University of Southampton

THE SYSTEMATIC DESIGN OF AN INDUCTIVE TRANSDUCER COIL WINDING SYSTEM

M. Phil Thesis

by

ROGER LEIGH

FEBRUARY 1991

ACKNOWLEDGEMENTS

Firstly, I would like to thank Dr. Geoff Pitts for his continued interest and advice throughout this project.

I would also like to thank everyone else at Southampton University with whom I had contact, in particular Brian Hodgson for many informative discussions.

Thanks also to the many people at Penny and Giles who offered help, advice and excursions to "The New Lodge". Particular thanks go to Ray New for overseeing the project and Ian Harris for teaching me much about designing LVDTs.

The continued support by my new employers KDG Mobrey Limited, is greatly appreciated. Thanks to Dr. Greg Primavesi for his interest in the work, and to Pearl for enlightening me on some of the mysteries of the word-processor and offering assistance during protracted battles with the printer.

Finally, thanks to Jackie for teaching me some of the practicalities of coil winding, and for becoming my fiancee.

CONTENTS PAGE

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF ENGINEERING AND APPLIED SCIENCE
MECHANICAL ENGINEERING

Master of Philosopy

THE SYSTEMATIC DESIGN OF AN INDUCTIVE TRANSDUCER COIL WINDING SYSTEM

by Charles Roger Aaron Leigh

The need for electromechanical transducers to measure distance is established. The operation of several inductive position transducers is described and a detailed technical review of Linear Variable Differential Transformers (LVDT) carried out. The wide range of LVDT designs are detailed with emphasis on the types and construction of the windings. Thus the need for a system to produce inductive transducer windings is established.

A systematic design procedure is described and followed in order to produce a design for the optimum winding system to fulfil the stated needs. This work involves producing a full specification of the system required. Based on the needs described in the specification, as full a selection of different possible design solutions are identified. This included a review of solutions described in the literature.

Evaluation of all possible solutions is attempted by a selection of techniques, including design optimization and the Morphological method. The Morphological method is found most suitable. This method is adapted and improved to allow more accurate evaluation.

Conclusions on the most suitable winding system are drawn from the results of the Modified Morphological method. The effectiveness of the Morphological method is assessed. Some further work to establish the suitability of the recommended systems is described.

TERMINOLOGY

Bobbin Spindle - Spindle on which bobbin to be wound is held.

Complimentary Winding - LVDT winding with primary over entire length and secondaries increasing in turns density from one end to the other (see appendix A).

Contoured Winding - LVDT winding with primary over entire length and secondaries over half winding with turns density increasing towards outside (appendix A).

Down Spooling - Spooling of wire from a large spool to a smaller one to allow side dereeling without an excessively large tension motor.

Even Layer Winding - Winding in which wire has been wound with ideally no cross-overs and no voids.

Graded Winding - Alternative name for a contoured winding.

Linearity - Term often used in place of non-linearity. Non-linearity is more strictly correct.

LVDT - The Linear Variable Differential Transformer is a type of inductive position transducer.

LVIT - The Linear Variable Inductive Transducer is a type of inductive transducer.

Non-Linearity - The non-linearity of a transducer is a measure of the amount by which its output versus the quantity measured deviates from the ideal of a straight line. This is almost invariably expressed as a percentage.

Null Position - Inductive transducer core is positioned equal distant into each measuring coil so output is minimum.

Null Voltage - Voltage obtained with core at null position.

Off-end Dereeling - Dereeling in which wire is fed from end of supply spool to the winding system.

Phase Angle - Angle between input waveform to primary and output waveform from secondaries.

Phase Opposition - Connection of LVDT secondaries such that direction of winding of each are in opposite senses.

Pitch - Spacing of one wire turn to the next.

Primary - Transformer coil which receives input signal.

Random Winding - Winding in which wire is allowed to position itself resulting in many cross-overs and voids.

Ratiometric Output - The output from an LVDT is measured as the ratio of the difference of the secondary voltages over the sum of the secondary voltages. With proper design this can give better non-linearity and temperature coefficient.

