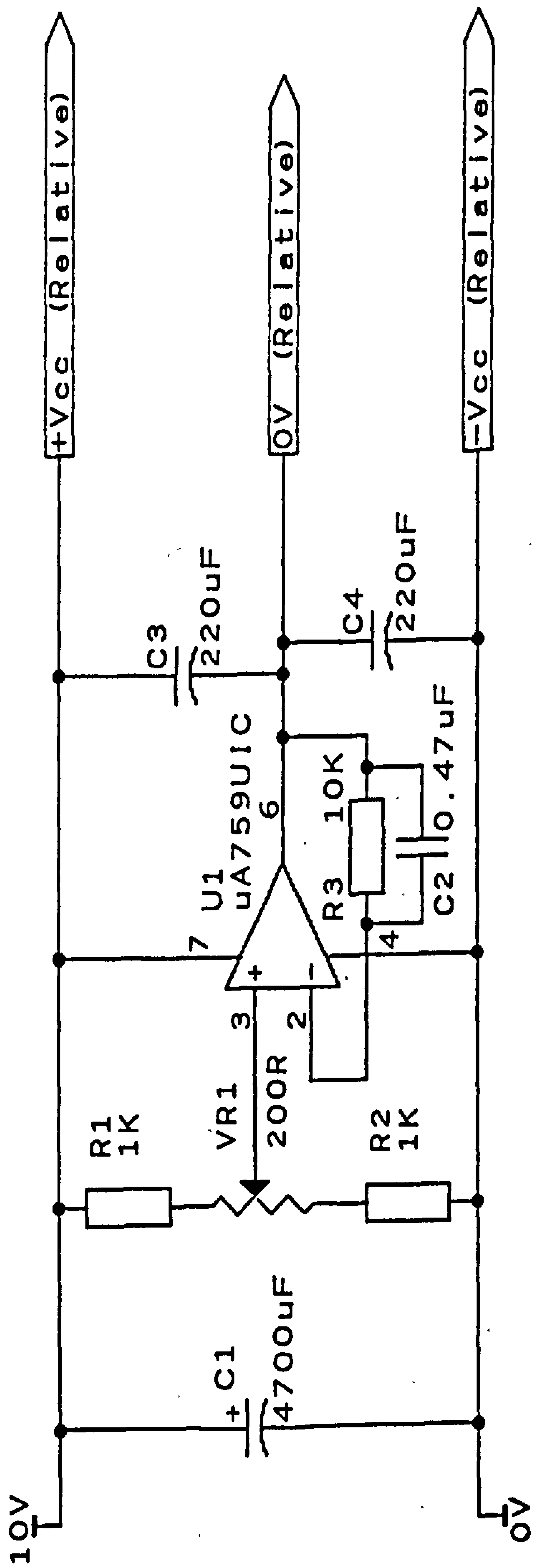


Figure 6.13

Precision Differential Amplifier

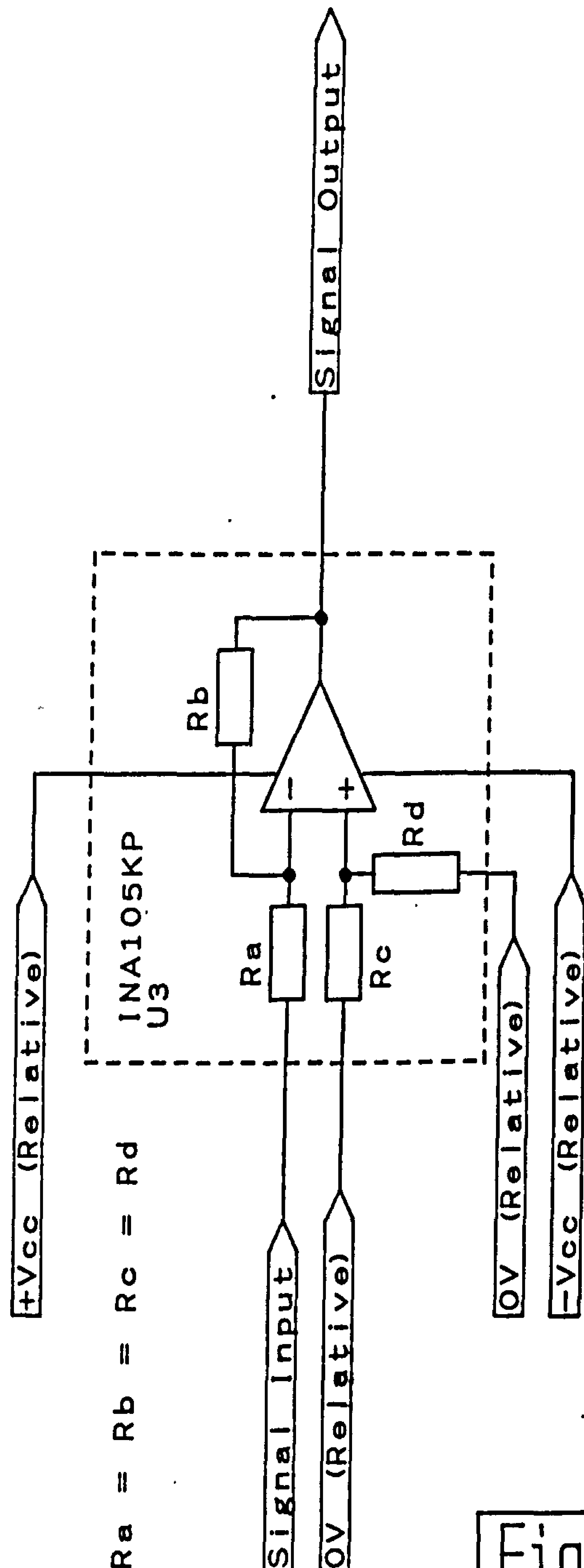


Figure 6.14

Conditioning Circuitry

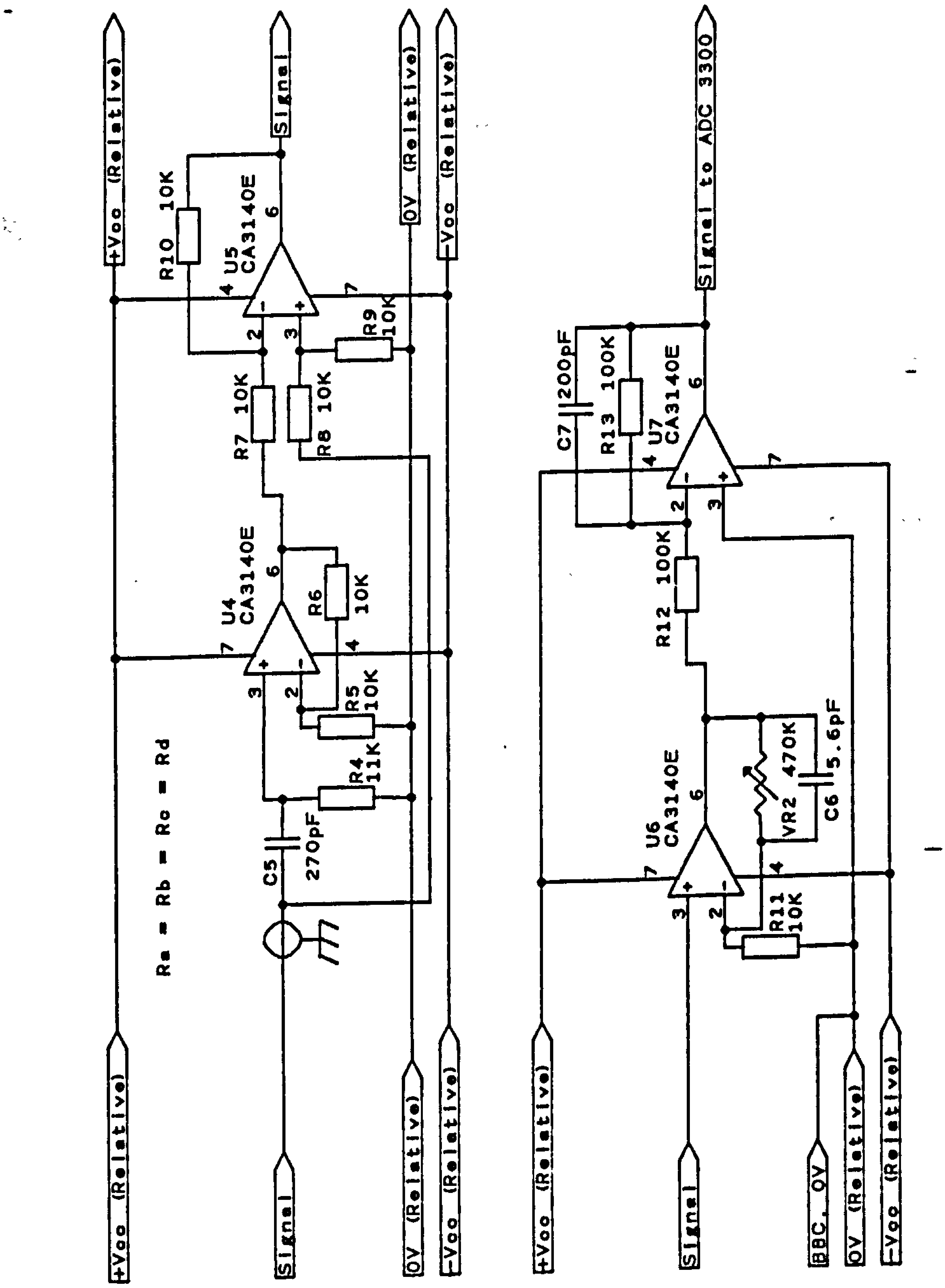


Figure 6.15

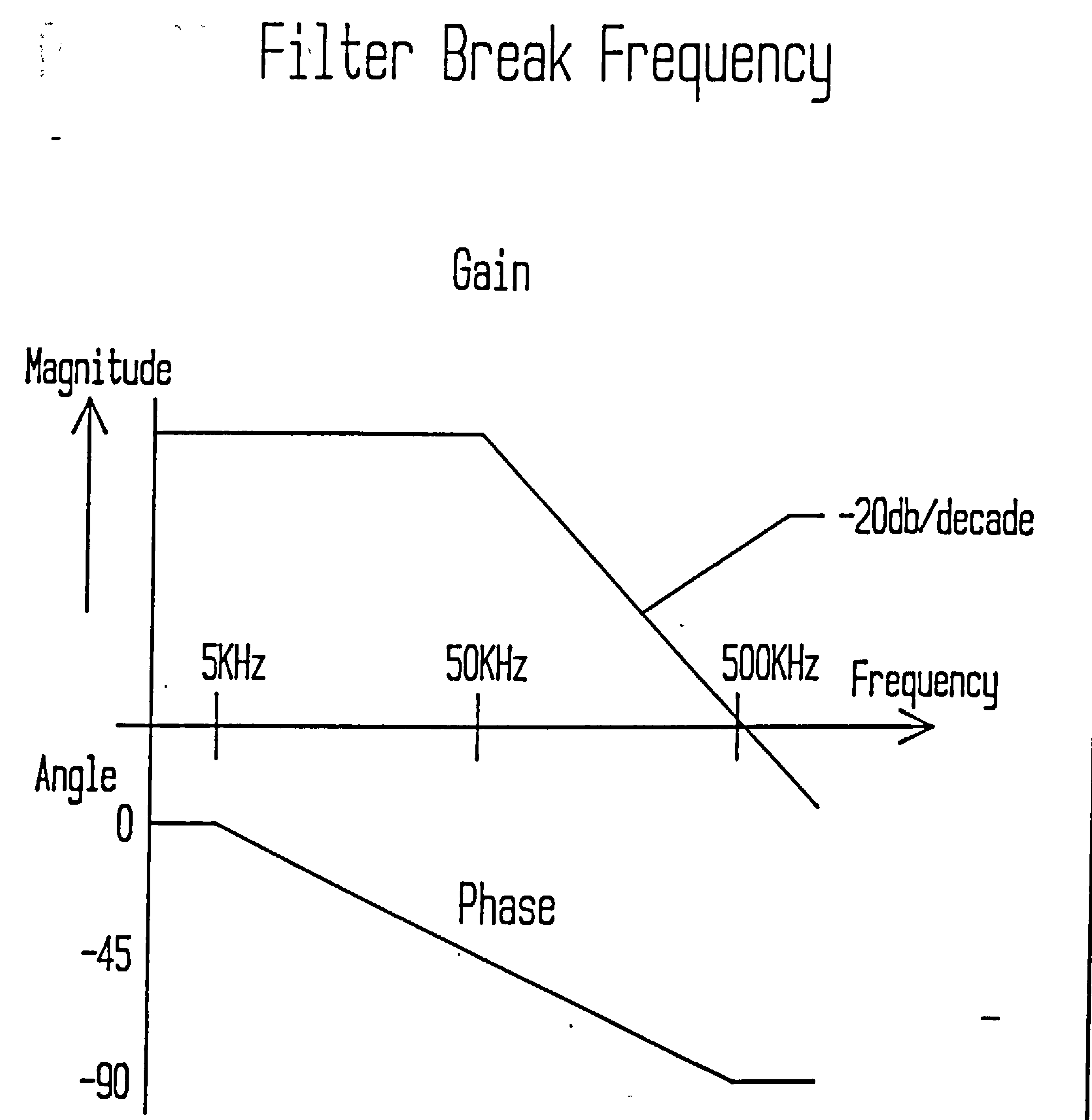

Filter Break Frequency
Gain
Magnitude
-20db/decade
5KHz
50KHz
500KHz
Frequency
Angle
0
-45
-90
Phase

Figure 6.16

The 3300 Conversion Cycle Timing Diagram

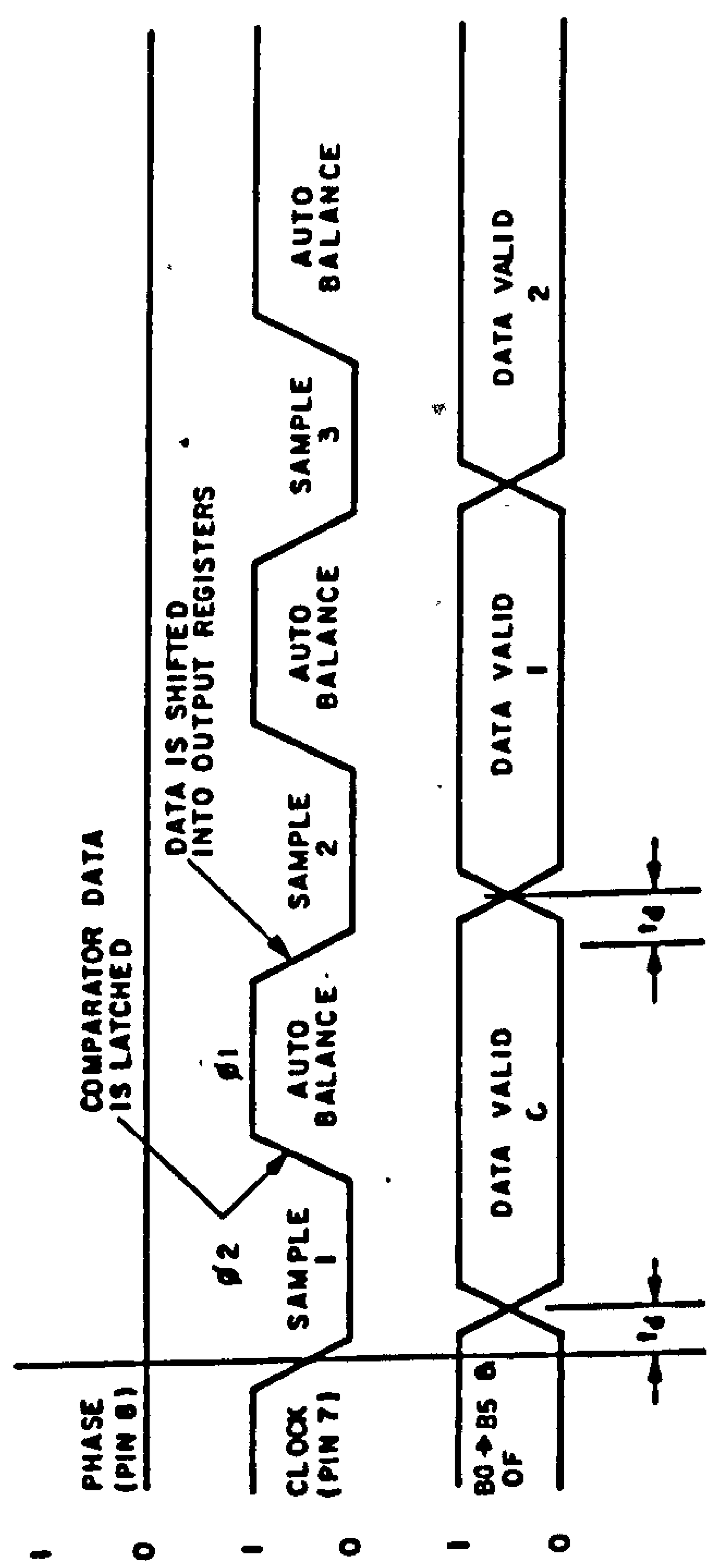


Figure 6.17

Internal Data Latches

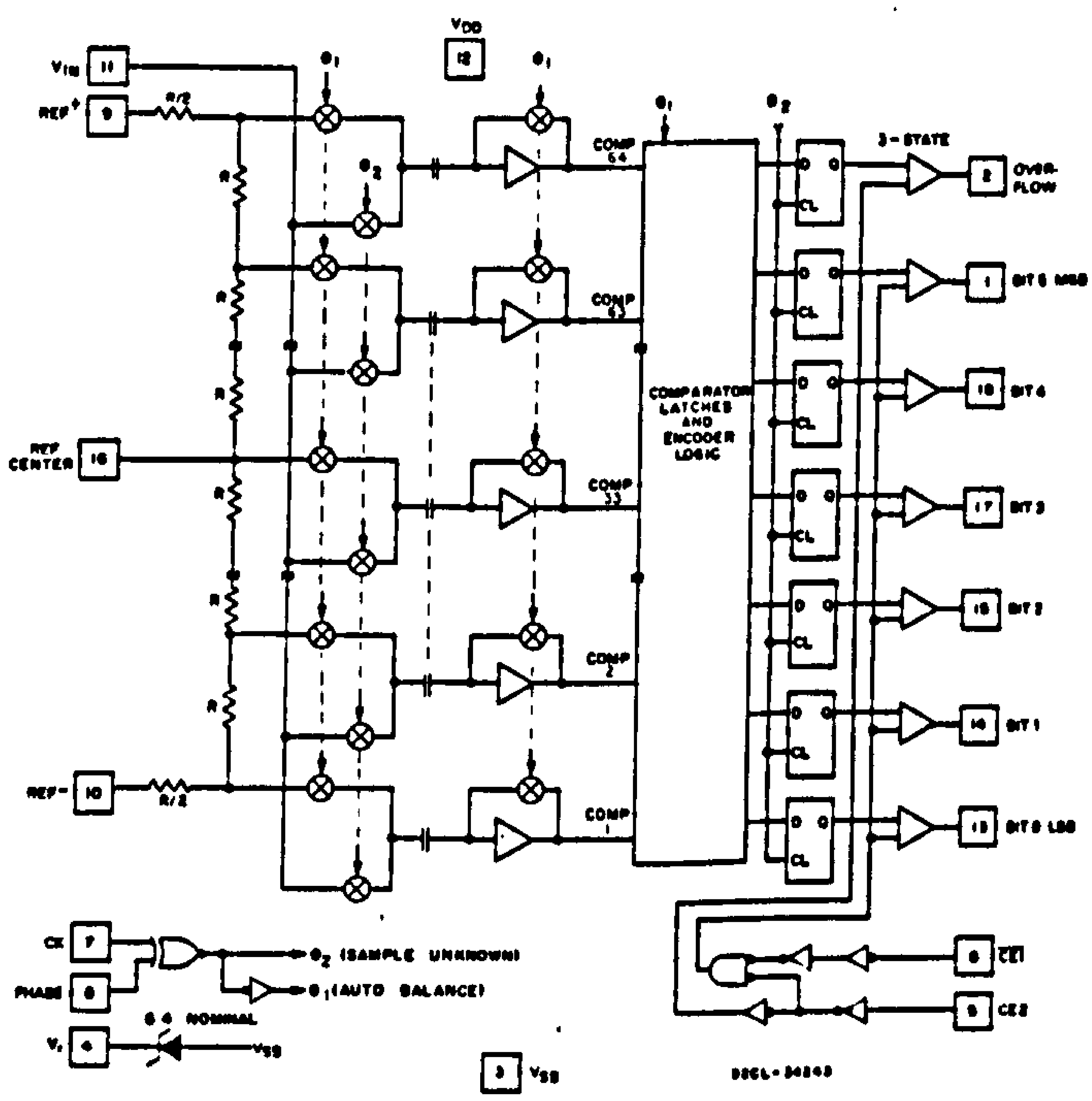


Figure 6.18

Load Pressure Versus Diameter Compression

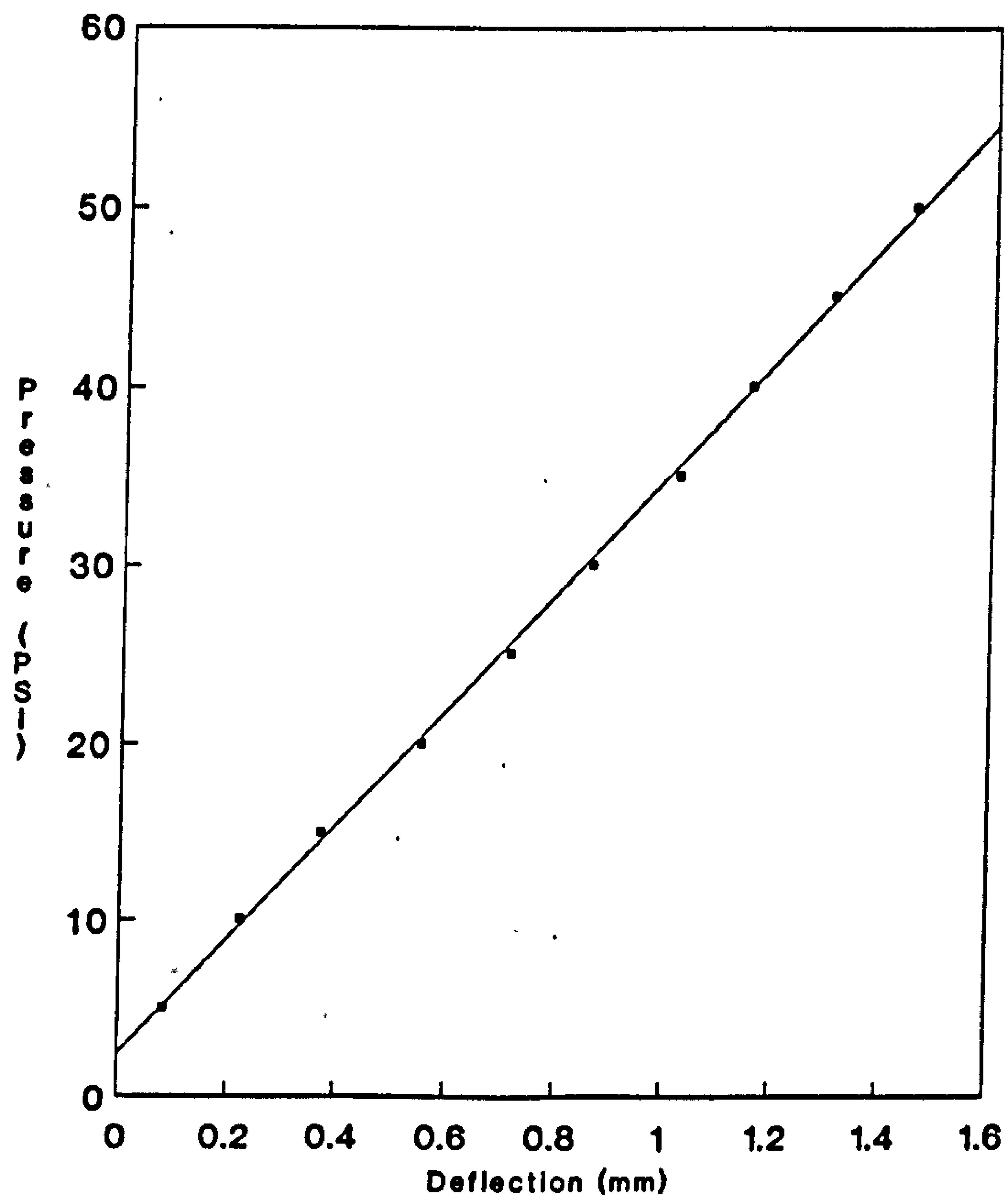


Figure 6.19

The Efficiency Of The Fast Fourier Transform

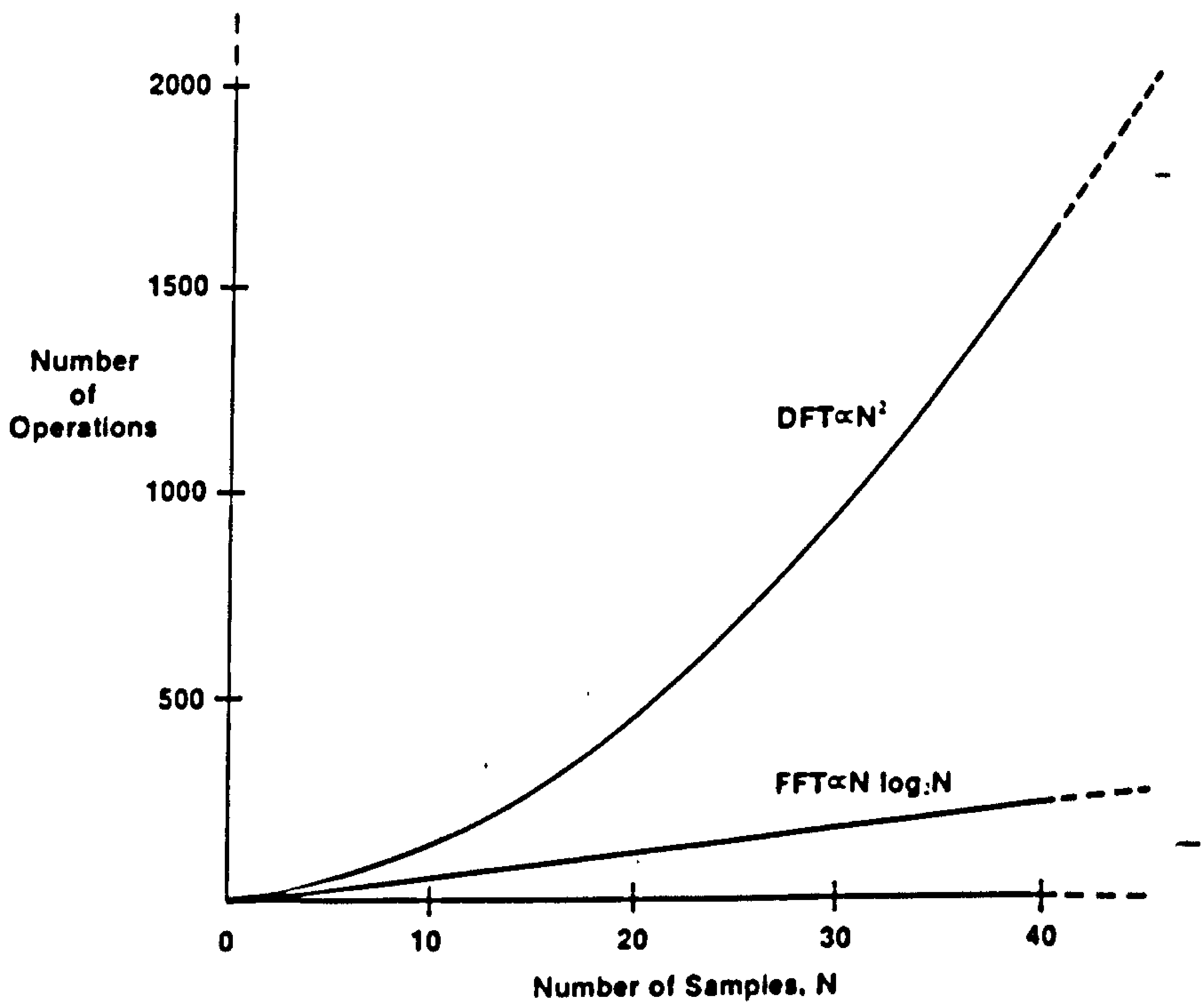


Figure 6.20

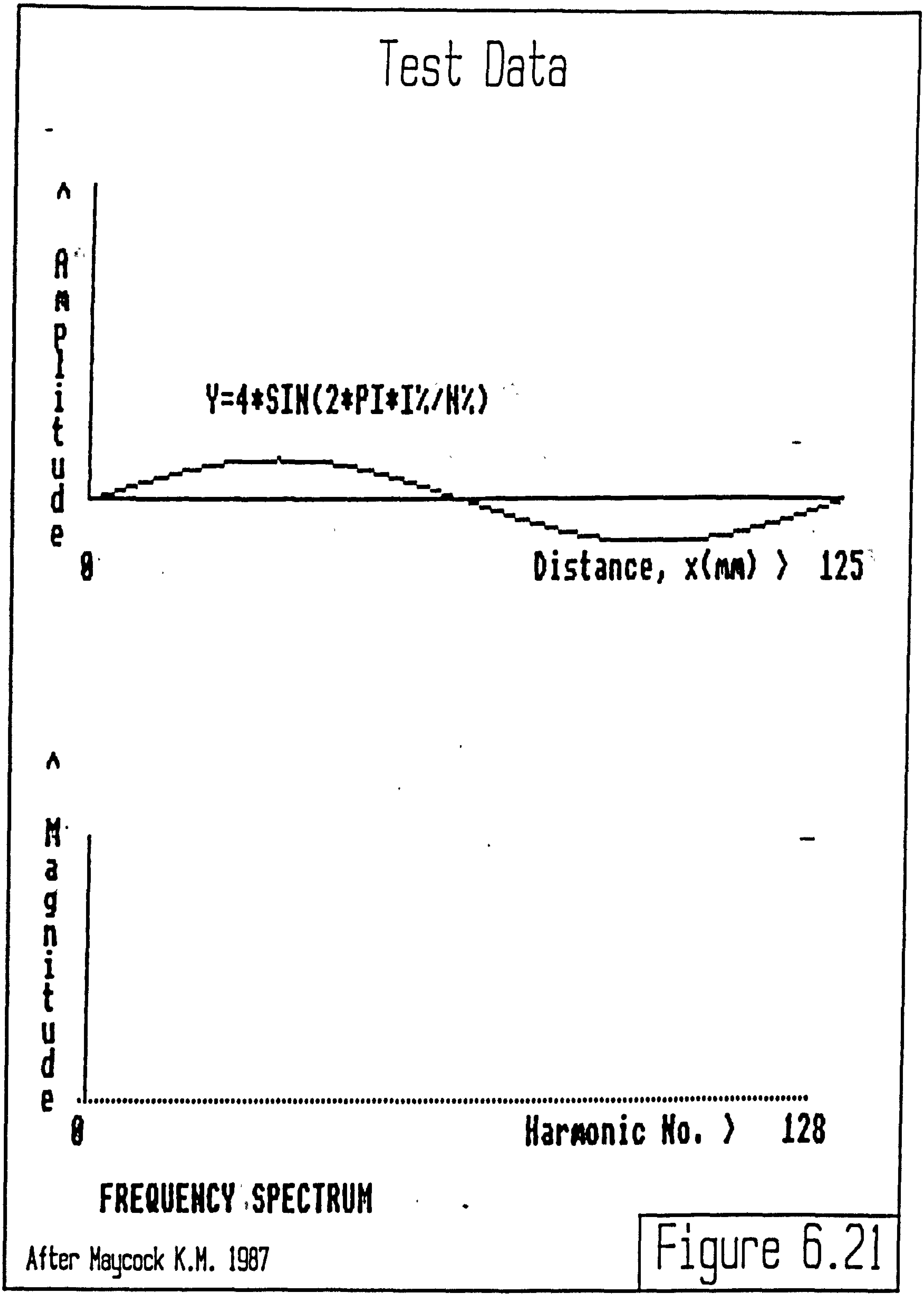
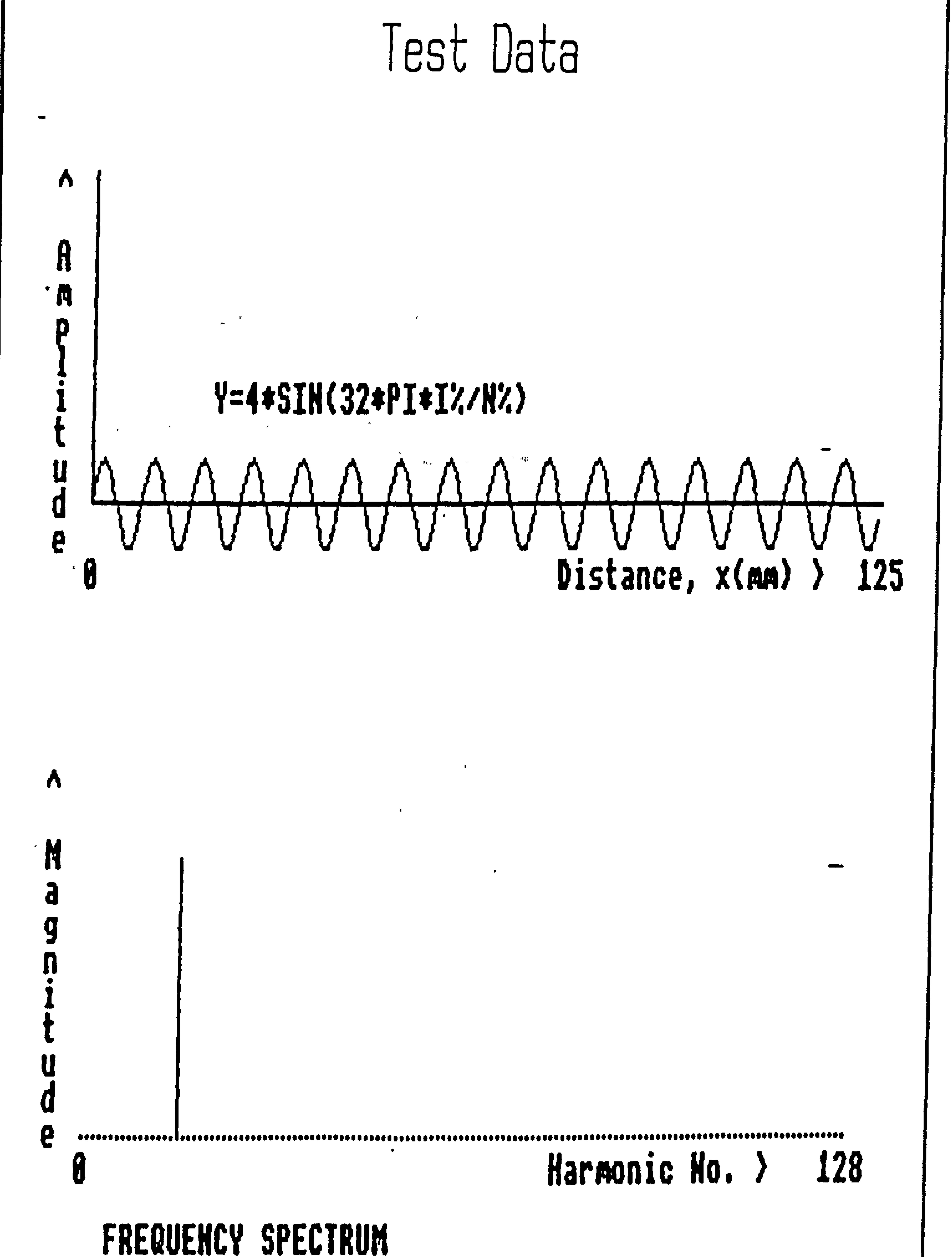

Test Data
Amplitude
Y=4*SIN(2*PI*I%/N%)
0
Distance, x(mm) > 125
Magnitude
0
Harmonic No. > 128
FREQUENCY SPECTRUM
After Maycock K.M. 1987

Figure 6.21



After Maycock K.M. 1987

Figure 6.22

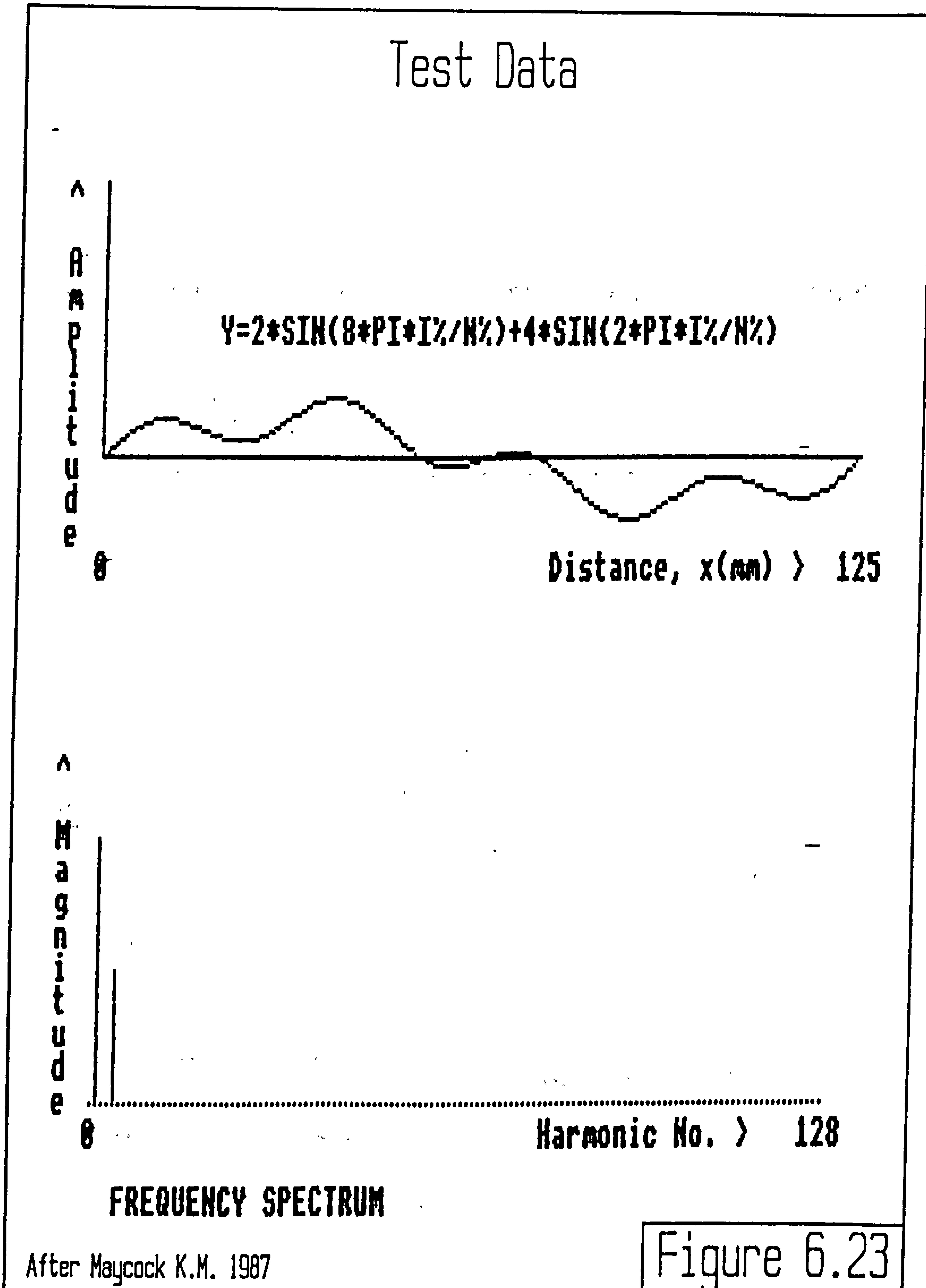

Test Data
Amplitude
Y=2*SIN(8*PI*I%/N%)+4*SIN(2*PI*I%/N%)
0
Distance, x(mm) > 125
Magnitude
0
Harmonic No. > 128
FREQUENCY SPECTRUM
After Maycock K.M. 1987

Figure 6.23

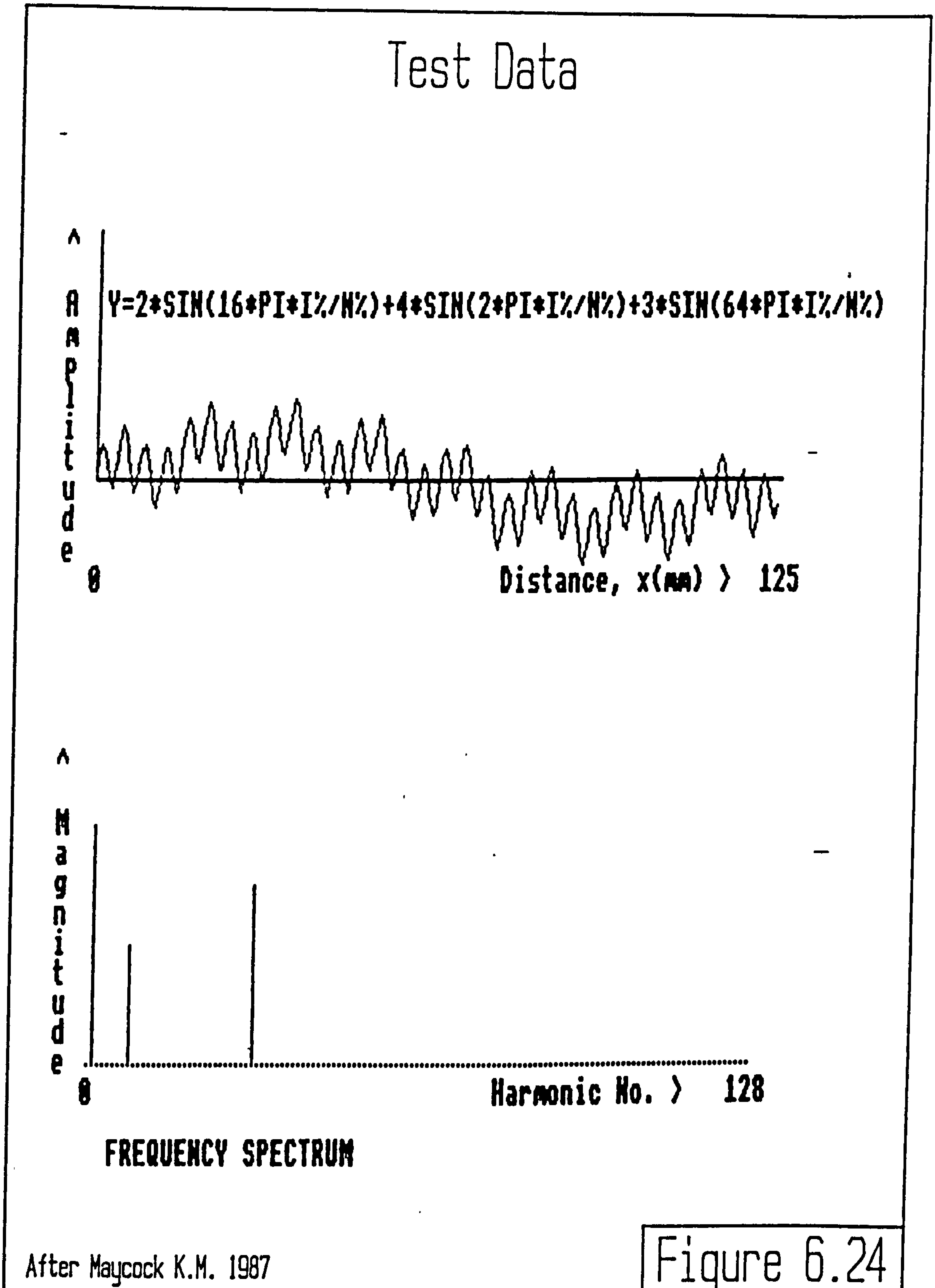
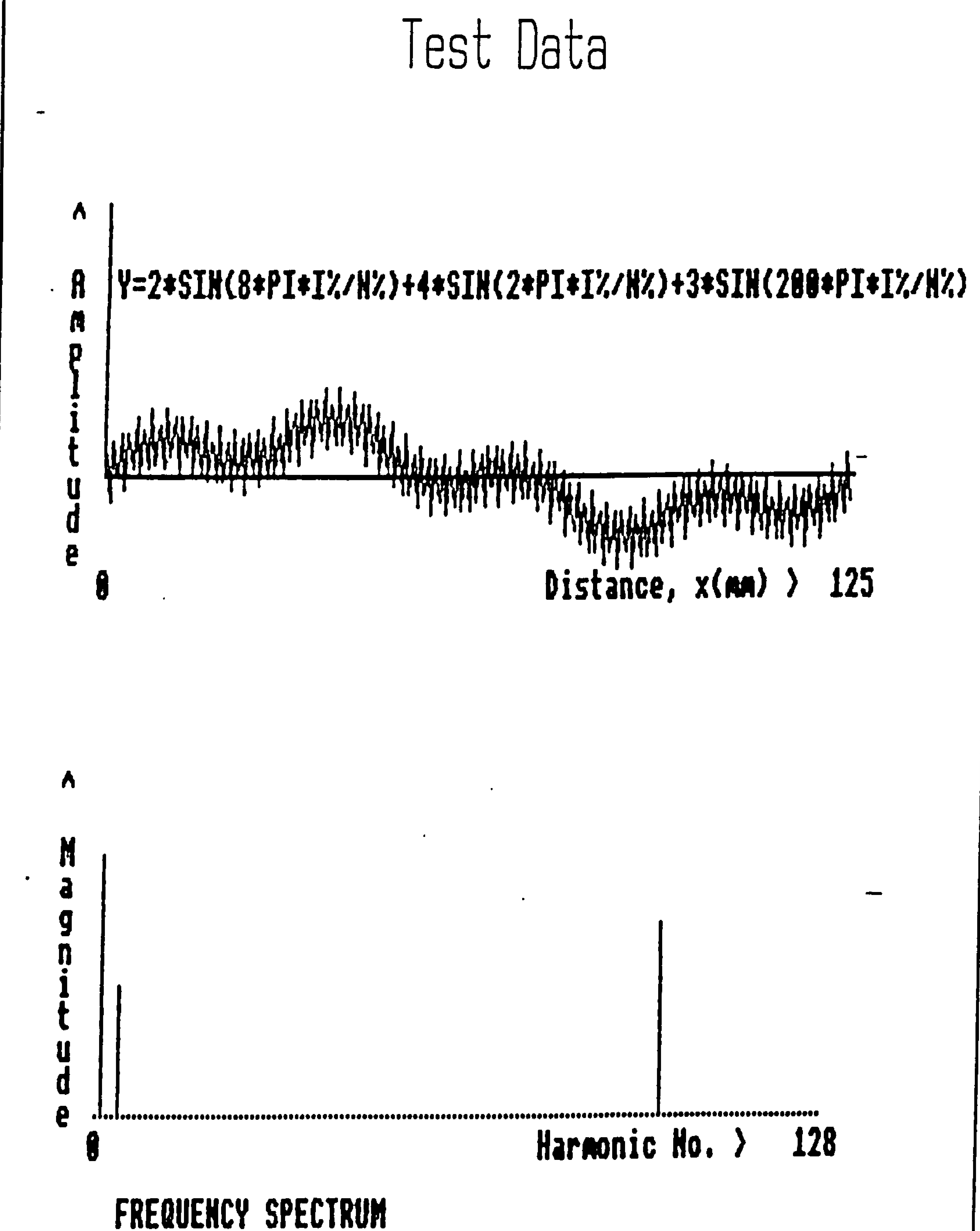

Test Data
Amplitude
Y=2*SIN(16*PI*I%/N%)+4*SIN(2*PI*I%/N%)+3*SIN(64*PI*I%/N%)
0
Distance, x(mm) > 125
Magnitude
0
Harmonic No. > 128
FREQUENCY SPECTRUM
After Maycock K.M. 1987

Figure 6.24



After Maycock K.M. 1987

Figure 6.25

Single Illumination

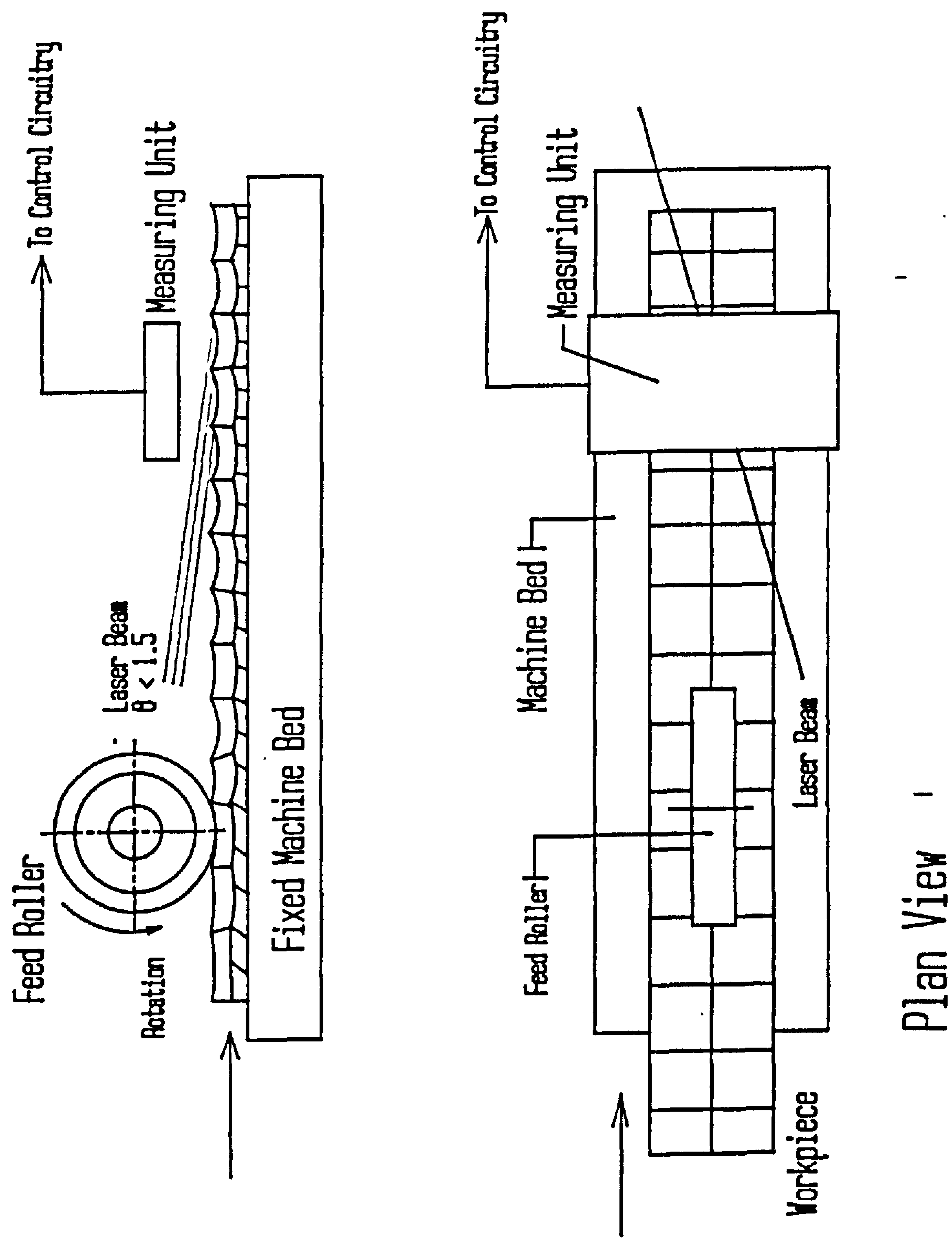


Figure 7.1

Single Illumination

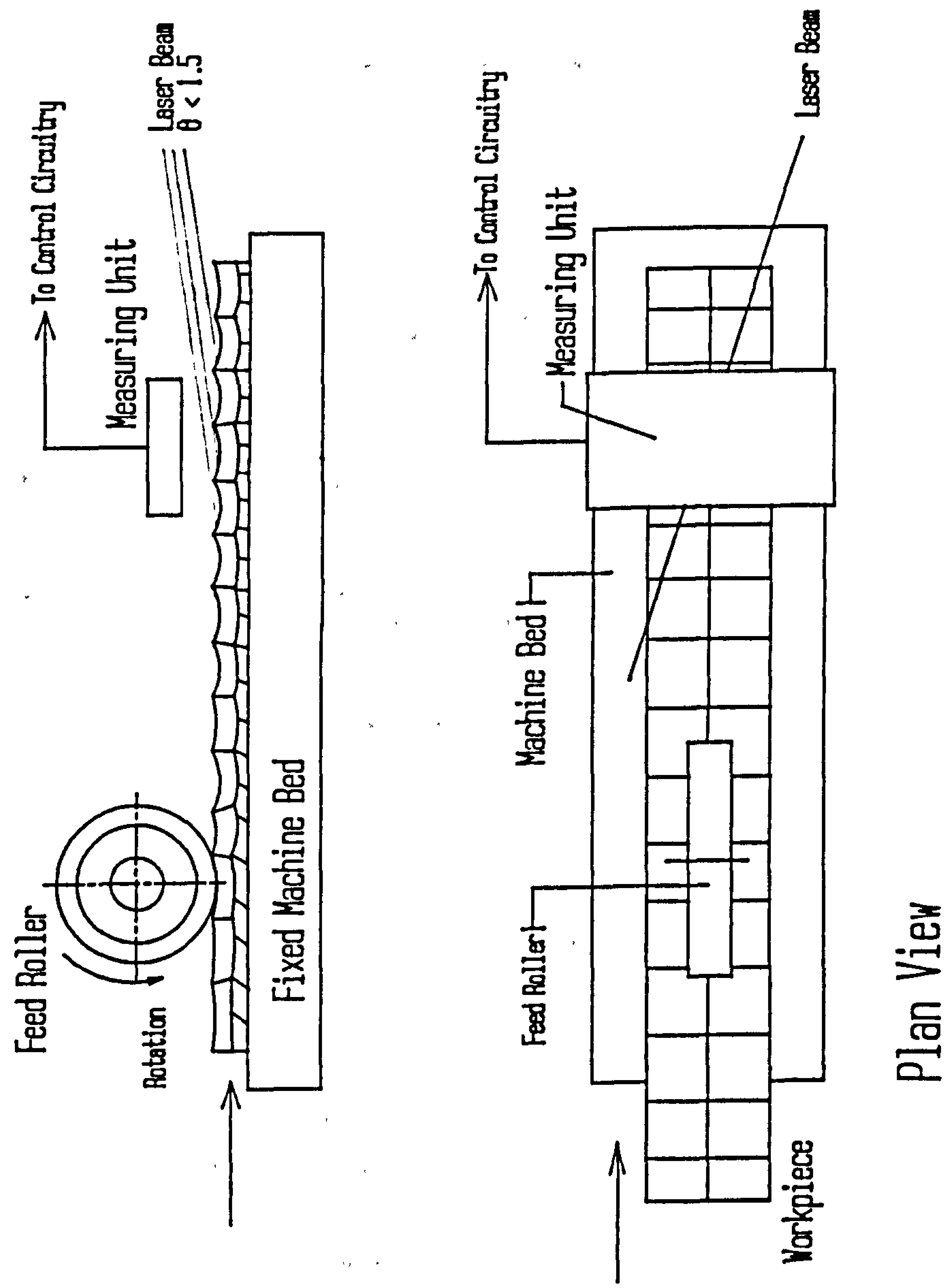


Figure 7.2

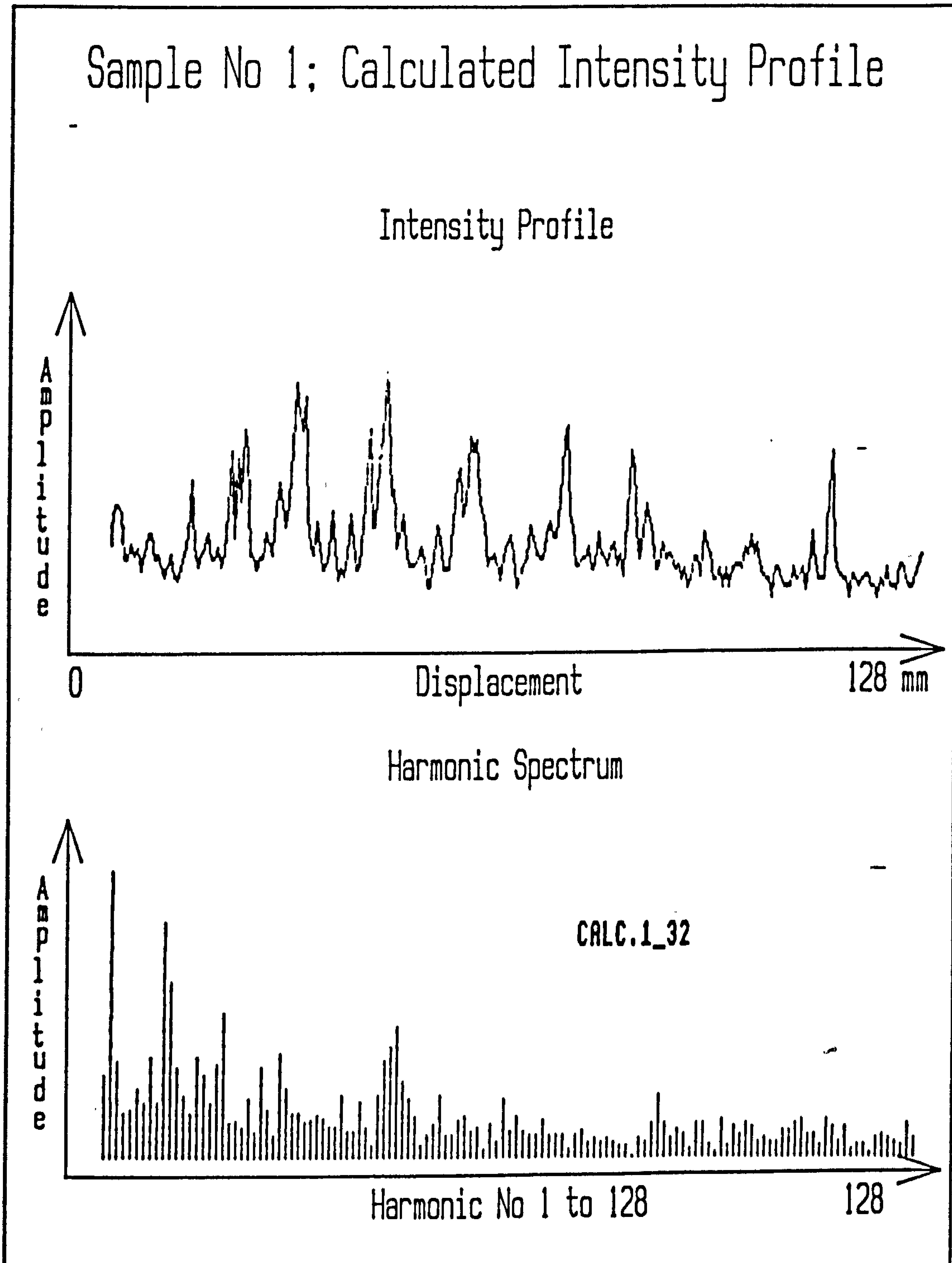

Sample No 1; Calculated Intensity Profile
Intensity Profile
Amplitude
0
Displacement
128 mm
Harmonic Spectrum
Amplitude
CALC.1_32
Harmonic No 1 to 128
128

