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**FILAMENT WINDING MACHINE CONTROL
USING B-SPLINE INTERPOLATION**

BY

SHAIQ A. HAQ
MS Mech Eng

**Thesis submitted to the University of Nottingham for the degree of
Doctor of Philosophy**

May 1994

DEDICATED

TO

MY PARENTS

The most sincere and loving friends I have ever had.

PROJECT OBJECTIVE

The objective of this project is to introduce a new technique of B-spline interpolation in filament winding machine controller design. This technique promises smoother, more accurate, and faster operation of the filament winding machine resulting in reduced fibre slippage and more even lay-down of material.

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ABSTRACT

Title: Filament Winding Machine Control Using B-Spline Interpolation

By: Shaiq A. Haq

Filament winding is a process for the placement of reinforcement fibres on to a rotating surface in a specified geometric pattern. A conventional straight line interpolation controller is not very appropriate for filament winding because the fibre pay-out-eye is at some distance away from the mandrel surface and its movement from one point to another may disturb the position of previously laid fibre on the mandrel. Filament winding demands a controller which can produce fast and smooth carriage movements, and have a path-anticipation capability so that while moving around curves the effect of pay-out-eye movement on previous fibre positions is minimised. This problem can be overcome by using an interpolation technique which determines the pay-out-eye path by considering more than two data points, and whose profile is continuous in nature up to its second derivative. In this project an IBM PC based filament winding controller, using B-spline interpolation technique, is developed. To test the performance of the controller a 3-axis CNC filament winding machine was designed and manufactured. For optimum performance, emphasis was given to the low inertia of the machine carriage, while at the same time maintaining the system's structural stiffness. To reduce the machine carriage weight, the DC servomotors were installed on the machine's frame, instead of the carriage, and a timing belt arrangement was used for power transmission. The controller's electronic hardware was assembled using servo amplifiers, DAC cards, and a purpose built optical encoder interface card. The controller software was developed using TURBO C++ as the main programming language, whereas the hardware interface routines were written in Assembly Language. Problems of winding path deviation as a result of B-spline approximation were tackled using knowledge based programming techniques. The results showed a considerable improvement in winding speed and less fibre slippage in the case of non-geodesic winding patterns, resulting in higher accuracy of fibre placement on the mandrel.

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NOMENCLATURE

The symbols used in this thesis have the following meanings unless stated otherwise in the text.

A	Mandrel rotation about X-axis
A_1, \dots, A_n	Coefficients
B	Pay-out-eye rotation about Y-axis
C	Pay-out-eye rotation about Z-axis
C_n	Actuation signal produced by the controller at the nth step
F	Friction constant
$G(s)$	Transfer function
$G_c(s)$	Controller transfer function
$G_p(s)$	Plant transfer function
$G'(s)$	Overall closed-loop transfer function
I_a	Motor armature current
J	Overall inertia of the motor and the load
J_L	Inertia of the load
J_m	Inertia of the motor
K	A constant
K_{amp}	Servo amplifier gain
K_E	Electrical constant of the motor
K_M	Mechanical constant of the motor
K_T	Torque constant of the motor
K_p	Proportional gain of the controller
K_d	Derivative gain of the controller
L	A constant force sufficient to overcome friction
R	Motor armature resistance
T_L	Load torque
T_m	Motor torque

W_c	Energy dissipated in the motor armature
X	Displacement along mandrel longitudinal axis
Y	Displacement along pay-out-eye cross feed axis
Z	Displacement along pay-out-eye height axis
a_1, \dots, a_n	Polynomial coefficients
b_1, \dots, b_n	Polynomial coefficients
c_1, \dots, c_n	Polynomial coefficients
i, n, m	Indices, when used in subscript or superscript
k	Slippage tendency
r	Mandrel radius
t	Time
v	Supplied voltage
v_m	Motor back emf
α	Winding angle
β	Winding pattern crossing angle
ψ	Slippage angle
θ	Present angular position
θ_d	Desired angular position
ω	Angular velocity
μ	Coefficient of friction
η	Efficiency
ϕ	Magnetic flux
τ_m	Motor coefficient in terms of time
τ_d	Controller derivative time

CHAPTER 1

INTRODUCTION

Composite materials are receiving much attention these days because of the demand for high strength light-weight structures. Composites, in the strictest sense, consist of multiphase materials having at least one matrix and one dispersed phase. The matrix phase can be any bonding agent like glue, plastics, or metals, and the dispersed phase may be in the form of fibres, particles, or flakes. Composite materials can be made with various processing techniques. The Filament winding process deals with that branch of composite materials in which plastics are used as the matrix material and the dispersed phase, responsible for reinforcement, is in the form of fibres. This branch of composite materials is called continuous-fibre-reinforced polymers. In filament winding, commonly used reinforcement materials are glass fibre, carbon fibre, and aramid fibre. The polymer can be of either thermoplastic or thermosetting type. Thermosetting resins, like epoxy and polyester resins, are very popular in the filament winding process.

1.1 Filament Winding:

Manufacturing of fibre reinforced polymers using various winding methods has a history that dates from the beginning of this century ^[5]. This process gained popularity in 1947 when US government began sponsoring intensive research and development efforts for the production of high specific strength pressure vessels ^[6]. According to Eshbaugh^[7], the first operation of a modern form of filament winding machine was reported in 1948. Due to the limitations of mechanical cam

and gear type winders, this early work was limited to the production of simple tubes and spherical pressure vessels ^[3]. Rosato and Grove have summarized the details of the filament winding process and applications up to 1964 in their book ^[6]. To the best of this author's knowledge, this is the only authentic book specifically written on the filament winding process. This book is a good source of very basic knowledge on the process, and contains most of the early references on filament winding. Other than this book, filament winding literature is available in numerous research papers and product information leaflets published by various manufacturers.

The filament winding process is the machine based technique whereby a fibre roving, wetted with a controlled amount of resin, is laid in an oriented manner on to a mandrel that provides the finished component shape. In this process fibre bands are accurately placed on the mandrel according to a pre-planned pattern. By aligning the filaments in the direction of the principal stresses ^[40], it is possible to manufacture components with a very high strength to weight ratio ^[5]. This specific strength, unmatched by any other composite material manufacturing process, makes filament winding very attractive for aerospace, automotive, and defence products. Some applications of the filament winding process are shown in Figure 1-1. For reliable repeatability of complex patterns, computer control found use in the seventies. In the late seventies micro computers started replacing mini computers and the cost of computer control fell sharply. With micro computers, due to computer-aided design and manufacture techniques in the filament winding process, complex shapes like T-pipe fittings were also included in the list of filament wound products ^[11]. Roser ^[43], Edwards ^[44], Owen et al ^[11], and Spencer ^[45] have reviewed the filament winding process and its modern day applications.

Due to advances in the manufacturing process, fibre-reinforced composite materials have become very popular as alternative engineering materials for their high mechanical strength, low density, corrosion resistance, and low cost processing. Filament winding has an additional advantage over other processing

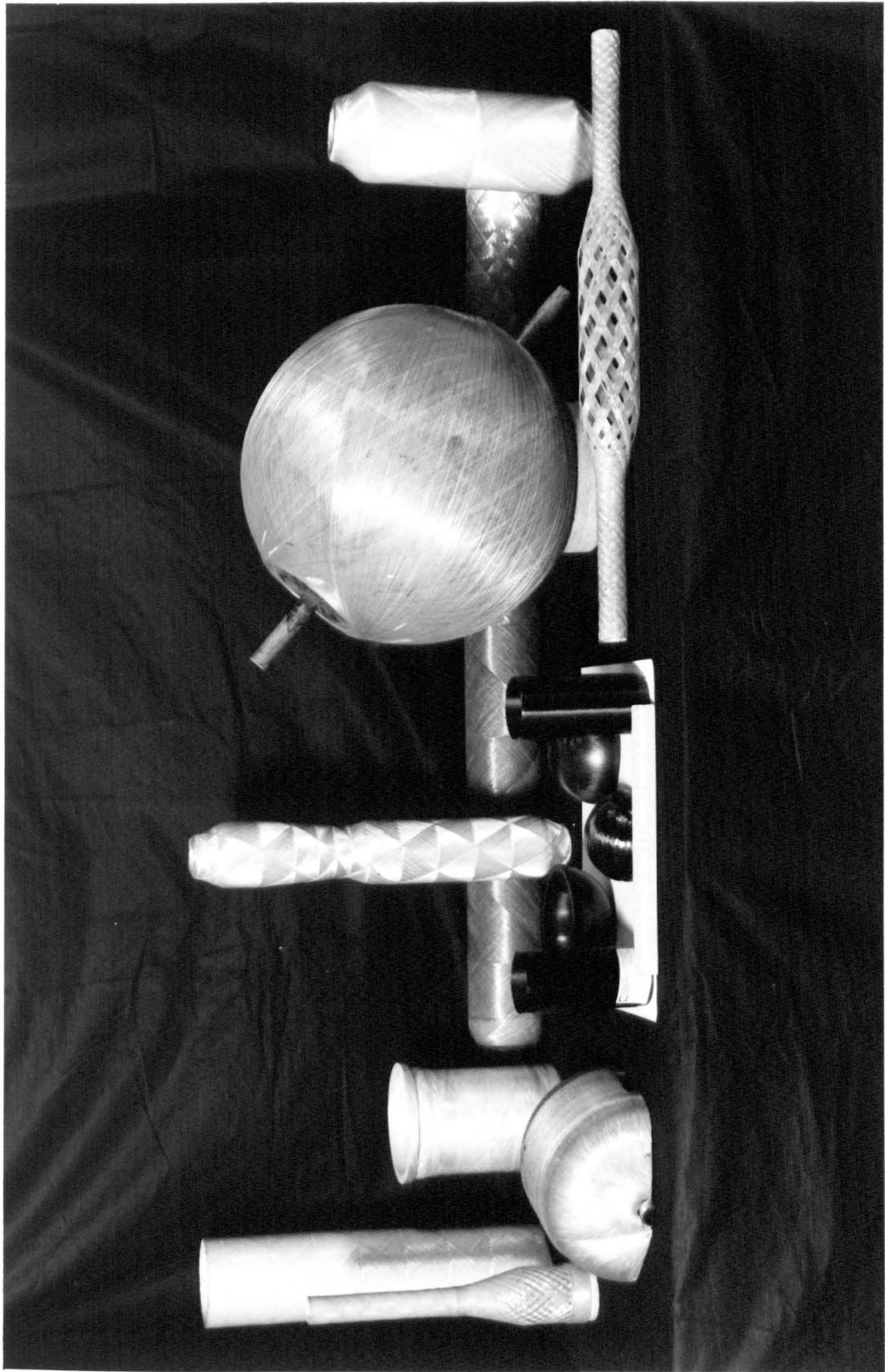


Figure 1-1: Some Applications of the Filament Winding Process

techniques in that different mechanical properties can be obtained by changing the winding pattern. *Fibre* orientation becomes very critical when the composite is to be designed for optimum strength, as in the case of pressure vessels, high speed rotating cylinders, and pipe couplings where complex shapes may be involved.

1.2 Filament Winding Machines:

The early filament winding machines, reported in the forties and fifties, were mechanical systems with a single electrical motor driving both the spindle and a chain-driven carriage. The ratio of the carriage motion to mandrel rotation, set by gear trains, established the winding angle and pattern ^[41]. The special winding requirements of dome-ended cylinders and rocket motor cases demanded more sophisticated machine control. In the sixties, machines with hydraulic servo controls, cam followers, and line tracing systems were developed to produce special motion necessary for winding geodesic paths on ovaloid domes. ^[7].

Attempts to computerize filament winding machines were started in the early seventies. In 1973 the first microprocessor-controlled filament winding machine was developed by Engineering Technology Inc. (Entec), under a US government contract. In 1976 the first commercially available computer controlled machine, the McClean Anderson model 60, was introduced ^[7]. Entec announced its 500 series and 900 series machines in 1980. Until 1980 approximately 70 micro-computer controlled filament winders were put in to operation, some 52 built by McClean Anderson, over 10 from Goldsworthy Engineering Inc., and 3 from Entec Inc, all manufactured in the USA ^[42]. A computer controlled filament winding machine developed by Pultrex Ltd., UK, is shown in Figure 1-2 and Figure 1-3. In 1986 Retek corporation reported a relatively inexpensive computer controlled winding system by retrofitting mechanical winding machines ^[7].



Figure 1-2: A CNC Filament Winding Machine Made by Pultrex Ltd.



Figure 1-3: The Fibre Tension Controller and Resin Impregnation System

Hermansen & Roser^[46] have given a review and selection criteria of various types of filament winding machines. A survey of the literature^{[2] [9] [10]} shows that mechanical helical winders provide a cost effective and reliable solution for simple tubular shapes. For small pressure vessels which require closed ends and higher production rates, polar winders are more popular. Computer controlled winders provide the best solution for non-linear winding applications and those are used where the machine needs frequent re-programming for different geometries.

Filament winding machine sizes and specifications vary a great deal, depending on the end-user requirements. Machine manufacturers have developed special machines dedicated to single applications. McClean Andersen built a multi-axis computer controlled machine to accommodate a mandrel of up to 14 m length, 4 m diameter, and 5 tonnes weight^{[41] [42]}, for MX missile rocket motor cases. Entec has reported a 5-axis computer controlled machine for manufacturing wind-turbine blades. This machine can accommodate a mandrel of up to 60 m length, and 8 m diameter^[42]. Successful attempts have been made to use a general purpose robotic arm^{[2] [16]} instead of a proper filament winding machine. The development of the adaptation mechanism and the high cost of the robot detract from using robotic arms for filament winding.

1.3 Filament Winding Controllers:

Due to advances in control technology and because of the demand for complex shaped filament wound structures, mechanically controlled filament winding machines have been eclipsed. With an increase in the demand for computer controlled machines with smooth interpolative movements, it is desired to develop new controllers specifically designed for filament winding operation.

Many of the present day computer controlled filament winding machines use

general purpose controllers which have been developed for metal cutting machines. In these controllers, the cutting tool path is specified by supplying a series of points lying on that path. The movement of the cutting tool is controlled in such a way that its path between two specified points is a straight line or circular interpolation and it is ensured that each point is met accurately. For metal cutting operations this control philosophy is perfectly adequate but for filament winding, in which the tool path is different from the fibre placement path on the mandrel, this technique is not very appropriate and slows down the winding operation. There is a need to develop new techniques for filament winding so that the speed of winding may be increased and the accuracy of fibre placement may be enhanced.

1.4 Objectives of Study:

To encourage and promote the use of fibre-reinforced composite materials as an alternative engineering material, the cost of manufacturing will have to be reduced and the quality of filament wound products will have to be improved. The quality of the product can be raised by improving the fibre placement accuracy and reproducibility of the process. The manufacture of complex shaped components by the filament winding process is relatively slow compared with other manufacturing processes and thus not suitable for applications demanding a high rate of production. There is a need for improving the rate of production in this manufacturing process. Other than meeting the production targets in time, the manufacturing cost can also be reduced by increasing the rate of production.

In the manufacture of filament wound components, based on glass fibre, the cost of raw material is relatively low but the cost of CNC filament winding machine is very high. Most of the commercial CNC filament winding machines do not provide the necessary return on investment for winding general commercial products. Also, this heavy initial investment makes the technology unaffordable

for small scale industries. To promote the use of filament wound components it is important to produce low cost filament winding machines, so that this technology is affordable even for small industries.

The main objective of this study is to design a controller for filament winding machine which will improve its performance in terms of speed of winding and accuracy of fibre placement. While developing a filament winding machine for this project, emphasis is given to the low cost of construction of this machine. The low cost and high performance of this equipment should be affordable for workshop type industries.

1.5 Contribution Towards Knowledge:

A new technique for filament winding machine control is used in this project. According to this technique, the winding path is planned and controlled using B-spline interpolation, rather than using linear interpolation technique. The use of the B-spline interpolation technique for filament winding machine control has not been reported previously in the literature. This new technique helps in smoother, more accurate, and faster operation of the filament winding machine.

Further minor contributions are made towards knowledge by introducing new concepts in the mechanical design and control of filament winding machine. Advances are made in reducing the weight of the filament winding machine carriage by mounting the servo motors on the machine frame rather than on the carriage itself. This reduces the weight of the carriage and a light weight carriage requires a smaller servo motor for its drive. The servo motor performance is further improved by matching the load moment of inertia with the rotor moment of inertia.

Generally different axes of a filament winding machine have different inertia and thus require different values of controller constants for the control system. The controller developed for this filament winding machine is tuned by a non-conventional technique which is specially developed for this project. This technique can be used to tune the controller gain constants in such a way that the same value of controller constants can be used for all the axes of the filament winding machine.

CHAPTER 2

FUNDAMENTALS OF FILAMENT WINDING

The method of filament winding machine control requires skills in filament winding which is a subject of mechanical engineering, and electronic control which is a specialty of electronic engineering. This thesis is written in such a way that it provides basic information about filament winding as well as electronic control.

In designing and manufacturing a filament winding machine and its controller, it is important to study the process from a practical point of view. Information about filament winding is scarce because most of the research work is done in the defence industry domain, or unpublished due to its commercial nature. The author has tried to gather together useful practical know-how about filament winding in this chapter. This collection of information and data, mainly gained through industrial experience, is essential if high quality components are to be manufactured by filament winding. Most of the literature on filament winding is published in the form of research papers in various technical conferences and journals. In the literature review, the Society for the Advancement of Materials and Process Engineering (SAMPE) in USA has emerged as the leading organisation on publishing good quality technical papers on composite materials and their processing.

2.1 The Filament Winding Process:

Filament winding is a processing technique for producing high specific strength

fibre-reinforced polymer products^[71]. General terms used in this process are collected and defined in the 'Glossary of Terms' at the end of this thesis. These terms are written in *Italic* when they appear in the text for the first time.

The filament winding process can be classified in to two major categories;

- i- *wet winding*
- ii- *dry winding*

The dry winding process^[68] deals with the winding of thermoplastics and *pre-pregs*. A pre-preg is a ready-to-mould material in which a fibre *roving* or *web* is pre-impregnated with resin which is partially cured so that the roving is handleable at room temperature. The dry winding process does not require any resin impregnation system at the winding stage. In the wet winding system^[43] the fibre rovings are passed through a resin impregnation system and then wound on the mandrel in a specified geometric pattern. The only difference between the two systems is in the method of impregnation.

In a typical wet winding process the fibre rovings are drawn from spools, through the impregnation system where they are wetted with the resin. The rovings are kept under tension and their position is controlled by a number of filament guides. The impregnated rovings are led, via the final guide, usually called the *pay-out-eye*, on to the rotating mandrel where winding takes place. For a successful winding, movement of the pay-out-eye along a specified path and its coordination with mandrel rotation is very essential^[4]. When winding is completed the composite is cured at room temperature, in an oven, or in an autoclave, subject to the type of *resin* system used. Depending on the design of the product, the mandrel can either be removed or left inside the winding as an integral part of the product.

A filament winding system (Figure 2-1) essentially consists of three basic units;

1. A fibre spool holder and the equipment for controlling the roving tension

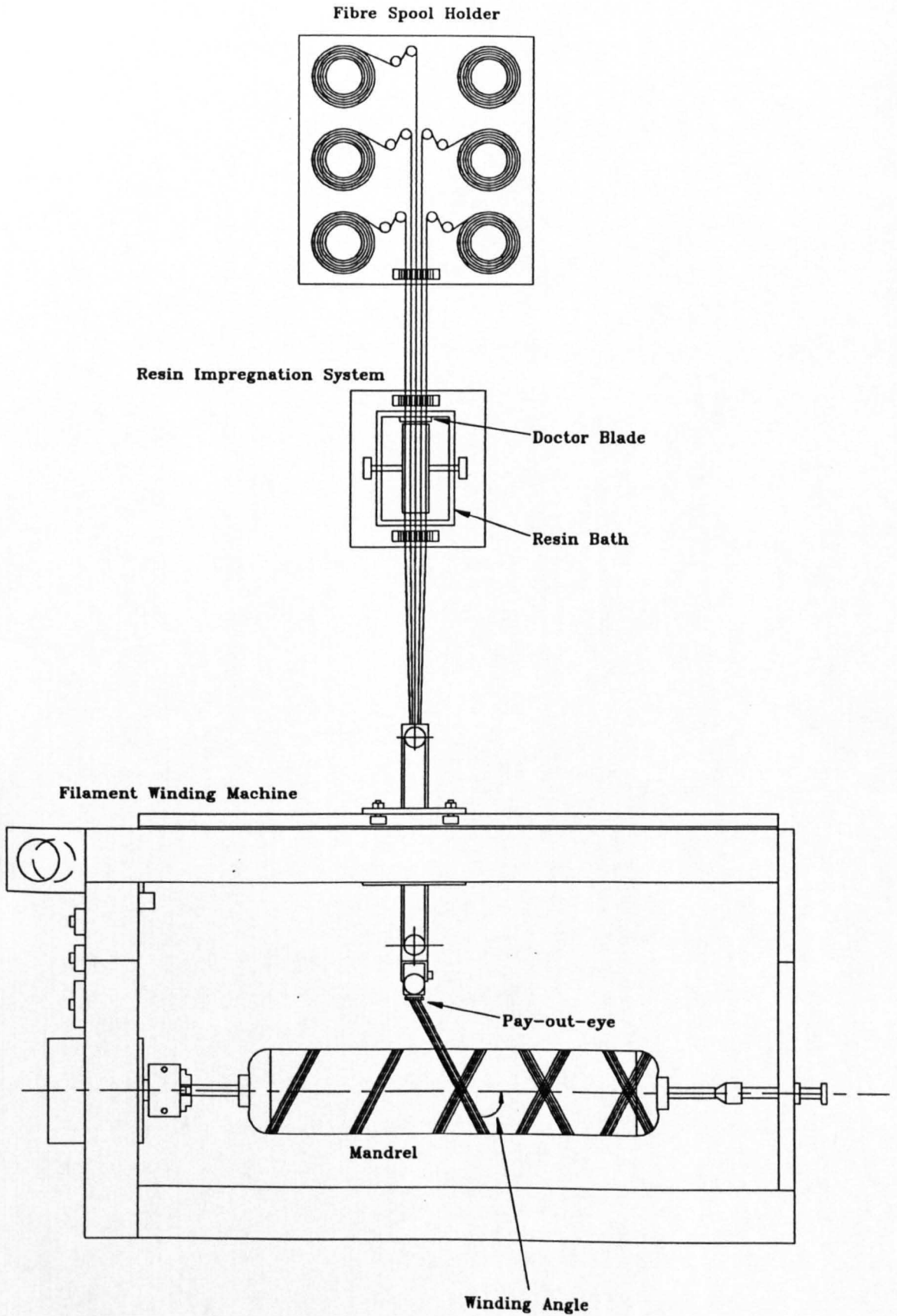


Figure 2-1: A Filament Winding System

2. An impregnation system which includes the resin bath and equipment necessary to control the resin impregnating the roving, e.g resin temperature control, pressure roller, *doctor blade* etc.
3. A winding machine by which the mandrel is rotated and the pay-out-eye is traversed to lay the fibres uniformly over the surface.

For accuracy and repeatability, and to produce high quality products, a high degree of automation is required in all the three units. These units can be controlled independently or together using a central computer system. The fibre tension control and resin impregnation control are simple analogue feedback systems. System interconnection is minimized by using independent hard-wired controllers in fibre tension control, and resin impregnation control. The winding machine, being more complex in nature, is controlled by a computer which can move the axes of the machine according to a given path.

2.2 Mandrels for Filament Winding:

Mandrels are used to provide the finished part internal geometry. Mandrel materials include; steel, aluminium, dissolvable or fusible materials, and inflatable rubber bladders. Steel is used for parts requiring a high cure temperature, part to part repeatability, and long tool life. Steel mandrels are generally heavy and care must be exercised in their use that the overall weight of the mandrel and the product does not exceed the mandrel weight bearing capacity of the filament winding machine. Some pressure vessels require internal metal liners because filament wound composites are porous at high pressures. The liners, which may be metal or thermoplastic, remain in the structure after winding and serve as stay-in-mandrels^[65]. Rocket motor cases, like pressure vessels, have closed or reduced end openings and require dissolvable or fusible mandrels. Some of the dissolvable materials used include sand with a water soluble binder, plaster,

eutectic salt, and low melting point alloys. Specialized mandrels that are used to a less extent include inflatable rubber mandrels and segmented metal mandrels which can be disassembled inside the part and removed through small end openings.

2.3 Materials for Filament Winding:

In filament winding the purpose of using a reinforcement fibre is to provide strength in the product. Various type of fibres are used in filament winding, among which glass fibre, carbon fibre and Kevlar are more common. E-glass fibre is the most popular fibre in filament winding due to low cost and high performance^[69]. S-glass (Strong glass) fibre is used where high strength of the composite is desired. Carbon fibre and Kevlar are used when high specific strength is desired in the composite.

The purpose of the matrix material is to bind the fibres together in to a rigid structure and to provide a shield from environmental effects. Any thermoplastic or thermosetting binding agent can work as the matrix material. In wet filament winding, more commonly used matrix materials are Epoxy resin and Polyester resin. Epoxy resin is more expensive than polyester resin but provides a higher bonding strength with the fibre and thus produces a more brittle structure. Polyester resin is cheaper and is preferred when higher toughness of the composite is desired^[53].

Before designing a filament winding machine, it is necessary to understand the effect of various process parameters and the function of machine parts in more detail.

2.4 Effects of Fibre Tension:

Fibre tension has a significant effect on the properties of the composite. Fibre content in the composite increases with increase in fibre tension because the resin-absorption-capacity of the fibre decreases with increasing tension. Higher fibre content results in higher strength of the composite material. In the filament winding process the fibre volume fraction range can be varied from about 20% to 75%, with 60% volume fraction being a commonly used figure. Fibre tension also influences the *Fibre spread* on the mandrel. Higher fibre tensions produce an improved fibre alignment which results in a higher composite modulus and a lower elongation at break in the direction perpendicular to the fibre. Maximum fibre tension is restricted by the tensile strength of the fibre. Generally its value is kept below 5% of the nominal tensile strength of the fibre. Ideally tensions should not be allowed to vary by more than 5%, otherwise fibre waviness and twisting would result and irregular surfaces will form on the mandrel. Roving tension is specified in terms of force per unit thickness of the roving. The units used for expressing roving thickness are *tex number*, number of *filaments* present in the roving, *yield*, and *denier size*. These terms are defined in the Glossary of Terms. Practical fibre tension values are, for glass roving 6-7 N/1000 *tex*, for carbon 3-4 N/1000 filaments, and for aramid 2-3 N/1000 filaments ^[53].

2.4.1 Fibre tension control:

Fibre tension can be controlled by passing the roving over a peg or a braking device. A braking device provides more precise control than a peg. In the braking method, the fibre tension can be controlled either by braking the spool or by braking the roving with a roller. Braking the spool is less harmful to the fibre but in this method the friction must be varied with the spool inertia and the spool diameter. The roving tension can be controlled by a spring loaded dancer roller or a torsion device in its path, as shown in Figure 2-2. The dancer arm

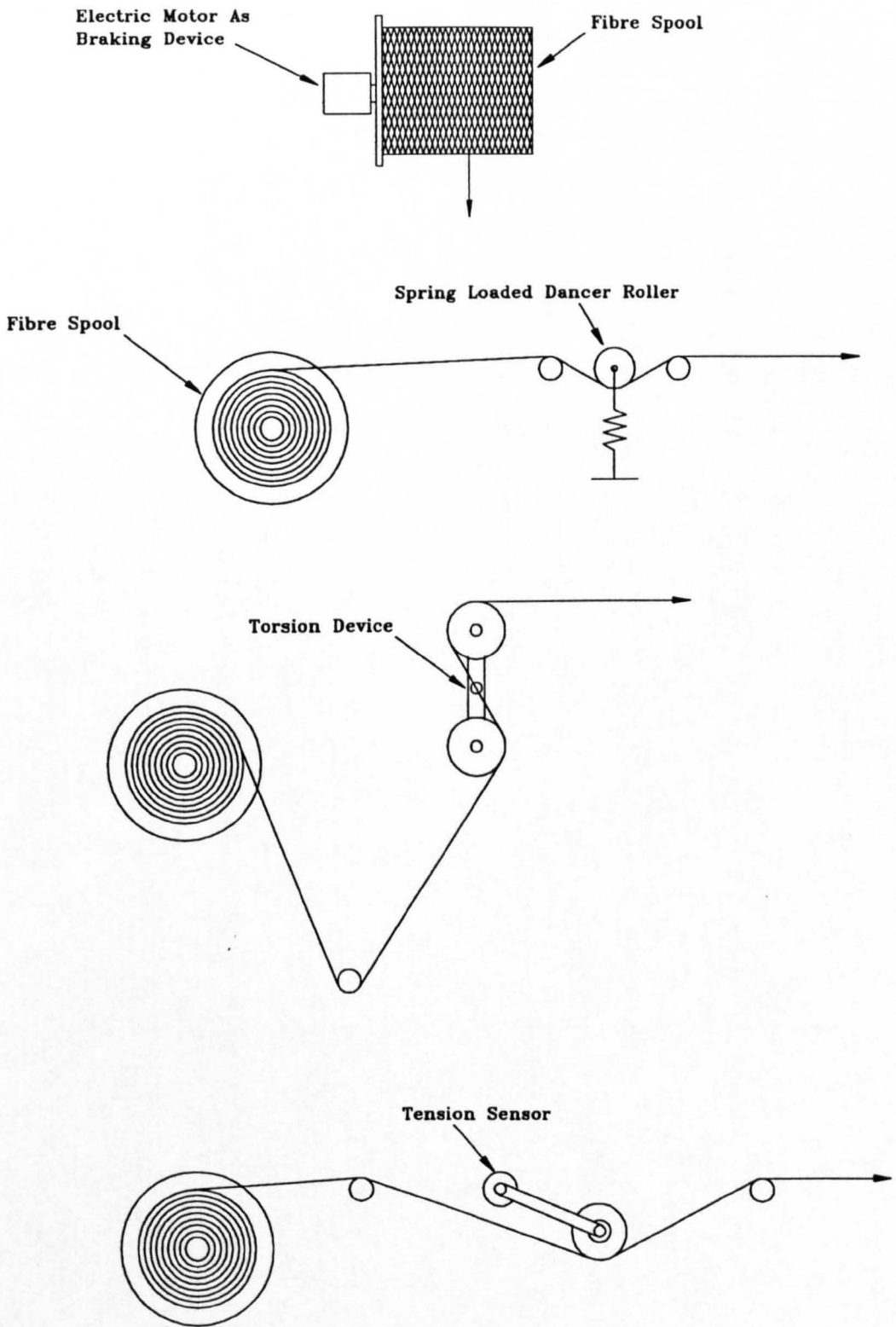


Figure 2-2: Fibre Tension Control Arrangements

absorbs the changes in the roving tension caused by the spool inertia effects.

In a preferred method of fibre tension control, the fibre tension is sensed by an in-line tension sensor and on the basis of this tension the spool is braked with an electric motor. This method provides a constant fibre tension throughout the winding process. The in-line tension sensor can be in the form of a potentiometer determining the position of a spring-loaded roller arm, or a strain gauged spindle. Depending on the roving tension, a voltage is generated which regulates the braking torque of the motor that drives the spool.

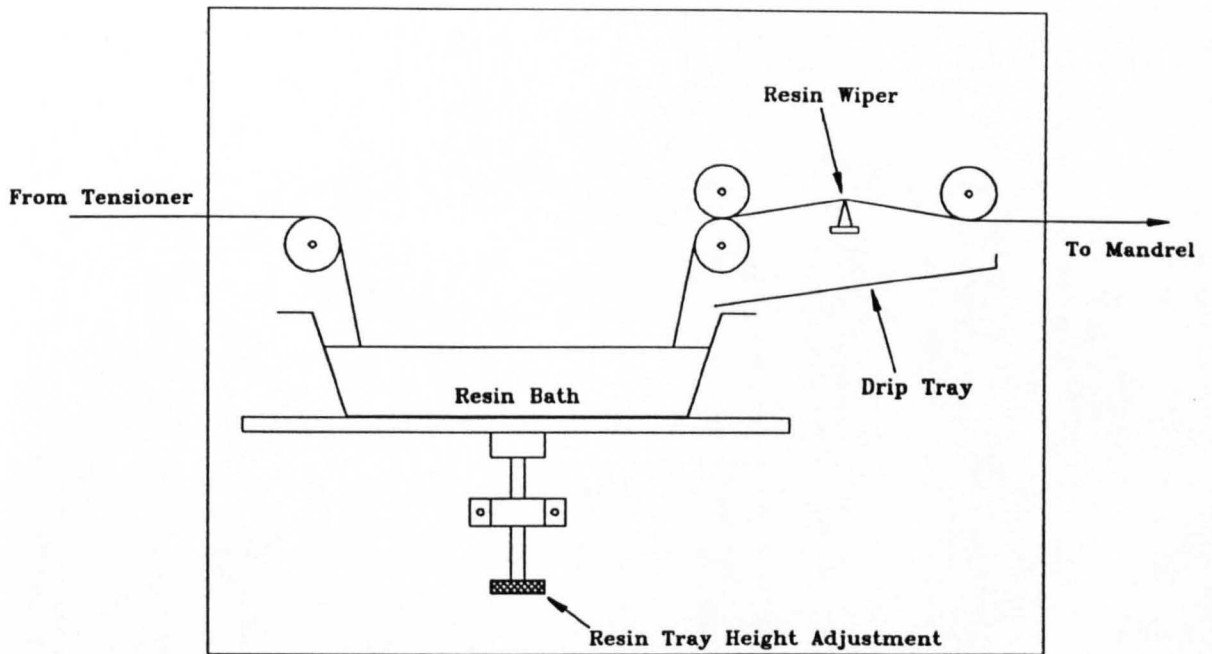
2.5 Resin Impregnation:

To bind the reinforcement fibres together a thin coating of resin is applied to the fibre roving in a resin impregnation system. The resin impregnation system is responsible for ensuring the correct amount of resin pickup and for the removal of air present in the roving. In addition, a good impregnation system should also separate filaments which may be stuck together by the *size* used in their manufacture, so that they can be embedded in an optimum way in the resin matrix.

2.5.1 Types of resin impregnation systems:

Two type of resin impregnation systems, namely *Dip Impregnation* and *Roller Impregnation* are commonly employed, Figure 2-3. In dip impregnation the roving passes under fixed bars immersed in the resin bath. The excess resin is removed with the help of resin wipers or pressure rollers. This process is useful when a high resin content is desired in the composite. For high fibre content in the composite, the roller impregnation system is used. In this system a controlled

DIP IMPREGNATION



ROLLER IMPREGNATION

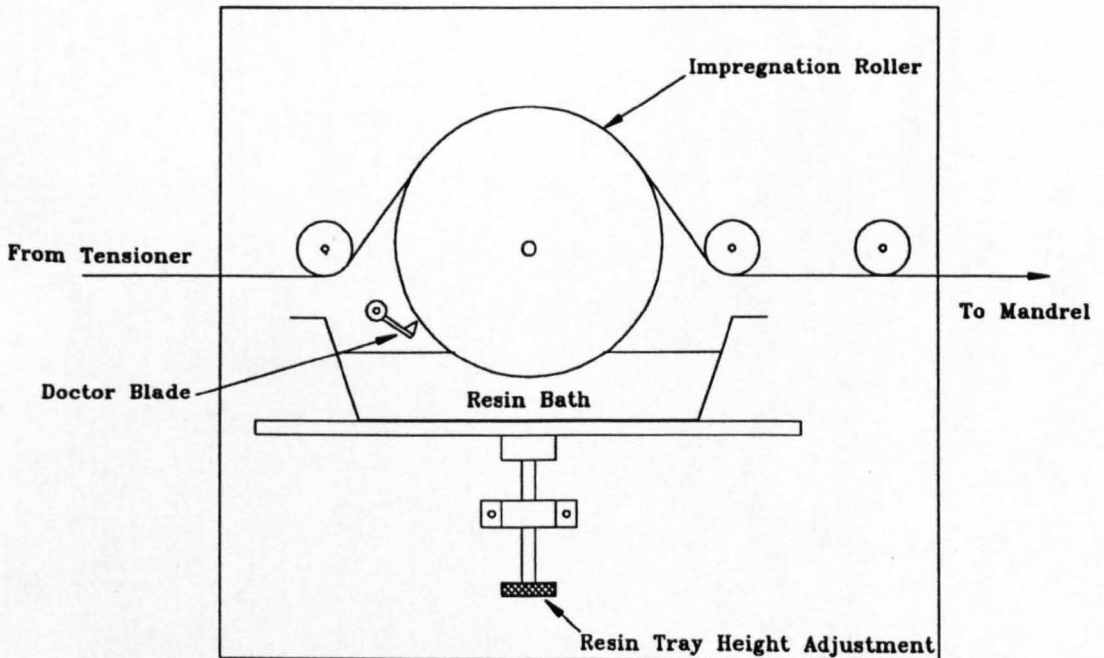


Figure 2-3: Two Types of Resin Impregnation Systems

amount of resin is picked up by a roller which partially dips in to the resin bath. The excess resin is removed with the help of a *Doctor Roller* or *Doctor Blade*. The fibre roving passes over the top of the roller and gets wetted in the resin. The moving roving friction with the roller causes it to rotate.

The driving force in roller impregnation is the difference in pressure between the underside and the topside of the roving. This pressure difference is caused by the tension in the roving which results in the pressure on the impregnation roller. Shorter impregnation times can be achieved by;

- a low viscosity resin mix in the bath
- an optimum tension in the roving
- well opened-out rovings
- large contact angle of roving on roller
- small impregnating roller diameter

2.5.2 Resin pickup:

The resin pickup, and hence the resin content in the composite, decreases with increase in fibre tension. This is because the *porosity* of the fibre decreases with increasing tension. The amount of resin pickup also depends on the method of impregnation and on the packing density of the fibre. The width of the roving should be as large as possible so that the impregnating roller can apply the maximum resin. A 1200 tex glass fibre roving will easily spread out to a width of 4-5 mm, and similar widths can be achieved with 12K carbon fibre *tow*.

Variations in resin pickup, and hence variations in fibre content, will clearly affect the properties of the wound composite. In practice, with a fibre content of 60% volume, local variations in fibre content of about 10% will generally be acceptable.

2.5.3 Resin viscosity:

A higher resin viscosity results in a higher resin pickup but more difficult progress through the fibre tow. Resin viscosity also has an influence on the air entrapment and foaming situation in the resin bath. Foaming in the bath is caused by air drawn in by the roving or the transfer drums. Generally higher winding speeds produce more foaming. The advantage of lower viscosity resin systems is that they are easier to deaerate, and thus produce low voids in the finished product. A void content of about 2% is generally considered acceptable in filament winding. For higher viscosity resin systems it is necessary to use a temperature controlled resin bath. It may sometime⁵ be beneficial to warm the roving before it enters the impregnating bath to prevent an increase in resin viscosity when resin and roving come into contact. X

2.6 Types of Winding Machines:

The main task of a filament winding machine^[41] is to place accurately resin impregnated fibre bands at predetermined angles on to the mandrel. The machine is programmed, mechanically or with the help of a computer, in such a way that the pay-out-eye and the mandrel move in a controlled geometrical relationship to one another, assuming the fibres to follow a specified path.

A mechanical filament winding machine, without a computer control, is adequate for the mass production of simple fixed geometry components such as pipes. As changing gear trains in a mechanical winder is a time consuming process and provides only limited flexibility, so its use becomes very cumbersome for complex shapes and for products of different designs. Sometimes the winding pattern is so complex that a manual or semi-automatic mechanical filament

winding machine can not wind that pattern. In such cases a computer controlled winder provides the only solution. In a dynamic company or in a research organisation, where the nature and the design of a product may be frequently modified, it is almost impossible to work without a computer controlled filament winding machine. These Computer Numerical Controlled (CNC) machines^[70] provide the flexibility in the design of the component as well as the production quality which is a characteristic of the computer control.

2.6.1 Winding machine coordinates:

Like a metal cutting machine, freedom of motion in all six degrees of freedom (see Figure 2-4) is possible for the mandrel and the pay-out-eye. However, depending upon the complexity of the object being wound it is possible to dispense with some of these movements. For simple tubular shapes, successful winding can be obtained by creating a relative motion between only two axes, i.e. mandrel rotation (A-axis) and linear motion along the X-axis. For items such as cones and dome-ended cylinders a third axis movement perpendicular to the cylindrical axis (Y-axis) is also necessary in order to lay down a precise pattern. Most of the axi-symmetrical shapes can be wound successfully with a 3-axis filament winding machine. Pay-out-eye rotation (B-axis) is provided to facilitate the turn around of multi-roving fibre feed and minimise effects due to twisting of the fibre band. This fourth axis also helps in keeping the same magnitude of tension in all the rovings particularly at the end of the product, while turning around. The fifth axis (Z-axis) controls the height of the pay-out-eye and helps in providing a better control over the pay-out-eye placement relative to the mandrel. 5-axis control is considered sufficient for almost all types of axisymmetric and non-axisymmetric filament winding products. The sixth axis (C-axis) is required only in polar winding case. Generally special polar winding machines are made for this purpose.

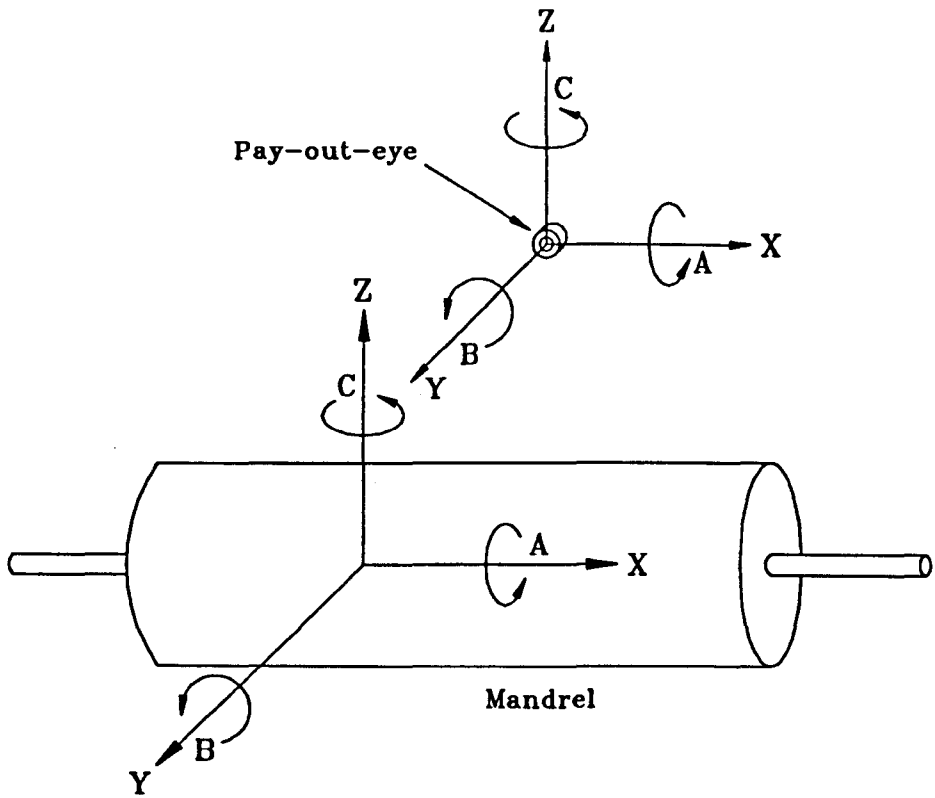


Figure 2-4: Six Degrees of Freedom of a Filament Winding Machine

A filament winding machine is specified by the number of axis^e present in it, the dimensions of the mandrel it can accommodate, and the resolution and maximum velocity of each axis. ✕

The accuracy of locating the roving^[41] depends on the mechanical tolerance of the winding machine. A distinction should be made between absolute accuracy and repeat accuracy. The absolute accuracy describes the deviation from a predefined point or path in space; the repeat accuracy is the deviation between two repeated movements in space. In filament winding the permitted tolerance for repeat accuracy is smaller than that for absolute accuracy. A repeat accuracy of ± 0.1 mm and an absolute accuracy of ± 0.5 mm, of the mechanical movements of the winding machine, should be adequate in practice. Visual irregularities in the winding pattern usually result from twisting of the roving or its individual filaments. Variations in the *tex number* also produce an irregular pattern and a thickening effect.

Filament winding machines are divided in to two major categories;

- i- Lathe type winding or Helical winding machines.
- ii- Polar winding machines.