Resolution - The smallest variation in the measured quantity which can possibly be detected by a transducer.

Secondary - Transformer coil from which output signal is taken. An LVDT has two secondaries.

Sensitivity - Scale factor for converting output of transducer to quantity measured. In the case of inductive position transducers this will be the voltage or current per unit length eg. V/mm.

Side Dereeling - Dereeling in which the supply spool is turned so that wire is fed from the side of the supply spool to the winding system.

Space Winding - Winding in which gaps are left between successive turns.

Step Winding - Winding in which successive layers are shortened to produce a stepped contour.

Stroke Length - Length of movement of position transducer shaft over which claimed accuracy is valid. In the case of inductive position transducers a reduced accuracy will be obtained over a greater length.

Stroke to Length Ratio - Ratio of the transducers stroke length to its physical length.

Tapered Winding - Alternative name for a complementary winding.

Temperature Coefficient - Variation of output with temperature often expressed in percent per ^{o}C.

Three Section Winding - LVDT winding in which the primary is in the centre with secondaries symmetrically either side.

1. INTRODUCTION

1.1 The Requirement for Windings

1.1.1 The Measurement of Distance

The accurate determination of displacement is one of the most common measurements made in modern engineering. In the majority of cases the result of this displacement sensing is required as an electrical signal which can be used for control, storage or processing. Hence there is an obvious need for devices to convert a displacement into a corresponding electrical signal. A wide range of displacement transducers have been developed to meet this need.

The features and merits of many electromechanical displacement transducers have been discussed and compared by a number of authors: New (1989), Neubert (1975), Sydenham (1972), Garrett (1979) and Small (1988). None have suggested one transducer is "the best", but have highlighted advantages and limitations of each.

For measurement of displacements from microns up to about one metre electromagnetic transducers have much to recommend them. This is particularly true in harsh environments and where high resolution or frictionless movement is required. The main type of electromagnetic transducer for displacement measurement is the inductive position transducer.

1.1.2 Inductive Position Transducers

There are several types of inductive position transducer. Sydenham (1972) stated that there are three main types : the linear variable differential transformer (LVDT), the solenoid push-pull winding transducer and the variable airgap reluctance transducer. A fourth type not mentioned by Sydenham but discussed by Carden (1988), McKenzie (1988) and New (1989) is perhaps the simplest in its basic form: the single coil variable inductance transducer.

The single coil variable inductance transducer (figure 1.1) has a coil which may be