Figure 7.3

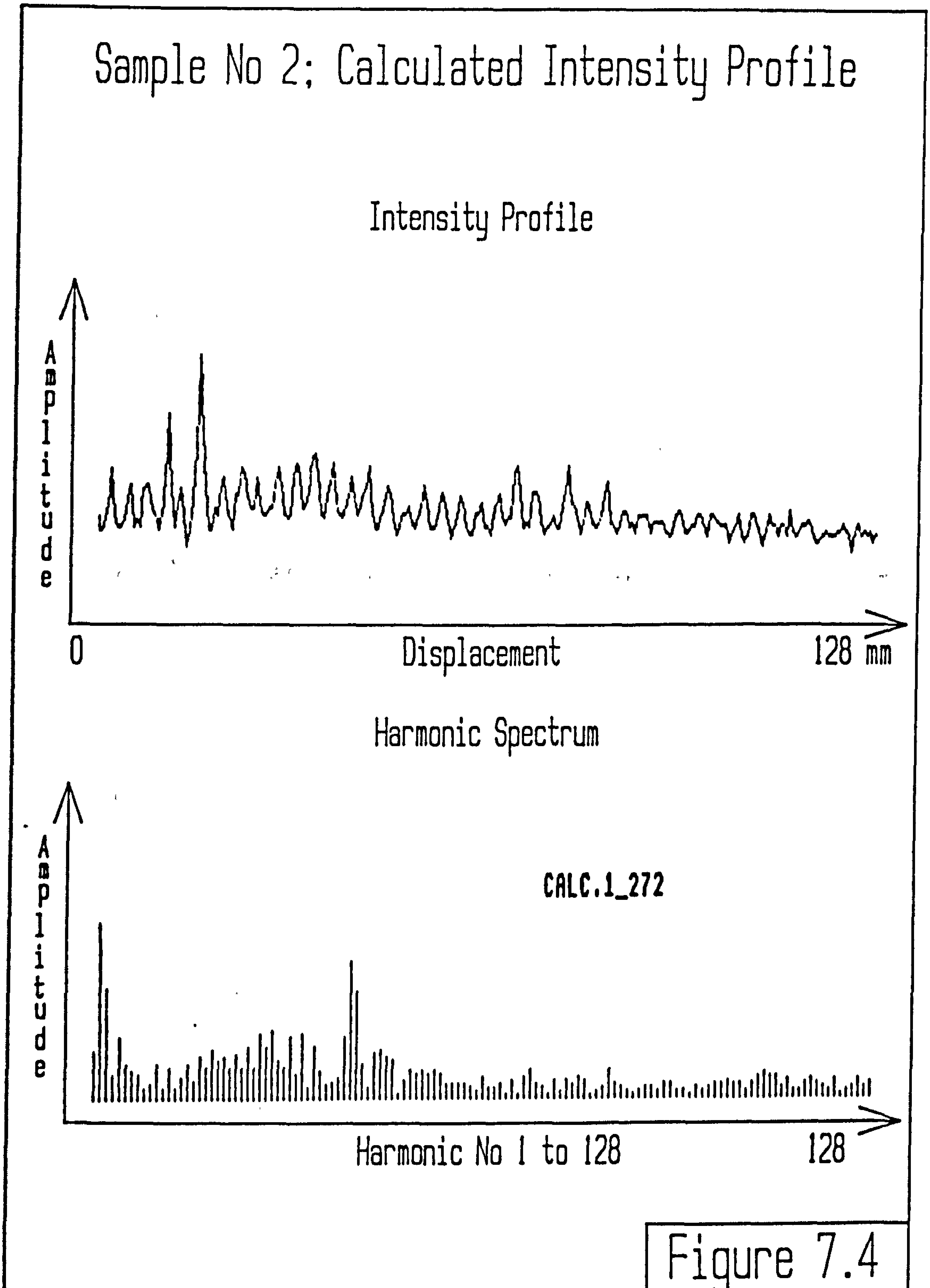
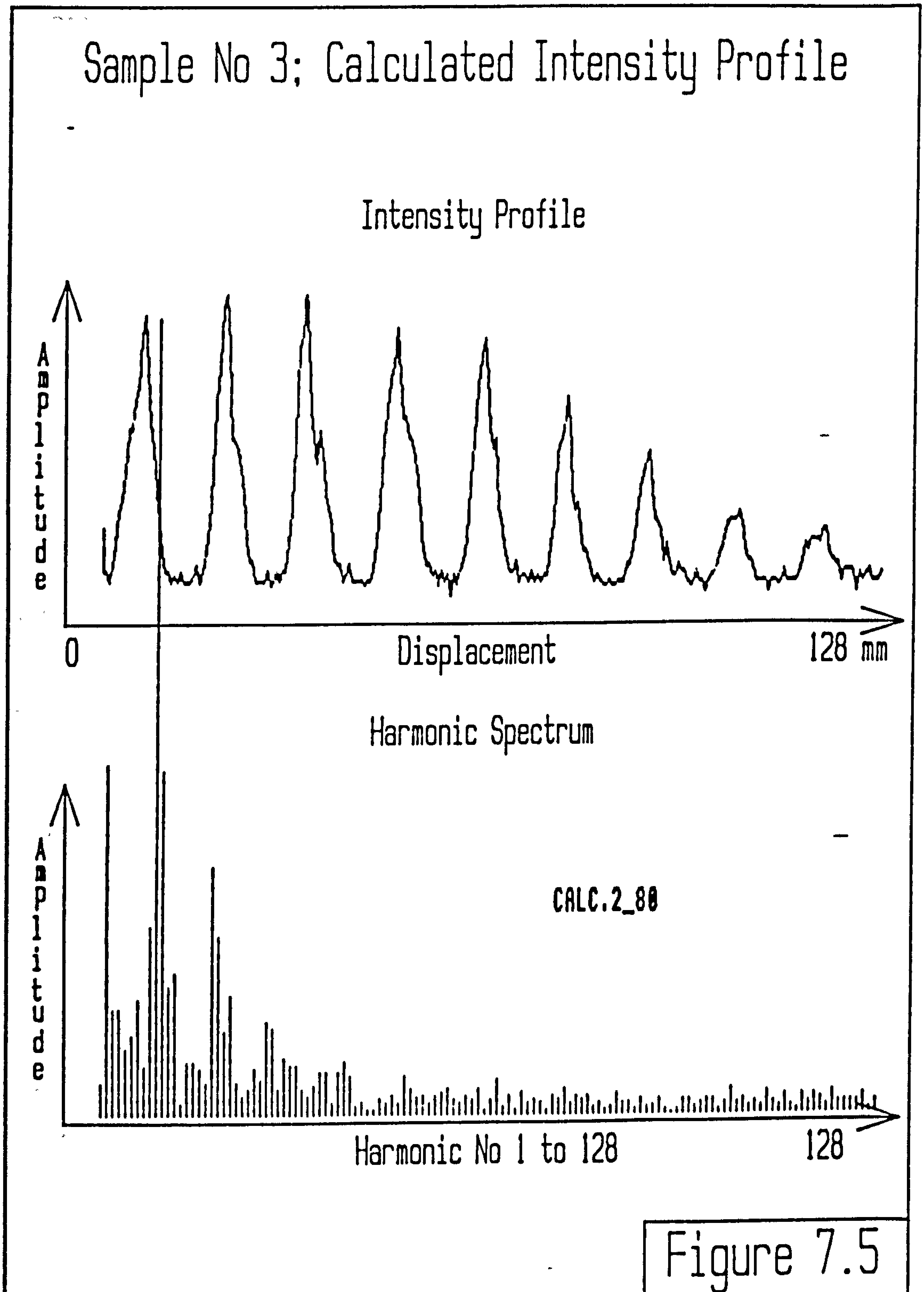

Sample No 2; Calculated Intensity Profile
Intensity Profile
Amplitude
0
Displacement
128 mm
Harmonic Spectrum
Amplitude
CALC.1_272
Harmonic No 1 to 128
128

Figure 7.4



Sample No 3; Calculated Intensity Profile
Intensity Profile
Amplitude
0
Displacement
128 mm
Harmonic Spectrum
Amplitude
CALC.2_80
Harmonic No 1 to 128
128

Figure 7.5

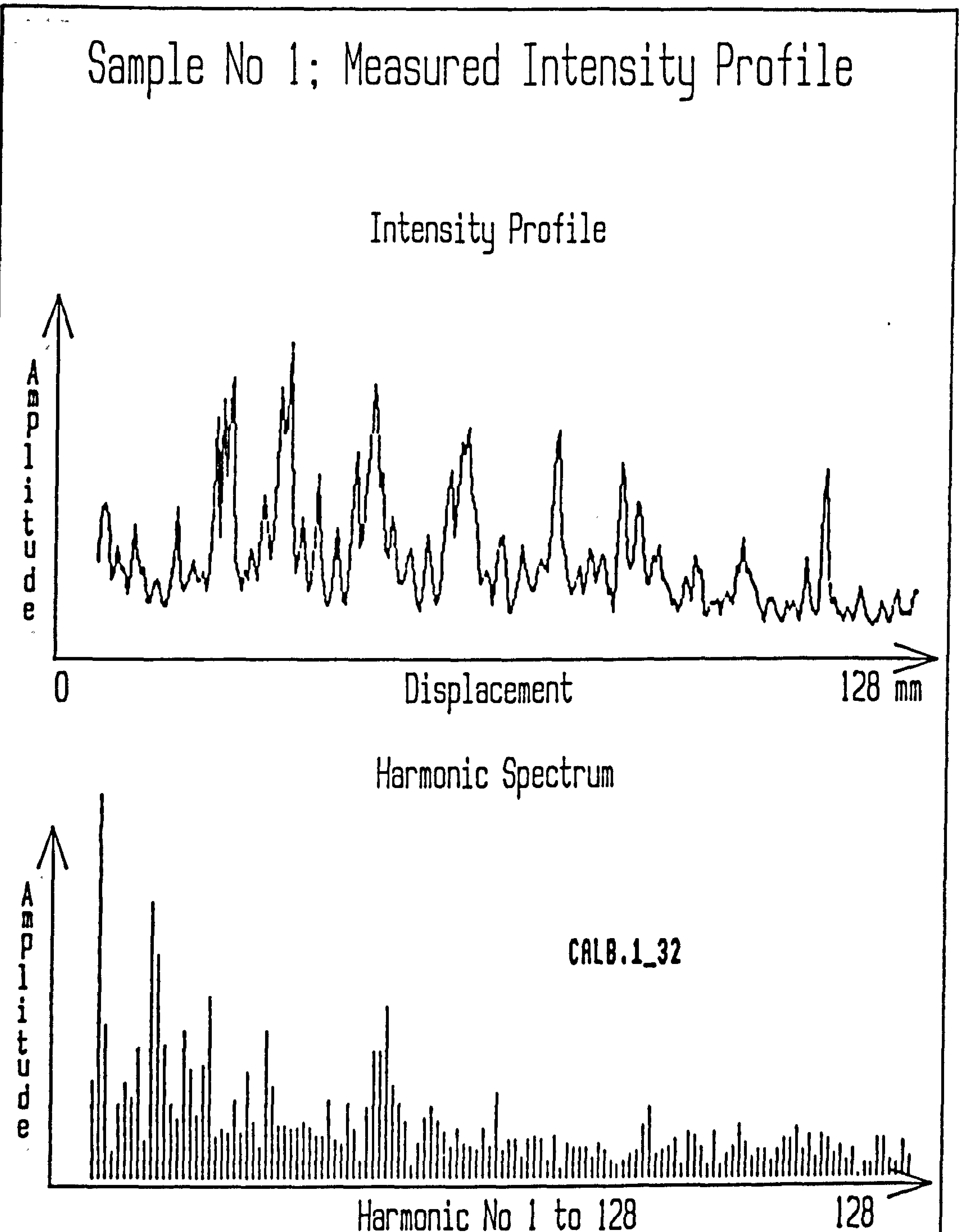

Sample No 1; Measured Intensity Profile
Intensity Profile
Amplitude
0
Displacement
128 mm
Harmonic Spectrum
Amplitude
CALB.1_32
Harmonic No 1 to 128
128

Figure 7.6

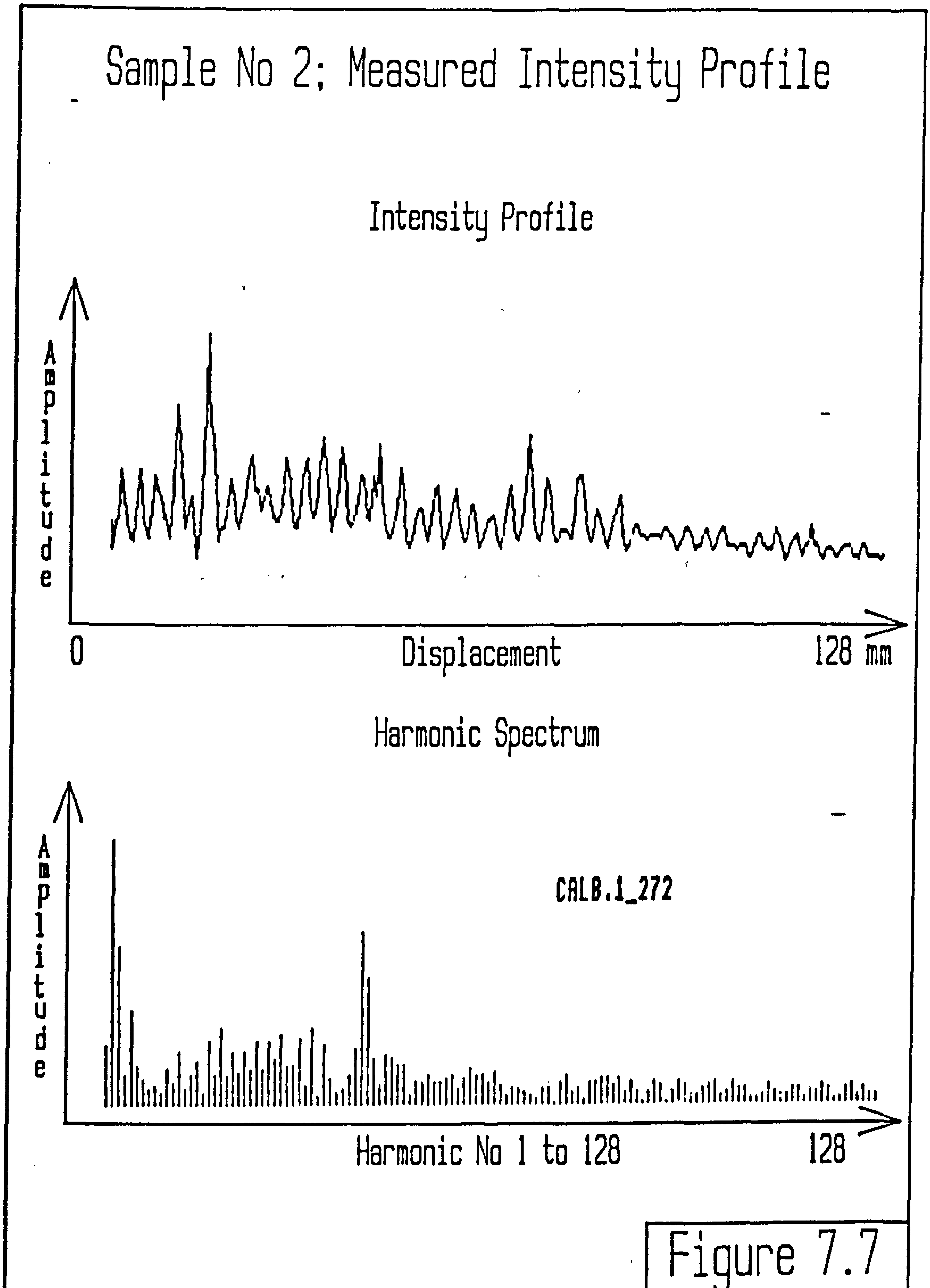

Sample No 2; Measured Intensity Profile
Intensity Profile
Amplitude
0
Displacement
128 mm
Harmonic Spectrum
Amplitude
CALB.1_272
Harmonic No 1 to 128
128

Figure 7.7

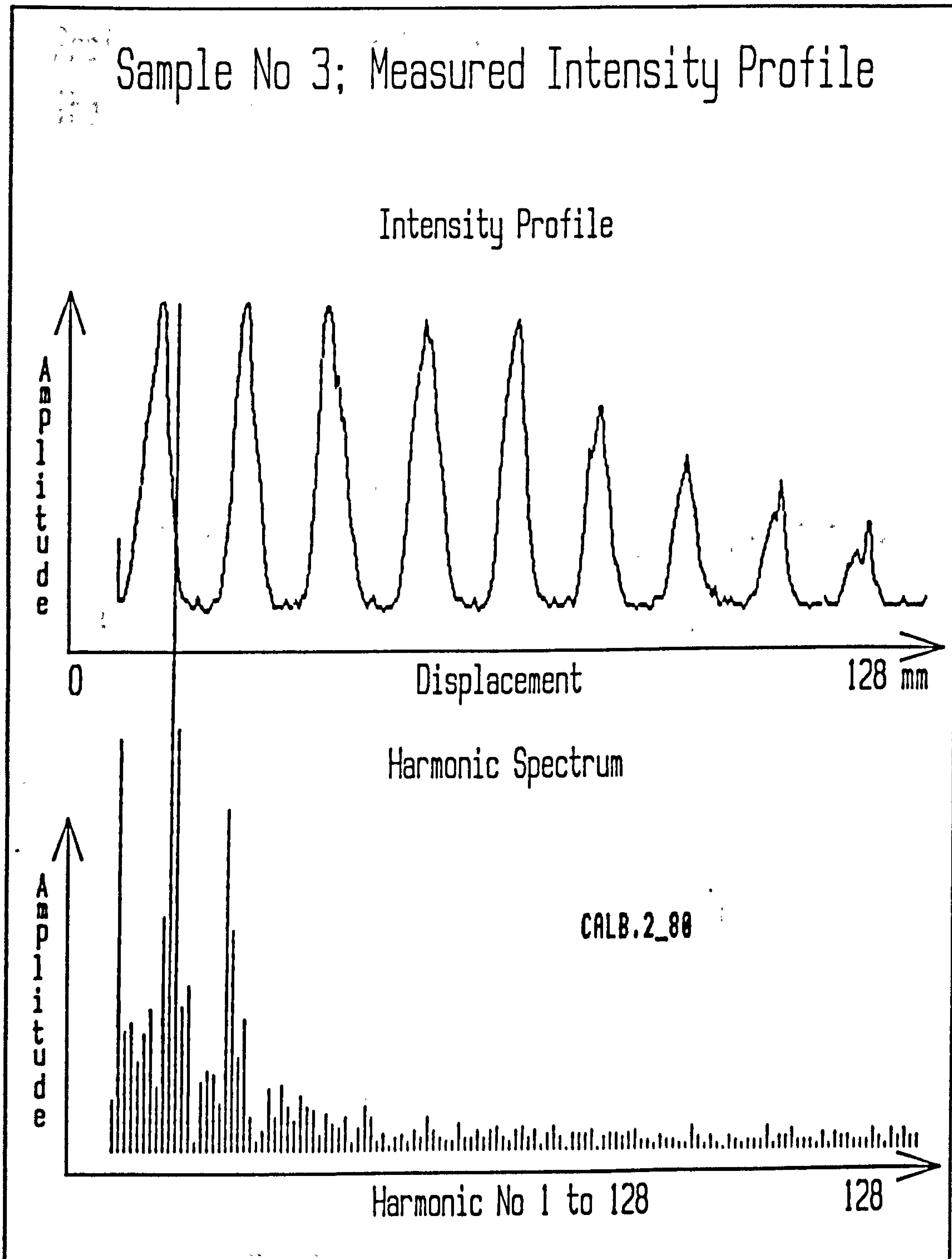

Sample No 3; Measured Intensity Profile
Intensity Profile
Amplitude
0
Displacement
128 mm
Harmonic Spectrum
Amplitude
CALB.2_80
Harmonic No 1 to 128
128

Figure 7.8

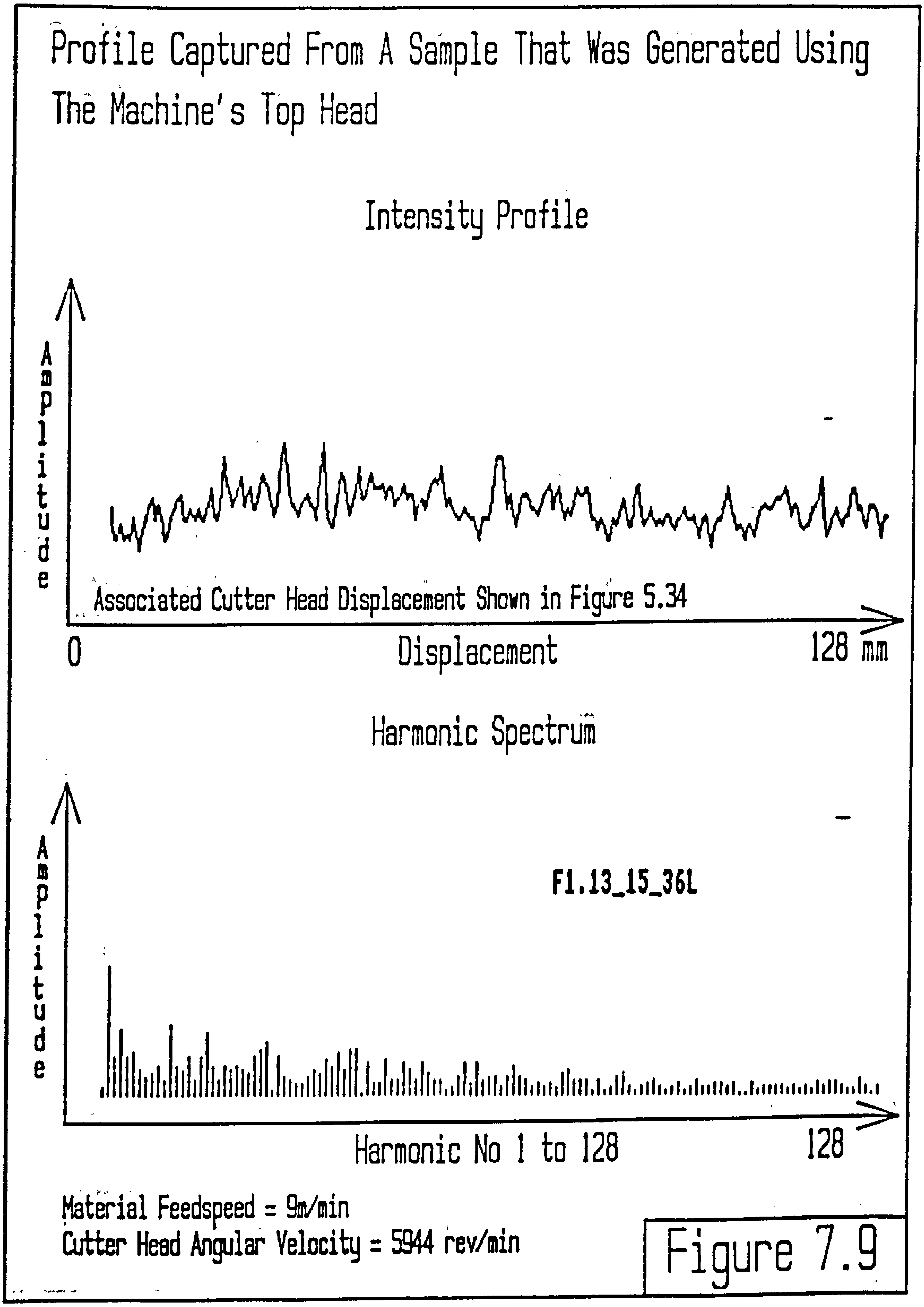
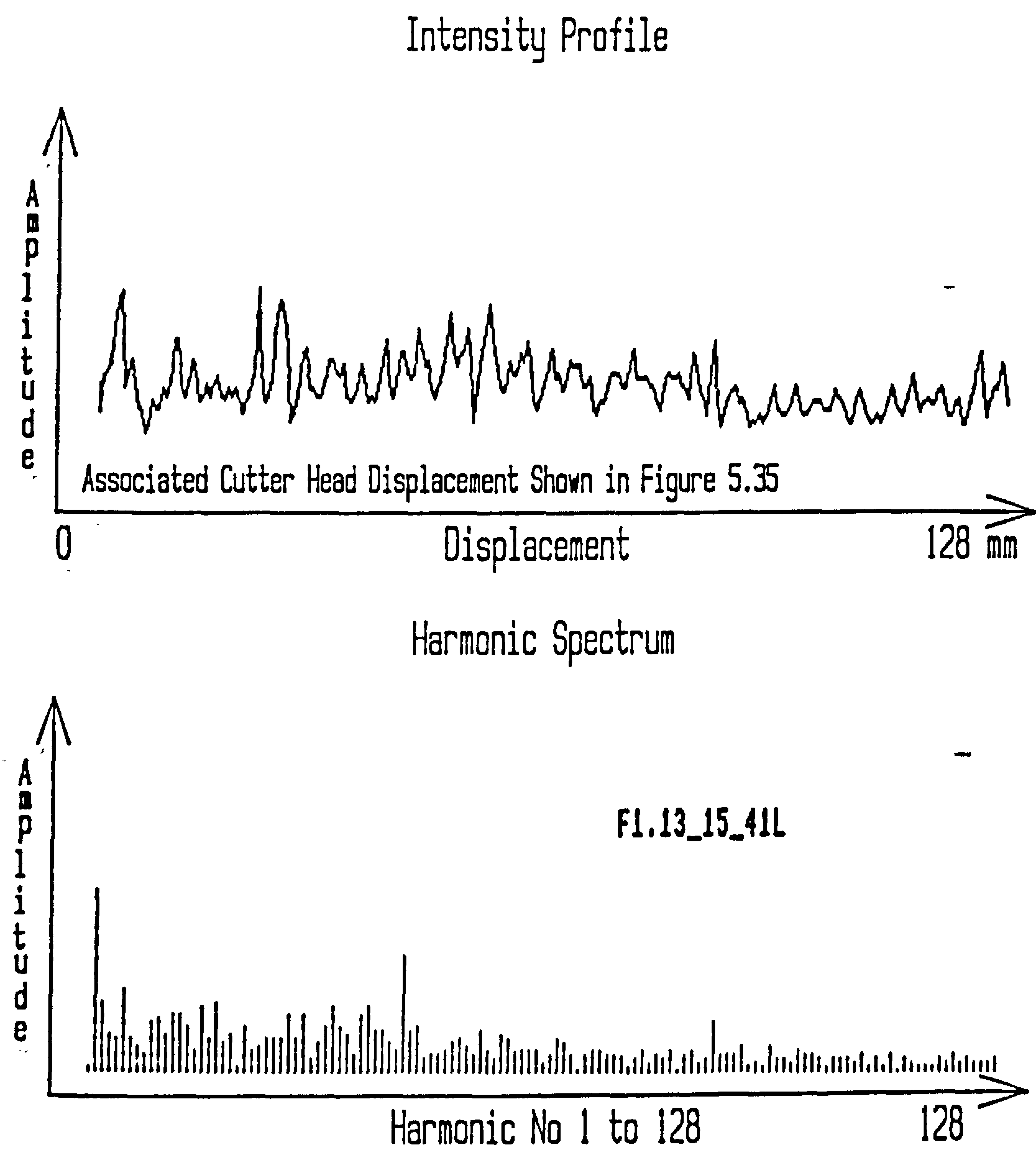

Profile Captured From A Sample That Was Generated Using The Machine's Top Head
Intensity Profile
Amplitude
Associated Cutter Head Displacement Shown in Figure 5.34
0
Displacement
128 mm
Harmonic Spectrum
Amplitude
F1.13_15_36L
Harmonic No 1 to 128
128
Material Feedspeed = 9m/min
Cutter Head Angular Velocity = 5944 rev/min

Figure 7.9

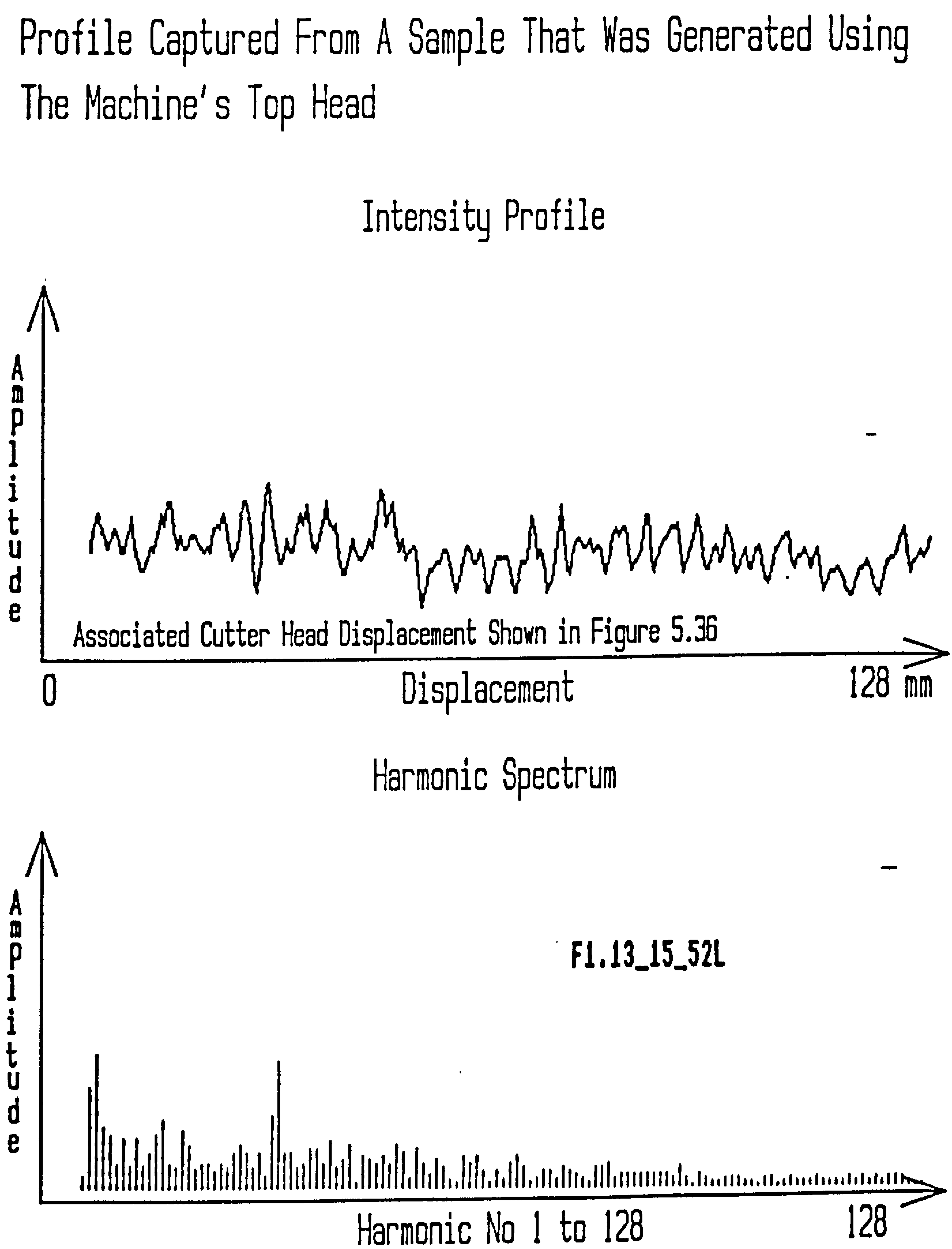
Profile Captured From A Sample That Was Generated Using The Machine's Top Head



Material Feedspeed = 18m/min

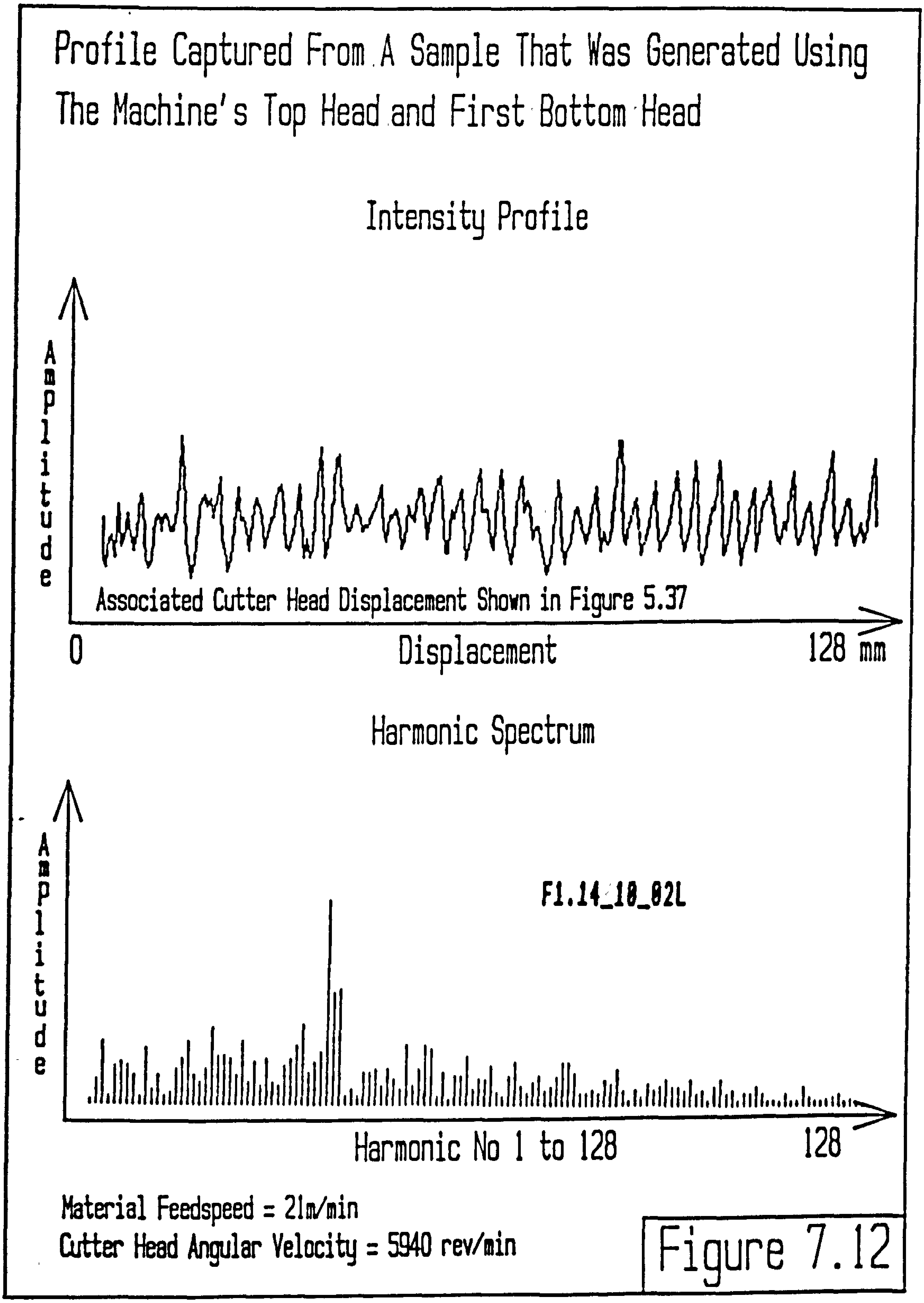
Cutter Head Angular Velocity = 5933 rev/min

Figure 7.10



Material Feedspeed = 27m/min
Cutter Head Angular Velocity = 5919 rev/min

Figure 7.11


Profile Captured From A Sample That Was Generated Using
The Machine's Top Head and First Bottom Head
Intensity Profile
Amplitude
Associated Cutter Head Displacement Shown in Figure 5.37
0
Displacement
128 mm
Harmonic Spectrum
Amplitude
F1.14_10_02L
Harmonic No 1 to 128
128
Material Feedspeed = 21m/min
Cutter Head Angular Velocity = 5940 rev/min
Figure 7.12

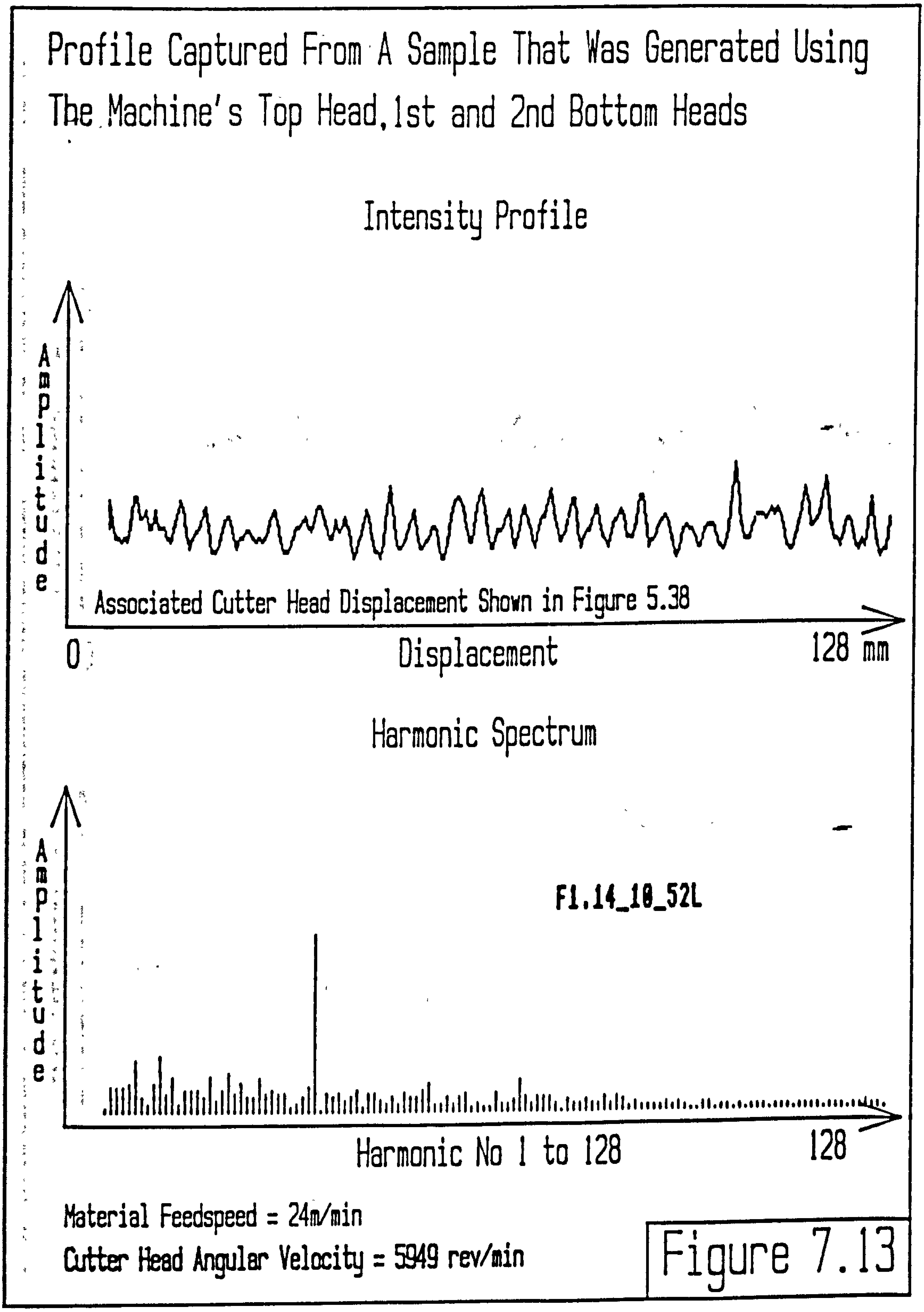
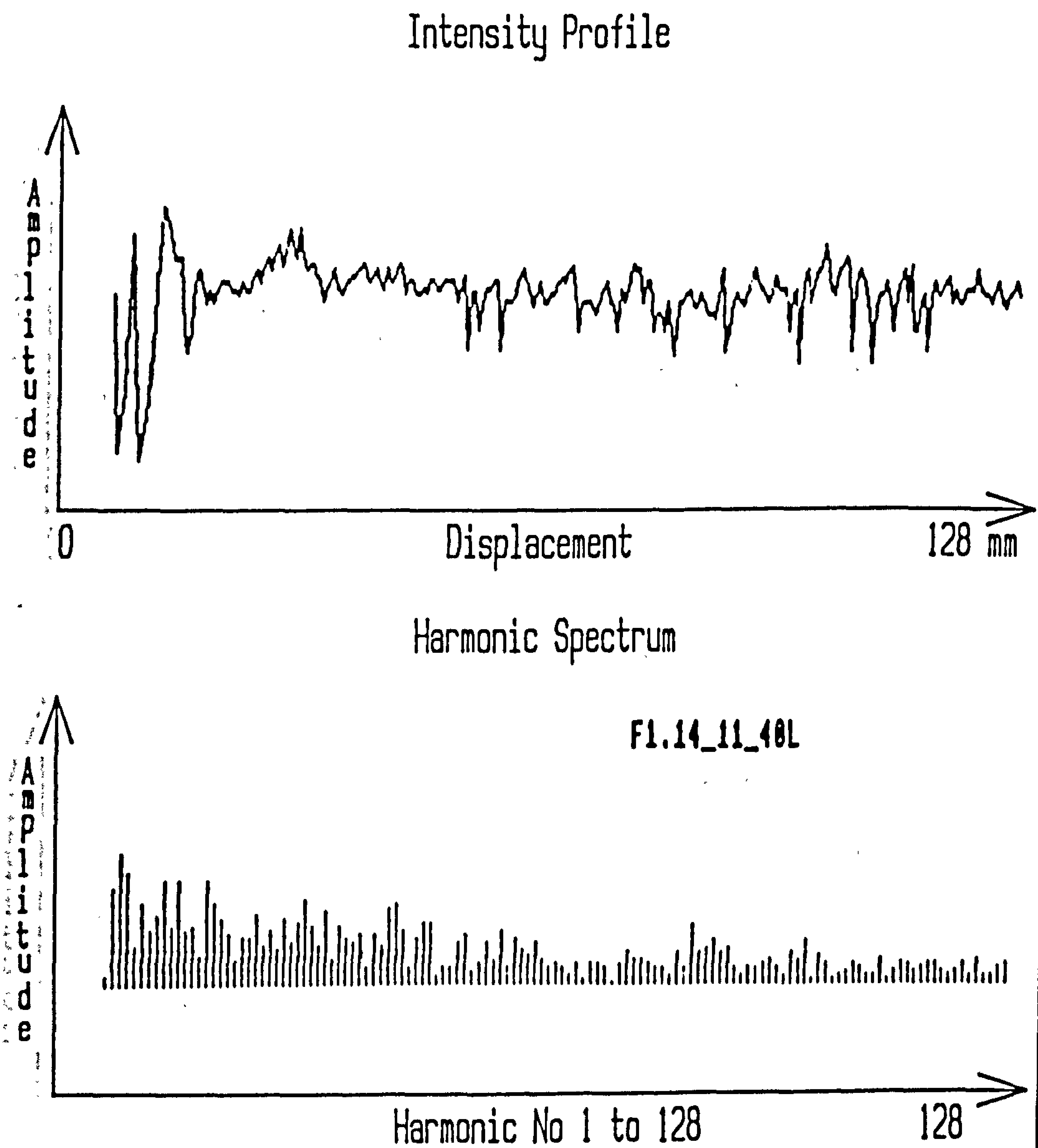

Profile Captured From A Sample That Was Generated Using
The Machine's Top Head, 1st and 2nd Bottom Heads
Intensity Profile
Amplitude
Associated Cutter Head Displacement Shown in Figure 5.38
0
Displacement
128 mm
Harmonic Spectrum
Amplitude
F1.14_10_52L
Harmonic No 1 to 128
128
Material Feedspeed = 24m/min
Cutter Head Angular Velocity = 5949 rev/min

Figure 7.13

Profile Captured From A Sample That Was Generated Using The Machine's Top Head (Out of Balance)



Material Feedspeed = 9m/min
Cutter Head Angular Velocity = 5945 rev/min

Figure 7.14

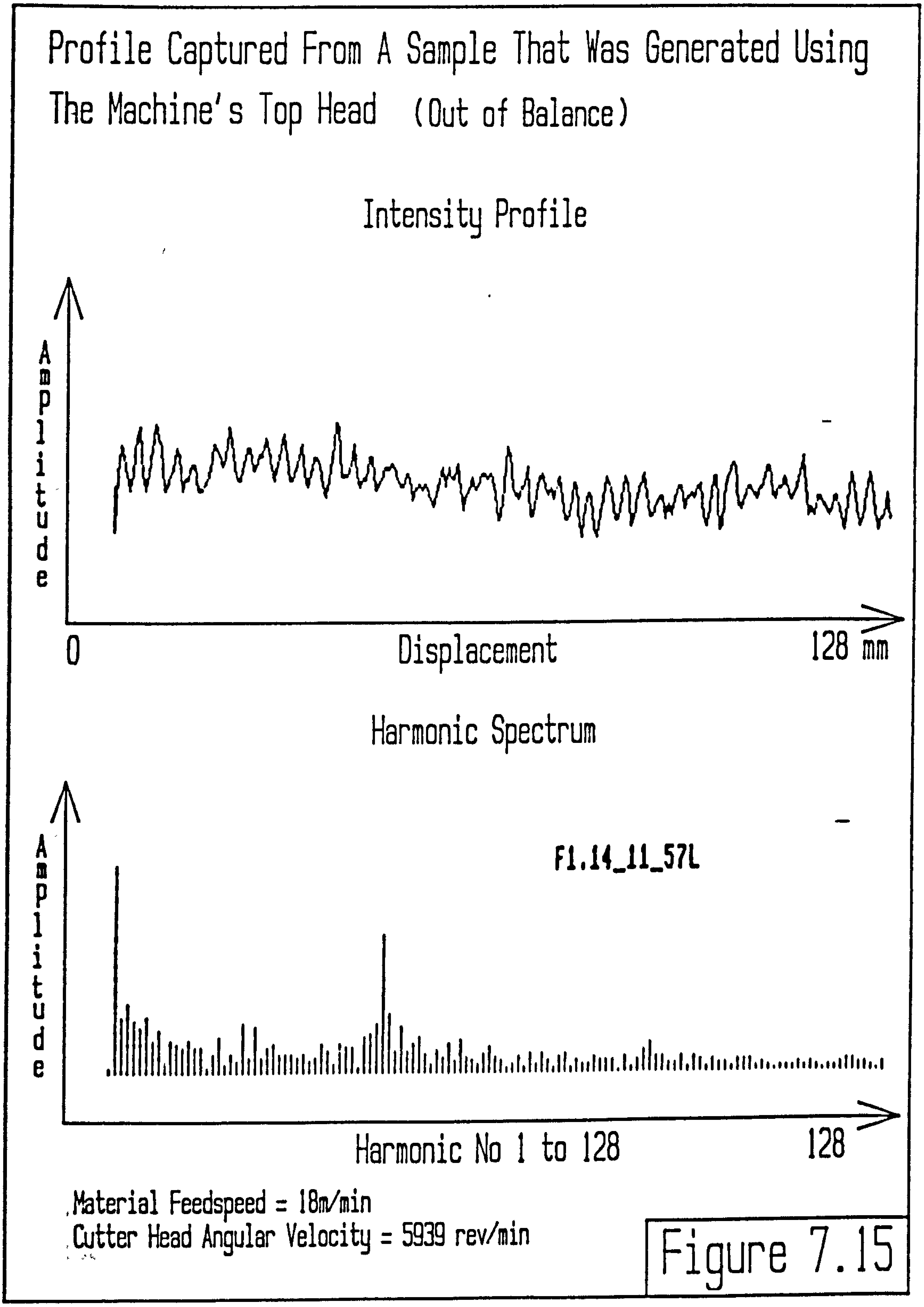
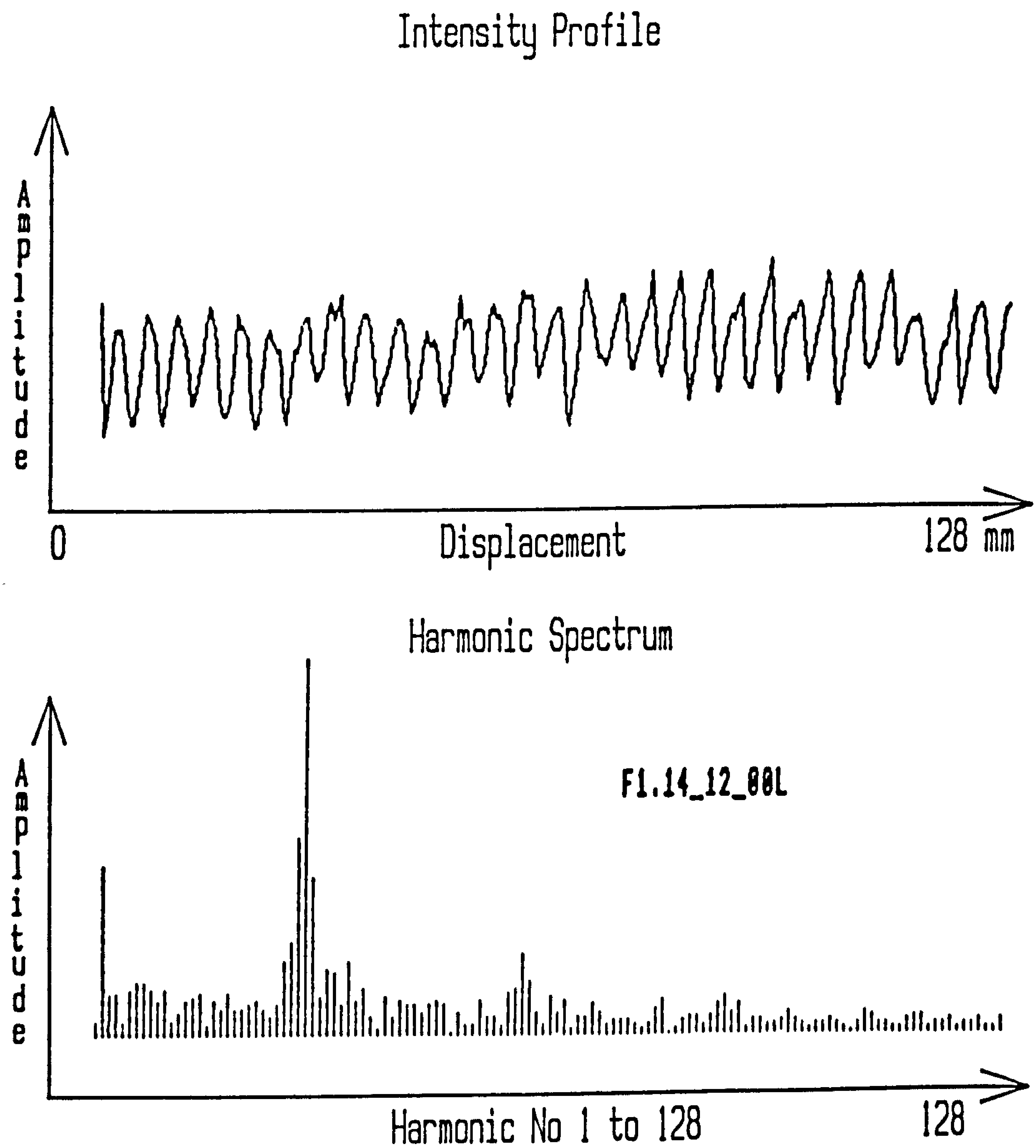

Profile Captured From A Sample That Was Generated Using
The Machine's Top Head (Out of Balance)
Intensity Profile
Amplitude
0
Displacement
128 mm
Harmonic Spectrum
Amplitude
F1.14_11_57L
Harmonic No 1 to 128
128
Material Feedspeed = 18m/min
Cutter Head Angular Velocity = 5939 rev/min

Figure 7.15

Profile Captured From A Sample That Was Generated Using The Machine's Top Head (Out of Balance)



Material Feedspeed = 27m/min
Cutter Head Angular Velocity = 5931 rev/min

Figure 7.16

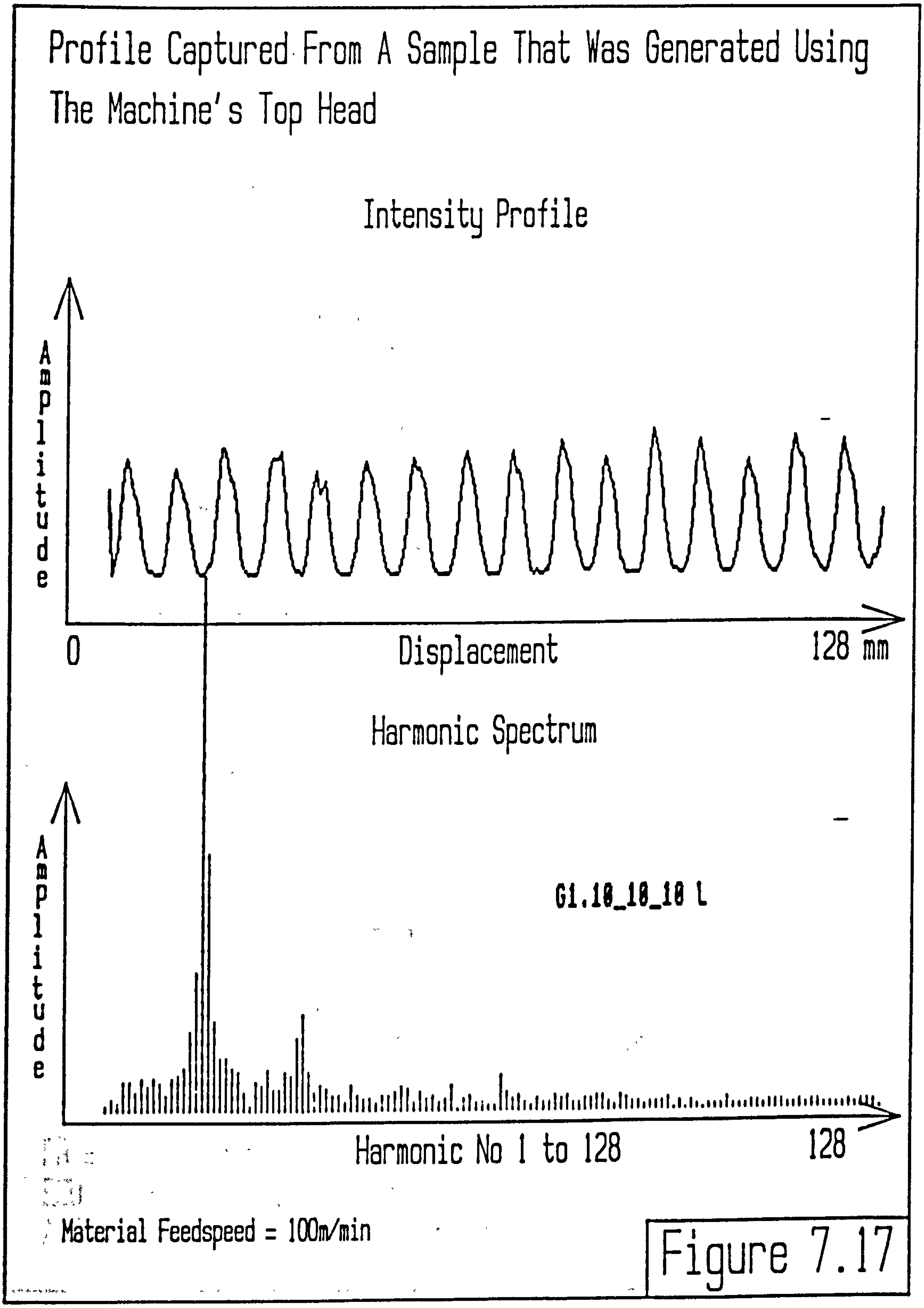
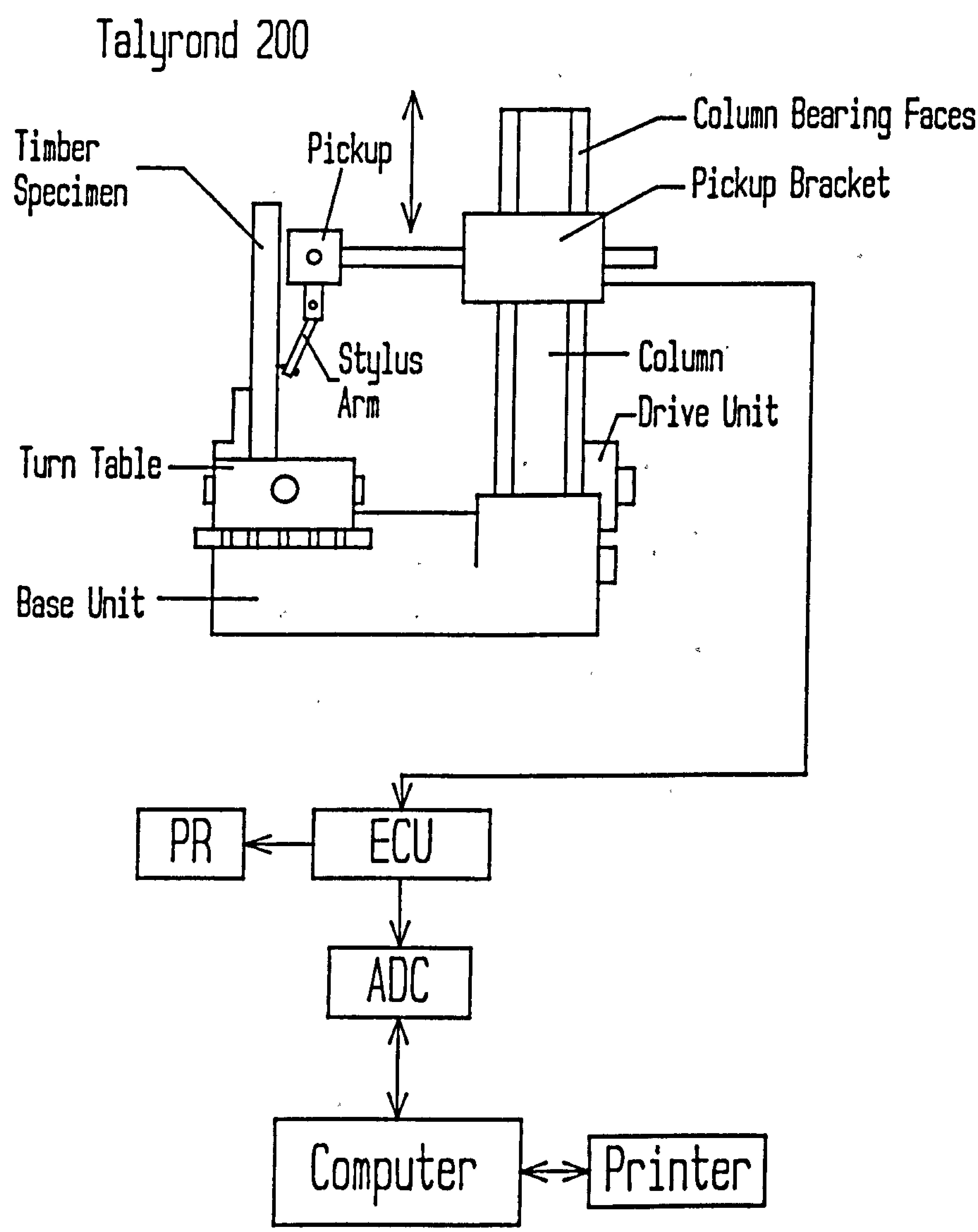

Profile Captured From A Sample That Was Generated Using The Machine's Top Head
Intensity Profile
Amplitude
0
Displacement
128 mm
Harmonic Spectrum
Amplitude
G1.10_10_10 L
Harmonic No 1 to 128
128
Material Feedspeed = 100m/min

Figure 7.17

Post Process Measurement System



PR = Polar Recorder
ECU = Electronic Control Unit
ADC = Anologue To Digital Convertor

Figure 7.18

Circuit Diagram of The 10 Bit ADC

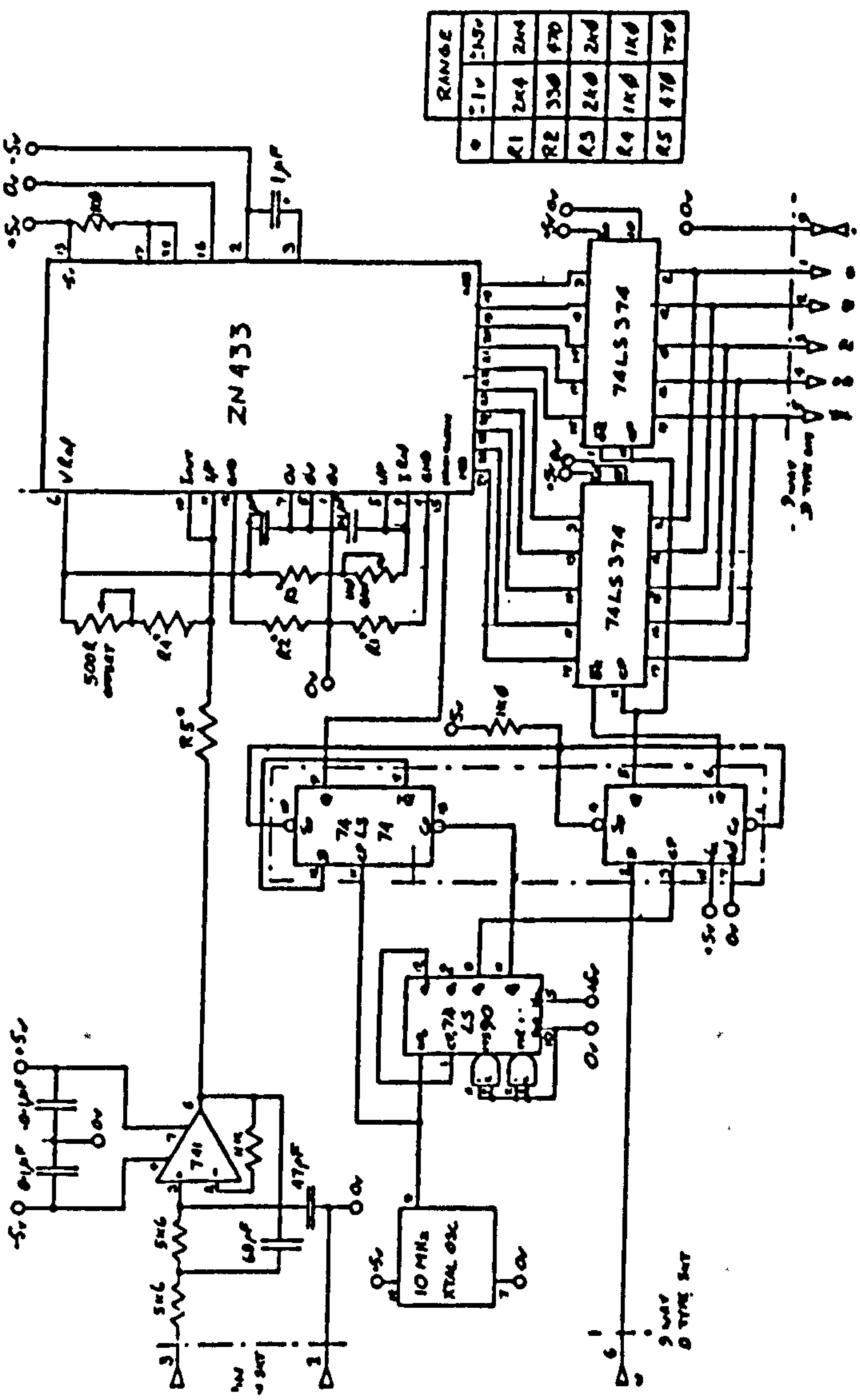


Figure 7.19

ADC Calibration

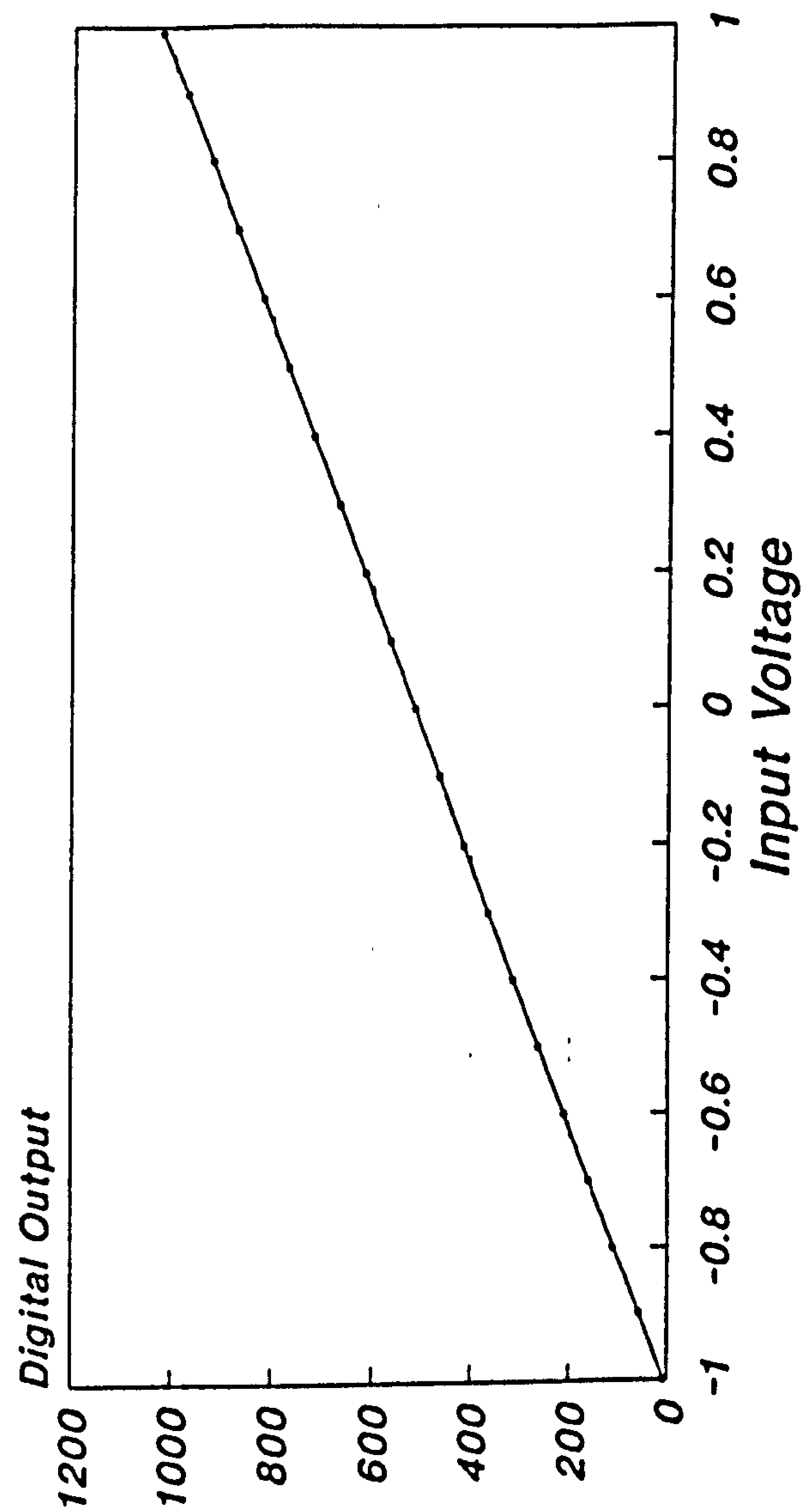
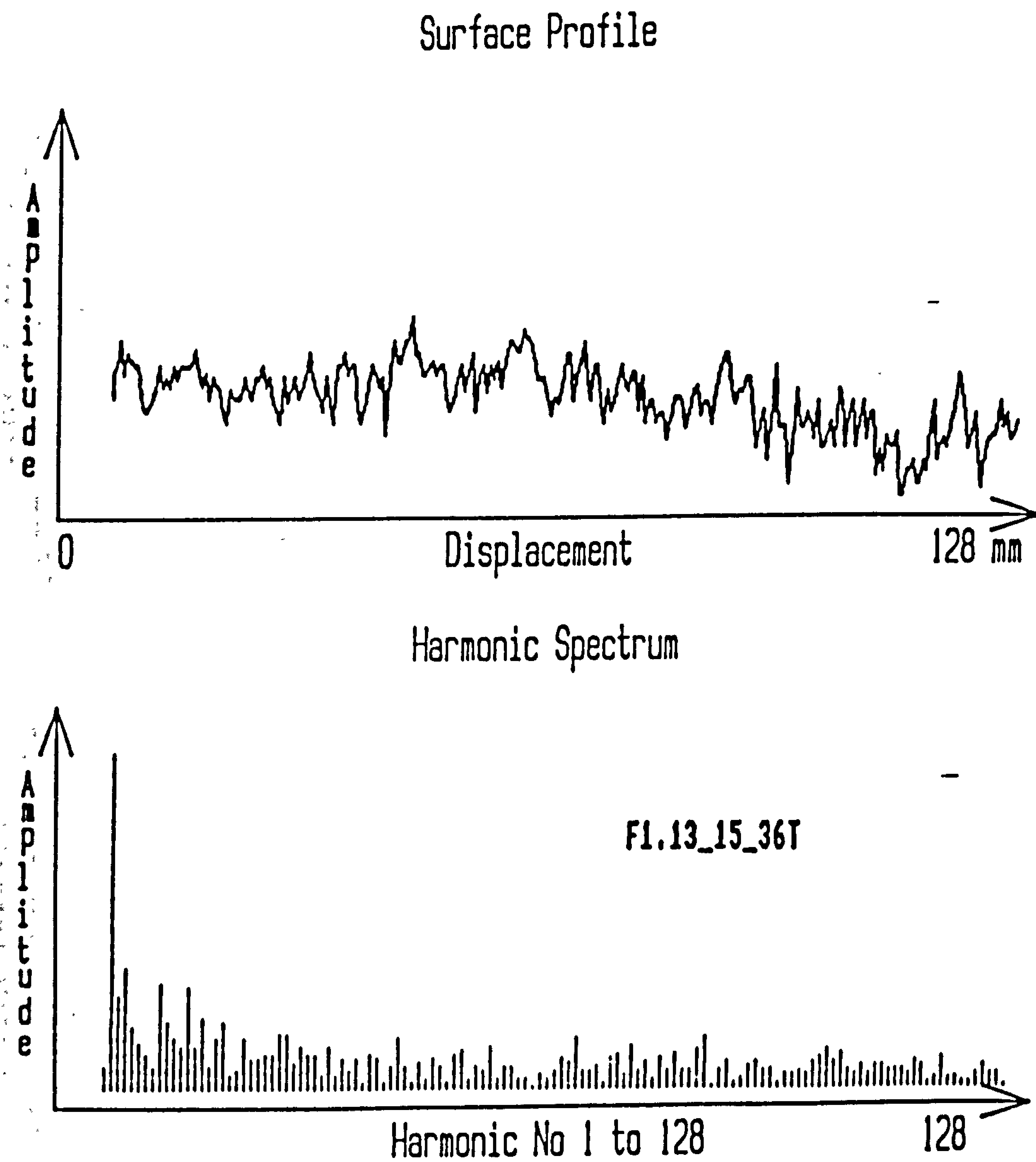