2.6.2 Lathe type winding machines:

In lathe winding, the mandrel rotates about its longitudinal axis and the pay-out-eye moves parallel to the axial direction of the mandrel. For dome-ended cylinders and for winding complex shapes two more axes for pay-out-eye motion (Y and Z), perpendicular to the mandrel longitudinal axis, are required. A pay-out-eye rotation axis (B) is added as the fifth axis. The lathe winding is illustrated in Figure 2-5. Theoretically the winding angle can be set anywhere between 0° (winding parallel to the mandrel axis) and 90° (purely circumferential

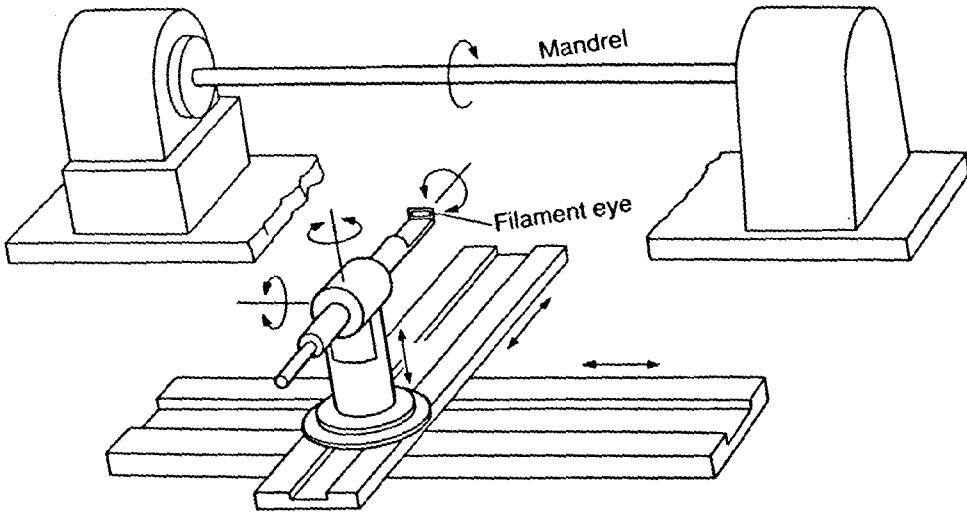


Figure 2-5: Lathe Type Filament Winding Machine

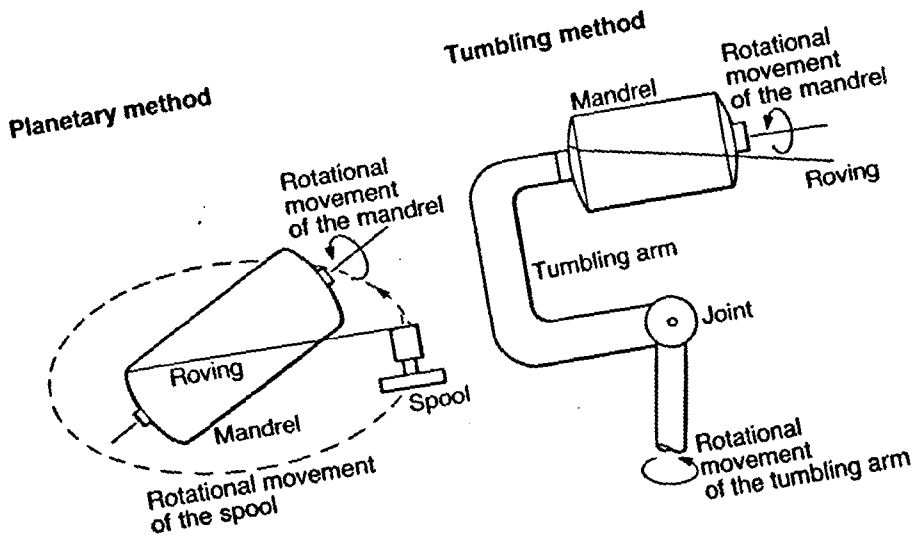


Figure 2-6: Two Types of Polar Winding Methods

winding). The lathe type winding machine can wind most types of winding patterns, and is the most popular type. A lathe type filament winding machine can be of Bed-type or Gantry-style. The bed type filament winding machine has the advantage that it can accommodate very heavy mandrels. The gantry style filament winding machine provides the freedom of movement around the mandrel.

2.6.3 Polar winding machines:

Polar winding machines are designed specifically for the manufacture of containers in which there is only a small polar part⁴⁶¹. A polar winding machine can be of two types; i)planetary system, ii)tumbling system. In the planetary system the mandrel rotates very slowly about its longitudinal axis, while the filament eye circles around it on an arm or a rail guide. In the tumbling system movements are carried out from the mandrel, which rotates perpendicular to its longitudinal axis for longitudinal winding. The two types of polar winding methods are shown in Figure 2-6. A feature of polar winding is that the paths can be easily set mechanically. The popularity of polar winding machines has been reduced drastically since the introduction of computer control in lathe type filament winding machines.

2.7 Pay-out-eye Design:

Guides are used to guide the fibre roving, without damaging it, from the spool through the impregnating bath to the mandrel. The final guide, the pay-out-eye, ensures that the rovings are correctly aligned for winding on the mandrel. The pay-out-eye also creates the *fibre spread* effect, which removes most of the remaining air thus ensuring a low void content in the finished composite. The pay-out-eye may be fixed or rotatable around a pivot and can take many shapes

e.g. combs, slots, eyelets, rollers, pegs, etc. The choice of shape depends on individual requirements which include complexity of part, path to be followed by the pay-out-eye and number of tows passing through the pay-out-eye.

The material from which guides are made should have a low coefficient of friction and high abrasion resistance. The material should also be electrically conductive in order to remove the electrostatic charges which can result from the friction between the fibre and guide. Guides are generally made from ceramics or metals such as chromium plated steel or brass.

The control of friction is important in guide design since quite small friction forces can cause damage to the fibres. Friction depends upon the nature of the two surfaces in contact i.e. the guide and the fibre, and also on factors such as angle of wrap, fibre tension, air humidity and temperature. It is recommended to install several roving guides with small changes of direction rather than few guides with corresponding larger changes. However, increasing the number of guides unnecessarily can also increase the frictional force so that in practice a compromise arrangement has to be worked out. Roving guides should be cleaned regularly to prevent the accumulation of fibre finish which will increase friction thus increasing *fuzz*.

To minimize *fuzz* it is advisable to fit an exhaust extraction device above the guides. This should always be done during the processing of electrically conductive carbon fibres. This will eliminate the risk of loose carbon fibres separating away in to the atmosphere which can cause a short circuit in electrical equipment.

In cases where the temperature of the impregnating bath is above room temperature, particularly when using resin systems with a relatively high viscosity, it may be necessary to warm the roving guides. If this is not done the resin may cool too much resulting in increase in viscosity, fibre damage, and void content.

2.8 Non-Geodesic Winding:

Laminates produced by filament winding are anisotropic in nature. Except for cylinders with a constant helix angle, the orientation of the fibres and the thickness of the laminates vary continually along the length of the mandrel. When fibres are laid down under tension they try to follow the shortest or geodesic path across the surface of the mandrel. In complex shapes, the optimum design orientation of the fibres, for strength or stiffness of the component, does not generally comply with geodesic path^[12]. Thus, it is not possible to produce all required shapes by filament winding. Because friction exists between the fibre and the mandrel surface, it is possible to deviate from the geodesic path^[5]. This deviation is generally very small because in wet winding the resin tends to act as a lubricant. In calculating a fibre path for a complex shaped geometry, geodesic paths are calculated first and then any possible deviation, available due to friction, is applied^[3].

2.9 Fibre Slippage Tendency:

For every curved surface, the greatest winding stability is obtained by following geodesic lines. This technique is limited to the most simple geometries because once the initial position and starting angle are selected, the path is thereafter defined. For complex shapes it is necessary to use the non-geodesic trajectories, that allow much more flexibility in the design of the composite. A non-geodesic pattern is stable and suitable if the slippage tendency of filaments is not greater than the slippage resistance caused by the friction^[17]. *Slippage tendency* is defined as the ratio between the lateral and the normal force. In filament winding, if ψ is the angle between the fibre line and the main normal, T the tension in the fibre, and μ the friction coefficient, then a condition that must be satisfied in order to avoid the slippage is:

$$|T \sin \psi| \leq |T \cos \psi| \mu$$

Slippage Tendency; $k = T \sin \psi / T \cos \psi = \tan \psi \leq \mu$

In wet filament winding, the resin acts as a lubricant and the coefficient of friction between the fibre and the mandrel surface, μ , decreases when the fibre is wetted with resin.

2.9.1 Non-geodesic path calculation:

According to Di-Vita et al^[54], the condition for winding stability along the non geodesic path can be expressed in the following manner if the winding angle α , slippage angle ψ , and mandrel radius r , are known;

$$|k| = \left| \frac{(\alpha' r \cos \alpha + r' \sin \alpha) [1 + (r')^2]}{r r'' \cos^2 \alpha - [1 + (r')^2] \sin^2 \alpha} \right| \leq \mu$$

It is interesting to see that if $\psi=0$, the equation is transformed in to the Clairaut's equation of geodesics^[54]:

$$r \sin \alpha = \text{constant}$$

2.10 Summary:

This chapter contains basic information about the filament winding process. The process is described from its practical application point of view so that a filament winding machine and controller can be manufactured. The important units of the process are outlined and the effects of some winding parameters, like fibre tension and resin impregnation are discussed. This chapter also contains useful practical data such as fibre volume fraction range, fibre spread, void content, fibre tension value for various type of fibres, and fibre placement accuracy limits etc. The

function of various parts of the filament winding system is described so that a computer controlled filament winding system can be manufactured and tests can be carried out on its control performance. The next chapter describes the requirements of a controller for filament winding machines.

CHAPTER 3

FILAMENT WINDING CONTROLLERS

The majority of filament winding performed prior to the seventies has been on simple cylindrical shapes. In the case of complex winding patterns, where a varying helix angle is required, computer aided design for winding pattern generation becomes a necessity^[11]. This chapter describes the role of computers in filament winding and highlights the need for developing a controller suitable to the requirements of the winding process.

3.1 Computerized Filament Winding; A Complete System:

Filament winding has a large potential for garage scale industries. The biggest difficulty in introducing this process in small industries is the technology know-how. A small engineering organisation can not afford to have full-time experts for composite material design, analysis and manufacturing. This difficulty can be overcome by developing a computerized filament winding system providing a complete solution to the problems of a small industry.

A computer-integrated filament winding system, Figure 3-1, basically consists of three major parts;

1. CAD software for design and analysis of filament wound structures.
2. CAD software for the pay-out-eye path generation.
3. Computer-controlled filament winding machine.

The filament winding process produces non-isotropic materials which require

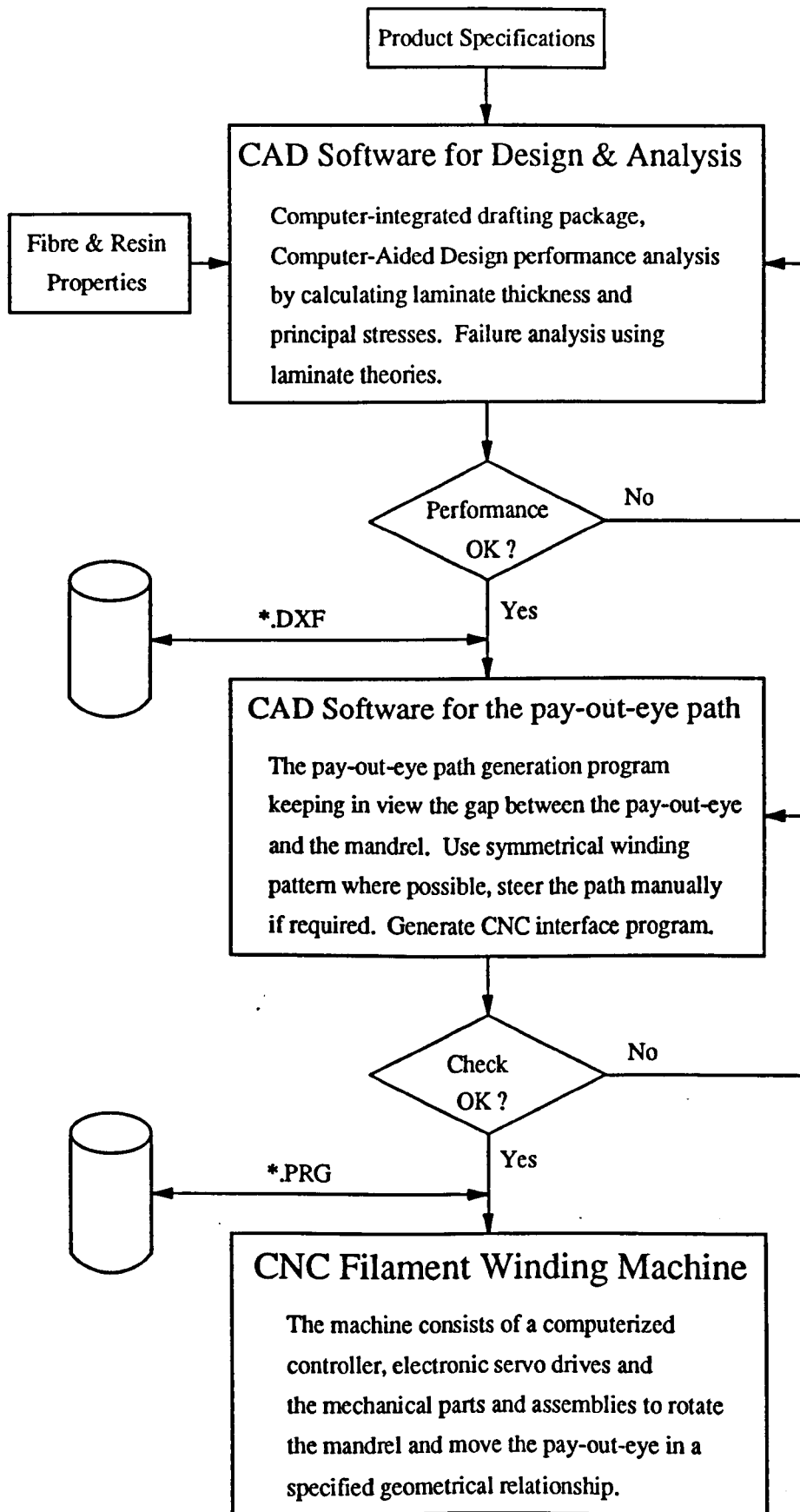


Figure 3-1: A Computer-Integrated Filament Winding System

special software for their design and analysis^[66]. Classical lamination theory can be applied to calculate material properties of the composite and then the design can be analyzed considering the geometry of the component. Properties of various fibres and resins are collected in the form of a materials database and made available to the CAD package.

The pay-out-eye path generation^{[54] [12] [40]} is another area which requires special software. For design optimization of the filament wound component it is important that this software package is fully integrated with the performance analysis software.

This project addresses the control problems related with one part of computer-integrated filament winding system, i.e the filament winding machine. Only the computer control related problems of a filament winding machine are addressed in this project.

3.2 The Job of a Filament Winding Controller:

The job of a filament winding controller is to read the pay-out-eye path as a sequence of coordinate points and to move all the axes of the machine smoothly according to that path. The filament winding machine controller reads the pay-out-eye path from a computer file and then generates appropriate voltage signals for each axis drive motor, such that for each specified point along the path, all the axes reach their destinations at the same time. All the specified points along the given path are met this way and the pay-out-eye path is completed. To accomplish the task of winding a controller requires electronic hardware as well as a software to perform the control action^[41]. The hardware includes parts such as servo motors, servo drives, CPU, and computer interface cards. The software consists of control logic, with which the magnitude and the polarity of the correcting signal is calculated, and other essential routines to provide the

hardware interface and the user interface. A filament winding controller can be developed using a programmable controller, microprocessor, or a microcomputer. A microprocessor based controller⁴¹ is suitable when the production volume is high and the cost of the controller is to be minimised. The development cost of a microprocessor based controller is quite high and once it is developed, it is not easy to make changes in its design. To provide flexibility in the microprocessor based systems, these are generally interfaced with another computer system. A microcomputer based controller is considered suitable when only a few controllers are required to be produced and the control system requires frequent modifications in its design. A microcomputer based control system has an added advantage that the computer's abilities can be utilized to run a completely computerized system for filament winding. For the success of a microcomputer based control system, the availability of suitable interface cards to drive the controller hardware is very important. The programmable controller option provides a middle path between the microprocessor option and the microcomputer option.

One of the important functions of a filament winding controller is to plan the pay-out-eye path in such a way that the pay-out-eye path is as smooth as possible. This PhD project addresses this problem and suggests a new technique of B-spline interpolation which provides a smoother control than the existing techniques.

3.3 Winding Controller Requirements:

Most of the commercial filament winding machines use standard NC controllers which are basically developed for general purpose CNC cutting machines or use dedicated controllers custom built for the filament winding operation. In either case, the controller treats the filament winding operation as a machining operation. The controller requirements of a filament winding machine differ considerably from that of a conventional cutting machine. A filament winding controller, which is designed keeping in view the specific requirements of

filament winding process, will perform the job in a much better way, thus providing higher quality components at a faster production rate.

The major differences between the filament winding process and the conventional machining process^[51] are outlined here;

3.3.1 Differences with conventional machining process:

- 1- In metal cutting machines the tool is in contact with the work surface, so that the cutting path of the tool is uniquely defined. In filament winding the fibre pay-out-eye is at some distance away from the surface of the mandrel. In a cutting operation, which can be regarded as a discrete process, any forward tool movement does not affect the previously machined surface. Whereas, in the filament winding operation, which can be regarded as a continuous process, the pay-out-eye movement from one position to another may disturb the previous fibre positions on the mandrel. This demands a *look ahead capability* in the controller so that while moving around curvatures the effect of pay-out-eye movement on previous fibre positions is minimal.
- 2- The carriage movement speed is much higher compared with the tool movement speed in metal cutting.
- 3- The load on the pay-out-eye is much less in comparison to the metal cutting load.
- 4- The fibre placement accuracy requirements are not as high as the cutting tool position accuracy.
- 5- A number of machining operations like coolant control, tool wear

compensation etc. are not required in filament winding. Elimination of these undesired functions from the controller memory can considerably reduce memory requirements.

Due to these differences in the requirements of a metal cutting controller and a filament winding controller, a new type of controller is required to be developed. The conventional machining operation, being a slow speed discrete process is not so demanding in tool path interpolation. Keeping these differences in view a controller is developed in this project which fulfills all the requirements of the filament winding operation. In this respect, improvements are made by introducing a new control philosophy of B-spline interpolation in calculating the path of the pay-out-eye.

The pay-out-eye path is calculated by the controller, using data points specified in the winding pattern. A controller can either fit a straight line between the two specified points or use any other interpolation technique to calculate the connecting path^[52]. According to the new technique used in this project, the controller reads the winding pattern from a data file and then calculates the final pay-out-eye path using B-spline interpolation. The pay-out-eye path computation methods and interpolation techniques are described in Chapter 8 of this thesis.

3.4 Experimental Set-up:

To implement and to test any control philosophy in a filament winding operation, a machine is required which should be available specifically for this purpose. As the cost of a commercial filament winding machine is very high, it can not be dedicated to these experiments alone. Moreover, it is difficult to make modifications in the software and the hardware of a standard controller, compared with developing a new one. In a purpose made machine the designer can implement new ideas and make modifications more easily than in a ready made

machine.

A 3-axis CNC filament winding machine was designed and produced to check the operation and the performance of B-spline interpolation technique as compared to Linear interpolation technique. The main purpose of this filament winding machine was to compare and analyze the performance of B-spline control philosophy and therefore a 3-axis control was considered sufficient for this purpose. A 3-axis filament winding machine can wind most of the axi-symmetric shapes. The controller for this filament winding machine was developed using IBM PC/AT computer as the CPU and all the hardware and the software was specifically developed for this project. The detail of the electronic hardware is given in Chapter 6, and the detail of the mechanical design of the filament winding machine is given in the next chapter.

CHAPTER 4

MECHANICAL DESIGN & MANUFACTURE

This chapter provides information about the mechanical design of the filament winding machine developed for this project. Its various parts are described and important design aspects are highlighted. Engineering design is a process to reach a reasonable compromise between various parameters. In ideal conditions, a compromise is made between two system parameters and the system components are selected based on the optimum design value. The most dominating constraint in the design process of this filament winding machine was the use of already available parts, recovered from the filament winding machine made by Louise Brown for her PhD project [2]. Based on these already available components, other components were designed and selected to improve the performance of the machine.

Most commercially available filament winding machines are large structures accommodating a mandrel up to 4 metres long and 1 metre in diameter. These are obviously expensive machines. Many filament winding applications, especially for complex shapes require travel of less than 1 metre. Thus the design brief for the machine to be developed was for a small, lightweight, and low cost system requiring a minimum of installation space and capable of easy transportation and set-up. The basic mechanical design of a 3-axis computer controlled filament winding machine requires a configuration with axis motions equivalent to a lathe. This comprises a head stock with spindle to rotate the mandrel, a linear motion x-axis parallel with the mandrel axis, and a linear motion y-axis perpendicular to the mandrel axis to provide a cross feed. All these three axes should be synchronous with each other through a computer control.

A photograph of the 3-axis CNC filament winding machine developed for this project is shown in Figure 4-1 and an isometric sketch of the same machine is shown in Figure 4-2. Other than the parts shown, a fibre tensioning system and a resin wet-out system are also required which can work independently. All the three axes, shown in the figure are driven by DC servomotors and mechanical power transmission arrangements. The actual displacement of each axis is fed back to the controlling computer using motor mounted optical encoders.

4.1 Important Considerations in the Mechanical Design:

The following are the factors affecting the selection of gear ratio and the servomotor;

- 1- Load moment of inertia
- 2- Desired maximum acceleration
- 3- Desired number of encoder counts
- 4- Other factors like friction, fibre tension etc.

For the optimum performance of motors, armature energy dissipation is the major criterion. This depends on the velocity profile as well as on the ratio of load moment of inertia and the rotor moment of inertia. So, for optimum output, motor and gear ratio should be selected such that the load moment of inertia equals the rotor moment of inertia ^[38]. This principle forms the basis of the power transmission's mechanical design and it suggests the use of light weight materials in the construction of moving parts.

The requirement for low friction bearings and the use of light weight low stiffness components are the two optimization requirements that lead to the design problem of the flexibility of the pay-out-eye arm. If the pay-out-eye is mechanically flexible then there is no point in having a very accurate high resolution computer

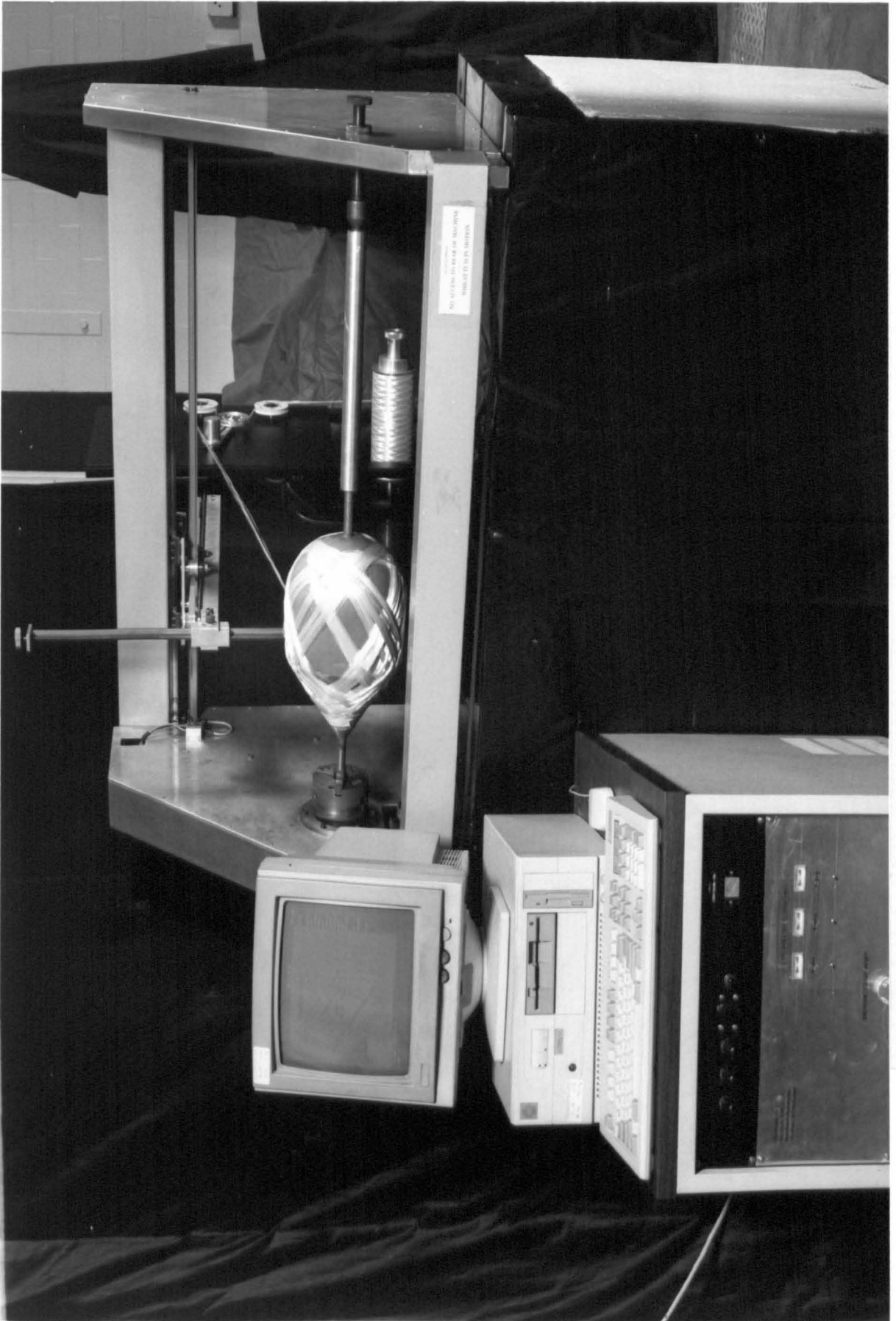
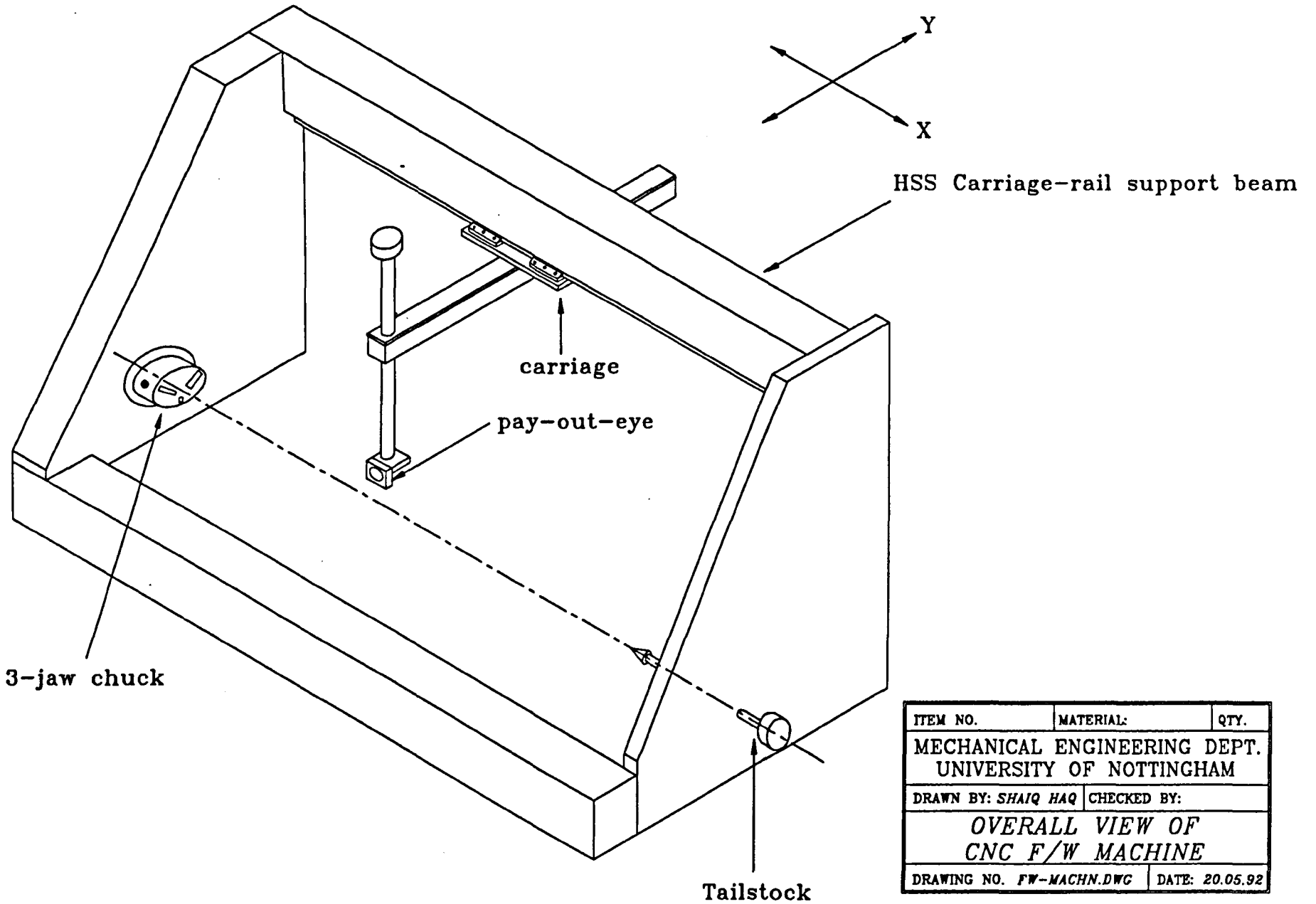


Figure 4-1: A Photograph of the 3-Axis CNC Filament Winding Machine

Figure 4-2: An Isometric Sketch of the 3-axis CNC Filament Winding Machine



ITEM NO.	MATERIAL:	QTY.
MECHANICAL ENGINEERING DEPT. UNIVERSITY OF NOTTINGHAM		
DRAWN BY: SHAIQ HAQ		CHECKED BY:
OVERALL VIEW OF CNC F/W MACHINE		
DRAWING NO. FW-MACHN.DWG		DATE: 20.05.92

control. These conflicting design requirements demand the use of good engineering practices to attain a mechanical design which has a stiff pay-out-eye support using light weight components and low friction support.

4.2 Machine Frame:

To keep the overall weight of the machine within limits, its frame is made as a hollow aluminium structure. The frame of the machine carries the load of the mandrel as well as other parts like motors, carriage-rail support beam, carriage, cross-member etc. To attain high stiffness and strength while maintaining its light weight, this frame is built with aluminium sheets riveted together to provide a hollow structure. The carriage-rail support beam is made of a 1400 mm long, 100 x 100 mm mild steel hollow-square-section (HSS) beam, because its stiffness requirements are higher than other members of the machine frame. Because of these weight saving measures the overall weight of the filament winding machine is less than 50 Kg. This machine can be fixed on a bench top.

4.3 System for Mandrel Rotation, A-axis:

This part of the filament winding machine should have the ability to hold and rotate the mandrel. A standard 3-jaw chuck is used for holding the mandrel. To hold heavier mandrels, a dead centre support is provided on the other end of the mandrel. The machine is designed for small mandrels, up to one metre long. These mandrels can be made of a specified fixed length. Thus the distance between the two centres is kept constant. Instead of providing a sliding movement in the tail-stock to adjust for variable length mandrels, a slight length adjustment is provided with a screw type arrangement. This arrangement, shown in Figure 4-3, simplifies the design. For shorter parts the mandrel can be

extended by a bar to meet the standard length. Power for rotation is provided with a DC servomotor through a timing belt and pulley arrangement having a speed reduction ratio of 1:3.167. Power transmission, as shown in Figure 4-4, could have been provided through a gear train, or chain and sprocket system, but timing belt arrangement was selected for its accuracy, low inertia, and low noise operation. In the filament winding machine developed, one timing belt and two pulleys, Synchroflex AL 30 T10/12-2 and AL 30 T10/38-2, are used for power transmission. For this speed reduction ratio one degree of mandrel rotation equals 35.18159 counts of the encoder.

4.4 X-axis Movement:

A photograph of the CNC carriage assembled with the filament winding machine is shown in Figure 4-5. The longitudinal traverse (X-axis movement) is provided through a timing belt and two pulleys by a DC servomotor connected to the carriage. The carriage moves on the carriage-rail (Figure 4-6 and Figure 4-7) by two types of bearing support systems. Two STAR ball-rail linear bearings and a guide rail, provide guidance and alignment in the XY plane, while four track rollers and a linear track provide the angular restraint in the XZ plane (Figure 4-8). The guide rail and the linear track are fixed on a 100 mm mild steel hollow-square-section. The STAR ball-rail linear bearings and four track rollers are mounted on the aluminium carriage. Two bearing support systems, are required for kinematic restraint, and to reduce the pitching flexibility of the y-axis due to cantilever effect.

The other alternatives to the timing belt drive system are lead-screw and chain drive arrangements. The timing belt arrangement, shown in Figure 4-9, was selected for its low inertia, accuracy, low noise, and fast movement. Tests had shown that this system was repeatable to 0.1 mm using stepper motor control.

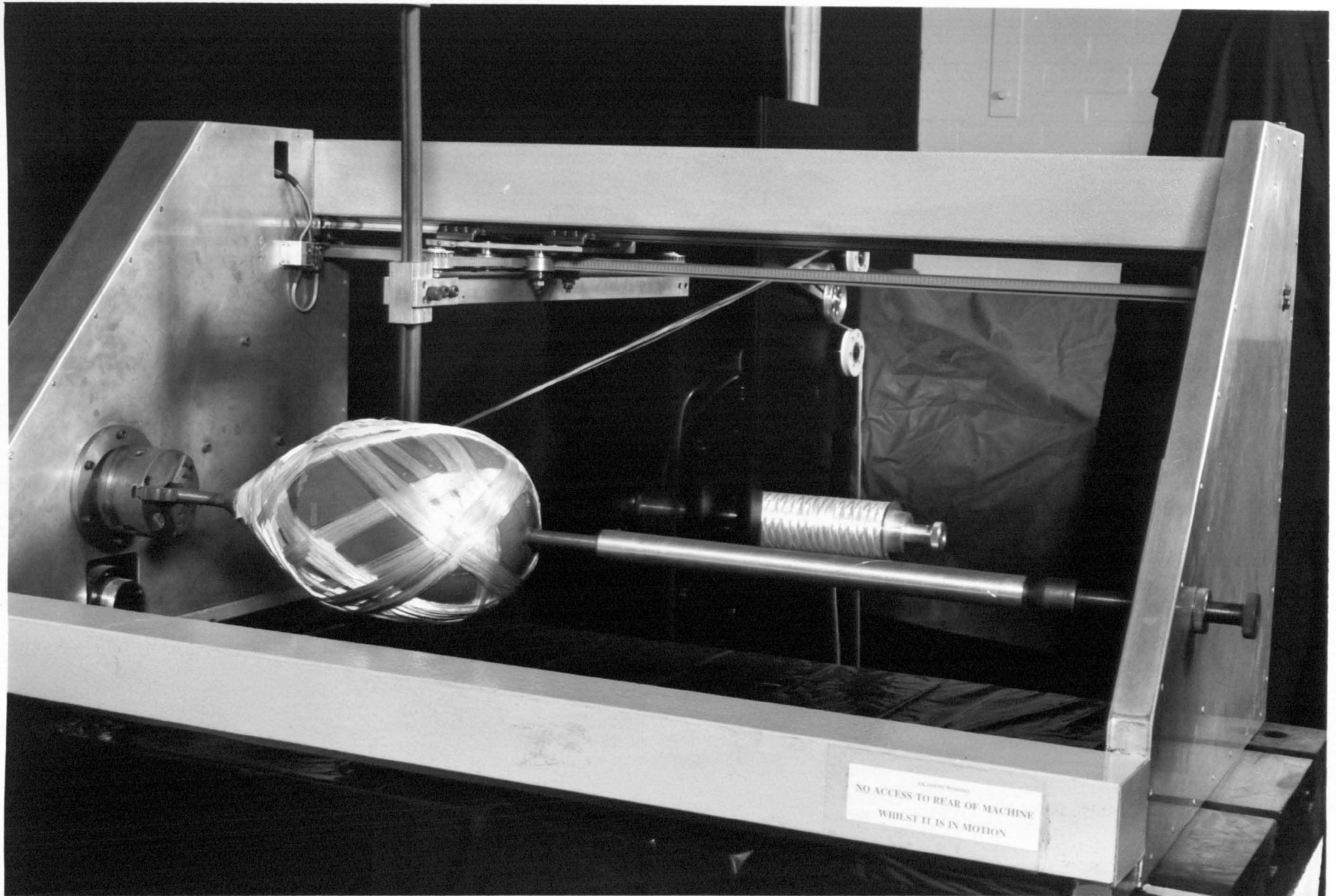


Figure 4-3: A Photograph of the Mandrel Mounting and Rotating System

Figure 4-4: Power Drive Arrangement for the A-Axis

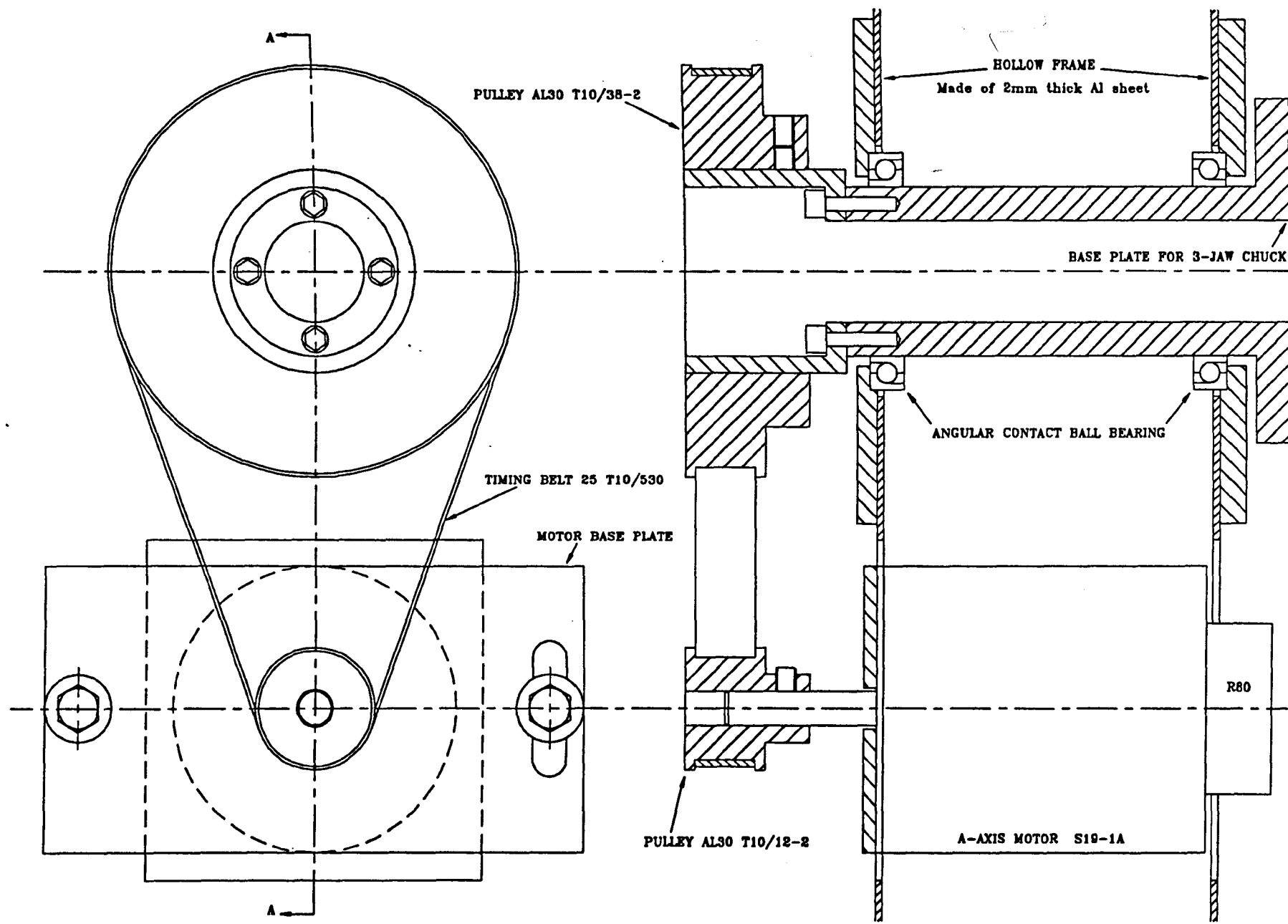




Figure 4-5: A Photograph of the CNC Carriage

SECTION B-B
of drawing FW-SADL8

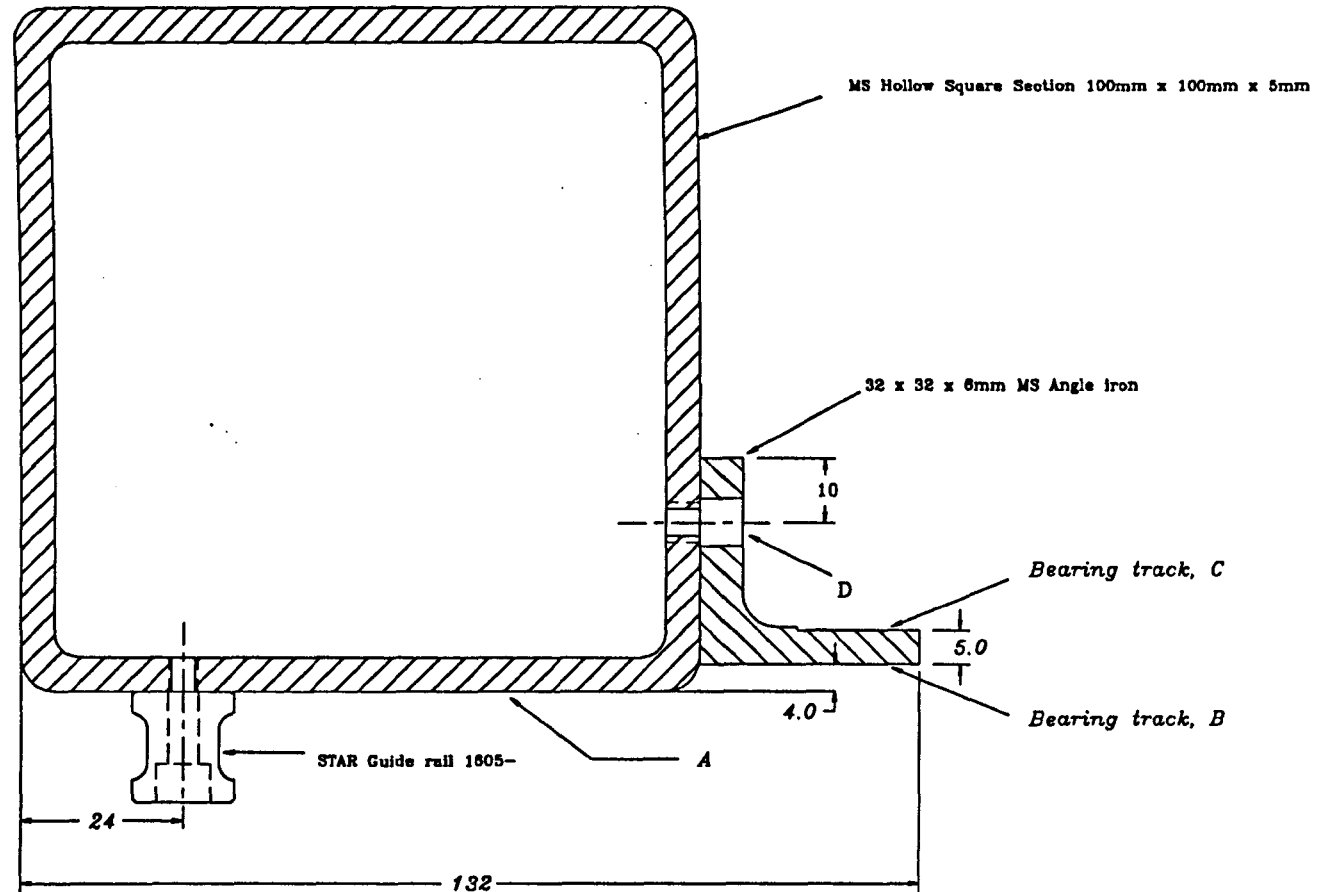


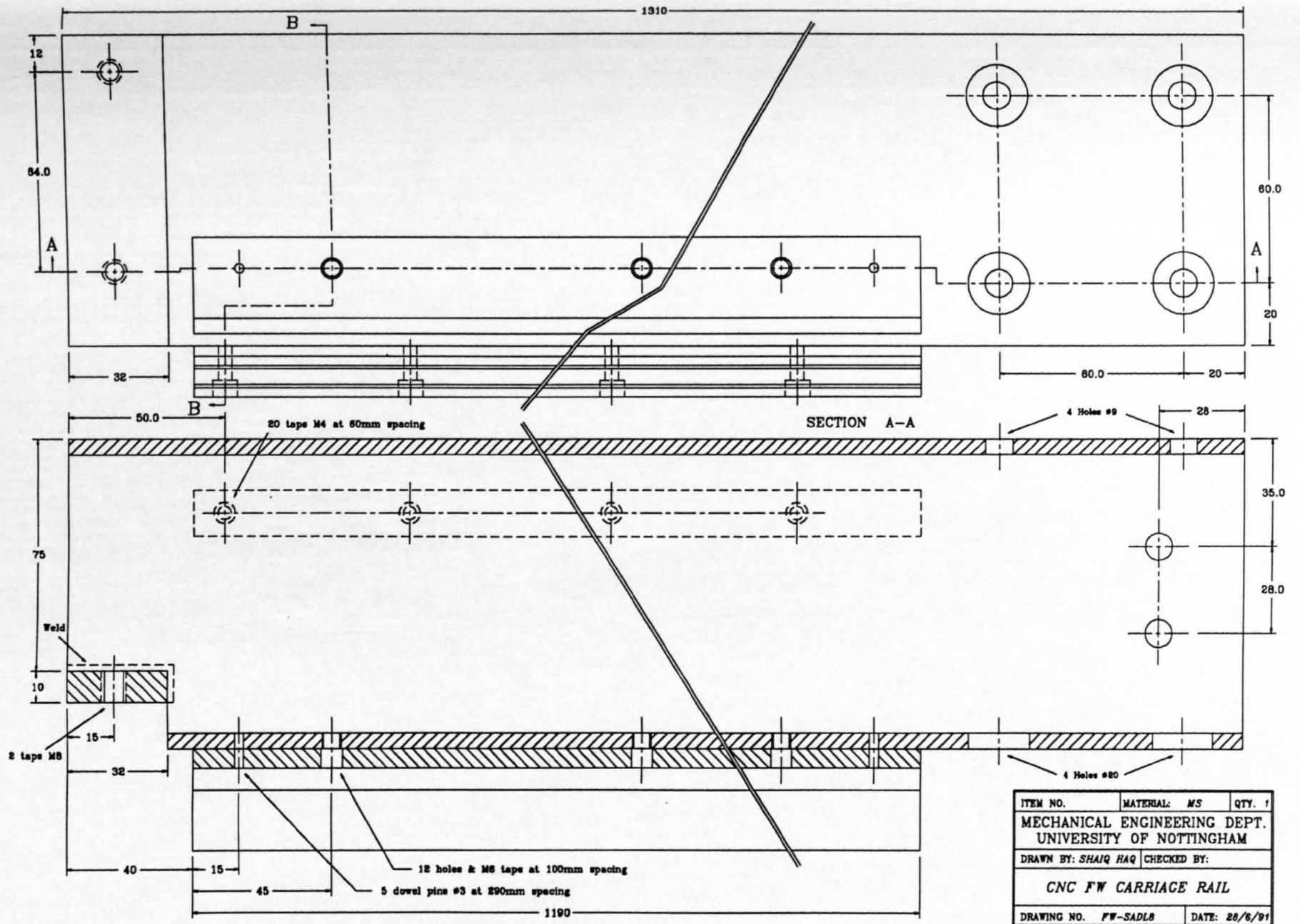
Figure 4-6: The Carriage-Rail Assembly; Side View

NOTES:

1. Grind surface A, B, and C.
2. Drill & tap 12 holes D M6.
3. Attach and lightly clamp angle track to HSS.
4. Check Bearing Track B to run true from ground face A.
5. Drill & dowel angle iron to HSS beam.