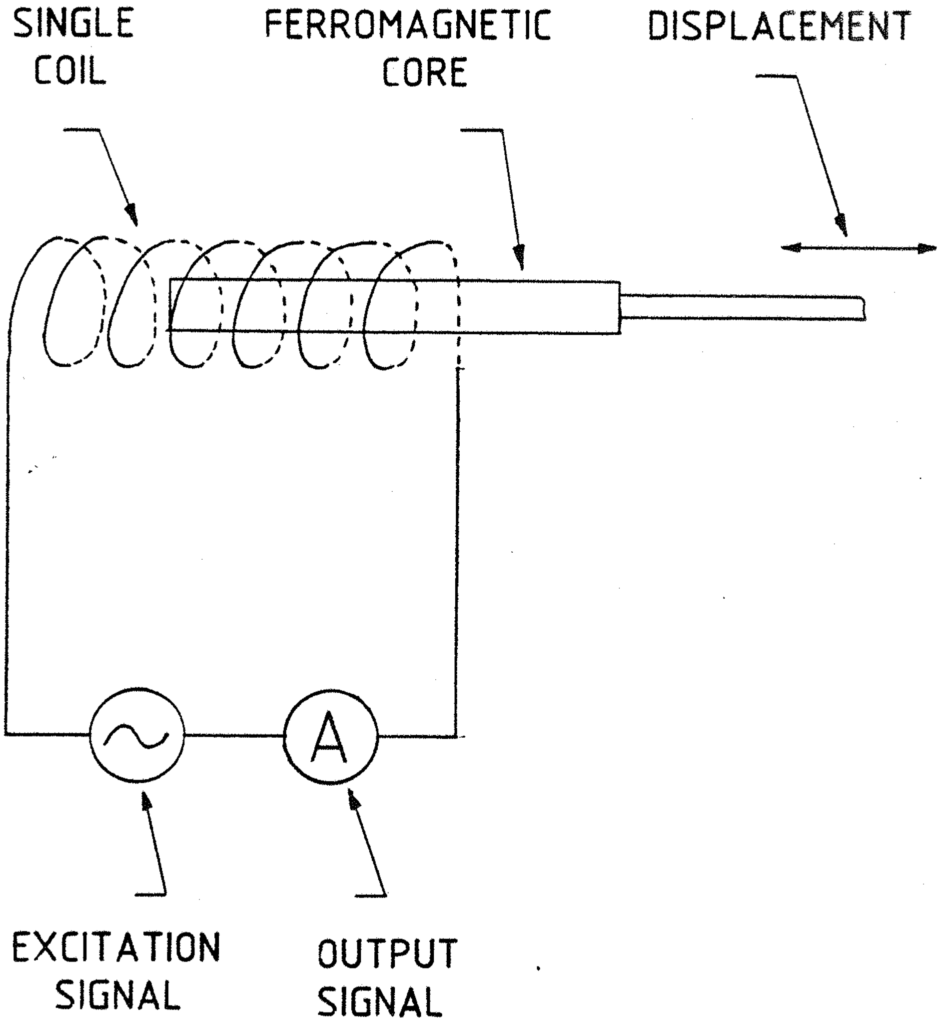

FIGURE 1.1 SINGLE COIL VARIABLE INDUCTANCE TRANSDUCER

one layer or several and has a ferromagnetic core free to move within the coil. As the core moves into the coil its inductance will increase. An AC signal is applied across the coil and the current is measured. As the core is moved into the coil the inductance increases and hence the current decreases. This variation is proportional to distance moved. The linearity of change in current against distance is worse at the ends. Several authors have discussed methods of linearising the output by shaping the coil (Heddle (1952), Carden (1988) and McKenzie (1988)). This shaping involves adding extra turns at the coil ends to improve the ~~non-linear~~ LINEARITY behaviour. Another problem is that the transducer can have large variations with temperature although circuits have been developed to compensate for this.

The variable airgap reluctance transducer senses variations in the airgap in a magnetic circuit. This circuit usually consists of an E shaped core with a sensing coil and a moving ferromagnetic plate (figure 1.2). Current through the sensing coil is measured as for the single coil variable inductance transducer. The current will vary as the reluctance of the magnetic circuit varies. This configuration is highly sensitive to small changes in airgap, but the output is non-linear with distance and is also sensitive to changes in the properties (uniformity) of the ferro-magnetic plate.

The solenoidal push-pull winding transducer is often known as an inductive half bridge displacement sensor or a linear variable inductance transducer (LVIT). A device of this type of design has been described by Moore (1988). The principle of operation is similar to the single coil variable inductance transducer, but the LVIT has two similar coils. The ferromagnetic core moves within the two coils from its null position. At null the core is equidistant into either coil (figure 1.3). Movement of the core causes the inductance of one coil to increase and the other to decrease by a similar amount. This means the transducer has a push-pull or differential output and so is less susceptible to external variations such as in temperature and will always have a constant load on the supply. This is not the case with single coil inductance