Figure 7.20

Profile Captured From A Sample That Was Generated Using The Machine's Top Head



Material Feedspeed = 9m/min
Cutter Head Angular Velocity = 5944 rev/min

Figure 7.21

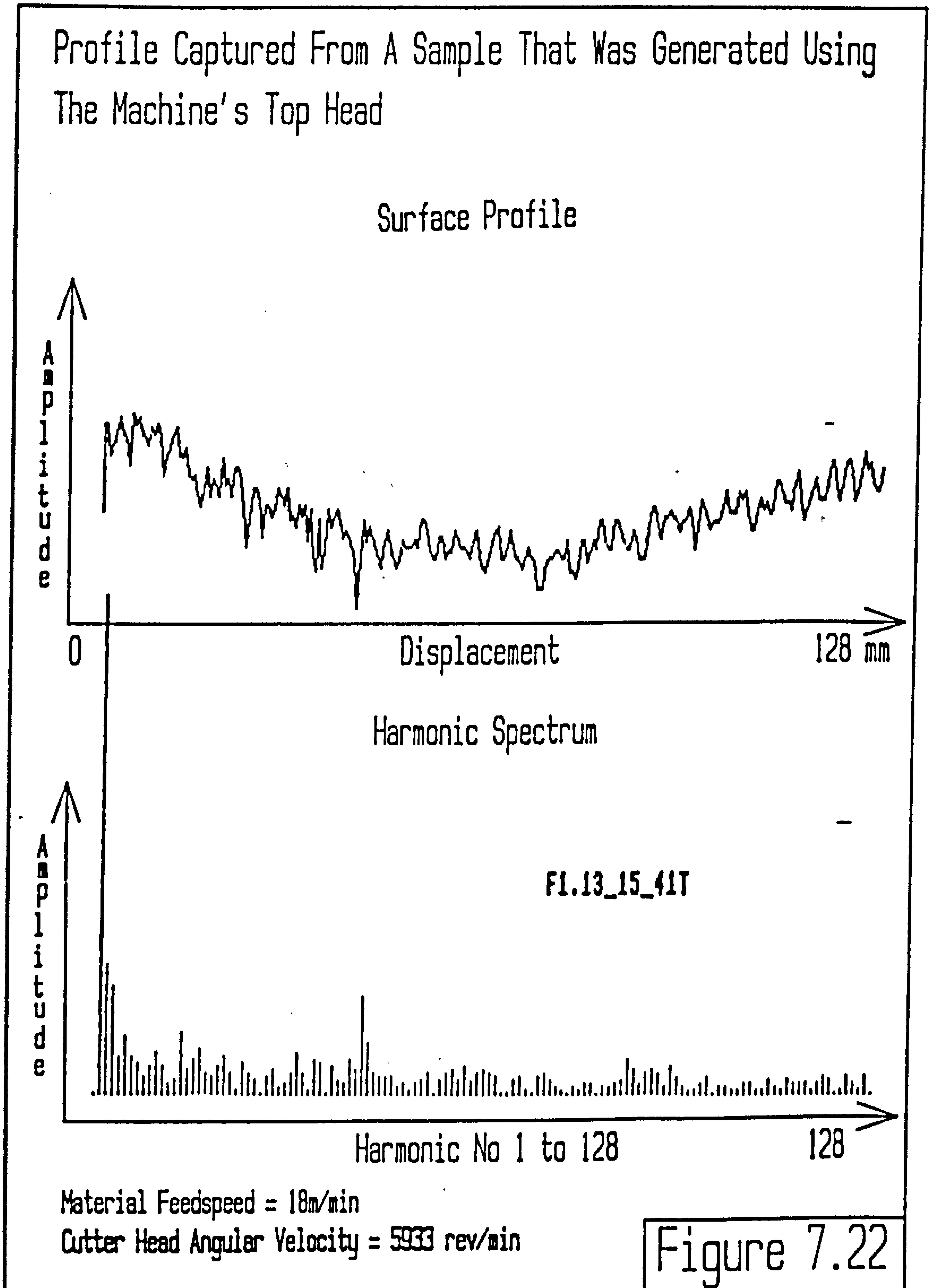
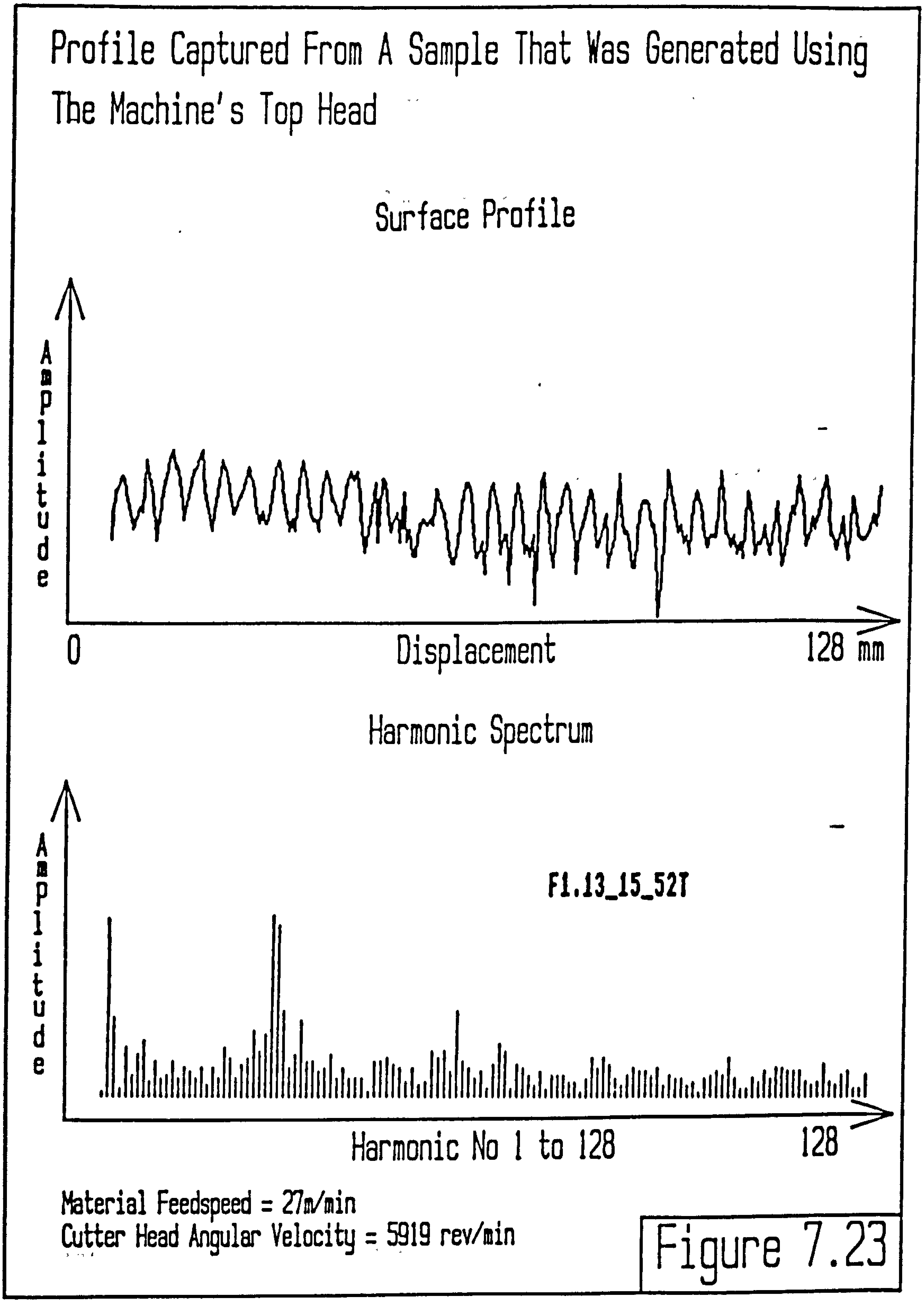

Profile Captured From A Sample That Was Generated Using The Machine's Top Head
Surface Profile
Amplitude
0
Displacement
128 mm
Harmonic Spectrum
Amplitude
F1.13_15_41T
Harmonic No 1 to 128
128
Material Feedspeed = 18m/min
Cutter Head Angular Velocity = 5933 rev/min

Figure 7.22



Profile Captured From A Sample That Was Generated Using The Machine's Top Head
Surface Profile
Amplitude
0
Displacement
128 mm
Harmonic Spectrum
Amplitude
F1.13_15_52T
Harmonic No 1 to 128
128
Material Feedspeed = 27m/min
Cutter Head Angular Velocity = 5919 rev/min

Figure 7.23

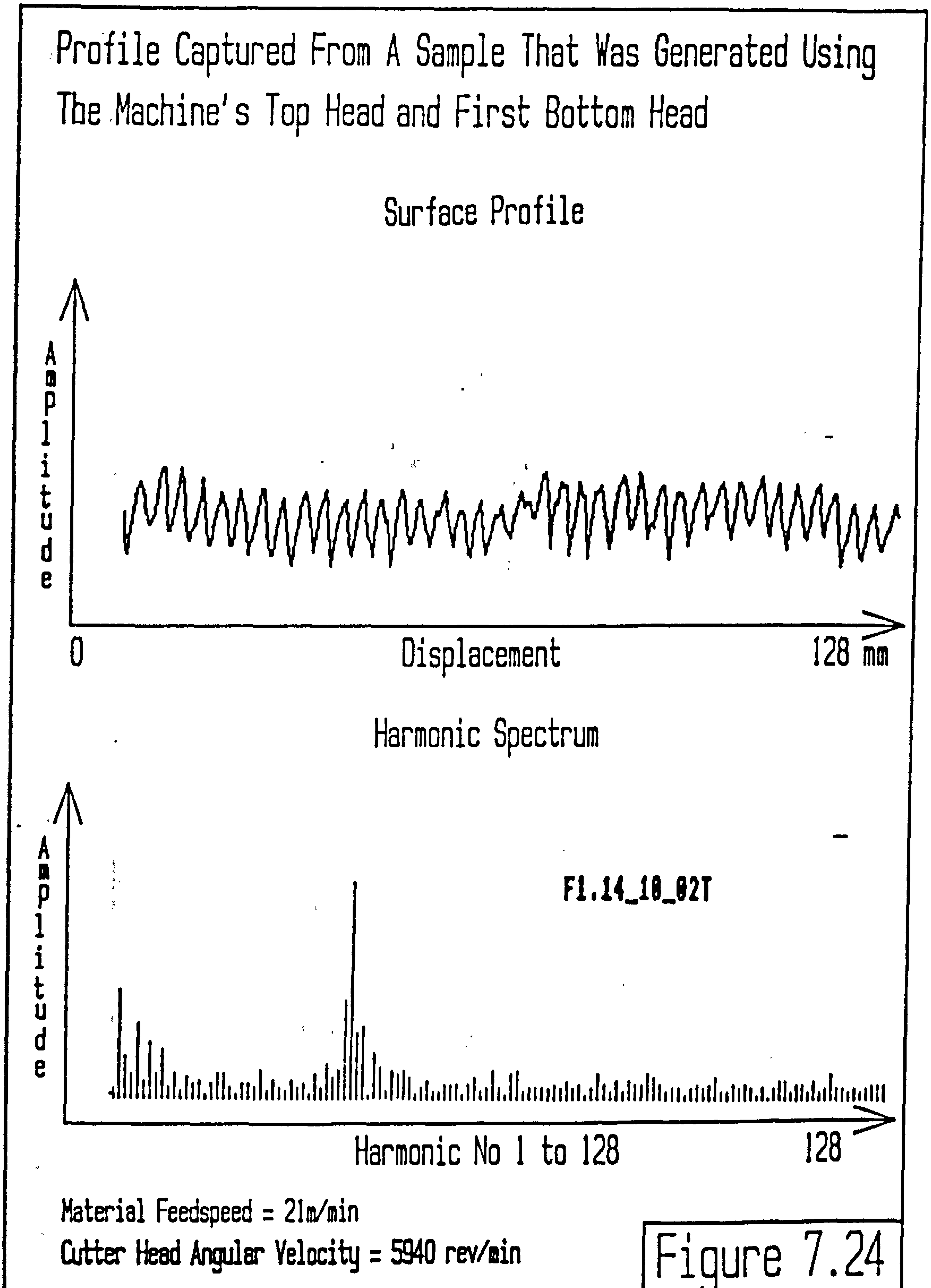
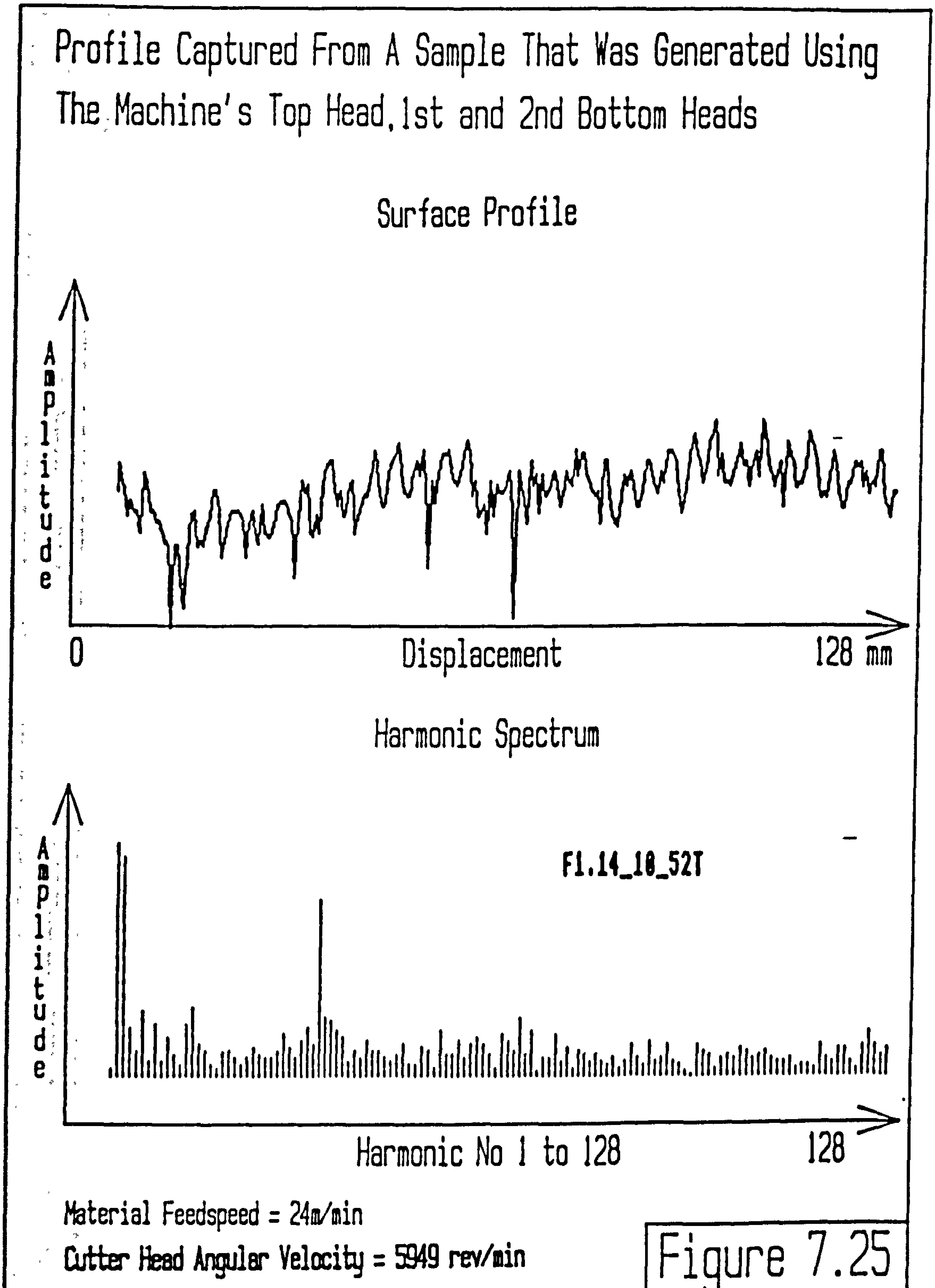

Profile Captured From A Sample That Was Generated Using
The Machine's Top Head and First Bottom Head
Surface Profile
Amplitude
0
Displacement
128 mm
Harmonic Spectrum
Amplitude
F1.14_10_02T
Harmonic No 1 to 128
128
Material Feedspeed = 21m/min
Cutter Head Angular Velocity = 5940 rev/min

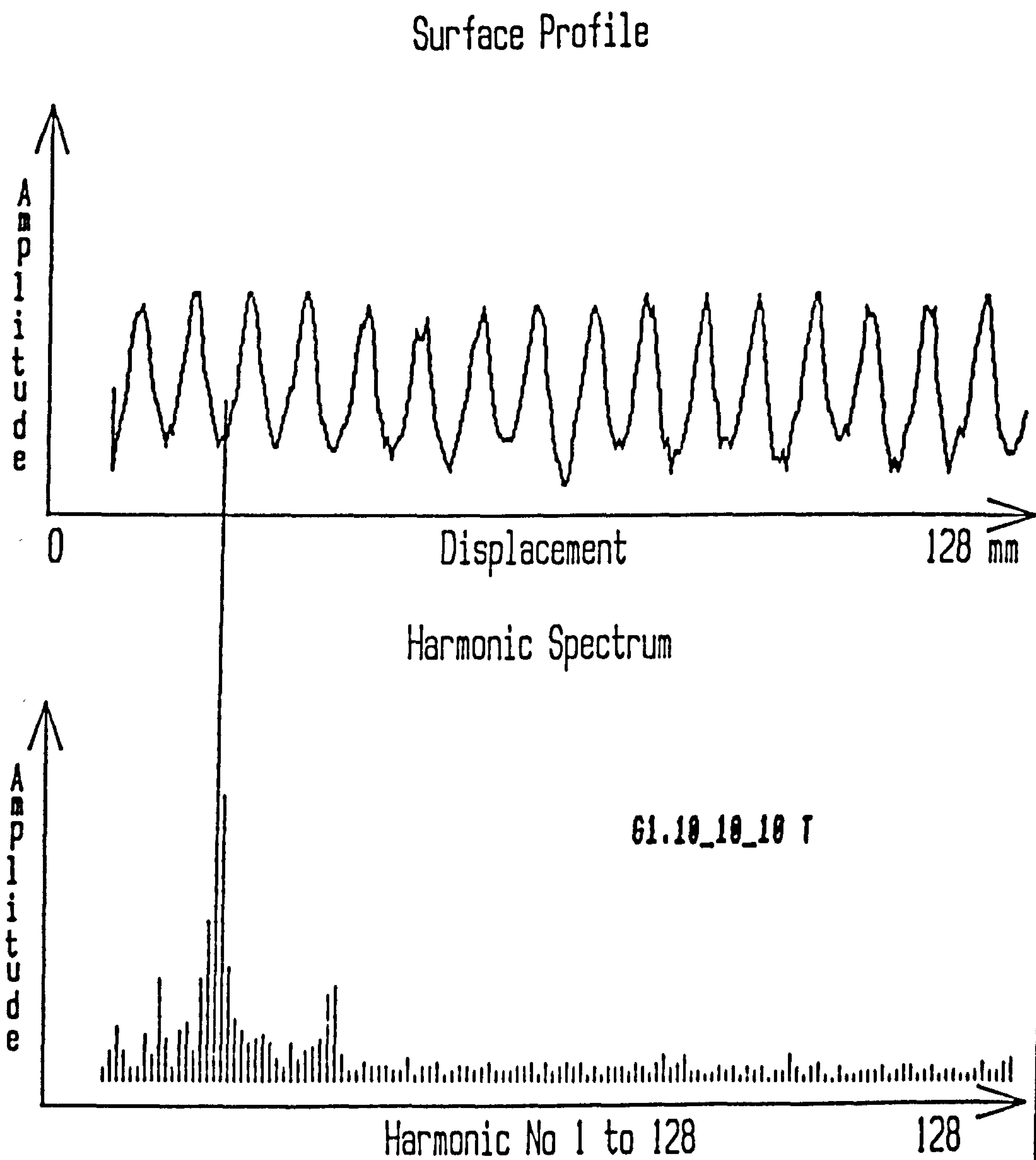
Figure 7.24



Profile Captured From A Sample That Was Generated Using The Machine's Top Head, 1st and 2nd Bottom Heads
Surface Profile
Amplitude
0
Displacement
128 mm
Harmonic Spectrum
F1.14_18_52T
Amplitude
Harmonic No 1 to 128
128
Material Feedspeed = 24m/min
Cutter Head Angular Velocity = 5949 rev/min

Figure 7.25

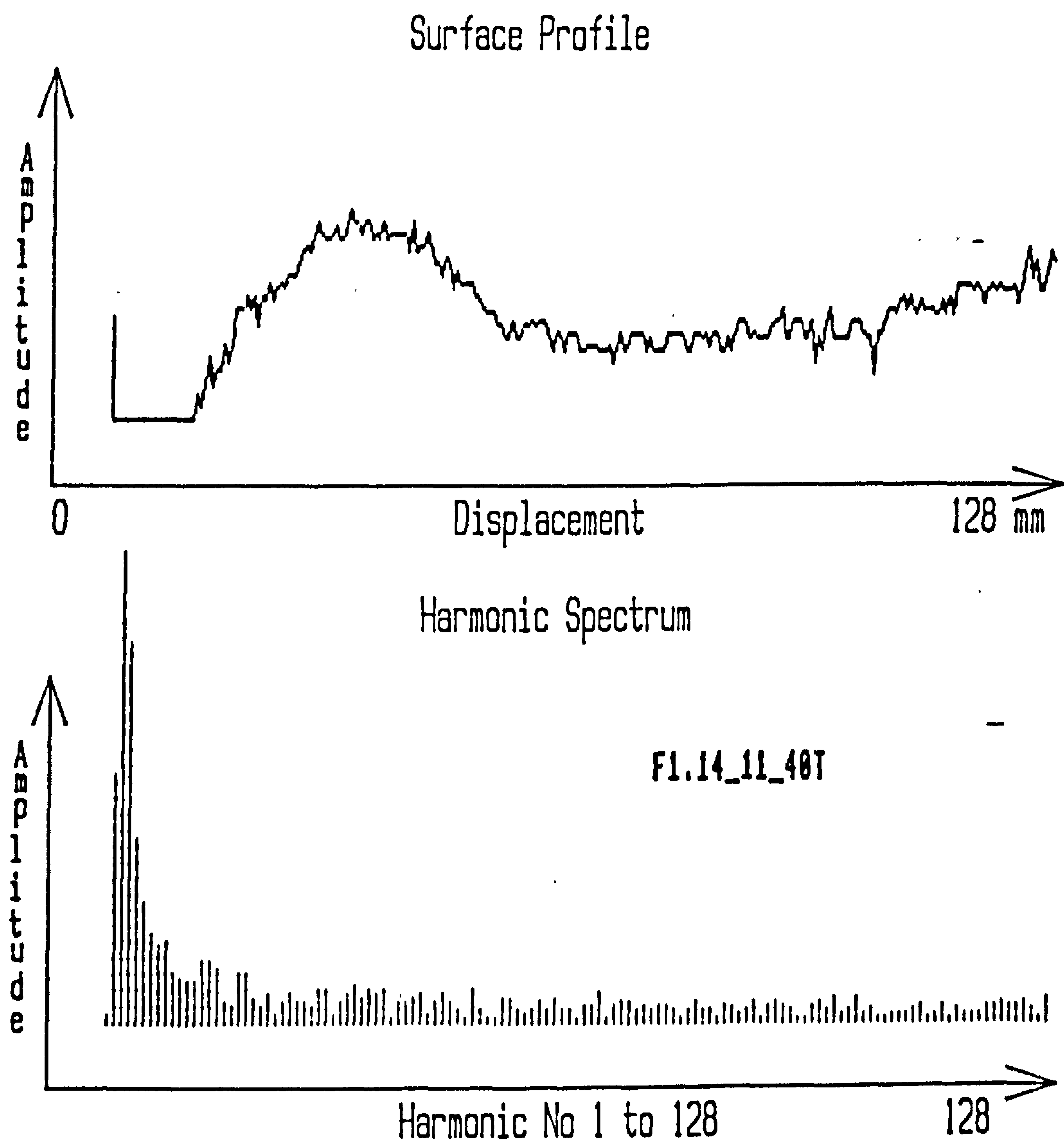
Profile Captured From A Sample That Was Generated Using The Machine's Top Head



Material Feedspeed = 100m/min

Figure 7.26

Profile Captured From A Sample That Was Generated Using The Machine's Top Head (Out of Balance)



Material Feedspeed = 9m/min
Cutter Head Angular Velocity = 5945 rev/min

Figure 7.27

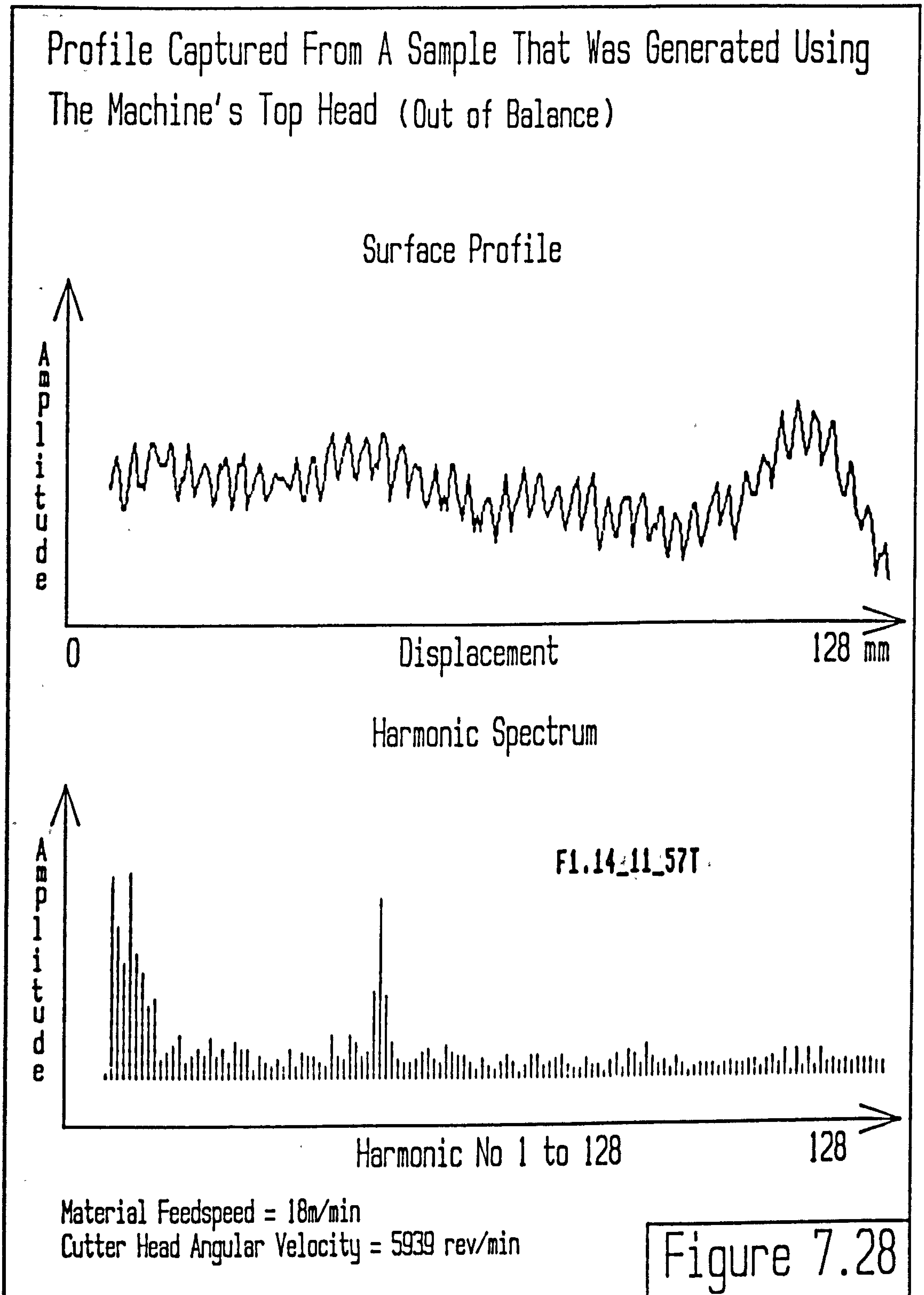
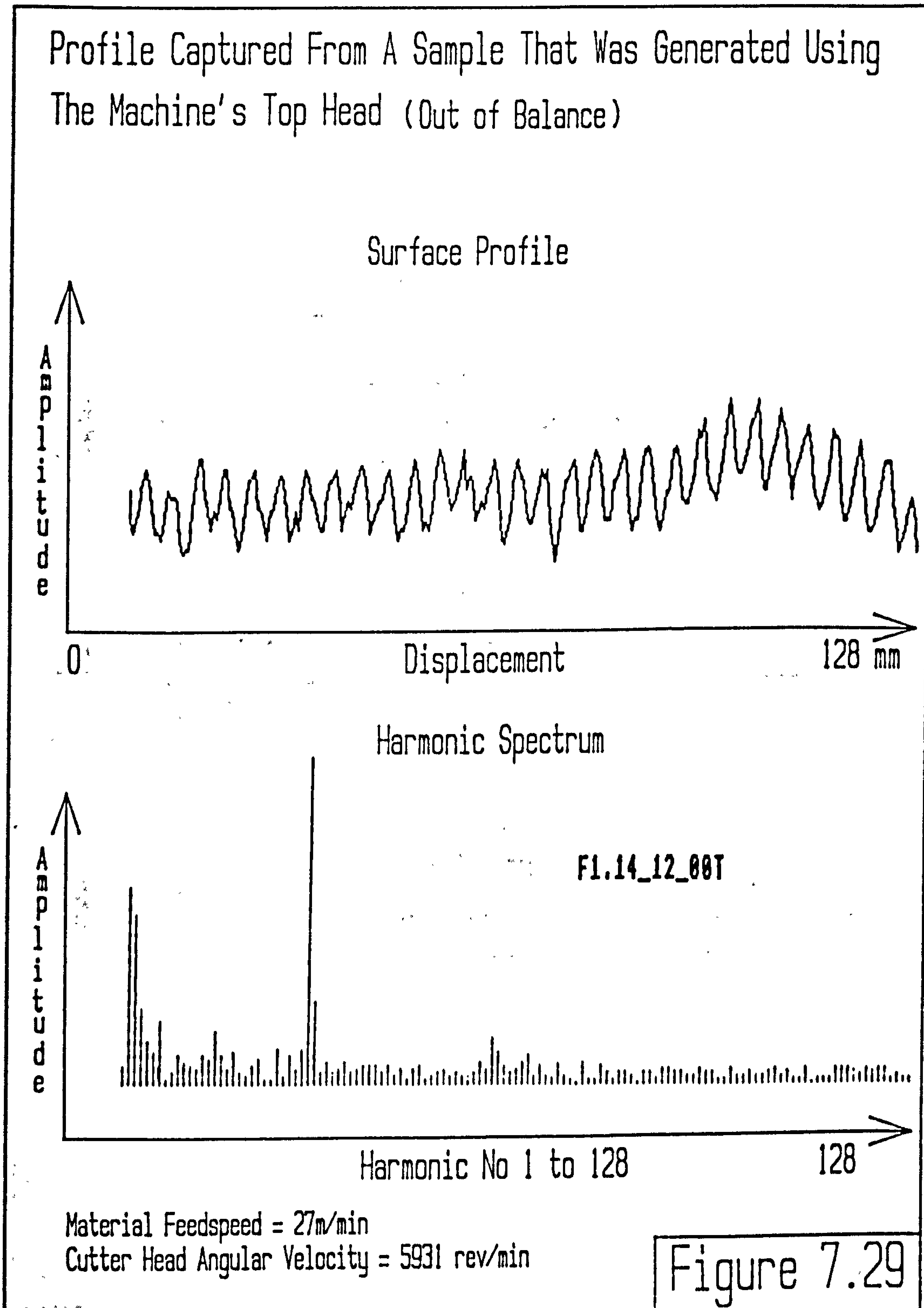

Profile Captured From A Sample That Was Generated Using
The Machine's Top Head (Out of Balance)
Surface Profile
Amplitude
0
Displacement
128 mm
Harmonic Spectrum
Amplitude
F1.14_11_57T
Harmonic No 1 to 128
128
Material Feedspeed = 18m/min
Cutter Head Angular Velocity = 5939 rev/min

Figure 7.28



Profile Captured From A Sample That Was Generated Using The Machine's Top Head (Out of Balance)
Surface Profile
Amplitude
0
Displacement
128 mm
Harmonic Spectrum
Amplitude
F1.14_12_80T
Harmonic No 1 to 128
128
Material Feedspeed = 27m/min
Cutter Head Angular Velocity = 5931 rev/min

Figure 7.29

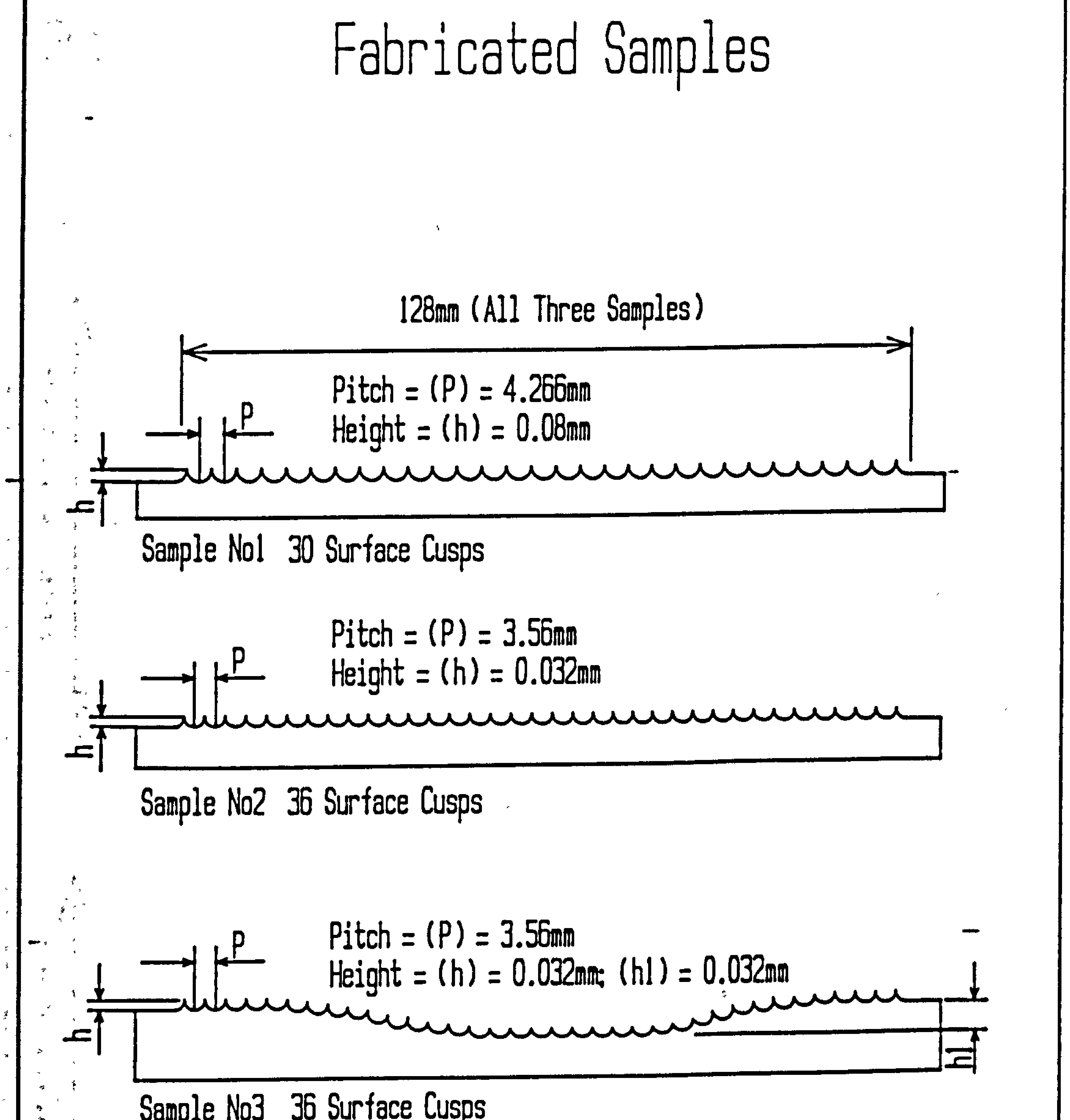

Fabricated Samples
128mm (All Three Samples)
Pitch = (P) = 4.266mm
Height = (h) = 0.08mm
P
h
Sample No1 30 Surface Cusps
Pitch = (P) = 3.56mm
Height = (h) = 0.032mm
P
h
Sample No2 36 Surface Cusps
Pitch = (P) = 3.56mm
Height = (h) = 0.032mm; (h1) = 0.032mm
P
h
h1
Sample No3 36 Surface Cusps

Figure 7.30

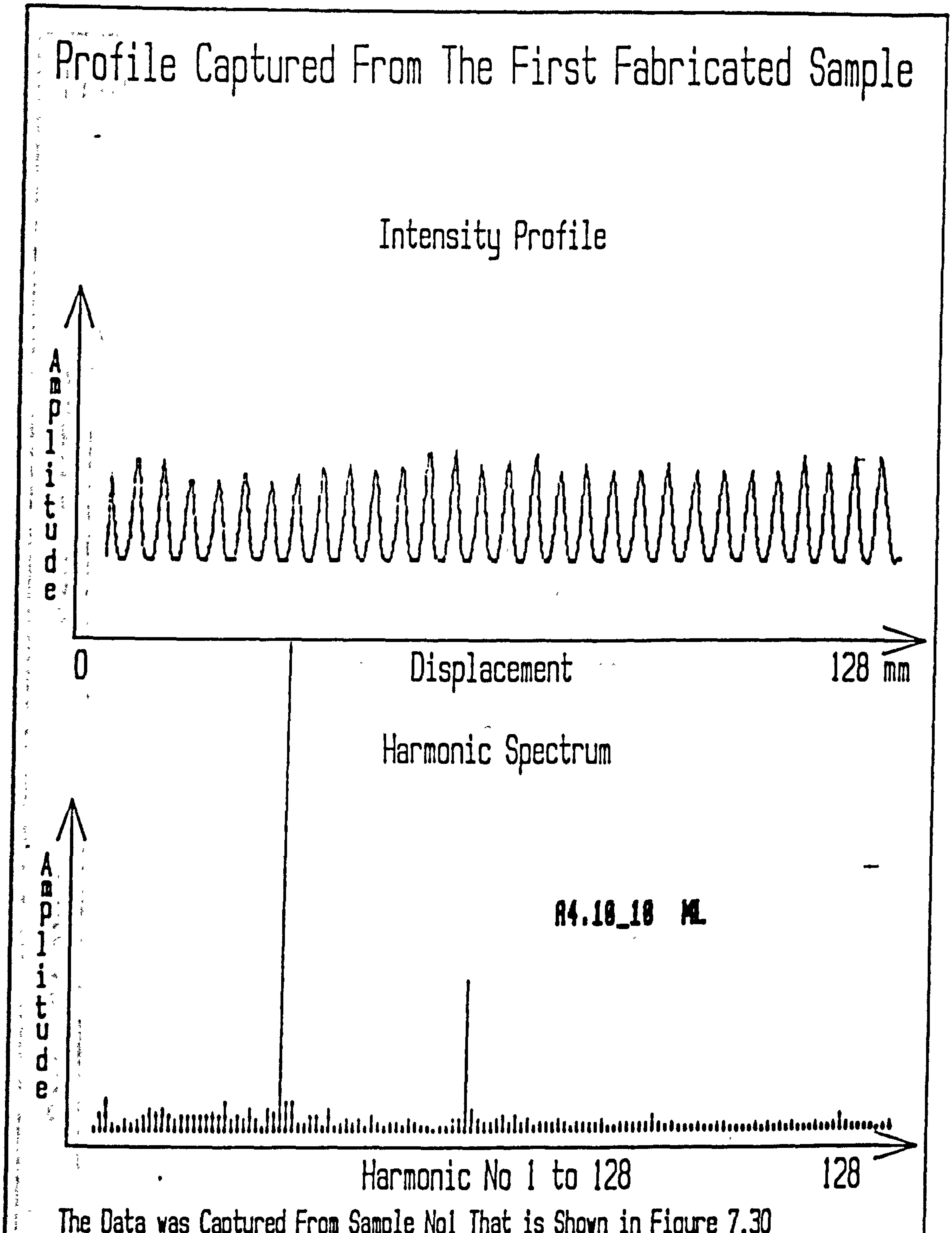
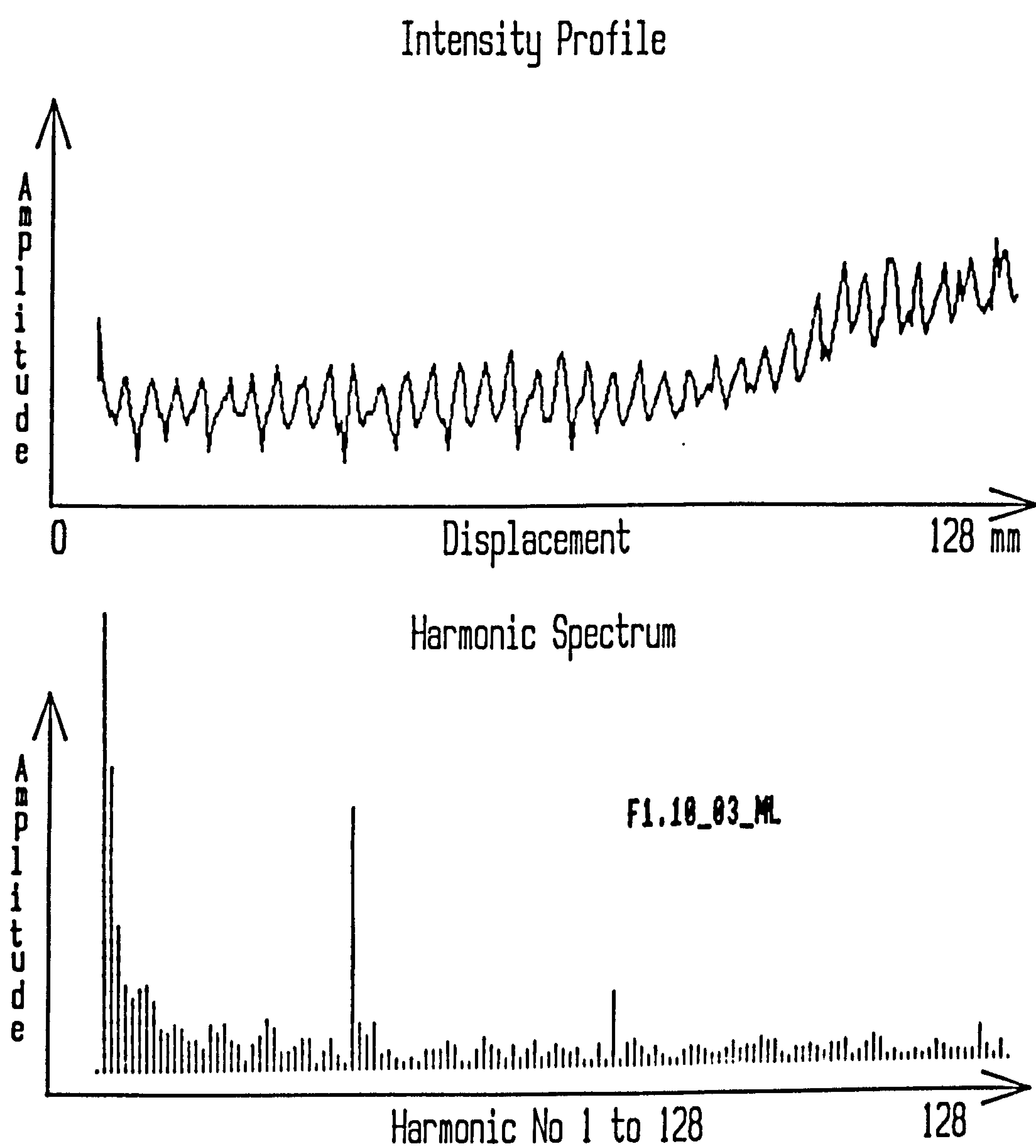

Profile Captured From The First Fabricated Sample
Intensity Profile
Amplitude
0
Displacement
128 mm
Harmonic Spectrum
Amplitude
A4.10_10 ML
Harmonic No 1 to 128
128
The Data was Captured From Sample No1 That is Shown in Figure 7.30

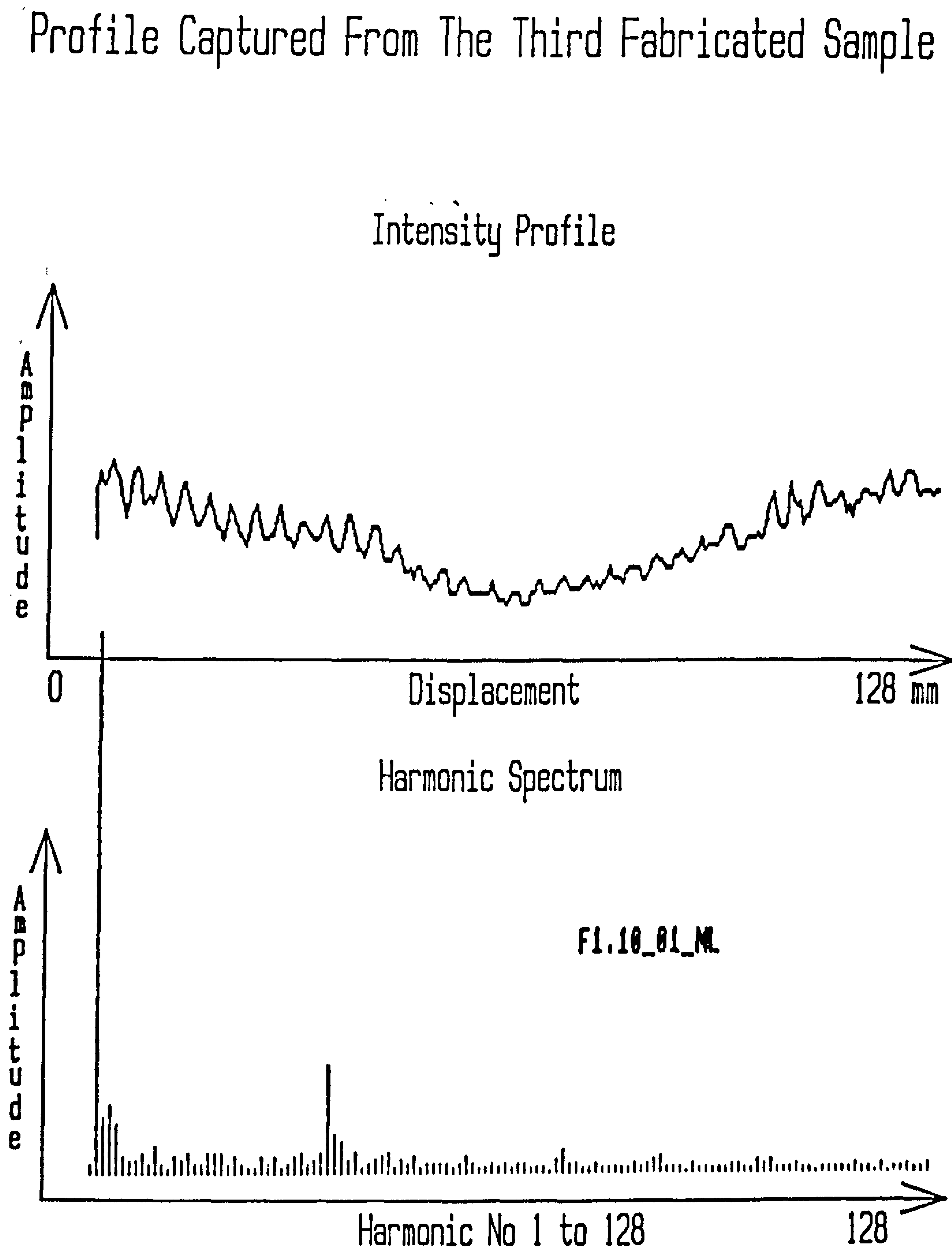
Figure 7.31

Profile Captured From The Second Fabricated Sample



The Data was Captured From Sample No2 That is Shown in Figure 7.30

Figure 7.32



The Data was Captured From Sample No3 That is Shown in Figure 7.30

Figure 7.33

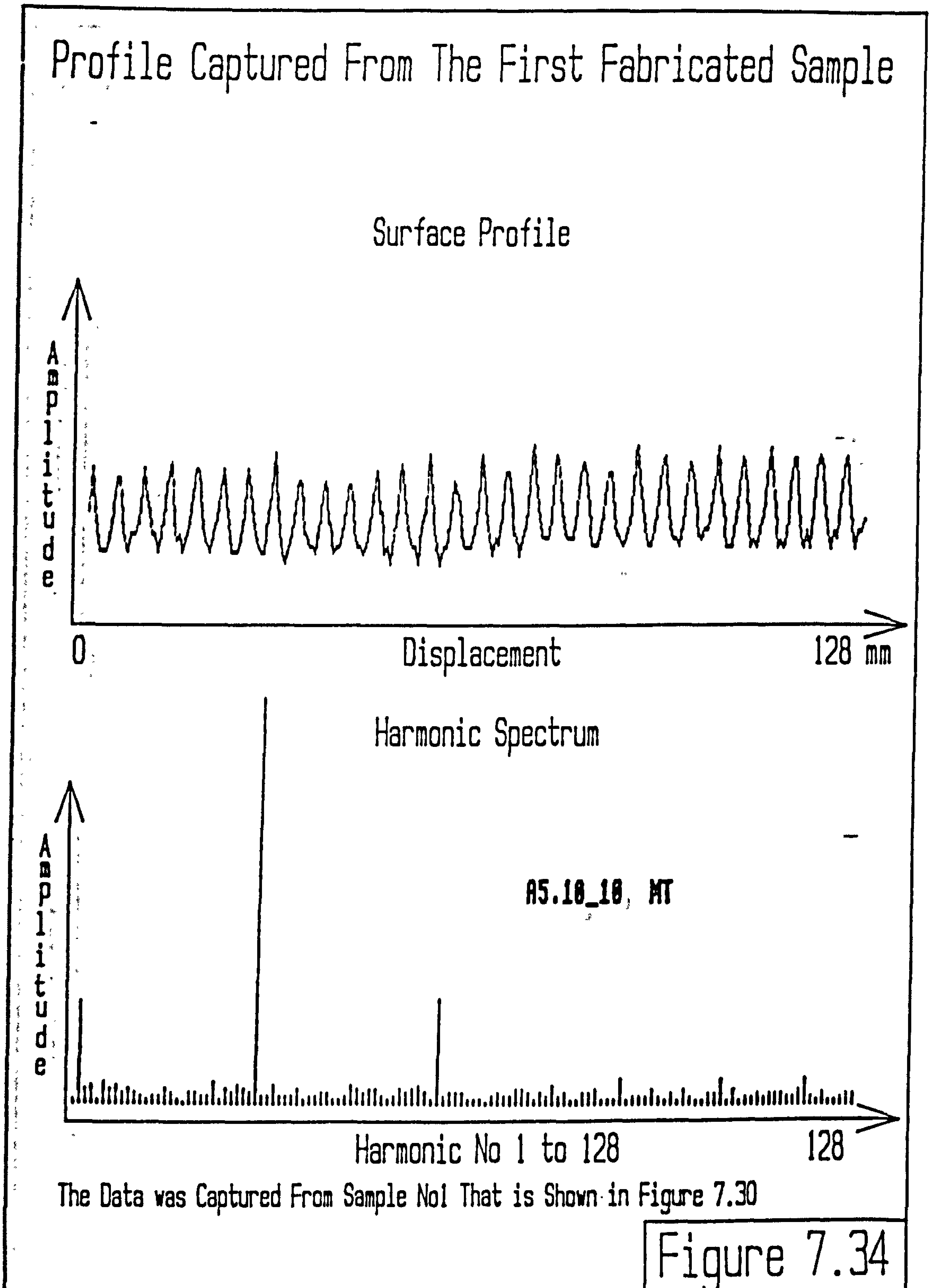
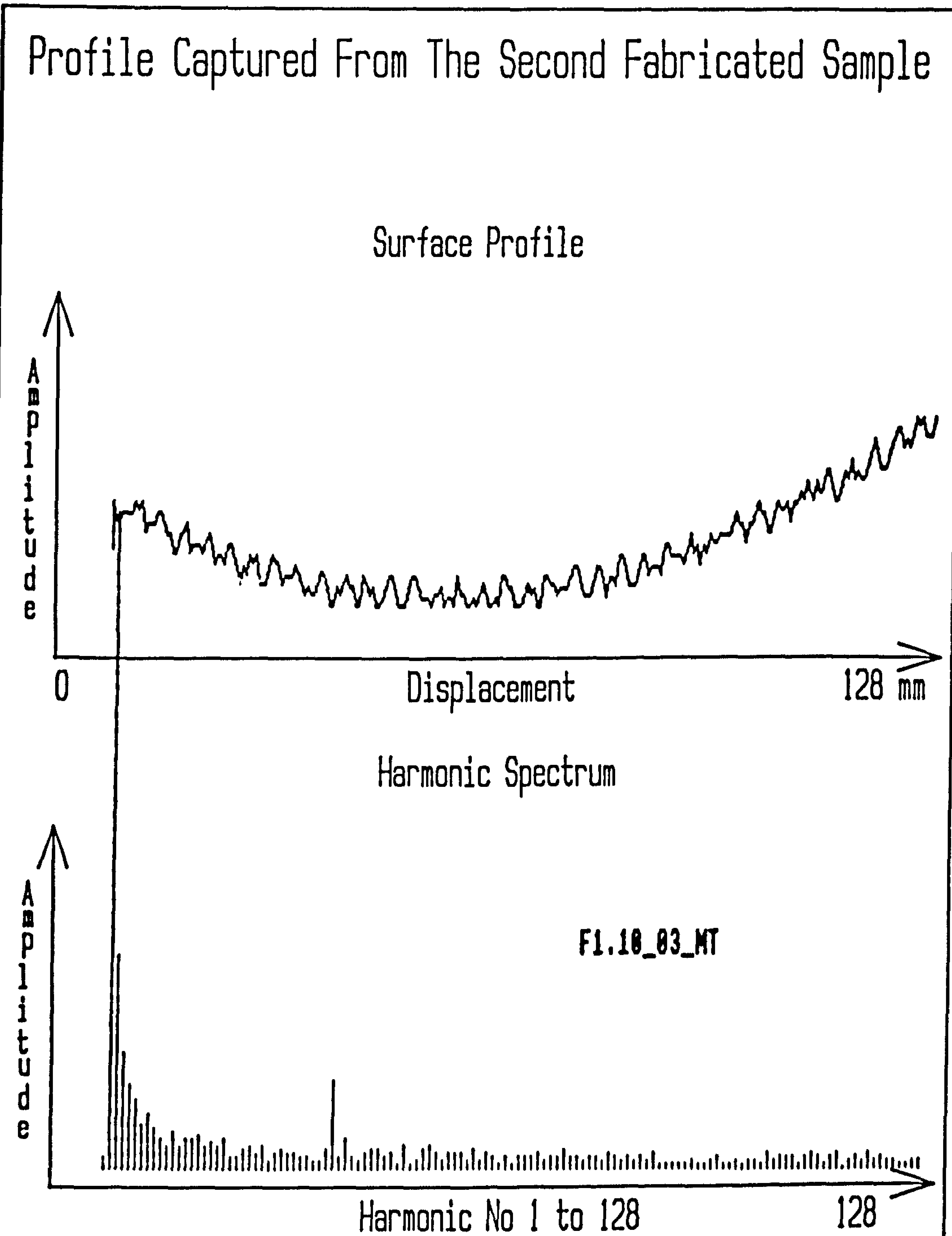

Profile Captured From The First Fabricated Sample
Surface Profile
Amplitude
0
Displacement
128 mm
Harmonic Spectrum
Amplitude
A5.10_10, MT
Harmonic No 1 to 128
128
The Data was Captured From Sample No1 That is Shown in Figure 7.30