ITEM NO.	MATERIAL: MS	QTY. 1
MECHANICAL ENGINEERING DEPT. UNIVERSITY OF NOTTINGHAM		
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CNC FW CARRIAGE RAIL		
DRAWING NO. FW-SADL2		DATE: 24/6/91

Figure 4-7: The Carriage-Rail Assembly: Top View



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CNC FW CARRIAGE RAIL		
DRAWING NO. FW-SADL8	DATE: 28/6/91	

SIDE VIEW

Mild Steel HSS 100 x 100 x 5mm

Angle Iron

INA Track rollers 2 x KR26

Aluminium Channel section

STAR Guide rail 1605-
L=1190mm

INA Track rollers 2 x KRE26

runner block
2 x 1604-

4 Guide pulleys for timing belt

4 x HEPCO guide rollers

HEPCO Slide

Figure 4-8: The Carriage Assembly Drawing
- 49 -

ITEM NO.	MATERIAL:	QTY.
MECHANICAL ENGINEERING DEPT. UNIVERSITY OF NOTTINGHAM		
DRAWN BY: SHAIQ HAQ	CHECKED BY:	
CNC CARRIAGE ASSEMBLY DRAWING		
DRAWING NO. FW-SADL1.DWG	DATE: 19.05.92	

BELT-DRIVE SYSTEM

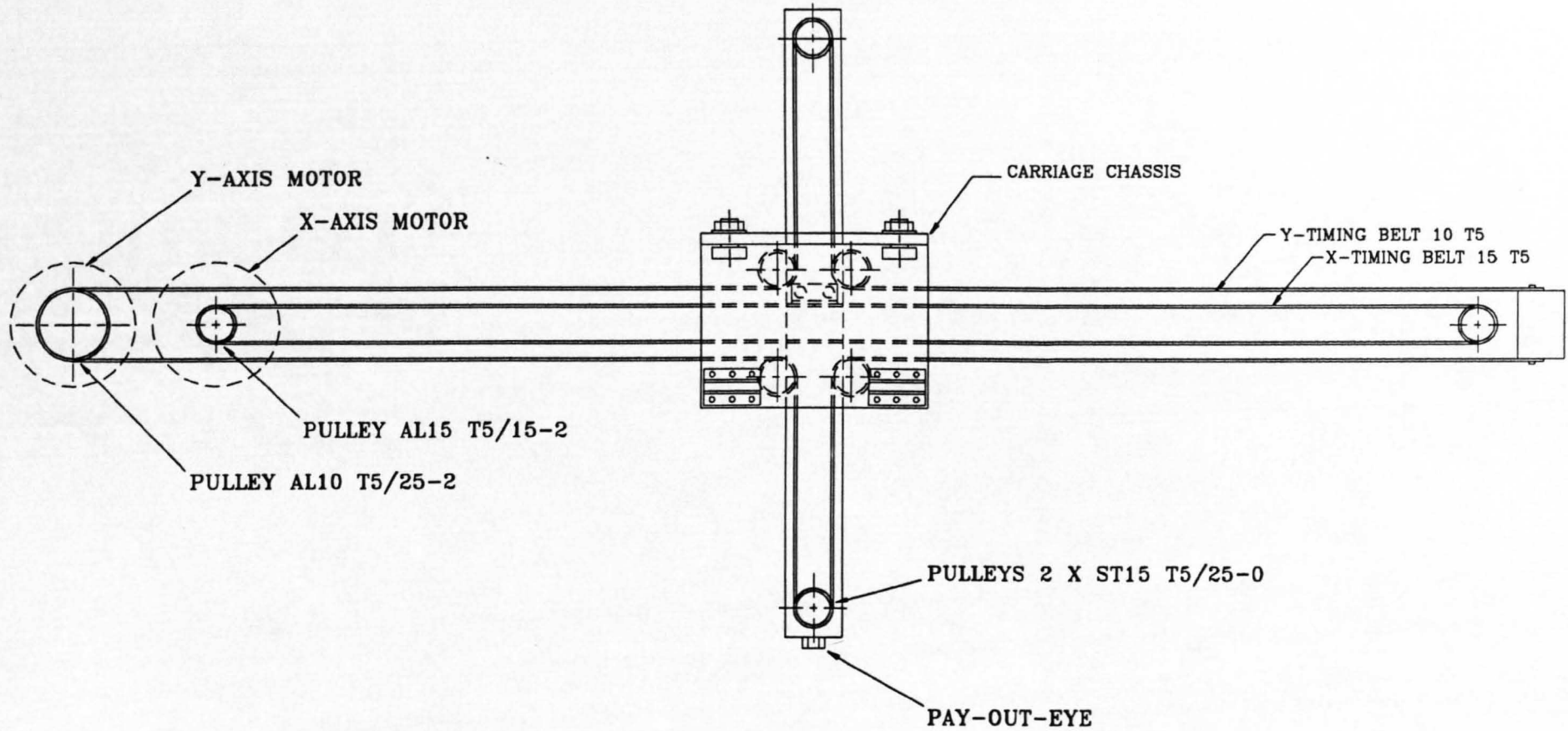


Figure 4-9: The Timing Belt Arrangement for the X-axis & Y-axis Drive

The overall gearing of the system develops 55.358 counts of the encoder for 1 mm of x-axis movement. This number can be easily modified by selecting alternative sized timing pulleys.

4.5 Y-axis Movement:

To reduce the weight hence the inertia of the moving parts it is important that the Y-axis drive motor is not mounted on the carriage but rather be on the stationary part of the machine. This requires the use of a power transmission arrangement remote from the carriage. A timing belt drive system was selected to minimize the weight of moving parts, enabling the drive motor to be mounted on the headstock. X

The cross slide (Y-axis) linear motion system is carried on HEPCO 'V' linear bearings. Four HEPCO V roller stud type guides are bolted to the 75 mm square on the aluminium carriage. These rollers provide support to a V rail which is rigidly connected to the pay-out-eye arm (cross-arm). Power is provided through a S19-1A DC servomotor, timing belt, and three pulleys. The timing belt is connected like a differential pulley, and a speed reduction of 1:2 is obtained by the timing belt.

1 mm of y-axis movement develops 62.294 counts of the encoder. Again resolution can be changed in the final design by pulley selection.

4.6 Z-axis Movement:

A manual adjustment is provided to change the height of the pay-out-eye (Z-axis). This adjustment is provided by a lead screw arrangement. The height of the pay-

out-eye is manually adjusted once for a particular mandrel and is not changed during the course of winding. A DC servomotor can be added in future to provide the automatic control for the height adjustment of the pay-out-eye.

4.7 Carriage / Saddle Design:

From the mechanical design point of view the carriage is the most important part of the CNC filament winding machine. Extreme care must be exercised in the design of this part. In order to reduce the pitching flexibility of the Y-axis, the cantilever deflection and bearing clearances at all the bearing contact points must be minimized. The system must provide angular support for the cross-member while permitting its extension with minimum friction. A small deflection in the carriage chassis can cause large deflections at the pay-out-eye. Due to high bending stresses at the carriage chassis, welds and bolted joints were avoided in the construction of the chassis. To avoid stress concentration effects and for accuracy reasons this part is made by machining from Aluminium C-channel section as the raw material. The carriage chassis drawing is shown in Figure 4-10.

4.8 Fibre Tensioning System:

The fibre tension controller (see Figure 4-11) developed for this project includes a small DC servomotor attached to the fibre spool fixture, serving as a brake. This is an independent stand alone system which contains one fibre spool holding fixture and fibre guide rollers and pulleys. The tension in the fibre is sensed by a resistance type rotary potentiometer connected to the centre of a tension sensing pulley. The weight of the pulley is balanced by the tension in the fibre, so the lift of the pulley is a measure of the tension in the fibre. A 4-quadrant hard

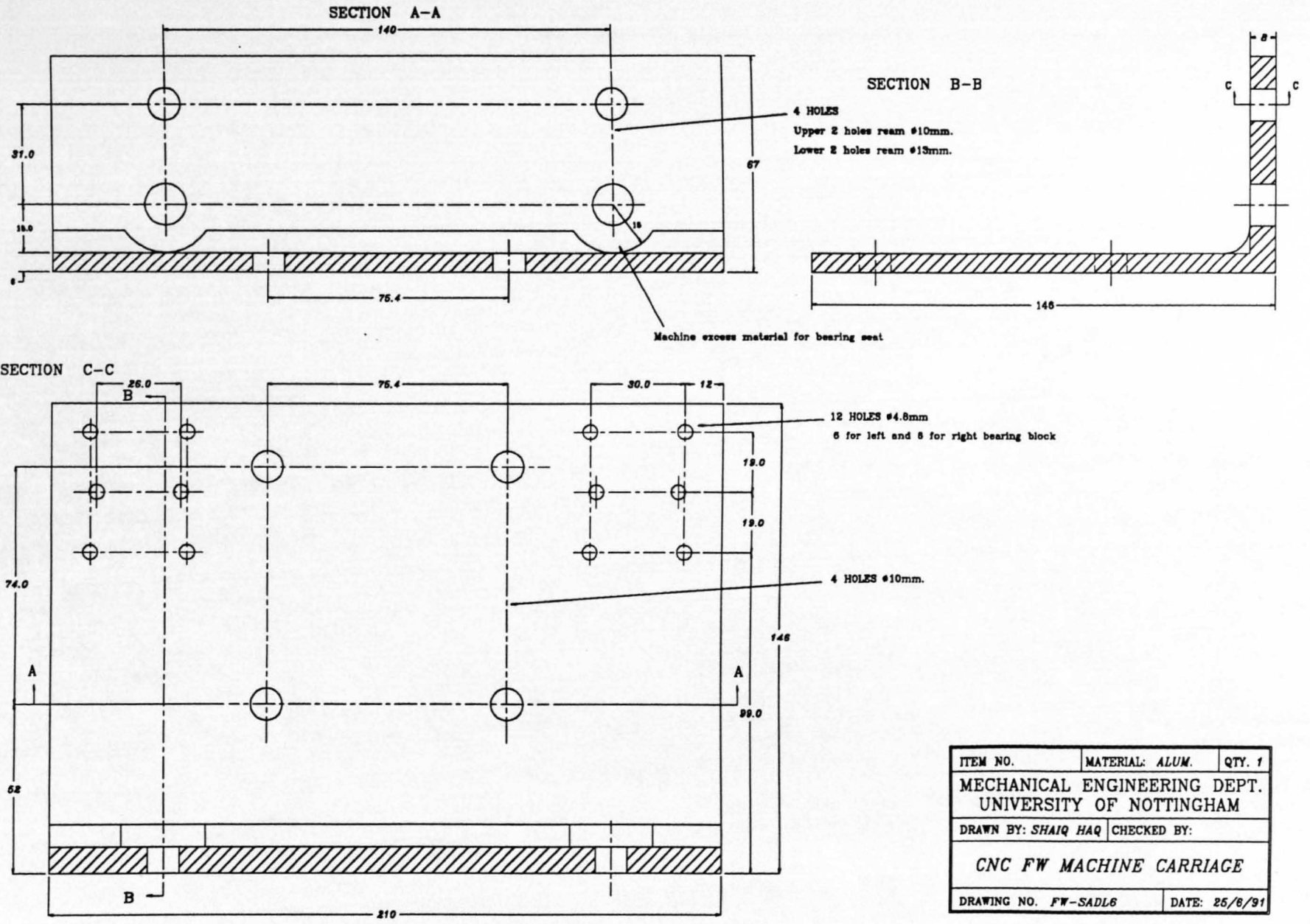


Figure 4-10: The Carriage Chassis Drawing

ITEM NO.	MATERIAL: ALUM.	QTY. 1
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CNC FW MACHINE CARRIAGE		
DRAWING NO. FW-SADL6		DATE: 25/8/91

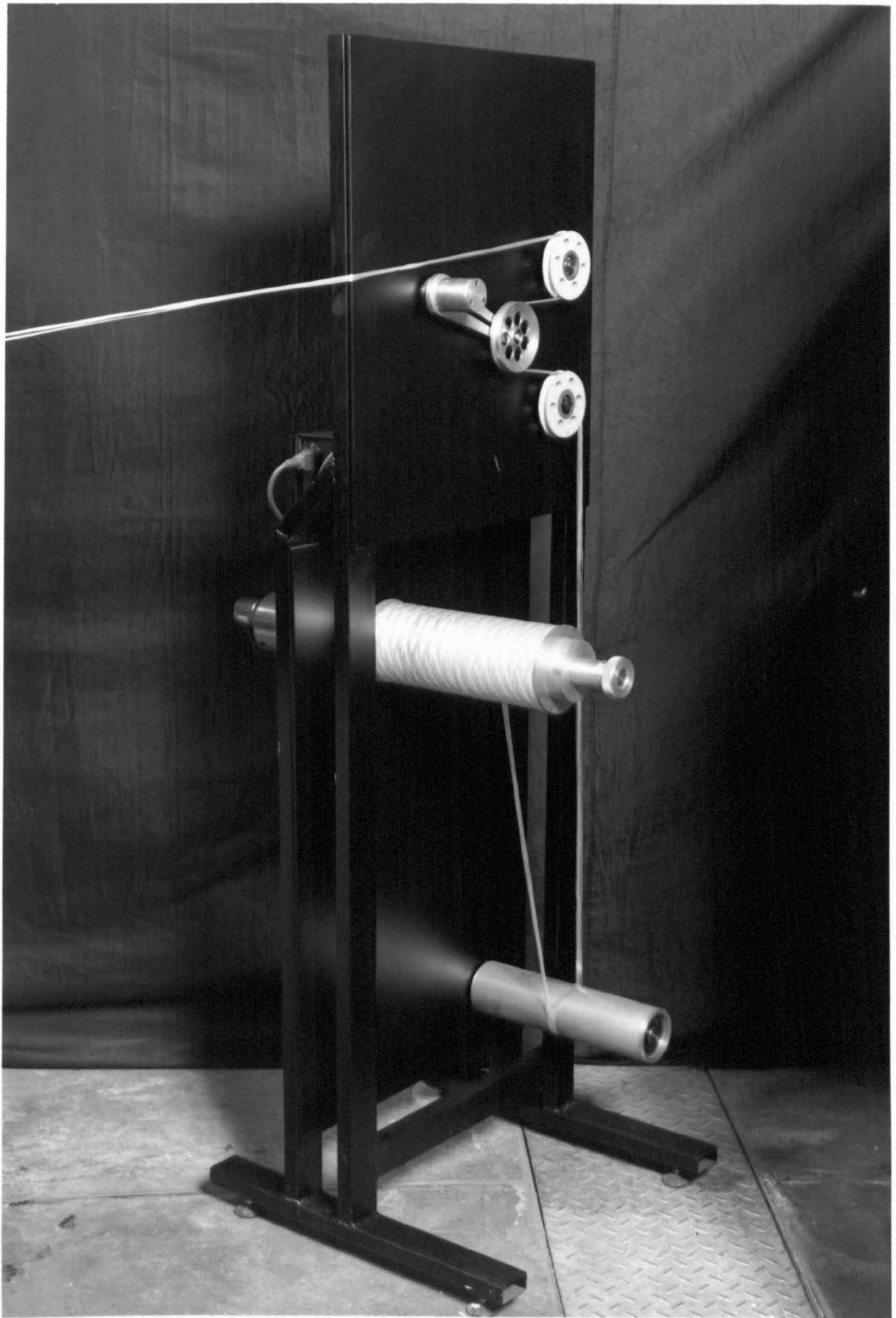


Figure 4-11: The Fibre Tension Control Arrangement

wired controller determines the magnitude and the polarity of the voltage supplied to the DC motor, driving the fibre spool. When the fibre tension decreases, a negative voltage is applied to the motor which results in increasing the motor braking action. At increased fibre tension, a positive voltage is applied to the motor which helps in unwinding the fibre and thus decreases the tension in the fibre roving. This fibre tension control system can be made or purchased as a separate unit. Its electronics have no link with the controller hardware of the CNC filament winding machine but a voltage output from the computer could be provided so that the tension set point could be controlled by the computer.

4.9 Summary:

This chapter describes the mechanical design of a 3-axis CNC filament winding machine which can wind components that are up to 1000 mm long and 200 mm in diameter. The drive arrangement for each axis is explained. The most important design aspect is to have a low inertia carriage to attain a better control performance. This design aspect is missing in most of the commercially available filament winding machines. Generally axis drive motors are mounted on the carriage which makes the carriage heavier and ultimately requires a heavier cross-slide and other machine components. In this filament winding machine the drive motors are fixed on the machine frame and the drive is supplied through a timing belt arrangement. The weight of the carriage is supported on the carriage-rail by two linear bearings which offer minimum friction. The pitching flexibility of the pay-out-eye is minimised by providing a four-point-contact support. The low inertia and the low friction of the carriage drive and the minimum flexibility of the pay-out-eye are the main features of this filament winding machine design.

The next chapter provides information about the control theory. The next three chapters describe the link between the mechanical parts of the filament winding machine and the computer control.

CHAPTER 5

CONTROL THEORY

This chapter provides a brief introduction to control theory and is specially written for readers who have had specific training in the subject. The term *Automatic Control* is generally applied to any system in which the application of an input signal causes a sequence of actuations resulting in the desired change of some output or controlled variable. There are many good books written on this subject. For further reading consult ^{[47] [48] [55] [56]}.

5.1 Feedback Control System:

A simple feed back control system is shown in Figure 5-1. A closed loop or feed back control system becomes necessary when the magnitude and frequency of disturbances would otherwise cause the controlled variable to depart from its desired value by more than an acceptable value. There are two main types of feed back systems;

- i- regulators
- ii- servomechanisms.

In regulator type feed back systems the reference signal is constant and the main objective of the control is to keep the output at a constant value, e.g temperature control of chemical reactions.

Servo systems differ from regulator systems in that the reference signal is

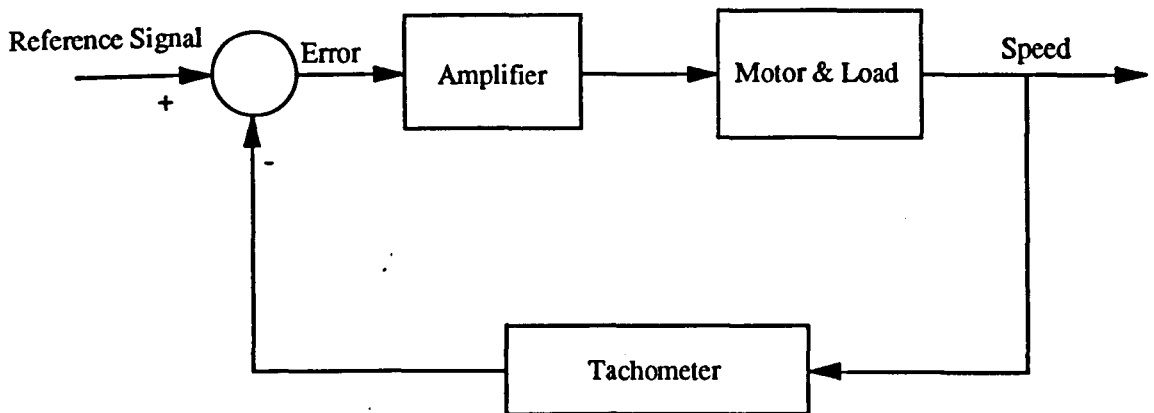
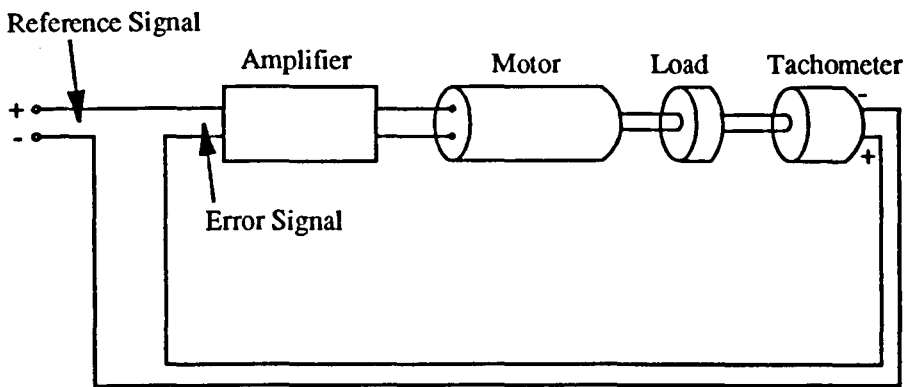


Figure 5-1: A Simple Feedback Control System

variable. The aim of the control system is to ensure that the controlled variable follows the variations of the input reference as accurately and as quickly as necessary, while being relatively unaffected by any disturbance inputs. Servomechanisms can be used in any system whose output is slaved to an input reference by feed back control. These systems are ideally suited for position or speed control mechanisms.

Like any other engineering design, feedback control system design is also an iterative process in which the system characteristics are determined, the performance is specified, components are selected, and then controller coefficients are fine-tuned. These steps may be repeated several times to reach an acceptable design.

5.2 System Performance Specifications:

The operating characteristics of the machine or process to be controlled must be understood and modelled by numerical expressions or graphical means. The dynamic and static characteristics of the system are specified using analytical and/or experimental techniques. The desired system performance is specified before controller synthesis can proceed. The importance of different performance parameters varies in different applications. These performance requirements are expressed either in terms of the system *transient response* (quantities such as the overshoot, rise time, settling time, damping factor and undamped natural frequency etc.) or in terms of the system *frequency response* (quantities such as the phase margin, gain margin, maximum magnification and error coefficients) or both. These performance specifications are described in more detail in Chapter 7.

5.3 Selection of Actuators and Sensors:

A controller requires certain output power to perform a specified task. This output is provided with the help of *actuators* whereas the output signal feedback to the controller is provided with *sensors*. The type and size of the actuator and sensor depends on the system performance specifications, environmental conditions and economic considerations.

5.4 Filament Winding Process Implementation:

To implement automatic control in filament winding, the winding process can be described as a position control system in which the position of the pay-out-eye should be coordinated with the angular rotation of the mandrel. As the pay-out-eye motion is required to follow a specified path and the reference position input, as detected by the control program, which is changing all the time, so servomechanisms are the best type of control system for the filament winding process. This type of control also has the ability to maintain its path against variations due to friction, inertia, and fibre tension.

The four main units of a control loop i.e, the plant, the actuator, the transducer and the controller, define the four main fields of control research and applications. In the context of the filament winding process these four units and their designs can be described as follows;

5.4.1 The plant modelling:

The plant is the system to be controlled. Before any control analysis or design can be attempted it is essential to represent the behaviour of the plant by differential equations -- i.e, to obtain a mathematical model for the plant. The

mathematical model can be deduced from the results of a series of systematic tests done on the plant. System modelling is a field of great importance and of great research interest. The system model of this filament winding machine is described in detail in Chapter 7.

5.4.2 The Actuator:

An actuator could be of electrical, hydraulic, or pneumatic type. DC motors, AC motors, hydraulic motors, hydraulic rams, heating elements, and flow control valves are typical examples of actuators. The two main functions of an actuator are;

- i- interfacing
- ii- power gain.

Interfacing is important because the controller generally supplies an electrical signal which may undergo several changes in form before the final actuation of the plant. Power gain is required because the actuator receives a low power signal from the controller, but has to develop enough power to actuate the plant. The most important aspect of the actuation, from a control viewpoint, is that it determines the maximum speed of response of the system. No matter how well the controller executes a control strategy, the system can not respond faster than the actuator can drive it.

DC servo motors are used as actuators in the control of all the three axes of the CNC filament winding machine. Their specifications and design details are given in Chapter 6.

5.4.3 The Transducer:

The controller requires information concerning the state of the system at any

instant so that it can correct for any deviation from the desired controlled state. The output signal from a transducer is generally an electrical voltage and ideally should be directly proportional to the measured variable. The overall accuracy of a feed back system is ultimately dependent on the accuracy of the transducer. An error in measurement by the transducer can not be eliminated by an integrator in the forward path. A displacement transducer produces output in the form of analogue or digital signal.

Electro-craft R-80 type optical encoders mounted on the motors are used as position transducers in this CNC filament winding machine. These encoders are discussed in more detail in Chapter 6.

5.4.4 The Controller:

The controller determines the polarity and magnitude of the actuation, based on the input error signal measured by the transducer. There are various control strategies to reduce the input error signal to its minimum value. The main objective of a control strategy is to achieve a suitable system response such that the difference between the measured value and the desired value of the control variable is kept to an acceptable minimum. A suitable system response means the optimum speed and shape of response is available, without bringing instability in the control system. In simple words the objective of a controller is to move the system in the direction that minimizes some error function.

There are various techniques for error control logic, such as, PE control, PI control, PD control, and PID control etc.

5.5 Proportional Error (PE) control:

In this type of control strategy the magnitude and polarity of the actuation signal

is directly proportional to the error function.

In case of a CNC filament winding machine axis, driven by a DC motor, a simple error function may be written as;

$$E = \theta_d - \theta$$

where θ_d is the desired angular position or the *set point*, and θ is the actual angular position. A control system producing an actuation signal C_n , proportional to $(\theta_d - \theta)$ will be called proportional error (PE) control.

$$C_n = K_p (\theta_d - \theta)$$

where K_p is a constant and is known as Proportional Gain. The simplified equation of motion of one axis of the winding machine can be described by the equation;

$$T_m = J d^2\theta/dt^2 + F d\theta/dt$$

where T_m is motor torque, $J = J_L + J_m$ is the equivalent inertia of the load reflected through the gears plus the inertia of the motor, F is the equivalent friction, and θ is the angular position.

The actuation signal or motor torque for a dc motor is equal to $K_T I$, where K_T is the torque constant of the motor and I is the armature current, hence.

$$K_T I = J d^2\theta/dt^2 + F d\theta/dt$$

If we decide to apply a PE control law, then

$$K_p (\theta_d - \theta) = J d^2\theta/dt^2 + F d\theta/dt$$

Let $\theta_d=0$, because the choice of an origin is somewhat arbitrary;

$$- K_p \theta = J d^2\theta/dt^2 + F d\theta/dt$$

The solution of this type of differential equation is given as;

$$\theta = \exp\left(-\frac{F}{2Jt}\right) \left[A_1 \exp\left(\frac{1}{2}\omega t\right) + A_2 \exp\left(-\frac{1}{2}\omega t\right) \right]$$

where

$$\omega = \sqrt{\frac{F^2}{J^2} - 4 \frac{K_p}{J}}$$

The *damping term*, $\exp(- F/2Jt)$ guarantees that, with increasing time, the axis

position will get closer and closer to its goal of $\theta=0$. Furthermore, we can see that if $F^2/4K_p > J$, then the term under the radical will be positive, resulting in even more damping. Such a solution is referred to as *overdamped*, and is shown in Fig 5-2a. If $F^2/4K_p < J$, then the exponent is complex and the solution is a damped sinusoid, as shown in Fig 5-2b. In simple words, high friction case means 'hard to start, easy to stop'; and high inertia case means 'hard to start, hard to stop'. If $F^2/4K_p = J$, the solution is *critically damped*. That is, it gets to the goal as quickly as possible without overshoot.

Clearly, by choosing K_p , we can affect the performance of the control system. For small K_p , enough motor torque may not be produced to overcome friction and the axis may stop before the desired position. As K_p is increased, the motor torque also increases and the response becomes faster. Generally, the response of a simple PE controller is oscillatory in nature.

There are some problems associated with the proportional error (PE) control system.

5.5.1 Steady state error problem:

A steady-state error problem arises when a force is required by the system to maintain its steady-state, such as holding a job against gravity or to keep a filament winding machine axis steady when the machine is not running but a constant fibre tension is applied. To do so requires a torque in the steady state, but in a simple PE controller no torque can be applied unless there is an error signal.

One approach to deal with steady-state error is to produce as output a torque $T=L+K_p(\theta_d-\theta)$, where L is a constant force sufficient to hold the load when $\theta_d-\theta$ is zero. The use of this approach requires that the load be known precisely. In

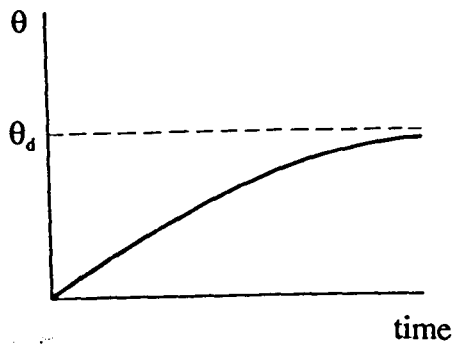


Figure 5-2a: Overdamped Response

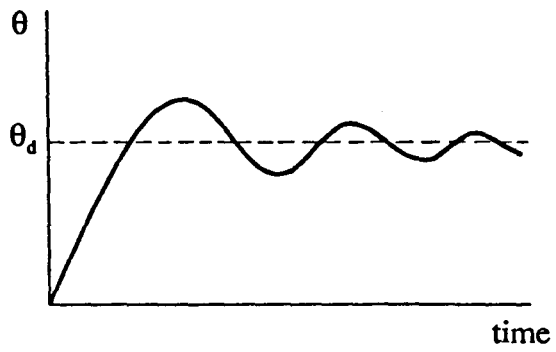


Figure 5-2b: Underdamped Response

the case of filament winding, this knowledge is difficult to achieve since the fibre tension is not constant at all instants.

An alternative is to make the drive signal equal to the integral of the error with respect to time. This is achieved by augmenting the purely proportional term with an additional component which is proportional to the integral of the error. The introduction of an integrator in to the forward path produces additional control effort which will continue to change until the error is zero. The resulting controller is known as 'Proportional Integrating' (PI) controller and is discussed in detail in references ^[56] ^[57].

In a filament winding machine, steady-state error due to fibre tension is comparatively very small and hence the integral action is not as important as in applications such as robotic arm where steady-state error due to gravity is very high.

5.5.2 The over-shoot problem:

A filament winding machine axis under PE or PI control has only friction to slow it down. To see this, suppose that the axis is close to its destination θ_d . Then $T=K_p(\theta_d-\theta)$ is quite small, but not negative. If there is much friction the axis may stop short of θ_d due to lack of drive, but if friction is small and inertia is large, then the axis may move on past θ_d . Now the error signal is negative, torque is backward, and the axis will be driven back to θ_d . In the meanwhile, however, it has overshoot its goal. After a few oscillations the axis may attain the desired position.

To reduce this over-shoot problem we can apply a large drive when the axis is a long way from the goal, and apply a negative drive when it is close to the goal. The simplest way to achieve this is to make the drive torque proportional to the derivative (rate of change) of position with respect to time:

$$T = K_p (\theta_d - \theta) - K_d (d\theta/dt)$$

where $d\theta/dt$ is the angular velocity. This equation defines the operation of a Proportional Derivative (PD) controller.

5.6 Proportional Derivative (PD) Control:

In a PD controller, the proportional action responds immediately to changes in deviation (error), but it is insensitive to how rapidly the deviation is changing. The derivative action adds in an extra term which is proportional to the rate of change of deviation. The effect of derivative action is to increase the speed of response and provided the derivative gain K_d , is correctly chosen, it improves the damping. Increasing K_d tends to slow down the filament winding machine axis movement since it increases the negative contribution to torque due to velocity. Decreasing K_d decreases the damping of the system, thus increasing the likelihood of overshoot.

5.7 Proportional Integral Derivative (PID) control:

A controller with derivative feed back can be combined with the concept of error integration to yield a PID controller ^[57] ^[58]. Because of its relatively simple implementation and the ability to adapt to varying conditions, PID control is the most widely used control method today, even though its performance is not necessarily optimal. An optimal control system ^[55] involves minimizing (or maximizing) a performance index which can be based on maximum overshoot, minimum energy, minimum settling time, or minimum steady-state error etc. This control method involves much mathematics and can only be implemented with the help of a fast digital computer.

In a PID control, the integral action can only have a significant effect if there is an error present for some time, such as a steady-state error. In filament winding, steady-state errors are not significantly high for a correctly designed controller, thus the integral action term can be eliminated. This leaves us with a simpler mathematics of PD type control. The simpler mathematics of a PD control system makes it more suitable for filament winding machine control. In filament winding a correction voltage is to be calculated for all the axes in a short interval of time. A simpler mathematics helps in the fast speed operation of the machine. Thus, PD type control is used in the CNC filament winding machine developed for this project.

The accuracy of a PD controller and the ability to handle overshoot problem depends on the gains of the controller, K_p and K_d , and the inertia and friction of the load. Zero overshoot is possible by choosing optimum values of K_p and K_d .

5.8 Tuning of Controller Constants:

If a perfect mathematical model of the control system is available, then the selection of controller gains can be done through simulation or other analytical techniques. In practice, these constants are most often determined experimentally and the procedure is termed control-loop tuning. Many techniques are available for control-loop tuning but none is suitable for all types of control systems, producing the same level of accuracy. Two techniques widely used in industry, 'continuous cycling method' and 'reaction curve method', are developed by Zeigler and Nichols. The objective of both methods is to produce settings which result in transient responses with a decay ratio of 1/4. These methods are described and compared by Golten and Verwer^[56].

A non-conventional technique was used for the tuning of controller constants for this filament winding machine. This technique is specially developed for this

project. Before applying this procedure, some information about the control system hardware components is required. These components are described in detail in Chapter 6.

The following procedure was adopted:

1. The servo amplifiers for all the three axes DC servomotors were calibrated according to the procedure given in Appendix B.
2. All the three axes of the machine were configured to operate in an open-loop environment, such that each control loop contains an independent Digital-to-Analogue Converter (DAC) channel, a servo amplifier, and a DC servomotor driving the axis. No feed back signal was used in this configuration.
3. The 'Signal Gains' of servo amplifiers, adjustable by hardware presets, were adjusted in such a way that for a given input voltage each axis moved with approximately the same velocity. This voltage signal was produced by the DAC channel, by generating a command from the computer keyboard. This step helped in calibrating all the three servo amplifiers in such a way that just one value of the proportional gain K_p , in the controller software, could be used for all the three axes.
4. The machine was reconfigured to operate in a closed-loop control environment by linking the position feed back signal, read by digital encoders, to the controller software. In this configuration only the proportional control law was applied in the controller software, derivative action term was made equal to zero by using $K_d=0$. A range of proportional gain K_p , in which the machine axes remained stable, was determined by varying K_p values in the software. A heavily oscillatory response was observed as a result of purely proportional control.

5. The derivative action term was brought in to effect by giving K_d a non-zero value. In this configuration K_p and K_d were optimized by varying their values over the operable range.

6. The optimized values for this machine were found to be $K_p=2$ and $K_d=4$.

It was found that the control system performance and stability depended on the controller gains K_p and K_d , as well as on the derivative time which is also known as interrupt time period. The controller performance improved when a shorter derivative time was used. For an interrupt time period of 10 msec or more, the control system stability heavily depended on the fine tuning of the controller gains. At this interrupt rate each axis required a different set of controller gains because inertia of each axis was different. For an interrupt time period of 5 msec or less, the control-loop tuning was less critical and the control system remained stable over a wide range of controller gains. Thus at this interrupt rate, the same values of K_p and K_d could be used for all the three axes. This helped in applying the same controller software loop to control all the three axes. The interrupt time period can not be reduced more than a certain limit. This problem is discussed in more detail in section 9.3.1.

This tuning procedure is found very appropriate and easy to apply for computer controlled servo systems.

5.9 Summary:

This chapter provides an introduction to the control theory as applied to filament winding machine. The proportional error control is discussed with its derivative action and the integral action effects. A PD type control is selected for the control of this CNC filament winding machine because of its simpler mathematics and suitability for high speed operation. A non-conventional technique is

suggested for tuning the controller constants. In this technique, each axis is first calibrated in an open-loop control and the servo amplifier gains are adjusted in such a way that for a given input voltage each axis moves with approximately the same velocity. In the second stage of the tuning process, a closed-loop control is applied and a range of K_p is determined for which all the axes remain stable. Finally, K_d is determined to fine tune the controller. The main advantage of this new tuning technique is that the same values of K_p and K_d can be used for all the three axes of the CNC filament winding machine.

CHAPTER 6

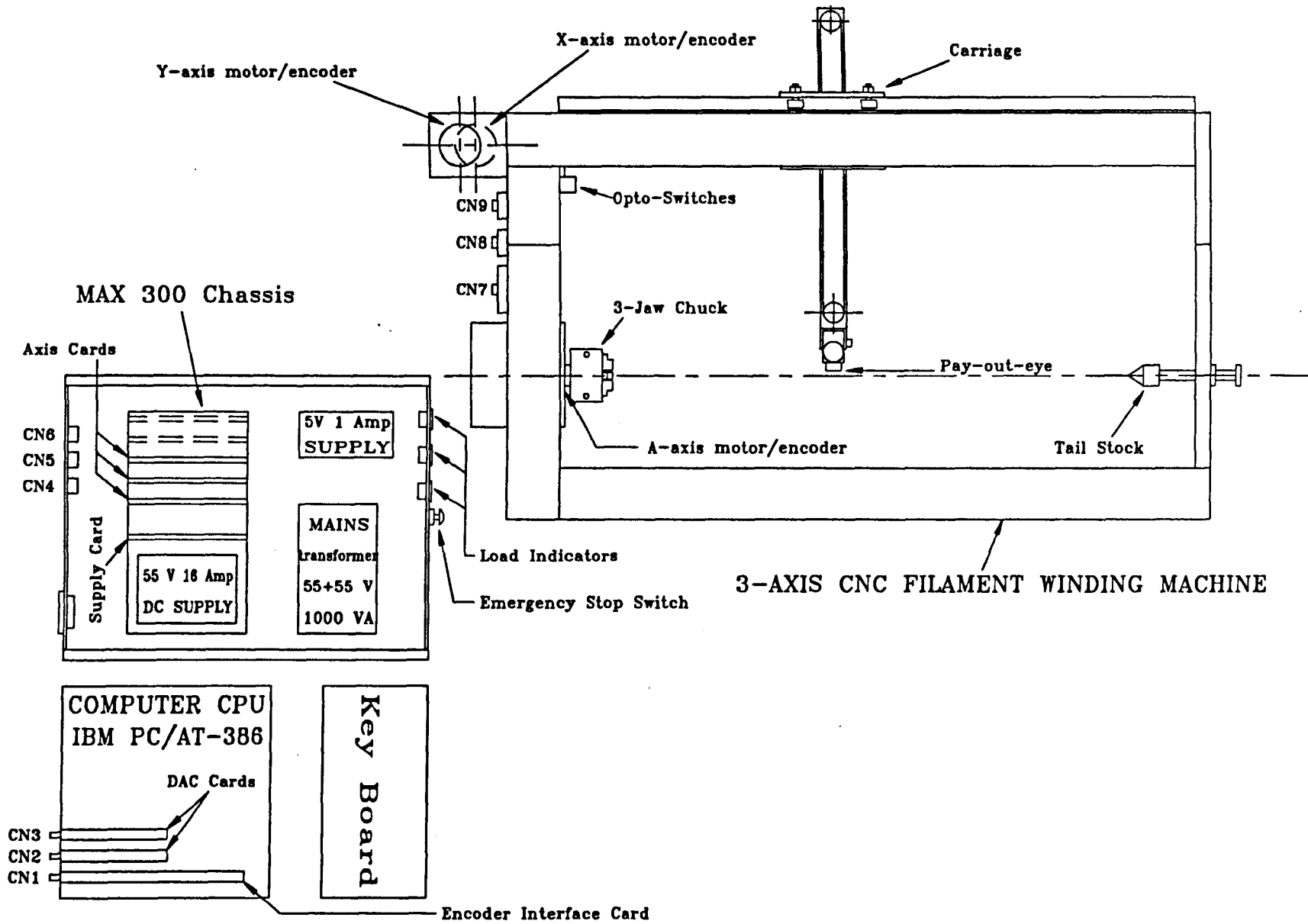
CONTROLLER HARDWARE

This chapter describes various electronic parts and assemblies used in building the controller hardware of the CNC filament winding machine. The layout of various hardware assemblies used in this filament winding machine is shown in Figure 6-1 and the controller's hardware block diagram is given in Figure 6-2. This controller hardware is designed to accommodate up to five axes. The present mechanical design utilizes only three axes but a provision is made in the controller to add two more axes in future. Various circuit diagrams and electrical connectors are described in Appendix B of this thesis. The description and specification of main components used in the controller hardware is given below;

6.1 IBM PC/AT:

An IBM PC/AT-386-25MHz compatible computer is used as the heart of the controller. An IBM PC has eight expansion slots to receive cards for data acquisition and control. Programs, specially designed for the filament winding process, can be developed to perform the CNC machine control action. The IBM PC is preferred over other computers and microprocessors because of its open architecture, suitability and availability of interfacing hardware, availability of good programming environment, execution speed, and lower cost. With the help of interrupt programming it can perform more than one task at a time. An alternative approach to using a personal computer was to develop the controller using a microprocessor. The biggest problem in developing a microprocessor based dedicated control is the cost of development, especially when the

Figure 6-1: Layout of Hardware Assemblies



HARDWARE BLOCK DIAGRAM

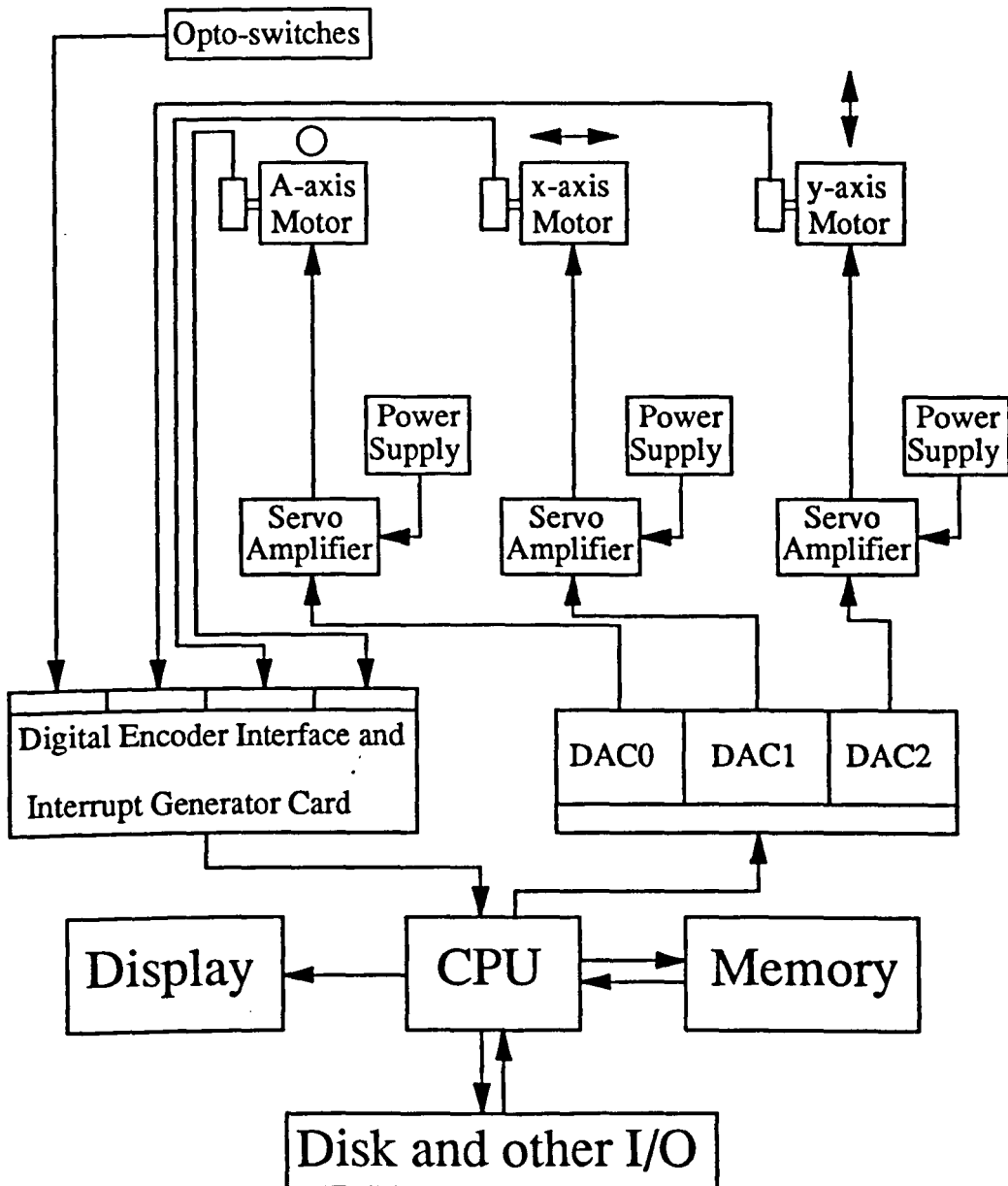


Figure 6-2: Hardware Block Diagram for the Filament Winding Machine

production volume is small. The microprocessor becomes obsolete and outdated with time and any change in the hardware design is not simple to introduce. In the IBM PC, new models with higher processing speeds and downward compatibility are being introduced regularly, so this type of computer control does not become obsolete so quickly.