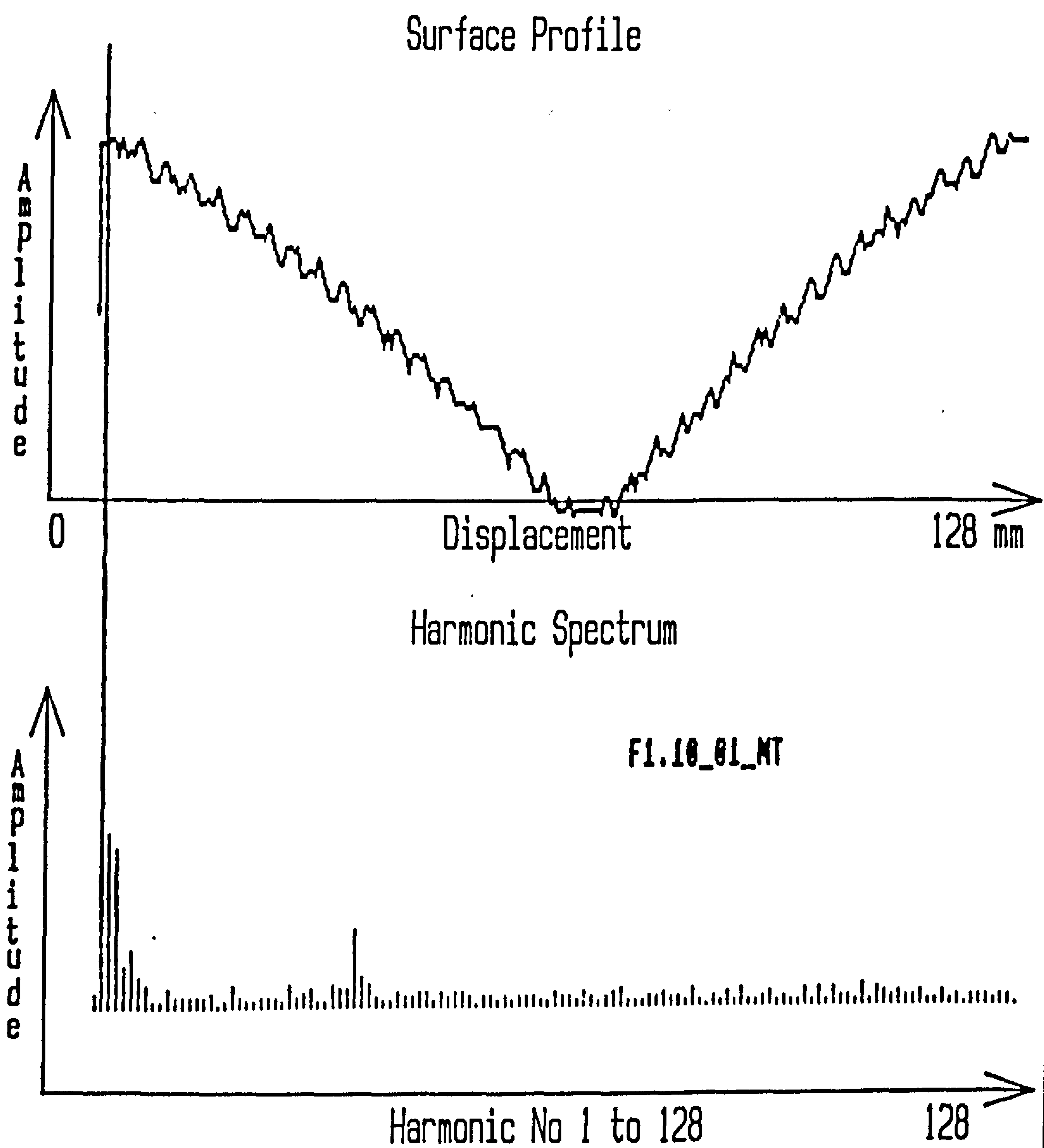
Figure 7.34



The Data was Captured From Sample No2 That is Shown in Figure 7.30

Figure 7.35

Profile Captured From The Third Fabricated Sample



The Data was Captured From Sample No3 That is Shown in Figure 7.30

Figure 7.36

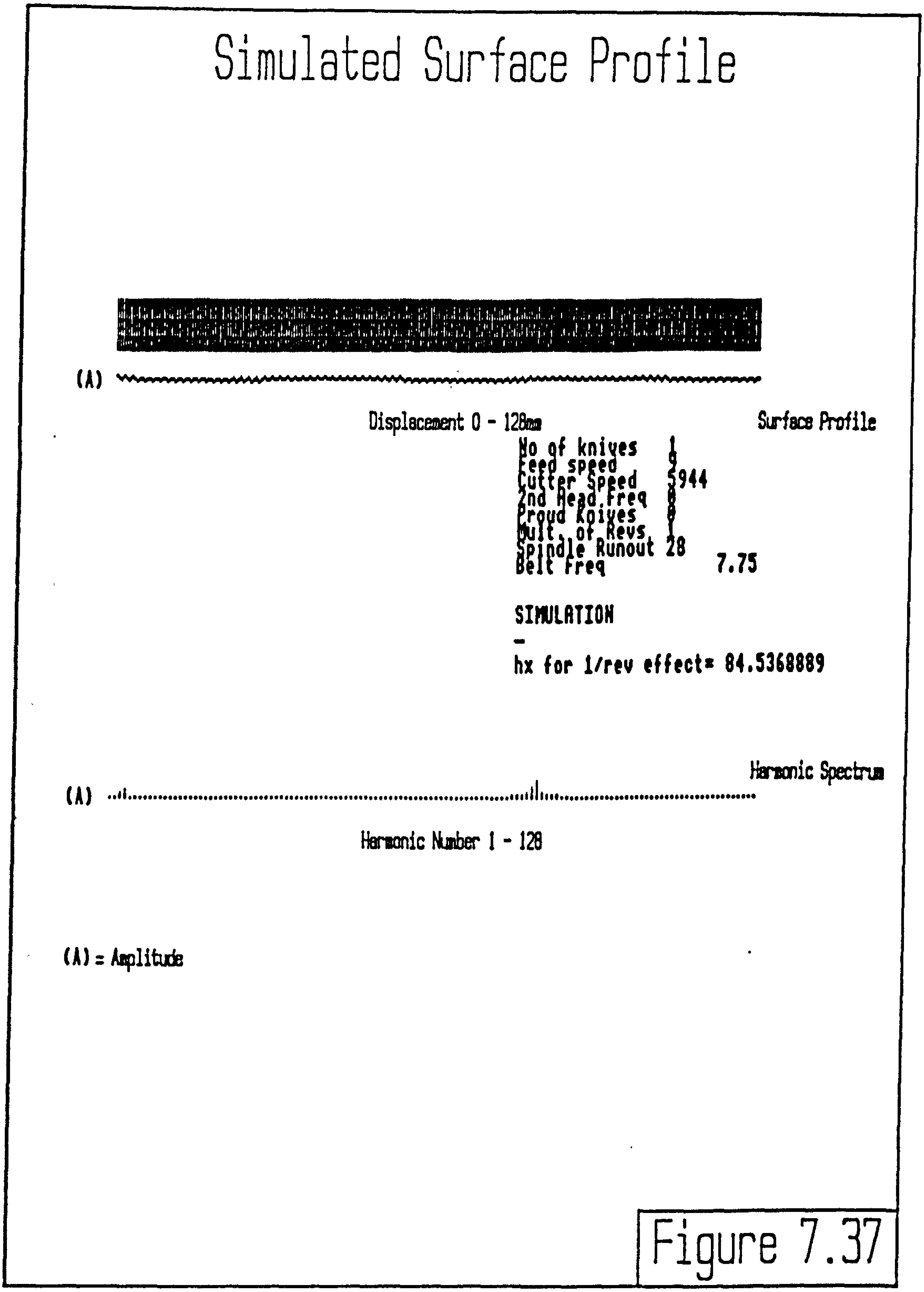

Simulated Surface Profile
(A)
Displacement 0 - 128mm
Surface Profile
No of knives 1
Feed speed 9
Cutter Speed 5944
2nd Head Freq 0
Proud Knives 0
Mult. of Revs 1
Spindle Runout 28
Belt Freq 7.75
SIMULATION
hx for 1/rev effect= 84.5368889
Harmonic Spectrum
(A)
Harmonic Number 1 - 128
(A) = Amplitude

Figure 7.37

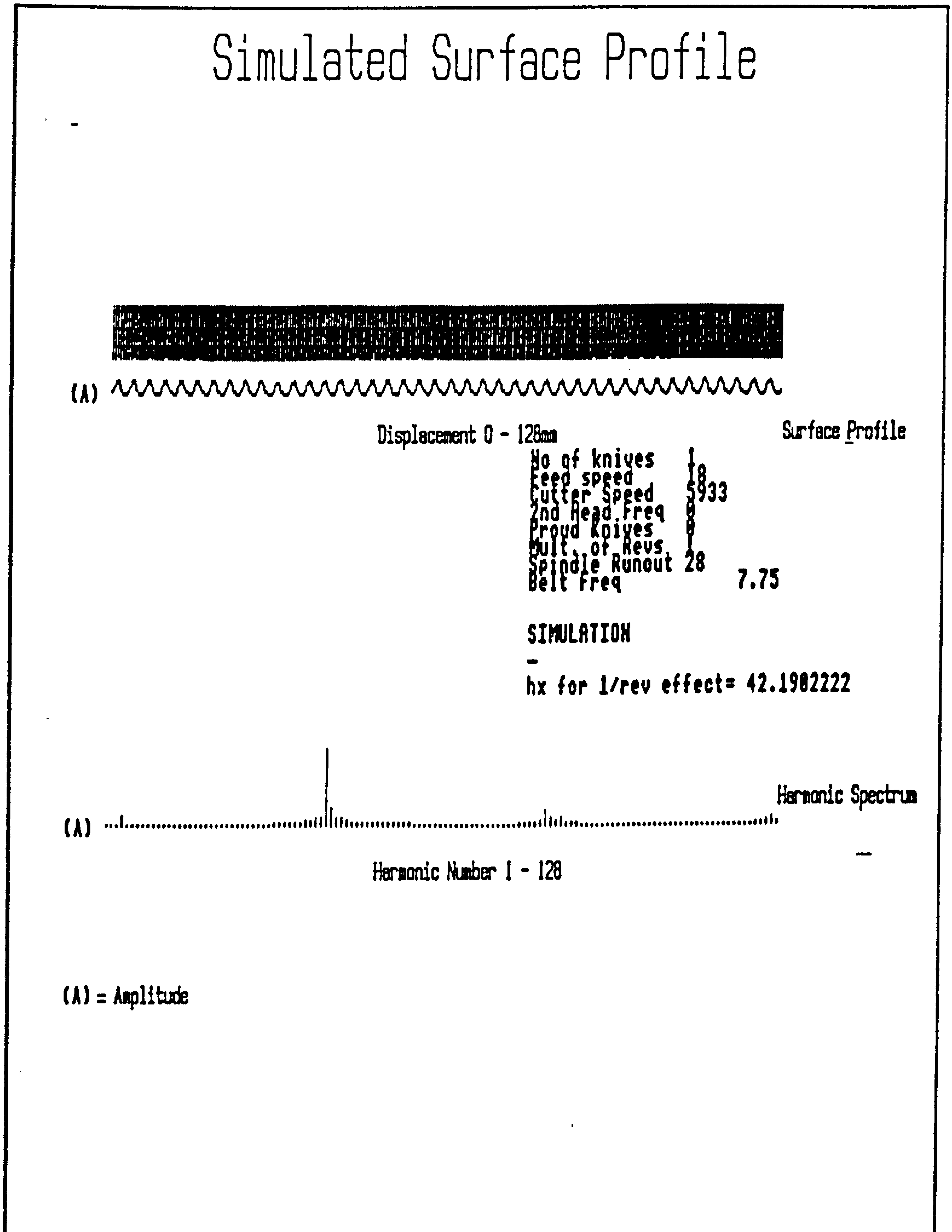

Simulated Surface Profile
(A)
Displacement 0 - 128mm
Surface Profile
No of knives 1
Feed speed 18
Cutter Speed 5933
2nd Head Freq 0
Proud Knives 0
Mult. of Revs 1
Spindle Runout 28
Belt Freq 7.75
SIMULATION
hx for 1/rev effect= 42.1902222
Harmonic Spectrum
(A)
Harmonic Number 1 - 128
(A) = Amplitude

Figure 7.38

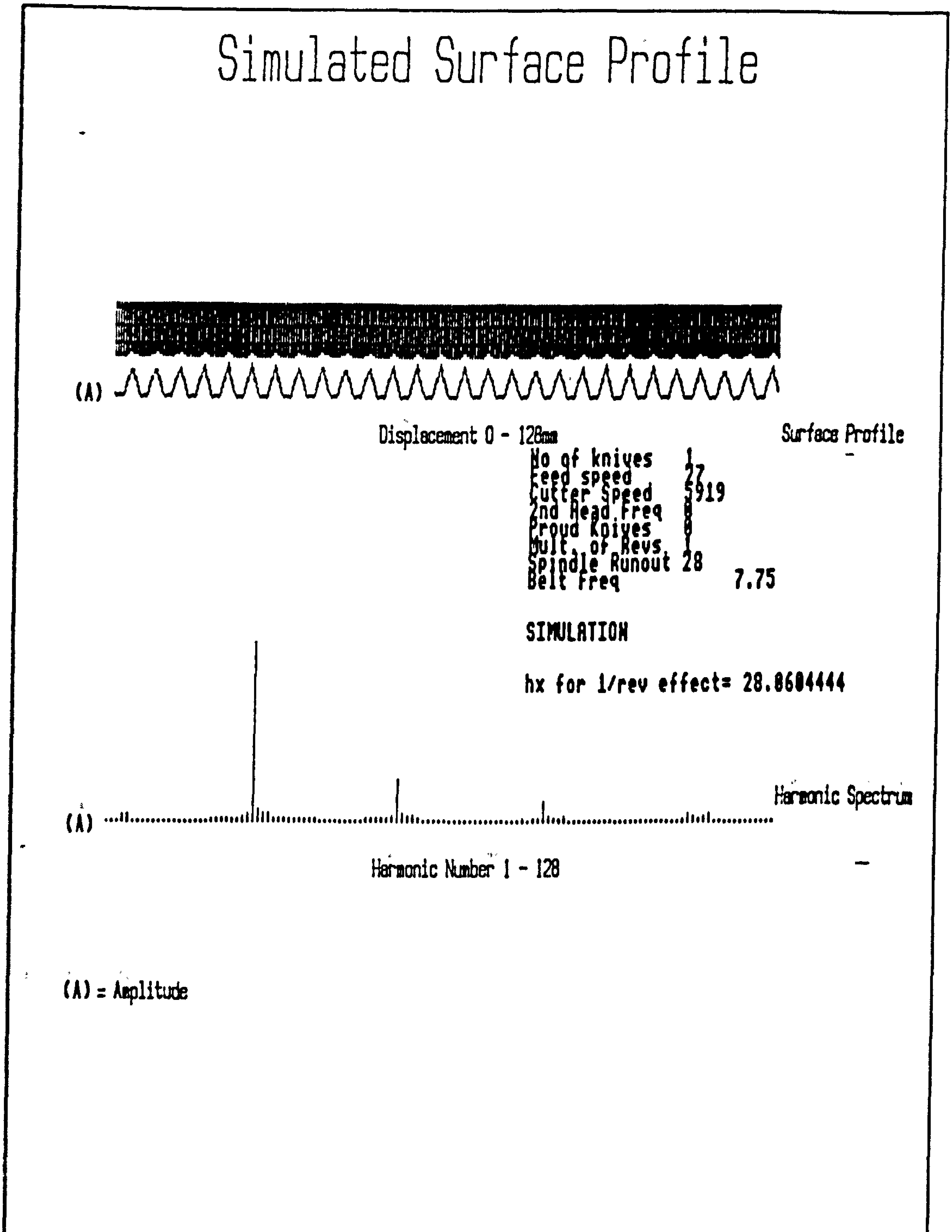

Simulated Surface Profile
(A)
Displacement 0 - 128mm
Surface Profile
No of knives 1
Feed speed 27
Cutter Speed 5919
2nd Head Freq 0
Proud Knives 0
Mult. of Revs 1
Spindle Runout 28
Belt Freq 7.75
SIMULATION
hx for 1/rev effect= 28.8604444
(A)
Harmonic Spectrum
Harmonic Number 1 - 128
(A) = Amplitude

Figure 7.39

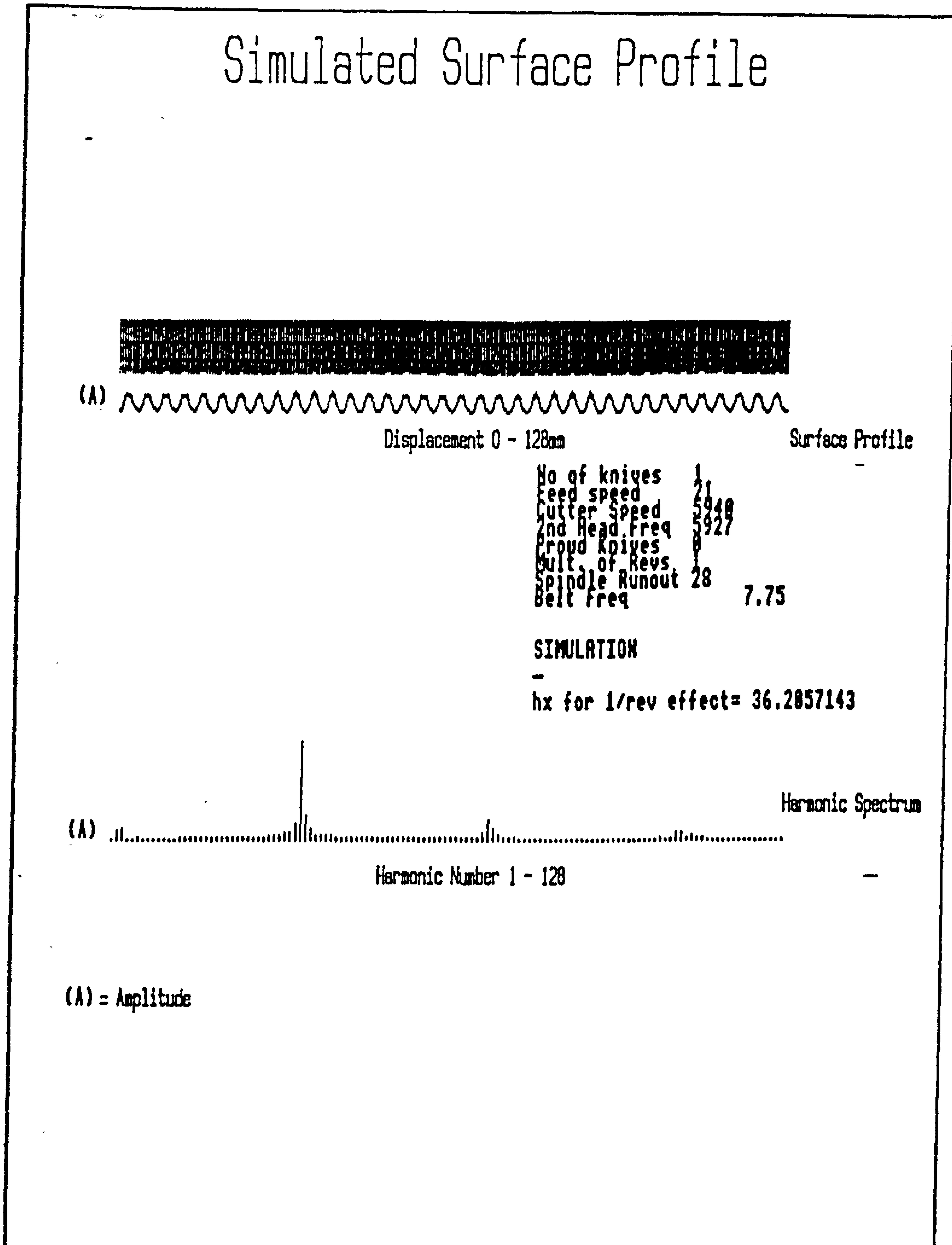

Simulated Surface Profile
(A)
Displacement 0 - 128mm
Surface Profile
No of knives 1
Feed speed 21
Cutter Speed 5940
2nd Head Freq 5927
Proud Knives 0
Mult. of Revs 1
Spindle Runout 28
Belt Freq 7.75
SIMULATION
hx for 1/rev effect= 36.2857143
Harmonic Spectrum
(A)
Harmonic Number 1 - 128
(A) = Amplitude

Figure 7.40

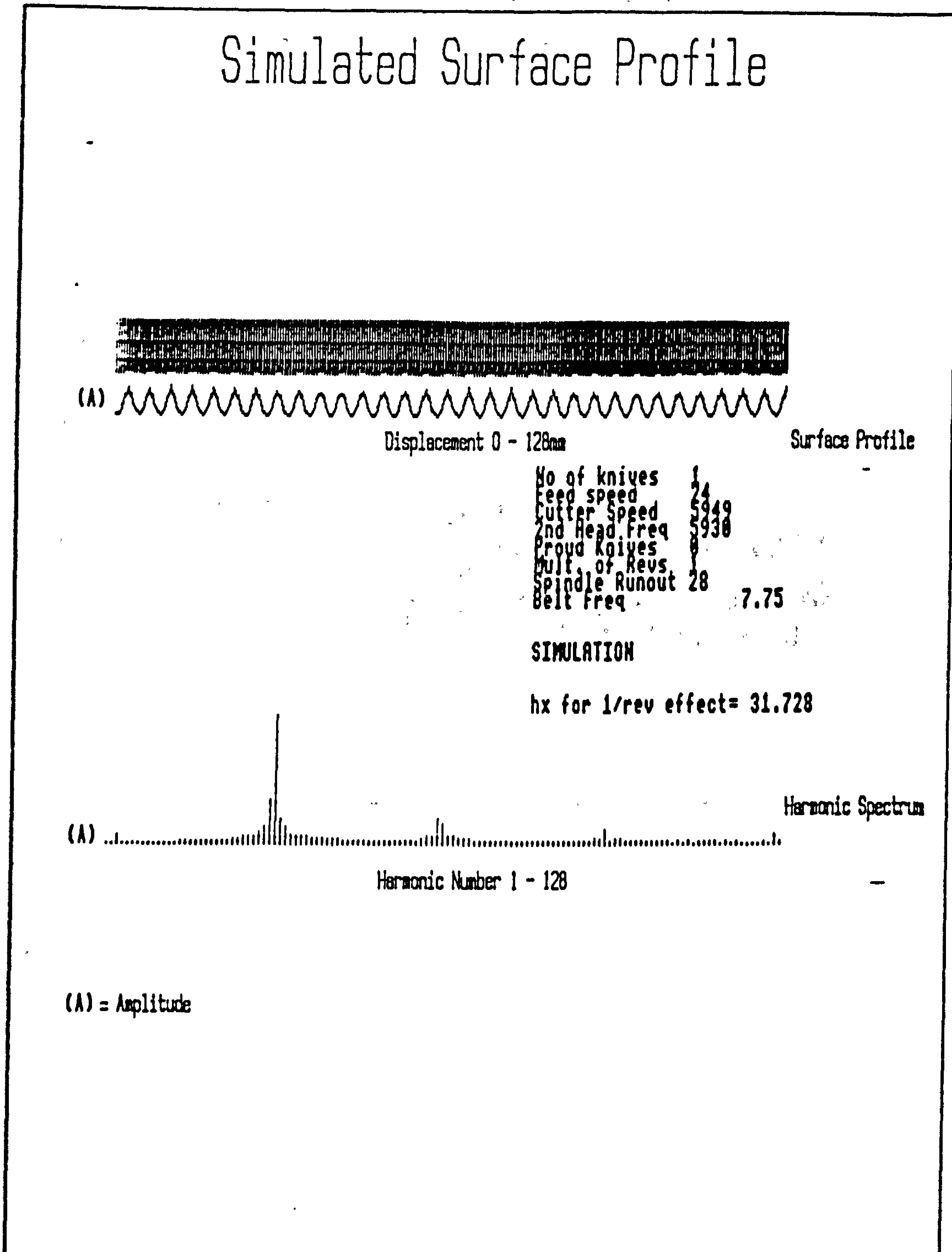

Simulated Surface Profile
(A)
Displacement 0 - 128mm
Surface Profile
No of knives 1
Feed speed 24
Cutter Speed 5949
2nd Head Freq 5930
Proud Knives 0
Mult. of Revs 1
Spindle Runout 28
Belt Freq 7.75
SIMULATION
hx for 1/rev effect= 31.728
Harmonic Spectrum
(A)
Harmonic Number 1 - 128
(A) = Amplitude

Figure 7.41

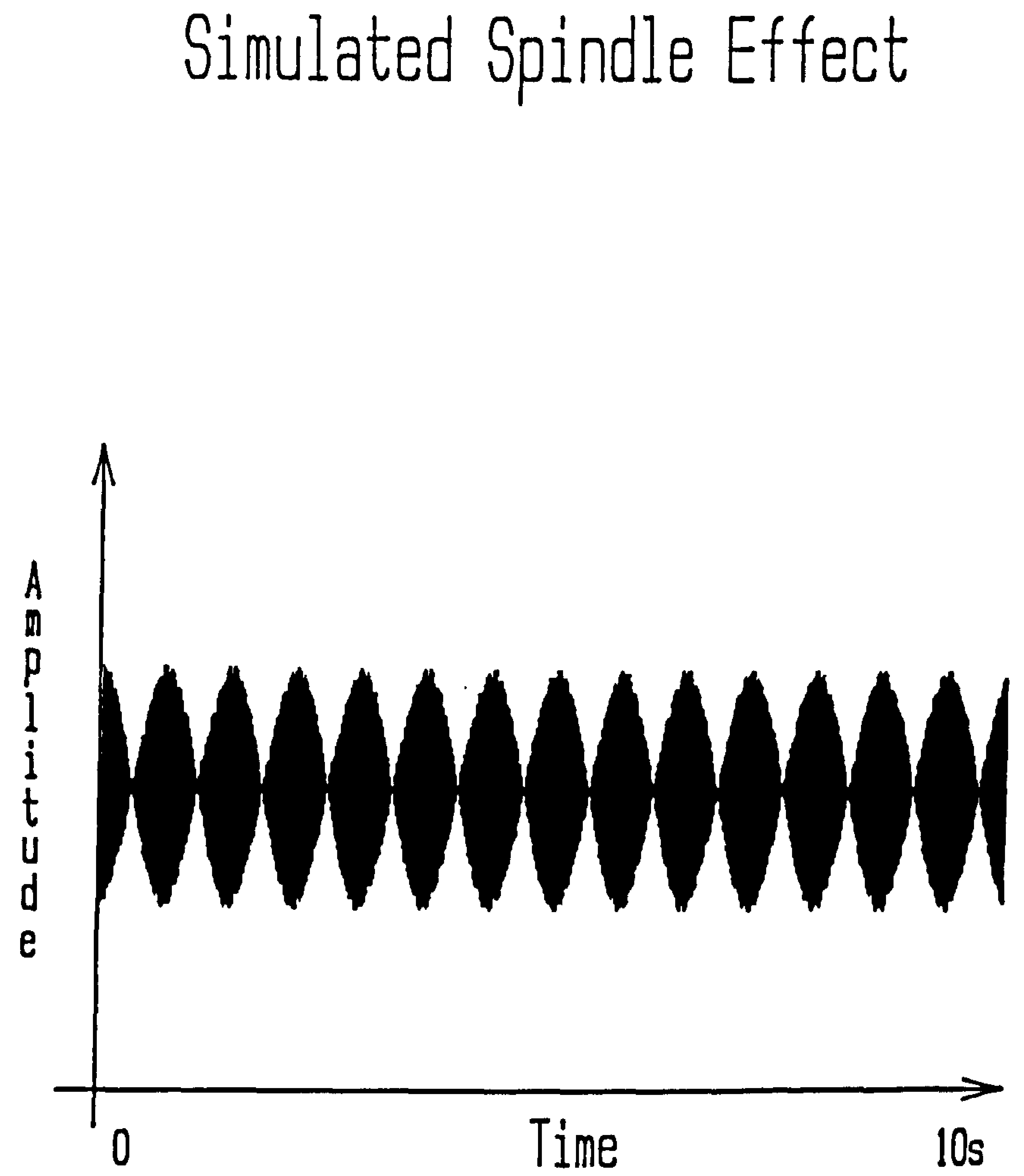


Figure 7.42

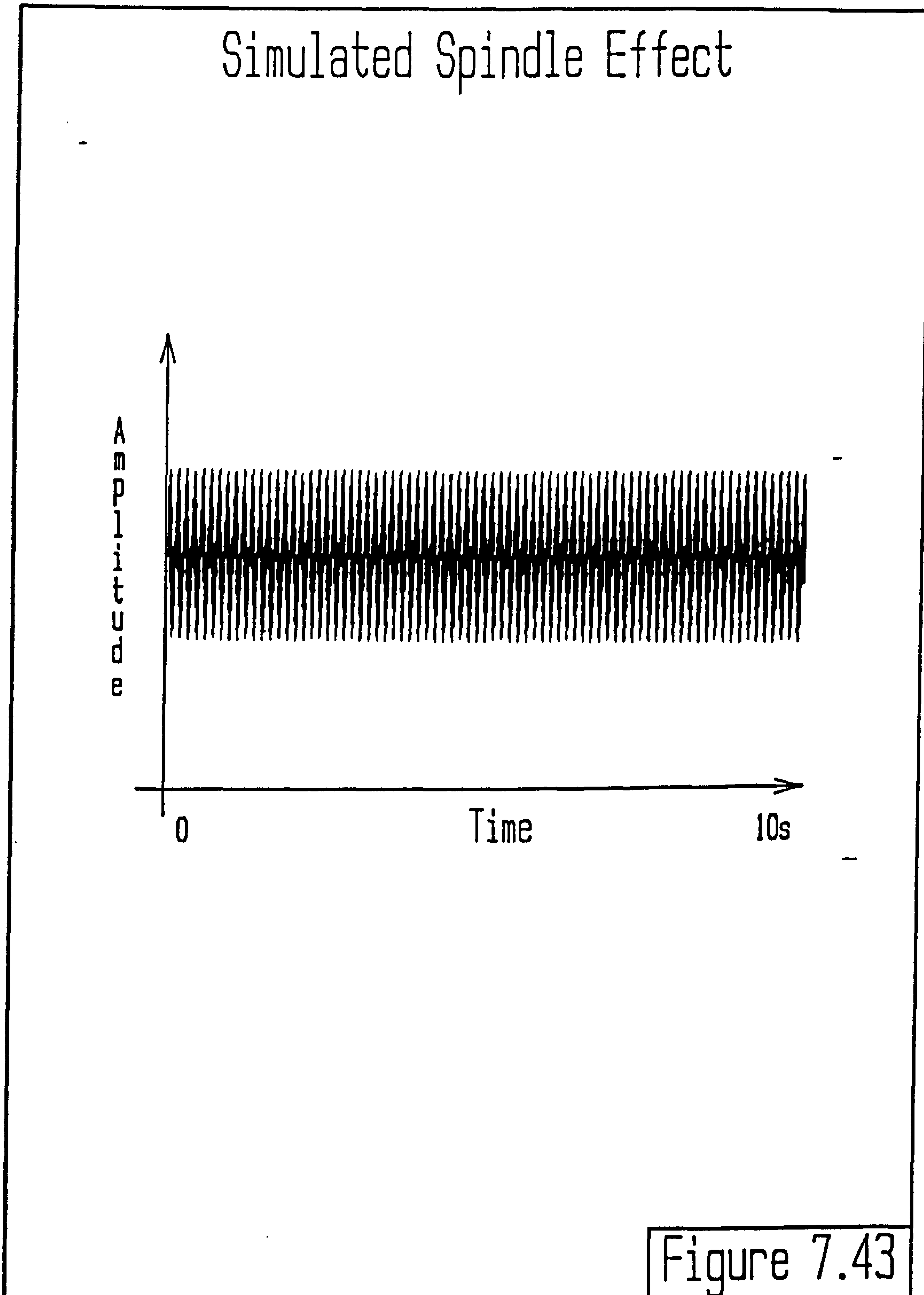


Figure 7.43

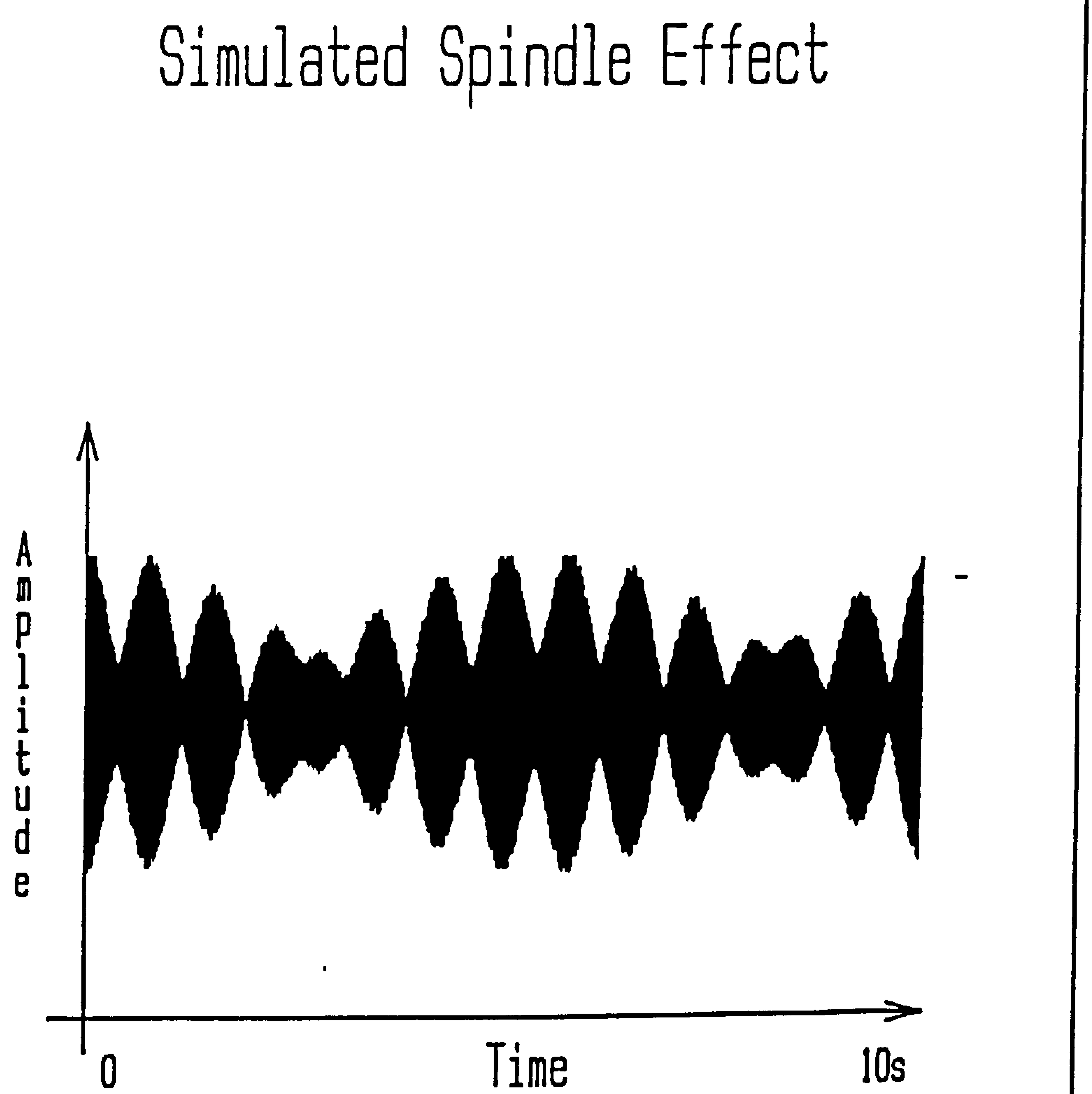


Figure 7.44

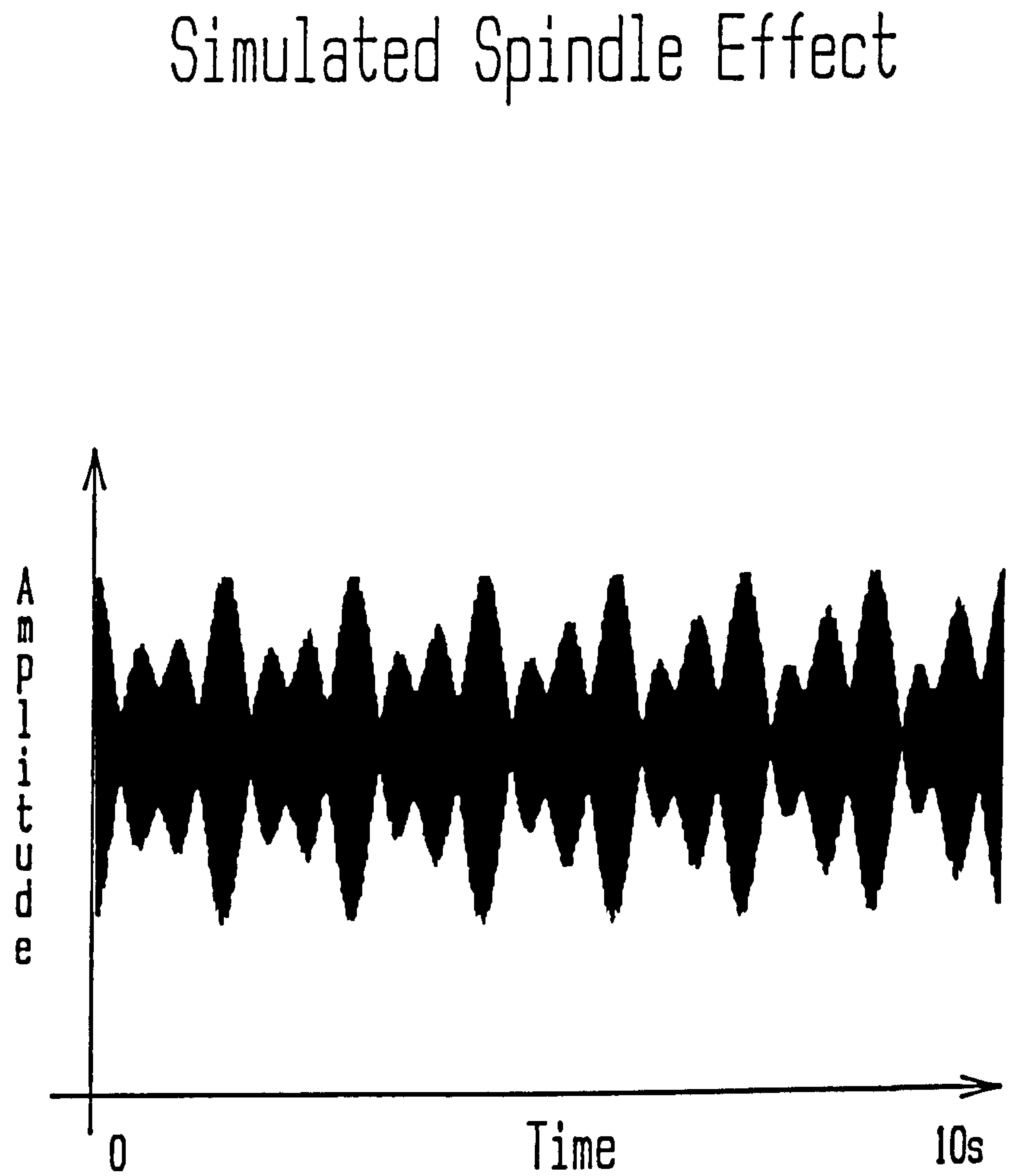


Figure 7.45

Appendix A
The Spherosyn Transducer

The Spherosyn Transducer

General Specification

General

The Spherosyn is a linear transducer producing a phase analogue output from an input reference signal. The transducer operates by inducing a magnetic field within the head, and detecting the variation in this field as it passes along the Spherosyn scale. This variation is caused by the precision steel balls in the scale which have been magnetically graded to achieve the required cyclic accuracy. The phase of the output signal relative to the drive input reference varies linearly within the accuracy specification, as the head moves along the scale, so that a 360° phase change takes place for each half inch movement.

The head contains the magnetic field generator, the field detectors and the electronic circuitry, to balance, filter and amplify the return signal. The head is fully sealed against the ingress of swarf or coolant, thus protecting the electronic circuitry. A flying lead from the head is protected by flexible conduit and terminated in an in-line connector plug.

The scale consists of a length of stainless steel tube housing a column of precision steel balls. The scale end caps, together with a spring assembly, maintain the balls under compression. The compression load is set during manufacture to calibrate the scale.

Electrical:

Note: Excluding the drive signals, all other signals are specified reference to 0v.

Supply requirement	+12v ± 5% at 25mA. Supply noise (ripple) less than 20mV.
Drive Reference Signal Requirement	85 to 90mA. r.m.s. sinewave to be fed into the drive loop which is connected between drive Hi and Drive Lo. Signal distortion to be less than 1%. Signal frequency - 1 KHz ± 0.2 Hz. Maximum potential to be applied between either Drive Hi or Drive Lo and 0v or case should not exceed 50 volts.

Sheet 1 of 2

The Spherosyn Transducer

Electrical (cont'd.)

Drive Input Characteristic	Drive Hi to Drive Lo resistance - 10 to 20 Ohms.
	Drive Hi to Drive Lo inductance - 10 to 15 mH.
	Impedance between Drive Hi or Drive Lo to 0v or case is greater than 100 KΩ at 1 KHz.
Output signal	Sinewave at same frequency as input in range 1.4 to 2.8v r.m.s., about a d.c. level of 4.5 to 6v.
	Noise voltage on output less than 4mV r.m.s.
Output loading	The impedance connected to the output signal shall not be less than 5 KΩ over the frequency range d.c. to 3 KHz.

Note: The transducer head case is connected to the cable screen, the connector body, and the 0v. line.

The connector pin functions are as follows:-

Pin 1	...	Drive Hi
Pin 2	...	Output Signal
Pin 3	...	+ 12v. supply
Pin 4	...	Drive Lo
Pin 5	...	0v.
Pin 6	...	not used
Pin 7	...	not used

Mechanical

The Spherosyn transducer consists of two main assemblies, viz. the head and the scale, which together with the scale mounting assembly and the guard, require a swept area over the travel length of 60 x 41mm. Details of the mounting are given on drawing ER-701 . There is no electrical connection to the scale. Connection to the head is made by means of a flying lead 3.5 metre long and terminated in an in-line plug. This plug is a 7-way Bleecon connector (manufactured by Belling Lee) and adapted to terminate the conduit.

The scale should never be brought into contact with a strong magnetic field (i.e. clock base), as this may permanently damage the scale calibration. In general, magnets kept a few inches from the scale (or when mounted on the machine outside the guard) will not have any effect.

Sheet 2 of 2

END

Appendix B The CASS Unit

Cutter block assemblies were measured, to obtain important manufacturing information (as detailed in section 3.1.2) using the CASS system. The information generated was used in conjunction with timber data (data that was generated from section drawing files) to ascertain machine spindle offsets (Sanusi T, Parkin R 1988). The machine offsets, calculated within the CASS unit, were required during machining operations.

The microprocessor architecture of the CASS system is shown in **Figure B.1.** Two memory cards, one for data storage and another for data transfer (data transfer between the CASS and the RDT unit) were used. The connections for one of the card holders is shown in **Figure B.2.**

Data editing and manipulation, required between back up storage and transfer memory cards, was performed via an alpha-numeric keyboard and LCD module (Figure B.3).

Measurements of individual cutter profile features were undertaken using spherosyn transducers. The transducers were incorporated within an existing measuring stand. Two transducers were utilised, one in the cutter block arbour's axial direction and the other in its radial direction.

The design of the conditioning and counter circuitry, re quired to interface each transducer to the CASS system was undertaken by the author. The work is illustrated in **Figure B.4.**

Signal Conditioning The Spherosyn transducers used required a five volt, peak to peak, one kilohertz sine wave input. The return signal from the transducers was a similar sine wave. This signal exhibited a referenced phase change of 360° for every 12.7mm traverse of the transducer's scale (Figure B.5).

The transducer's 1KHz reference signal was produced from a 5.08MHz master oscillator by first dividing 4 (using several 74HC74 flipflops) followed by a further division by 1270 using a 4059B divide by (n) counter to give a 1KHz square wave. Signal conditioning circuitry was then used to produce the 1Khz/180ma sinusoidal signal required by the transducers. The signal shape changing was performed using several stages of resistor and capacitance networks (Parkin R. 1988[2]). Intermediate gain amplification stages were needed to recover the magnitude losses that occurred through each integrating circuit.

Counter circuitry The 1.27 MHz clock signal was used to increment the enabled four decade synchronous counters during the phase change gating period. Each 360° of phase shift, between the transducers supply and return signal, enabled 1270 counts. **Figure B.6** illustrates the logic signals employed to generated the gating period signal used on the transfer pin (pin 24) of each counter (X and Y channel signals shown). Utilising these control signals each counter counted directly in 10μm intervals. This approach avoided unnecessary mathematical computations.

Transducer investigations identified that the spherosyn unit's supply and return signal phase shift remained accurate over an operating band of approximately ±20%, that of the recommended supply frequency. As a result small errors in actual crystal (a component of the oscillator circuit) frequency had no detrimental effects on the operation accuracy of the circuit.

Due to each signal's phase reference no transducer calibration system was necessary. Consequently component aging had no effect on accuracy, repeatability or long term stability.

The system microprocessor was interrupted every one millisecond during measurements, using the rising edge of a compared supply signal. The interrupt initialised the software procedure that determined new count values from the, alternatively enabled, counters.

10μm Counter Software description A schematic diagram of the operation of the counters software is shown in **Figure B.7.** Initially the 740 "module" file was created containing all non standard 6502 instructions. The file was an important integrative bridge between the standard 6502 assembler and the 50734SP microprocessor (Mitsubishi hardware manual 1987). Within this module each enhanced 6502 instruction was equated to the machine code value handled by the processor.

The module (D. Vari) was designed to allocate specific memory locations (addresses) to labelled variables. This programming approach simplified the complexity of the program in terms of user readability.

The module (D. Reset) was used to reset the system when it as initially powered up. The first line of code, in this module, immediately disabled the interrupt capabilities of the processor.

The status registers (T) flag was then cleared, which allowed operational results between two memories locations to be stored in the accumulator (Series 740 Users manual 1988). The address of the first memory location, in this type of operation, was specified by the contents of the index register (X) while the address of the second memory location was specified by the normal addressing mode. As this type of instruction was an enhanced processor code it was byte equated into the assembler.

The processor used could be operated in either decimal or binary mode, so the decimal flag was cleared to select binary operation mode.

The required programmable I/O lines were then initialised to ensure safe and correct configuration status. $Port_{31}$ was initialised as an output, while $port_{30}$ and $port_{01}$ were both set as inputs. $Port_{31}$ was assigned as the counter clear control line, while $port_{30}$ and $port_{01}$ handled the counter status and interrupt requirements respectively. All of the pins of $port_1$ were then programmed as inputs (these were the counter's data lines).

With all the corresponding I/O lines set up, the interrupt code "start address" was loaded in the two byte interrupt vector of the processor. On an interrupt service (with the interrupts enabled) the start address of the interrupt code was found via an indirect memory jump, which was determined by the "address" contents of the interrupt vector.

With the I/O status of the processor now correct, the interrupt request and enable bits were cleared thus enabling the processor to receive interrupts.

For development purposes the counter software transmitted counter values to a Video Display Unit (VDU). This was undertaken using the monitor program's subroutines (RCS Micro systems manual 1985).

The module (D.Disp) being the foreground program, immediately cleared the screen of the VDU. The (X) counter's four Binary Coded Decimal (BCD) characters were then transmitted to the screen. The (Y) counter's four BCD characters were subsequently transmitted to the screen and displayed. These characters were continually updated and displayed in a scanning loop.

As the signal used, to trigger the interrupts, on the interrupt pin of the processor, was a 1KHz square wave (using a positive edge trigger), an interrupt occurred every one millisecond. This interrupt initialised the (D. Count) module interrupt code which monitored the counter's operational status and count data.

The first lines of the interrupt code pushed the processor registers onto the stack. This was necessary to preserve their values at the time the interrupt was generated. The code then checked the status of each counter, if for example the feed signal of counter (Y) was in a low state the software identified this counter as being in the read condition. If however the signal was in a high logic state the software identified the counter as being in the count condition, and similarly for the (X) counter. As each counter channel's hardware was identical in design, programming was simplified.

If the (Y) channel's feed signal was thus identified high and the (X) channel's feed signal low, the (X) channel's data was captured. This was achieved initially by equating the (X) register to zero and setting a variable called mask to 1 before reading the data port.

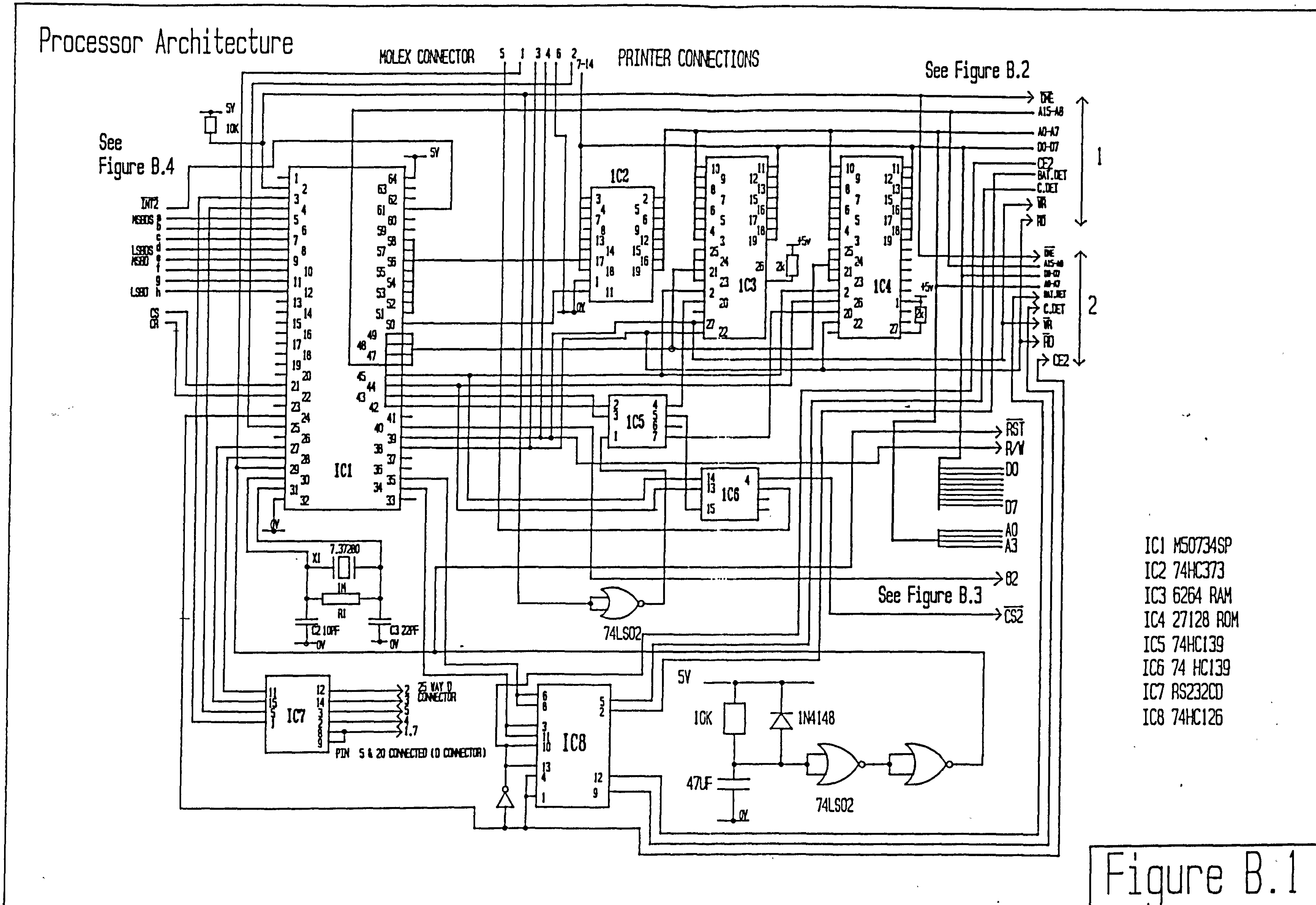
$Port_1$ of the processor (the counter data) was then read and stored in a variable called (temp). The output byte of the counter consisted of 4 data bits plus 4 data select bits. The data select bits required monitoring for correct capture of the counter's data bits. This synchronisation was achieved using the variable mask. The mask value was shifted and compared with the data select bits until all the valid data bits were captured from the counter. As only four bits of every byte composed valid data (the other 4 being select bits) a logical operation was performed to eliminate the unwanted data.

The correct count data was then stored in a convenient memory buffer. The mask value was then arithmetically shifted four times to extract the counter's decade information.

Once the counter had been successfully read it was then reset by clearing pin 1 of $port_3$ (the processor counter clear pin). The interrupt request bit was then cleared, allowing interrupts to the processor to be monitored again.

When counter (Y) required reading, the second half of the software module's code was utilised (this was counter status dependent). At the end of the interrupt code the processor's registers were restored enabling the processor to execute the remaining lines of the foreground program.

Figure B.1



Processor Architecture
MOLEX CONNECTOR
PRINTER CONNECTIONS
See Figure B.2
See Figure B.4
See Figure B.3
IC1
IC2
IC3
IC4
IC5
IC6
IC7
IC8
74LS02
7.3728O
1N4148
10K
47UF
25 WAY D CONNECTOR
PIN 5 & 20 CONNECTED (D CONNECTOR)
RST
R/W
D0
D7
A0
A3
Ø2
CS2
IC1 M50734SP
IC2 74HC373
IC3 6264 RAM
IC4 27128 ROM
IC5 74HC139
IC6 74 HC139
IC7 RS232CD
IC8 74HC126

Figure B.1

Figure B.2

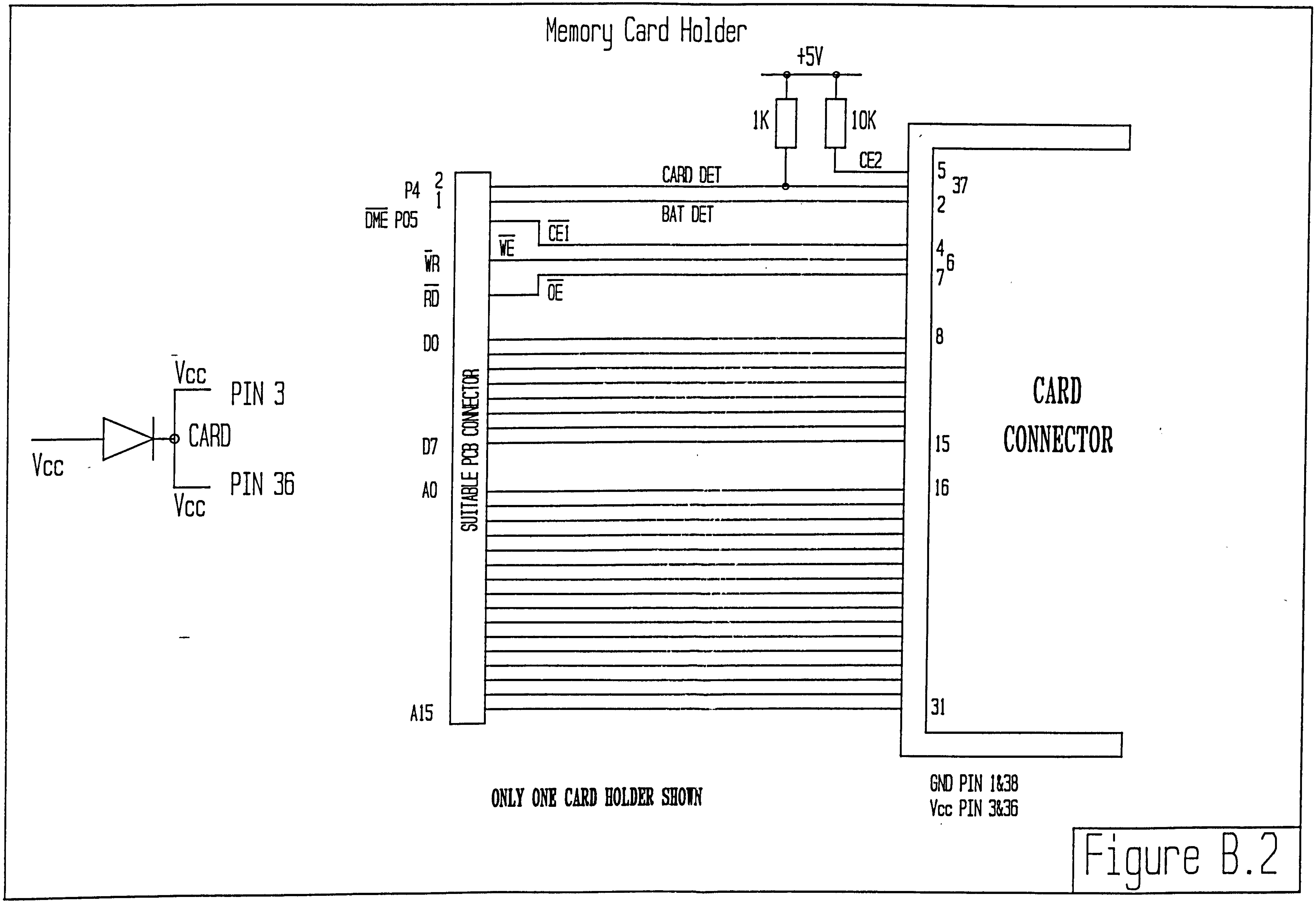

Memory Card Holder
+5V
1K
10K
CE2
CARD DET
BAT DET
P4
2
1
DME P05
CE1
WE
WR
RD
OE
D0
D7
A0
A15
SUITABLE PCB CONNECTOR
5
37
2
4
6
7
8
15
16
31
CARD CONNECTOR
Vcc
PIN 3
CARD
PIN 36
Vcc
Vcc
ONLY ONE CARD HOLDER SHOWN
GND PIN 1&38
Vcc PIN 3&36

Figure B.2

Figure B.3

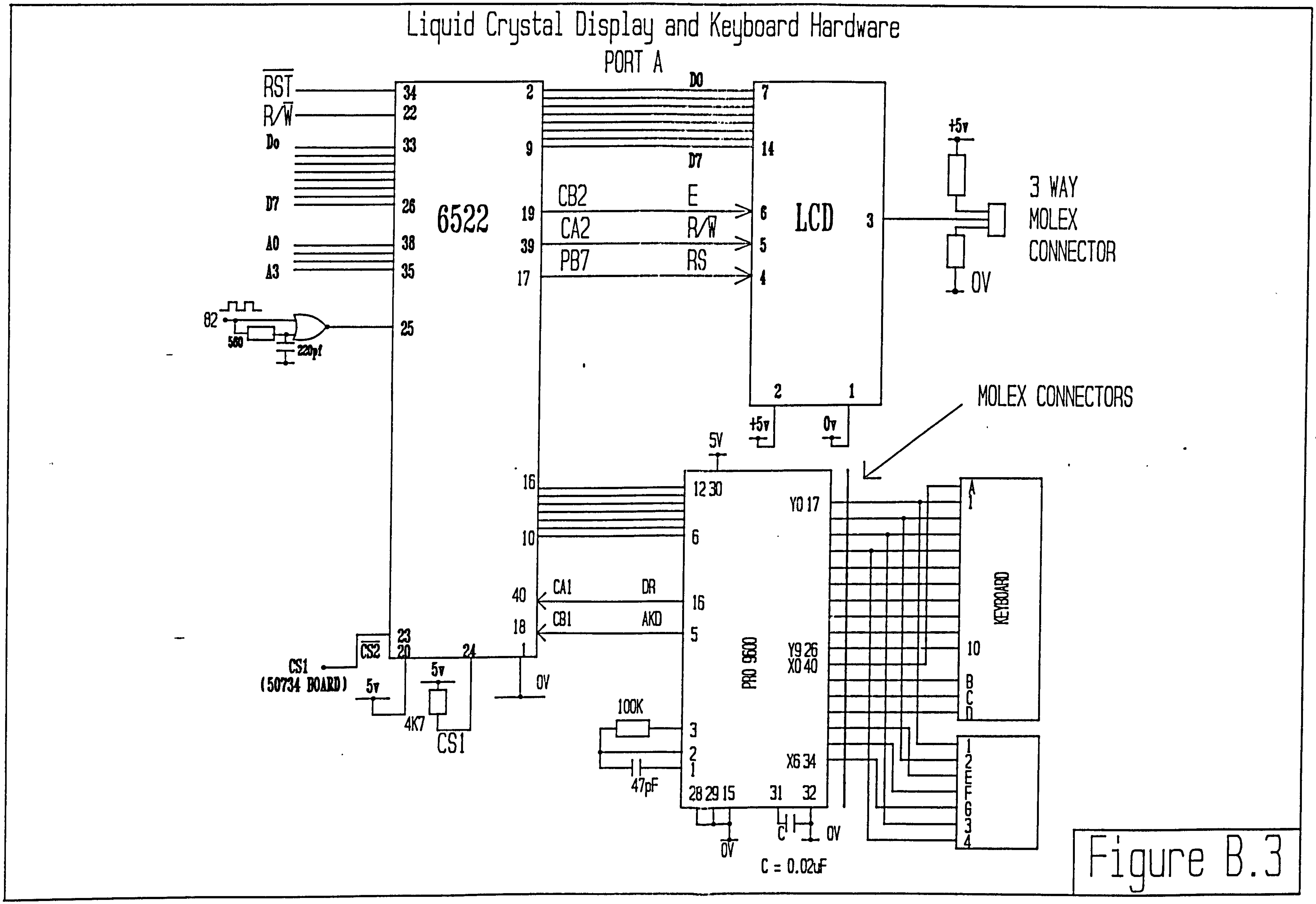

Liquid Crystal Display and Keyboard Hardware
PORT A
RST
R/W
D0
D7
A0
A3
82
560
220pf
6522
34
22
33
26
38
35
25
2
9
19
39
17
CB2
CA2
PB7
E
R/W
RS
D7
7
14
6
5
4
LCD
3
2
1
+5v
0v
3 WAY
MOLEX
CONNECTOR
0V
MOLEX CONNECTORS
5V
16
10
12 30
6
Y0 17
CA1
CB1
DR
AKD
40
18
16
5
PRO 9600
Y9 26
X0 40
X6 34
23
20
24
1
CS2
CS1
(50734 BOARD)
5v
4K7
CS1
0V
100K
47pF
3
2
1
28 29 15
31
32
C
C = 0.02uF
KEYBOARD
A
1
10
B
C
D
1
2
E
F
G
3
4

Figure B.3

Figure B.4

Counter Circuitry

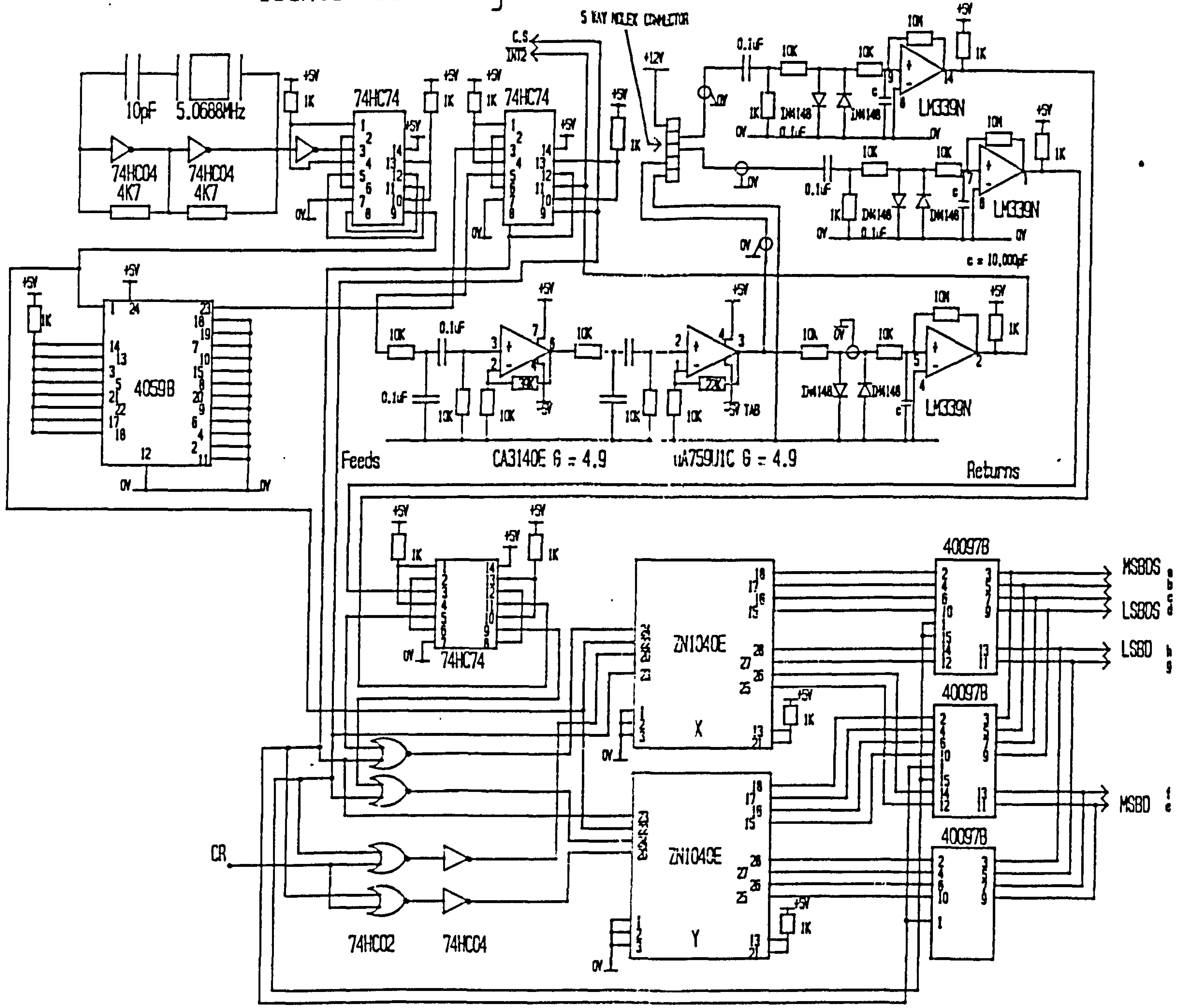


Figure B.4

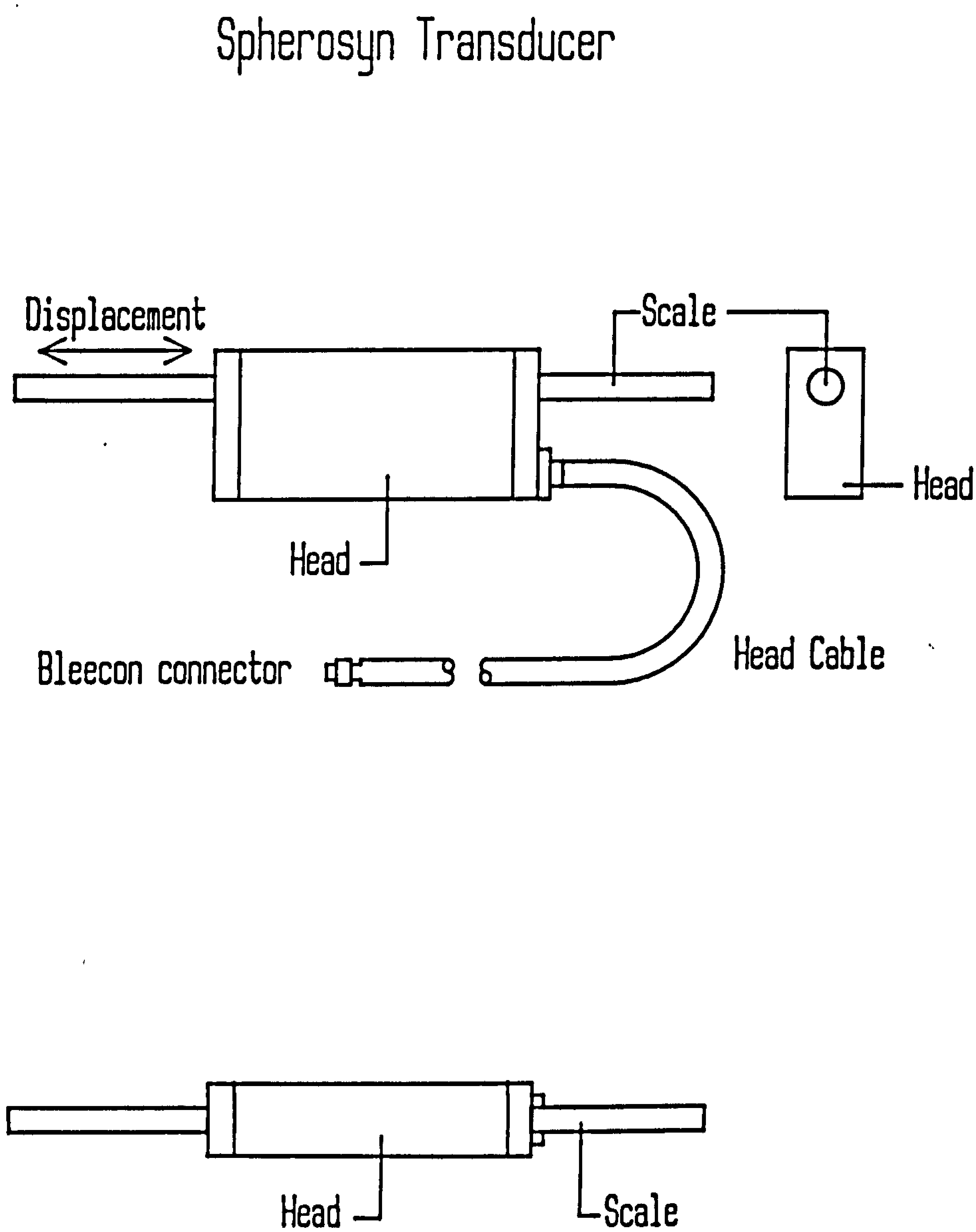

Spherosyn Transducer
Displacement
Scale
Head
Head
Bleecon connector
Head Cable
Head
Scale

Figure B.5

Counter Logic and Timing Diagrams

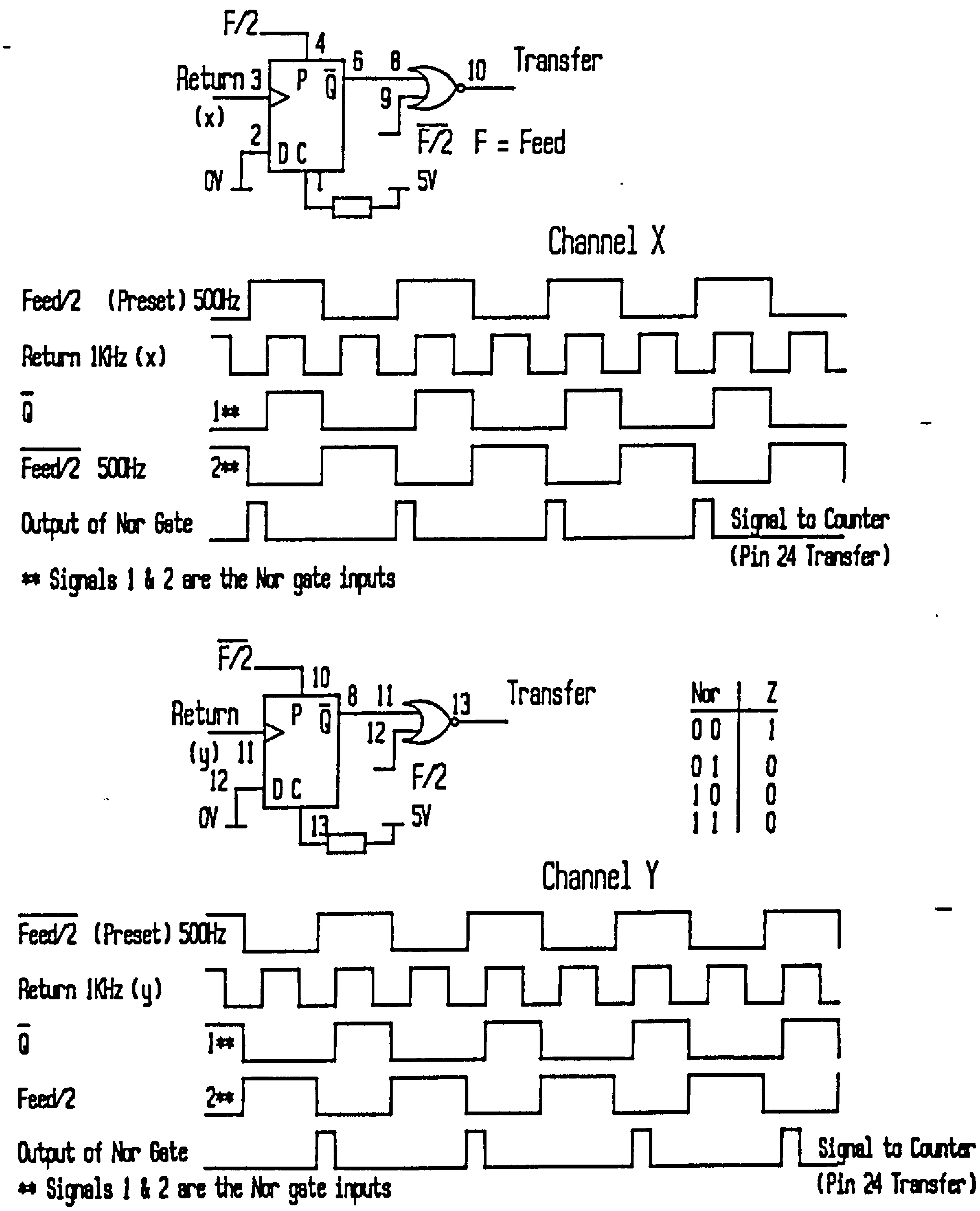


Figure B.6

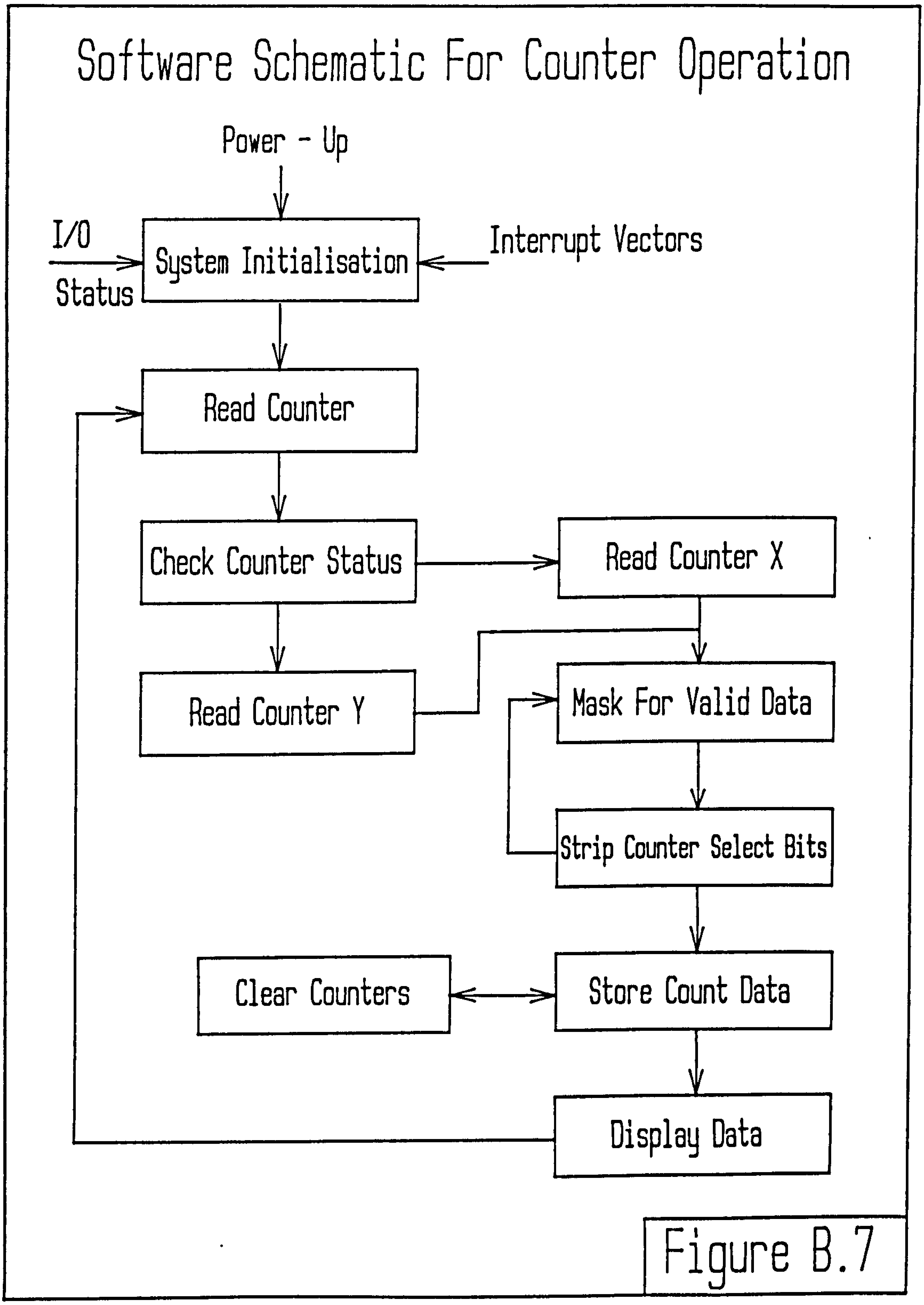
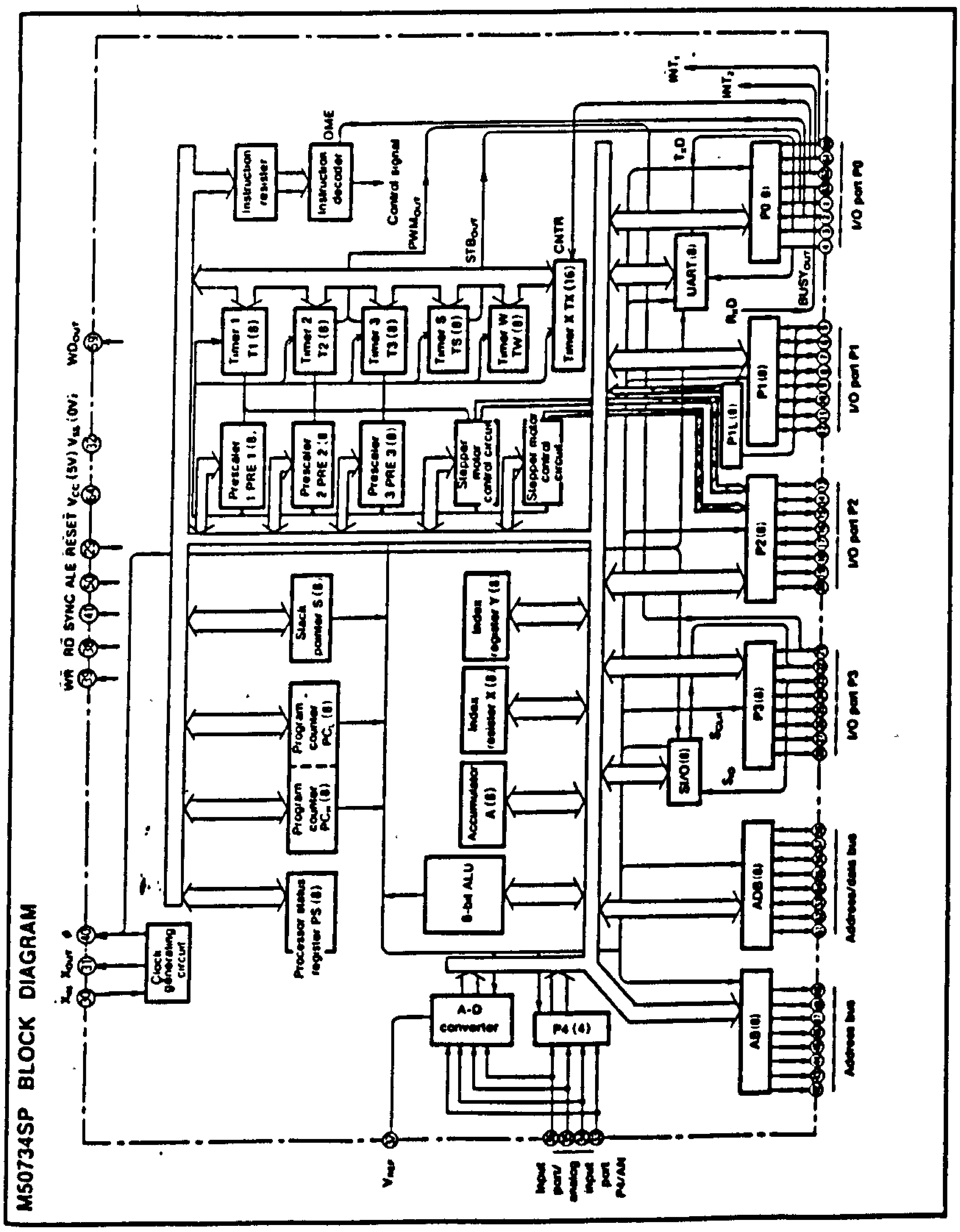

Software Schematic For Counter Operation
Power - Up
I/O
Status
System Initialisation
Interrupt Vectors
Read Counter
Check Counter Status
Read Counter X
Read Counter Y
Mask For Valid Data
Strip Counter Select Bits
Clear Counters
Store Count Data
Display Data

Figure B.7

Appendix C
The M50734SP Microcomputer

8-BIT CMOS MICROCOMPUTER



Appendix D
The LCD Module

Alphanumeric dot matrix liquid crystal display

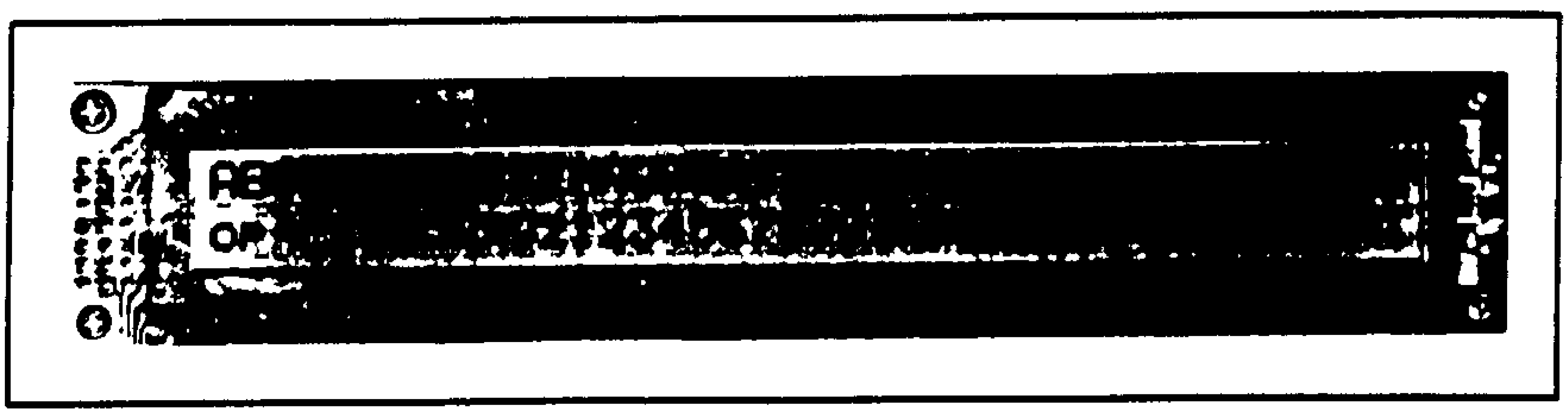
Intelligent, alphanumeric, dot matrix modules with integral CMOS microprocessor and LCD display drivers. The modules utilise a 5 x 7 dot matrix format, with cursor, and are capable of displaying the full ASCII character set plus up to 8 additional user programmable custom symbols. The displays are virtually burden free to the host processor. Internal registers store up to 80 characters and all update and refresh is internal. Software development is greatly eased by powerful, single step, instructions which eliminate many lines of conventional coding.

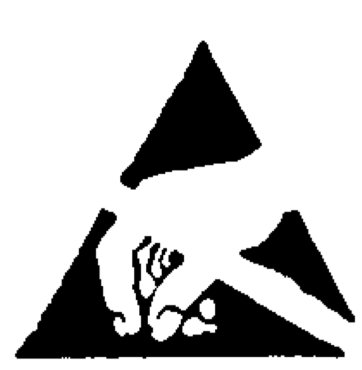
Applications

▲ Telecommunications
▲ Medical instruments
▲ Hand-held terminals
▲ Electronic typewriters
▲ Point of sale terminals
▲ Test instruments
▲ Word processors

Features

- 5V, 2mA, single power supply
- High contrast, dot matrix characters for good readability
- Wide adjustable viewing angle
- Compact and lightweight
- TTL and 5V CMOS compatible
- Interfaces to 4 or 8-bit data busses
- Powerful instructions
- Display 'Blank', 'Flash' or 'Flash Limited Area'
- ASCII compatibile
- 192-Character generator ROM (96 Alphanumerics/Symbols, 64 Kata kana, 32 Euro/Greek/Symbols)
- 8-User programmable RAM locations for custom symbols
- 80-Character memory allows easy scrolling or general purpose storage
- Cursor 'Flash', or off
- Automatic display shift – simple command structure
- Scrolls left or right or alternates complete lines.



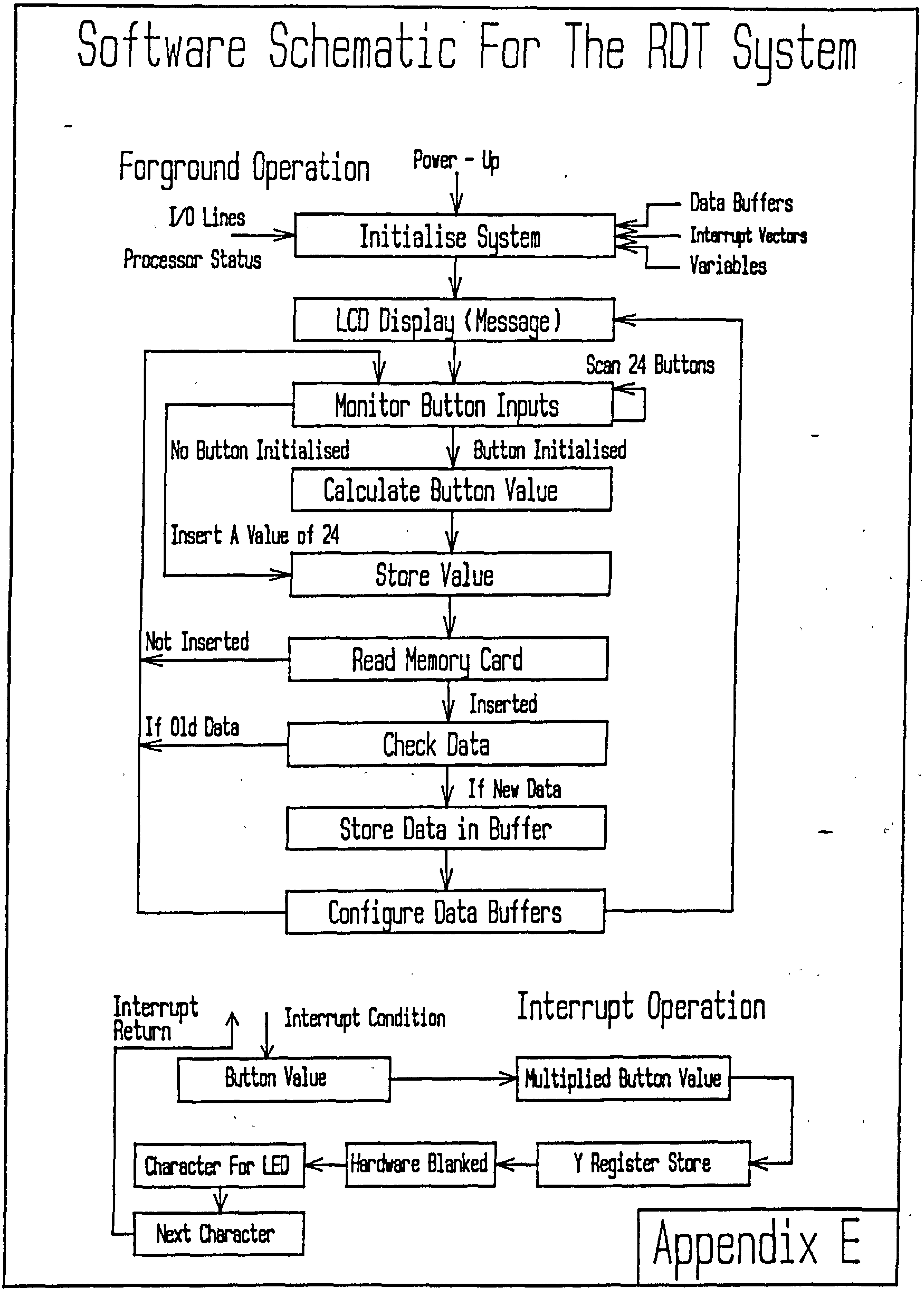


ATTENTION

OBSERVE PRECAUTIONS FOR HANDLING

ELECTROSTATIC SENSITIVE DEVICES

Appendix E



Software Schematic For The RDT System
Forground Operation
Power - Up
I/O Lines
Processor Status
Initialise System
Data Buffers
Interrupt Vectors
Variables
LCD Display (Message)
Scan 24 Buttons
Monitor Button Inputs
No Button Initialised
Button Initialised
Calculate Button Value
Insert A Value of 24
Store Value
Not Inserted
Read Memory Card
Inserted
If Old Data
Check Data
If New Data
Store Data in Buffer
Configure Data Buffers
Interrupt Return
Interrupt Condition
Interrupt Operation
Button Value
Multiplied Button Value
Character For LED
Hardware Blanked
Y Register Store
Next Character
Appendix E

Appendix F

The initial Tension Between Pulleys

The pulley arrangement, housing and motor of the planing and moulding machine is shown in **Figure F.1.** The tension of the pulley belts was determined by the fitter , using a specially designed tensioning tool, during assembly. Tensioning was carried out by inserting the location pin on the tool into the designated hole of the pulley housing. By rotating the tool varying amounts of tension were achieved, as a result of subsequent motor displacement, between the pulleys.

As the belt tension levels of the machine were subjectively set, variations between individual machine assemblies arose. As a result, tension level measurements were necessary.

Indirect Tension Measurements Initially a hole was machined in the drive housing at a point half way between the pulley spindles. The inner belt of the system, using the hole for access, was then deflected by applying various loads. The resulting relationship obtained between the belt's deflection and applied load (with the load being exerted at an angle perpendicular to the pulley belt) is shown in **Figure F.2.** Using the deflection information the initial tension, of the pulley assembly, was determined by reconstructing an identical system on a **Mayes** tensile testing machine.

Initial Tension The pulley belt system was set up on the testing machine as shown in **Figure F.3.** A Tensile load was increasingly applied until an identical load and deflection relationship, established previously on the planing machine, was simulated. The initial tension value recorded from this situation was 1.35KN.

The Coefficient of Friction Between The belt and the Pulley

Figure F.4 represents a V belt and pulley in which motion of the belt impends clockwise on the pulley. The relationship between the tight and slack side tension, when slip occurs is:-

$$\frac{T1}{T2} = e^{\mu\Phi/\sin\beta} \qquad \text{---(F1)}$$

(Higdon A. et al 1976)

Where
- T1 = Tight side tension
- T2 = Slack side tension
- Φ = The angle of lap
- β = Half the included angle of the belt
- μ = The coefficient of friction
- e = 2.718

To establish the value for the coefficient of friction, between the belt and the pulley, an experiment using the apparatus shown in **Figure F.5** was undertaken. As shown the angle of lap for the belt was initially set to zero. The weight holder was then incrementally loaded to a maximum of 25Kg. The calibration results obtained, from the dial test indicator which was attached to the cantilever, for the belts tight side tension are illustrated as a deflection relationship in **Figure F.6.**

To obtain the belt's slack side tension the weight holder was unloaded and the angle disc was rotated through 20° and locked into position. The system was once again incrementally loaded and the cantilevers deflection, representing the belt's slack side tension, was observed again using the DTI. An ordinate relationship was then determined for the tension ratio and is shown in **Figure F.7.**

To obtain the value for the coefficient of friction between the belt and pulley the natural logarithm of equation (F1) was taken as follows:-

$$\ln \frac{T1}{T2} = \ln(e) \cdot \frac{\mu\Phi}{\sin\beta} \qquad (\ln(e) = 1)$$

$$\mu = \frac{\ln(T1/T2) \cdot \sin\beta}{\Phi} \qquad \text{---(F2)}$$

Where Φ is in radians.

Using equation (F2), in conjunction with load variations of 0 to 24Kg, an average value for the coefficient of friction was calculated (see table F1). To establish that the value for the coefficient of friction remained independent, in relation to the angle of belt lap, further experimentation was carried out.

The slack side tension was consequently measured, using a tight side load of 24Kg, at a number of lap angles. The results obtained are presented in **Figure F.8**, with table (F2) illustrating the frictional coefficient value obtained at each angle.

Drive System Arrangement

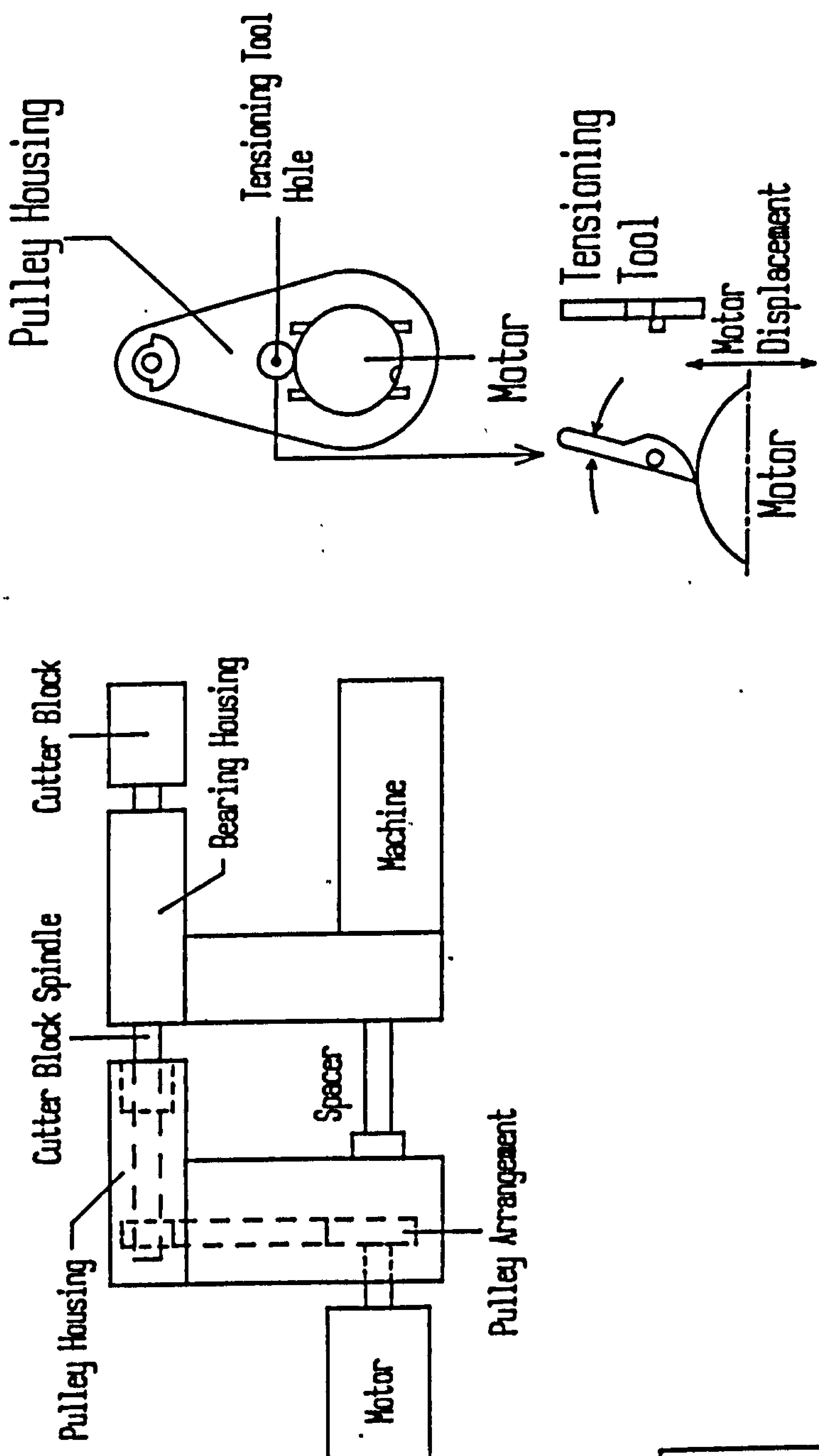
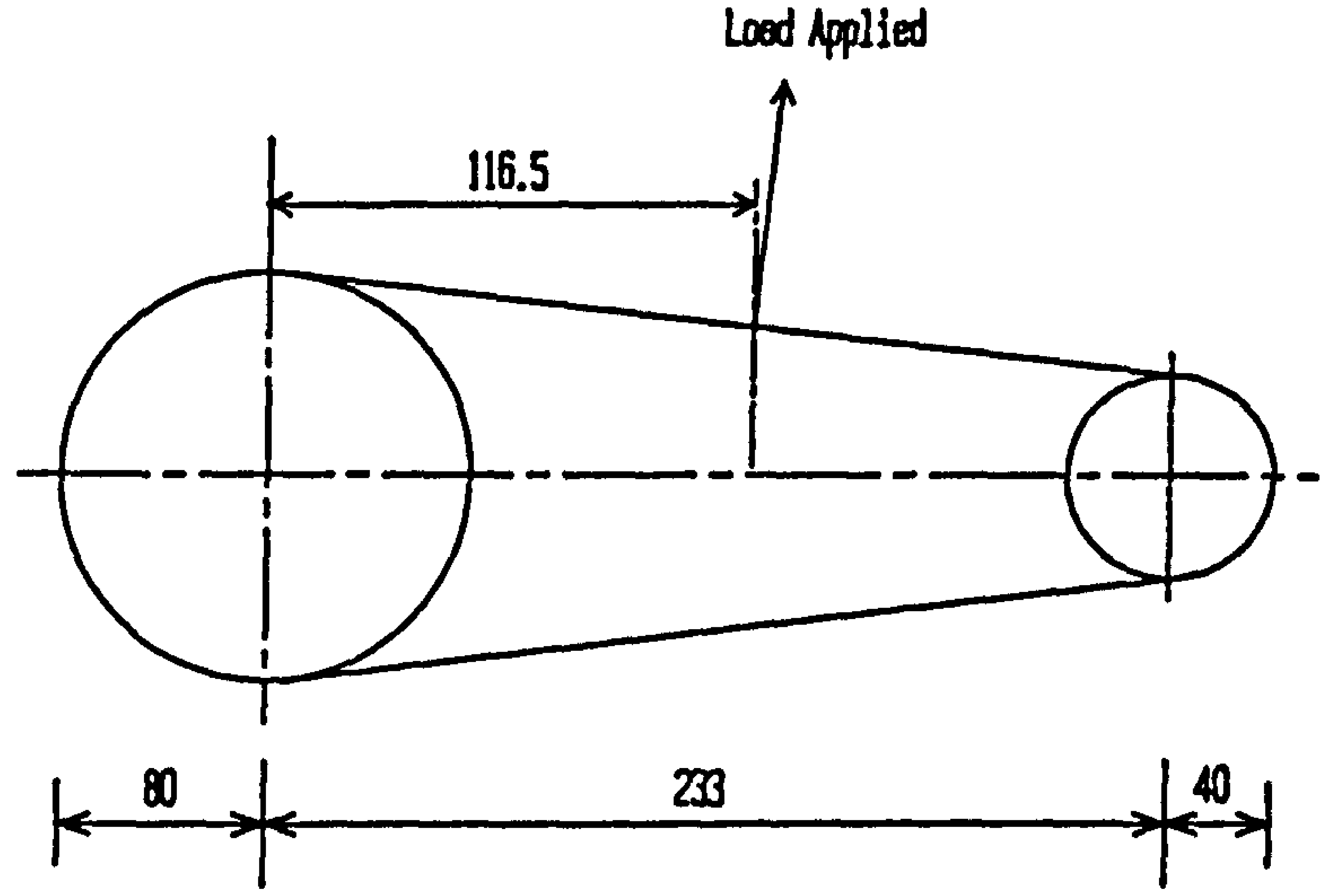


Figure F.1

Belt Deflection



Pulley Belt Deflection Versus Load

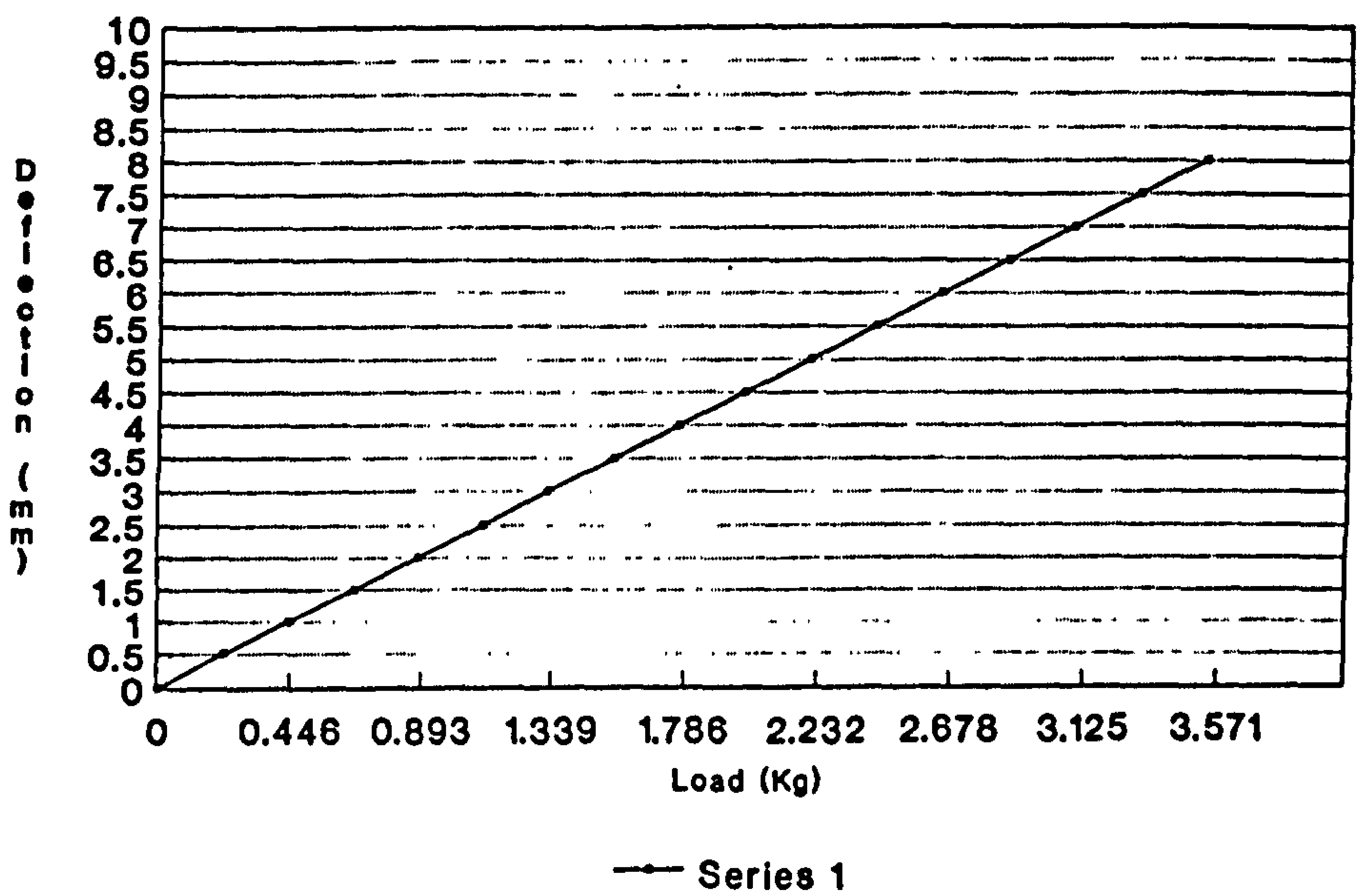


Figure F.2

Testing Arrangement

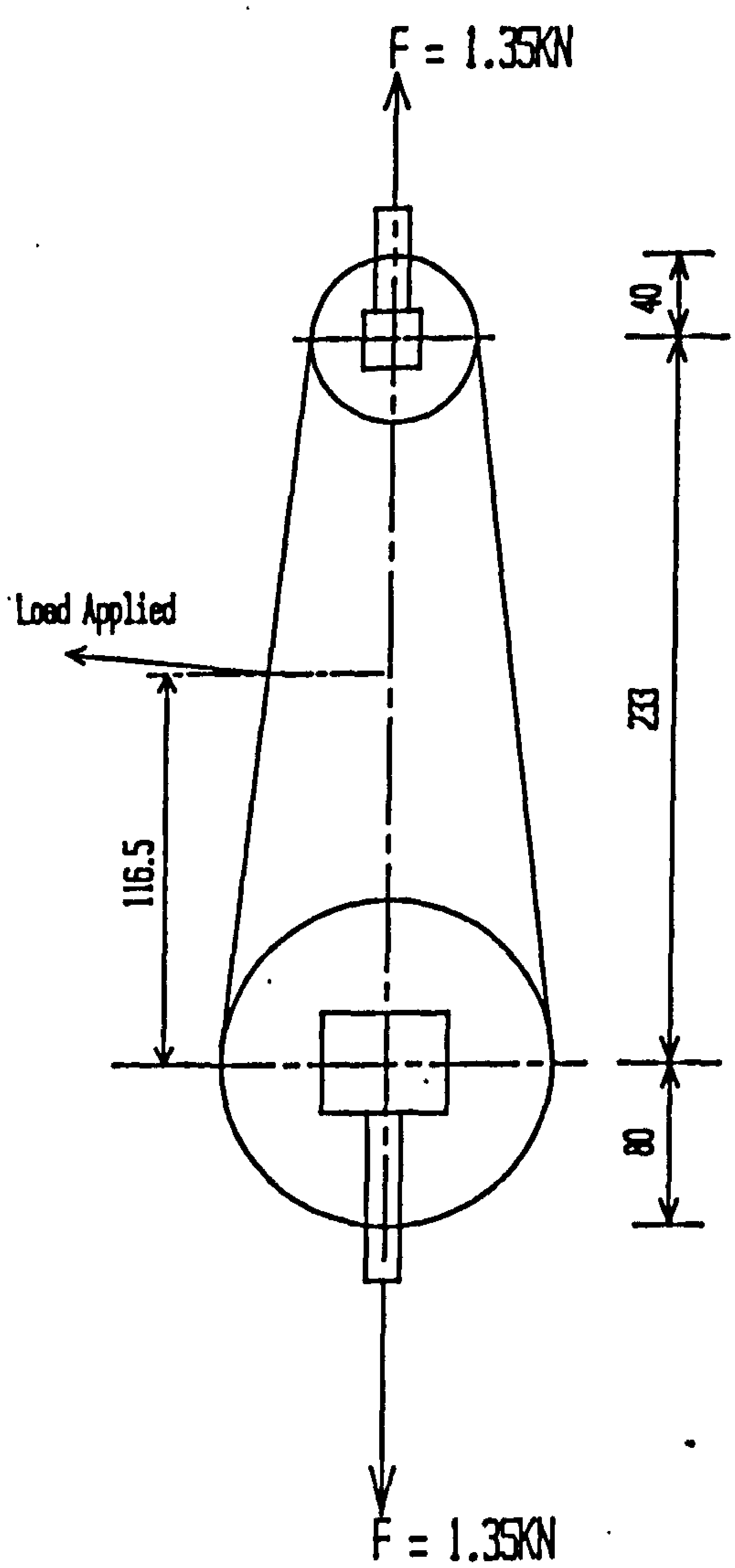
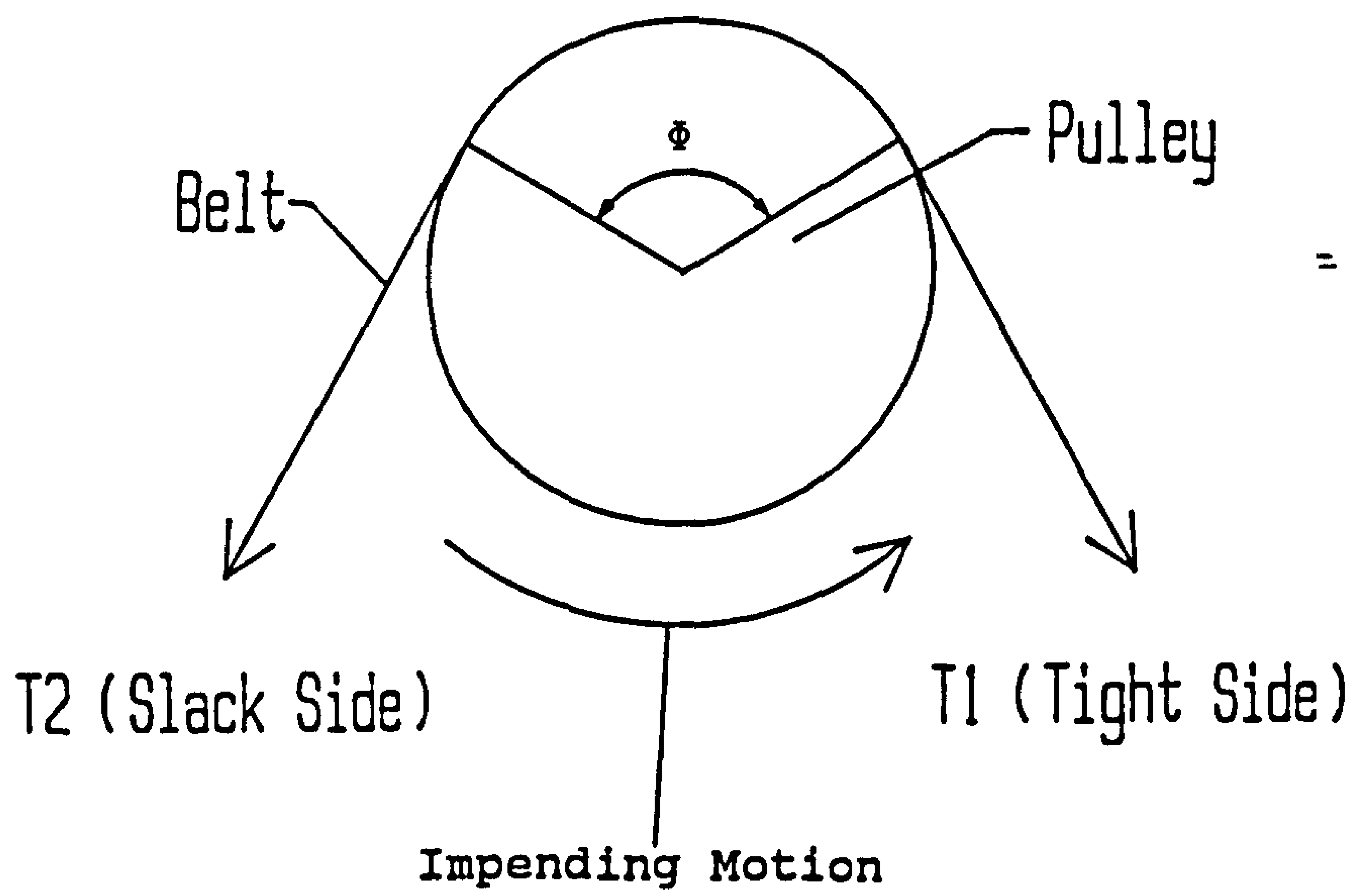


Figure F.3

Belt and Pulley



$$\frac{T1}{T2} = e^{\mu\Phi/\sin\beta}$$

Figure F.4

Experimental Apparatus

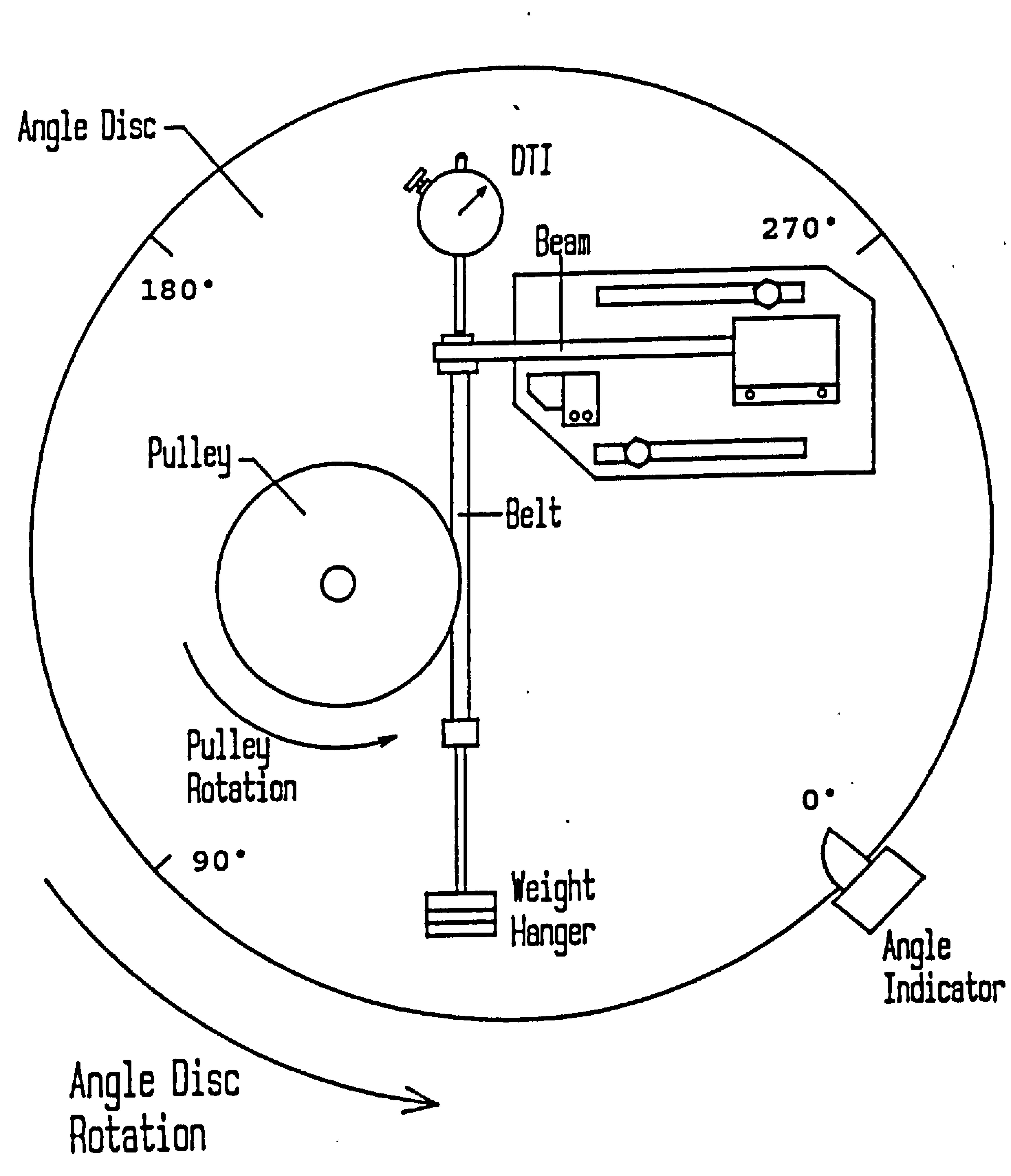


Figure F.5

Cantilever Calibration

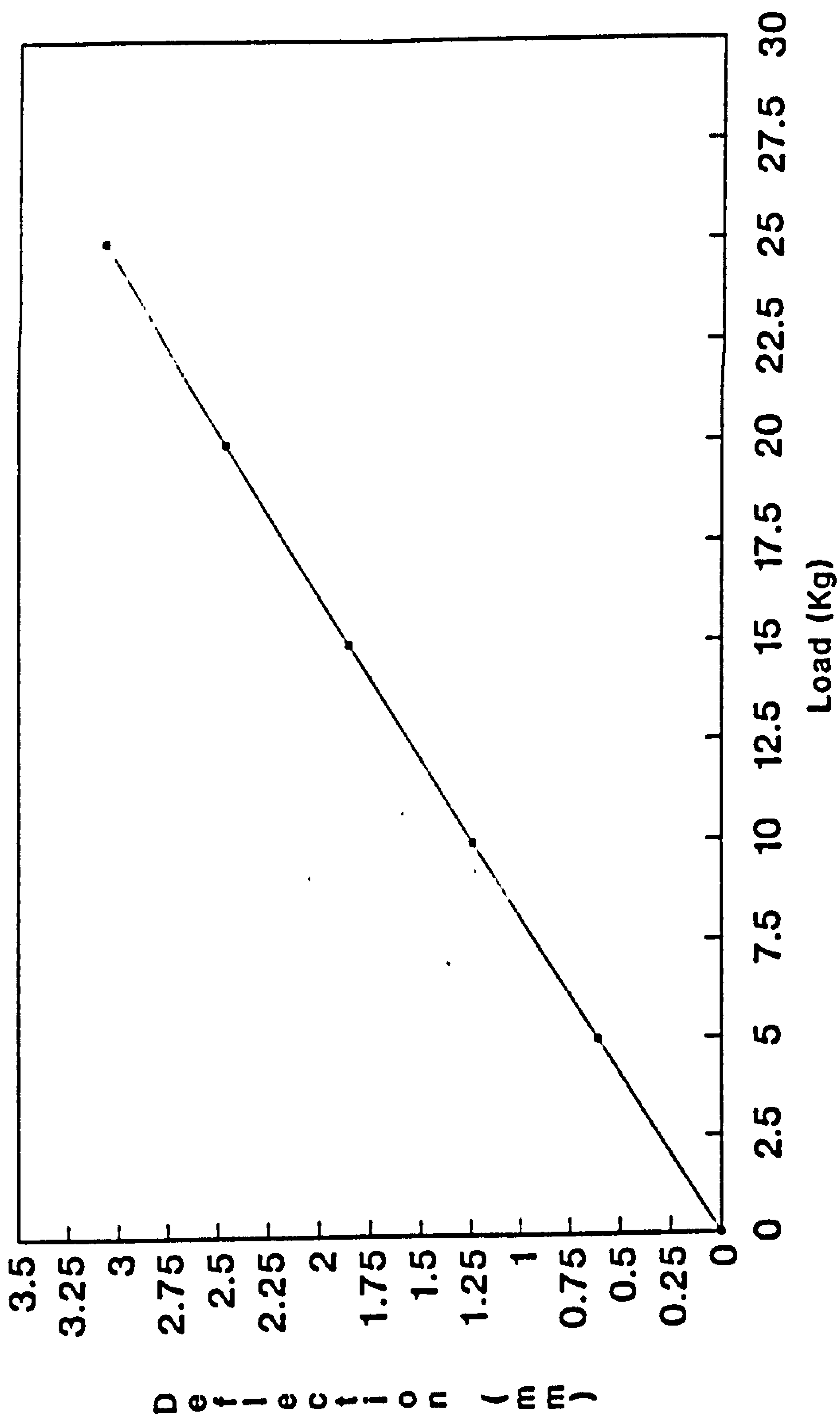


Figure F.6

Tension Ratio

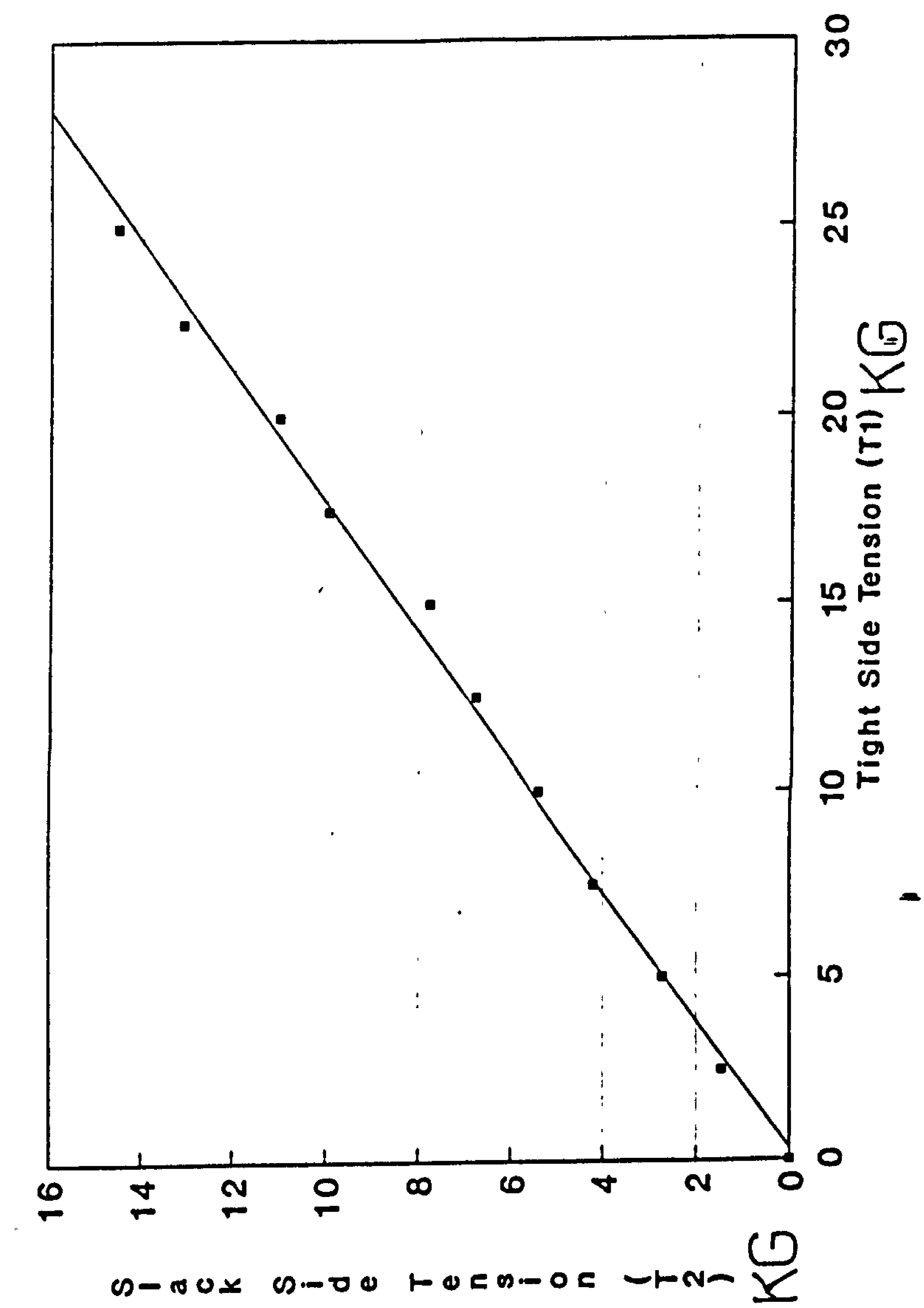


Figure F.7

Slack Side Tension (T2) Versus Lap Angle

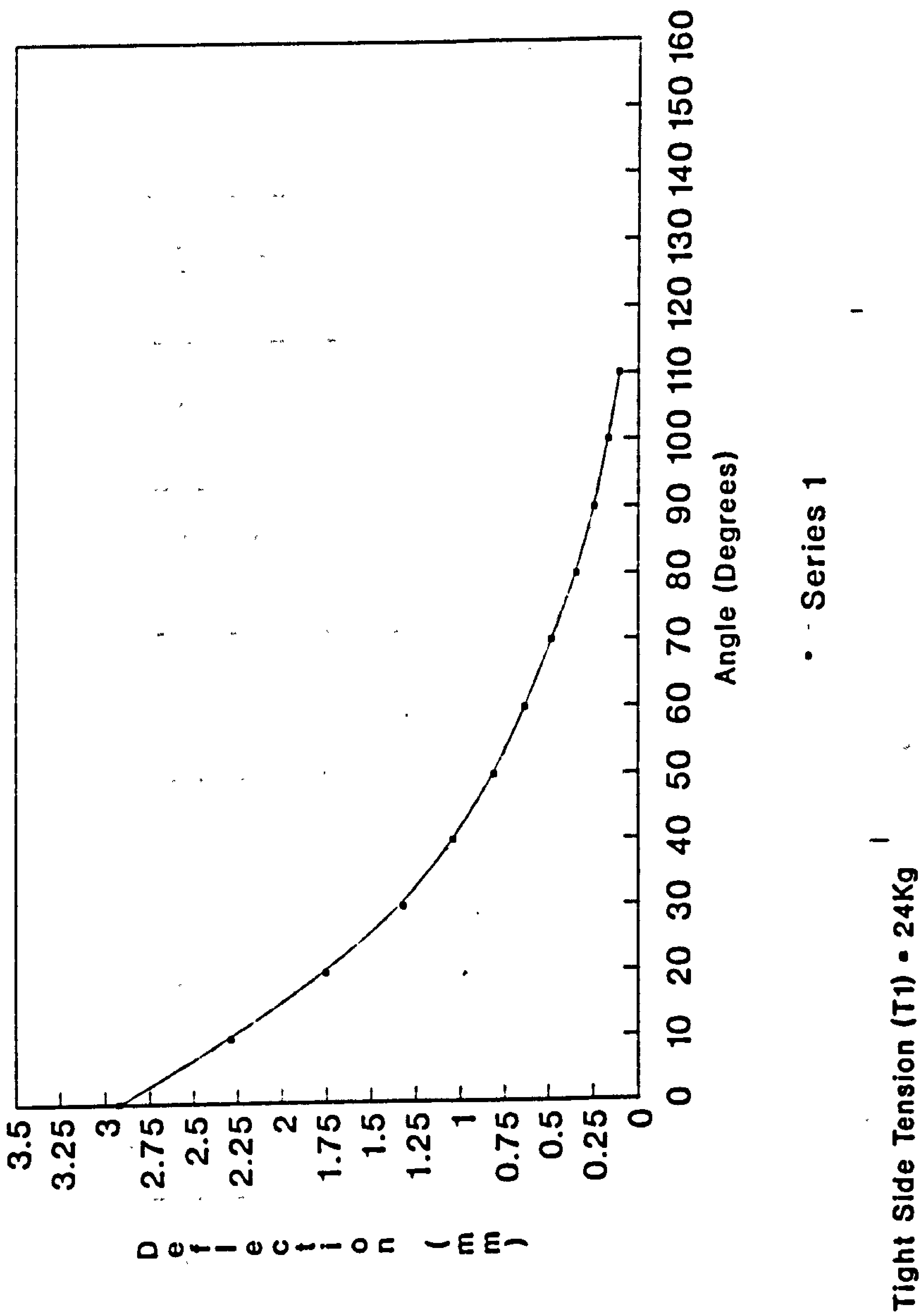


Figure F.8

TABLE F1

Load T1	2.5	5	7.5	10	12.5	15	17.5	20	22.5	25
T2	1.4531	2.713	4.188	5.39	6.797	7.78	9.97	11.03	13.125	14.53
T1/T2	1.7205	1.843	1.7968	1.8553	1.8390	1.9280	1.7553	1.8132	1.7143	1.7206
ln(T1/T2)	0.5426	0.614	0.5823	0.6180	0.6092	0.6565	0.5626	0.5909	0.5390	0.5427
ln(T1/T2) .Sinβ	0.1586	0.1788	0.1703	0.1807	0.1781	0.1919	0.1645	0.1728	0.1576	0.1587
μ	0.4545	0.512	0.487	0.5176	0.51	0.549	0.4712	0.4949	0.4515	0.455

$\mu = \frac{\ln(T1/T2).\sin\beta}{\Phi}$

$\beta = 17°$

$\Phi = 20° = 0.34907$ rads

$\sin\beta = 0.292371704$

NB: T1 and T2 were measured in Kilogrammes

Table F1

TABLE F2

Angle	10°	20°	30°	40°	50°	60°	70°	80°
T1	24	24	24	24	24	24	24	24
T2	18.54	14.172	10.625	8.4156	6.594	5.1953	3.6875	1.9688
T1/T2	1.2945	1.6935	2.2588	2.8518	3.6397	4.6196	6.5085	12.191
ln(T1/T2)	0.2581	0.5268	0.8148	1.0480	1.2919	1.5304	1.873	2.5007
ln(T1/T2) .Sinβ	0.0755	0.1540	0.2382	0.3064	0.3777	0.4474	0.5476	0.7311
Φ	0.1745	0.3491	0.5236	0.6981	0.8727	1.0472	1.2217	1.396
μ	0.4324	0.4412	0.4549	0.4389	0.4328	0.4273	0.4483	0.4491

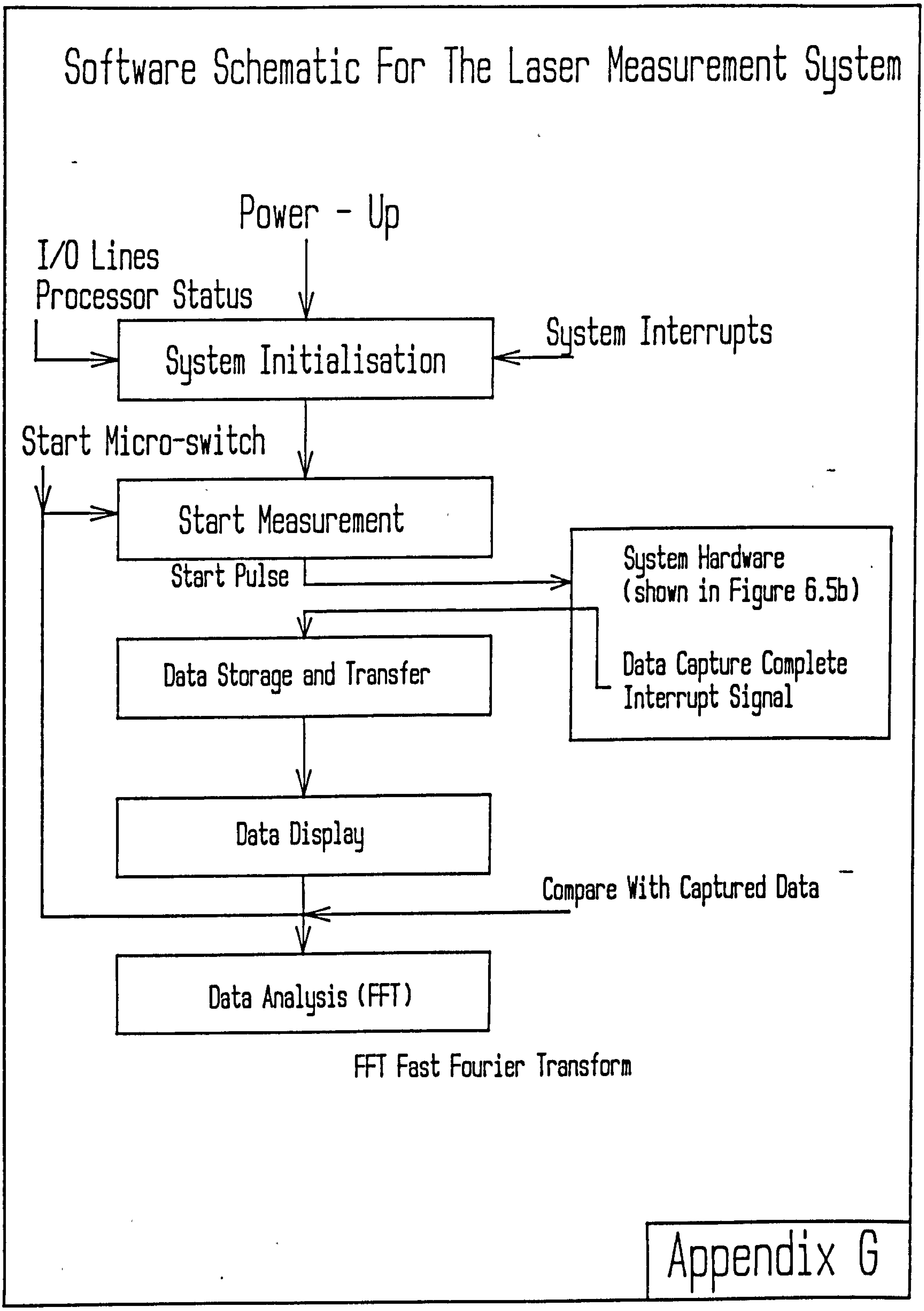
$$\mu\text{average} = \frac{\Sigma \mu}{8}$$

$$\mu_{average} = \frac{35249}{8}$$

$$\mu_{average} = 0.441$$

Table F2

Appendix G


Software Schematic For The Laser Measurement System
Power - Up
I/O Lines
Processor Status
System Initialisation
System Interrupts
Start Micro-switch
Start Measurement
Start Pulse
System Hardware
(shown in Figure 6.5b)
Data Capture Complete
Interrupt Signal
Data Storage and Transfer
Data Display
Compare With Captured Data
Data Analysis (FFT)
FFT Fast Fourier Transform
Appendix G

Appendix H

The Use of In-Process Surface Topography Measurements as a Predictor of Machine Performance and Condition.