6.2 Digital-to-Analog Converter Card:

A digital-to-analog converter, commonly known as a DAC, is an electronic circuit which produces an analog voltage output corresponding to a binary digital input signal. As a part of the controller hardware it converts digital data from the computer in to an analog voltage, which drives a DC motor through a servo amplifier. The basic structure of a DAC involves a network of precision resistors, a precision voltage source, some form of logic switches for level shifting and an interface circuit.

In selecting a DAC card for CNC applications, three parameters are very important;

- 1- Range of analog output voltage.
- 2- Resolution in number of bits.
- 3- Number of DAC channels available on the card.

Two Metra-Byte DAC-02 cards are used to provide inputs to servo amplifiers. Each of these cards consists of two separate 12 bit DAC channels with IBM PC interface circuitry. These cards are configured for ± 10 volt output range selected by connecting appropriate pins at the peripheral connector on each card. The card can be calibrated with the help of software sent with the card and a digital volt meter.

6.3 DC Servo Motors:

A servo motor provides the mechanical power for axis movement in a servo control loop. A permanent magnet dc servo motor, S19-1A, made by Electrocraft Ltd. is used to drive each axis of the filament winding machine. The specifications are as given below;

Continuous output power	=	179 Watts
Continuous stall torque	=	0.66 N-m
Maximum stall current	=	8.0 Amp
Torque constant; K_T	=	8.2×10^{-2} N-m/Amp
Mechanical constant; K_M	=	11.0 ms
Electrical constant; K_E	=	8.6 volt/Krpm

In a permanent magnet dc motor, the torque, T_m , is related to the magnetic flux ϕ , and armature current I_a , by the relationship;

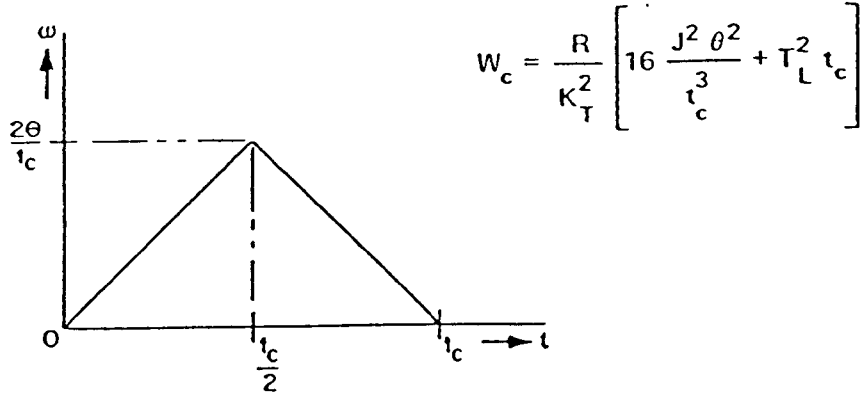
$$T_m = K_T \phi I_a$$

Since ϕ is a constant in a permanent magnet motor, so in the steady state, the torque is proportional to the armature current.

For optimum armature energy dissipation the motor moment of inertia should be equal to the load moment of inertia, and the velocity profile should be smooth^[38], as shown in the optimized velocity profile diagram, Figure 6-3.

6.4 Servo Amplifiers:

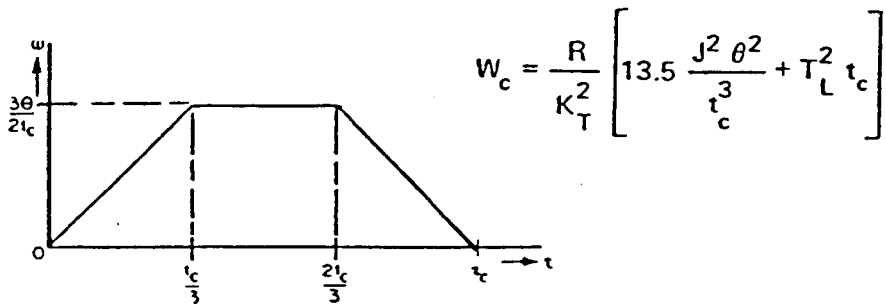
The DAC card can provide an output of ± 10 volt with a maximum current output of ± 5 mA, but the servomotor can demand a stall current of 8 Amp., so, an amplifier must be incorporated to boost the current supply. The servo amplifier



$$W_c = \frac{R}{K_T^2} \left[16 \frac{J^2 \theta^2}{t_c^3} + T_L^2 t_c \right]$$

Triangular velocity profile.

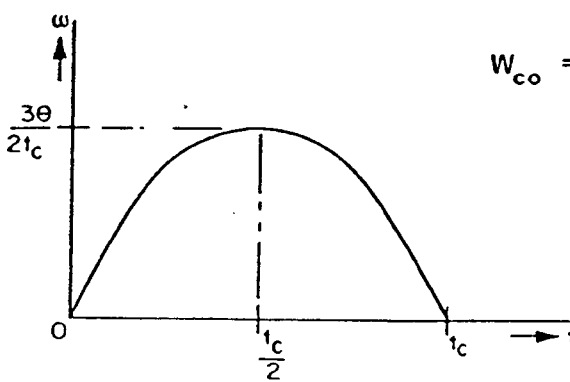
$\eta = 0.75$



$$W_c = \frac{R}{K_T^2} \left[13.5 \frac{J^2 \theta^2}{t_c^3} + T_L^2 t_c \right]$$

Trapezoidal velocity profile.

$\eta = 0.889$



$$W_{co} = \frac{R}{K_T^2} \left[12 \frac{J^2 \theta^2}{t_c^3} + T_L^2 t_c \right]$$

Optimized velocity profile.

$\eta = 1$

Figure 6-3: Motor Velocity Profile Optimization^[38]

does this job. Basically a servo amplifier is a linear current amplifier circuit in which the current output is proportional to the voltage input. It is specified by the maximum output current, the type of amplifier, and the amplifier gain.

Two types of servo amplifiers, namely the push-pull amplifier and the Pulse-Width Modulation (PWM) amplifier, are in common use. The PWM amplifier is the most versatile and popular servo amplifier today. In this type of amplifier the load current is switched *on* and *off* at a high frequency and the output power is changed by varying the duty cycle of the output pulses.

The design of a power amplifier for motor control requires some special considerations. A motor control requiring both high current and high speed may place unreasonable demands on a power amplifier. As the servomotor turns rapidly, a significant back emf is generated which opposes the applied drive voltage. To maintain a constant current, the applied drive voltage must increase accordingly. A second consideration in designing a motor driver is the fact that excessive armature current will demagnetize the permanent magnetic field magnets. This circumstance generally leads to a requirement for limiting the maximum armature current in the servo amplifier.

The MAX 300 series dc servo drive made by Electro-craft Ltd. is used to drive all the three axes. It consists of a power chassis with the ability to accommodate up to five axis cards. Each axis card is capable of delivering a continuous output power of over 1 hp (750 Watt). Maximum continuous motor current per axis is ± 12 Amp with a typical motor supply voltage of 85 volt dc. The power is supplied through a 55+55 volt, 1000 VA mains transformer. The axis cards are configured to operate as torque amplifiers with a maximum power gain of 4 Amp/volt. The actual power gain can be controlled by adjusting the 'Input Signal' potentiometer given on each axis card. The axis card calibration procedure described in MAX 300 servo drive manual is not suitable for this project because of differing set up and conditions. Another calibration procedure has been developed by the author and is given in Appendix C.

6.5 Optical Encoders:

The purpose of an optical encoder is to monitor the displacement of an axis and encode this displacement in the form of electrical pulses. It consists of four components; (i) a light source, which can be an infra red LED, (ii) a disc having a pattern of opaque and transparent segments, (iii) an infra red light sensor, (iv) a signal conditioning circuit to shape up the pulses. The number of lines on the disc and the number of pulses per revolution determine the resolution of the optical encoder.

An R80 type encoder, made by Electro-craft Ltd., is used to monitor the displacement of each axis. This encoder has a line density of 1000 lines per revolution. Due to quadrature sensing capability it is possible to record 4000 counts per revolution with a data frequency limit of 100,000 counts per second.

6.6 Digital Encoder Interface Card:

The purpose of a digital encoder interface is to read pulses from digital encoders and to convert these to the form of displacement. Basically it consists of binary up/down counters, storage registers, and computer interface circuit.

The interface card used in this project is specially designed to interface optical encoders with IBM PC and compatible computers. The design is based on a 74LS 2000 incremental encoder interface IC, developed by Texas Instruments. This card has the ability to read five encoders simultaneously, although only three channels are being used in this project. Each optical encoder outputs two pulse streams in quadrature to the interface card, which deduces the position and the direction of motion of each axis from these signals. The encoder counter operates

in double count quadrature sensing mode in which each line on the optical encoder gives a count of four pulses to the counter. As soon as the displacement data is available to the computer, it calculates a position error signal and then generates a corresponding output voltage at the respective DAC card.

This card was initially designed by Dr. D G Elliman for Crescent Consultants Ltd. Due to some noise and signal strength problems this card was unable to sustain its zero reference position after reading some positive and negative displacement. The author has made some changes in the electronic circuit to improve the signal strength and added capacitors in the input lines to suppress the noise. In the present state the interface card works reasonably accurately.

6.7 Interrupt Generator:

The computer needs an interrupt facility for periodic data acquisition from optical encoders and for generating appropriate voltages at the respective DAC channels at regular intervals. An interrupt is a signal, generated by software or hardware, which causes the operation of the currently executing main program to be interrupted. On receiving an interrupt signal, control is transferred to a form of subroutine known as *interrupt service routine*. The interrupt routine in this controller reads current encoder positions and generates appropriate voltages at the respective DAC channels. When the computer has completed the interrupt routine, the main program is rejoined at the point where the interrupt occurred. This way the computer can perform the axes movement control task at regular intervals and perform any calculation on the data simultaneously.

A hardware clock of 200 Hz is used as the interrupt generator for this filament winding machine controller. This interrupt generator is made with a Motorola bit generator IC, MC 14411. A 2 MHz crystal oscillator is the clock source for the frequency network of the interrupt generator circuit. This interrupt generator

provides the clock for data acquisition and control at every 5 mSec interval. The interrupt generator circuit is made on a 1"x 2" pcb which is fixed on the encoder interface card as a piggy-back card.

6.8 Summary:

This chapter describes the electronic hardware used in the filament winding machine controller developed for this project. An IBM PC/AT-386 computer is used as the heart of the logic controller. The correction signal generated by the controller software is supplied to a Metra-Byte DAC card which generates appropriate voltage signal for the axis drive. This voltage signal is amplified by the servo amplifier unit, MAX 300, and then sent to the DC servo motor, S19-1A, which moves the respective axis. The actual position of the axis is fed back to the logic controller by R80 type optical encoder, which is fitted on the rotor of each axis servo drive motor.

CHAPTER 7

CONTROL SYSTEM ANALYSIS

In previous chapters the hardware components used in the filament winding machine controller are described and a control technique based on proportional derivative control logic is chosen. Chapter 5 described an experimental technique for tuning the controller constants of the CNC filament winding machine. This chapter presents an alternate numerical approach and deals with the theoretical analysis and analytical assessment of the controller design. Before analyzing the performance of a control system, it is important to understand the system modelling and analysis techniques. A computer-aided design and simulation package called CODAS^[56] is used for the control system response analysis. A brief introduction of the terms and techniques used in control system analysis is also given in this chapter.

7.1 Introduction to Control System Synthesis:

There are many analytical techniques available for the design and analysis of control systems, all requiring a knowledge and understanding of the behaviour of the system to be controlled. For mechanical systems the equations of motion are developed for each section of the system, in the form of differential equations, starting from Newton's laws of motion. These equations are collectively known as the *mathematical model* of the system. In case of nonlinear differential equations, simplifying assumptions are employed to transform these to linear differential equations. Characteristic equations of each section are written and *transfer functions* are obtained. The solution to differential equations can be

obtained by either the classical method or by Laplace transformations. This solution yields the complete steady-state and *transient response* of the system for a given input. The transient response indicates the system stability while the *steady-state response* is very useful in determining the steady-state error when the system is subjected to a sinusoidal input. For the synthesis, the analysis and design of the control system the root locus, Bode plot, Nyquist plot, Nicholl's plot and closed-loop pole zero location methods^[55] are recommended. Usually if the performance specifications are expressed in terms of the system transient response, the root locus method is chosen to design the system and if, these are expressed in terms of the *frequency response*, either Bode plot or the Nyquist plot is used. For this filament winding machine a damping factor of 0.7 is chosen and the control system response time is less than 125 msec.

The correct description of the system or component dynamic performance by differential equations is basic to all methods of analysis and synthesis. Often mathematical models are constructed not only for control-system-design work but for other purposes, for example in obtaining a greater understanding of the behaviour of the system, or to amend and improve the performance of the system.

7.2 Linear Differential Equation:

In general, mathematical models of complicated systems take the form of the nth order linear differential equations, which may be written as follows^[48];

$$a_0 \frac{d^n x}{dt^n} + a_1 \frac{d^{n-1} x}{dt^{n-1}} + \dots + a_{n-1} \frac{dx}{dt} + a_n x = b_0 \frac{d^m u}{dt^m} + b_1 \frac{d^{m-1} u}{dt^{m-1}} + \dots + b_{m-1} \frac{du}{dt} + b_m u \quad (7-1)$$

where $x(t)$ is the output from the system and $u(t)$ is the input to the system, and n, m are indices such that $n \geq m+1$; coefficients a_i and b_i are constant.

In the case of the carriage control system of the filament winding machine, as shown in Figure 7-1, this equation reduces to;

$$J \frac{d^2\theta}{dt^2} + F \frac{d\theta}{dt} = T_m \quad (7-2)$$

where J includes the motor inertia J_m and the load inertia J_L reflected through the gear ratio N , such that $J = J_m + J_L/N^2$. F is the equivalent friction and T_m is the motor torque.

The solution of a linear differential equation can be obtained either by the classical method or by Laplace transformation.

7.2.1 Classical method of solution:

In the classical method, the solution of a linear differential equation has two components: the *complimentary function* and the *particular integral* ^[47]. The complementary function is obtained by solving the differential equation as it stands and represents the steady-state or forced solution of the equation. The particular integral is the solution of the differential equation when the right hand side is made equal to zero. This equation is called the *characteristic equation* and its solution represents the transient behaviour of the system as it moves from its initial state to a final steady-state. The characteristic equation is independent of the forcing input.

Considering the general equation (7-1) but with the input function remaining constant, that is;

$$a_0 \frac{d^n x}{dt^n} + a_1 \frac{d^{n-1} x}{dt^{n-1}} + \dots + a_{n-1} \frac{dx}{dt} + a_n x = b_0 u \quad (7-3)$$

The complete solution ($x = x_c + x_p$) of this type of equation, as given by Marshall^[47];

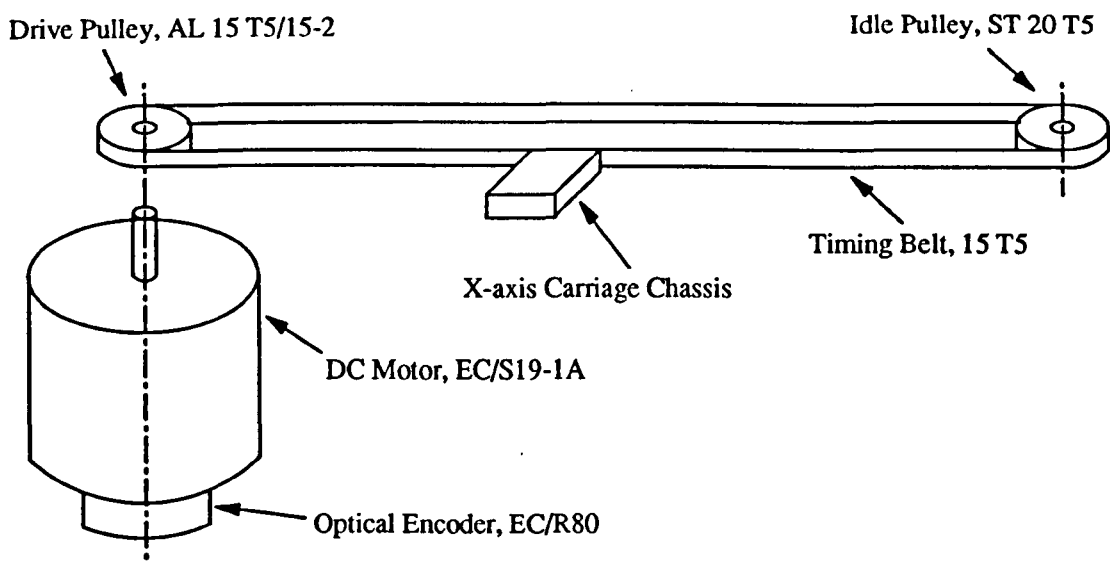


Figure 7-1: Motor Drive Mechanism for X-axis Carriage of the Filament Winding Machine

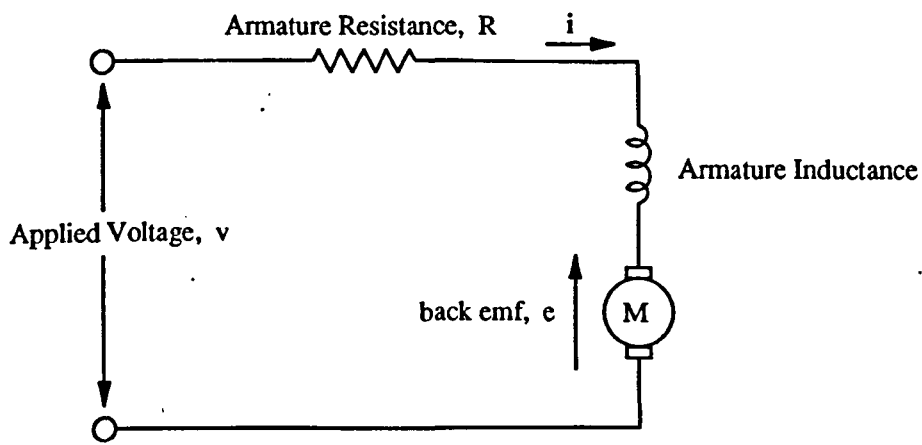


Figure 7-2: Equivalent Circuit for a Permanent Magnet DC Motor

$$x = \sum_{i=1}^n A_i e^{m_i t} + \frac{b_0}{a_n}$$

The m_1, m_2, \dots, m_n are the roots of the auxiliary equation derived from the complementary function and the unknown coefficients A_1, A_2, \dots, A_n are obtained from knowledge of n initial conditions.

For most of the control systems, the classical method of solving differential equations is very tedious and too mathematical involving many unknown coefficients. It does not provide a deep engineering insight in to the behaviour of the control system. For control problems, it is easier to use Laplace transforms for solving the differential equations.

7.2.2 Laplace transformation:

From the control engineering point of view, the Laplace transformation provides a more convenient and a more engineering-type approach to the solution of the differential equations. In this method the differential equation, in the time domain, is transformed in to an algebraic equation, in the s - or complex frequency domain. The solution of this algebraic equation is calculated and then the inverse transform of this solution is obtained, which is the solution of the original differential equation. To find out the Laplace transform of a differential equation help is taken from the compiled tables ^[47] ^[48] of transform pairs. Similarly, the inverse transform of a function is obtained using the same table, reading from right to left rather than left to right.

Using Laplace transform pairs table, the n -th order differential equation (7-1) can be transformed in to;

$$a_0 s^n X(s) + a_1 s^{n-1} X(s) + \dots + a_{n-1} s X(s) + a_n X(s) = b_0 s^m U(s) + \dots + b_m U(s) \quad (7-4)$$

where $X(s)$ and $U(s)$ are the Laplace transforms of $x(t)$ and $u(t)$, respectively. Equation (7-4) is an algebraic equation and may be resolved to give;

$$X(s) = \left[\frac{b_0 s^m + b_1 s^{m-1} + \dots + b_{m-1} s + b_m}{a_0 s^n + a_1 s^{n-1} + \dots + a_{n-1} s + a_n} \right] U(s) \quad (7-5)$$

Equation (7-5) represents the transformed relationship between the input $U(s)$ and the output $X(s)$ and the term in square brackets is called the *transfer function* between the input and the output provided the initial conditions are zero. The transfer function is of paramount importance in understanding the behaviour of a control system and that is why the mathematical model of a system is usually expressed in this form.

In order to obtain the time domain solution $x(t)$ of equation (7-1), the inverse Laplace transform of equation (7-5) is obtained by factorising the denominator, expressing the resulting ratio of polynomials in partial-fraction form, and reading the transform table.

7.3 Transfer Functions:

The transfer function of a system or element is the ratio of the Laplace transform of the output to the transform of its input, under the conditions of zero initial energy^[39]. It is a complete description of the dynamic properties of a system and may be represented as a mathematical expression of the frequency response or the time response, to a specified input. It depends only upon the system and not upon the form of input. The concept of transfer function is very important for determining the stability of a control system.

Let us consider the motor drive mechanism for x-axis carriage of the filament winding machine, as shown in Figure 7-1 and Figure 7-2. The differential equation of the system is as given in equation (7-2). The developed torque T_m , for a permanent magnet DC motor is given by;

$$T_m = K_T I_a \quad (7-6)$$

where $K_T=0.082 \text{ Nm/Amp}$ is the motor torque constant and I_a is the armature current supplied to the motor. The voltage equation of the motor can be written in terms of supplied voltage v , and the back emf v_m , as

$$v = I_a R_a + v_m \quad \text{and} \quad v_m = K_E d\theta/dt$$

where $K_E=8.6 \text{ volt/Krpm}$ is the voltage constant of the motor, and $R_a=0.4\Omega$ is the armature resistance. The motor armature inductance is neglected in this case.

$$\text{so } I_a = \frac{v - v_m}{R_a} = \frac{v}{R_a} - \frac{K_E}{R_a} \frac{d\theta}{dt} \quad (7-7)$$

Then from (7-2), (7-6), and (7-7);

$$T_m = K_T I_a = \frac{K_T}{R_a} v - \frac{K_T K_E}{R_a} \frac{d\theta}{dt} = J \frac{d^2\theta}{dt^2} + F \frac{d\theta}{dt}$$

The equation may be written as;

$$J \frac{d^2\theta}{dt^2} + \frac{FR_a + K_T K_E}{R_a} \frac{d\theta}{dt} = \frac{K_T}{R_a} v \quad (7-8)$$

If we take the Laplace transform of this equation and solve for the transfer function, the result is;

$$\frac{\theta(s)}{V(s)} = G(s) = \frac{\frac{K_T}{R_a}}{Js^2 + \frac{FR_a + K_T K_E}{R_a} s}$$

$$G(s) = \frac{\frac{K_T}{R_a}}{s \left(s + \frac{F R_a + K_T K_E}{J R_a} \right)} \quad (7-9)$$

which is the desired transfer function of the DC servo motor connected to a belt-pulley drive. In this case $\theta = x/r$ and $J = J_m + mr^2$, where m is the mass of the carriage, $r=11.94\text{mm}$ is the radius of the pulley attached to the motor, x is the linear distance travelled by the carriage and $J_m=1.2 \times 10^{-4} \text{Kg/m}^2$ is the rotor moment of inertia.

Assuming a very small friction, equation (7-9) reduces to;

$$G(s) = \frac{1 / K_E}{s(1 + s \tau_m)} \quad (7-10)$$

where

$$\tau_m = \frac{J R_a}{K_E K_T} \quad \text{sec}$$

For the X-axis motor drive; $K_E=0.082 \text{ v/rad-s}^{-1}$ and $\tau_m=0.0214 \text{ sec}$, thus;

$$G(s) = \frac{570}{s(s + 46.7)}$$

The DAC card used in this project has a resolution of 12 bits and gives an output of ± 10 volts. Therefore the transfer function of the DAC is 20 volt / 4096 count.

The position, θ , is sensed by an optical encoder which gives a resolution of 4000 counts per revolution. Thus, the encoder transfer function is 4000 count / 2π rad.

The servo amplifier gain, K_{amp} , is adjusted physically by tuning the 'Signal Gain' preset on the servo amplifier. Its value can vary between 0 and 8. It is set experimentally to achieve a motor velocity of about 1.5 rad/s for an input of 3 volt.

In a control system analysis, two or more elements can be combined to produce a single transfer function. Most of the computer programs for control system analysis require the control system to be divided in two transfer functions. One is called the plant transfer function, $G_p(s)$, which includes all the hardware elements of the control system. The second transfer function is called the controller transfer function, $G_c(s)$, which is based on the controller logic used in the control system. There are several computer programs available in market which take the input in the form of plant transfer function, $G_p(s)$, and controller transfer function, $G_c(s)$, and then plot the response of the control system.

By combining all the continuous elements of the X-axis control system for the filament winding machine, the combined plant transfer function becomes;

$$G_p(s) = \frac{20}{4096} \times K_{amp} \times \frac{570}{s(s + 46.7)} \times \frac{4000}{2\pi}$$

$$\text{or } G_p(s) = \frac{1772 K_{amp}}{s(s + 46.7)} \quad \text{rad/volt} \quad (7-11)$$

The transfer function for a PD controller can be represented by the equation^[62];

$$G_c(s) = \frac{1 + s \tau_d}{1 + s \tau_d / a} \quad (7-12)$$

where $\tau_d=0.005$ sec is the derivative time and a is the taming factor^[56] for the tuning of the controller. The value of a is less than unity for a lag compensator and greater than unity for a lead compensator.

7.4 Block Diagram Representation:

A block diagram is a simple way of representing the relationships between inputs, disturbances and outputs of a linear system in transfer function form. Complex

systems may be represented by many blocks connected together, each block representing the transfer function of an individual part of the system (see Figure 7-3). It displays the functional relationships and gives a clear insight to the problem from the control point of view. Thus, a mathematical model, a transfer function and a block diagram are three identical ways of expressing the input-output information of a linear system.

A simplified block diagram representing the belt driven x-axis carriage of the filament winding machine is shown in Figure 7-4. For reasons of simplicity the complete mechanism for the axis motion, including the DAC, servo amplifier, motor drive and the encoder is modelled as a single unit. In Figure 7-4, $r(s)$ is the transform of the reference value $r(t)$, $x(s)$ is the transformed output, $G_c(s)$ is the transfer function of the controller and $G_p(s)$ is the combined transfer function of the plant.

In most cases, once a machine is built, the transfer function $G_p(s)$ can not be changed while the value of $G_c(s)$ is not fixed. The value of $G_p(s)$ is calculated analytically or experimentally, whereas the value of $G_c(s)$ is varied to get an optimum performance from the control system. The value of $G_c(s)$ is varied, by changing the type of controller.

For the X-axis control system for the filament winding machine, the following relationships can be written;

$$e(s) = r(s) - x(s) \quad (7-13)$$

$$u(s) = G_c(s) e(s) \quad (7-14)$$

$$x(s) = G_p(s) u(s) \quad (7-15)$$

Combining these equations, the overall input-output relationship can be determined as;

$$x(s) = \frac{G_c(s) G_p(s)}{1 + G_c(s) G_p(s)} r(s) \quad (7-16)$$

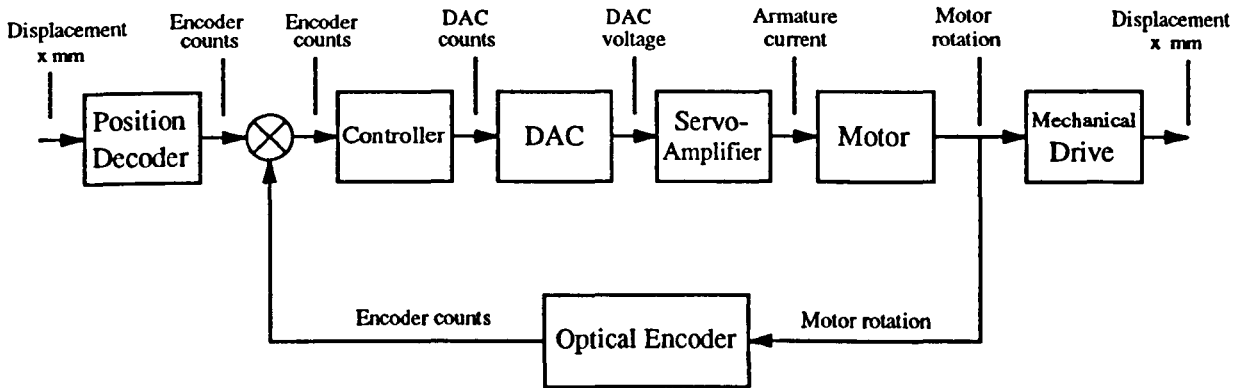


Figure 7-3: Block Diagram Representation of X-axis Control System

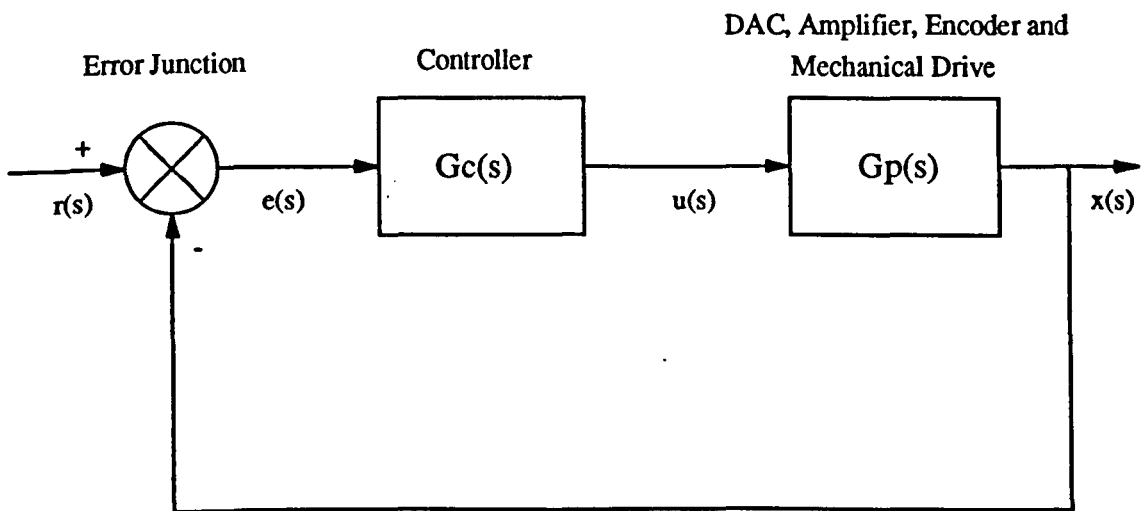


Figure 7-4: Simplified Block Diagram of X-axis Control System

and the overall transfer function of the control system is

$$G'(s) = \frac{G_c(s) G_p(s)}{1 + G_c(s) G_p(s)} \quad (7-17)$$

From this overall transfer function the characteristic equation of the control system can be written as;

$$1 + G_c(s) G_p(s) = 0 \quad (7-18)$$

It is the roots of this equation that determine the transient performance and stability of the control system. These roots are influenced by the choice of $G_c(s)$ and the servo amplifier gain and hence the stability depends on the use of correct design procedures.

7.5 Transient Response:

Once a mathematical model of a control system is calculated, the performance specifications outlined and the block diagram along with necessary transfer functions prepared, the behaviour of the control system can be analyzed using *time domain* analysis or *frequency domain* analysis. In practice it is usual to apply either the complex plane or frequency domain technique in the initial stages of the analysis or design of a system and then to check its behaviour in the time domain. The behaviour of the closed-loop system can be analyzed if the roots of its characteristic equation are known. Sometimes it is not easy to calculate the roots numerically; in that case graphic techniques are used. The complex plane analysis method is based on graphical techniques that are able to provide information on the stability and behaviour of the closed-loop control system on the basis of the knowledge of the characteristics of the open-loop system. It is easier to obtain the transient response of an open-loop system because usually, the open-loop transfer function is in factored form, whereas, the closed-loop transfer

function is not. Consider the overall closed-loop transfer function of the single axis of a filament winding machine, equation (7-17).

It can be seen that the overall transfer function $G'(s)$ cannot be written in factored form because of the form of equation (7-17). Hence, there is a need for techniques from which the closed-loop system can be obtained. Evans(1954) has developed a graphical method of factorising the closed-loop transfer function $G'(s)$, known as *Root Locus Method*. This method requires information about the poles and zeros of the open-loop transfer function $G(s)$, which can be obtained by drawing the pole-zero diagram.

The response of the X-axis control loop of the filament winding machine is shown in Figure 7-5. This response is plotted using CODAS[®], by supplying it the transfer functions, $G_p(s)$ and $G_c(s)$, as given by equations (7-11) and (7-12) respectively. The figure shows the output of the control system for three different values of the servo amplifier gain, $K_{amp}=0.2, 0.45$ and 2.0 . At $K_{amp}=0.2$, the system response time is more than 500 msec and thus it is not a suitable value for the servo amplifier gain. At $K_{amp}=2.0$, the response time is about 50 msec but it suffers from an overshoot problem. At $K_{amp}=0.45$, the system response time is close to the desired value of 125 msec and there is no overshoot problem. Therefore, $K_{amp}=0.45$ is the most suitable value for the X-axis servo amplifier gain.

These results show that for a given controller transfer function, $G_c(s)$, the desired response of an axis control system can be obtained by varying the servo amplifier gain, K_{amp} . Figure 7-5 also tells that for any value of the system inertia there is always a value of K_{amp} at which the control system is stable. An axis control system with high inertia requires a bigger value of K_{amp} to produce the desired response and an axis control system with low inertia requires a smaller value of K_{amp} to produce the same response. These results suggest that the same controller logic can be used for all the three axes of the filament winding machine if their servo amplifier gains are tuned according to the procedure given in section 5.8

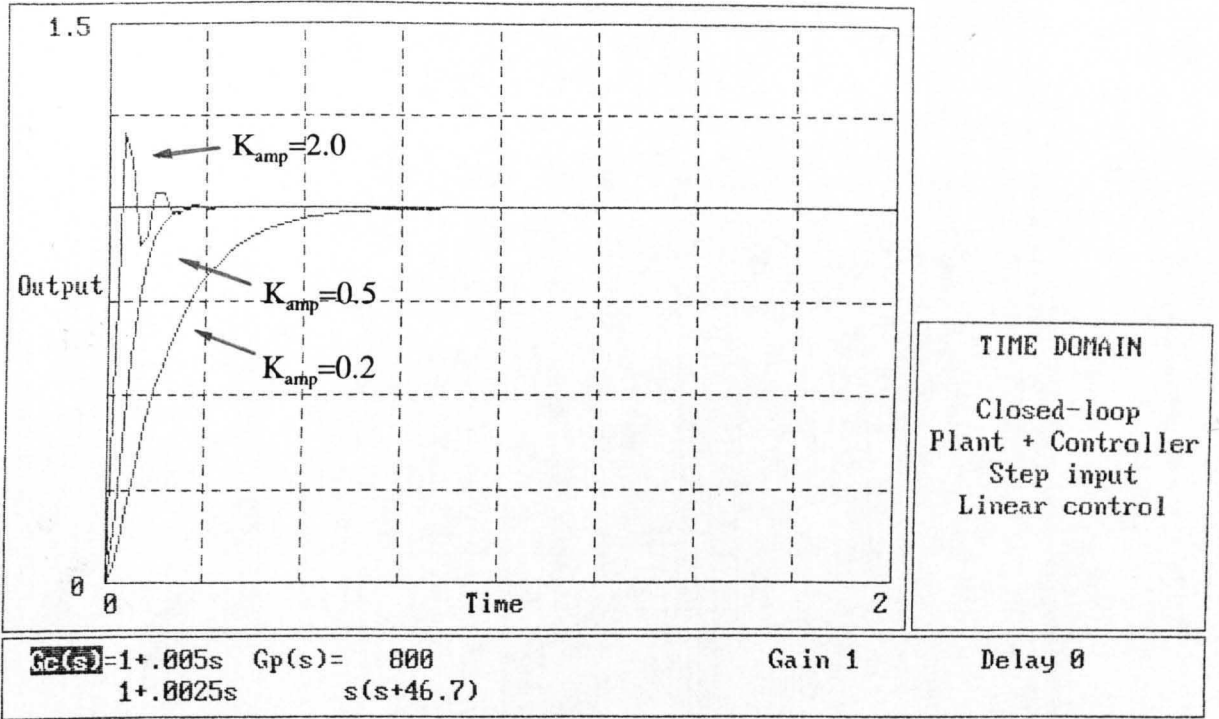


Figure 7.5: The Response of X-axis Control at Different Servo Amplifier Gains

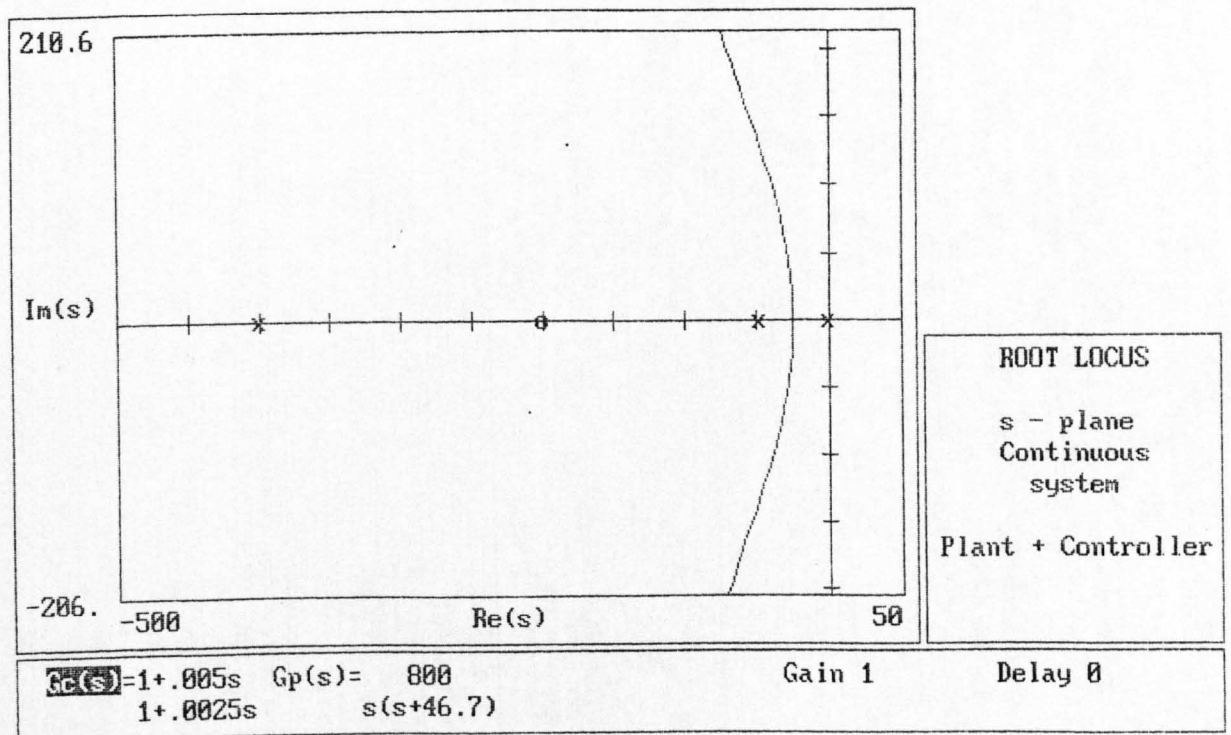


Figure 7-6: The Root-Locus Diagram of X-axis Control System

of this thesis.

7.6 Pole-Zero Diagram:

The stability of a control system can be determined by finding out the *poles* and *zeros* of its transfer function. *Poles* of a transfer function are found by calculating the roots of the denominator part of the transfer function, when set equal to zero. When s is set equal to any of these values the transfer function $G(s)$ becomes infinity. The position of these poles is marked with a 'x' on the s -plane. *Zeros* of a transfer function are obtained by calculating the roots of the numerator part of the transfer function. These roots are called zeros since setting s equal to any of these values makes $G(s)$ zero. The position of these zeros is marked with a '0' on the s -plane. The location of poles and zeros of the open-loop transfer function $G(s)$ on the complex plane is known as the Pole-Zero Diagram.

7.7 Root Locus Diagram:

The root locus method provides a much simpler graphic method of determining the roots of the characteristic equation of a closed-loop system, as compared with numerical methods. This method requires the knowledge of open-loop system poles and zeros which can be obtained numerically. Root locus diagram provides a considerable insight in to the behaviour of the system and clearly indicates the stability of the control system. The method of constructing root locus diagram is given in many books ^[48]^[49] on control engineering. The root locus is the locus of the closed-loop roots as a function of open-loop roots. It represents the loci of the closed-loop poles for all values of the control gain K , as K varies from zero to infinity. Using this diagram it is then possible to select the values of K

for which the control system will remain stable.

Once the root locus diagram is drawn and a suitable value of the gain K is chosen, it is recommended to obtain the actual transient behaviour so as to check whether the choice is good. The root locus diagram of the control system described with equation (7-17) was plotted with the help of computer program CODAS[®]. The results are shown in Figure 7-6.

7.8 Stability Criteria:

Stability is the property of a system or element whose response to a stimulus dies down, if the stimulus is removed. A statement that a system is stable means that the system is stable under all normal operating conditions and for all types of stimuli normally encountered. A system may be referred to as being stable in one region of operation and not in another.