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R. Parkin B.Sc, PhD, CEng, MIEE, MIMechE
K. Maycock B.Sc

Leicester Polytechnic School of Engineering and Manufacture
Department of Mechanical and Production Engineering

Abstract

As manufacturing industries become progressively automated emphasis is increasingly placed on machine or process control. To this end research work presently under way at Leicester Polytechnic has concentrated on an automatic surface monitoring system for in-process production control.

Recent woodworking machinery has achieved large increases in material feed rates and cutter head spindle speeds. Typical spindle speeds of modern machinery is in the region of 6000 rev/min. For high quality machined components, spindle speeds of 15000 rev/min (max) are required with multi knife cutter head assemblies.

Advancements in technology contribute dominantly to the high production rates and associated component quality which can now be produced. However, the adoption of technology has brought with it some undesirable and expensive problems. As the quality of the process is reflected in the surface finish of the artifact, and production rates are very high, the development of a non-contact surface monitoring system is examined.

Consideration is given to machine vibration origins, with correlation of specific topographical anomalies to machined surfaces. Prediction software and Fourier analysis have been used to attain encouraging results from machinery exhibiting known operational parameters.

Background

Manufacturing industries are becoming increasingly automated, using complex computers for the control of production processes and machinery (Ref 1). However, the processes and machines still propagate functional vibrations to the components under production. The period and energy content of the inherent cyclic undulations, when analysed, build up a frequency signature which is representative of characteristic operational conditions.

The repetition and amplitude of generated vibrations are usually unique for individual machines. However a machine vibration frequency spectrum can generally be predicted when analysing the design specifications. Distinctive periodic peaks, present within resultant frequency spectra, can be detected and, usually, associated with specific system mechanisms. Important, machine related, period information can be utilised as a basis for machine condition evaluation.

Machine vibration can be segregated into low, medium and high frequency ranges, dependent on origin. Usually large periodic oscillations are produced from such mechanisms as out of balance rotating masses, misalignments or bent shafts. Medium range undulation components such as meshing gears within gearboxes give rise to multiple shaft revolution frequencies. Short wavelength fluctuations generally originate from areas such as rolling element bearings.

Vibration Origins

A rotating system and resultant frequency spectrum can be seen in Figure (1) illustrating the origins of typical periodic undulations. Point A on the spectrum identifies a spectral peak produced from an out of balance; this type of fault appears at shaft revolution frequencies. Point B (Figure(1)) correlates the spectral crest to gear teeth meshing. The frequency of tooth mesh corresponds to rotational speed multiplied by the number of teeth located on the gear. As imperfect rolling action (sliding due to wear), loading and deflection (dependent on the number of teeth in mesh) vary, then higher harmonics, in addition to the tooth meshing frequency, are present (Figure (2)).

If local incipient faults such as a cracked (but not fully broken) tooth occurs on a gear wheel, then the resultant time and frequency spectra are affected. The damaged tooth will deflect more in mesh altering normal operational vibration characteristics as shown in Figure (3a). The affect of a single cracked tooth in the time domain signal is that of a healthy, or maybe worn gearbox signal with a series of superimposed pulses upon it. This type of local fault generates low level sidebands in the frequency domain spectrum (Figure(3b)). As this type of fault propagates (i.e. several faulty teeth in mesh) then the periodic characteristics alter (Figure (4a)). An amplitude modulated effect transpires transforming the time domain signal. The effect of this change in the frequency domain being an increase in the sideband amplitudes (Figure(4b)).

Point C of Figure (1) represents a typical defect frequency generated from rolling element bearings. There are several defects possible within rolling element bearings (Figure (5a)). Faults such as cracks or blemishes (corrosion pits) can develop on either of the bearing races or even on the rolling elements themselves. If a fault occurs on the surface of the outer race (outer race fixed) then small amplitude impulses arise every time a rolling element passes over the affected area. The amplitude of these impulses are constant (Figure (5b)), with frequency rates as indicated in Figure (6). If an imperfection arises on the surface of the inner race (rotating race), then the resultant energy impulses vary in amplitude with the changes in rolling element load (Figure (5c)). In both cases the energy impulses are transmitted to the bearing housing, which in turn vibrates at its natural frequency.

As vibration origins can be identified using machine frequency spectra, it is possible to monitor machine status. Transitions between initial "healthy" and eventual worn or failed machine spectra can be recorded. As the operation time of the system increases and the frequency spectrum alters, thresholds can be established on required operating conditions. The thresholds imposed can be used to initialise planned preventative maintenance work, before eventual failure occurs.

As incipient operational vibrations can, and are, transferred to the workpiece, analysis of the machined commodity surface can provide (using suitable measurement/monitoring facilities) important machine operating status information.

The Process

This paper will investigate planed and spindle moulding of wooden artifacts. The woodworking industry desperately requires a reliable method by which to quantify and categorise the surface quality of its planed and spindle moulded products. The current practice is that of visual tactile inspection, which results in a wide variance in what is classed as an acceptable or defective surface finish; what one manufacturer may reject as an unacceptable standard, another may accept as "good". These methods, by their very nature, are subjective and restricted to post process applications.

Woodworking machinery has unique problems due to high speeds of operation. Modern woodworking machines "extrude" timber at extremely high rates, often in excess of 140 m/min. To achieve these rates, high cutter head rotational speeds are used (up to 15000 rev/min) resulting in high levels of noise and vibration with attendant risk of machine bearing failure. Thus if the process develops a fault; eg, blunt cutters, imbalance, then a considerably large quantity of sub standard (defective surface finish) timber can be produced before the symptoms are detected. It is evident, due to these operational speeds, that non-contact sensors capable of monitoring the quality of the product require development.

The planed and spindle moulding process is comparable with the milling of metals in the up cutting mode (Figure (7)). Although these operations are analogous, there are some fundamental differences. The major discrepancy is that milled components are firmly clamped to the machine bed, while the bed is traversed past the cutting head. With planing and spindle moulding, the bed and the cutter heads are fixed and the workpeice is traversed using pressurised feed rollers (Figure (8)). Also material machining speeds are extremely high when compared to the milling process.

Because the cutting circle diameter used on planing machines is relatively large (typically 200mm), the depth, h (Figure (9)) of each cusp, produced on the surface of the product, is of the order of a few microns. Due to the surface amplitudes being small, height variations, as such, are undetectable by the naked eye. Investigations (Ref 2) have shown that it is the consistency with which the apexes repeat that affect the aesthetic qualities of the machined surface. It is then surface wavelength, or periodic beat, information that is essential for product evaluation by the manufacturer.

Surface Finish

As faults develop within the system, the surface contours generated on the artifact depart from the ideal. This departure contains information regarding the corresponding anomalies. As machine faults develop, changes in the sur face parameters may be analysed to predict the mechanism of the defect. The defects may be either slow moving trends or catastrophic in nature

If machine cutting conditions were ideal, with all operational factors known, the profile of the resultant manufactured surface would be that shown in Figure (10). The profile would consist of knife traces (arcs), detailed A_1 to A_n, with corresponding arc radii R_1 to R_n. The origin of each arc being separated by a theoretical feed pitch per knife (identical wavelengths (Ref 3)). However, in practice, the ideal is rarely achieved; vibration, spindle dynamic imbalance, proud knives, etc all affect the cutter locus and hence surface profile. The greater the level of vibration, dynamic imbalance,etc the further the surface departs from the ideal. A more typical profile of a planed surface is shown in Figure (11). With a single knife finish the displacement (δ) of the cutter head occurs every two revolutions of the cutter head (2P). With a total head displacement of (2δ) between the theoretical feed pitch (P), an imperfect surface profile results. Instead if identical wavelengths of (P) (ideal surface profile), the wavelengths of arc A_2 and A_3 are in fact equal to;

$$(P+(4R\delta/P))$$

and

$$(P-(4R\delta/P))$$

respectively (Ref 4). Where (R) is the radius of the cutter head and (δ) is the instantaneous cutter head displacement.

This type of effect could be generated if an out of balance drive motor pulley was run at half the angular velocity of the cutter head spindle (2:1 pulley ratio). Amplification of the drive motor pulley imbalance, due to structural resonance, could create significant cutter head displacement.

As machine setup and operational conditions vary widely, it is evident that many surface contours are achievable on the product. With the realisation of this phenomenon, two stages of research were undertaken. Initially simulation software was written, for the prediction of surface profiles obtainable on moulding machines exhibiting known operating conditions. In conjunction with this research, an opto-electronic non-contact, in-process surface measurement/monitoring system was developed.

Surface Simulation

Extensive software has been developed which explored the geometric trochoidal relationship between the cutter locus and the workpeice traverse. All practical operating conditions, such as out of balances, proud knives, revolution effects, etc were incorporated within the software.

The programs allowed Fourier analysis of the simulated data, for data conversion from the time domain to that of the frequency domain (wavelength being essential surface information). Real data, gathered from the optical measuring system and a more classical stylus system (contact, post process), could also be processed by the software to establish the frequency content of real surface data. With the whole process accurately modelled the simulation software could be used to predict machined surface profiles. The accuracy of the model was evaluated against the existing surface measurement systems and the novel opto-electronic surface measurement system mentioned previously. The results and comparisons of the simulated data are discussed and illustrated later with correlation to the advanced opto-electronic surface measurement system.

Optical Surface Measurement System

Objective

The foregoing discussion clearly indicates the requirement for a fast-response non contact, method of measuring the surface quality of machined timber; an integral part of this requirement is the determination of parameter(s) which can readily indicate and identify defects.

The "non-contact-rapid-response" nature of light, coupled with recent advances in laser and opto-electronic technology, has brought about interesting and new possibilities for in-process assessment of product quality.

Realisation

Previous work has investigated certain types of machine faults that give rise to identifiable surface waveforms on produced timber (Ref 5).The monitoring system has been designed to measure the surface characteristics of the wooden component in-process. Figure (12) represents the basis of the in-process measurement system. A broad laser beam illuminates the machined surface at grazing incidence ($\theta < 1.5°$). The illumination is in the same plane as the traversing workpeice, which gives prominence to the leading slope faces of each surface cusp. A fringe pattern of bright and dark regions is readily observed representing the surface slope along the product.

A single element silicon photo diode is used to detect variations in diffusely reflected surface laser light as the timber passes from the machine. Automatic gain control and signal conditioning circuitry is used to amplify and filter the output voltage of the photo diode to give maximum dynamic range to the analogue to digital conver

tor. The sampled output voltage of the photo diode is synchronised using the output of a rotary position encoder, as the system clock for the analogue to digital convertor. Additional electronics control the clock signal

for correct read/write operations and memory sequencing. As soon as the periodic surface information has been captured (in real time) in the computer memory, it can be analysed in terms of its frequency content, using Fourier Analysis Techniques. The data captured is not prone to distortion due to vibration, as the plane of vibration is almost perpendicular to the illumination. As the laser beam is broad and of grazing incidence to the surface the vibration levels do not exceed the outer limits of the beam. This phenomenon only occurs because diffuse and not specular reflection is being monitored.

At present, actual material throughput is in the region of two to two and a half metres per second. The new system has been designed to cope with a maximum material movement of five metres per second, thus allowing increased capacity as machine operating conditions improve. The system is capable of monitoring wavelengths of one millimetre and greater (one millimetre being a very fine planed surface suitable for furniture manufacturers requirements).

Results

Figure ((13)a,b,c) show the resultant surface profiles and associated frequency spectra of a machined surface, obtained using a Talyrond, the novel laser monitoring system and simulation software respectively. Figures (14) and (15), in the same manner, show other machined surfaces. To obtain the results in Figure (13), the responsible ma chines cutter head was set up containing six knives and was run at six thousand rev/min. With a material feed speed of ninety metres per minute and a deliberate out of balance effect generated at knife number three (added weights), Figure (13b) was recorded using the laser system.

With a sample length of one hundred and twenty five millimetres and one hundred and twenty eight frequency harmonics shown; wavelengths of one hundred and twenty five millimetres down to approximately one millimetre can be represented. The dominant frequency harmonics present in Figure (13b) are numbers ten and nineteen (12.5mm and 6.58mm wavelengths). These peaks are caused by the out of balance effect and individual cutter head knife markings of the process. Because the out of balance effect occurs once every revolution of the cutter head it would be expected for the frequency harmonic to be approximately number eight or nine with these specific operating conditions. It would take 0.833 seconds to pass one hundred and twenty five millimetres of material, through the machine, at a feed rate of ninety metres per minute. With a cutter head speed in the order of six thousand rev/min there would be approximately eight and one half revolutions within the sample length. In fact from Figure (13b) it can be seen that there are ten revolutions present. This small discrepancy is due to inaccuracies arising from the feed and cutter head speed equipment. As there is an out of balance effect, the knife marks vary in surface wavelength, thus in the frequency spectrum the knife marks are spread over several rather than a single harmonic (eg harmonic numbers 10, 19, etc).

Figure (14) shows similar conditions as that in Figure (13). Here again there is a deliberate once per revolution effect caused on a four knife cutter head. In this instant the feed speed of the machine (eighteen metres per minute) is much slower, but the cutter head speed of six thousand rev/min remains the same. The effect of the slow feed speed on the surface is the translation of the out of balance dominant frequency along the frequency spectrum (Higher frequency due to slower moving feed material). A second effect being the smoothing of knife marks on the surface, which is indicated in the frequency spectrum due to a lack of other higher dominant frequency harmonics.

Figure (15) shows a single knife finish surface. This surface was obtained using a four knife cutter head with three of the knives used as balancing masses only. With no out of balance effect present, the dominant frequency in the frequency spectra is now due to the cutter knife marks on the surface. With a feed speed of eighteen metres per minute it would take 0.416 seconds to pass one hundred and twenty five millimetres of timber past the cutter head. Again with a six thousand rev/min cutter head there would be 41.6 revolutions of the cutter head (with a single knife this would be 41.6 identical knife marks) in the sample length. As shown in each of the frequency spectra the dominant harmonic is number forty five (wavelength of 3mm). This small discrepancy resulting again from feed and cutter head equipment inaccuracies.

Conclusion

This paper has discussed typical vibration origins of machines and the effects they have on the surface of the manufactured component. Prediction software as well as non-contact measuring/monitoring hardware has been developed to control the quality of the artifacts and the process. Good correlation between existing surface measuring systems (Talyrond) and the novel laser measurement system has been obtained using harmonic analysis. This comparison has been achieved using a Fast Fourier Algorithm to convert real time surface data to the frequency domain. Faults such as corrosion pits or cracks on bearing races or gears will be present at higher harmonics of the frequency spectra. Future work regarding the frequency spectra of trend or catastrophic failures is required for correct initialisation of feedback action.

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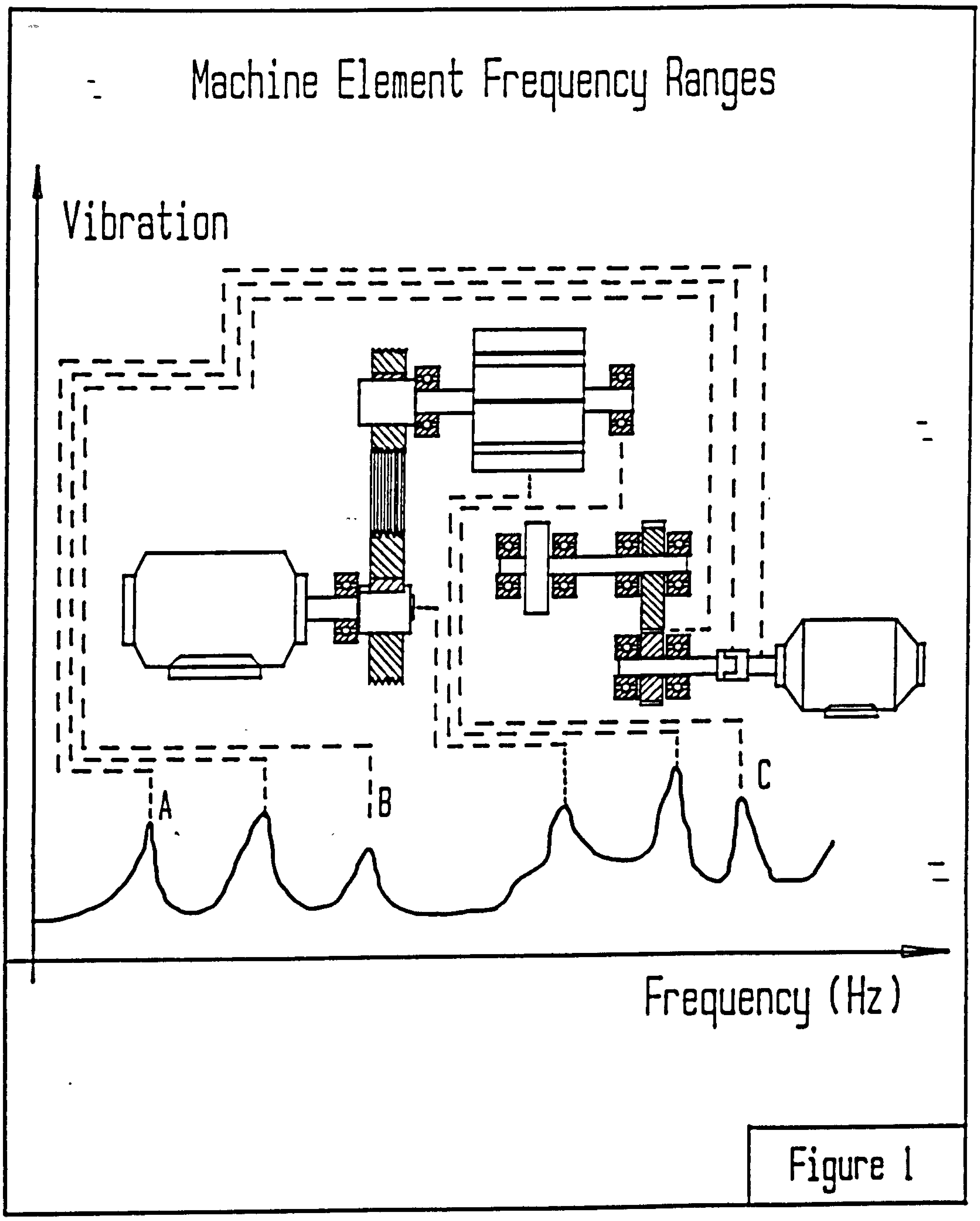

Machine Element Frequency Ranges
Vibration
A
B
C
Frequency (Hz)

Figure 1

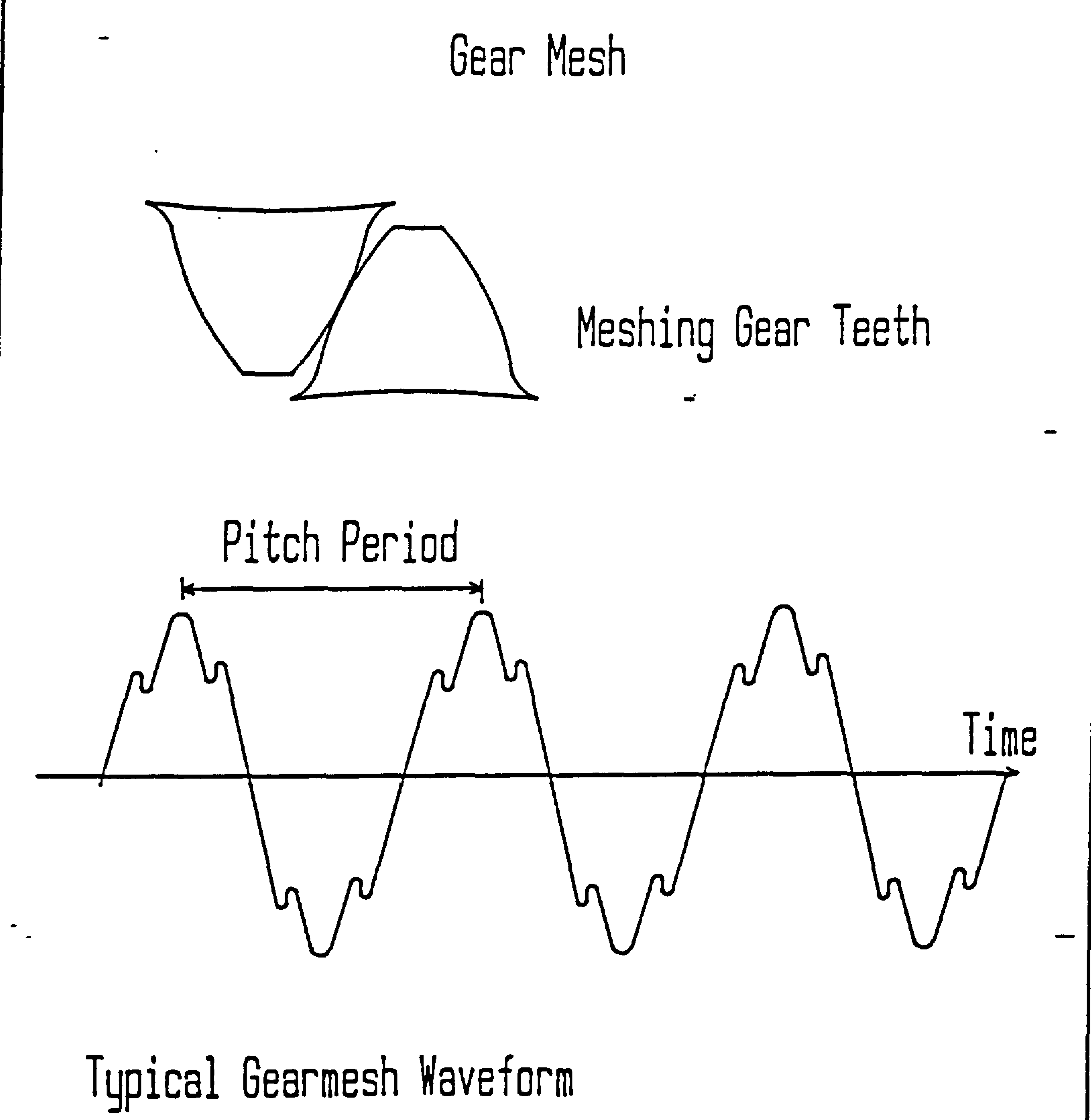

Gear Mesh
Meshing Gear Teeth
Pitch Period
Time
Typical Gearmesh Waveform

Figure 2

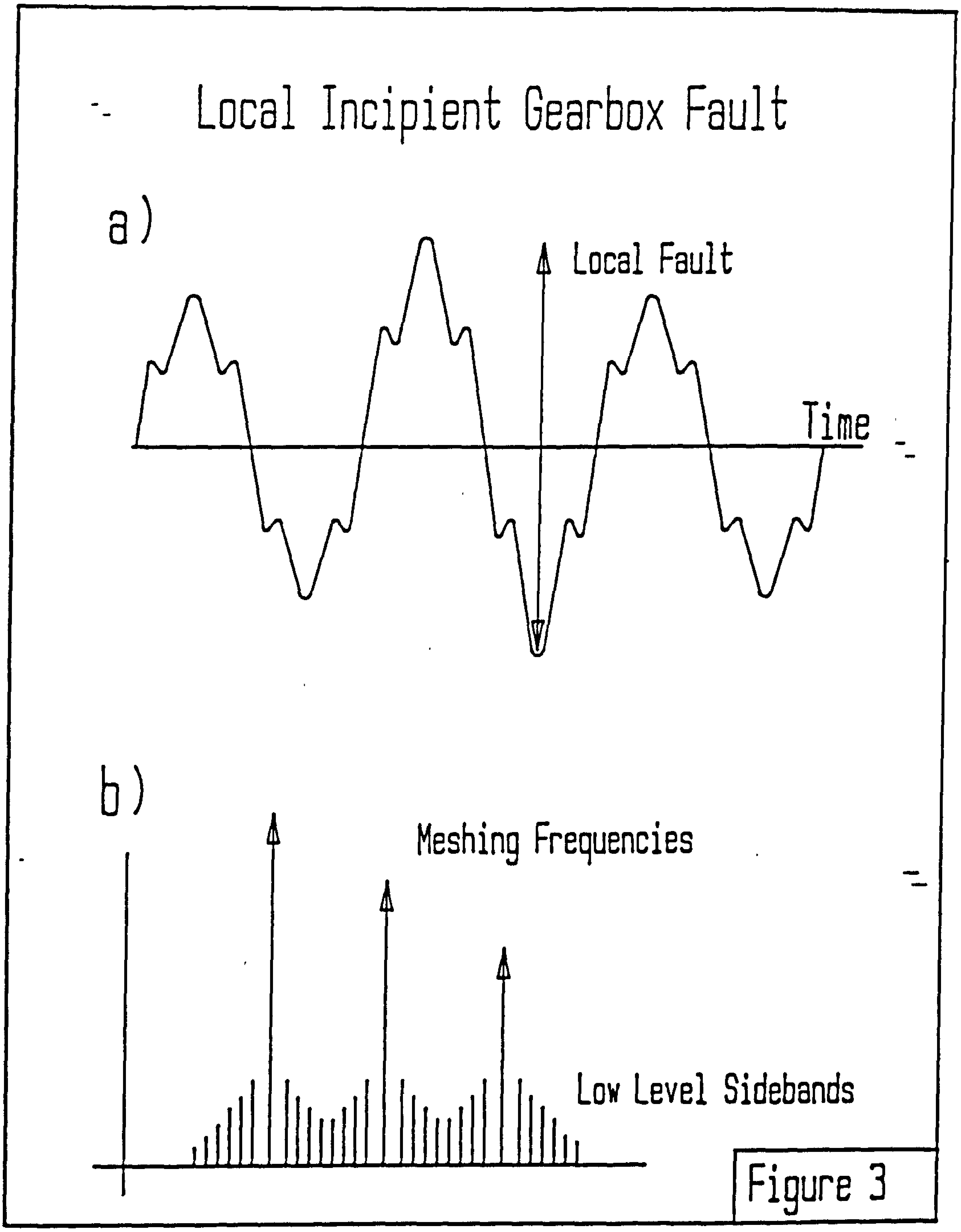

Local Incipient Gearbox Fault
a)
Local Fault
Time
b)
Meshing Frequencies
Low Level Sidebands

Figure 3

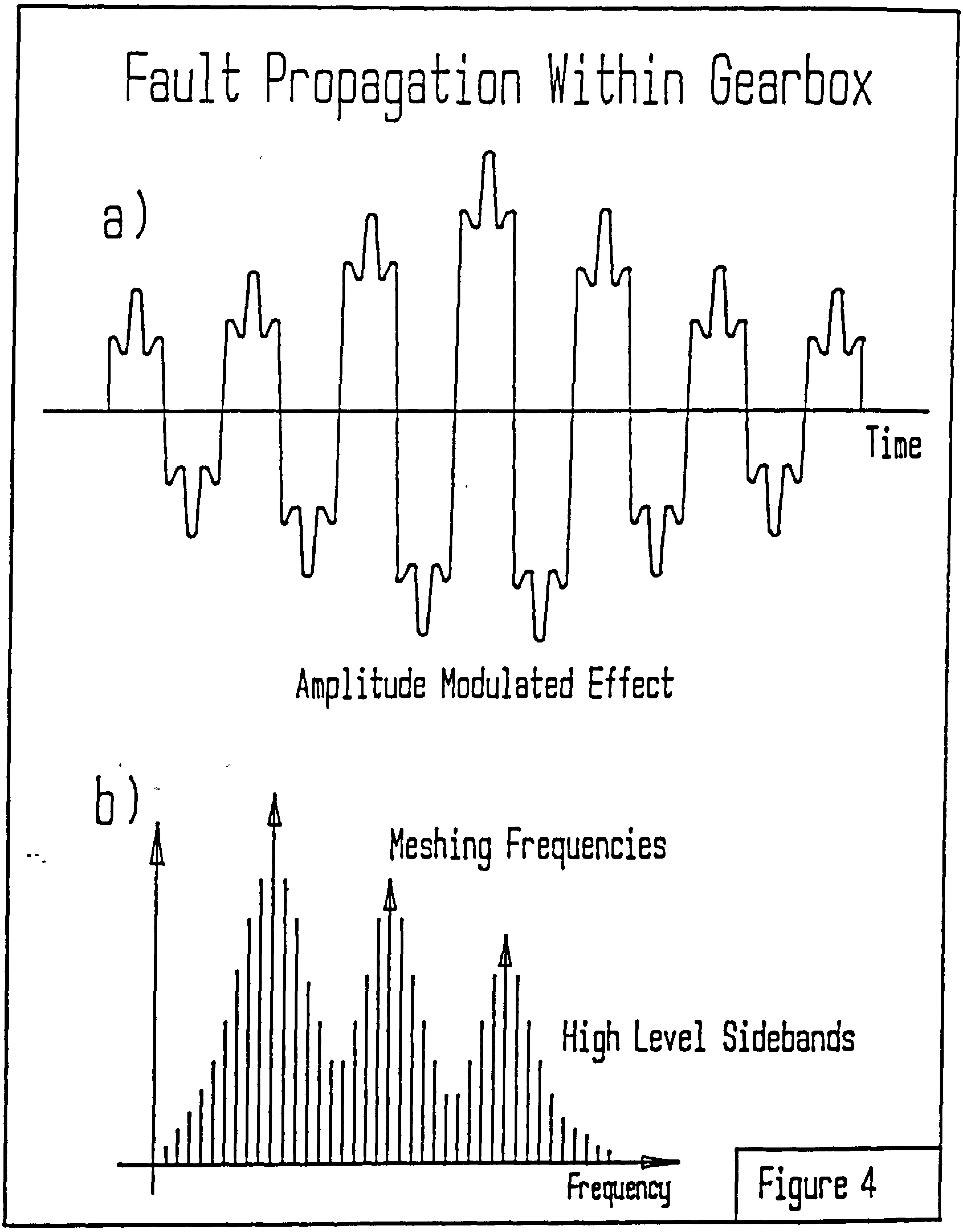

Fault Propagation Within Gearbox
a)
Time
Amplitude Modulated Effect
b)
Meshing Frequencies
High Level Sidebands
Frequency

Figure 4

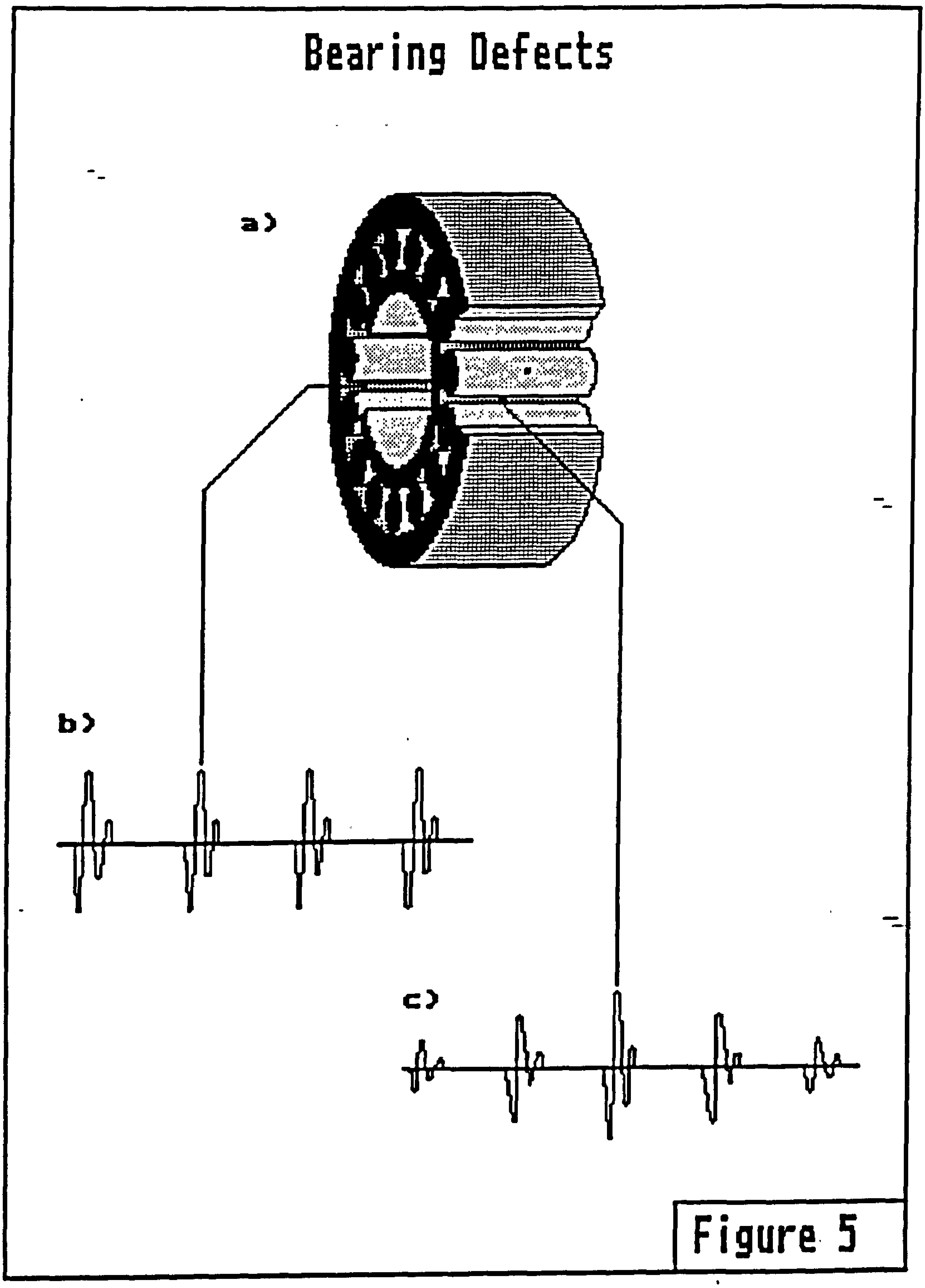
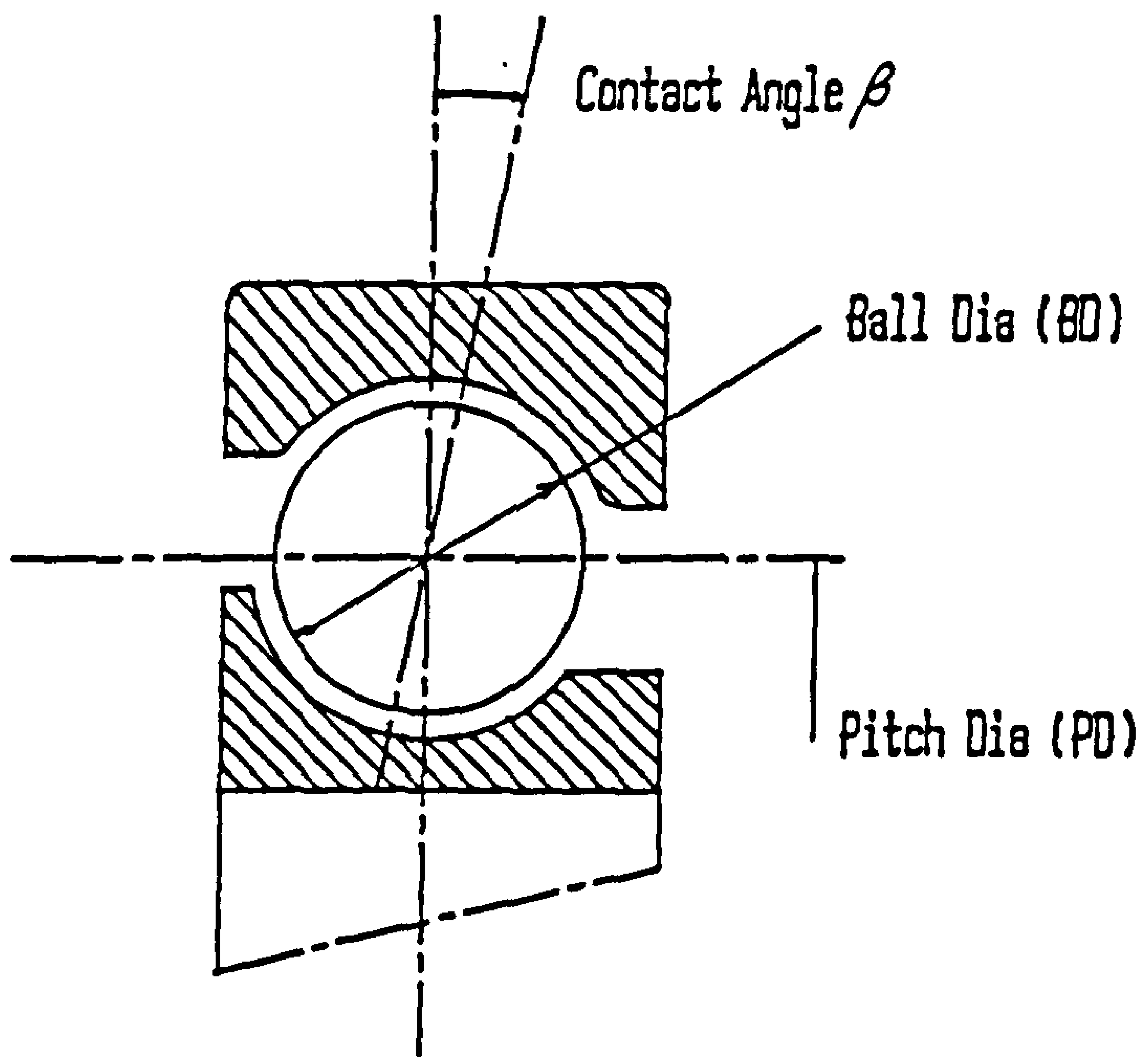


Figure 5

Rolling Element Bearing Frequencies

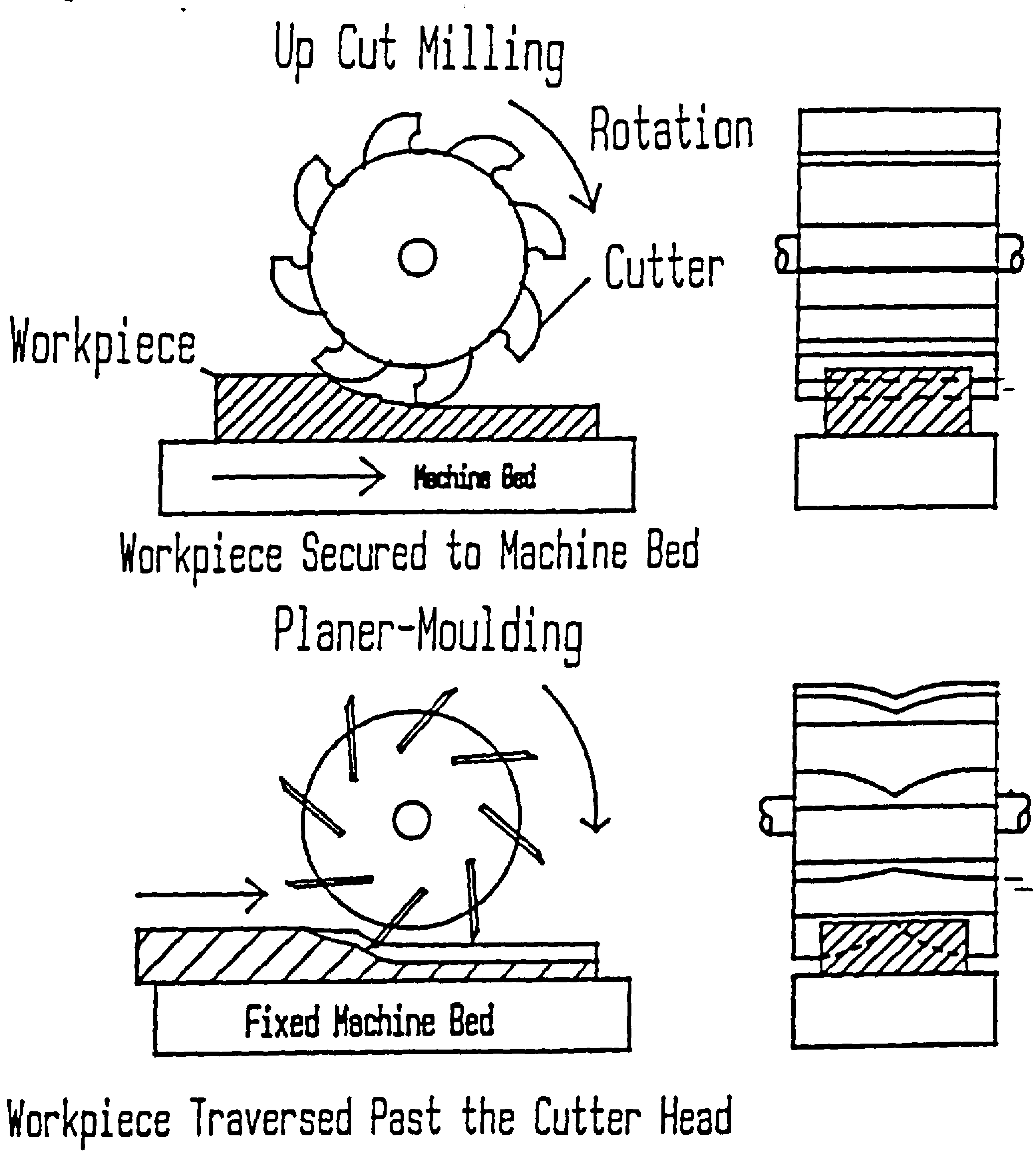


N = Number of Balls or Rollers
1 = Relative rev/s Between Inner and Outer Races

Impact Rates f(Hz) (assuming pure rolling motion)

For Outer Race Defect: $f(Hz) = N/2\ 1(1-(BD/PD)\cos\beta)$
For Inner Race Defect: $f(Hz) = N/2\ 1(1+(BD/PD)\cos\beta)$
For Ball Defect: $f(Hz) = (PD/BD)\ 1(1-((PD/BD)\cos\beta))$

FIGURE 6



Moulding Process Showing Single Cutter Head

Figure 7

4 Head Planer - Moulder

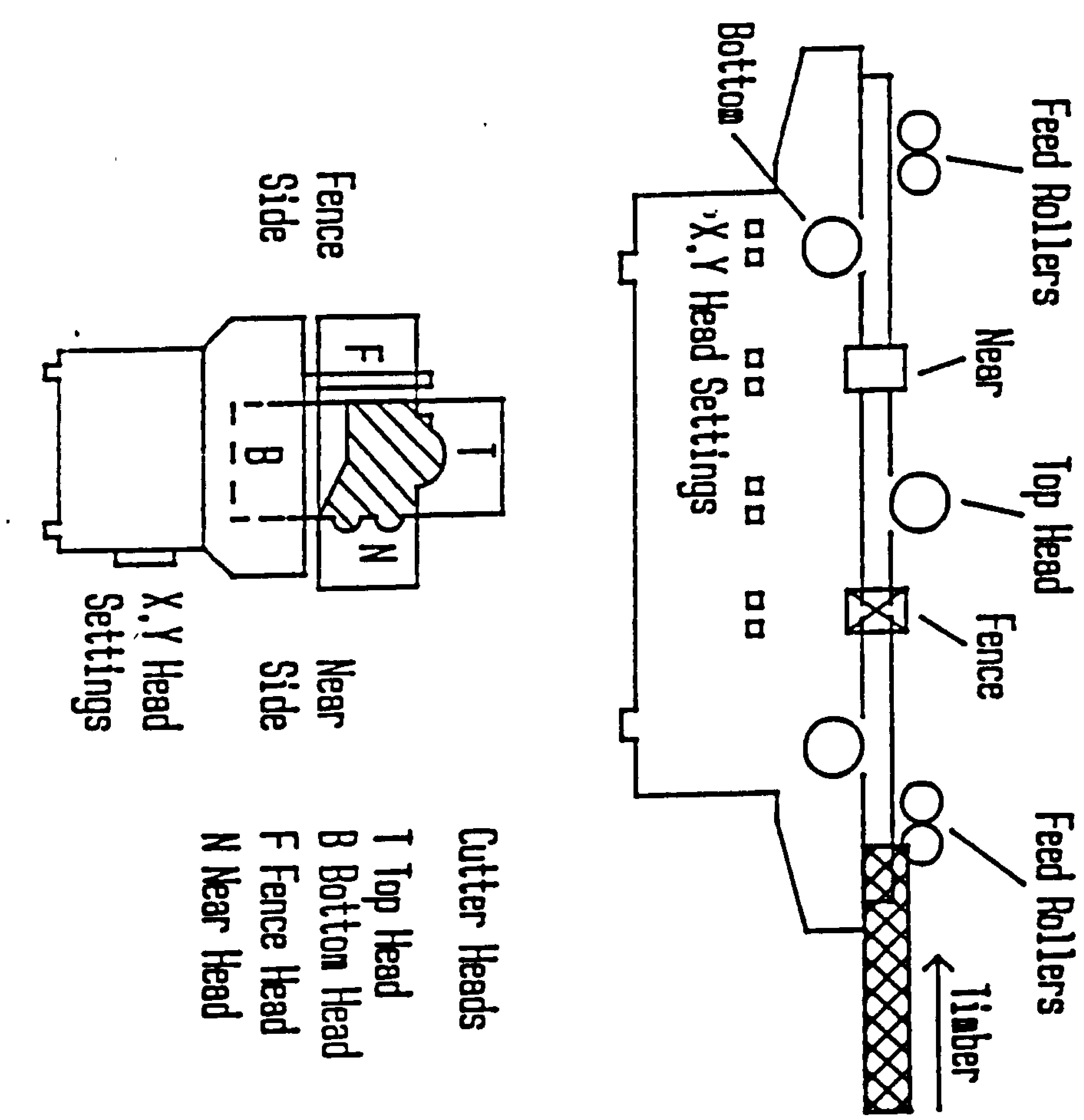
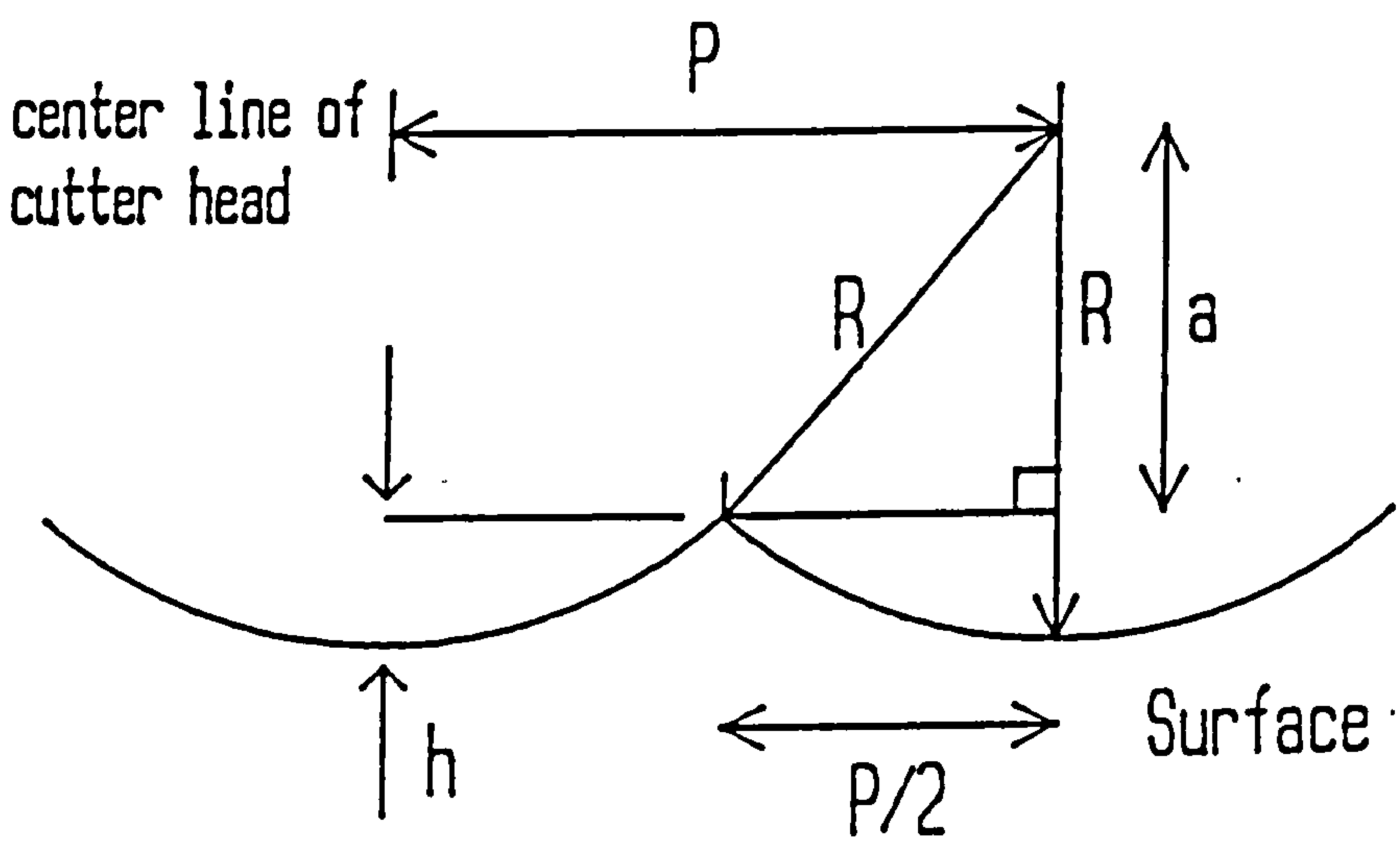


Figure 8

Surface Profile Height and Pitch



$$a = R - h$$

$$a^2 = R^2 - (P/2)^2 \qquad P = (f.\ 10^3)/nN$$

$$a = (R^2 - (P/2)^2)^{1/2}$$

$$h = R - a$$

$$h = R - (R^2 - P^2/4)^{1/2}$$

Figure 9

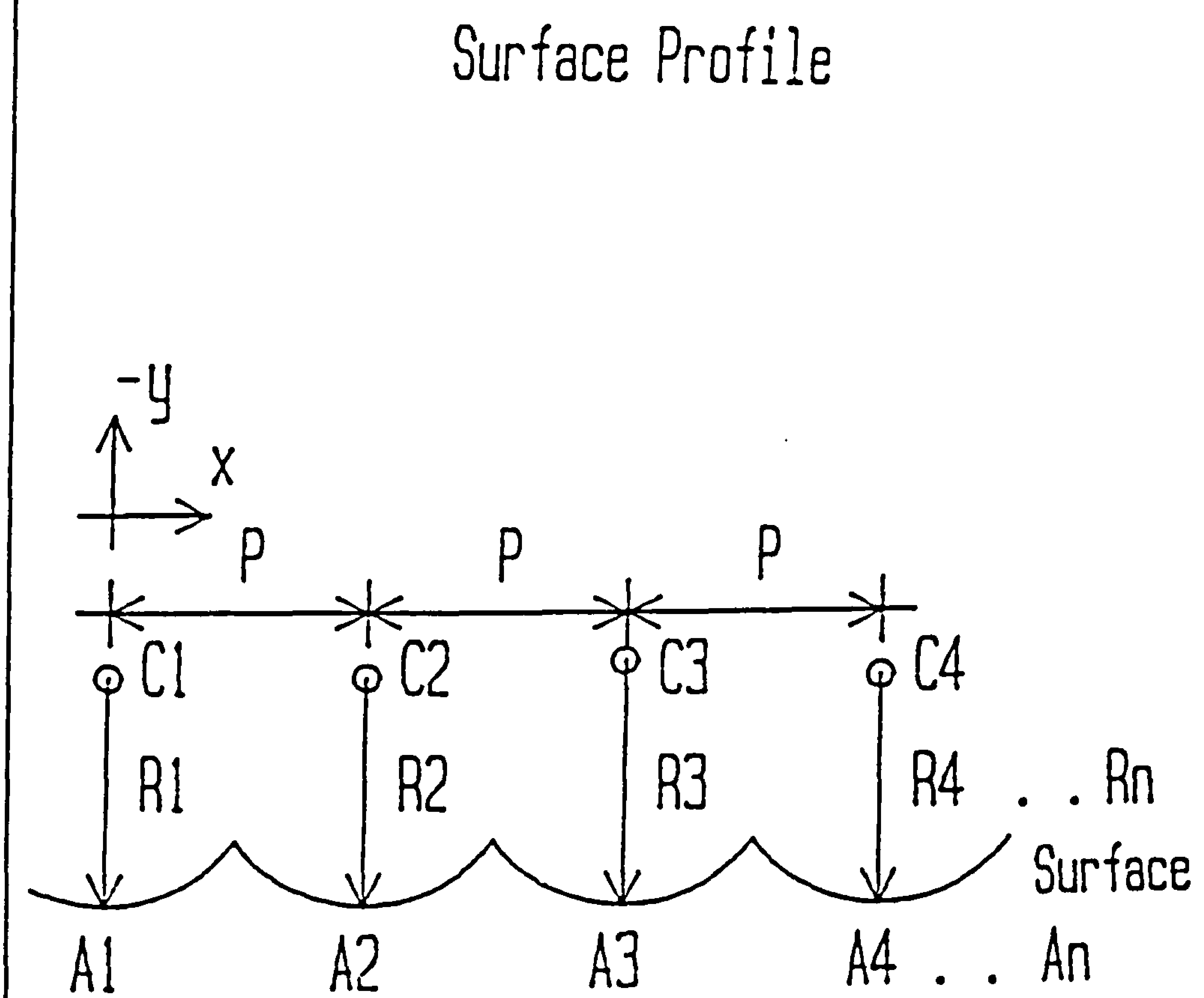

Surface Profile
-y
x
P
P
P
C1
C2
C3
C4
R1
R2
R3
R4 . . Rn
Surface
A1
A2
A3
A4 . . An

Figure 10

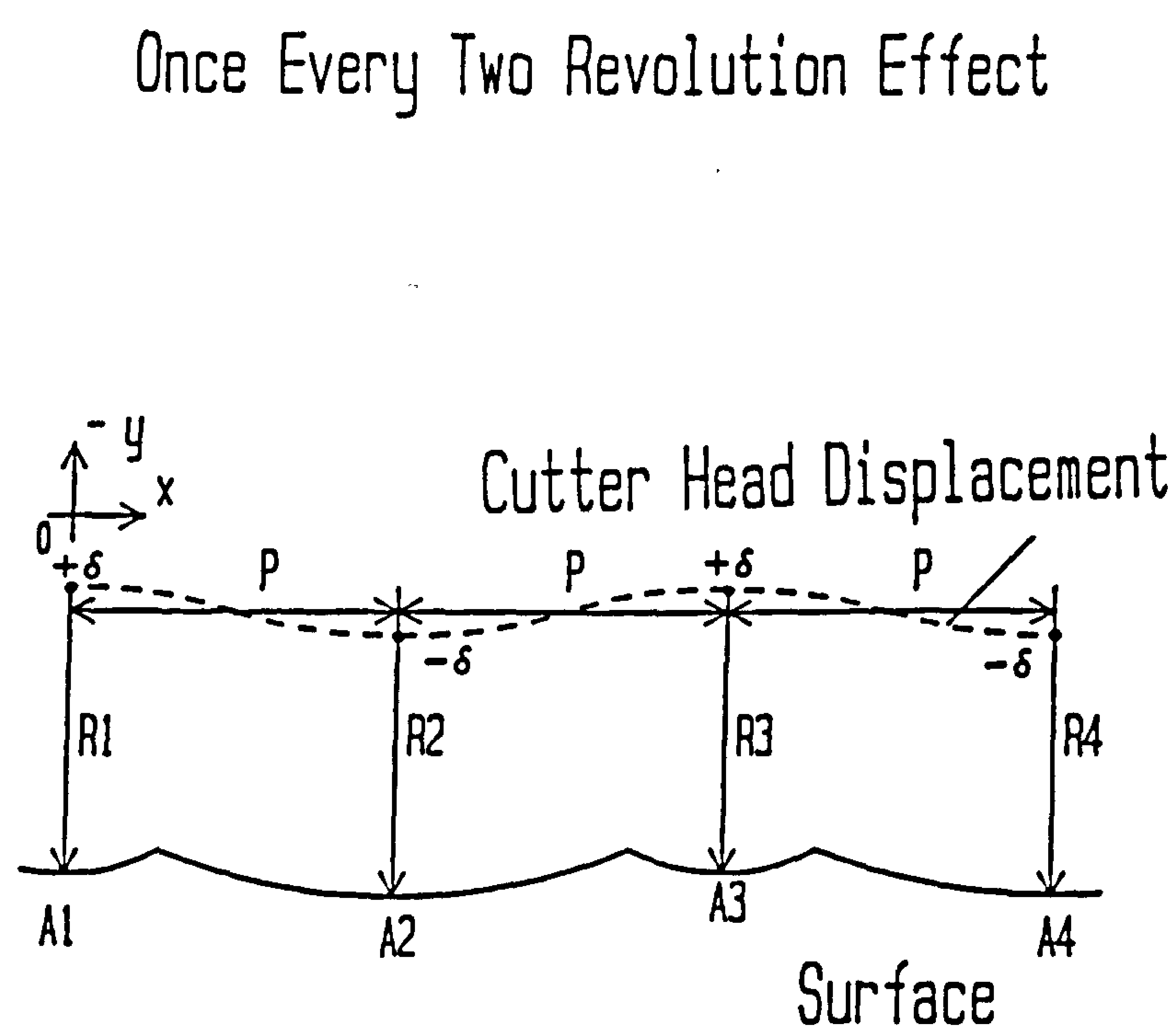

Once Every Two Revolution Effect
-y
x
0
Cutter Head Displacement
+δ
P
P
+δ
P
-δ
-δ
R1
R2
R3
R4
A1
A2
A3
A4
Surface

Figure 11

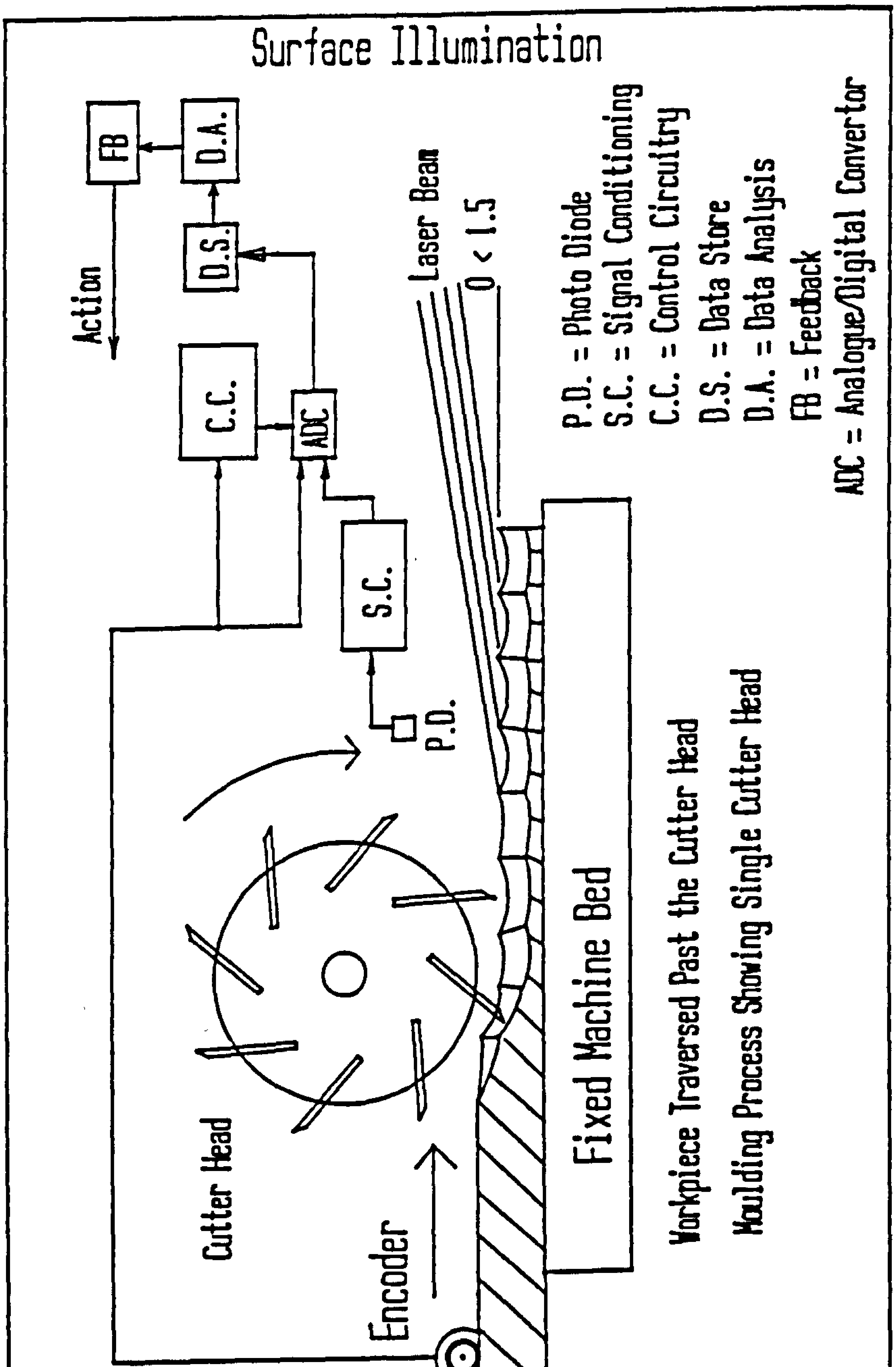

Surface Illumination
FB
D.A.
D.S.
Action
C.C.
ADC
S.C.
P.D.
Laser Beam
0 < 1.5
Cutter Head
Encoder
Fixed Machine Bed
P.D. = Photo Diode
S.C. = Signal Conditioning
C.C. = Control Circuitry
D.S. = Data Store
D.A. = Data Analysis
FB = Feedback
ADC = Analogue/Digital Convertor
Workpiece Traversed Past the Cutter Head
Moulding Process Showing Single Cutter Head

Figure 12

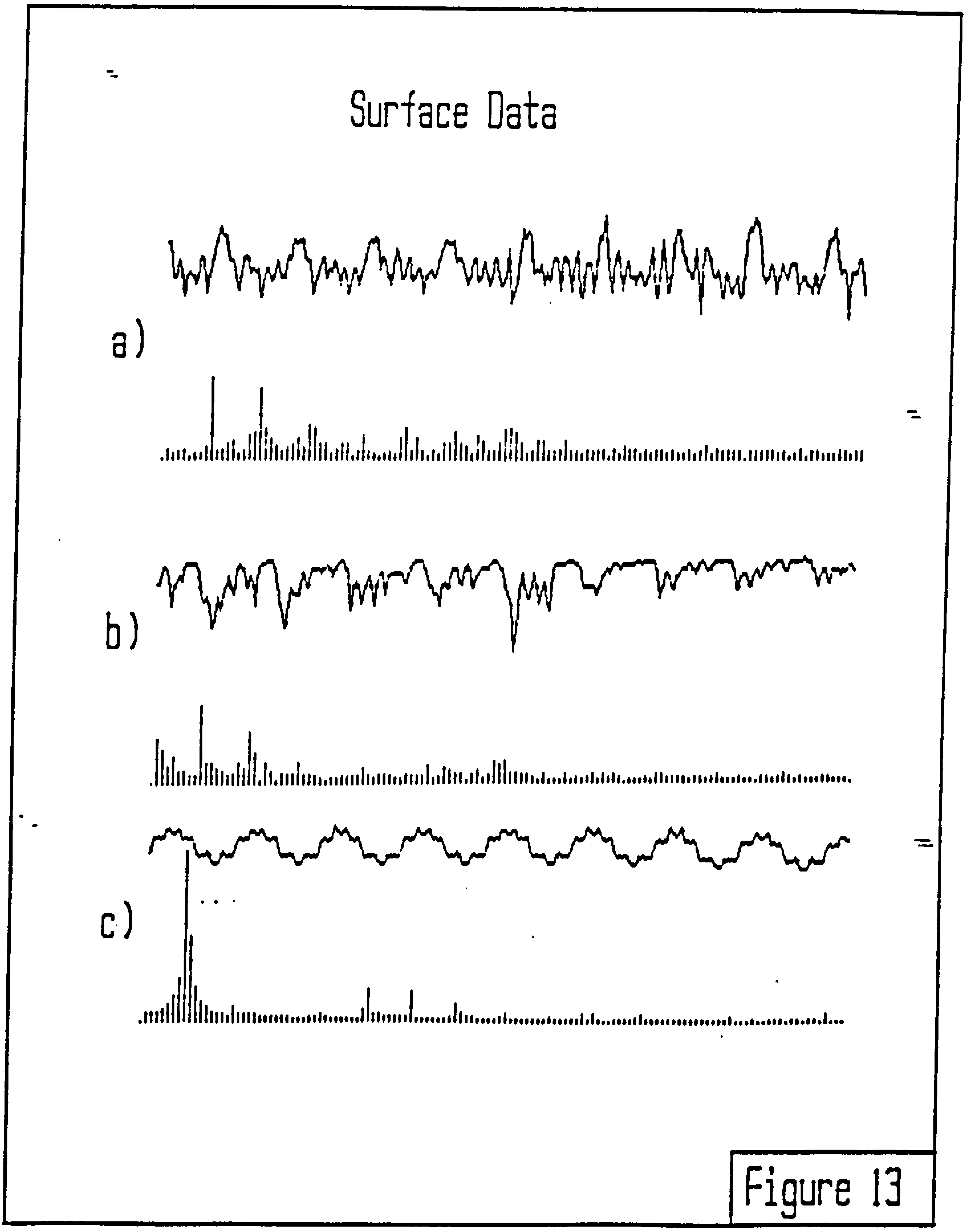


Figure 13

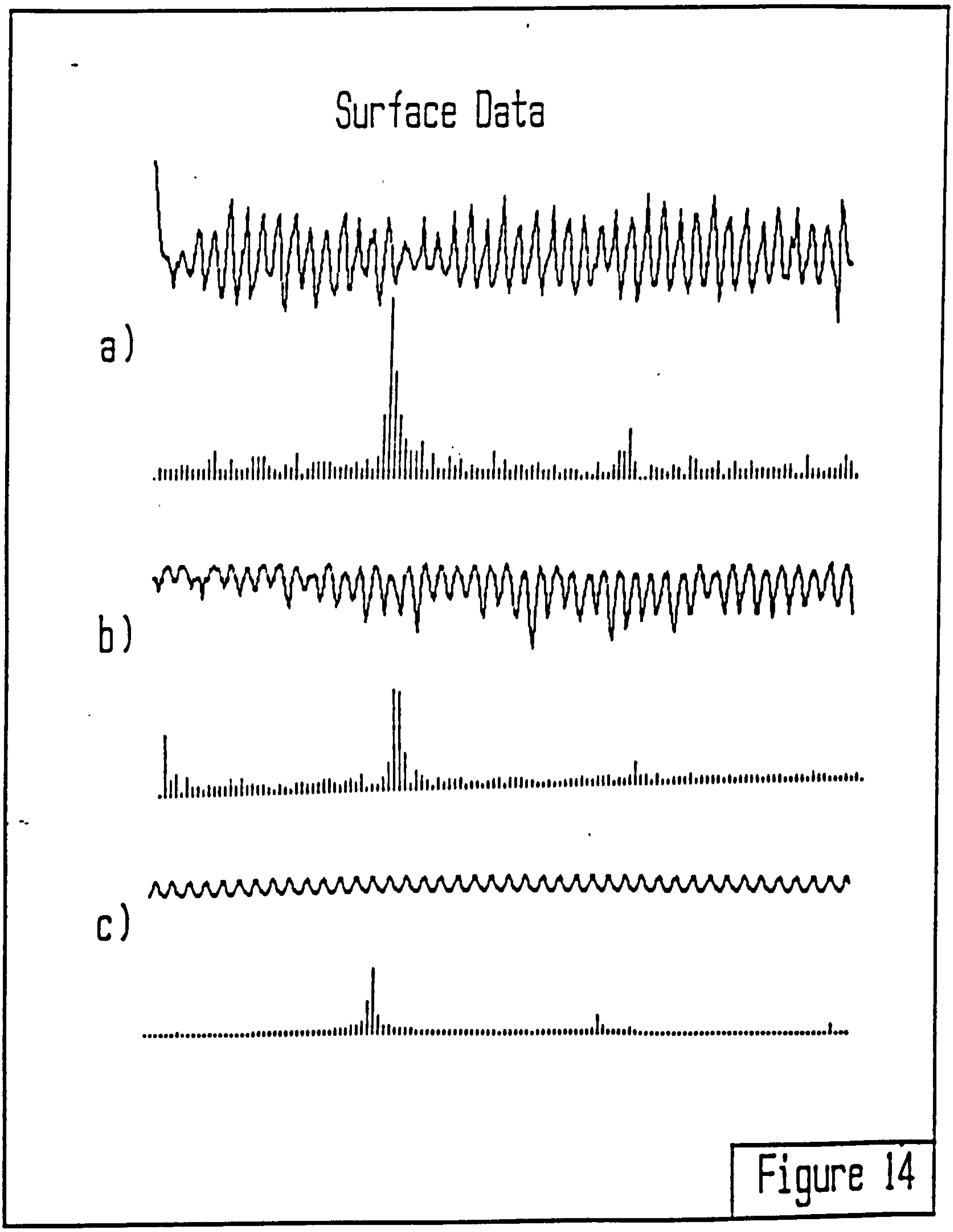


Figure 14

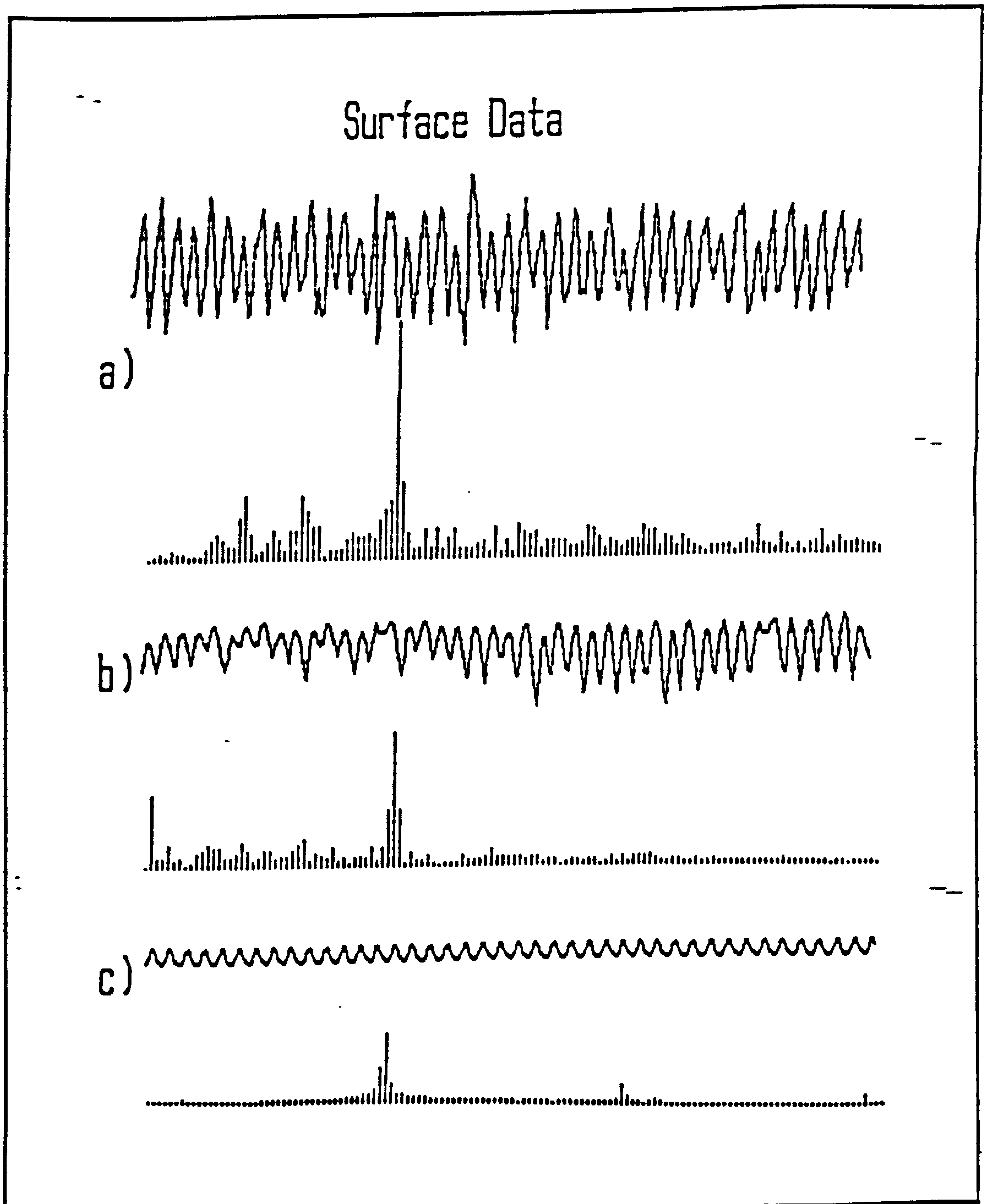


Figure 15

Appendix I Publications

MEASUREMENT AND CONTROL TECHNIQUES FOR TIMBER PRODUCTION PROCESSES

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R Parkin BSc, PhD, CEng, MIEE, MIMechE
Leicester Polytechnic School of Mechanical & Production Engineering

SUMMARY
The use of computers for the control of production processes and machinery is widespread. Woodworking machinery has unique problems due to the high speed of operation. The production rate of planed and spindle moulded timber products is currently running at approximately 1 m/s. To achieve these rates high speed cutters are used (up to 15000 rev/min) resulting in high levels of noise and vibration and risk of bearing failures. Faults in the machine result in a poor quality product. The quality of the product is normaly assessed by subjective visual means, i.e. does it look alright?

Previous work has investigated certain types of machine fault that give rise to identifiable surface waveforms of the produced timber. This paper proposes a system for the management and control of the production process to identify and rectify product defects.

An important feature of this work is the development of a "smart" sensor to measure the surface waveforms of the timber sections produced, in order to identify machine faults, prior to taking corrective action.

Contact measumement methods are inappropriate due to high speeds and vibration levels present in the process. This paper describes a microprocessor controlled, non contact, measuring "block" for incorporation into the overall machine management and control system.

The measurement system incoporates a novel laser and photodiode array combination and utilises real time Fast Fourier analysis techniques. The possible applications of the system are widespread, i.e. any process in which the surface waviness (wavelength => 1mm) is important (e.g. steel production, plating/coating industry). The sensor system is the subject of a patent application.

Background

The woodworking industry desperately needs a reliable method by which to quantify and categorise the surface quality of its planed and spindle moulded products. The current practice is that of visual and tactile inspection, which results in a wide variance in what is classed as an acceptable or defective surface finish; what one manufacturer may reject as an unacceptable standard, another may accept as "good". These methods, by their very nature, are subjective and are restricted to post-process application.

Modern woodworking machines "extrude" timber at extremely high rates, often in excess of 140m/min. Thus, when the process develops a fault, eg blunt cutters, a considerably large quantity of sub-standard (defective surface finish) timber is produced before the symptoms are detected by post-process inspection.

Evidently, to ensure consistent quality and economy, it is necessary to develop sensors capable of monitoring the quality of the product, at the instant that it is produced, so that any necessary remedial action may be effected immediately. At the same time, a practical and more precise method of specifying machined wood finish is required to ensure consistent quality of production.

Surface Geometry

The production of machined timber has some similarities with the milling of metals; the workpiece is fed into the revolving cutter, which shears chips from the surface, in the up-cutting mode (Figure 1). However, with wood, the feed (typically 100 m/min) and cutter speeds (typically 15000 rev/min) far exceed those of milling; also in metal machining the workpiece is clamped to a moving bed, whilst in wood machining the bed is fixed and the workpiece is traversed.

Due to the physics of the process, the geometry of the machined surface consists of a series of, essentially, cicular arcs; their distribution and linear spacing being dependent on the feed speed, cutter speed and the number of knives used on the final cutter head. Figure 2 shows the ideal surface finish of planed wood; $R_1 = R_2 = R_3 = R_4$, no cutters proud, no vibration, dynamically balanced spindles etc (Ref. 1).

As can be expected, in practice, the ideal is never achieved; vibration, spindle dynamic imbalance, proud knives, etc, all affect the cutter locus and hence surface profile. Obviously, the greater the level of vibration, dynamic imbalance, etc, the further the surface form departs from the ideal. A more typical profile of a planed surface is shown in Figure 3

Current Surface Metrology

Stylus Methods

Current and popular methods of surface analysis have their origins within the metalworking industry. Surface roughness measurements are normally made using stylus instruments having relatively short traverse lengths. Established analysis techniques offer a means of characterising profiles. Broadly speaking the various methods may be divided into categories which define the amplitude, or the wavelength, variation, although some methods are found to deal with both regimes simultaneously (Ref. 2).

The Centre Line Average (R_a) or Root Mean Square (R_q) parameters are very limited for describing amplitude variations, and often misleading, since profiles clearly different in form can have the same numerical value of R_a or R_q (Ref. 2). Moreover, within the context of wood machining, with its high levels of vibration, the in-process monitoring of surface quality using delicate stylus instruments is impossible; even if the instruments were made more robust (Ref. 1), their response (400 Hz bandwidth) would be inadequate to track suface profiles traversing at 140 m/min as the required bandwidth is 2.3 kHz for 1mm wavelengths.

Visual/Tactile Methods
Visual/tactile methods have been used since the early days of woodworking. Today, it is still the most popular technique used, by customers and manufacturers alike, for assessing the quality of planed timber. Because of its subjective nature, the method has many shortcomings. There is no quantitative assessment of the degree of waviness defects and, as such, no standards can be formulated; this results in a wide variance in the classification of surface finishes throughout the industry. This problem is compounded by the fact that there are no definite standards for the waviness quality of planed timber. Considerable conflict is thus caused between manufacturers and customers when each use their own, different, subjective assessment 'standards'.

Optical Techniques
Researchers Elmendorf and Vaughan (Ref. 3), Stumbo (Ref. 4) and Peters and Cummings (Ref. 5) have investigated the use of optical light sectioning as a technique for surface quality assessment. The method is quantitative in that measurements are taken using a microscope to assess the overall peak-to-valley height. The technique, which uses light incident at 35 degrees, is very time consuming, hence it has not been adopted by the woodworking industry, although furniture related industries have used this technique.

A variation on the optical light sectioning technique uses oblique lighting to illuminate the object surface. This provides visual enhancement of the appearance of the forms of defect, but not a quantitative assessment of surface waviness. Oblique illumination is sometimes used to improve the eye's ability to ascertain variation of surface waviness (Ref. 6), but is of limited use for in-process surface assesment.

Laser and Optoelectronic Techniques
In recent years, laser techniques have been, and are being, developed to measure surface profile and roughness. They all monitor the specular reflection of a laser beam focused on the surface to be assessed. The angle of incidence of the beam is of the order of 45 degrees; photo-detectors record the variation of the reflected angle as the object surface is traversed (Figure 4).

A typical example of systems being developed by Mitsui (Ref. 7) is shown in Figure 5. Mitsui uses a He-Ne laser, of 1mW output, as a light source. The laser beam is directed onto the object surface through a series of mirrors and an objective . For the detection of the reflected light position, a photodiode array, that can measure cèntre position of the light spot directly as a voltage, is used. It is necessary to scan the array quickly enough to detect movement.

While Mitsui reports a measuring range of -30um to 20um with his measuring system, like other researchers in this field (Ref. 11,12), mention is made with regard to the effect of surface vibration on the measuring technique.

Object surface vibration would have a marked effect, introducing spurious data and causing inaccurate results. Most of the laser surface assessment techuiques are being investigated within the context of metal machining, where the workpiece is fixed to the same datum (the machine table) as the measuring device, hence minimising relative vibration. With wood machining, however, the workpiece is not clamped to the machine table, but fed across it using pressure pads as guides, thus a high level of vibration prevails. For these reasons, major difficulties are envisaged in adopting the laser techniques described above for assessing the surface quality of timber, in-process.

OBJECTIVE

The foregoing discussion clearly indicates the requirement for a fast-response, non-contact, method of measuring the surface quality of machined timber; an integral part of this requirement is the determination of parameter(s) which can readily indicate and identify defects.

The "non-contact-rapid-response" nature of light, coupled with recent advances in laser and opto-electronic technology, has brought about interesting and new possiblities for in-process assessment of product quality.

Proposed Parameters

Because the cutting circle diameter used on planing machines is relatively large (typically 200mm), the depth, h (see Figure 2, of each cusp, produced on the surface, is of the order of a few microns (typically 10 um). These are very small amplitude variations and, as such, are not detectable by the naked eye. Amplitude variation, then, cannot account for any "defects" as perceived by the human eye. However, the eye is extremely sensitive to changes in slope (Ref. 8) ie boundaries or lines on the surface. Hence the eye detects the change, from positive to negative slope, where the cicular arcs intercept, ie the apexes.

Investigations have shown that it is the consistency with which the apexes repeat that affect the aesthetic qualities of the machined surface; ie any variation in the surface wavelength, or long periodic "beats" superposed thereon, are detectable by the eye and, as such, render the surface quality defective (Ref. 9,10).

Therefore it would seem reasonable to analyse the surface form in terms of the frequency information inherent on any machined (planed) wooden surface.

Proposed Instrument
The technique proposed uses laser light to highlight the apexes at the intersection of the surface arcs (Figure 6). A broad beam of laser light is directed at grazing incidence (0 < 1.5 degrees) to the surface being machined, and in the same plane as the traversing workpiece. This has the effect of highlighting the leading slopes of each cusp in the beams path and produces a pattern of bright and dark regions on the surface of the workpiece. This pattern, which contains the periodic information of interest, is traversed past a single photodiode.

The output voltage of the photodiode is proportional to the intensity of the light incident upon it. This voltage is sampled (utilising a position encoder to define sample points), digitised using an Analogue to Digital Convertor, and stored in a computer's memory for subsequent analysis.

With appropriate sampling frequency, the data captured over a given length can be analysed, in terms of its frequency content, using Fourier Analysis Techniques.

The data captured is not prone to distortion due to vibration as the plane of vibration is almost perpendicular to the broad incident beam.

The initial investigations into the technique outlined above were undertaken in a microprocessor/instrumentation laboratory with no access to woodworking machinery. The high cost of operating such machinery also means that even the collaborating machinery manufacturers do not produce any significant amounts of machined timber. The cooperation of certain machinery users has been secured for later developmental stages.

The philosophy adopted, therefore, was to use and develop the technique on stationary, pre-machined timber samples. This was accomplished by utilising a linear array of photodiodes rather than a single diode. Traversing was achieved by scanning the diode array instead of traversing the timber. Optical lenses are used to focus the image of a given length of timber on to the photodiode array. Scanning of the array provides data which is then captured for subsequent analysis.

RESULTS
Data Capture
Figure 7(a) shows a typical graphical display of surface data captured from a timber sample (relative lightintensity being plotted against lateral position) which had been planed using a feedspeed of 106 m/min, cutterspeed of 6000 rpm and *** knives on the cutter head.

Frequency Spectra of Surface Data
The surface data set obtained from the timber sample was transformed to the frequency domain using an FFT algorithm. The resulting frequency spectrnm is shown in Figure 7(b).

DISCUSSION
There is close correlation between the peaks of the Talysurf trace and the peaks of the captured light intensity data.

The data set was analysed in terms of its harmonic content using an FFT algorithm. The result is shown in Figure 7(b)' which clearly show maximum magnitude at the dominant harmonics. Notice there are 48 local maxima in the plot of light intensity verses distance - the spectrum reveals this fact with a maxima at harmonic 48. The low, undesirable frequency beats present are clearly visable in the plot and are highlighted in the spectrum.

CONCLUSION

An optical in-process sensor for assessing the surface quality of planed timber was introduced. Due to the growing intrest in product quality, the automation of measurement and development of accurate measurement techniques are urgently needed. The method introduced has been applied to materials other than wood eg alumiium, plastics which indicates the possible diversity of its application.

FUTURE WORK

Future work will include the relating of known process faults and associated defective surface finish with frequency spectra "signatures"; this will enable the indentification of specific faults when they occur.

The in-process application of the technique will be pursued; this necessitates dispensing with the use of a general purpose computer, replacing it with a dedicated "chip-level" device in order to achieve the speed required, incorporating the use of maths coprocessors and FFT analysers.

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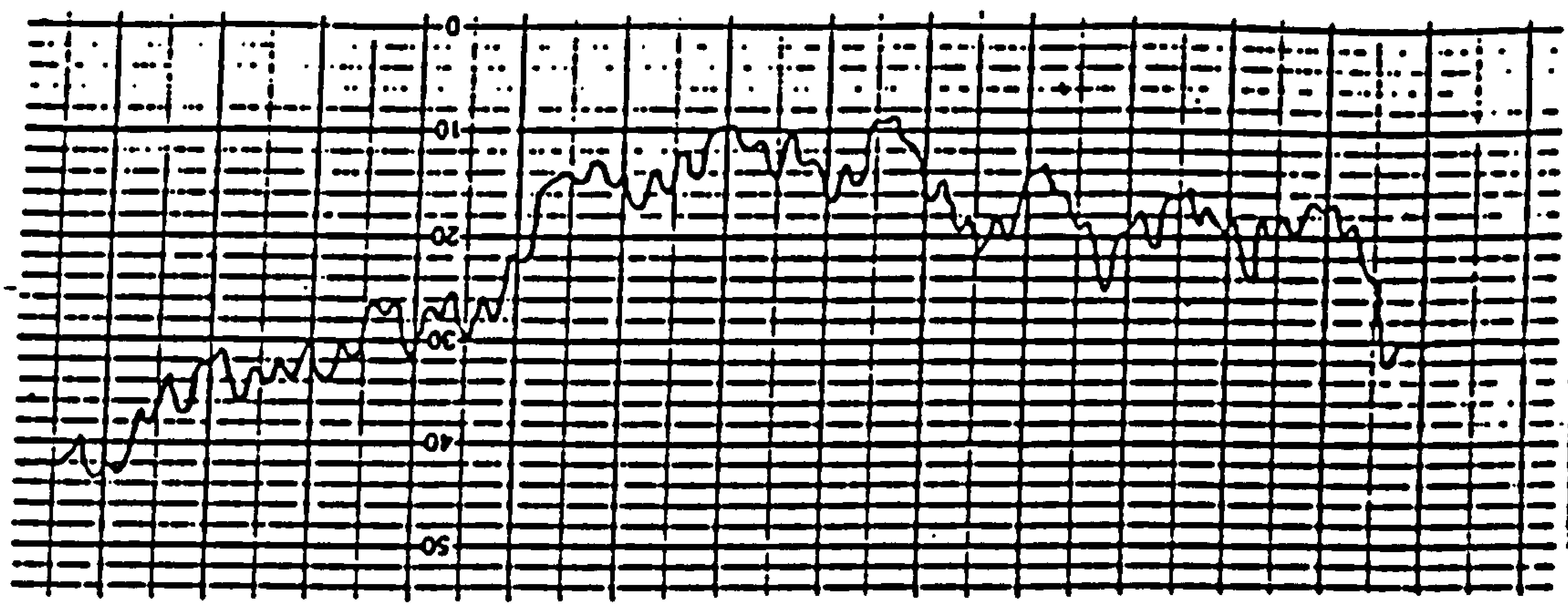


Figure 7(a) Talysurf Trace

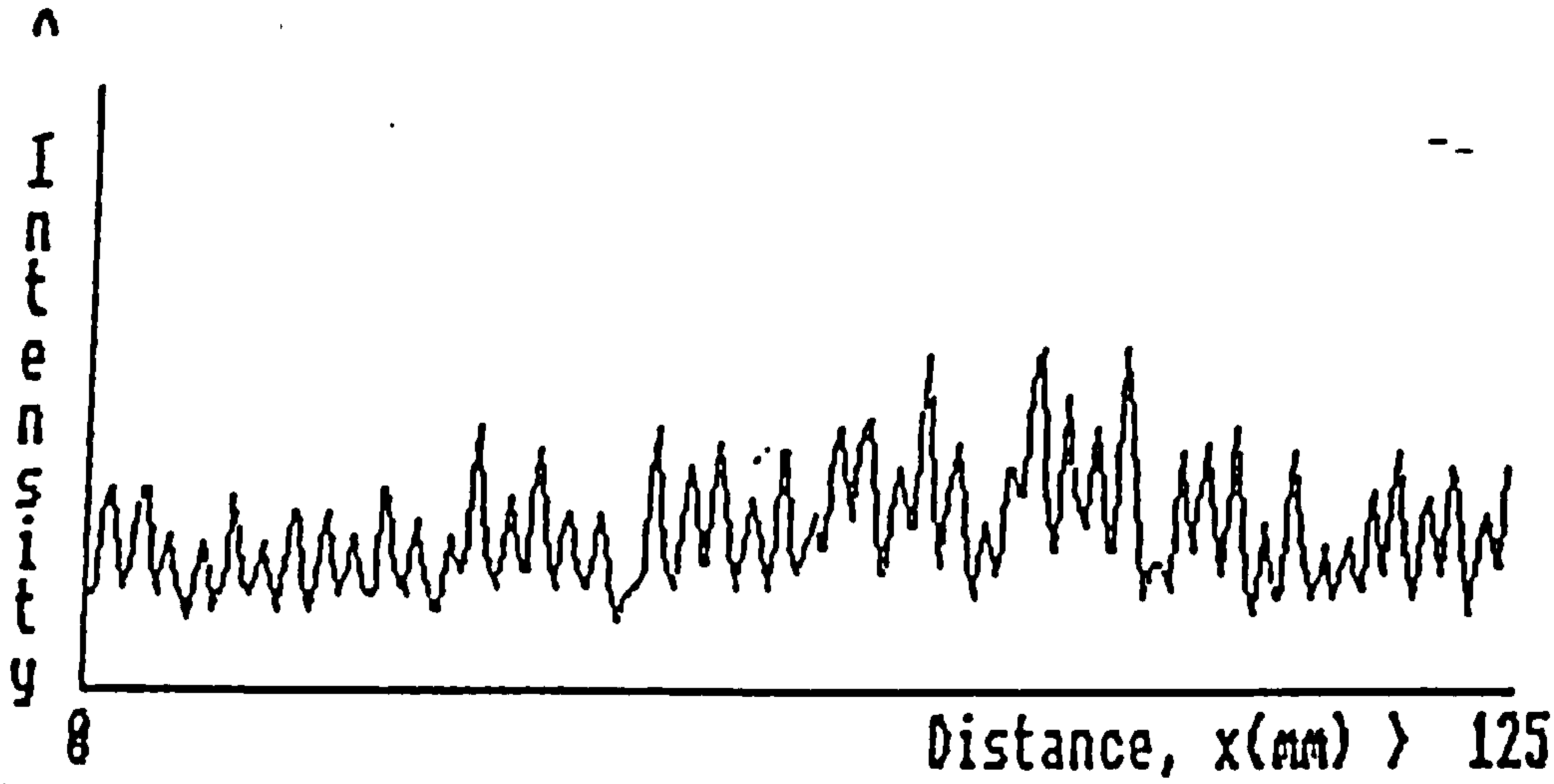


Figure 7(b) Light Intensity

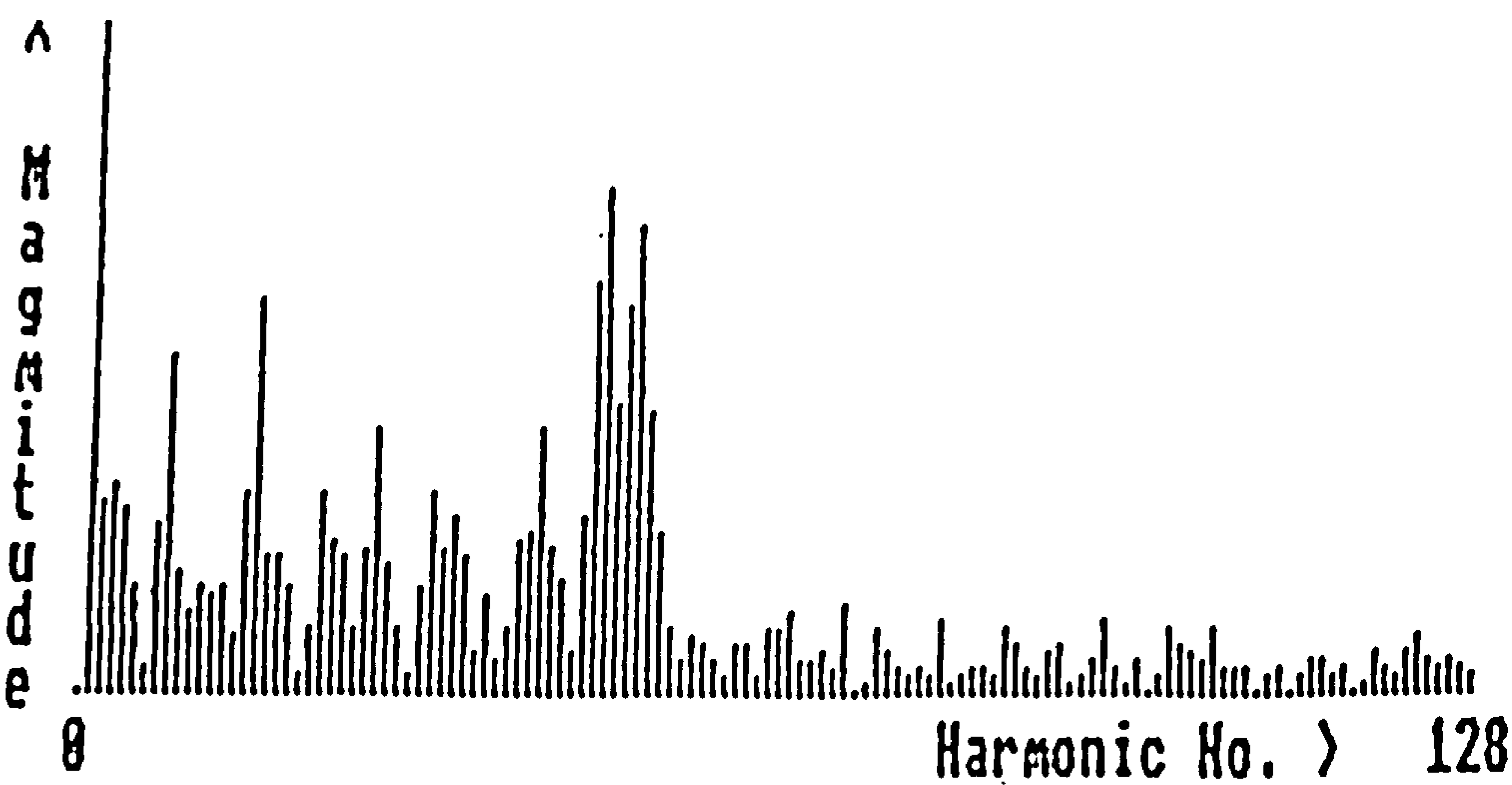


Figure 7(c) Spectrum [I.8]

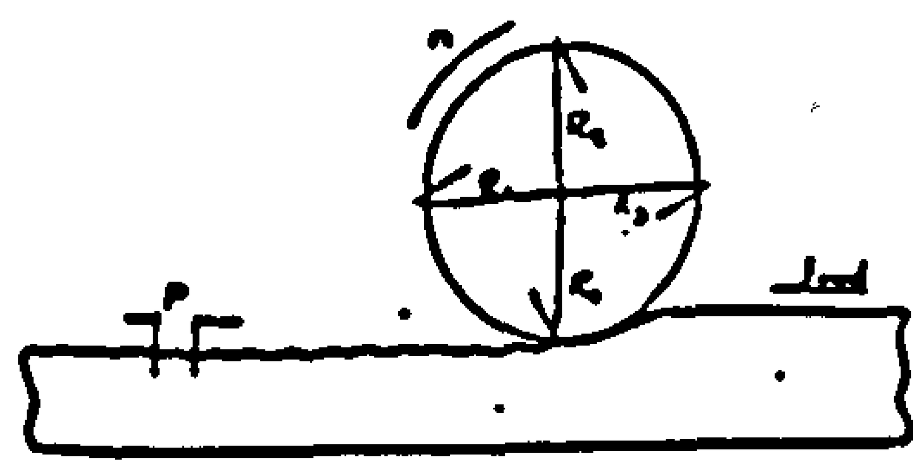


Figure 1

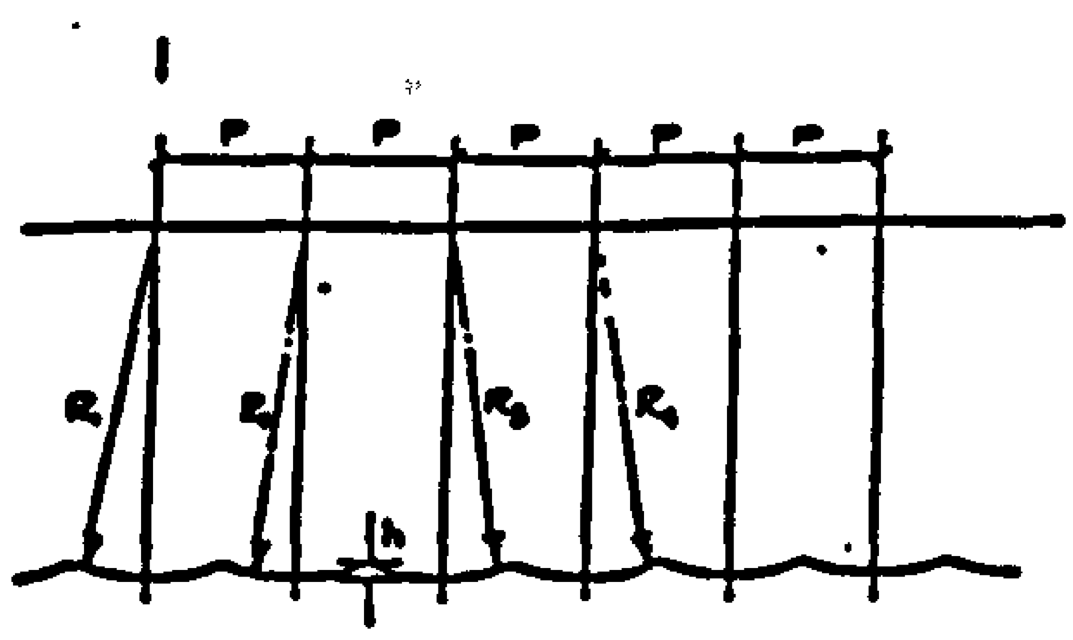


Figure 2

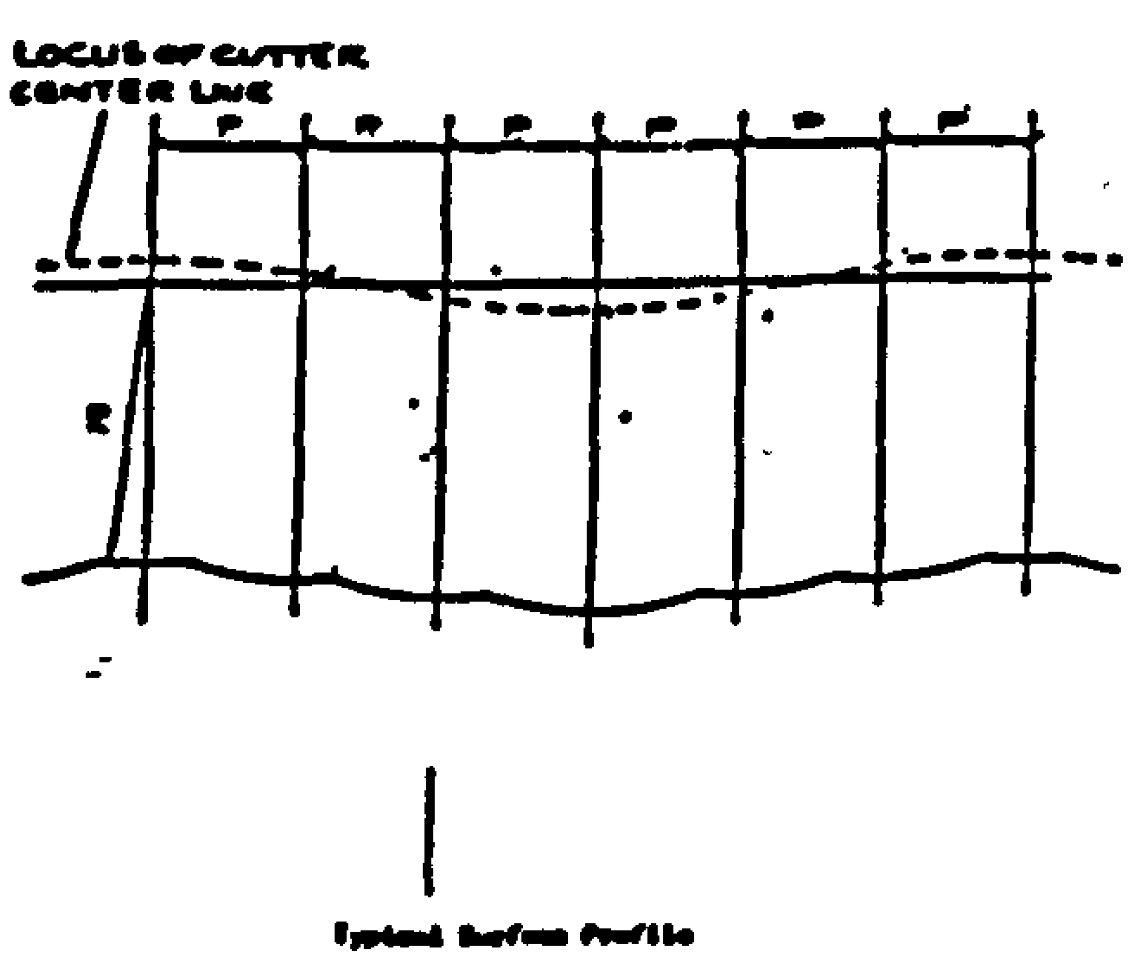


Figure 3

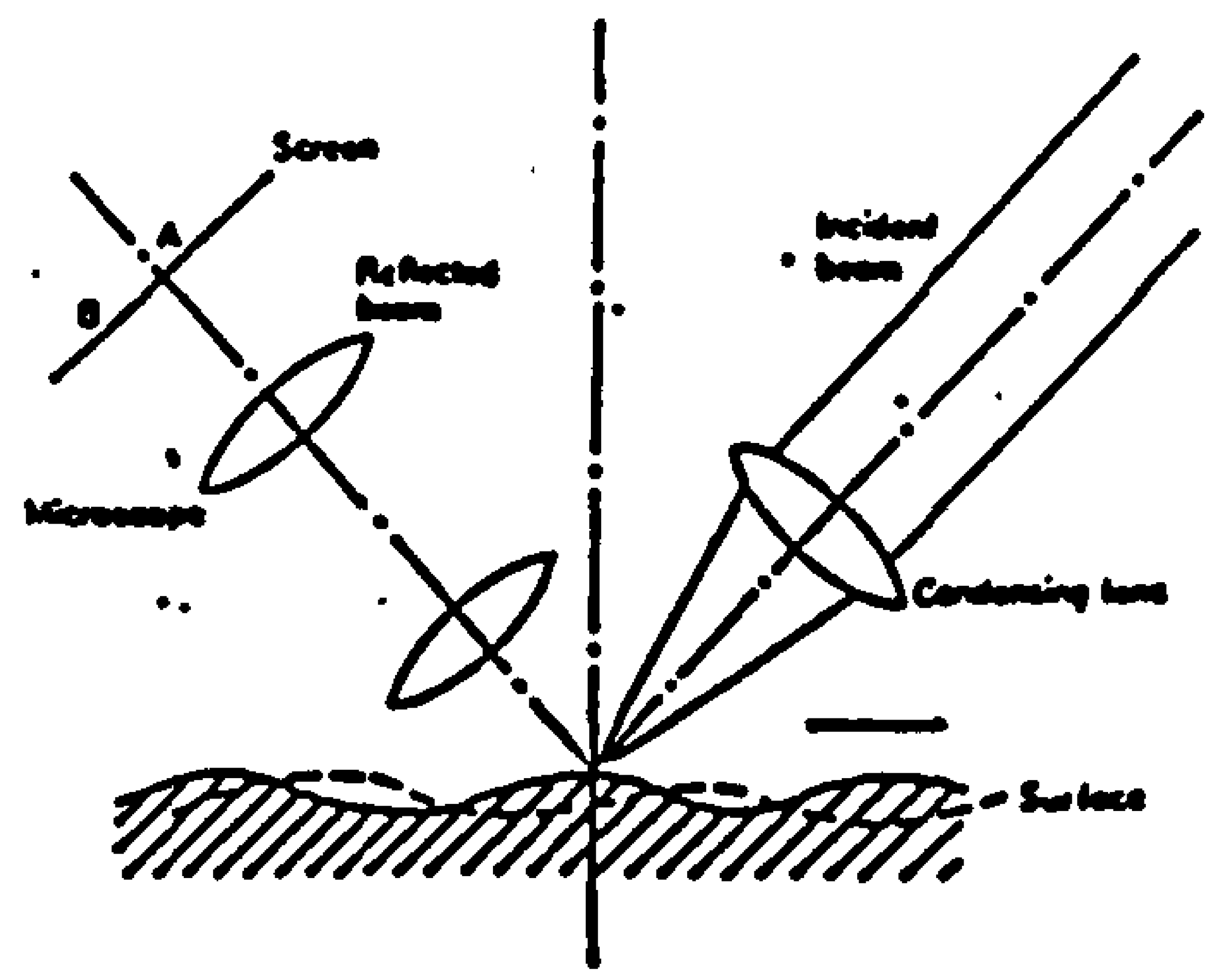


Figure 4

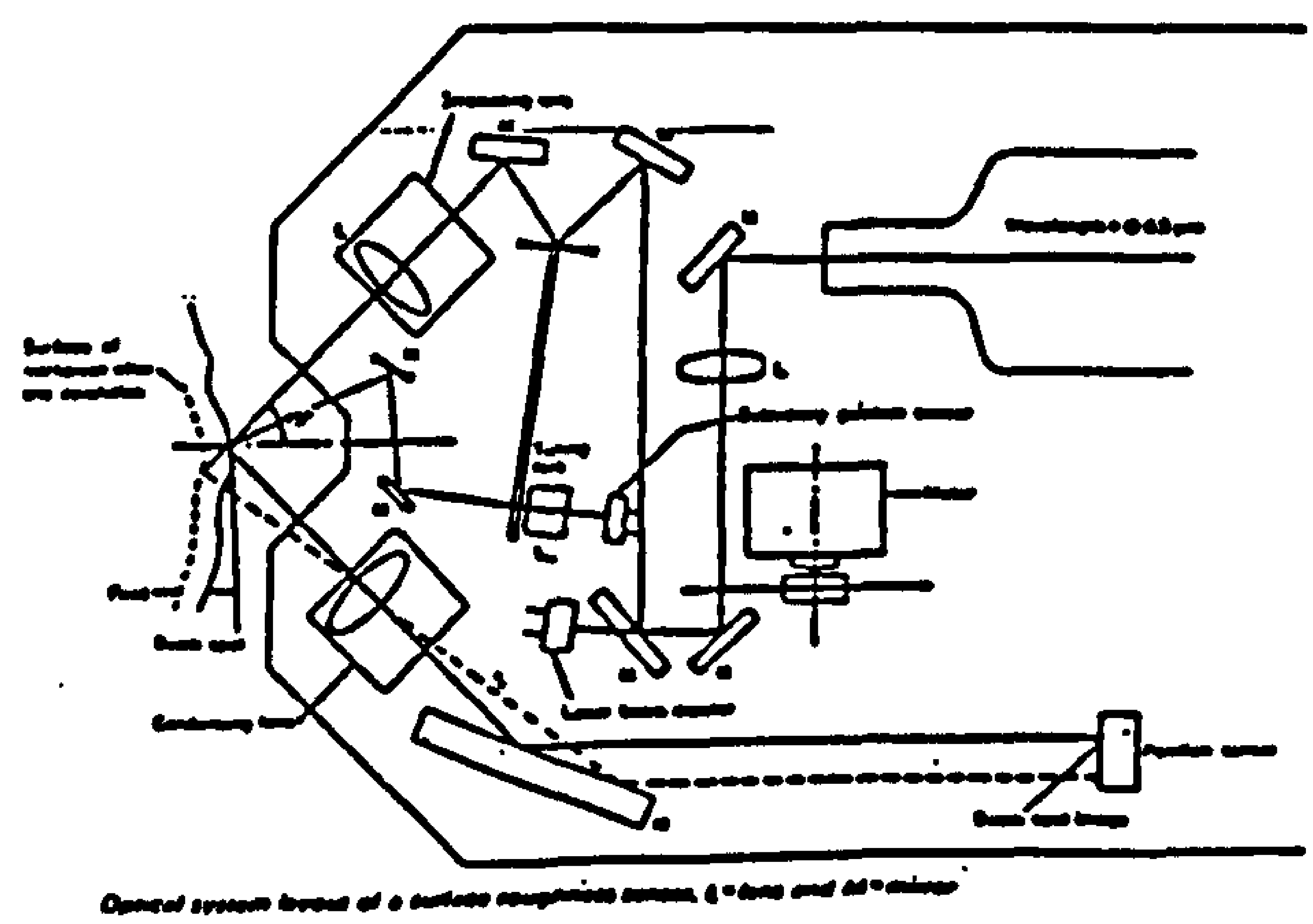
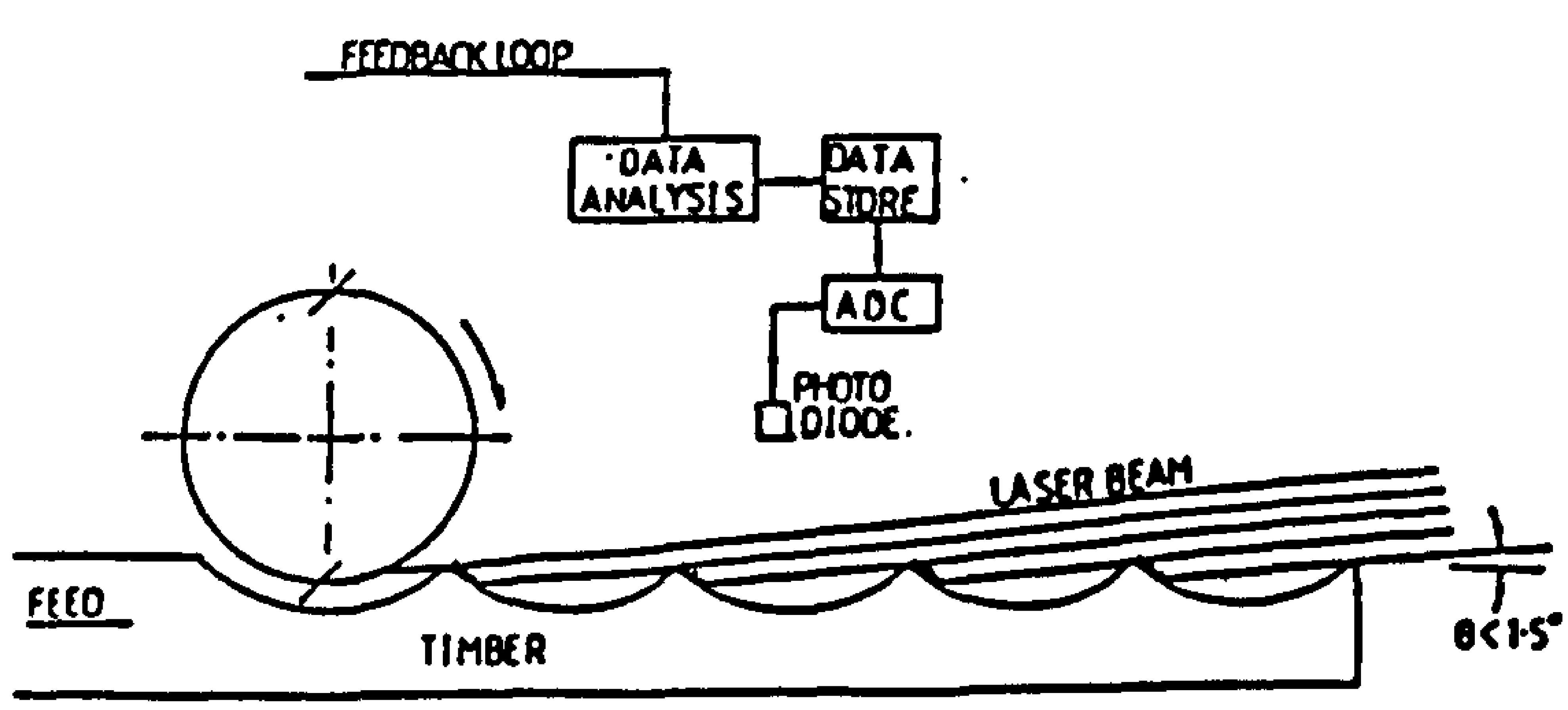


Figure 5



PROPOSED METHOD

Figure 6

Surface Measurement of Planed and Moulded Timber Products

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Abstract

Surface quality of planed and moulded wooden components is primarily affected by machine performance during manufacture. Woodworking machinery has unique problems due to high speeds of operation. With raw material throughput rates of 180 m/min and cutter head speeds of 15000 rev/min, large quantities of poor quality material can arise in short periods if machine faults are allowed to develop. At present the quality of the product is principally assessed by subjective visual/tactile means.

Preceding research has explored specific types of machine fault that give rise to identifiable surface waveforms, inherently found on moulded wooden components.

With a present deficiency of in-process surface monitoring systems for moulded artifacts, the feature of this work is the development of an optical non contact measuring transducer. The in-process system will be used to measure the surface waveforms of the timber sections produced, in order to identify machine faults, prior to taking corrective action.

Contact measurement methods are inadequate for this application due to the high levels of vibrations and feed speeds present in the process. This paper discusses the underlying principles of the overall measuring system, and novel laser/photo-diode combination.

With the quality of the process being reflected in the resultant surface finish, Fast Fourier analysis is performed on accumulated surface data. The surface data samples are transformed to associate harmonic frequencies for surface evaluation.

The possible applications of the system are widespread, i.e. any process where the surface wavelengths of one millimetre or greater is important.

BACKGROUND

As current trends of technology advance, machines and processes become more complex and sophisticated. It is usually desirable for duty cycles, where possible, to be optimised and waste materials to be curtailed. Consequently, however, quality of the end commodity will always remain one of the highest production constraints. Within the industry of woodworking machinery manufacturers, competitiveness and salability is very essential (Wadkin plc). It is always therefore paramount that the machinery produced be economic, moderate in setting times and capable of high material throughput in addition to yielding good quality artifacts.

The emphasis of this paper is that of material quality, produced by planers and spindle moulders. It is possible for a variety of these machines to "extrude" timber up to a maximum rate of 180 metres per minute. Allowing such a process to develop operational faults would result in considerably large quantities of sub standard timber being produced in a short period of time.

Palpably, to ensure consistent high quality and efficiency, a system capable of monitoring the surface quality of machined material is essential. The monitoring system would evidently have to be an optical non-contact solution, due to the inherent high speeds and excessive vibration levels of the process. Complete appreciation of the process and the surface geometry of the product is required before development of such a measurement system.

The Process

When planing/moulding components, the feed material is not clamped to the machine table. The workpiece is pressed to the table, using pressurised feed rollers, as it passes the cutter heads (Figure (1)). The machine bed of the planer/moulder is fixed and the workpiece is traversed past the rotating cutter heads.

Due to the physics of the process, the geometry of the machined product surface consists essentially of circular arcs (M.R. Jackson). As can be expected, in practice, the ideal is never achieved; vibration, spindle dynamic imbalance and proud knives all affect the cutter-locus and hence the surface profile. Obviously, the greater the level of vibration, dynamic imbalance, etc, the further the surface departs from the ideal.

Surface Generation

The wood removal process of planing/moulding machines is intermittent as shown in Figure (2) (M.E. Martellotti 1941). The locus taken by a cutter head knife tip, while in the process of chip severance, is actually cycloidal or, more broadly speaking, trochoidal (Koch 1955).

In practice it is difficult to reproduce ideal machine operating conditions. The resultant arcs produced on the part, due to the practical effects mentioned, give rise to many different perturbations of shape. Figure (3) shows a common surface profile obtained with a once every two revolution displacement effect of the cutter head.

As the planing and spindle moulding process generates a variety of surface shapes on the product, which are dependent on the machine operating conditions, monitoring of the products surface profile is important.

Surface Assessment Instrumentation

Presently there are several types of surface measurement instruments and techniques capable of post process assessment of surface finish. These range from "visual/tactile" and optical techniques to precision stylus instrumentation. The latter being capable of calculating surface roughness values with permanent recording facilities. Obviously each method of surface assessment has its own merits and short falls.

Although a variety of techniques and instrumentation capable of post-process measurement of surface irregularities exist, they are however either very subjective or very time consuming. The contact instrumentation is inadequate for the measurement of in-process surface profiles, as traversing rates are in the order of millimetres per minute. Typical machining rates being hundreds of meters per minute for the moulding process.

It is therefore evident, primarily due to production speeds, that a non contact in-process surface monitoring system needs to be developed and evaluated.

In-Process Measurement Proposal

The monitoring system has been designed to measure the surface characteristics of the wooden component in-process. Figure (4) represents the basis of the in-process measurement system. A broad laser beam illuminates the machined surface at grazing incidence (θ <1.5°). The illumination is in the same plane as the traversing workpiece, which gives prominence to the leading slope faces of each surface cusp. A fringe pattern of bright and dark regions is readily observed representing the surface slope along the product.