A control system is called stable if the roots of its characteristic equation (or of the denominator of its transfer function set equal to zero) have negative real parts. Computation of these roots can be extremely time-consuming. There are alternative methods of assessing whether a system is stable or not. One commonly used method is Routh and Hurwitz criterion^[59]. Other methods are based on graphical techniques like pole-zero diagram and root-locus diagram etc.

The filament winding machine control system, described by equations (7-11) and (7-12), was analyzed using CODAS[®], and it was found that the poles of the control system are real and negative, as shown in Figure 7-6, thus the system is stable.

7.9 Summary:

This chapter presents methods for the theoretical analysis and the analytical assessment of the CNC filament winding machine control. A transfer function method is selected for this purpose. A mathematical model of the control system for the X-axis of the CNC filament winding machine is developed. The servo amplifier tuning procedure given in section 5.8 is verified by showing the control system response at different values of the servo amplifier gain. The stability of this control system is analyzed by plotting the root-locus diagram using CODAS®. The main objective of this filament winding machine controller is to compare the control performance of the linear interpolation logic with the B-spline interpolation logic. For this comparative study a control system which is reasonably stable is considered enough, a high standard optimization of the controller is not very important.

CHAPTER 8

PAY-OUT-EYE PATH CONTROL

Once the mechanical set up and the controller hardware are ready, the position of each axis can be read and an output voltage can be sent to the respective servo motor to change this position in a controlled manner. The magnitude and the polarity of the output voltage is determined by a Proportional Derivative type control scheme, as described in Chapter 5. For a filament winding machine to perform some useful task it is important to move its pay-out-eye along a certain specified path. This chapter is about the elementary task control — how a specified path may be taught and executed. Linear interpolation and B-spline interpolation techniques, which are used in the trajectory planning of this filament winding machine, are described in this chapter.

8.1 Path Computation:

In most texts the terms *path* and *trajectory* are used interchangeably but in this thesis both the terms have different meanings as distinguished by Snyder^[57]. The pay-out-eye path is defined as the space curve traced by the pay-out-eye. The pay-out-eye trajectory is defined as the time history of the position of each axis required for specifying the pay-out-eye path. The path generation and the trajectory generation are two different design problems.

A pay-out-eye movement task is specified by supplying a series of points through which it must pass. The position of the pay-out-eye at each important point on the path is specified in cartesian coordinates, using absolute coordinates or

incremental displacement of each axis. The sequence of points along the desired pay-out-eye path is stored in a text file, called *part program* file. This file is composed of one or more subroutines of fibre paths which are repeatedly indexed to generate the entire coverage of the mandrel surface. More information about the structure and features of this file is given in section 9.4

The pay-out-eye path is selected in such a way that the fibre is laid on a geodesic path on the mandrel surface. Slight deviations from the geodesic path, within the fibre and mandrel surface friction limit are allowed. Large deviations from the geodesic path result in fibre slippage.

There are several methods for generating the pay-out-eye path. The CNC filament winding controller developed for this project accepts the pay-out-eye path generated by any one of these methods.

8.1.1 Keyboard input method:

This method is useful only for very simple winding patterns for producing cylindrical shapes. The pay-out-eye coordinates are entered manually in the part-program file using a text file editor. This part program file is then supplied to the CNC filament winding machine controller to execute the task. Accuracy of the adopted path depends on the skill and experience of the person entering the data. For slightly complex winding patterns this method becomes impossible to use in practice. The real advantage of this keyboard editing method is obtained when it is used in conjunction with teach-in method. The part program file is created by teach-in method or by CAD techniques and then a text editor is used to make slight changes in the pay-out-eye path.

8.1.2 Teach-in method:

In the teach-in method^[8] the pay-out-eye is moved under manual control along the desired path and when it is judged that an appropriate section of the roving has been laid, the pay-out-eye position is recorded by pressing a control button. This method is very time consuming and unless positions are recorded at close intervals, leads to fibre slippage and short cutting of the fibre path. For simple geometries this is the cheapest way of generating pay-out-eye path.

8.1.3 Computer generated path:

There are several computer programs in the market which generate pay-out-eye paths based on the geometry of the mandrel. These programs generally develop a filament path equation based upon geodesic or other criteria ^[8]. Tangents are projected from the filament path to intersect an imaginary surface on which the pay-out-eye moves. This imaginary surface envelops the mandrel. The points of intersection on this imaginary surface define the pay-out-eye path relative to the mandrel rotation.

This method is considered the most efficient for complex shaped mandrels. The cost of the software is the biggest impediment in using this type of program. The filament winding machine controller developed for this project accepts computer generated paths produced by other computer programs. These computer generated paths are input to the filament winding machine through part program files written in standard NC format.

8.2 Data Interpolation:

If all the data points of the pay-out-eye path are specified in the part-program file,

the size of the file would become impractically large to handle. For example, in this experimental arrangement there are 200 *interrupts* per second and 3 axes to control, so 600 data points are required for a program that will run for one second only. In order to maintain the size of the part-program file, relatively few of the data points are supplied in the part-program file. The trajectory generation program interpolates data for all the other points in-between. There are various techniques for data interpolation such as linear interpolation, circular interpolation and polynomial interpolation etc.

8.3 Trajectory Generation:

Computation of speeds for each axis to produce a coordinated motion is called pay-out-eye trajectory generation. In trajectory generation the exact displacement of each axis for each interrupt cycle is calculated based on the type of interpolation used. These incremental displacements of each axis are then supplied to the controller program in the form of arrays. To commence the actual motion, the controller program simply reads a vector value from the arrays and then moves the pay-out-eye by supplying an appropriate voltage to the servo motor through the respective DAC channel. The movement along the path is completed when all the values in the array are executed in the given sequence.

In filament winding it is better to provide a *continuous path* control^[58] as opposed to *point-to-point* control^[57]. In a point-to-point control, no control is required over either the speed of the individual axes or the in-between path of the axes. Since the individual axes may move at different rates, or have different distances to travel, one axis may reach its destination and stop long before another. With a point-to-point control the controller is programmed to pause at each point to plan the next step. The point-to-point control offers greater precision in terms of accuracy and repeatability but the path of the axis between two end-points is completely unpredictable. The filament winding process requires that the motion

of the pay-out-eye must be coordinated with the mandrel rotation at all points. Specifying the path points alone is not enough to guarantee a smooth movement along a certain path. For coordination among all the axes it is important that each axis starts and ends its motion at the same time and the correct speed of each axis be specified along with the path points. Thus the speed and the position of each axis must be controlled all along its path. This type of path control is called the continuous path control.

The pay-out-eye trajectory generation is a machine dependent process because in planning a trajectory it is important to ensure that the planned trajectory does not require exceeding the voltage and torque limitations of the respective DC servo motors. The maximum acceleration and speed limits can be different for different axes of the machine and these specifications can vary from one filament winding machine to another. Thus the trajectory generation program is generally a part of the controller software and depending on the type of interpolation used and the maximum acceleration limits of the machine a different trajectory may be generated for a different machine. Whereas, the pay-out-eye path generated for a particular mandrel shape remains the same for all types of filament winding machines.

There are several different methods in which a trajectory can be generated. These methods can be divided in to two major categories;

1. On-line trajectory calculation
2. Off-line trajectory calculation

8.3.1 On-line trajectory calculation:

In on-line trajectory calculation^[21] method the data interpolation of the path points and the calculation of speed for different axes takes place at the time when the

axes are in motion. This technique is also known as real-time trajectory generation, or cartesian control. The controller has to control the motion of all the controlled axes as well as compute the trajectory as a function of time. This technique can be implemented on very fast computers only. It is used at times when precise positioning is important, but the controlled axes are moving slowly. This technique is not very appropriate for filament winding because of its suitability for slow speed operations only.

8.3.2 Off-line trajectory calculation:

In off-line trajectory calculation the trajectory is calculated well before the motion is to commence^[14], so that the controller will have adequate time to control the motion of the axes using a PD or PID type control. So this technique utilizes off-line trajectory computation and on-line motion control. From the specified path the desired velocities of all the axes at each interrupt are calculated and stored in the form of arrays or tables. These desired velocities as a function of time are input to a PD or PID type position controller which moves the axes to the desired position. This is also known as velocity-based path control. The advantage of off-line trajectory generation is that it can be implemented with a computer of minimal capability^[18]. This technique is particularly suitable for operations where the high speed of operation is important and thus is used in the design of this filament winding machine controller.

For a good trajectory generation, it is important that the trajectory produced should be as close as possible to the one intended, and the requested velocity and acceleration are within the limits of the actuators. The type of interpolation scheme used plays the most important role in trajectory generation. There are various interpolation schemes. The interpolation scheme which produces the smoothest motion of the axes is considered the best. For interpolation purposes a smooth function is one which is continuous and has a continuous first

derivative. Sometimes, a continuous second derivative is also desirable. Rough, jerky motions tend to cause increased wear on the mechanism, and cause vibrations by exciting resonances in the axes drive mechanism.

8.4 Linear Interpolation:

In linear interpolation the controller program assumes that the velocity of each axis, between two given data points, is uniform and does not change. In any interpolation technique it is important that all the axes reach their destinations at the same time. For the uniform velocity calculations the number of interrupts in which this total displacement will be covered is determined and then the displacement of each axis per interrupt is calculated. This displacement per interrupt is measured in encoder counts per interrupt, and it represents the velocity of that axis. The first derivative of a displacement is the velocity, the second derivative is the acceleration, and the third derivative is the jerk. The position, velocity and acceleration profiles for a linear path are shown in Figure 8-1.

Two different types of linear interpolation techniques are used in this filament winding machine. In one technique, axis movement is *point-to-point*, which means the velocity of each axis becomes zero before addressing the next set of data points. Although the control is not very smooth, this technique ensures that all the data points are met accurately. This method is useful for moving the filament winding machine axes when the axes coordination is not important, such as in moving the pay-out-eye to a desired offset position. In the other linear interpolation technique, which provides continuous path control, all the data points are not met absolutely and the carriage velocity does not become zero before addressing the next set of data points. The magnitude of deviation from the actual data point depends on the feed rate. The control is much smoother in this method at the cost of slight deviation from the actual target point.

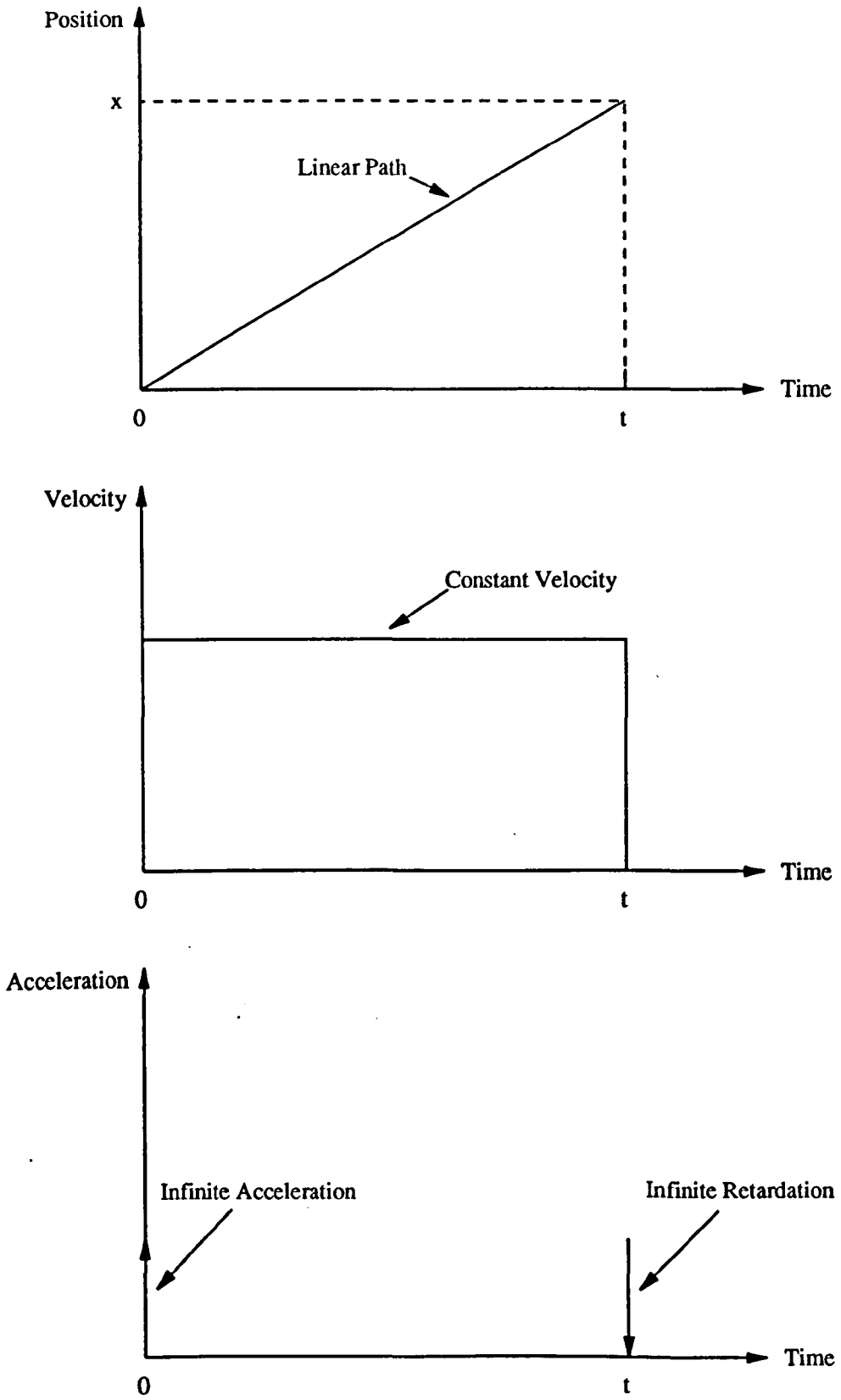


Figure 8-1: Position, Velocity, and Acceleration Profiles for a Linear Path

There is a problem with linear interpolation that it does not take in to account acceleration. At the beginning of an axis movement it demands an infinite acceleration and at the time of stopping it requires an infinite retardation. It is impossible for a servo motor to provide such accelerations, so a position error results for a short interval of time which is compensated later by the controller. The position error caused in one segment of a linear path is carried over and compensated in the next segment.

8.5 Linear Interpolation with Parabolic Blends:

It is recommended to plan the trajectory in such a way that each axis undergoes a smooth acceleration. To avoid infinite acceleration at the start and end of a linear profile segment, the profile is modified slightly and blended with a parabolic profile. The modified profile has three parts, as shown in Figure 8-2; a parabolic initial section, a linear mid-section, and a parabolic final section. This type of trajectory generation is discussed by Craig^[60], Brown^[2], and Lewis et al^[61]. This type of profile results in smooth movement between the end-points but discontinuities in velocity and acceleration occur at the end-points. These discontinuities at the end-points result in jerky motion. A motion is called *jerky* if at any point during the motion, its third derivative of displacement becomes infinity. The problem of jerks is not very obvious in most of the controllers because in practice the drive motor does not change its acceleration from zero to its maximum value in zero time.

8.6 Polynomial Interpolation:

To reduce the possibility of jerks, it is highly desirable that the velocity profile should be a smooth curve without discontinuities in it. This profile is also desired

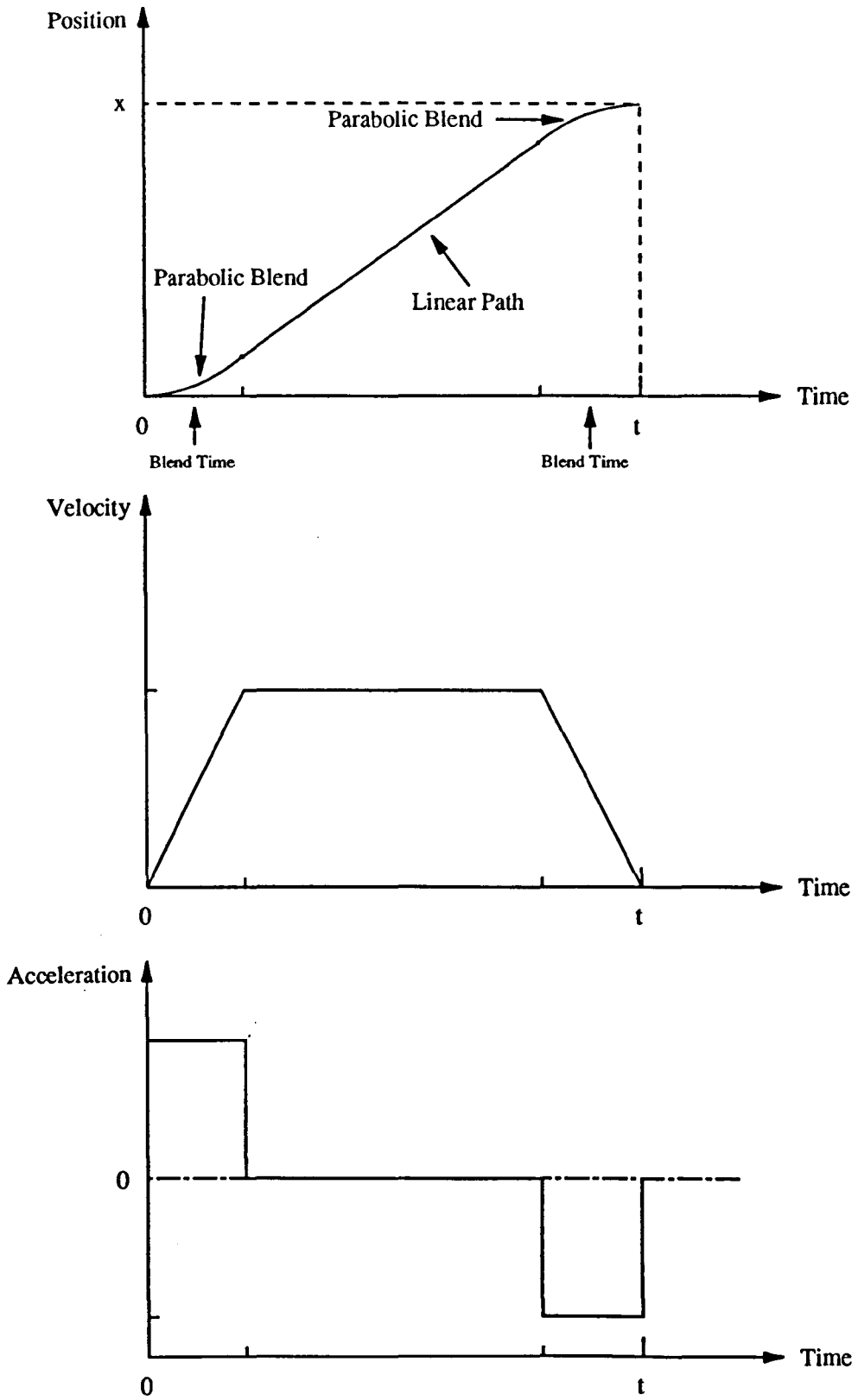
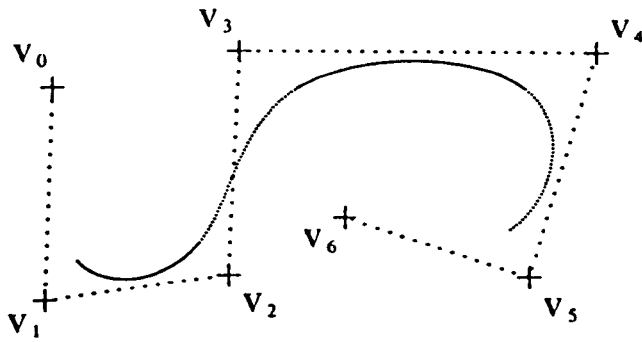


Figure 8-2: Position, Velocity, and Acceleration Profiles for a Linear Path with Parabolic Blends

to achieve the optimum velocity profile for maximum armature energy dissipation, as shown in Figure 5-2. This type of profile can be obtained by using an interpolation technique which considers more than two data points for determining the shape of the curve segment. The polynomial interpolation provides with such a solution. The polynomial interpolation is computationally more complex than other interpolation techniques but it can connect continuously and smoothly two neighbouring regions. The velocity and acceleration profiles obtained as a result of polynomial trajectory generation are smooth and continuous in nature ^{[60] [61]}. However, higher order polynomials have many undesirable properties. The main problem is that a polynomial can make the trajectory undershoot or overshoot the desired position^[21]. Both of these situations are undesirable. This is specially of concern during the departure and approach phases of the movement task. The undesirable properties of higher order polynomials can be overcome by using lower order spline functions.

8.7 Introduction to B-Spline Interpolation:

A spline curve is one which is a piecewise polynomial and which has an appropriate amount of continuity where the pieces join. B-spline or Basis-spline technique is a natural progression from Bezier curves, and these curves are the piece-wise analog of the Bernstein polynomials^{[22] [24] [25]}. The B-spline form yields smoother curves than any other method, at the price that the curves may not exactly pass through the given points^[1]. The curve can be made to pass through certain points if sufficient interpolated points, called knots^[22], are supplied around those points. The B-spline method of curve approximation was introduced by Schoenberg in 1947^[21]. This method is successfully being used in geometric modelling and in generating computer images from a set of given points. An example of B-spline curve approximation from a set of given points is shown in Figure 8-3.



1. V_0, \dots, V_6 are given points.
2. The curve is smooth and continuous at all points.
3. The first and the last point are not approximated.
4. The curve's shape can be changed by varying the number of intermediate points (knot spacing) between two given points.
5. The curve can be made to pull closer to a given point by supplying more points near that position.

Figure 8-3: An Example of B-Spline Curve Approximation

The most important property of the B-spline curves is that even their second derivatives are continuous at the points where two successive curve segments meet^{[11] [23]}. This property makes it very suitable for trajectory planning of a filament winding machine pay-out-eye path. If a pay-out-eye path is continuous at all points up to its second derivative then there is no discontinuity in the acceleration profile and the pay-out-eye motion is smooth without any jerks. If we consider the acceleration profile of a linear path (Figure 8-1) and the acceleration profile of a linear path with parabolic blends (Figure 8-2), the discontinuities are observed. These discontinuities result in a jerky motion. Even in circular interpolation^[58], where the path looks smooth, these discontinuities are observed at the points where two successive curve segments meet. The position, velocity and acceleration profiles for a B-spline path are shown in Figure 8-4. The B-spline interpolation does not suffer from this problem of discontinuities because it calculates the path between two given points by considering four points, i.e, the two given points and their two neighbouring points. That is why the first and the last point in a given sequence are not approximated.

8.8 B-Spline Trajectory Generation:

The B-spline interpolation not only can satisfy continuity on each point of the trajectory but can also provide the shortest trajectory that satisfies constraint conditions. Computationally it provides a much simpler solution than polynomial interpolation. The problem of overshoot or undershoot in higher order polynomials is also overcome in B-spline trajectory generation. A B-spline curve naturally resembles the continuous fibre laid on a mandrel. In filament winding the pay-out-eye is at some distance away from the mandrel and any sharp change in the acceleration of the pay-out-eye results in fibre pulling which disturbs the position of the previously laid fibre on the mandrel. This interpolation technique is particularly suitable for a filament winding machine controller because it results in less fibre slippage on the mandrel. The filament winding process demands a

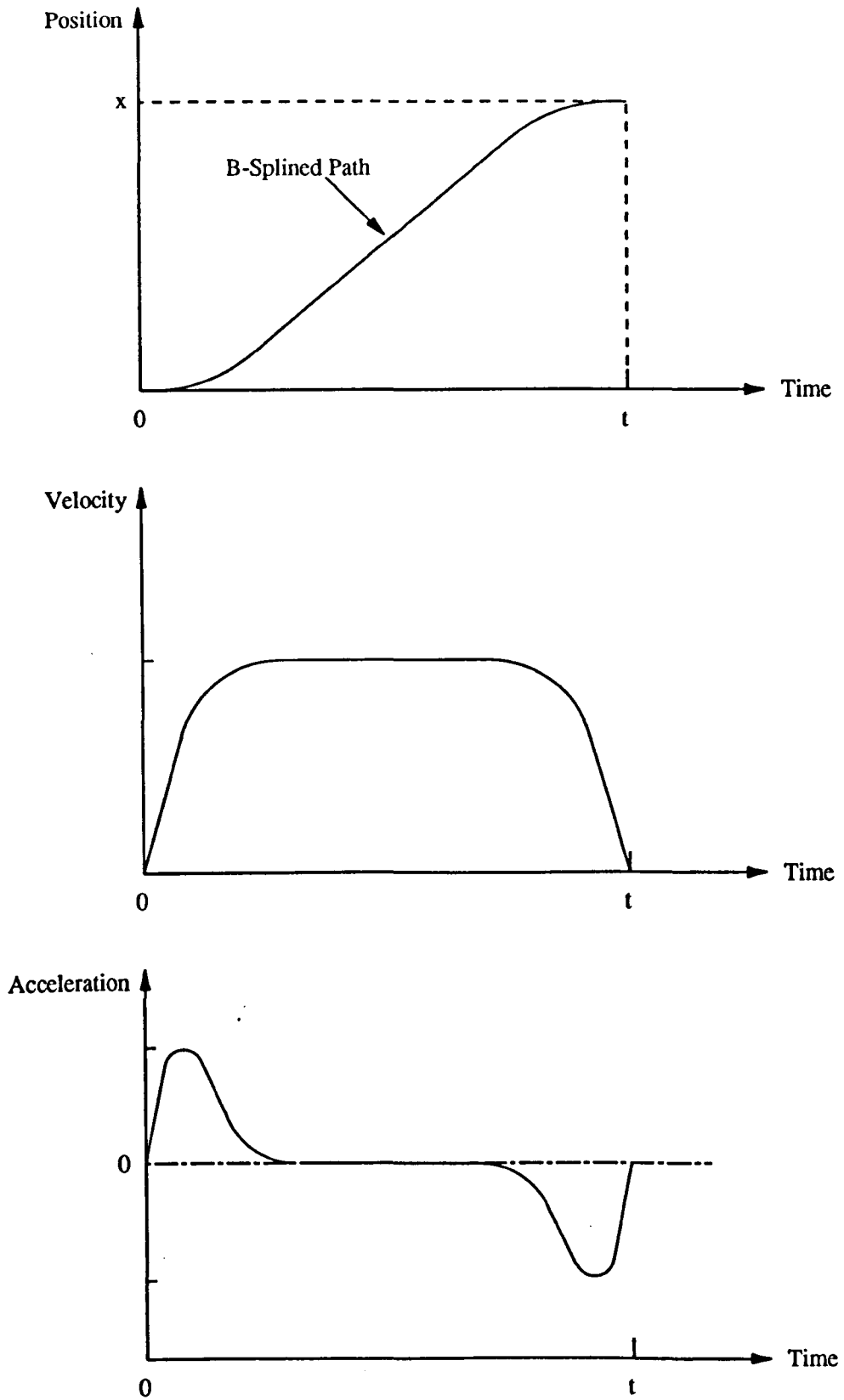


Figure 8-4: Position, Velocity and Acceleration Profiles for a B-Splined Path

controller which has a look-ahead capability so that while moving around curvatures the effect of pay-out-eye movement on previously laid fibre positions is minimal. B-spline trajectory helps in introducing this feature in the controller by considering four points for calculating its path between two given points. The B-spline interpolation produces a pay-out-eye path that is closer to geodesic as compared with the linearly interpolated path. The acceleration profile produced by B-spline interpolation is smoother than any other method discussed so far. All these characteristics make the B-spline interpolation very suitable for use in a filament winding controller.

In B-spline interpolation, the path does not necessarily pass through the given data points but it can be forced to do so by allowing two points to coincide at the given data point. The interpolated path can be made to pull towards a given point by supplying more points near the desired position. In filament winding the pay-out-eye is at some distance away from the mandrel so while turning around edges and curved surfaces, the fibre tries to follow the geodesic path on the mandrel. As far as the fibre placement on the mandrel is concerned, there can be many possible pay-out-eye paths which will produce exactly the same fibre placement on the mandrel. A pay-out-eye path for a cone-dome-cylinder mandrel, planned by the linear interpolation and by the B-spline interpolation is shown in Figure 8-5. The pay-out-eye path generated by B-spline interpolation is smooth and resembles a blown-up envelope of the mandrel surface and thus can wind roving with less *over-travel* of the pay-out-eye. The smooth displacement profile results in smooth velocity and acceleration profiles. From filament winding controller's point of view, the following properties regarding B-spline curves are very useful in pulling the interpolated path towards a desired point;

- 1- Gross changes to a curve's shape can be made anywhere, without moving the interpolation points, by varying the knot spacing.
- 2- The end conditions affect the entire curve, but their principal influence is felt at the end points.

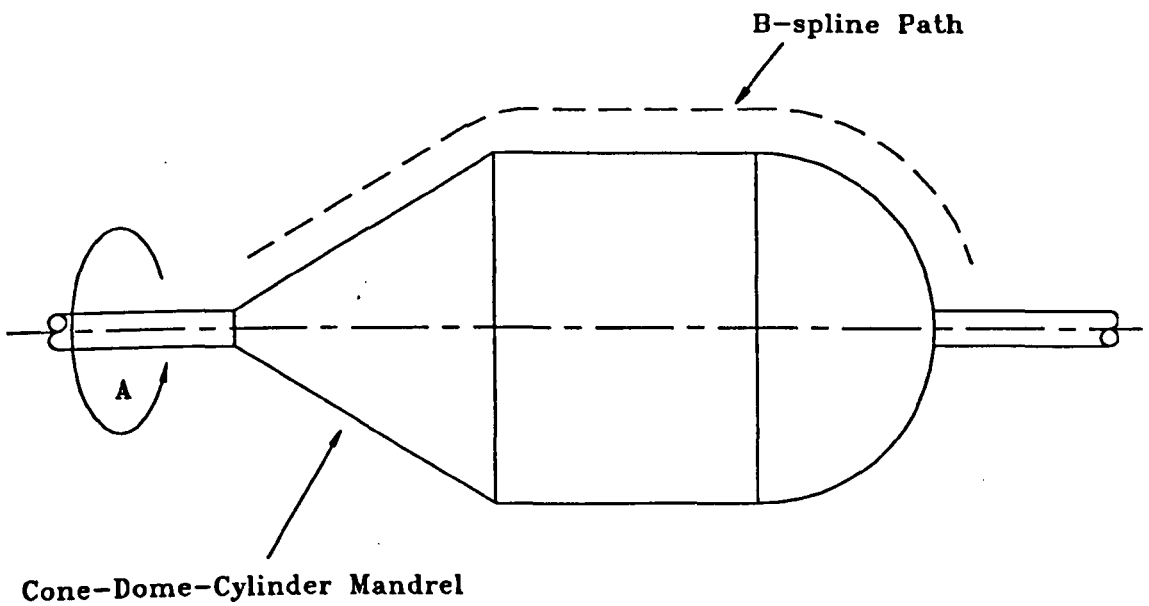
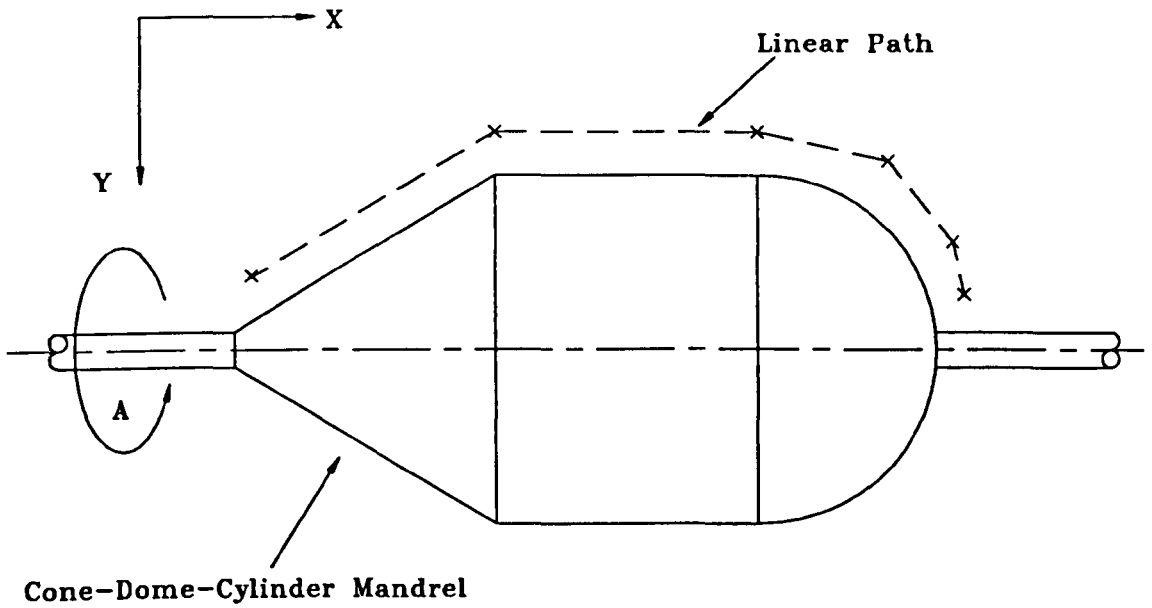


Figure 8-5: A Comparison of the Pay-Out-Eye Path

- 3- Two or more successive points are allowed to coincide. This can be used as a means to 'pull' a curve to a given point. For example, we can give the very first point the numbers 1, 2, 3, which will force the curve to begin exactly in this point.

8.8.1 Mathematical model for B-spline interpolation:

B-Spline surface segments between two successive points are obtained by computing $x(t)$, $y(t)$, & $A(t)$, where t grows from 0 to 1^[1]:

$$\begin{aligned} X(t) &= a_3t^3 + a_2t^2 + a_1t + a_0 \\ Y(t) &= b_3t^3 + b_2t^2 + b_1t + b_0 \\ A(t) &= c_3t^3 + c_2t^2 + c_1t + c_0 \end{aligned}$$

Coefficients of these polynomials are given as;

$$\begin{aligned} a_3 &= (-X_{i-1} + 3X_i - 3X_{i+1} + X_{i+2}) / 6 \\ a_2 &= (X_{i-1} - 2X_i + X_{i+1}) / 2 \\ a_1 &= (-X_{i-1} + X_{i+1}) / 2 \\ a_0 &= (X_{i-1} + 4X_i + X_{i+1}) / 6 \end{aligned}$$

$$\begin{aligned} b_3 &= (-Y_{i-1} + 3Y_i - 3Y_{i+1} + Y_{i+2}) / 6 \\ b_2 &= (Y_{i-1} - 2Y_i + Y_{i+1}) / 2 \\ b_1 &= (-Y_{i-1} + Y_{i+1}) / 2 \\ b_0 &= (Y_{i-1} + 4Y_i + Y_{i+1}) / 6 \end{aligned}$$

$$\begin{aligned} c_3 &= (-A_{i-1} + 3A_i - 3A_{i+1} + A_{i+2}) / 6 \\ c_2 &= (A_{i-1} - 2A_i + A_{i+1}) / 2 \\ c_1 &= (-A_{i-1} + A_{i+1}) / 2 \\ c_0 &= (A_{i-1} + 4A_i + A_{i+1}) / 6 \end{aligned}$$

With m given points in the input file, the output array will contain K points, where;

$$K = (m-3)N + 1$$

Where N is the number of intervals between two successive given points.

8.9 Summary:

This chapter describes how a computer controlled filament winding machine executes a pay-out-eye path that is supplied to it through a part-program file. Various methods of data interpolation and trajectory generation are discussed. Most of the filament winding controllers use the linear interpolation technique for trajectory generation. This technique suffers from discontinuities in the velocity and acceleration profiles and results in a jerky motion of the pay-out-eye, which can produce a fibre slippage on the mandrel. Some other interpolation techniques are also discussed in this chapter. The author has suggested the use of B-spline interpolation as a better alternative to linear interpolation. The B-spline interpolated path does not suffer from any discontinuity in it and is continuous up to its second derivative. This path is closer to geodesic as compared with the linearly interpolated path. The B-spline interpolation introduces a look-ahead capability in the filament winding controller, which gives it the ability to foresee and modify the tangent of its path between two given data points, according to the tangent of the path between the next set of data points. This results in a motion without jerks and less fibre slippage on the mandrel.

CHAPTER 9

CONTROLLER SOFTWARE FEATURES

This chapter describes various features of the software developed to control the filament winding machine. A user's manual of the controller software, developed for this project, is given in Appendix A.

9.1 Selection of Programming Language:

There are many high level languages like GW-Basic, Q-Basic, Pascal, Fortran, and C, in which this program could have been written. C-language is selected as the main programming language because of its speed of execution, versatility, and its ability to interface with Assembly language. As all these high level languages are unable to handle hardware interrupts, so the controller software and interrupt routine is written in Assembly language. The main program, written in TURBO C[®], features pull-down menus and icons for selecting various functions to run the filament winding machine. The front-end of the program is in graphic environment so that computer-aided designing and drafting capabilities may be added to the program at a later stage.

9.2 Control Over Various Machine Parameters:

The filament winding machine configuration can be changed by changing various parameters in a file called FW-CNC.PAR. Presently the control is given over

normal feed rate, maximum feed rate limit, default speed for manual control, number of knots for B-spline interpolation and interval after which actual positions should be recorded. The program is written in such a way that in future a user will be able to define the number of machine axes and controller gain terms, in this file.

9.3 Interrupt Programming:

There are two ways in which an interrupt signal can be generated on a computer to perform a data acquisition and control task. The first method, called *Software Interrupt* approach, uses computer's system clock to generate an interrupt signal. In this method the timer chip of the computer is reprogrammed^[35] through software to generate the interrupt signal at the desired periodic intervals. In the second method the interrupt signal is generated by an external hardware clock. This method is known as *Hardware Interrupt* approach. The hardware interrupt signal is given to the computer through one of the sixteen interrupt request (IRQ) lines^[33] provided on the IBM AT system^[28]. As all of these IRQ lines are reserved for peripherals like keyboard, printer, communication ports (COM1: – COM4:) etc., so the function of one of these devices is replaced with the function of the desired controller.

Both the interrupt generating approaches have their own merits and demerits. The software interrupt approach does not require any external hardware but demands greater programming skills. Many advanced high level computer languages can recognize software interrupts. These languages provide library functions to generate and handle software interrupts which makes interrupt programming easier as compared with interrupt programming in Assembly language. Care must be exercised in reprogramming the computer timer chip^[27] because this chip is also used for the memory refresh cycle of the computer. In the absence of the memory refresh cycle for more than a specific time period^[35], the computer will hang. For small interrupt routines, which do not operate at high interrupt

frequencies, the software interrupt approach is recommended.

The hardware interrupt approach is used for high frequency interrupt functions. Present day high level programming languages do not recognize hardware interrupts so the interrupt routine must be written in Assembly language. Due to its suitability for high speed operations, the hardware interrupt approach is used in the controller software for this filament winding machine.

Before starting the filament winding operation, a hardware clock with an interrupt frequency of 200 Hz, replaces the COM1: interrupt request (IRQ4). Every time an interrupt pulse is sensed, the computer temporarily halts the operation of its main program and executes the controller interrupt routine. After finishing the interrupt routine, the computer resumes its operation from where it suspended it in the main program. When the filament winding operation is finished, IRQ4 is restored back to its normal function.

9.3.1 Selection of interrupt frequency:

As said earlier (section 5.8) that the controller performance improves as the data sampling and control rate is increased, so the interrupt frequency should be as high as possible. The computation speed of the computer imposes a restriction on using interrupt frequency higher than a certain limit. It is essential that one interrupt routine cycle must be executed completely before the next interrupt signal is sensed. There are about 400 Assembly language instructions in the interrupt routine to execute the control loop for all three axes of the filament winding machine. IBM PC/AT-386 25 MHz is claimed to execute general purpose instructions at a rate of 1.76 MIPS (Million Instructions Per Second)^[28]. This gives an approximate time of 0.3 msec to execute its interrupt routine. For an interrupt frequency of 200 Hz, the delay between two interrupts is 5 msec, which leaves a good safety margin and allows for adding more axes to the control

loop in future. The same controller software can also work on an IBM PC/AT-286 or compatible computer.

9.4 The Part-Program File:

A part-program file contains a sequential list of instructions for a CNC filament winding machine to produce a filament wound component. This filament winding machine accepts part-program files written in standard NC format^[31]. This file contains information about the winding path, feed rate, type of interpolation used and number of cycles to be wound. The winding path data is stored in the form of a subroutine bearing the pay-out-eye coordinates with respect to the mandrel rotation. This subroutine is repeatedly indexed about the mandrel axis to produce a fibre path covering the entire mandrel. The part-program file can be produced by CADFIL[®] or any other filament winding path generating program. If the pay-out-eye coordinates are known this file can be created using any text editor. The structure of a part-program file to produce a cone-dome-cylinder is shown in Figure 9-1.