A single element silicon photo diode is used to detect variations in diffusely reflected laser light as the timber passes from the machine. Automatic gain control and signal conditioning circuitry is used to amplify and filter the output voltage of the photo diode to give maximum dynamic range to the analogue to digital convertor. The sampled output voltage of the photo diode is synchronised using the output of a rotary position encoder, as the system clock for the analogue to digital convertor. Additional electronics control the clock signal for correct read/write operations and memory sequencing. As soon as the periodic surface information has been captured (in real time) in the computer memory, it can be analysed in terms of its frequency content, using Fourier Analysis Techniques. The data captured is not prone to distortion due to vibration, as the plane of vibration is almost perpendicular to the illumination. As the laser beam is broad and of grazing incidence to the surface the vibration levels do not exceed the outer limits of the beam. This phenomenon only occurs because diffuse and not specular reflection is being monitored.

At present, actual material throughput is in the region of two to two and a half metres per second. The new system has been designed to cope with a maximum material movement of five metres per second, thus allowing increased capacity as machine operating conditions improve. The system is capable of monitoring wavelengths of one millimetre and greater (one millimetre wavelengths represents a very fine planed surface, suitable for furniture manufacturers requirements).

With appropriate sampling frequency, the data captured over a given sample length can be analysed, in terms of its frequency content, using Fourier Analysis Techniques.

Results

Figure ((5)a,b) show the resultant surface profiles and associated frequency spectra of a machined surface, obtained using a Talyrond and the novel laser monitoring system. Figures (6) and (7), in the same manner, show other machined surfaces.

To obtain the results in Figure (5), the machines cutter head was set up containing six knives and a deliberate out of balance effect generated at knife number three (added weights).

With a sample length of one hundred and twenty five millimetres used and one hundred and twenty eight frequency harmonics shown; wavelengths of one hundred and twenty *five millimetres* down to approximately one millimetre can be represented. The dominant frequency harmonics present in Figure (5b) are numbers ten and nineteen. These peaks are caused by the out of balance effect and individual cutter head knife markings of the process.

Figure (6) shows similar conditions as that in Figure (5). Here again there is a deliberate once per revolution effect caused on a four knife cutter head. In this instant the feed speed of the machine is much slower.

Figure (7) shows a single knife finish surface. This surface was obtained using a four knife cutter head with three of the knives used as balancing masses only. With no out of balance effect present, the dominant frequency in the frequency spectra is now due to the cutter knife marks on the surface.

Conclusion

Good correlation between existing surface measuring systems (Talyrond) and the novel laser measurement system has been obtained using harmonic analysis. This comparison has been achieved using a Fast Fourier Algorithm to convert real time surface data to the frequency domain.

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4 Head Planer - Moulder

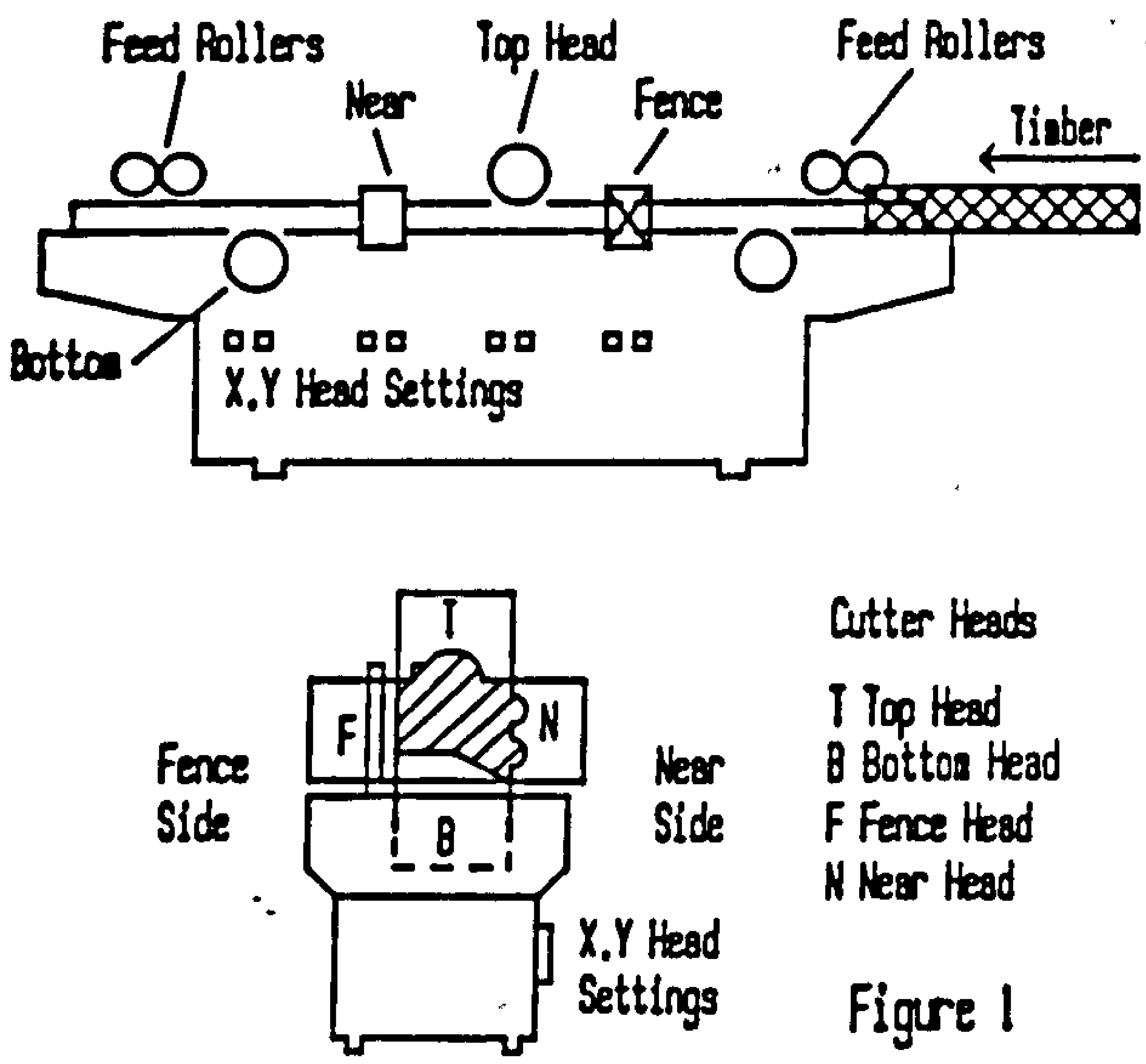
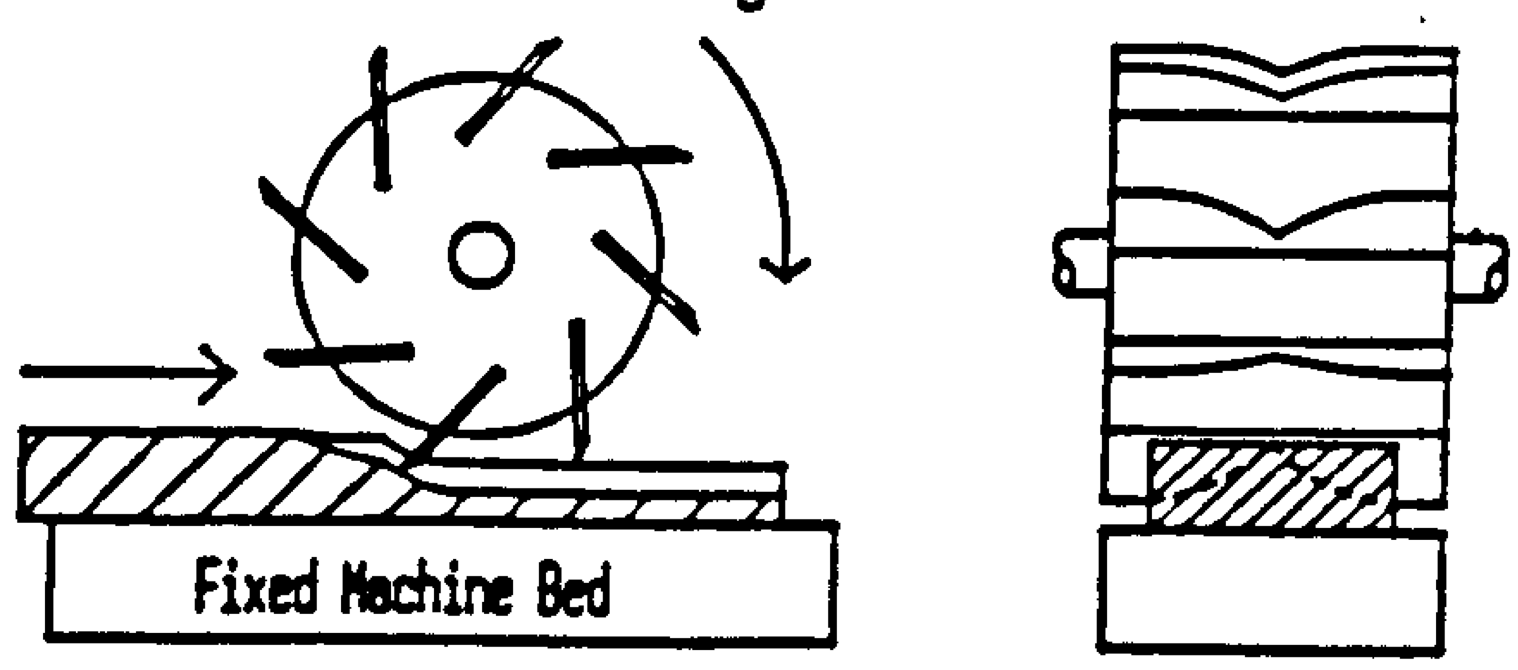


Figure 1

Planer-Moulding



Workpiece Traversed Past the Cutter Head

Moulding Process Showing Single Cutter Head

Figure 2

Once Every Two Revolution Effect

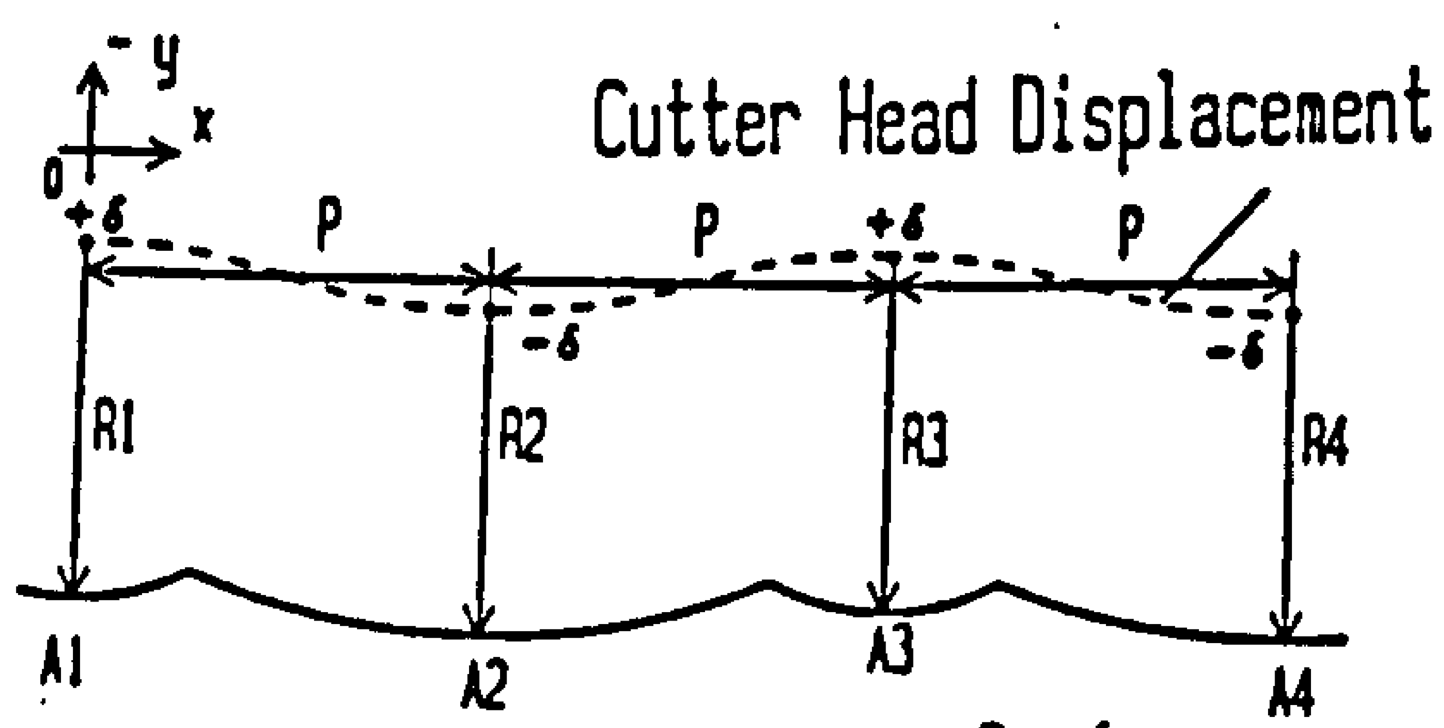
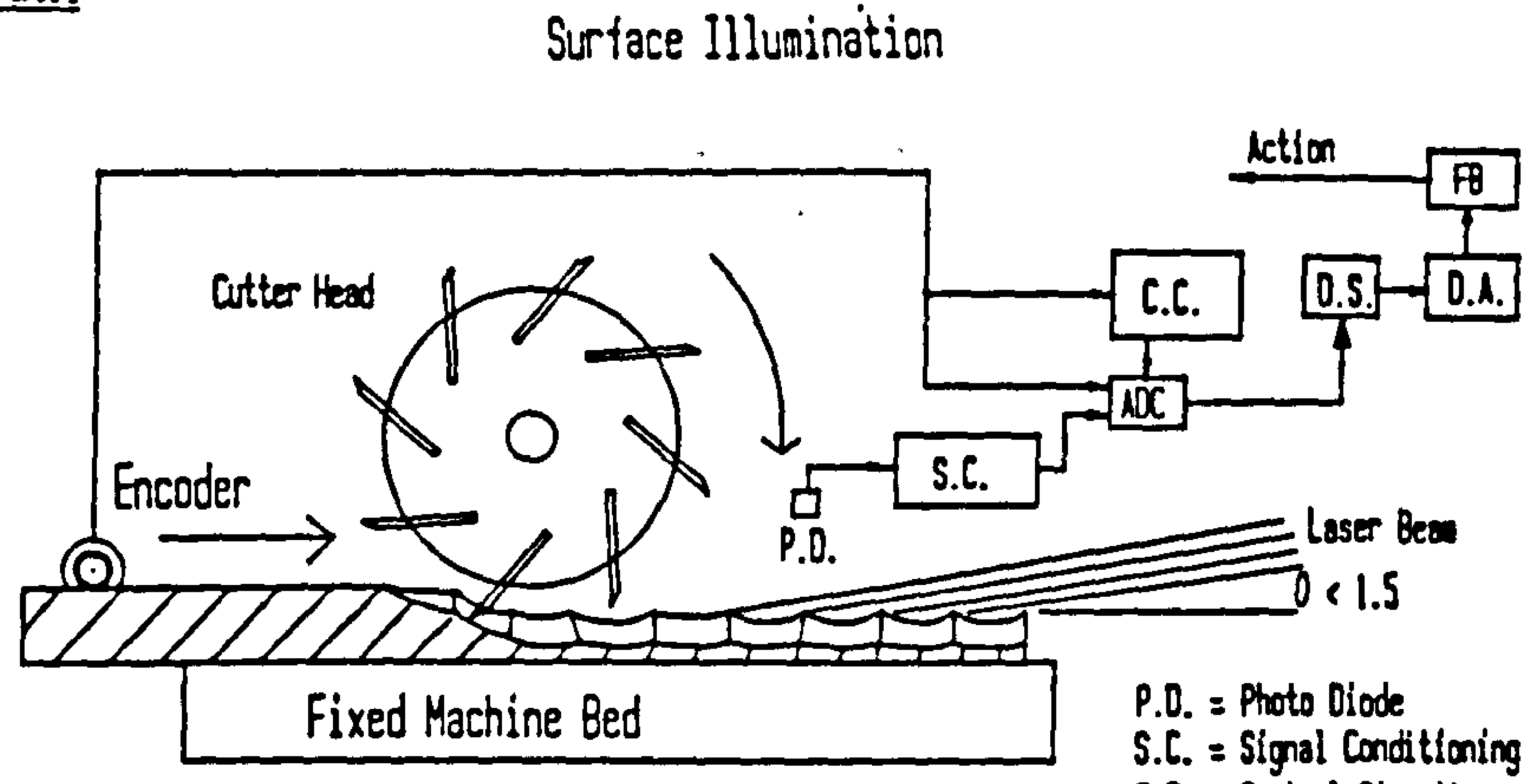


Figure 3



P.D. = Photo Diode
S.C. = Signal Conditioning
C.C. = Control Circuitry
D.S. = Data Store
D.A. = Data Analysis
FB = Feedback
ADC = Analogue/Digital Convertor

Workpiece Traversed Past the Cutter Head

Moulding Process Showing Single Cutter Head

Figure 4

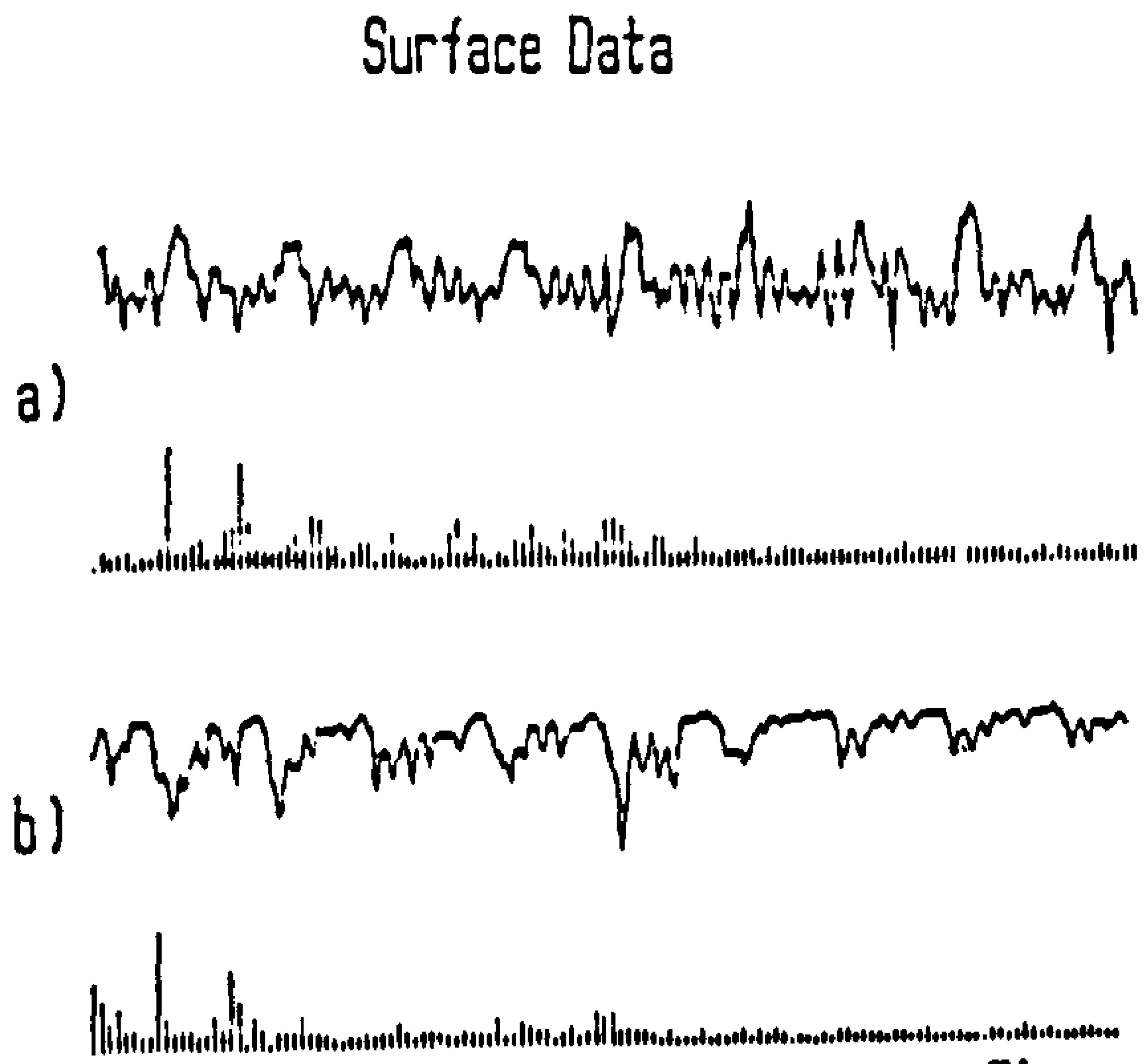


Figure 5

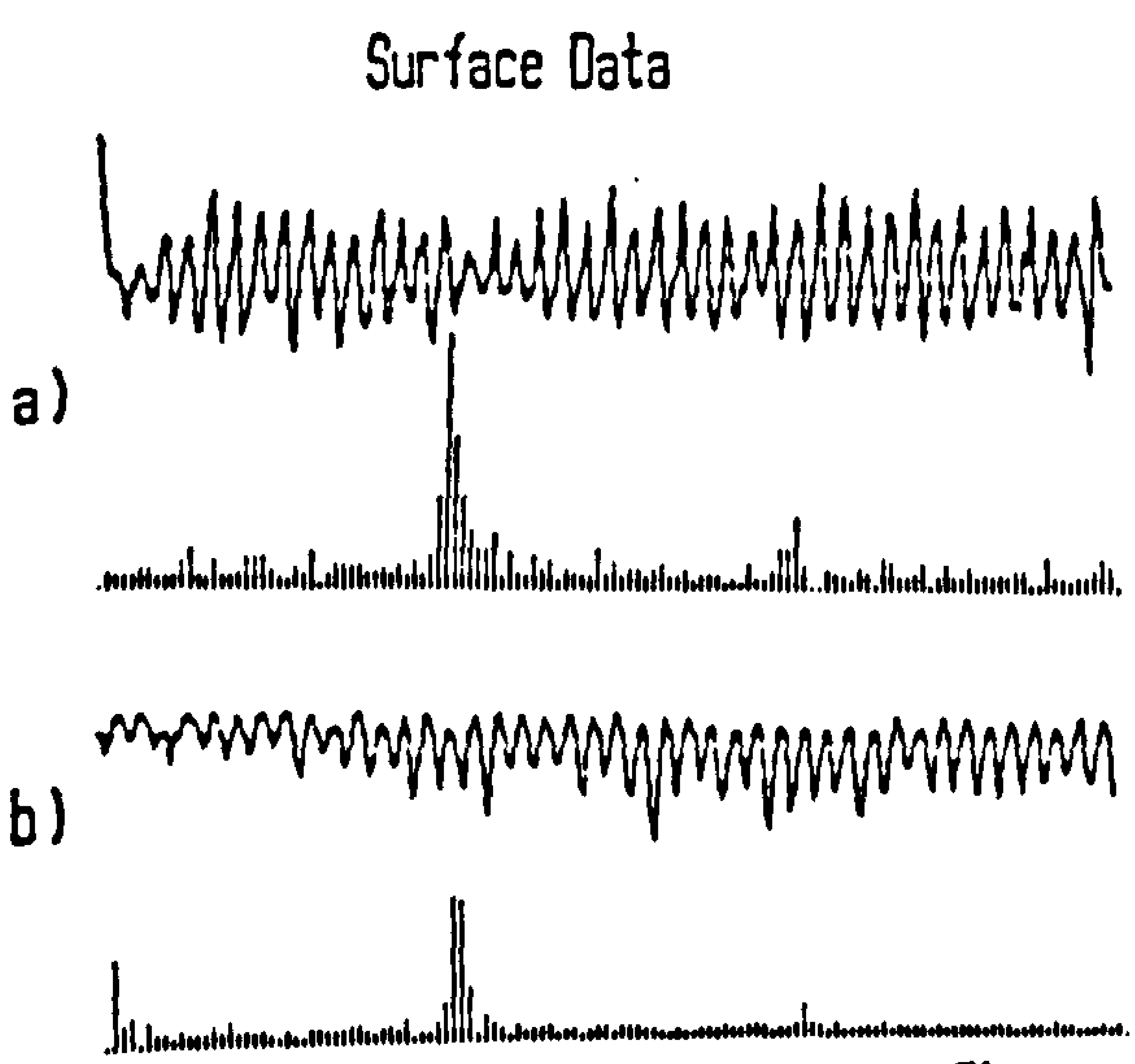


Figure 6

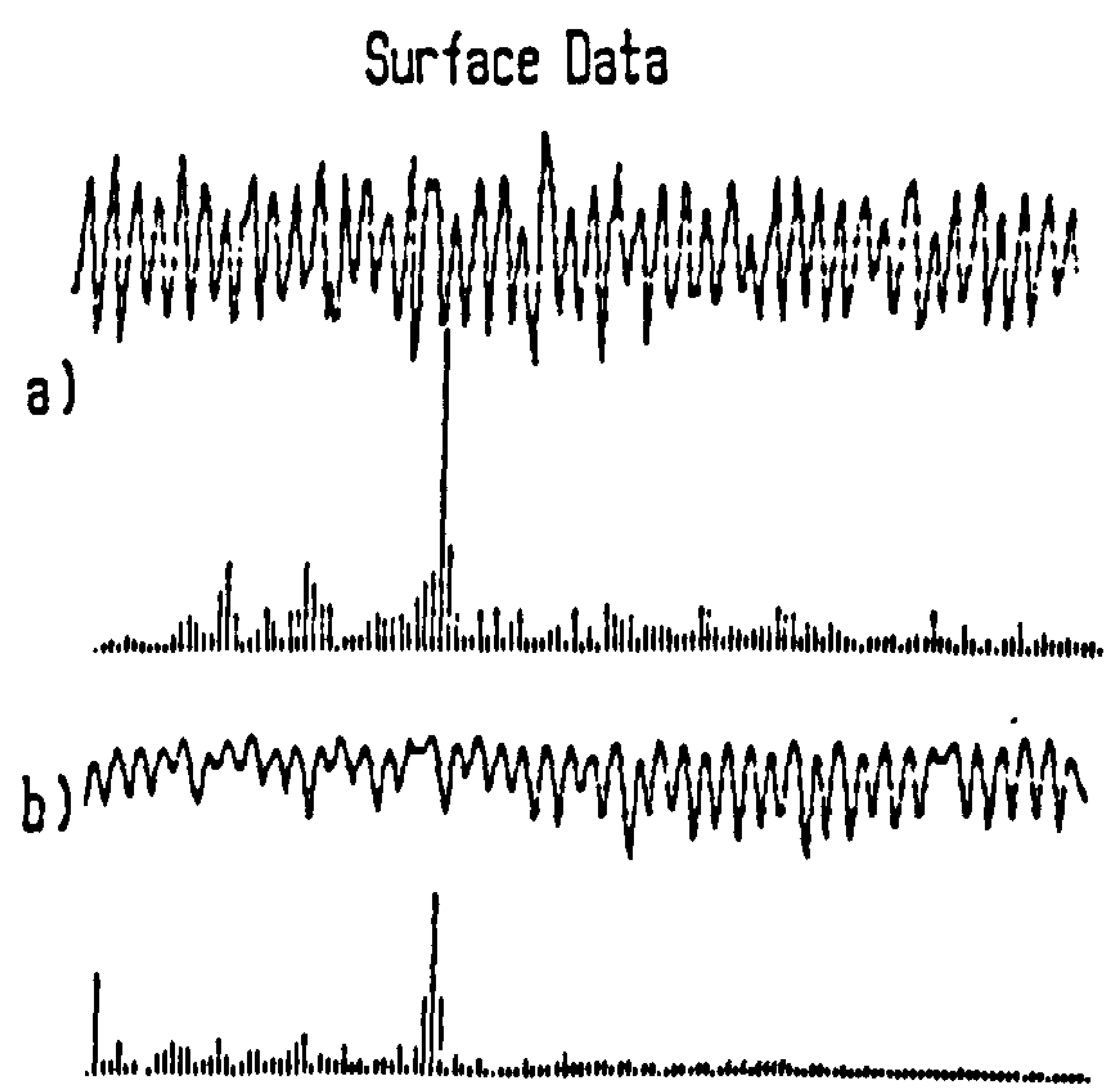


Figure 7

In-Process Surface Topography Measurements Predict Machine Performance and Condition.

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Introduction

This review investigates planed and spindle moulding of wooden artifacts (Figure (1)). The woodworking industry desperately requires a reliable method by which to quantify and categorise the surface quality of its planed and spindle moulded products. The current practice is that of visual tactile inspection, which results in a wide variance in what is classed as an acceptable or defective surface finish; what one manufacturer may reject as an unacceptable standard, another may accept as "good". These methods, by their very nature, are subjective and restricted to post process applications.

Woodworking machinery has unique problems due to high speeds of operation. Modern woodworking machines "extrude" timber at extremely high rates, often in excess of 100 m/min. To achieve these rates, high cutter head rotational speeds are used (up to 15000 rev/min) resulting in high levels of noise and vibration with attendant risk of machine bearing failure. Thus if the process develops a fault; eg, blunt cutters, imbalance, then a considerably large quantity of sub standard (defective surface finish) timber can be produced before the symptoms are detected. It is evident, due to these operational speeds, that non-contact sensors capable of monitoring the quality of the product require development.

Because the cutting circle diameter used on planing machines is relatively large (typically 200mm), the depth, h (Figure (2)) of each cusp, produced on the surface of the product, is of the order of a few microns. Due to the surface amplitudes being small, height variations, as such, are undetectable by the naked eye. Investigations have shown that it is the consistency with which the apexes repeat that affect the aesthetic qualities of the machined surface. It is then surface wavelength, or periodic beat, information that is essential for product evaluation by the manufacturer.

Realisation

The foregoing introduction clearly indicates the requirement for a fast-response non contact, method of measuring the surface quality of machined timber. Thus the "non-contact-rapid-response" nature of light, coupled with recent advances in laser and opto-electronic technologies, brings about interesting and new possibilities for the in-process assessment of product quality.

Previous work has investigated certain types of machine faults that give rise to identifiable surface waveforms on produced timber. The monitoring system has been designed to measure the surface characteristics of the wooden component in-process. Figure (3) represents the basis of the in-process measurement system. A broad laser beam illuminates the machined surface at grazing incidence ($\theta<1.5°$). The illumination is in the same plane as the traversing workpiece, which gives prominence to the leading slope faces of each surface cusp. A fringe pattern of bright and dark regions is readily observed representing instantaneous surface slope along the product.

A single element silicon photo diode is used to detect variations in diffusely reflected surface laser light as the timber passes from the machine. Automatic gain control and signal conditioning circuitry is used to amplify and filter the output voltage of the photo diode to give maximum dynamic range to the analogue to digital convertor. The sampled output voltage of the photo diode is synchronised using the output of a rotary position encoder, as the system clock for the analogue to digital convertor. Additional electronics control the clock signal for correct read/write operations and memory sequencing.

As soon as the periodic surface information has been captured (in real time) in the computer memory, it is analysed in terms of its frequency content, using Fourier Analysis Techniques (Fast Fourier Transforms). The data captured is not prone to distortion due to vibration, as the plane of vibration is almost perpendicular to the laser illumination. As the laser beam is broad and of grazing incidence to the surface the vibration levels do not exceed the outer limits of the beam. This phenomenon only occurs because diffuse and not specular reflection is being monitored.

At present, actual material throughput is in the region of two to two and a half metres per second. The new system has been designed to cope with a maximum material movement of five metres per second, thus allowing increased capacity as machine operating conditions improve. The system is capable of monitoring wavelengths of one millimetre and greater (one millimetre being a very fine planed surface suitable for furniture manufacturers requirements).

Results

Figure ((4)a,b,) show the resultant surface and illumination profiles with their associated frequency spectra of a machined timber surface, obtained using a Talyrond and novel laser monitoring system respectively. Figures (5) and (6), in the same manner, show other typical machined timber surfaces. The resulting profiles in figure ((4)a,b) were obtained on a six knife cutter head machine. The cutter head was run at six thousand rev/min with a corresponding material feed speed of ninety metres per minute. A deliberate out of balance effect was generated at knife number three on the cutter head (added weights), which resulted in the creation of particular frequency harmonics.

With sample lengths of one hundred and twenty five millimetres and one hundred and twenty eight frequency harmonics shown; wavelengths of one hundred and twenty five millimetres down to approximately one millimetre are representable. The dominant frequency harmonics present in Figure ((4)a,b) are numbers ten and nineteen (12.5mm and 6.58mm wavelengths). These peaks are caused by the out of balance effect and individual cutter head knife markings respectively. Because the out of balance effect occurred once every revolution of the cutter head the approximate frequency harmonic expected was number eight or nine, with these specific operating conditions. It would take 0.0833 seconds to pass one hundred and twenty five millimetres of material, through the machine, at a feed rate of ninety metres per minute. With a cutter head speed in the order of six thousand rev/min there would be approximately eight and one half revolutions within the sample length. In fact from Figure ((4)a,b) it can be seen that there are ten revolutions present. This discrepancy is due to inaccuracies arising from the feed and cutter head speed equipment. As there is an out of balance effect, the knife marks vary in surface wavelength, thus in the frequency spectrum the knife marks are spread over several rather than a single harmonic (eg harmonic numbers 10, 19, etc).

Figure (5) shows similar conditions as that in Figure (4). Here again there is a deliberate once per revolution out of balance effect caused, however, now on a four knife cutter head. In this instant the feed speed of the machine (eighteen metres per minute) is much slower, but the cutter head speed of six thousand rev/min remains the same. The effect of the slow feed speed on the surface is the translation of the out of balance dominant frequency along the frequency spectrum (Higher frequency due to slower moving feed material). As it would take 0.4166 seconds to pass one hundred and twenty five millimetres of timber at eighteen meters per minute. An out of balance frequency would now be generated at approximately harmonic No forty two (Figure((5)a,b)) in the frequency spectra. In addition to the out of balance phenomenon there is a secondary effect resulting in smoothed surface knife marks, this event is indicated in the frequency spectrum due to a lack of other higher dominant frequency harmonics.

Figure ((6)a) shows a single knife finish surface. This surface was obtained using a four knife cutter head with three of the knives used as balancing masses only. With no out of balance effect present, the dominant frequency in the frequency spectra is now due solely to the cutter knife marks on the surface. With a feed speed of eighteen metres per minute it would again take 0.416 seconds to pass one hundred and twenty five millimetres of timber past the cutter head. With a six thousand rev/min cutter head there would be 41.6 revolutions of the cutter head (with a single knife this would be 41.6 identical knife marks) in the sample length. As shown in each of the frequency spectra (figure ((6)a,b)) the dominant harmonic No is number forty five (wavelength of 3mm). The discrepancy resulting again from feed and cutter head equipment inaccuracies.

Conclusion

Non-contact measuring/monitoring hardware and software has been developed to control the quality of planed artifacts. Good correlation between existing surface measuring systems (Talyrond) and the novel laser measurement system has been obtained using harmonic analysis. This comparison has been achieved using a Fast Fourier Algorithm to convert real surface data from the time to the frequency domain. Results have shown that certain machine fault signatures are inherent within manufactured product surface contours. Future work regarding the frequency spectra of trend or catastrophic failures is required for correct initialisation of machine feedback action.

4 Head Planer - Moulder

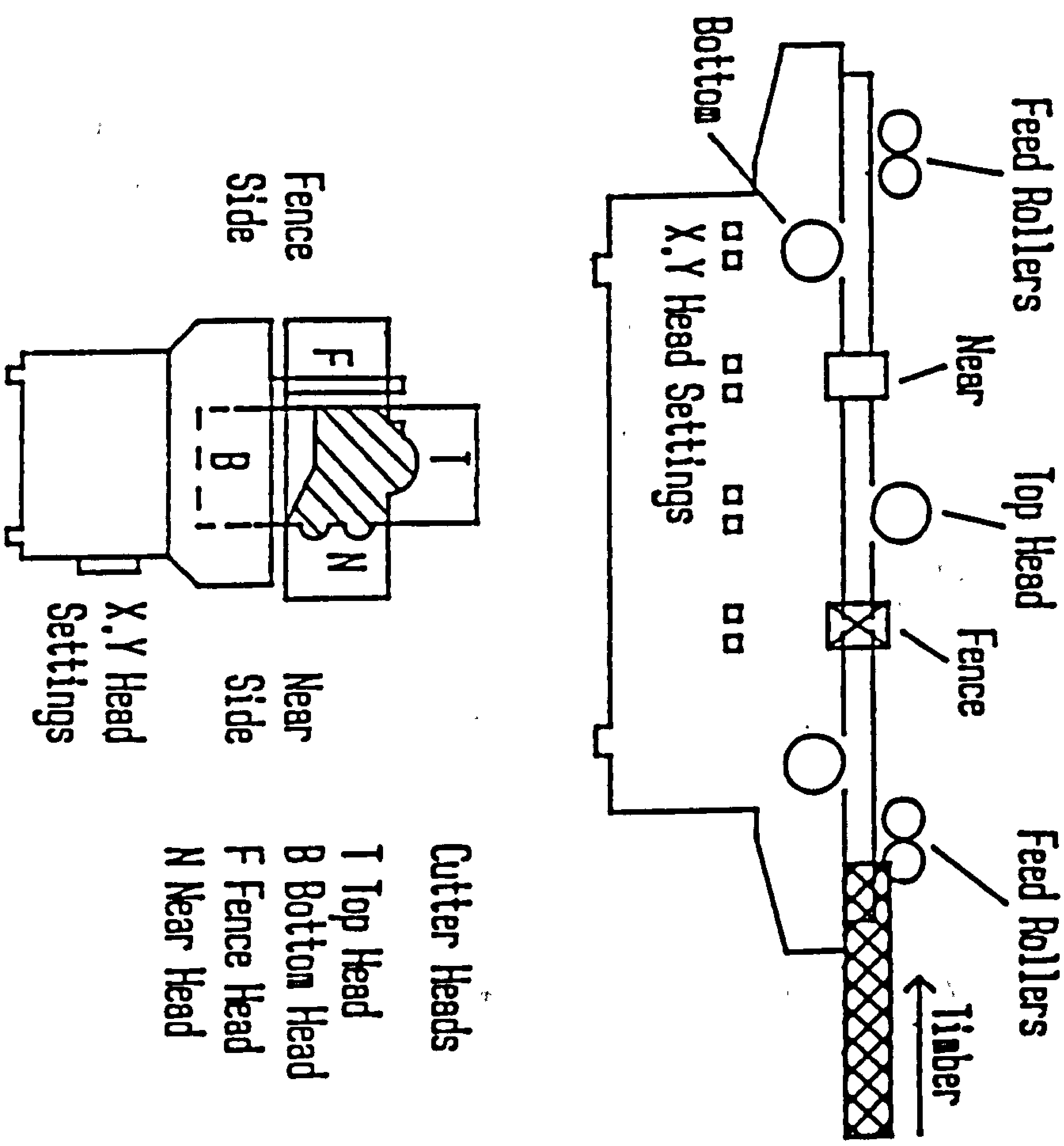
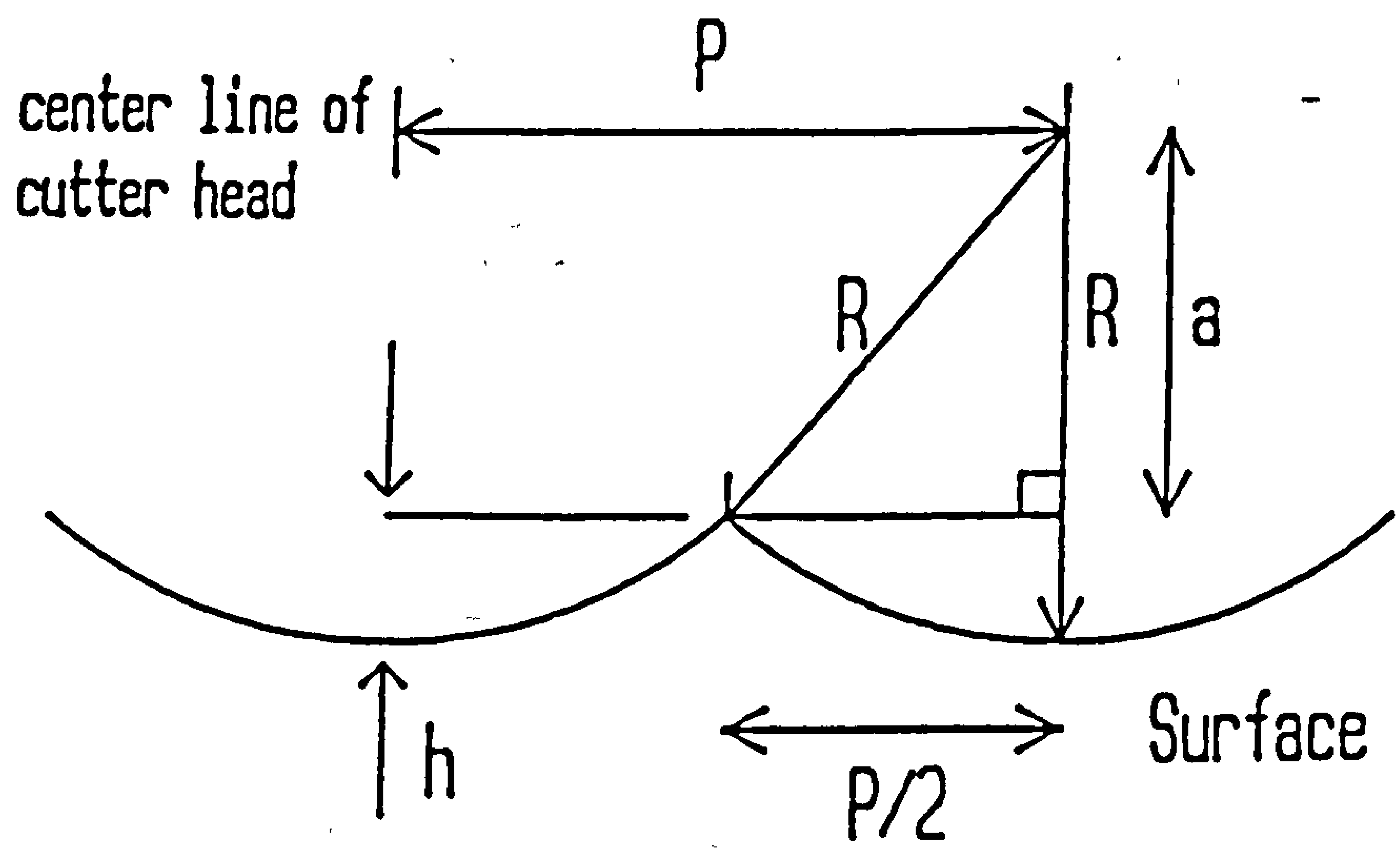


Figure 1

Surface Profile Height and Pitch



$$a = R - h$$

$$a^2 = R^2 - (P/2)^2$$

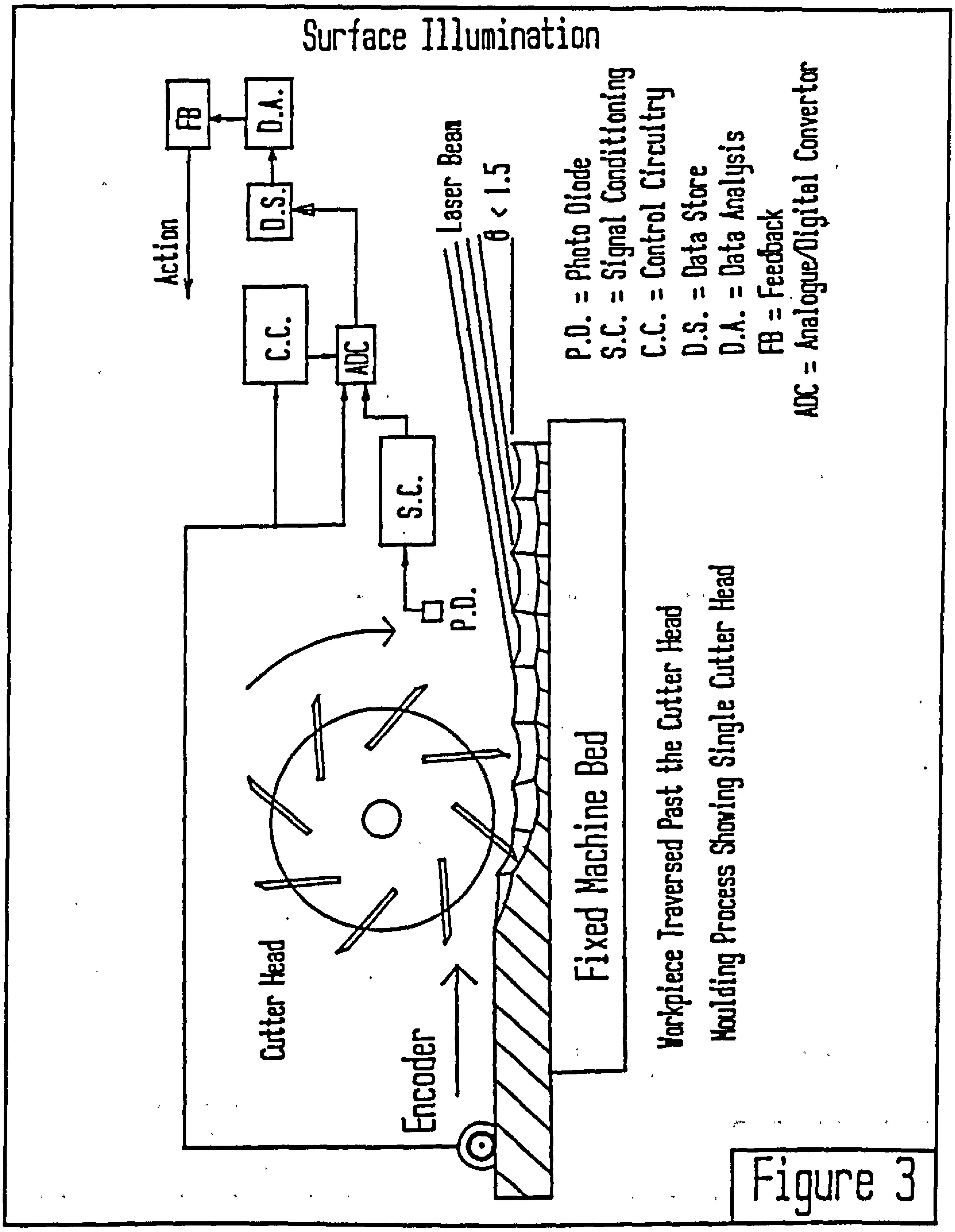
$$a = (R^2 - (P/2)^2)^{1/2}$$

$$h = R - a$$

$$h = R - (R^2 - P^2/4)^{1/2}$$

$$P = (f.\ 10^3)/nN$$

Figure 2



Workpiece Traversed Past the Cutter Head

Moulding Process Showing Single Cutter Head

Figure 3

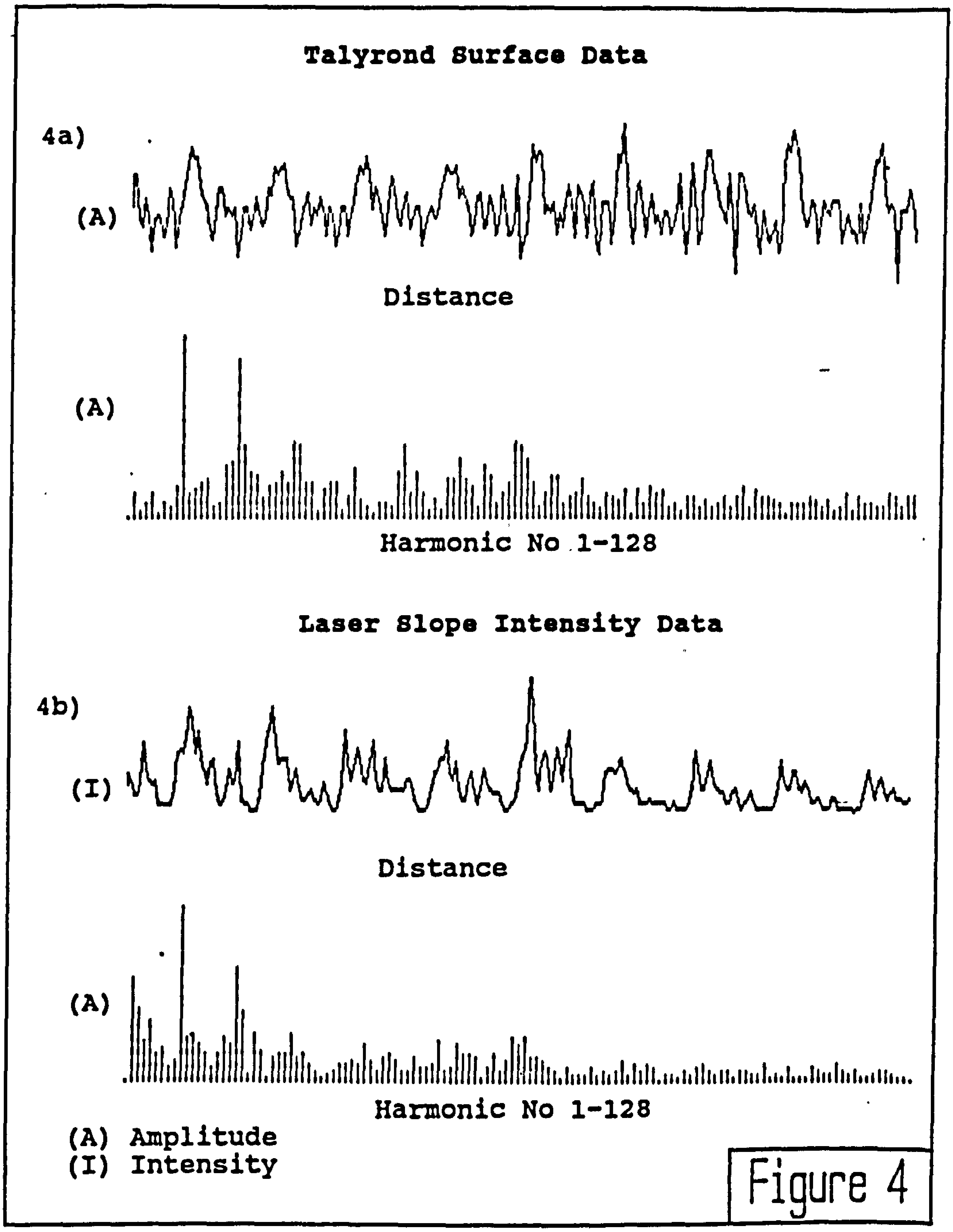

Talyrond Surface Data
4a)
(A)
Distance
(A)
Harmonic No 1-128
Laser Slope Intensity Data
4b)
(I)
Distance
(A)
Harmonic No 1-128
(A) Amplitude
(I) Intensity

Figure 4

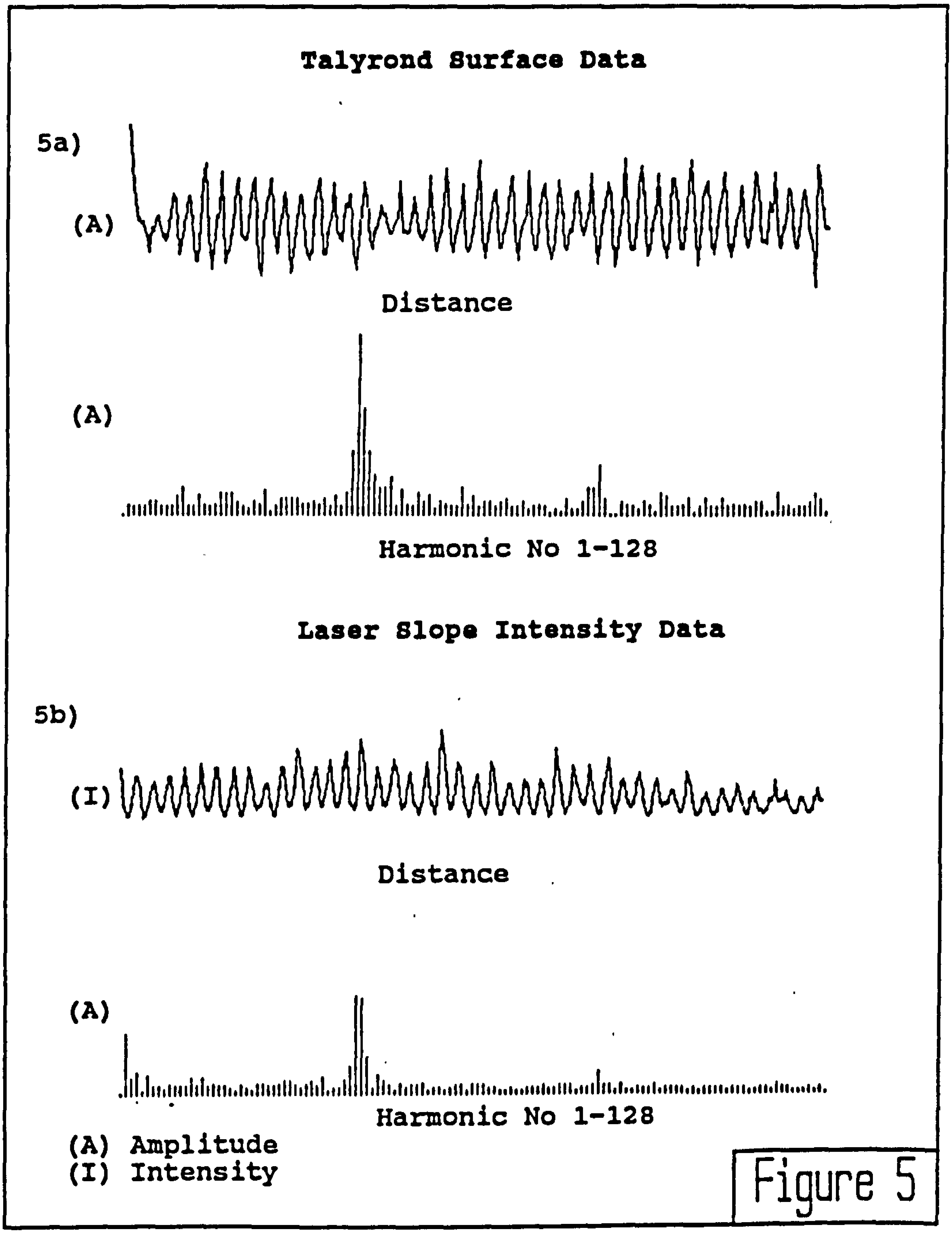

Talyrond Surface Data
5a)
(A)
Distance
(A)
Harmonic No 1-128
Laser Slope Intensity Data
5b)
(I)
Distance
(A)
Harmonic No 1-128
(A) Amplitude
(I) Intensity

Figure 5

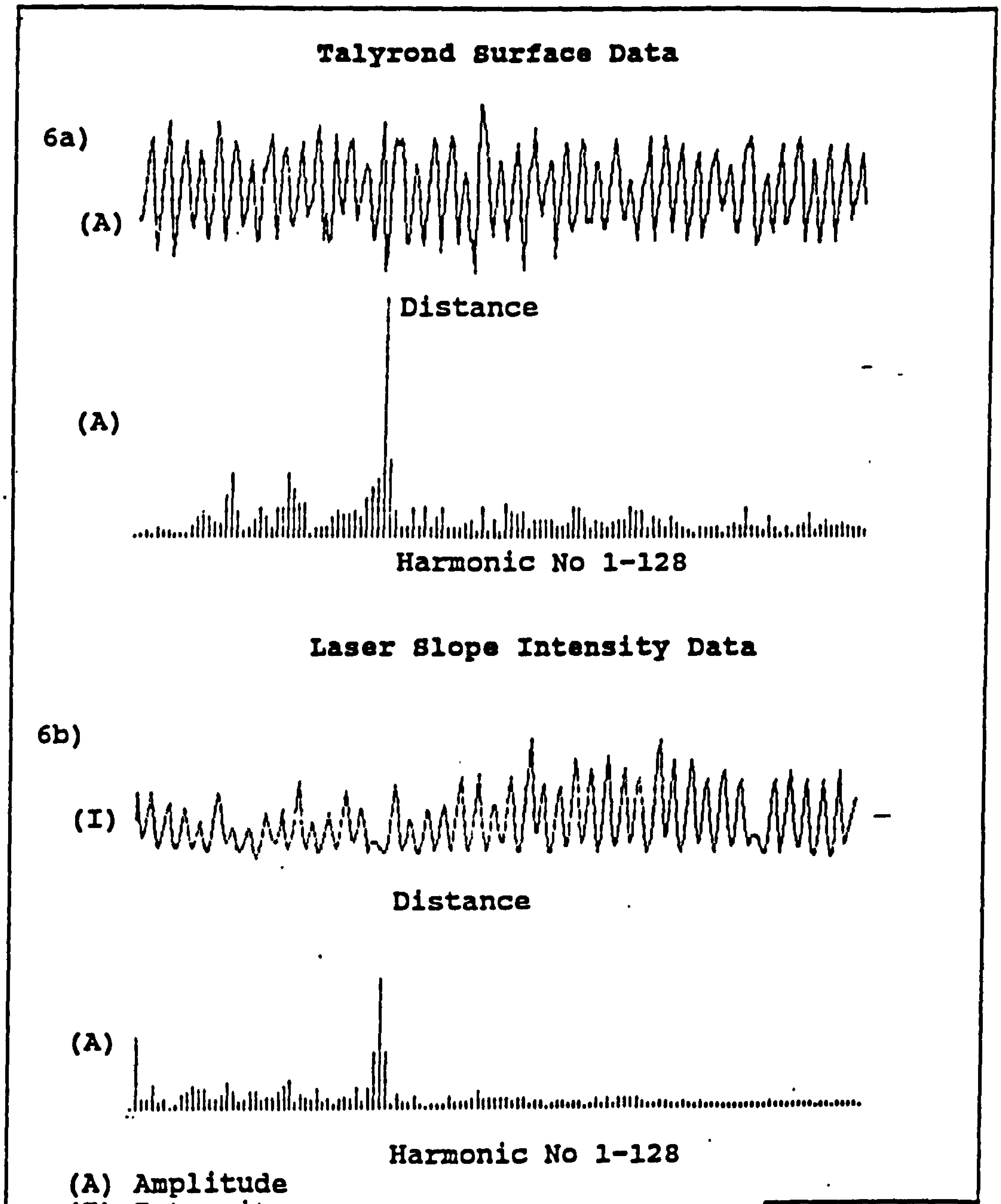

Talyrond Surface Data
6a)
(A)
Distance
(A)
Harmonic No 1-128
Laser Slope Intensity Data
6b)
(I)
Distance
(A)
Harmonic No 1-128
(A) Amplitude
(I) Intensity

Figure 6

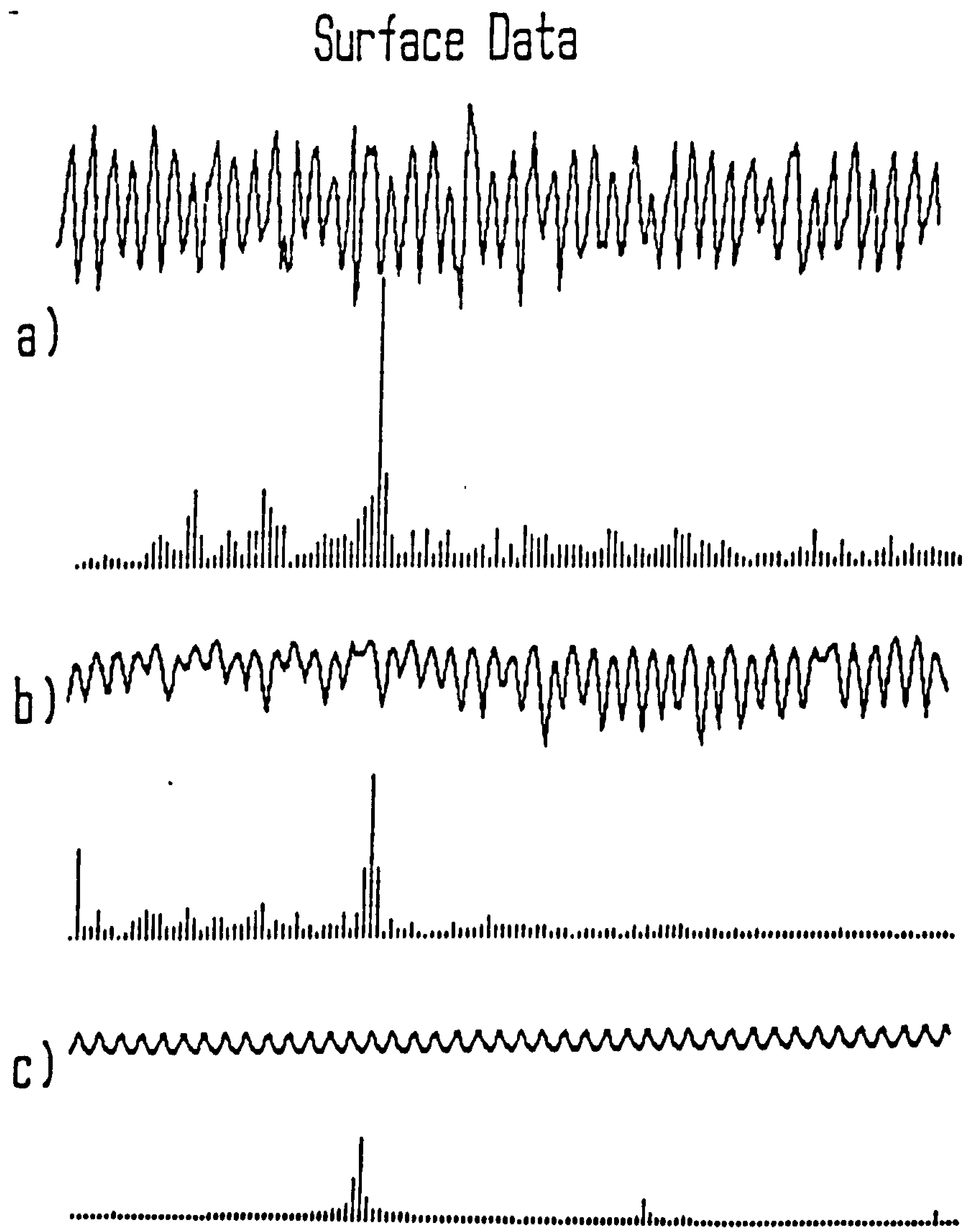


Figure 15