9.5 Linear Interpolation Logic:

The objective of the interpolation routine in the controller software is to read the pay-out-eye path specified in the part-program file and then plan a smooth trajectory to follow that path. The linear interpolation technique calculates a constant velocity for each axis to move the pay-out-eye from one point to another. A simplified logic flow diagram of the linear interpolation function is shown in Figure 9-2. To move the pay-out-eye between two given points, the desired displacement of each axis is read in terms of encoder counts. From the maximum feed rate (encoder counts/interrupt cycle) specified in CONFIG.PAR file, the time

```

%
O 999 N 10 A 10.13 X 15.79 F12000;
N 15 A 10.64 X 18.01 ;
N 20 A 9.79 X 19.18 ;
N 25 A 17.68 X 42.61 ;
N 30 A 13.03 X 45.36 ;
N 35 A 34.77 X 119.56 ;
N 40 A 18.10 X 54.48 Y 25.70 ;
N 45 A 17.54 X 9.39 Y 28.53 ;
N 50 A 18.98 X 5.77 Y 17.57 ;
N 55 A 26.04 X 1.21 Y 3.64 ;
N 60 A 25.89 X -3.12 Y -9.45 ;
N 65 A 19.66 X -7.55 Y -22.96 ;
N 70 A 16.58 X -21.14 Y -43.03 ;
N 75 A 7.94 X -31.35 ;
N 80 A 8.98 X -39.95 ;
N 85 A 6.69 X -30.29 ;
N 90 A 7.88 X -39.13 ;
N 95 A 14.20 X -58.98 ;
N 100 A 22.65 X -82.27 ;
N 105 A 22.40 X -79.75 ;
N 110 A 57.27 X -39.24 Y 22.44 ;
N 115 A 27.50 X 7.43 Y -22.44 ;
N 120 A 22.46 X 32.53 ;
N 125 A 22.60 X 30.82 ;
N 130 A 11.47 X 15.64 ;
N 135 A 10.11 X 14.99 M99;

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O 998;
N 15 G01 F 2000;
N 20 G91;
N 25 M98 P 999 L 3;
N 30 M00;
N 35 M30;
%

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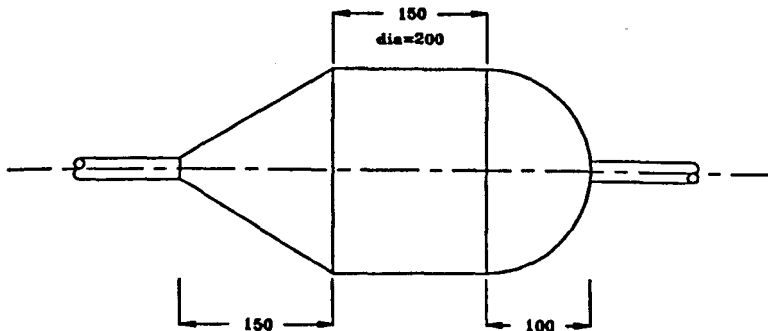


Figure 9-1: The Structure of a Part-Program File to Produce a Cone-Dome-Cylinder

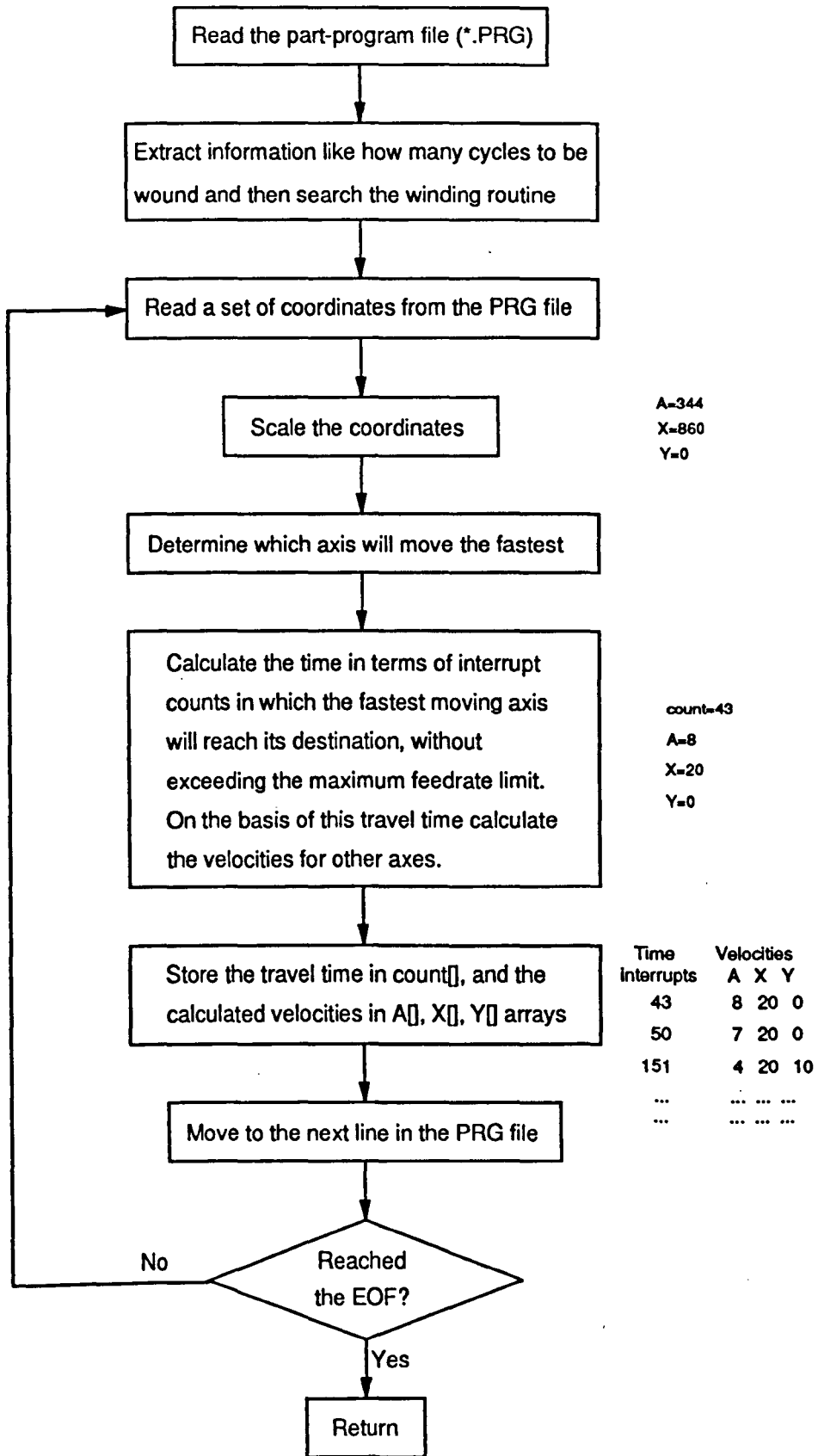


Figure 9-2: A Simplified Logic Flow Diagram for the Linear Interpolation Function

required for the axis having the biggest displacement, is calculated. This is the travel time that each axis should take to reach its target point. This method of travel time calculation ensures that no axis will move with a velocity higher than the specified maximum feed rate. The travel time is calculated in terms of interrupt counts. On the basis of the displacement of each axis and the travel time between two points, a velocity for each axis is calculated in terms of encoder counts per interrupt. The travel time between two given points and the velocity for each axis, is stored in the form of an array and supplied to the control loop. This process is repeated to calculate velocities and travel time for every two given points in the part-program file.

9.6 B-Spline Interpolation Logic:

A simplified logic flow diagram of the B-spline interpolation function is shown in Figure 9-3. On the basis of the mathematical model given in Chapter 8, a B-spline trajectory is generated. Due to the nature of B-spline curves, all the given points in the filament winding path must be read and considered simultaneously. All of these given points are first stored in an array and then B-spline coefficients are calculated for the trajectory between two points. B-spline curves do not approximate the first and the last point of the given sequence. To ensure that the trajectory starts at the specified starting point, the B-spline interpolation function adds two extra points which have the same coordinates as the given starting point. This technique ensures that the pay-out-eye trajectory would start at the given point. The same treatment is applied for the end point in the given path sequence to ensure that the end point is also met in the interpolated trajectory. The rest of the B-spline interpolation function is like the linear interpolation. The travel time and the velocity of each axis for that time period is calculated and stored in an array. It is ensured that an axis velocity does not exceed the velocity limit specified in the part-program file. The B-spline trajectory array length is many times greater than the length of the trajectory array generated in linearly

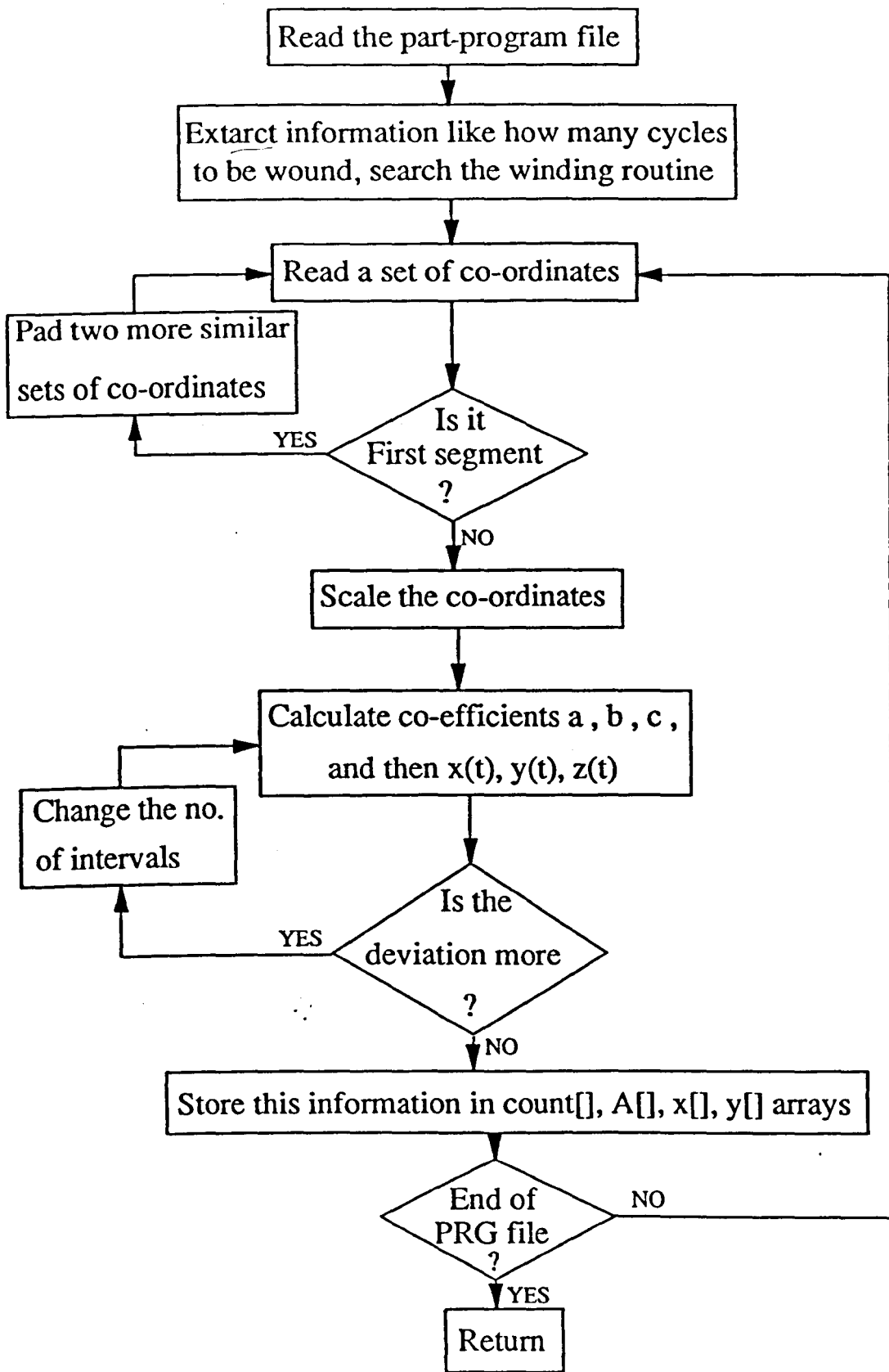


Figure 9-3: A Simplified Logic Flow Diagram for the B-Spline Interpolation Function

interpolated path.

Once the trajectory array is generated, it is the job of the control loop to ensure that each axis moves with the specified velocity for the specified travel time between two points.

9.7 Simplified Logic for the Control Loop:

The control loop is the heart of the controller software. A simplified logic flow diagram of the control loop is shown in Figure 9-4. In the interrupt routine, for filament winding according to a specified path, the present position of all the encoders is read and compared with the desired trajectory. The trajectory which is supplied to the control program in the form of an array, contains the desired velocity information for each axis of the machine and the time for which that velocity is to be maintained to move the axis to a particular position. A PD control law, as given in Chapter 5, is applied to each axis one by one and the appropriate voltages are generated at the respective DAC channels to move the axes. This control loop is executed once for each interrupt cycle so that all the axes follow the specified path in a controlled manner. When all the entries in the trajectory array are executed, the winding path is completed and the machine comes to a stop after finishing the winding.

9.8 Manual Axis Control & Position Display:

The pay-out-eye carriage movement and the mandrel rotation can be controlled manually. The manual control is provided by the use of keyboard cursor movement keys. The speed of movement can be altered using '+' or '-' key. In the manual control mode the pay-out-eye coordinates are continuously updated

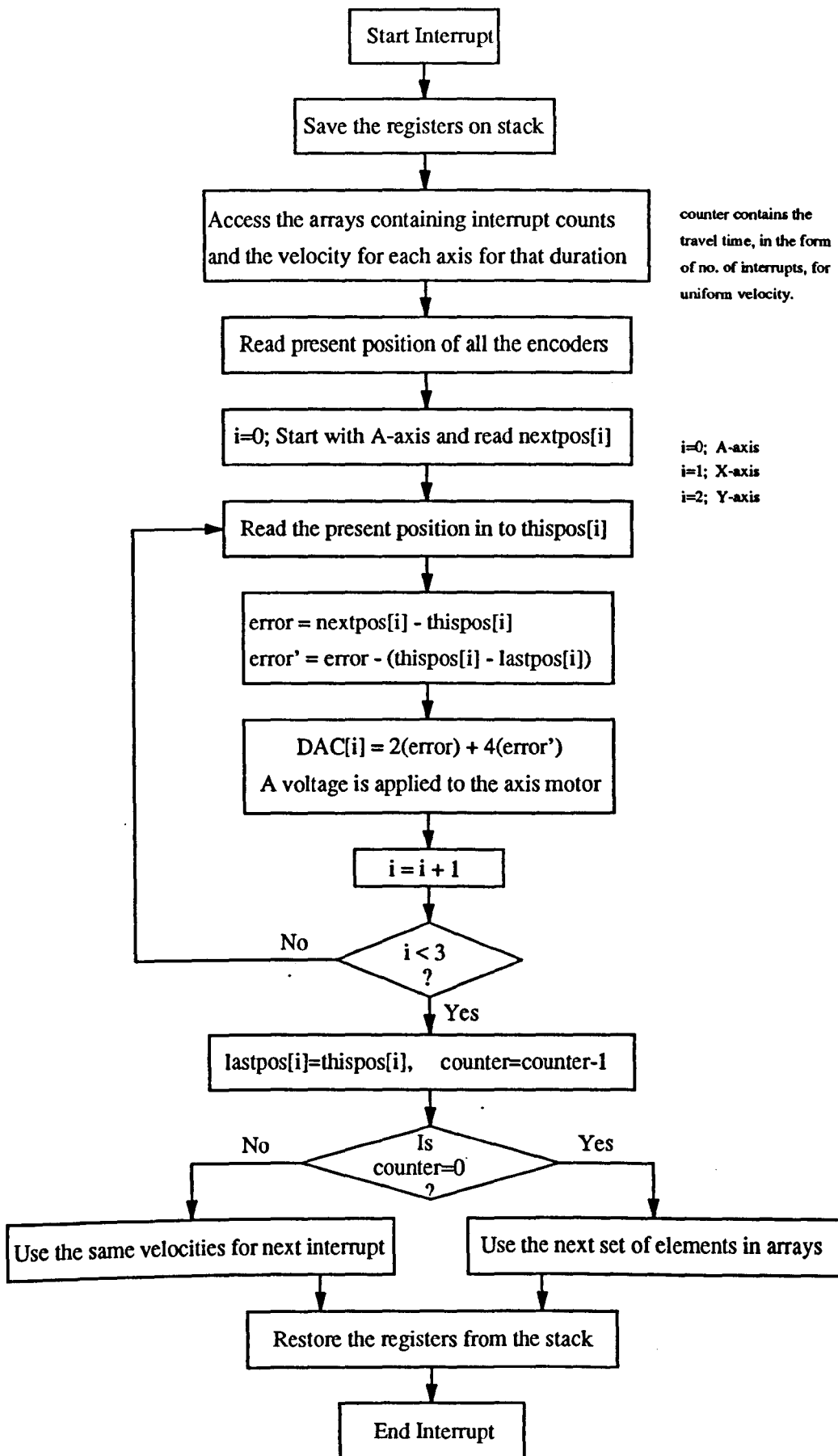


Figure 9-4: A Simplified Flow Diagram for the Control Loop

and displayed on the monitor screen.

9.9 Tracing the Actual Path:

To analyze the filament winding path accuracy, it is important to record the actual distance travelled by the machine axes. A provision is made in the controller software to record the displacement of all the axes while executing the control loop. This displacement, read by optical encoders, is stored in the computer memory and at the end of the winding operation it is recorded on to an output file on the computer disk. To control the size of the output file it is possible to record encoder positions after every 'n' number of interrupts, where 'n' varies from 1 to 32K. This output file is very helpful in analyzing the performance of the filament winding in case of the B-spline interpolated path as compared with the linearly interpolated path. The results are given in the next chapter.

9.10 Compatibility With Other Software Packages:

The pay-out-eye path data is input to this controller software in the form of a part-program file. This part-program file or PRG file is fully compatible with CADFIL® output or any other standard CNC part-program file. This controller software generates an output file containing the actual displacement data of all the axes. This output file is an ASCII text file and it is fully compatible with most of the spread sheet packages available on IBM PC and compatible computers. The data in the output file can be plotted using any of these spread sheets.

9.11 Safety Features:

Various safety features are provided in the software. Extreme changes in the DAC voltage are protected by sensing the polarity of previous input, if the present polarity is reverse then a zero volt pulse is introduced. This technique protects the servo amplifiers from back emf surges and peak current spikes. Extreme limits of x and y-axis motion are defined by hardware limit switches which, if operated, disconnect the power supply to that axis motor.

9.12 Summary:

This chapter describes some functions of the controller software developed for this project. The software is mainly written in C language. The control routines are written in Assembly language. A hardware interrupt is used to periodically monitor the position of the optical encoders and to send the output power signal to the servo motors. The delay between two interrupt signals is 5 msec. The controller software has the ability to accept part-program files generated by other computer programs. A simplified logic flow diagram of the linear interpolation function, the B-spline interpolation function and the logic controller is described. A provision is made in this controller software to record the actual displacement of all the axes while following a path. This provision helps in comparing and analyzing the performance of the filament winding machine while executing a path that is generated by different interpolation techniques. The next chapter uses this facility and compares the performance of a B-spline path with a linear path.

CHAPTER 10

PERFORMANCE ANALYSIS

To check the performance of the B-spline interpolation technique, the three axis CNC filament winding machine was made to run with B-spline interpolation and then with linear interpolation control philosophy. As the comparison is made on the same machine and all the other parameters are kept the same, the performance of the two interpolation techniques can be compared easily.

10.1 Analysis of Fibre Placement Accuracy:

For a true comparison of the performance of the B-spline interpolated path with the linear interpolated path a four dimensional graph is required for a 3-axis machine. Although the actual advantage of B-spline interpolation is observed when all the three axes are in motion simultaneously, but for the sake of simplicity, each axis is investigated separately. Only one axis is moved at a time according to B-spline interpolated path and then the same displacement is traversed using linear interpolated path. All the other variables are kept the same during the test.

To check the accuracy of actual fibre placement on the mandrel surface, a system is required in which actual fibre position on the mandrel can be measured physically. A simple system may consist of an ink-soaked thread winding on a mandrel which is wrapped in a graph paper. A cone-dome-cylinder shaped mandrel provides a good shape for checking the fibre slippage tendency. A more sophisticated system for measuring and recording the actual fibre placement

accuracy may consist of a coordinate measuring machine and an electrostatic recording of fibre placement. The former approach is too crude and messy, and the results are not impressive for presentation. The later approach is very costly and requires expensive measuring equipment.

In another technique for judging the fibre placement accuracy, the actual displacement of the pay-out-eye is recorded and from this displacement data the velocity and acceleration profiles are drawn. The pay-out-eye displacement data is recorded by storing the optical encoder data, at a specified rate, as mentioned in section 9.9 of this thesis. This technique is based on the assumption that the accuracy of the fibre placement is linked with the accuracy of the pay-out-eye positioning. This technique also assumes that the pay-out-eye path given in the part-program file is perfectly accurate and if wound correctly, no fibre slippage results. The encoder data recording technique is not the best technique for measuring the absolute accuracy of the fibre placement but it can be safely used for comparing the performance of two different control techniques traversing the same pay-out-eye path. Thus, this technique is used for comparing the control performance of the B-spline path with the linear path, on the developed CNC filament winding machine. This comparison is made at different winding speeds to see if the B-spline interpolation offers any advantage in controlling the filament winding machine at higher operating speeds.

10.2 Comparison of Displacement Profiles:

To check the accuracy of the filament winding machine control system the actual displacement data, read with the help of the encoders, is compared with the planned displacement data. A small part-program file is written which moves only x-axis up to a displacement of 180 mm (10,000 encoder counts) and then brings it back to its original position. An axis demands the maximum control effort when its velocity is reversed from one extreme to the other. The actual

displacement of the pay-out-eye is recorded by the optical encoder and then compared with the planned path. Figure 10-1 shows the comparison between the linear planned path and the path actually followed by the x-axis at a feed rate of 10 encoder counts per interrupt. The linear planned displacement profile is a straight line from point A to point B and then from point B to point C. The actual displacement profile closely follows the planned profile except for slight oscillation at the start of the pay-out-eye motion and when it reverses its direction after reaching point B. The amplitude of this oscillation depends on the inertia and friction of the axis and the speed of motion. The B-spline interpolation results of the same path are plotted in Figure 10-2. At low feed rates the B-spline displacement profile is not much different from the linear displacement profile. In the linear interpolation, velocity increases from zero to the feed rate limit in one single step and then stays uniform till the next change. In the B-spline interpolation, the change in velocity from zero to the feed rate limit is gradual in small steps. At lower feed rates, the number of steps required to reach the feed rate limit are very few and hence this change is barely noticeable in the displacement profile in Figure 10-2. Thus, at low feed rates the B-spline interpolation produces the same results as the linear interpolation.

In Figure 10-3, the same pay-out-eye path (x-axis displacement = 0 to 180mm to 0) is plotted at a feed rate of 80 encoder counts per interrupt (290 mm/s) Due to the higher feed rate the amplitude of oscillation becomes very noticeable and the overshoot problem becomes high enough to nearly destabilize the control. Figure 10-4 shows that at higher feed rates the controller response is much better in the case of B-spline interpolation as compared with the linear interpolation. The B-spline interpolation produces a pay-out-eye path in which sharp changes are replaced with smooth curves. The change in velocity at all points is gradual and due to this smooth change in velocity, the deviation of the actual path from the planned path is much less. In the B-spline planned path the tangent of the displacement profile is continuous all the time. The comparison of Figure 10-3 and Figure 10-4 shows that at higher feed rates the B-spline interpolation offers a much better control performance as compared with the linear interpolation. The

LINEAR PATH DISPLACEMENT PROFILE (Feed rate = 10)

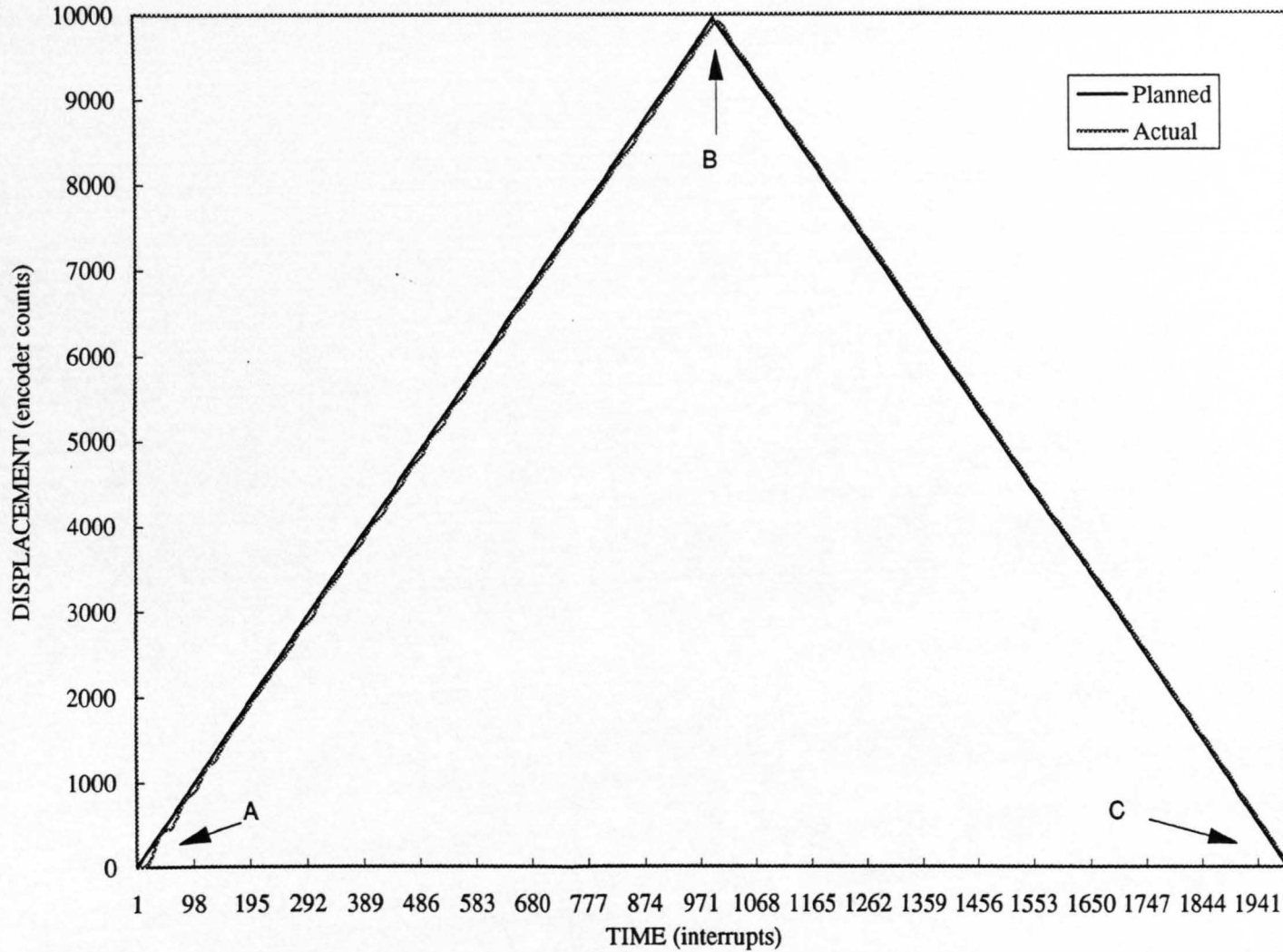


Figure 10-1: A Comparison of the Linear Planned Path with the Experimentally Obtained Path at Feed Rate=10

B-SPLINE PATH DISPLACEMENT PROFILE (Feed rate=10)

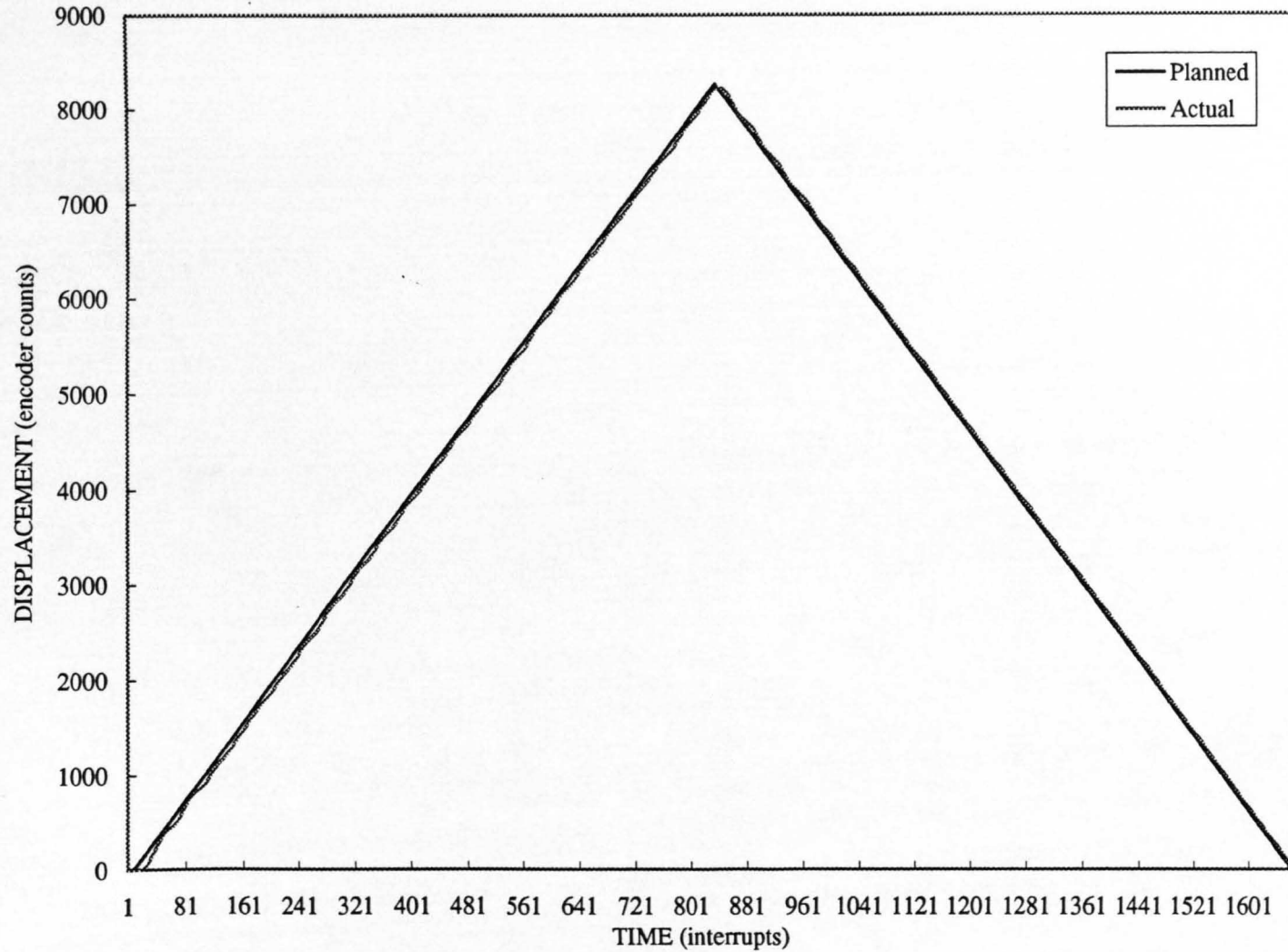


Figure 10-2: A Comparison of the B-Spline Planned Path with the Experimentally Obtained Path at Feed Rate=10

LINEAR PATH DISPLACEMENT PROFILE (Feed rate=80)

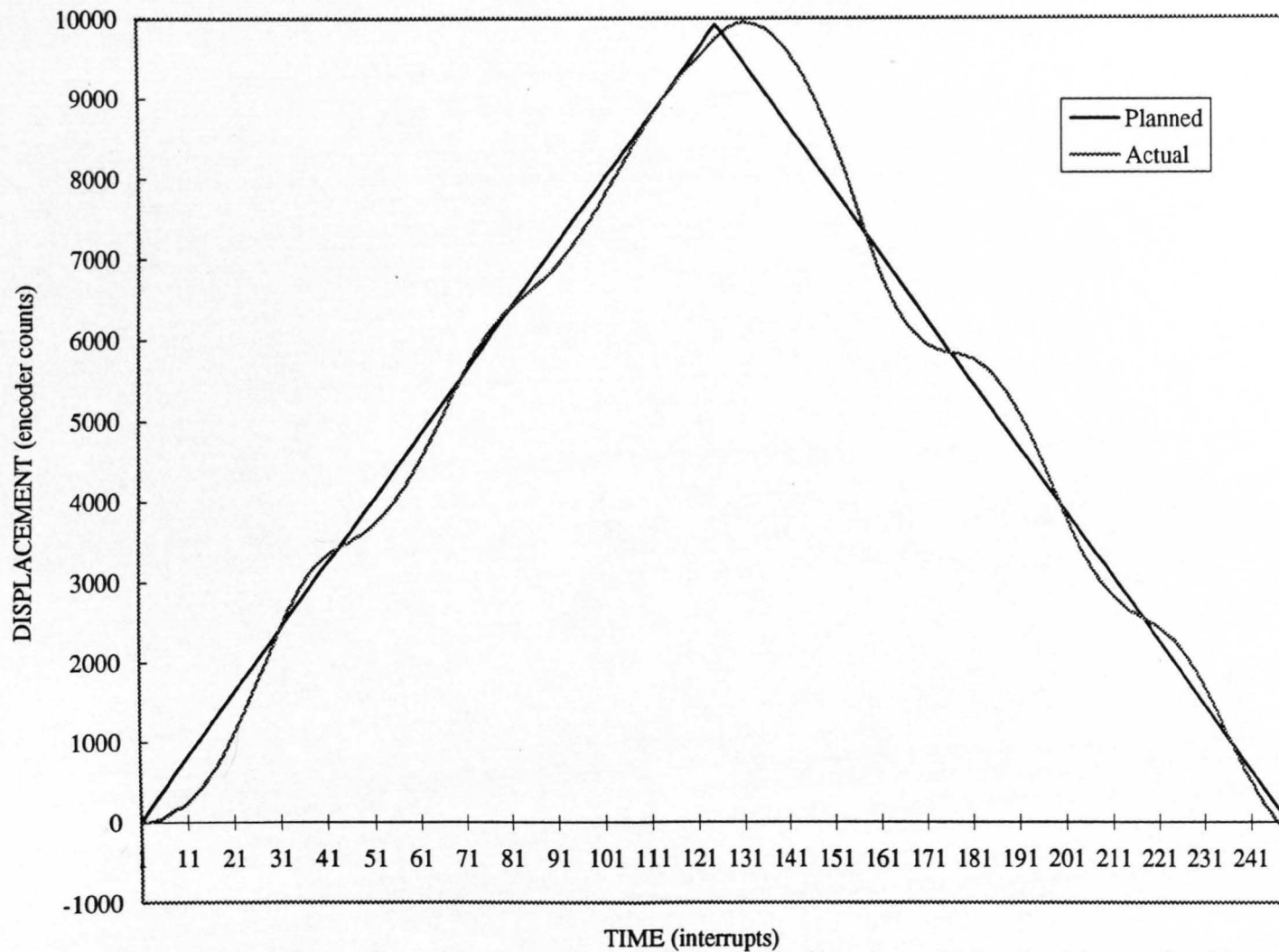


Figure 10-3: A Comparison of the Linear Planned Path with the Experimentally Obtained Path at Feed Rate=80

B-SPLINE PATH DISPLACEMENT PROFILE (Feed rate=80)

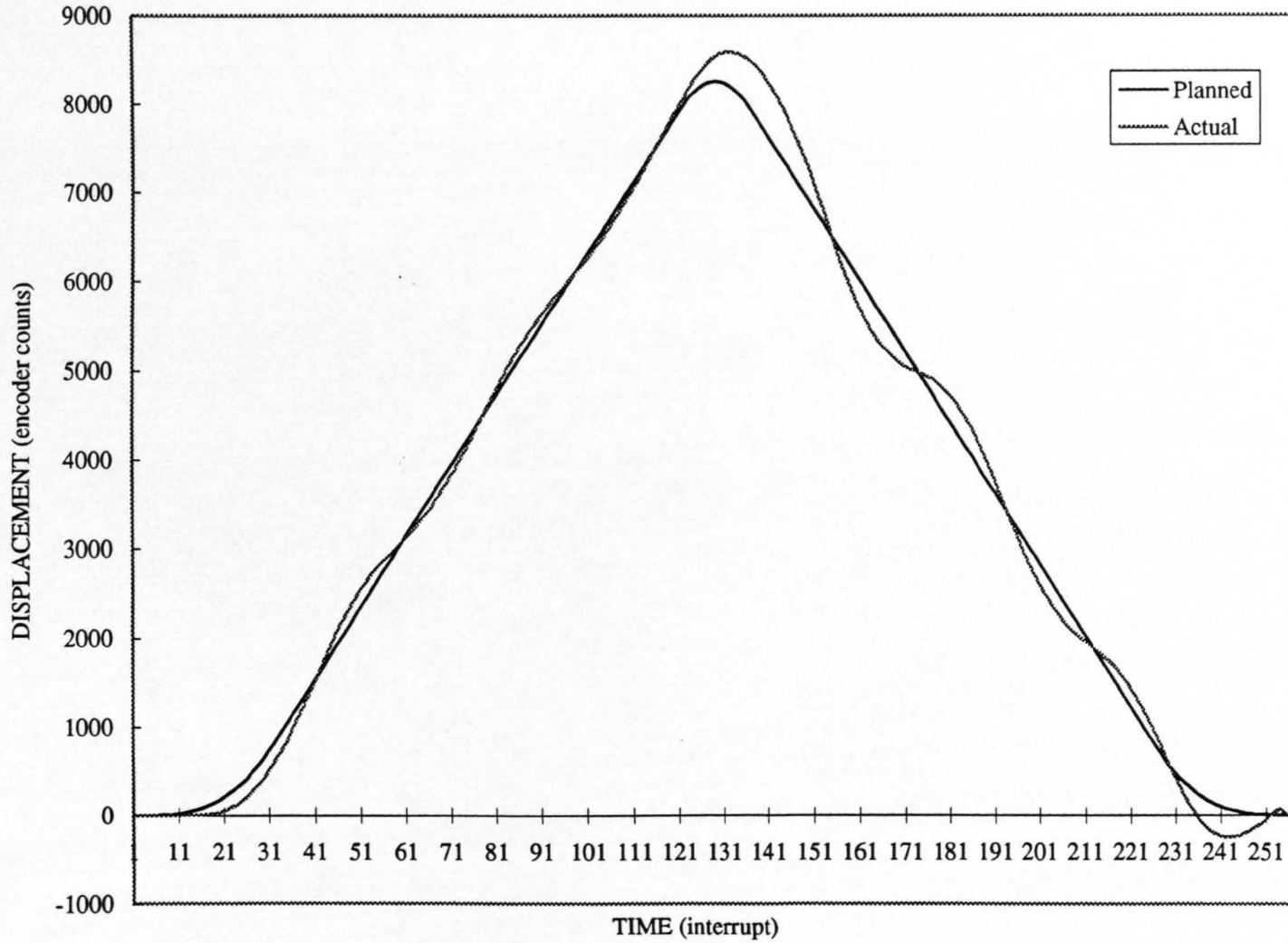


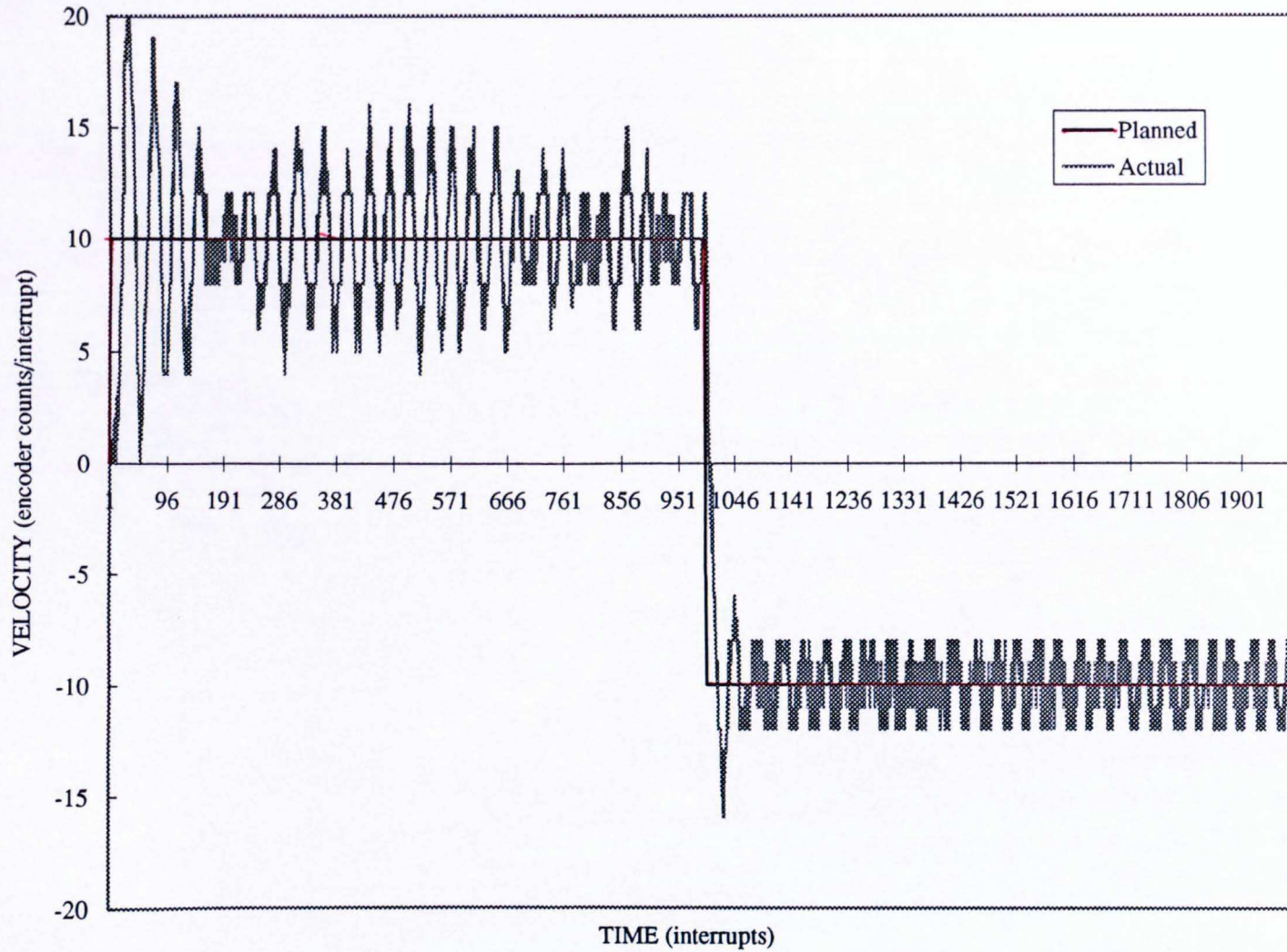
Figure 10-4: A Comparison of the B-Spline Planned Path with the Experimentally Obtained Path at Feed Rate=80

comparison of Figure 10-2 and Figure 10-4 shows that the B-spline interpolation routine used in this controller has the ability to adjust its path and make it smoother according to the requirement of the path and the feed rate. At higher feed rates the continuity and the smoothness of the displacement profile becomes much more important than at lower feed rates. The shape of the B-spline path can be modified by adding more points in the part-program file or by varying the knot spacing in the FW-CNC.PAR file.

10.3 Comparison of Velocity Profiles:

As the actual displacement data, recorded by encoders, is stored at a known frequency so velocity between two recorded points can be obtained by taking the difference between the displacements. A velocity profile is drawn by calculating the axis velocity at each interrupt cycle. The velocity profile and the acceleration profile of the servo drive motor describe the smoothness of the control system. The magnitude of variations in the acceleration profile determines the level of instability in the control system. In Figure 10-5 to Figure 10-8 the planned velocity profile is compared with the experimentally obtained velocity profile. Figure 10-5 shows the linearly planned velocity profile in comparison with the actually obtained velocity profile at a feed rate of 10. Figure 10-6 shows the same combination for the B-spline planned path. Figure 10-7 and Figure 10-8 show a comparison of the planned velocity against the experimentally obtained velocity at a feed rate of 80 encoder counts per interrupt for the linear interpolation and for the B-spline interpolation respectively. The linear velocity profiles (Figure 10-5 and Figure 10-7) suffer from a discontinuity at the time of reversal of the direction of motion as well as at the two ends. This discontinuity in the velocity profile demands a theoretically infinite acceleration and should cause severe jerks in motion. In actual practice the servo motor velocity cannot increase to its maximum value in zero time and therefore the magnitude of the jerks is not infinity. Still, this phenomenon can cause severe enough jerks if a

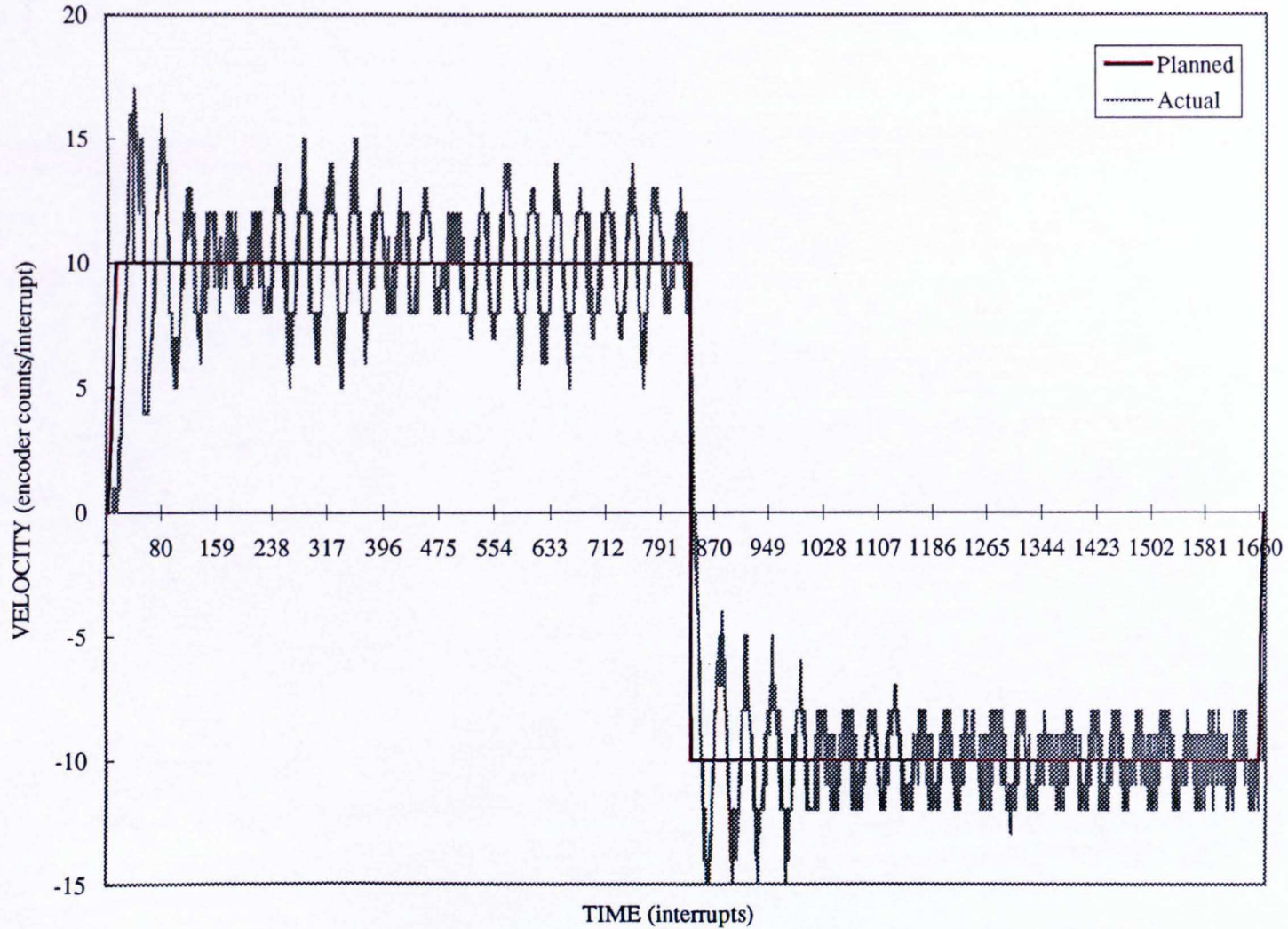
LINEAR PATH VELOCITY PROFILE (Feed rate=10)



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Figure 10-5: A Comparison of the Linear Planned Velocity Profile with the Experimentally Obtained Velocity Profile at Feed Rate=10

B-SPLINE PATH VELOCITY PROFILE (Feed rate=10)



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Figure 10-6: A Comparison of the B-Spline Planned Velocity Profile with the Experimentally Obtained Velocity Profile at Feed Rate=10

LINEAR PATH VELOCITY PROFILE (Feed rate=80)

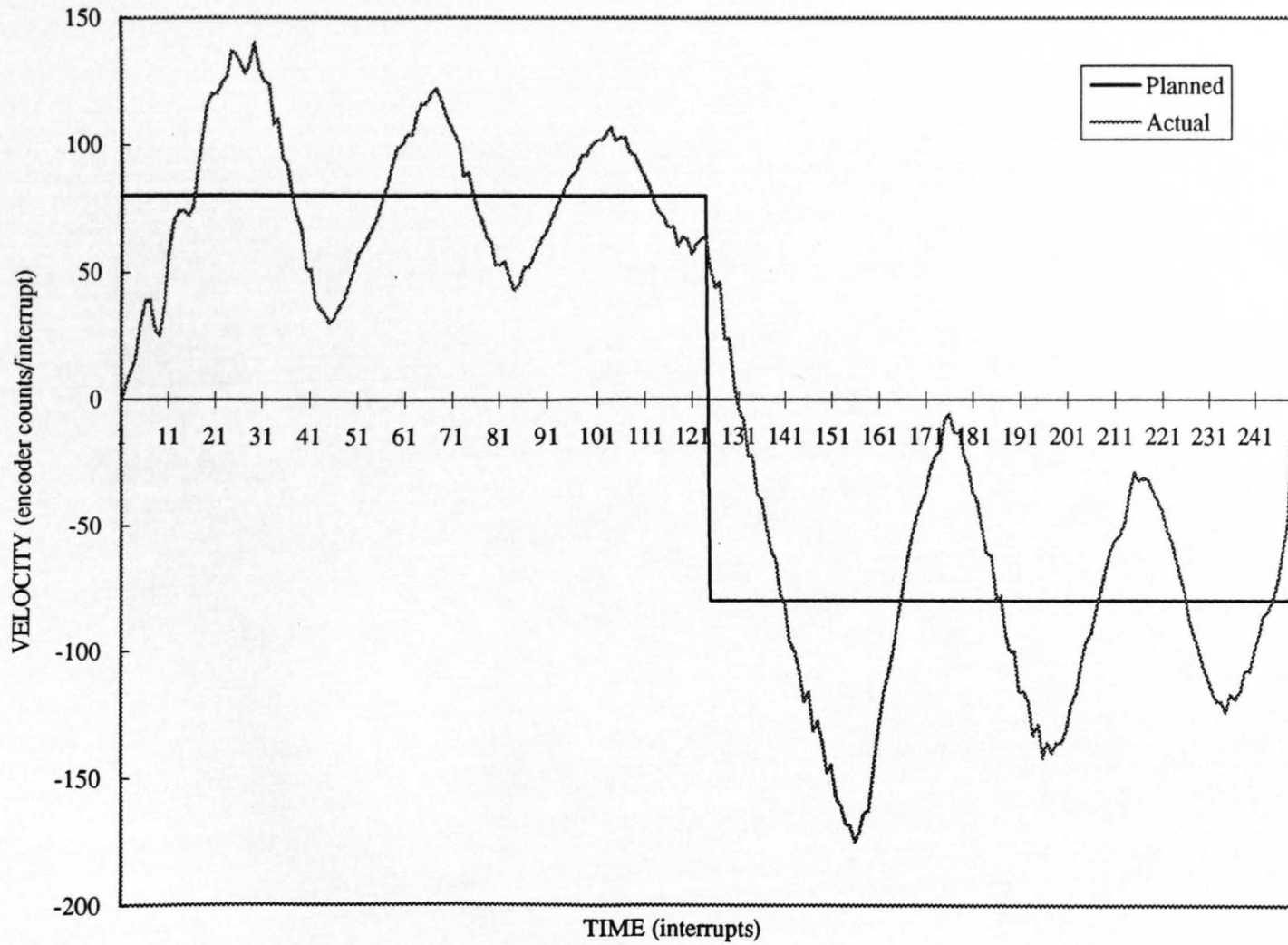
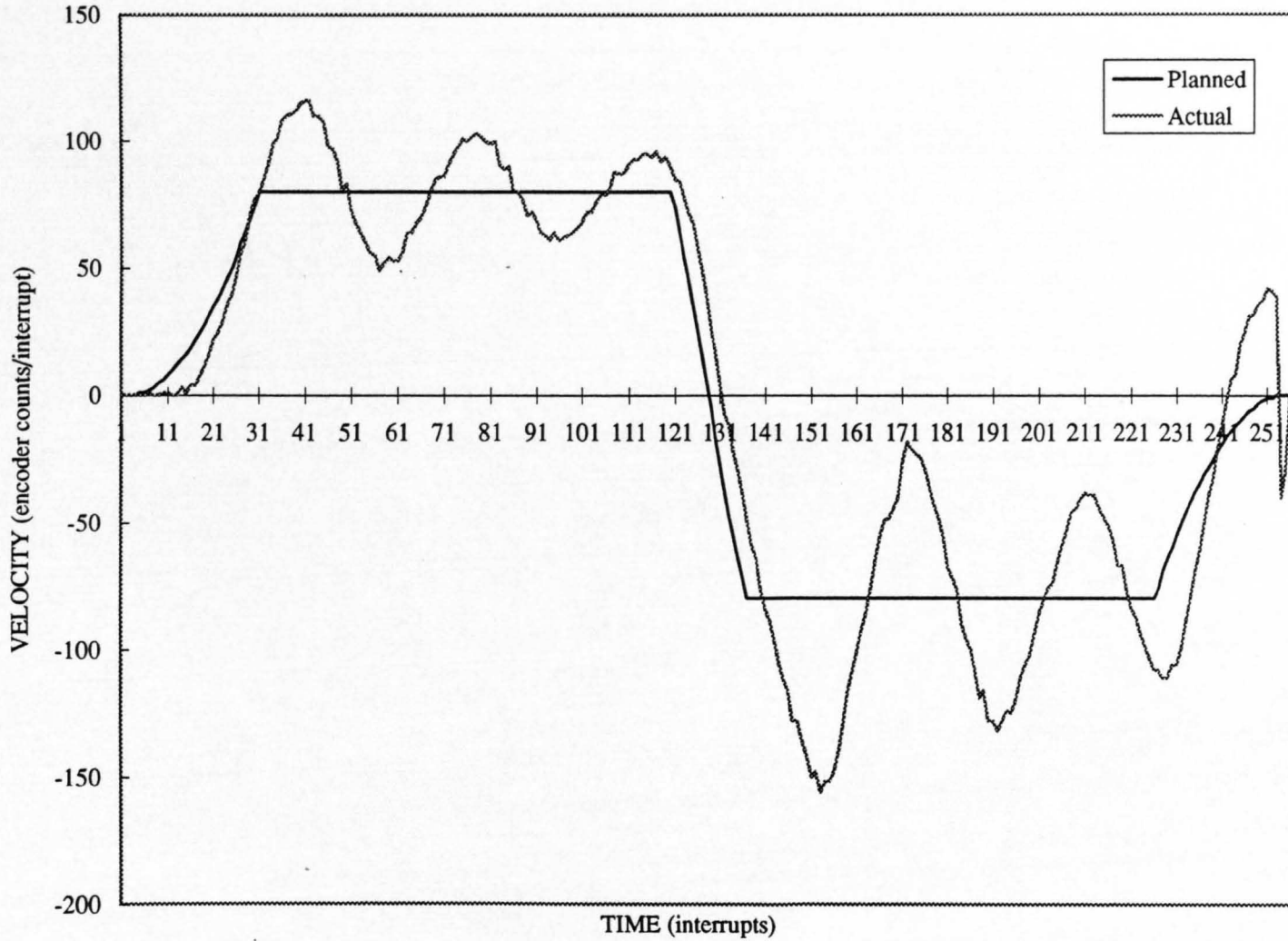


Figure 10-7: A Comparison of the Linear Planned Velocity Profile with the Experimentally Obtained Velocity Profile at Feed Rate=80

B-SPLINE PATH VELOCITY PROFILE (Feed rate=80)



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Figure 10-8: A Comparison of the B-Spline Planned Velocity Profile with the Experimentally Obtained Velocity Profile at Feed Rate=80

powerful servo motor is used in the control system.

In the case of B-spline interpolation (Figure 10-6 and Figure 10-8) the planned velocity profile is much smoother and thus the experimentally obtained velocity profile is also smoother. This difference is more noticeable at higher feed rates when Figure 10-7 is compared with Figure 10-8. In the B-spline velocity profile at a feed rate of 80 (Figure 10-8), the planned velocity increases slowly from zero to its maximum value which is set by the feed rate limit and then stays uniform. Any change in velocity in the B-spline profile is gradual. Due to this smooth transition, the variation in acceleration profile is also less. A smooth velocity profile results in a smooth acceleration profile.

10.4 Comparison of Acceleration Profiles:

In filament winding operation, a smooth acceleration profile results in a more accurate fibre placement and less tendency of fibre to slip. Due to the reduced jerks in the motion, the filament winding process can be performed at higher speeds.

In Figure 10-9 to Figure 10-12 the acceleration profiles of the linear path and the B-spline path at a feed rate of 10 and 80, are given. In the case of linear path only the actual acceleration profile is plotted because the planned acceleration is infinity at the points of discontinuity in the velocity profile. At lower feed rates (Figure 10-9 and Figure 10-10) the improvement in the control performance due to the B-spline interpolation is not very significant but at higher feed rate this improvement is very noticeable. By comparing Figure 10-11 with Figure 10-12 it can be seen that the variation in the magnitude of the B-spline acceleration profile is much less as compared with the linear acceleration profile. This reduced variation in the acceleration magnitude results in less jerks which can be noticed visually on the machine as well. The improvement in the B-spline

LINEAR PATH ACCELERATION PROFILE (Feed rate=10)

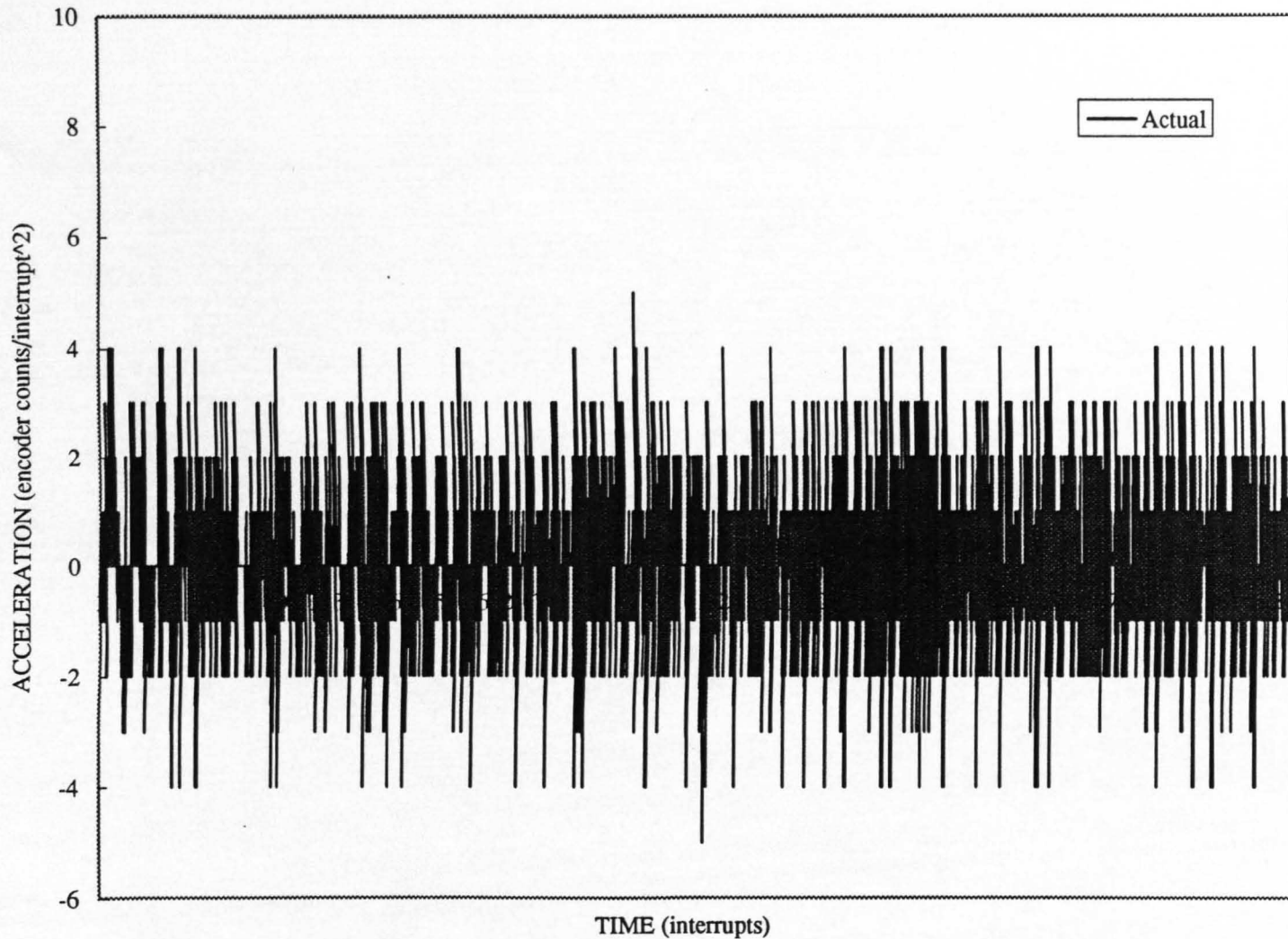
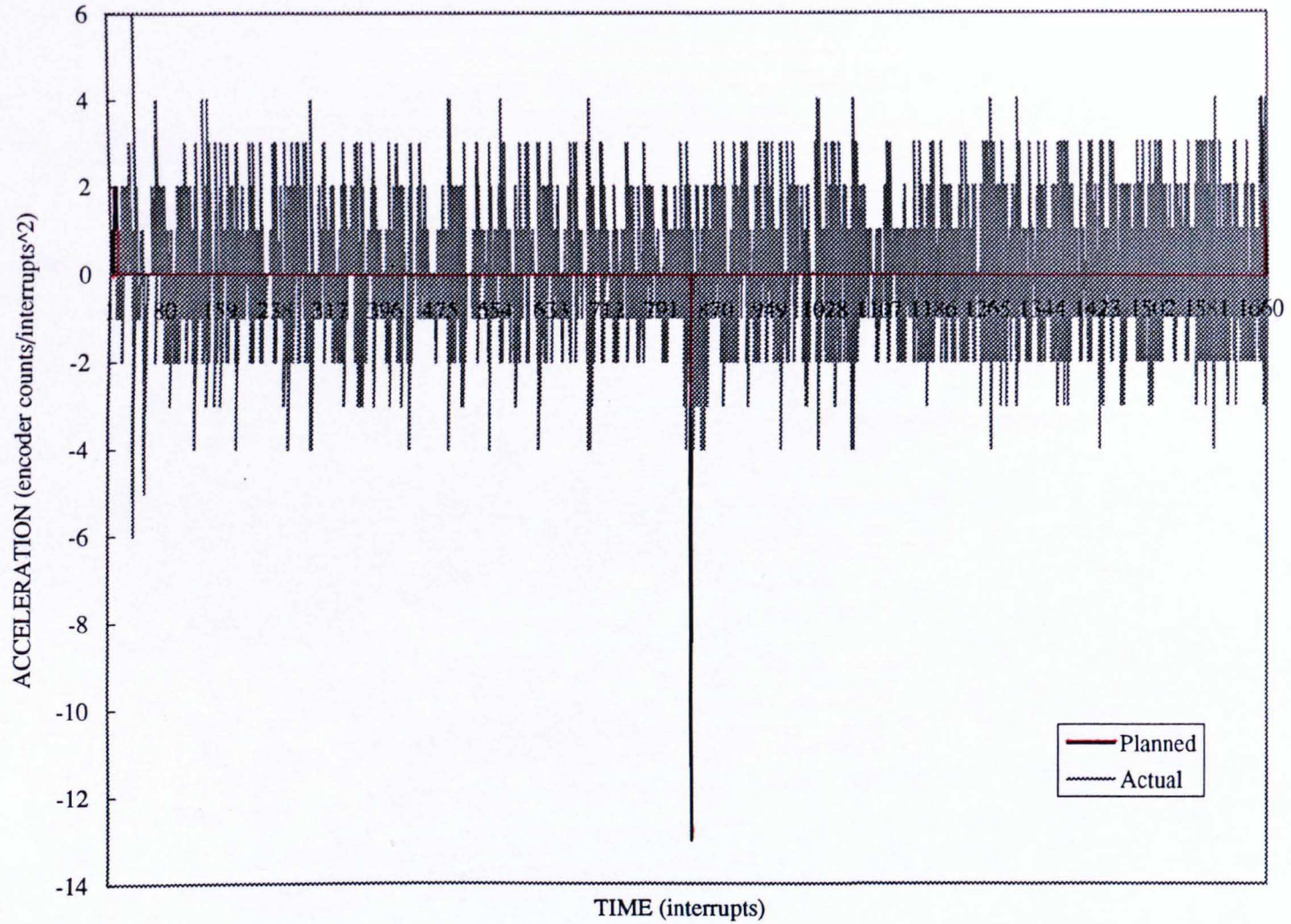


Figure 10-9: Experimentally Obtained Acceleration Profile for the Linear Path at Feed Rate=10

B-SPLINE PATH ACCELERATION PROFILE (Feed rate=10)



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Figure 10-10: A Comparison of the B-Spline Planned Acceleration Profile with the Experimental Profile at Feed Rate=10

LINEAR PATH ACCELERATION PROFILE (Feed rate=80)

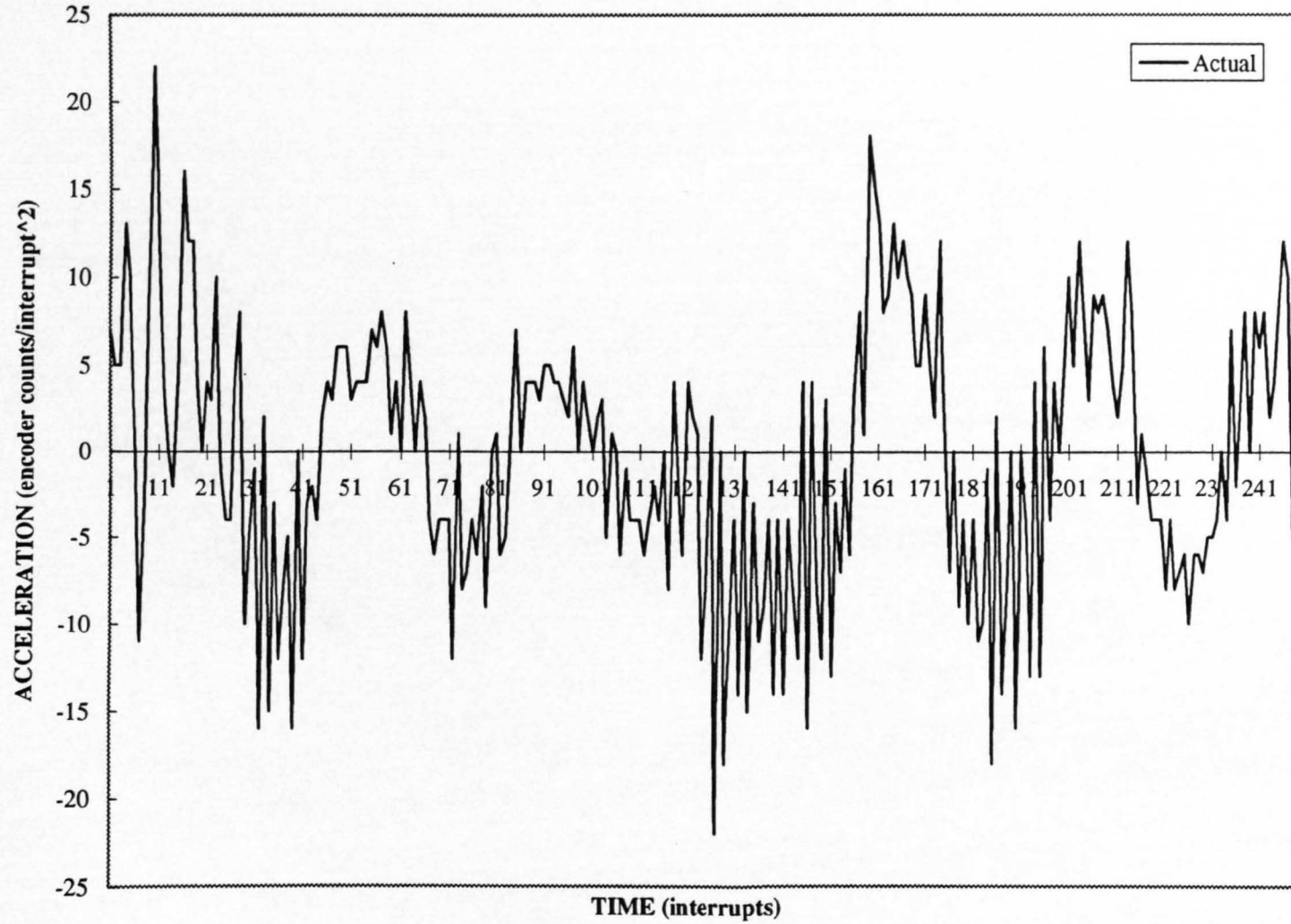


Figure 10-11: Experimentally Obtained Acceleration Profile for the Linear Path at Feed Rate=80

B-SPLINE PATH ACCELERATION PROFILE (Feed rate=80)

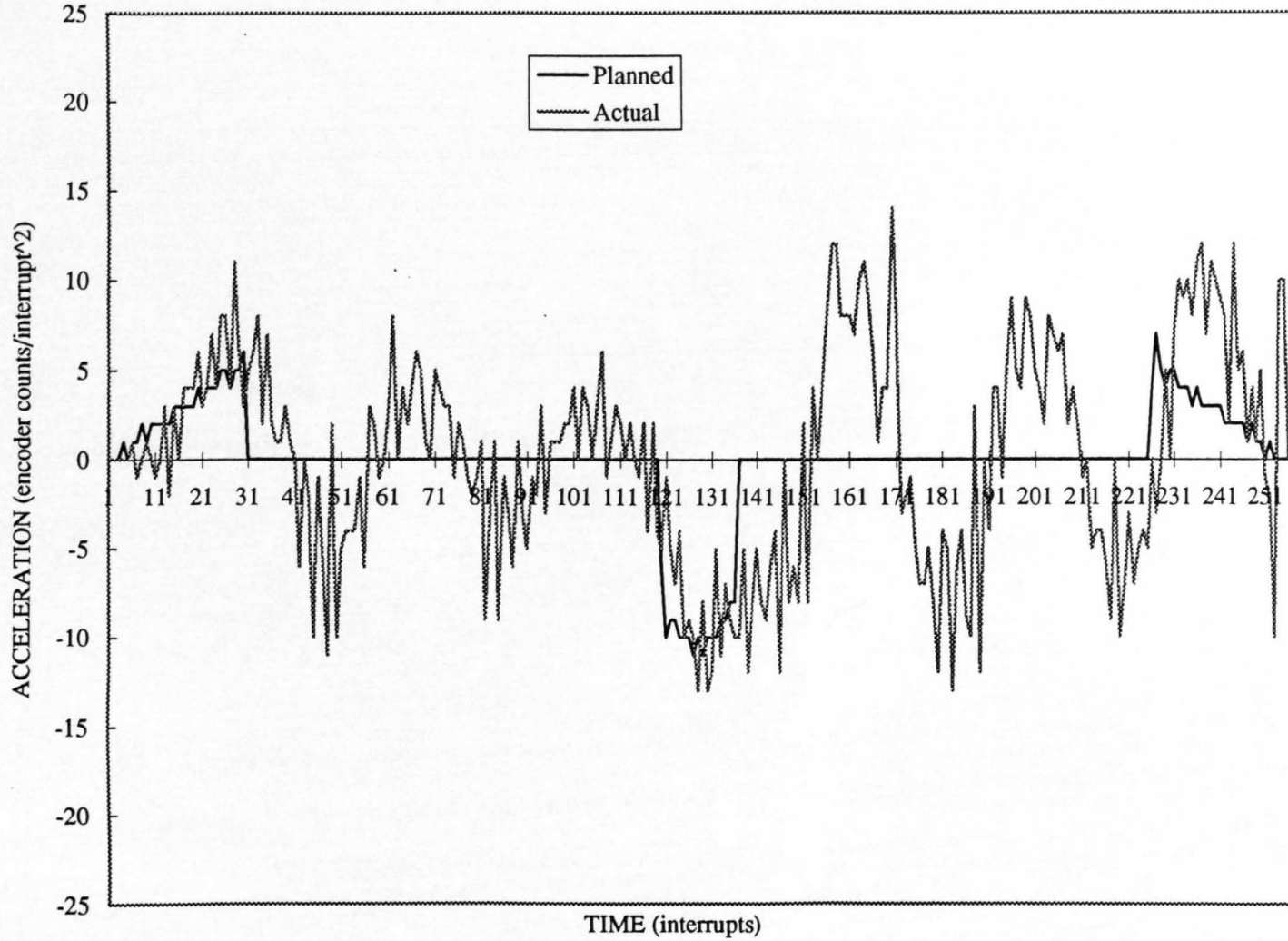


Figure 10-12: A Comparison of the B-Spline Planned Acceleration Profile with the Experimental Profile at Feed Rate=80

acceleration profile allows the machine to operate at higher winding speeds as compared with the winding speed limits obtained in the case of the linear interpolation.

10.5 Comparison of the Maximum Winding Speeds:

The maximum winding speed of a filament winding machine can be described as the maximum speed of operation at which the control does not become unstable and the fibre placement accuracy is within acceptable limits. The maximum winding speed depends on the filament winding machine, the controller hardware, the given pay-out-eye path, and the shape of the velocity profile. For a particular filament winding machine, the maximum winding speed limit can be increased by supplying it a velocity profile which is smooth and continuous as in B-spline interpolation. To make this comparison, a few tests were performed on the CNC filament winding machine. The same path was wound at various different feed rates, using the linear interpolation technique as well as using the B-spline interpolation technique. The feed rate at which the pay-out-eye inaccuracy became more than ± 0.5 mm, was considered to be the maximum winding speed limit. The experiments showed that the maximum winding speed to wind that particular path was 100 mm/s in the case of linear interpolation and 200 mm/s in the case of B-spline interpolation. This showed that the maximum winding speed limit of a filament winding machine can be increased by 100% using B-spline interpolation instead of using linear interpolation.

10.6 Tests with CADFIL[®] Output Files:

Two part-program files, generated by CADFIL[®] program, were tested on this filament winding machine. The controller software accepts both the PRG files

without requiring any modification. The results of cone-dome-cylinder are presented here. The actual path followed by the pay-out-eye in the linear interpolation and in the case of B-spline interpolation was traced by the optical encoder data. The y-axis movement with respect to the x-axis movement is plotted in Figure 10-13 for the linear interpolation case and in Figure 10-14 for the B-spline interpolation case.

10.7 Recommendations for Further Research:

The biggest problem in implementing the B-spline interpolation technique in filament winding control is that in this method the path does not necessarily pass through the given data points. The decision, whether the deviation from the specified path is within the acceptable limits or not, requires some intelligence in the software. On the basis of this deviation it is decided whether to readjust the fibre path or not. For more accurate results, it is suggested to add a winding simulation routine in the existing software. The graphic capabilities of Fil-W-CAD can be utilized to simulate winding operation prior to actual winding on the mandrel. The B-spline path can be modified by adding more points in the vicinity of the desired position. In winding long straight cylindrical sections, it is better to use linear interpolation rather than the B-spline interpolation. The existing software calculates the entire pay-out-eye path either by linear interpolation or by B-spline interpolation. It is suggested to make the interpolation program intelligent enough to decide whether to use B-spline interpolation or the linear interpolation for a section of the pay-out-eye path.

In this project the accuracy of fibre placement is measured by recording the pay-out-eye path. The real advantage of B-spline interpolation is observed when the fibre placement accuracy and the fibre slippage is physically measured on the mandrel. The fibre slippage on the mandrel depends on many variables like the

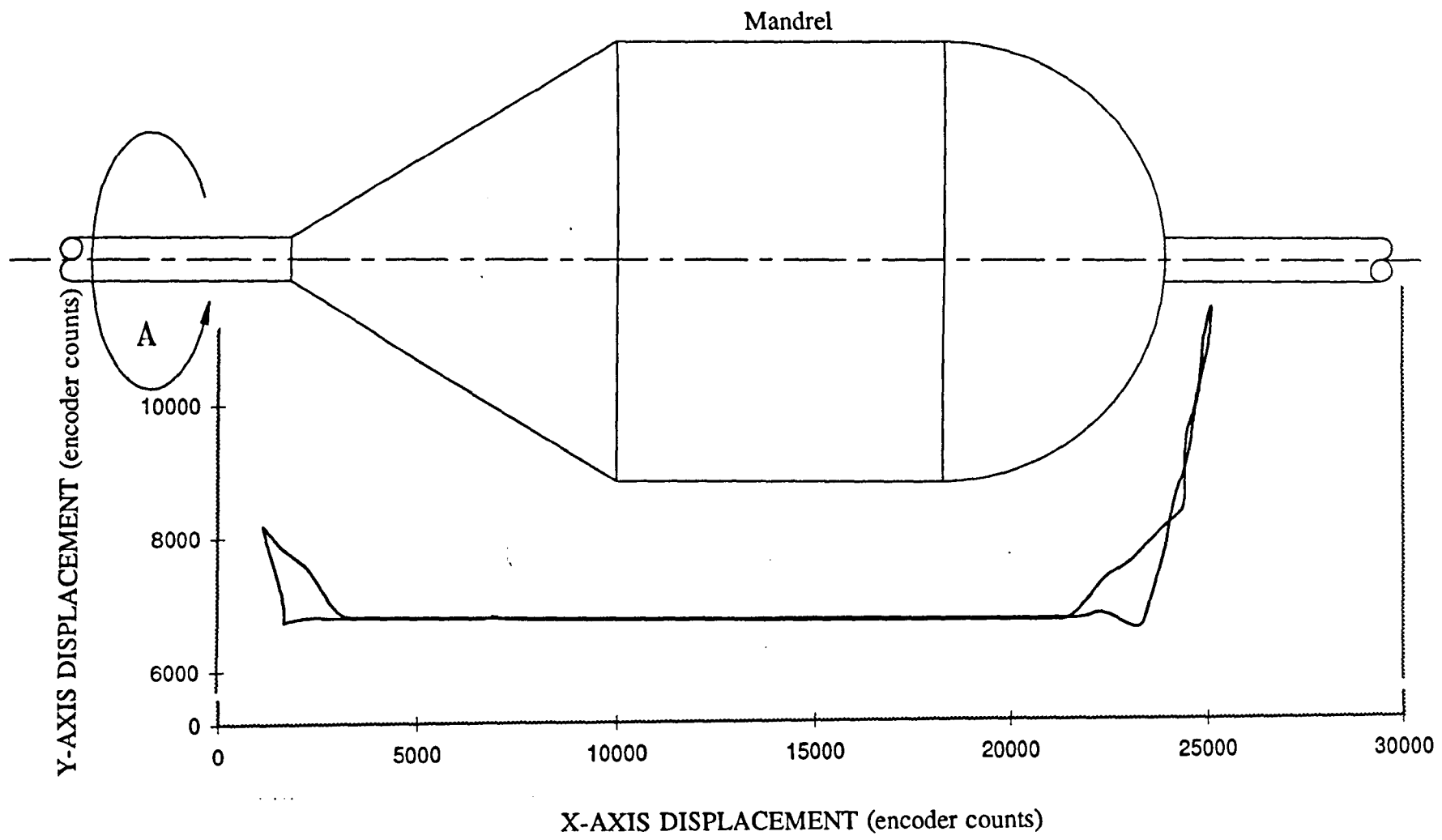


Figure 10-13: The Pay-Out-Eye Path Trace for the Cone-Dome-Cylinder Wound by the Linear Interpolation

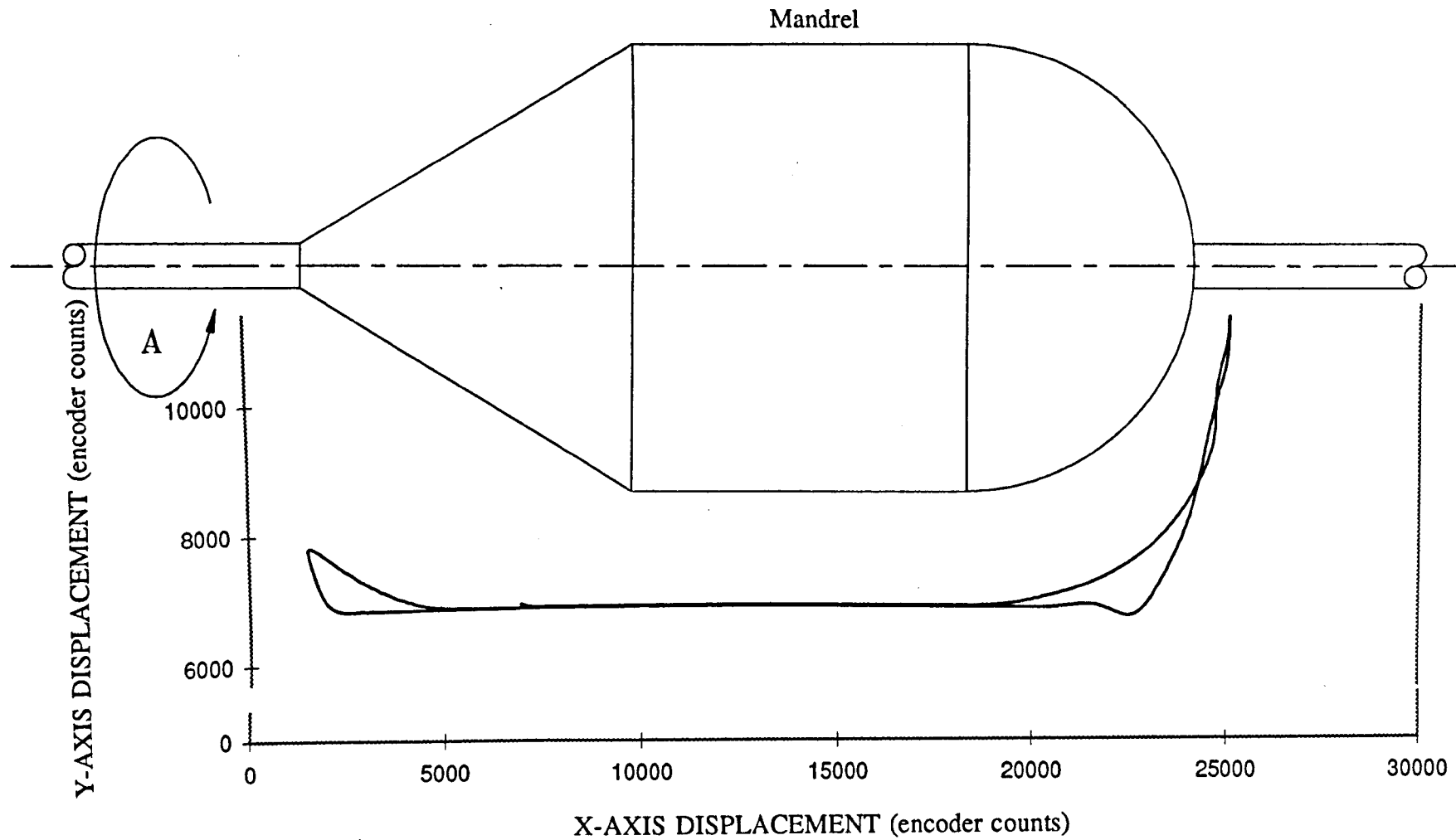


Figure 10-14: The Pay-Out-Eye Path Trace for the Cone-Dome-Cylinder Wound by the B-Spline Interpolation

shape and the curvature of the mandrel, friction between the fibre and the mandrel surface, speed of winding, the supplied pay-out-eye path accuracy and the control performance of the CNC machine controller. The accurate measurement of actual fibre slippage on the mandrel requires a good measuring system and some research in developing a measurement criteria.

The present version of Fil-W-CAD software developed for this project includes a CNC filament winding machine control package and a computer-aided drafting package. To complete a fully computerised filament winding system it is suggested to add a computer-aided design and analysis package for filament wound components and a package for the pay-out-eye path generation. All these packages should be fully compatible with each other.

The mains transformer used in this filament winding machine controller is a 1000 VA transformer, with two secondary windings of 55-0-55 volt at 4 Amp. This transformer is unable to supply more than 4 Amp to any axis drive motor, whereas the DC servo motors can demand up to 8 Amp. At high torque demands, the mains transformer is unable to meet the power requirements. It is recommended to replace this with a 1000 VA transformer having two secondary windings of 55 volt, at a current of 8 Amp per winding.

In this project the servo amplifier gain was tuned approximately by supplying a voltage signal at which the axis motor starts to rotate. The control loop for each axis can be tuned more accurately by fine tuning the signal gain of the servo amplifier by reading the axis velocity using the respective optical encoder. This can be done by writing a small program for tuning which applies a small voltage signal to the DAC channel of an axis and then reads and displays the velocity of the axis using the encoder. The servo amplifier gain can be adjusted to attain the desired velocity.

CHAPTER 11

CONCLUSIONS AND DISCUSSION

The completion of this project required expertise in the filament winding process, mechanical design and fabrication, electronic hardware assembly and trouble shooting, familiarisation with computer hardware, and computer programming in C language and Assembly language. Considering the volume of work, a research period of 3½ years seemed insufficient. Some important conclusions drawn in this research work are described here.

CNC machine controllers developed for metal cutting machines are not very appropriate for filament winding machines because of the higher operating speeds required by the latter. An important requirement of the filament winding operation is to have a look-ahead capability in the controller so that while moving around curves the effect of the pay-out-eye movement on previous fibre positions is minimised. This feature can be introduced in the controller by using an interpolation technique which considers more than two data points for determining the shape of the curve segment. Also, the curve along with its first and the second derivative should be continuous in nature, at the points where two successive curve segments meet. This results in a motion with smooth acceleration profile, without jerks in it. The B-spline interpolation technique gives a clear advantage in filament winding process where high speed and smoothness of the control is more important. In case of non-geodesic winding patterns, a more accurate placement of the fibres is observed because the effect of pay-out-eye movement on the previous fibre positions is controlled due to the look-ahead capability and also because less fibre slippage results in a motion without jerks. While using B-spline interpolation technique it is very important to check whether the deviation between the interpolated path and the specified

path is within the limits or not. This deviation can be controlled by adding more points near the problem area or by changing the knot spacing.

Most of the commercial filament winding machines are large heavy frame structures. Although the fibre roving is very light weight and the load on the pay-out-eye of the machine is very small but heavy structures are used to provide a rugged support for the pay-out-eye so that it is not flexible. In this project a new trend has been introduced in the mechanical design of the filament winding machine by reducing the weight of the CNC machine carriage. This is achieved by mounting the servo motors on the frame of the machine rather than on the carriage itself. A smaller motor is required to drive a lighter weight carriage. To further improve the performance of the servo motors the load moment of inertia is matched with the rotor moment of inertia. The mass of the CNC machine carriage, developed for this project is about 4.0 Kg and the overall mass of the filament winding machine is less than 50 Kg.

A non-conventional technique for tuning filament winding controller constants is also developed in this PhD work. This technique is simple to use and more appropriate to filament winding controllers. The main advantage of this new tuning technique is that it results in controller constant values (K_p and K_d) that can be used for all the axes of the CNC filament winding machine. Using the same values of K_p and K_d in all the control loops of the filament winding machine makes the computer program simpler and faster. A faster control program can accommodate control loops for more number of axes and can be used for a high speed filament winding.

conclusion

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GLOSSARY OF TERMS

Accelerator. An agent used to hasten a reaction to reduce the time required for a thermosetting resin to cure or harden.

Actuator. Part of a control system responsible for providing the output signal. It can be an electric motor, hydraulic drive, heating element, or flow control valve.

CAD/CAM. Computer Aided Design/Computer Aided Manufacture.

CADFIL. Trademark of software package for filament winding of axisymmetric shapes marketed by Crescent Consultants Ltd., Nottingham.

Catenary. A measure of the difference in length of the strands as a result of unequal tension.

Closed-loop control. An automatic control system in which the control action depends on the reference input signal as well as on the output feedback signal sensed by a transducer.

CNC. Computer Numerical Control.

Continuous filament. An individual rod of glass of very small diameter with flexibility and great or indefinite length.

Creel. A stand or frame for holding the required number of roving balls or supply packages in desired position for winding operation.

DAC. Digital-to-Analog Converter.

Delamination. The separation of a laminate into layers owing to failure of adhesion of the binding resin.

Denier. The weight, in grams, of 9,00 meters of yarn is the denier. The lower the denier, the finer the yarn. Also see Tex number, Yield.

Doctor roller or blade. A device in resin impregnation system for regulating the amount of liquid resin on the fibre or the impregnator roller.

Dry winding. Filament winding using pre impregnated roving or dry roving.

Encoder. Optical Encoders are angular sensors providing information on the angular displacement of the shaft on which they are mounted, using a binary code TTL.

Epoxy resin. Two compound binding adhesive based on ethylene oxide, its derivatives or homologs. Epoxy resins form straight-chain thermoplastics and thermosetting resins, for example, by the condensation of bisphenol and epichlorohydrin.

Fabric. Any woven, knitted, felted, bonded, or knotted textile material, generally composed of fibres commonly used in winding operation.

Feedback control. See *closed-loop control*.

Feed Rate. A number indicating the winding speed of the filament winding machine. In this thesis, the velocity of the fastest axis specified in terms of encoder counts per interrupt is taken as the feed rate.

Felt. A fibrous material made up of interlocked fibres by mechanical or chemical action, moisture or heat.

Fibre. This term in general refers to relatively short lengths of very small cross sections of various materials. In filament winding this term is used for a collection of continuous filaments. Glass fibre, carbon fibre, and aramid fibre are the commonly used fibres in filament winding.

Fibre circuit. A filament winding part-program file normally contains a subroutine which is repeatedly indexed to produce the entire coverage of the mandrel. The fibre path wound by one cycle of this subroutine is called a fibre circuit. Generally it is the path of the pay-out-eye from one end of the mandrel to the other end and back.

Fibre layers. A fibre layer consists of many fibre circuits wound in such a way that the mandrel is entirely covered with the fibre.

Fibre spread. Width of the fibre roving when placed on the mandrel during filament winding. A 1200 tex glass fibre roving can spread out to a width of 4–5mm.

Filament. A single, thread-like fibre or a number of these fibres put together. It is the basic fibre unit. A typical glass fibre strand comprises 200 or more filaments. Carbon fibre is specified by the number of filaments present in a tow.

Filament winding. Filament winding is a composite material processing technique that applies a series of continuous resin-impregnated fibres to a rotating mandrel in a specified geometrical pattern under controlled tension.

Frequency response. The frequency response of a system is the steady-state ratio of magnitude and the difference in phase of the output with respect to a sinusoidal input. The range of frequency and the conditions of operation and measurement must be specified.

Fuzz. A measure of broken filaments in a strand or roving.

Geodesic. The shortest distance between two points on a curved surface.

Guide eye. see *Pay-out eye*.

Honeycomb. Manufactured product consisting of sheet-metal or a resin-impregnated sheet material (paper, fibrous glass, etc.) which has been formed into hexagonal-shaped cells. Used as core material for sandwich constructions.

Interrupt. Signal which causes computer to save its current state, execute a special service routine, and then return to what it was doing before.

I/O Port. Input / Output Port.

Knot-point. An interpolated path between two data points is divided in to small segments. The intersection of two segments is known as a knot-point.

Knot-spacing. The spacing between two knot points, or the length of interpolated segments, is called knot-spacing.

Lap. A matted sheet of fibrous material wound on a spindle, produced by the picker.

Lay. The spacing of the roving bands on the roving package expressed in the number of bands per inch.

Lay-up. The arrangement of reinforcing material and the resin on a filament wound product.

Look-ahead Capability. Ability of a filament winding controller to fore-see the next set of data points and modify its path accordingly, such that while moving around curvatures, the effect of pay-out eye movement on previous fibre positions is minimum.

Loops and snarls. Small open places in the strands owing to the excessive length of one or more strands, which is the result of unevenly distributed tension allowing certain strands or filaments to slip while others are completely controlled.

Mandrel. The core around which resin-impregnated fibre roving is wound to form pipes, tubes, or wound products of complex geometry.

Mat. A felt of fibres in which fibres are randomly oriented.

Mould release. A lubricant, often wax, used to coat a mould cavity to prevent the moulded piece from sticking to it, and thus to facilitate its removal from the mould.

Open-loop control. A control system in which the control action depends on the reference input signal only. There is no feed back of the actual state of the system.

Over travel. The travelling of a CNC machine carriage past a specified position is called the over travel.

Off-line trajectory generation. In off-line method an array of desired pay-out-eye positions for each interrupt cycle is calculated before actual motion starts to commence.

Part-Program. A sequential list of instructions for a CNC machine to produce a component.

Path. The space curve traced by the interpolation program is called the path of the trajectory.

Path-anticipation capability. see Look-ahead capability.

Pay-out eye. An eye through which fibre roving passes when directed from creel to mandrel.

PD control. Proportional Derivative control.

PID control. Proportional Integrating Derivative control.

Plasticizer. A chemical agent added to plastic compounds to make them softer and/or more flexible.

Ply. In general denotes fabrics or felts consisting of several layers (laminates etc.). Also refers to yarn resulting from twisting operation.

Post-Processor. A program which produces a part-program for a specific machine tool from a design output produced by a CAD system.

Pot life. Life of a liquid resin from the time the catalyst has been added to the time when it is no longer usable because of gelatinization or initial cure.

Prepreg. Ready-to-mould material in web form, which may be fibre impregnated with resin and stored for use.

Resin. The binding material in filament winding.

Response time. The time taken by a control system to reach its final value as a result of a step response.

Root locus diagram. The root locus diagram is a graphical method for finding the closed loop roots of the characteristic equation. The analysis starts from the

factored roots of the open loop equation and uses the complex plane for the manipulation. The root locus is the locus of the closed loop roots as a function of open loop gain.

Roving. A collection of bundles of continuous filaments as untwisted strands. In filament winding rovings are generally used as a bundle of parallel continuous strands. A typical glass fibre roving consists of 20 strands.

Segment. Portion of machine axis path between two data points given in the part-program file.

Servo mechanism. A servo mechanism is a feedback control system in which the controlled variable is mechanical position.

Shelf life. Life of a resin when stored in its shipping container and without the addition of a catalyst. Life depends on exposure to sunlight, storage temperature, and humidity.

Sizing. Application of a lubricant and binding material in the production of fibres, so that the fibres may hold together and the damage to the fibres due to friction is minimum possible.

Sliver. A number of staple or continuous-filament fibres aligned in a continuous strand without twist. See Strand.

Slippage tendency. The ratio between the lateral and the normal force in the roving while moving around curved surfaces.

Staple fibres. Fibres of short length, ranging up to a couple of centimetres.

Steady-state error. Final error existing between desired and actual output of a controller.

Steady-state response. The part of overall response of a dynamic system which is left when the transient has indeed died away to zero. It helps in determining the static accuracy or steady-state error of the system.

Strands. A bundle of parallel continuous filaments combined in a single compact unit without twist. A glass fibre strand comprises 200 or more filaments.

Tack. Stickiness of an adhesive or filament reinforced resin prepreg material.

Tex Number. Weight in grams of 1000 meter length of roving. Also see Yield, Denier.

Teach-in. A facility on a CNC machine for generating part-programs by moving axes and storing co-ordinates data simultaneously under manual operation.

Trajectory. A time history of position, velocity, or acceleration for each axis of a CNC machine.

Transfer function. The transfer function of a system is the relationship between the output and the input under specified conditions.

In a linear system the transfer function is the ratio of the transform of the output to the transform of its input under the conditions of zero initial energy storage. It is a complete description of the dynamic properties of a system and may be represented as a mathematical expression, the frequency response, or the time response, to a specified input.

Tow. For carbon fibre the term tow is used instead of roving.

Transient response. The time response of a system is the output as a function of time following the application of a prescribed input under specified operating conditions. It is specified in terms of overshoot, rise time, settling time, damping factor, and undamped natural frequency etc.

Web. A woven or wound pattern.

Wet winding. Filament winding operation in which fibre strands are impregnated with resin just before contact with the mandrel.

Winding Angle. The angle between the filaments and an arbitrary line on the surface of a mandrel. The line remains stationary relative to the mandrel.

Winding pattern. A winding pattern normally consists of many layers of fibre. It is specified by the number of layers in the laminate and the winding angle of each layer. It is also known as Laminate Code.

Yarn. A collection of twisted fibres or strands.

Yield. Yield of a fibre roving is specified in Yards per pound. Also see Tex number, Denier.

APPENDIX A

Fil-W-CAD User's Manual

This user's manual is written to provide instructions for using Fil-W-CAD program which is required to run the CNC filament winding machine. The CNC filament winding machine and FIL-W-CAD, both are specially developed for this PhD project.

Fil-W-CAD Introduction:

A complete computerized filament winding system includes a computer controlled filament winding machine and computer programs for drafting, designing, performance analysis, pay-out-eye path generation, and CNC machine control. Fil-W-CAD is a computer program designed to meet all these requirements of a computerized filament winding system. This program runs in an environment of DOS 2.0 or higher on the IBM PC/AT family of computers, along with all true compatibles. It is a modular computer program in which computer codes are integrated as packages or modules. These packages are written such that these are fully compatible with each other and partly compatible with other computer programs developed by different vendors. Fil-W-CAD is an easy-to-run user friendly computer program which provides menu choices, icon displays and mouse or keyboard interaction. In the present version of Fil-W-CAD only two packages, namely CNC filament winding machine control package and computer aided drafting package, are available. Filament winding Design & Analysis package is not available at the moment but it will be included in future. The pay-out-eye path generation package will also be introduced in Fil-W-CAD later; at present this task is done by CADFIL which is developed by Crescent Consultants of Nottingham.

Minimum Hardware Requirements:

Fil-W-CAD requires a special hardware to run the CNC filament winding machine which includes an encoder interface card and two DAC cards. These cards are plugged in to the expansion slots of the computer. Other than these special hardware cards, Fil-W-CAD requires an IBM PC/AT-286 or compatible computer with 512KB RAM, one floppy disk drive, and any graphics adapter card. The program checks the type of graphics adapter card and then adjusts its display according to the highest resolution available on the card.

To achieve a good performance from Fil-W-CAD it is recommended to implement this system on an IBM PC/AT-386 or compatible computer with 2MB RAM or more, a hard disk of 40MB or more, one 3½ inch floppy disk drive, one mouse, two serial and one parallel port, one SVGA graphics card and a 14 inch SVGA monitor.

Fil-W-CAD Installation:

Fil-W-CAD program is supplied on a single 3½ inch 1.44MB diskette. Being a modular program it consists of many files – all present on one diskette. To install this program on your computer, create a directory of a suitable name (e.g FILWCAD) on your hard disk and copy all the files from the Fil-W-CAD diskette to that directory, using `COPY *.*` command. If you are not sure about this step, consult your DOS manual. The following 33 files must be present in your default directory;

FILWCAD.BAT	batch file to run Fil-W-CAD
FW-CNC.EXE	CNC filament winding machine control program
FW-CNC.PAR	CNC machine configuration parameters file

FW-DRAW.EXE	computer-aided drafting program
MENU.DAT	multiple package integrator file
README.COM	for displaying the help document on screen
FILWCAD.DOC	the help document for Fil-W-CAD
BE.EXE	to display the Fil-W-CAD menu
ZEROX.ICN	icon for moving the CNC machine X-axis to zero
ZEROALL.ICN	icon for moving all the axes to zero position
MAND_OFF.ICN	icon for manual control providing an off-set for a mandrel
RESET.ICN	icon to reset the machine parameters
CALCULATE.ICN	icon to calculate the pay-out-eye path for a selected file
WIND.ICN	icon for starting the winding operation on the CNC machine
HAND.ICN	icon for moving an object in the drafting package
POINTER.ICN	icon for selecting an object in the drafting package
LINE.ICN	icon for drawing a line
LETTER.ICN	icon for writing text
FILLPOLY.ICN	icon for drawing a filled polygon
CIRCLE.ICN	icon for drawing a circle
DUPLICATE.ICN	icon for duplicating an object
SCISSOR.ICN	icon for deleting an object
FLIPFRNT.ICN	icon for changing the priority of an object
FLIPBACK.ICN	icon for reversing the priority of an object
ROTATE.ICN	icon for rotating an object
CGA.BGI	graphics driver file for CGA displays
EGAVGA.BGI	graphics driver for EGA and VGA displays
HERC.BGI	graphics driver for Hercules mono colour display
ATT.BGI	graphics driver for ATT400 series displays
IBM8514.BGI	graphics driver for 1024 x 768 and 640 x 480 pixels display
PC3270.BGI	graphics driver for 720 x 350 pixels display
GOTH.CHR	stroked Gothic font for writing text in the drafting package
SANS.CHR	stroked Sans-serif font for text in the drafting package
TRIP.CHR	stroked Triplex font for text in the drafting package
LITT.CHR	stroked Small font for text in the drafting package

To Run Fil-W-CAD:

Once Fil-W-CAD is successfully installed on your hard disk, the program can be started by the following procedure;

1. Select FILWCAD directory as the default directory, using command;

```
CD \FILWCAD <Ret>
```

2. Run Fil-W-CAD by typing the command;

```
FILWCAD <Ret>
```

A chime is heard from the computer speaker and the following main menu appears on the computer screen (Figure A-1):

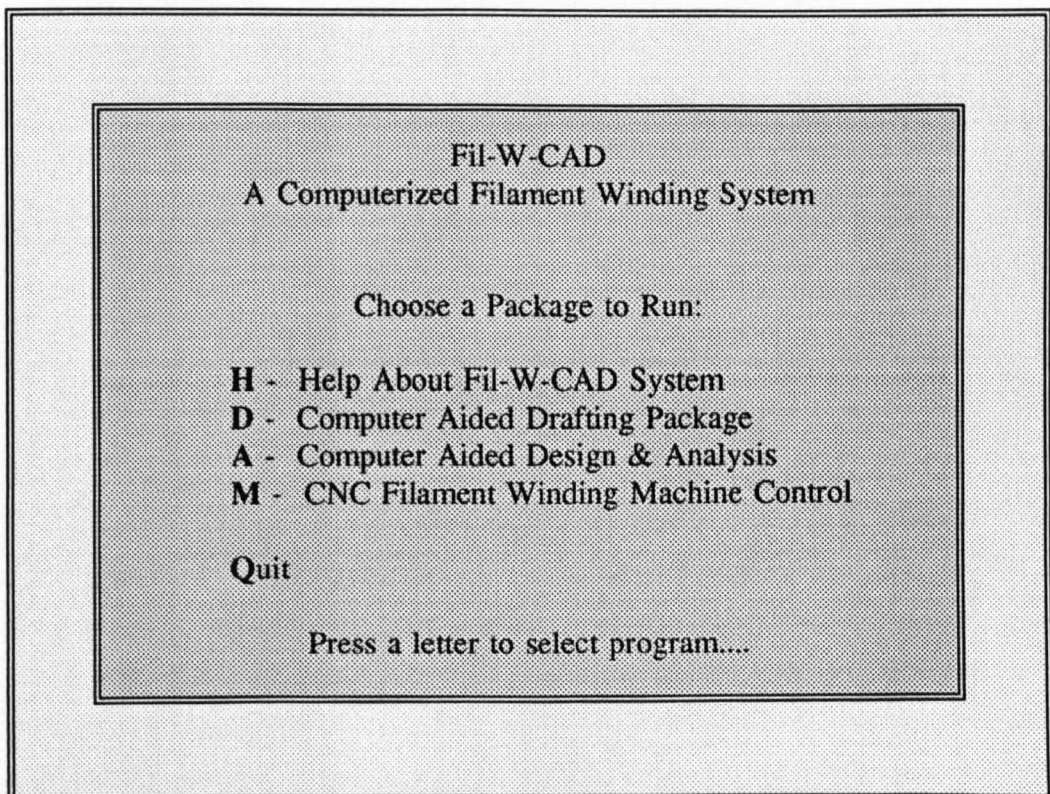


Figure A-1: The Main Menu of Fil-W-CAD

In the main menu any option can be selected by pressing the highlighted character written against that option. Pressing <Q> key ends the Fil-W-CAD program. In this manual the sign '< >' represents a single key press.

H - Help About Fil-W-CAD:

Pressing <H> key in the main menu selects this option and displays the contents of this user's manual on screen. This help document is displayed in the form of pages so that the user can read it easily. To scroll through the displayed pages, use <Page Up>, <Page Dn> and cursor keys. Pressing <Esc> key ends the help display session and the Fil-W-CAD main menu is displayed again.

D - Drafting Package:

Pressing <D> key in the main menu selects and executes the computer aided drafting package. A screen as shown in Figure A-2 appears on the screen. On the top line options like 'Grid', 'Text', 'Line', 'Clear' and 'Quit' are shown. On the left side of the screen 11 icons are displayed. These icons are for drawing lines, circles, polygons and writing text as well as for selecting, moving, duplicating, rotating and deleting drawn objects. At the bottom of the screen available drawing colours and fill patterns are displayed in the form of icons. To select any icon or function, move the mouse cursor to the desired icon or function and click the mouse left button.

In the top line menu, the 'Grid' option toggles the grid on the screen which provides a help for approximate dimensions of the drawn object. On selecting the 'Text' option in the top line menu, a pull down menu appears on the screen. This pull down menu contains graphic text fonts. The selected font becomes the current font for writing any more text after that. On selecting the 'Line' option

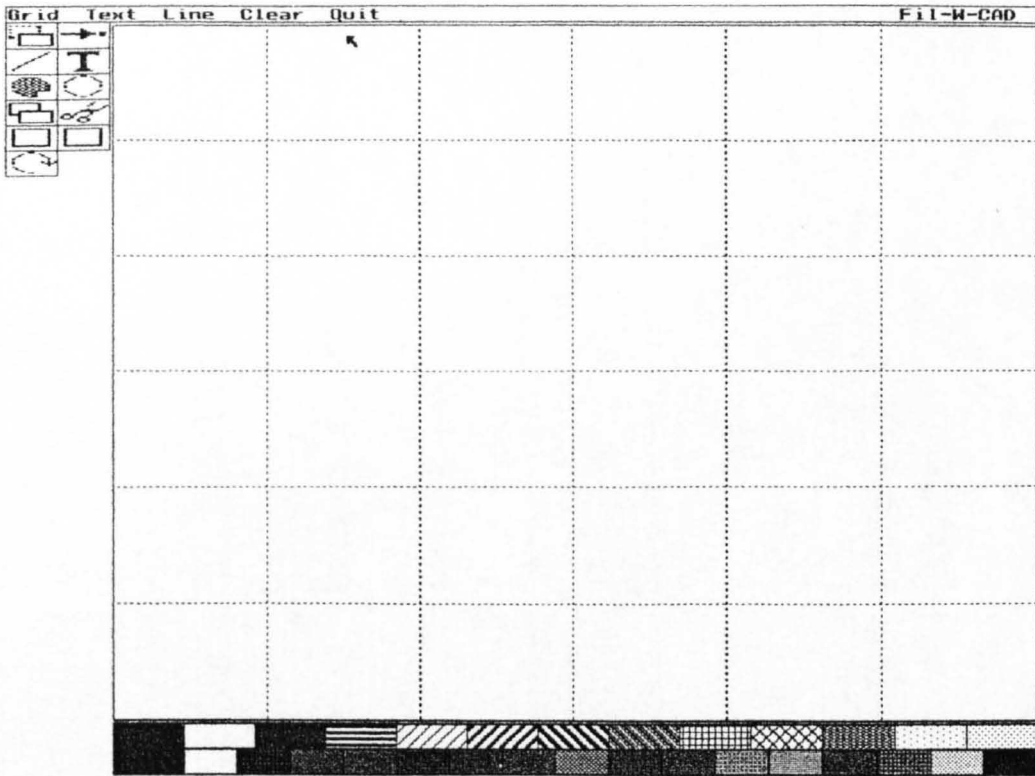


Figure A-2: Computer Screen for Computer-Aided Drafting Package

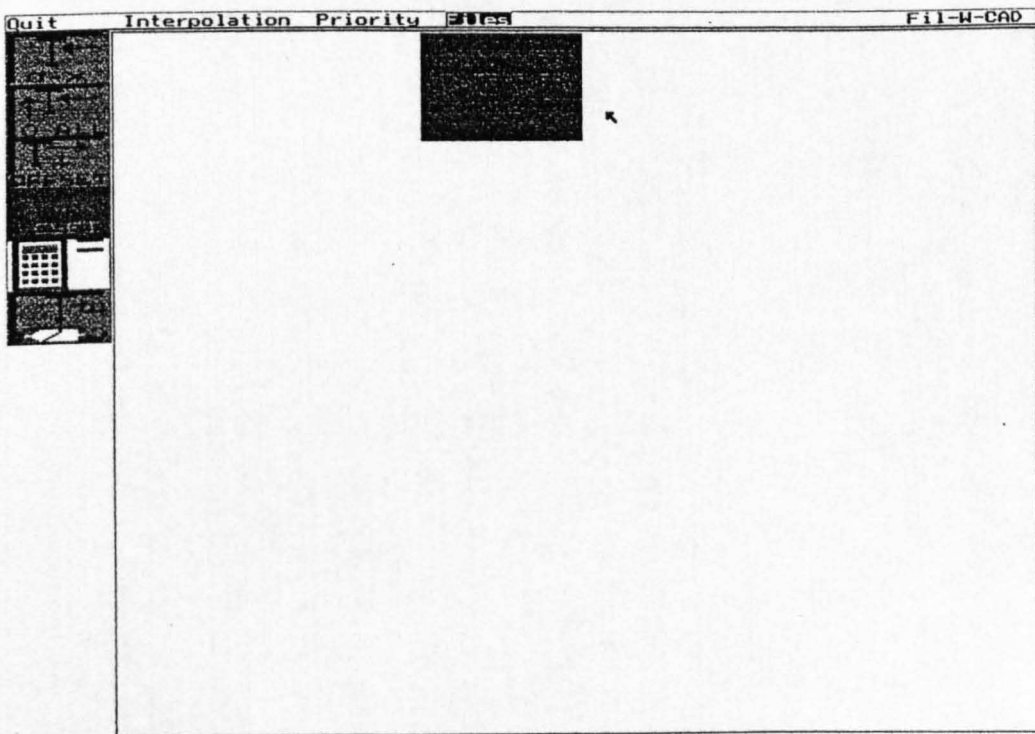


Figure A-3: Computer Screen for Filament Winding Machine Control Package

in the top line menu, a pull down menu showing various line styles appears on the screen. Any one of these line styles can be selected for drawing further objects in that line style by clicking the mouse left button on the desired line style. In the current version of the drafting package seven line styles are available, namely continuous, dashed, dotted, centre line, dimension line, left leader, and right leader. On selecting the 'Clear' option all the drawn objects displayed on the screen are cleared and the screen is ready for a new drawing. On selecting the 'Quit' option in the top line menu, the drafting package session ends and the Fil-W-CAD main menu appears on the screen.

The icons on the left side of the screen are for drawing lines, circles, and polygons etc. These icons are self explanatory.

A - Design & Analysis Package:

Pressing <A> key in the main menu selects the Design & Analysis package. This option is not available in this version of Fil-W-CAD.

M - CNC Machine Control:

Pressing <M> key in the main menu selects and executes the CNC filament winding machine control package. A screen as shown in Figure A-3 appears on the screen. At this stage, switch on the mains power supply to the servo drive unit. For safe operation of the machine, the mains power should be switched on only when the CNC machine control menu is displayed on the screen and no option is selected from the menus. It is recommended to give a warming up period of at least one minute before performing any other operation on the axes motors.

On the top line of the screen menu options like 'Quit', 'Interpolate', 'Priority' and 'Files' are shown. On the left side of the screen 6 coloured icons are displayed. These icons are for moving the CNC machine carriage to its zero reference position and for performing the winding operation. To select an icon, move the mouse cursor to the desired icon and click the mouse left button. The selected icon changes its colour and the desired function is executed.

Moving the mouse cursor to the 'Quit' option in the top line menu ends the CNC machine control program and the main menu of Fil-W-CAD reappears on the screen.

To move the X-axis of the machine to its zero position, move the cursor mouse to the first icon ('0-X') on the left side of the screen and select it. The machine carriage will start moving to its left until it reaches the end. When the carriage reaches the extreme left position, the X-axis limit opto-switch is activated and the carriage stops. Instead of using a mouse, this task can also be performed by pressing <x> key on the computer keyboard. When the carriage has reached its destination and stopped its motion, a display appears on the screen which shows the current position of all the X-axis, Y-axis and A-axis encoders. To move both, X-axis and Y-axis to their reference zero positions, move the cursor to the icon for '0-all' and press the mouse left button. This task can also be selected by pressing <a> key on the computer keyboard. On selecting this function, first X-axis moves to its zero position and then Y-axis moves to its zero position. After reaching their destinations the axes motors stop and a display showing the current encoder position of A-axis, X-axis and Y-axis is displayed on the screen. Whenever current encoder positions are displayed on the screen, it means the manual control of the filament winding machine is active. In this manual mode any machine axis can be moved by keyboard keys. The <←> key moves the X-axis towards left, <→> key moves the X-axis towards right, <↑> key moves the Y-axis towards its zero position, <↓> key moves the Y-axis away from its zero position, <Page Up> key rotates the A-axis in the +ve direction, and <Page Dn> key rotates the A-axis in the -ve direction. The axis motion can be stopped by

pressing any key on the keyboard. The speed of motion can be controlled by using <+> and <-> key on the keyboard. The <+> key increases the speed of motion and the <-> key decreases the speed of motion.

To wind a particular mandrel, first of all appropriate part-program file is chosen by selecting the 'Files' option from the top-line menu. On selecting the 'Files' option, all the files in the current directory with *.PRG format appear in a pull-down menu. Select the appropriate file by clicking on it. The next step is to select the speed 'priority' from the top line menu. Optimum speed is a safe choice. Then select 'Linear' or 'B-spline' from the 'Interpolate' pull down menu. Now Fil-W-CAD is ready to calculate the pay-out-eye path. Select the calculator icon from the left side screen icons. The interpolation program will calculate the pay-out-eye trajectory and show the results on the screen how many interrupt cycles are required to complete one circuit, how many circuits to be wound, and the total number of data points recorded for storing the plotting data etc. It is necessary that the total number of data points recorded in the resultant plot file does not exceed 5000. Instead of recording the plotting data after every interrupt if it is recorded after every 'n' number of interrupts, the size of the resultant plot file can be reduced. The parameter 'n' is specified in the CNC machine configuration file FW-CNC.PAR. After showing the interpolation results on the screen the program asks the user to start the winding or quit. If you are satisfied with the plotting data frequency and other parameters then the winding can be commenced. Once a mandrel is mounted on the filament winding machine and the roving is attached to the mandrel, the winding operation can be started by selecting the appropriate icon from the left side of the screen or by pressing <w> key on the keyboard. The machine starts filament winding according to the path specified in the given part-program file. After winding the requested number of circuits on the mandrel, the machine stops. A plot file containing the actual movement record of X-axis, Y-axis and A-axis is created in the same directory as that of the part-program file. The name of the created plot file is the same as the part-program file, with an extension of *.PLT.

The Description of FW-CNC.PAR File:

This file contains the CNC filament winding machine configuration parameters like feed rate limit, average feed rate, manual control initial feed rate and the number of interrupts after which the actual position of the encoders is recorded. The first three lines in the file are for comments bearing the file name and description. All the other lines in the file contain an integer number and a comment which begins with a semicolon. This file can be modified using a text file editor. The format of the file is as given below;

```
FW-CNC.PAR -- CNC filament winding machine parameters file
First three lines are for comments, all the other lines are also
formatted bearing an integer and a comment beginning with <;>.
20 ; Initial feed rate for manual control
10 ; Normal feed rate
30 ; Feed rate limit
20 ; Number of interrupts after which actual positions are recorded
4 ; Number of knot points to be interpolated between two points
```

APPENDIX B

Controller Connections and Wiring Diagrams

There are total nine electric connectors used in this CNC filament winding machine. Each connector has a name ranging from CN1 to CN9 and consists of a male and a female part. The male part, called Plug, is identified by 'P' added to its name, such as CN1-P. The female part, called Socket, is identified by 'S' in its name, such as CN1-S. A diagram showing the location of each connector is given in Figure B-1.

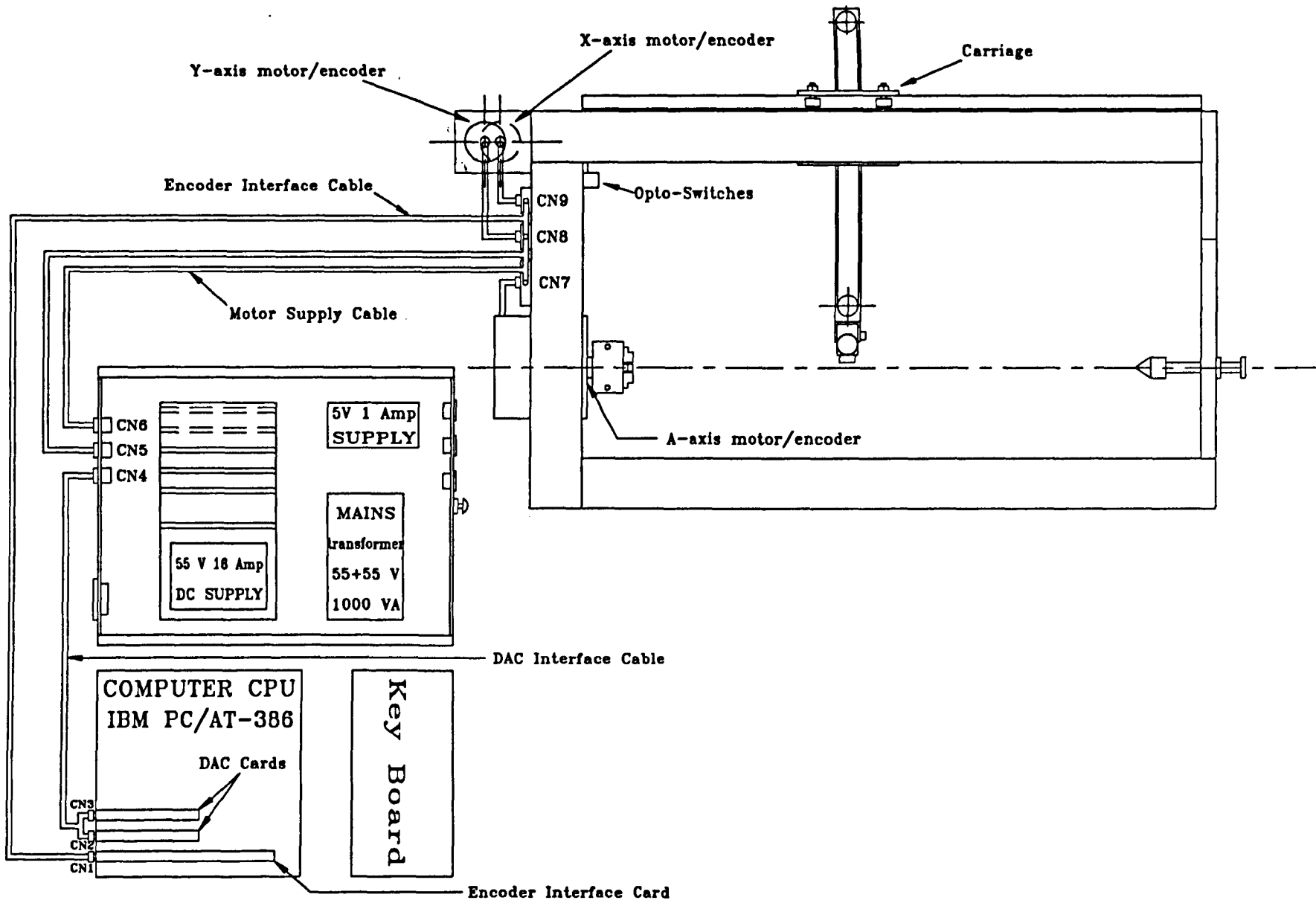


Figure B-1: The Location of Electrical Connectors and Their Connections

CNI-S:

Encoder Interface Connector. CN-1S is a 37 pin D-type chassis mounting socket located on the Encoder Interface Card which is installed in the computer. CN1-S receives signals from optical encoders and optical limit switches, and supplies these signals to the computer.

Pin Number	Signal	Port Address
1	Opto-switch, Y-axis	030ch, 8th bit
2	Opto-switch, X-axis	030ch, 7th bit
3	Fault / Inhibit	030ch, 6th bit
4	For future expansion	030ch, 5th bit
5	do	030ch, 4th bit
6	do	030ch, 3rd bit
7	do	030ch, 2nd bit
8	do	030ch, 1st bit
9	NC	
10	B-axis encoder line 2	
11	B-axis encoder line 1	0302h
12	Z-axis encoder line 2	
13	Z-axis encoder line 1	0304h
14	Y-axis encoder line 2	
15	Y-axis encoder line 1	0306h
16	X-axis encoder line 2	
17	X-axis encoder line 1	0308h
18	A-axis encoder line 2	
19	A-axis encoder line 1	030ah
20	Ground	
21	Ground	
22	Ground	
23	Ground	
24	Ground	
25	Ground	
26	Ground	
27	Ground	
28	B-axis encoder line 4	
29	B-axis encoder line 3	
30	Z-axis encoder line 4	
31	Z-axis encoder line 3	
32	Y-axis encoder line 4	
33	Y-axis encoder line 3	
34	X-axis encoder line 4	
35	X-axis encoder line 3	
36	A-axis encoder line 4	
37	A-axis encoder line 3	

Pin 20 to 27
are connected
together at the
interface card.

CN1-P:

Encoder Interface Connector. CN-1P is a 37 pin D-type cable plug soldered on the end of the encoder interface cable. The encoder interface cable is a 15 wire screened cable, having CN1-P on one end. The other end of the cable is fixed to the filament winding machine frame by soldering connections to various terminals in CN7-S, CN8-S and CN9-S.

Pin Number	Signal	Wire Colour
1	Opto-switch, Y-axis	Grey
2	Opto-switch, X-axis	Violet
3	Fault / Inhibit	Black
4	NC	
5	NC	
6	NC	
7	NC	
8	NC	
9	NC	
10	NC	
11	NC	
12	NC	
13	NC	
14	Y-axis encoder line 2	Blue
15	Y-axis encoder line 1	Green
16	X-axis encoder line 2	Yellow
17	X-axis encoder line 1	Orange
18	A-axis encoder line 2	Red
19	A-axis encoder line 1	Brown
20	Ground	
21	Ground	
22	Ground	
23	Ground	
24	Ground	
25	Ground	
26	Ground	
27	Ground	
28	NC	
29	NC	
30	NC	
31	NC	
32	Ground	
33	Ground	Light Blue
34	Ground	
35	Ground	Pink
36	Ground	
37	Ground	White

CN2-S & CN3-S:

DAC Card Connectors. CN2-S and CN3-S are two identical 25 pin D-type chassis mounting sockets located on the two DAC cards which are installed in the computer. These connectors connect the analogue voltage signal, generated by the DAC cards, to the servo amplifiers of A-axis, X-axis and Y-axis DC motors. An analogue output voltage signal ranging from +10 volt to -10 volt, can be generated by sending a digital number ranging from 0 to 4095, at the appropriate port address of the computer.

D/A port address for A-axis (D/A #1 on CN2-S) = 0332h
 D/A port address for X-axis (D/A #0 on CN2-S) = 0330h
 D/A port address for Y-axis (D/A #1 on CN3-S) = 033ah

Pin Number	Signal	Signal Direction
1	Ground	
2	Ground	
3	Ground	
4	Ground	
5	Ground	
6	Ground	
7	Ground	
8	Ground	
9	Ground	
10	Ground	
11	Ground	
12	Ground	
13	+5 Volt supply for output	Out
14	-10 volt Reference	Out
15	-5 volt Reference	Out
16	D/A #1 Reference Input	In
17	D/A #1 Bipolar Output	Out
18	D/A #1 Unipolar Output	Out
19	D/A #1 4-20 mA Output	Out
20	-10 volt Reference	Out
21	-5 volt Reference	Out
22	D/A #0 Reference Input	In
23	D/A #0 Bipolar Output	Out
24	D/A #0 Unipolar Output	Out
25	D/A #0 4-20 mA Output	Out

CN2-P & CN3-P:

DAC Card Connectors. CN2-P and CN3-P are two identical 25 pin D-type cable plugs soldered on one end of the DAC card interface cable. These connectors receive analogue voltage signal generated by the DAC cards and supply them to the respective servo amplifiers. Pin 14 is connected to pin 16, and pin 20 is connected to pin 22 to provide the necessary reference voltage signal to the DAC card.

The DAC card interface cable consists of a 6 wire screened cable having two connectors, CN2-P and CN3-P, on one end and one connector CN4-S on the other end of the cable.

Pin Number	CN2-Plug		CN3-Plug	
	Signal	Colour	Signal	Colour
1	NC		NC	
2	NC		NC	
3	NC		NC	
4	NC		NC	
5	NC		NC	
6	Ground	Green	Ground	Black
7	NC		NC	
8	NC		NC	
9	NC		NC	
10	NC		NC	
11	NC		NC	
12	NC		NC	
13	NC		NC	
14	Connected to pin 16		Connected to pin 16	
15	NC		NC	
16	Connected to pin 14		Connected to pin 14	
17	A-axis DAC out	Red	Y-axis DAC out	Blue
18	NC		NC	
19	NC		NC	
20	Connected to pin 22		Connected to pin 22	
21	NC		NC	
22	Connected to pin 20		Connected to pin 20	
23	X-axis DAC out	Yellow	For future use	
24	NC		NC	
25	NC		NC	

CN4-S:

Connector for DAC Input to Servo Drive. CN4-S is 9 pin D-type cable socket soldered at the end of the DAC card interface cable.

Pin Number	Signal	Wire Colour
1	A-axis DAC signal	Red
2	X-axis DAC signal	Yellow
3	Y-axis DAC signal	Blue
4	NC	
5	NC	
6	NC	
7	Signal Ground	Green
8	NC	
9	Shield Ground	Shield

CN4-P:

Connector for DAC Input to Servo Drive. CN4-P is 9 pin D-type chassis mounting plug located at the back panel of the Servo Drive unit. CN4-P receives analogue voltage signals from the DAC interface cable and supplies them to the respective servo amplifiers installed in the Servo Drive unit.

Pin Number	Signal	Wire Colour
1	A-axis DAC signal	Red
2	X-axis DAC signal	Red
3	Y-axis DAC signal	Red
4	NC	
5	NC	
6	NC	
7	Signal Ground	Blue
8	NC	
9	Shield Ground	Shield

CN5-S:

5 Volt Supply / Limit Switches Connector. CN5-S is a 9 pin D-type chassis mounting socket located on the back panel of the Servo Drive unit. This connector supplies 5 volt DC to the encoders fixed on the DC motors and connects X-axis and Y-axis limit switches signal to the Servo Drive unit.

Pin Number	Signal	Wire Colour
1	Supply Ground	Blue
2	+5 volt supply	Red
3	Shield Ground	Shield
4	X-axis limit switch 2	Red
5	X-axis limit switch 1	Blue
6	Common for all limit switches	Shield
7	Inhibit / Fault	
8	Y-axis limit switch 2	Red
9	Y-axis limit switch 1	Blue

CN5-P:

5 Volt Supply / Limit Switches Connector. CN5-P is a 9 pin D-type cable plug. This connector supplies 5 volt DC to the encoders fixed on the DC motors and connects X-axis and Y-axis limit switches signal to the Servo Drive unit.

Pin Number	Signal	Wire Colour
1	Supply Ground	Black
2	+5 volt supply	Red
3	Shield Ground	Shield
4	X-axis limit switch 2	Yellow
5	X-axis limit switch 1	Green
6	Common for all limit switches	White
7	Inhibit / Fault	Brown
8	Y-axis limit switch 2	Violet
9	Y-axis limit switch 1	Blue

CN6-S:

DC Motors Supply Connector. CN6-S is a 6 way bayonet locking multipole chassis mounting socket located at the back panel of the Servo Drive unit. This connector supplies motor current, generated by the servo amplifiers and supplies them to the respective DC motors. This connector can handle electric currents up to 10 Amp per contact.

Pin Number	Signal	Wire Colour
A	A-axis MT1	Red
B	A-axis MT2	Green
C	X-axis MT1	Red
D	X-axis MT2	Green
E	Y-axis MT1	Red
F	Y-axis MT2	Green

CN6-P:

DC Motors Supply Connector. CN6-P is a 6 pin bayonet locking multipole cable plug soldered at the end of the DC motors supply cable. This cable supplies motor current, generated by the servo amplifiers and supplies them to the respective DC motors. This connector can handle electric currents up to 10 Amp per contact.

Pin Number	Signal	Wire Colour
A	A-axis MT1	Black
B	A-axis MT2	Green
C	X-axis MT1	Black
D	X-axis MT2	Green
E	Y-axis MT1	Black
F	Y-axis MT2	Green

CN7-S:

A-axis Motor Supply Connector. CN7-S is a 8 way bayonet locking multipole chassis mounting socket located on the filament winding machine frame.

Pin Number	Signal	Wire Colour
A	A-axis MT2	Green
B	A-axis MT1	Black
C	A-axis encoder line 1	Green
D	A-axis encoder line 2	White
E	NC	
F	+5 volt encoder supply	Red
G	Encoder ground supply	Black
H	NC	

CN8-S:

Y-axis Motor Supply Connector. CN8-S is a 8 way bayonet locking multipole chassis mounting socket located on the filament winding machine frame.

Pin Number	Signal	Wire Colour
A	Y-axis MT2	Green
B	Y-axis MT1	Black
C	Y-axis encoder line 1	Yellow
D	Y-axis encoder line 2	Blue
E	NC	
F	+5 volt encoder supply	Red
G	Encoder ground supply	Black
H	NC	

CN9-S:

X-axis Motor Supply Connector. CN9-S is a 8 way bayonet locking multipole chassis mounting socket located on the filament winding machine frame.

Pin Number	Signal	Wire Colour
A	X-axis MT2	Green
B	X-axis MT1	Black
C	X-axis encoder line 1	Green
D	X-axis encoder line 2	Blue
E	NC	
F	+5 volt encoder supply	Red
G	Encoder ground supply	Black
H	NC	

CN7-P, CN8-P & CN9-P:

Motor Supply Connectors. CN7-P, CN8-P and CN9-P are 8 way bayonet locking multipole cable plug type connectors. These three connectors are identical and come fitted with the DC motor and encoder combination, as supplied by Electro Craft Ltd. CN7-P is connected to the A-axis motor, CN8-P is connected to the Y-axis motor, and CN9-P is connected to the X-axis motor. Each connector has connections for the DC motor supply as well as for the optical encoder supply and the optical encoder output.

Pin Number	Signal	Wire Colour
A	Motor MT2	Red
B	Motor MT1	Black
C	Encoder line 1	White
D	Encoder line 2	Green
E		Yellow
F	+5 volt encoder supply	Brown
G	Encoder ground supply	Blue
H	NC	

APPENDIX C

DC Servo Drive Calibration Procedure

The DC servo drive, MAX300, used in this filament winding machine, is fitted with three axis cards. The description of the servo drive is given in the manual *Electro Craft User Information, MAX 300 Series DC Servo Drive*. There are six potentiometer type preset controls on each axis card. The correct setting of these controls is very important to obtain a proper response from the servo drive. The servo drive setting-up procedure, given in section 10.2 of the MAX 300 User Manual, is not suitable for the configuration used in this filament winding machine. This procedure assumes a tachometer type velocity feed back signal, whereas, we are using an optical encoder type displacement feed back signal. To overcome this problem, a new calibration procedure is developed, which is given below;

- Step 1: Rotate the 'TIME CONSTANT' preset fully clockwise and the remaining five presets fully anticlockwise. Note that 20 turn potentiometers are fitted.
- Step 2: Rotate the 'I LIMIT' preset 5 turns clockwise.
- Step 3: Rotate the 'BALANCE' preset 10 turns clockwise.
- Step 4: Switch on the mains supply to the servo drive, check that the fan is running and that no fault LEDs are illuminated.

Step 5: Apply a +2.5 volt DC signal to the input pins (VELOCITY COMMAND 1 and VELOCITY COMMAND 2).

Step 6: Rotate the 'SIGNAL GAIN' preset slowly in clockwise direction till the motor starts to rotate. Note that the load on A-axis, X-axis and Y-axis is different so the setting of 'SIGNAL GAIN' preset will be different for different axes.

With this calibration procedure we can set the three axis cards at three different signal gains, such that the machine axis with high inertial load is set at high gain and the machine axis with low inertial load is set at low gains. With this setting, all the three axis drive motors would start rotating when a voltage of +2.5 volt is applied, although their loads may be different. This technique helps in allowing the use of the same controller gains (K_p and K_d) in the controller software, for all the three axes.

APPENDIX D

List of Components and Suppliers

Approximate estimate of the components cost:

1- IBM PC/AT compatible computer with VGA colour monitor =	£800
2- Encoder interface card =	£500
3- Digital-to-analog converter card =	£600
4- DC Servo motors with encoders =	£1600
5- Servo Amplifiers and power supplies =	£1500
6- 3-jaw chuck and dead centre =	£200
7- Linear bearings and guide rails =	£600
8- Timing belt and pulleys =	£300
9- Carriage and HSS beam machining =	£200
10-Side supports and stand etc. =	£200
11-Miscellaneous =	£500

Total = £7000

List of components:

1. IBM PC/AT-386 25MHz compatible computer with the following specifications;

- 4 MB RAM on board
- 40 MB Hard disk
- one floppy disk drive 3.5"
- one floppy disk drive 5.25"
- one Mouse
- two serial and one parallel port
- 14" VGA colour monitor with SVGA card

This computer can be purchased locally.

2. DAC card, DDA-06, 6 channel, 12-bit analog output.

Manufactured by: Keithley MetraByte, USA

Supplier address: Keithley Instruments Limited
The minster, 58 Portman Road
Reading, Berkshire RG3 1EA, UK

Tel. (0734) 575666

Fax. (0734) 596469

Approximate price of the card = £525, Quantity required = one card

3. dc servo drive unit, MAX 300.

It should consist of a power chassis with a provision of accommodating up to five axis cards. Only three axis cards will be bought for the time being. A 1500 VA mains power transformer and three dc servomotors should also be purchased from the same source.

<u>Qty</u>	<u>Description</u>	<u>Part Number</u>	<u>Price</u>
1	MAX 300 Complete Chassis 3 COMM	21-0021	£1438.00
1	1.5 KVA Transformer	58-0062	£180.00
2	S26-1A+RM21-1000-LD motors with encoder	TBA	£568.00
1	S19-1A+RM21-1000-LD motor with encoder	TBA	£343.00

Manufactured by: Electro-Craft Inc, USA

Supplier address: Electro-Craft Limited
Fourth Avenue
Crewe CW1 1XL, UK

Tel. (0270) 580142

Fax. (0270) 580141

4. In the manufacture of Encoder Interface Card the component that requires special attention from the procurement point of view is the IC 74LS2000. All the other components are easily available from RS Electronics and other component suppliers.

Supplier address: Quarndon Electronics (Semiconductors Ltd.)
Slack Lane
Derby DE3 3ED

Tel. (0332) 32651

Approximate price of one THCT2000 IC = £10.00, quantity required = 5 ICs.

5. The following components are used in x-axis bearing support and power transmission;

- a- DC servomotor; Electro-craft S19-1A
- b- Optical encoder; Electro-craft R80 5V 1000
- c- Drive pulley; Synchroflex AL 15 T5/15-2
- d- Idle pulley; ST 20 T5
- e- Timing belt; Synchroflex 15 T5
- f- Four stud type track rollers; 2 x INA KR 26 and 2 x INA KRE 26
- g- STAR Guide rail; type 1605-104-31, length 1190 mm
- h- STAR Runner block; 2 x type 1604-194-10
- i- Aluminium carriage chassis made by the University workshop
- j- Mild steel HSS beam fitted with linear track made by University workshop

6. Linear motion bearings and guide rail;

<u>Qty</u>	<u>Description</u>	<u>Part Number</u>	<u>Approx. Price</u>
2	Runner Block, Size 15	1604-194-10	£100.00
2m	Guide Rail, Size 15	1605-104-31	£140 per meter

Manufacturer: STAR Ball Rail System
Supplier Address: Hepco Slide Systems Ltd.
1 Aintree Road
Greenford Middlesex
England

Tel. (081) 997 0649
Fax. (081) 997 7926

7. Stud type track rollers;

<u>Qty</u>	<u>Description</u>	<u>Part Number</u>	<u>Approx. Price</u>
2	Stud type track roller, KR-26		£20

2 Stud type track roller, KRE-26 £30

Manufacturer: INA Bearing Company Limited
Supplier Address: INA Bearing Company Limited
Forge Lane Minworth
Sutton Coldfield
West Midlands B76 8AP

Tel. (021) 351 3833

8. Timing belts and pulleys;
Supplier address: William Kenyon & Sons Ltd (Power transmission)
Shepley Works
Dukinfield Road
Hyde, Cheshire SK14 4RP