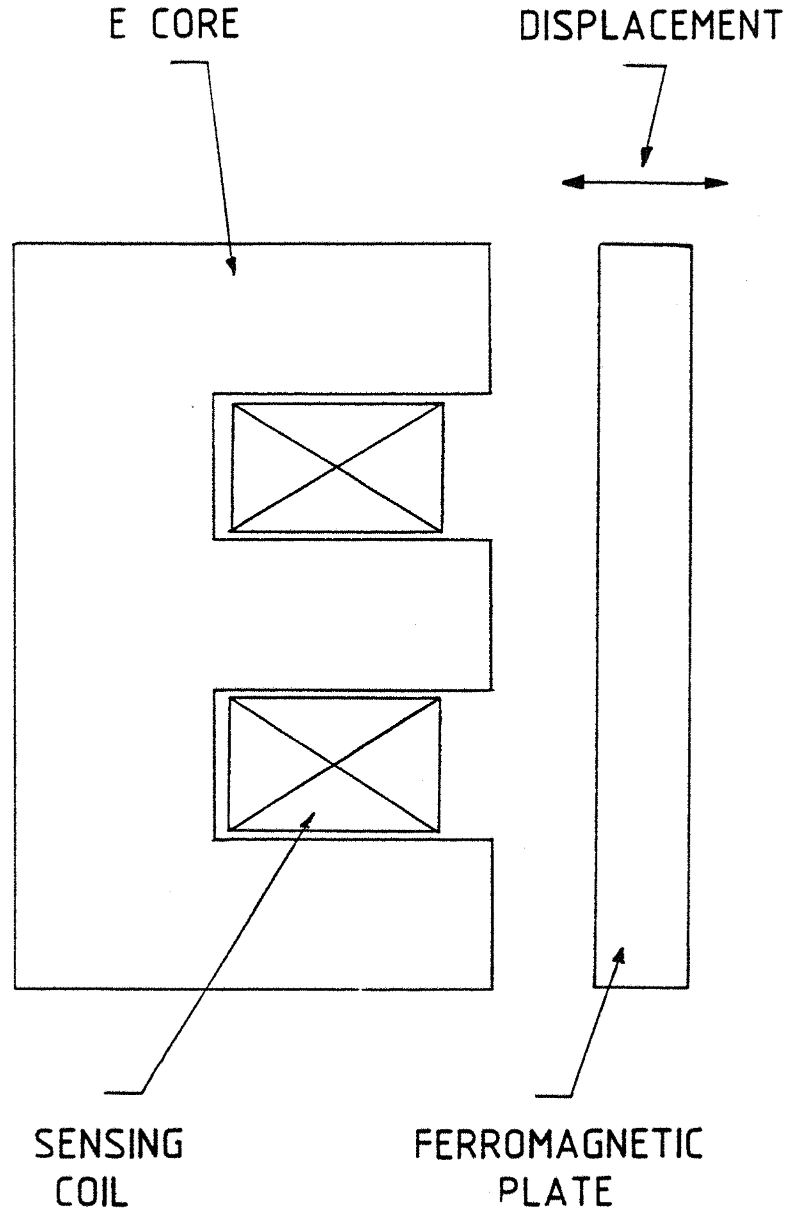

FIGURE 1.2 VARIABLE AIRGAP RELUCTANCE TRANSDUCER

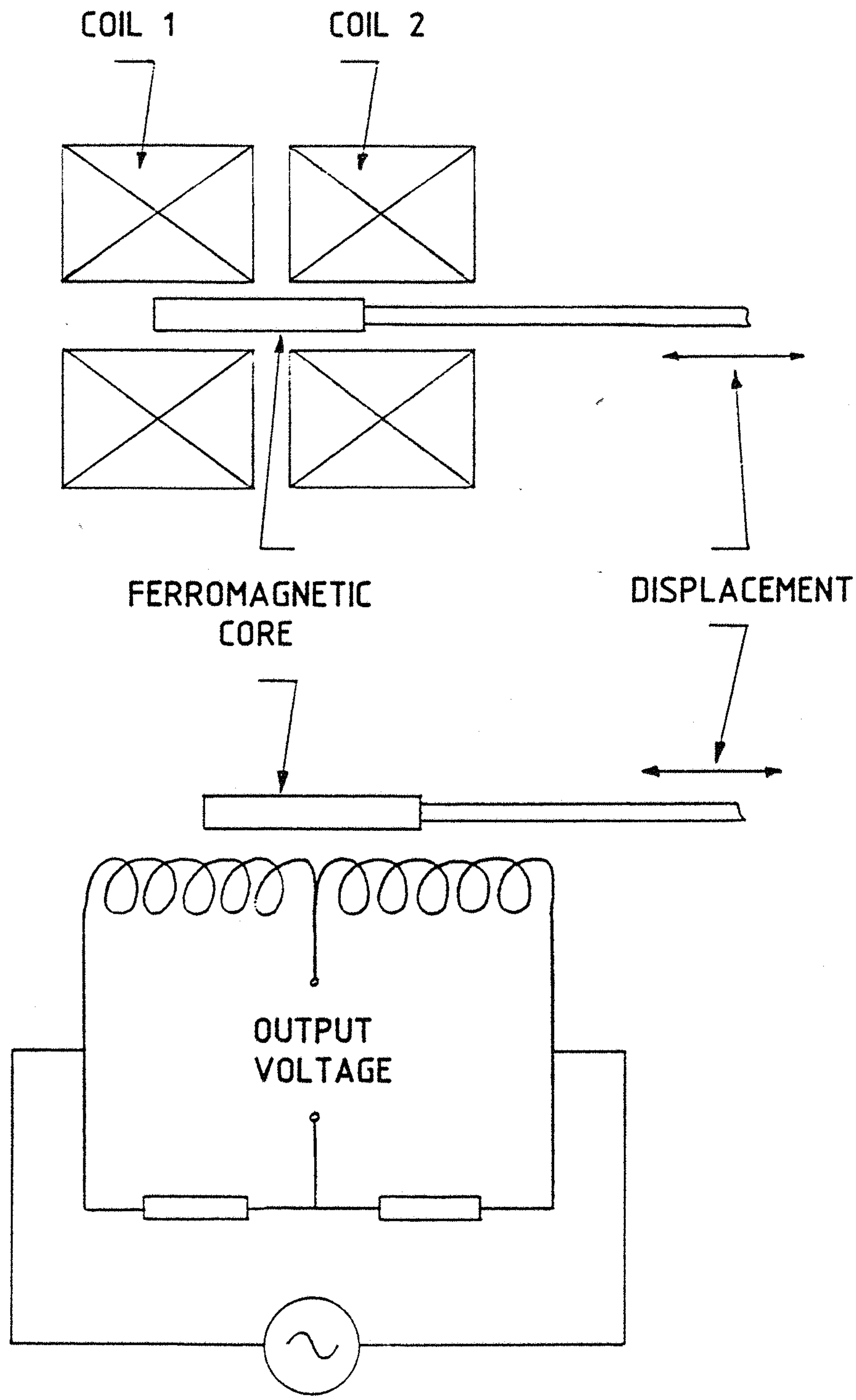

FIGURE 1.3 LINEAR VARIABLE INDUCTIVE TRANSDUCER - LAYOUT AND AC BRIDGE OPERATION

transducers.

The LVIT is normally used as one half of an AC bridge with two precision resistors forming the other half (figure 1.3). Movement of the core from the central null position causes an imbalance in the bridge giving an output signal directly proportional to distance moved.

The LVDT consists of a primary coil and two secondary coils which are coaxial with the primary and symmetrical with each other about the LVDT central null position. As with the LVDT a ferromagnetic core moves along the middle of the coils (figure 1.4).

The primary coil is fed with an AC excitation signal which generates a voltage in the secondaries because of the magnetic coupling of the core. As the core moves the amount of coupling with each secondary changes differentially. Hence the voltage across the secondaries changes. The secondaries are connected in phase opposition (figure 1.4) so the output is the difference of the two voltages. Ideally this voltage is directly proportional to core displacement. This proportionality relies on the magnetic field being uniformly distributed. Secondary coil shaping as mentioned earlier is often used to help achieve this required uniformity.

1.1.3 LVDT Characteristics and Selection Factors

According to Small (1988) "the LVDT is probably the best known device for precision linear displacement measurement" and Schaevitz (1975) states "the LVDT is the optimum transducer element for thousands of industrial, military and aerospace applications."

The reason for the LVDT's popularity is its characteristics which can satisfy a wide range of requirements. These characteristics are discussed by Herceg (1976) and Alloca and Stuart (1984) and include:

Core movement is frictionless giving excellent life.

Core and coil are separate.

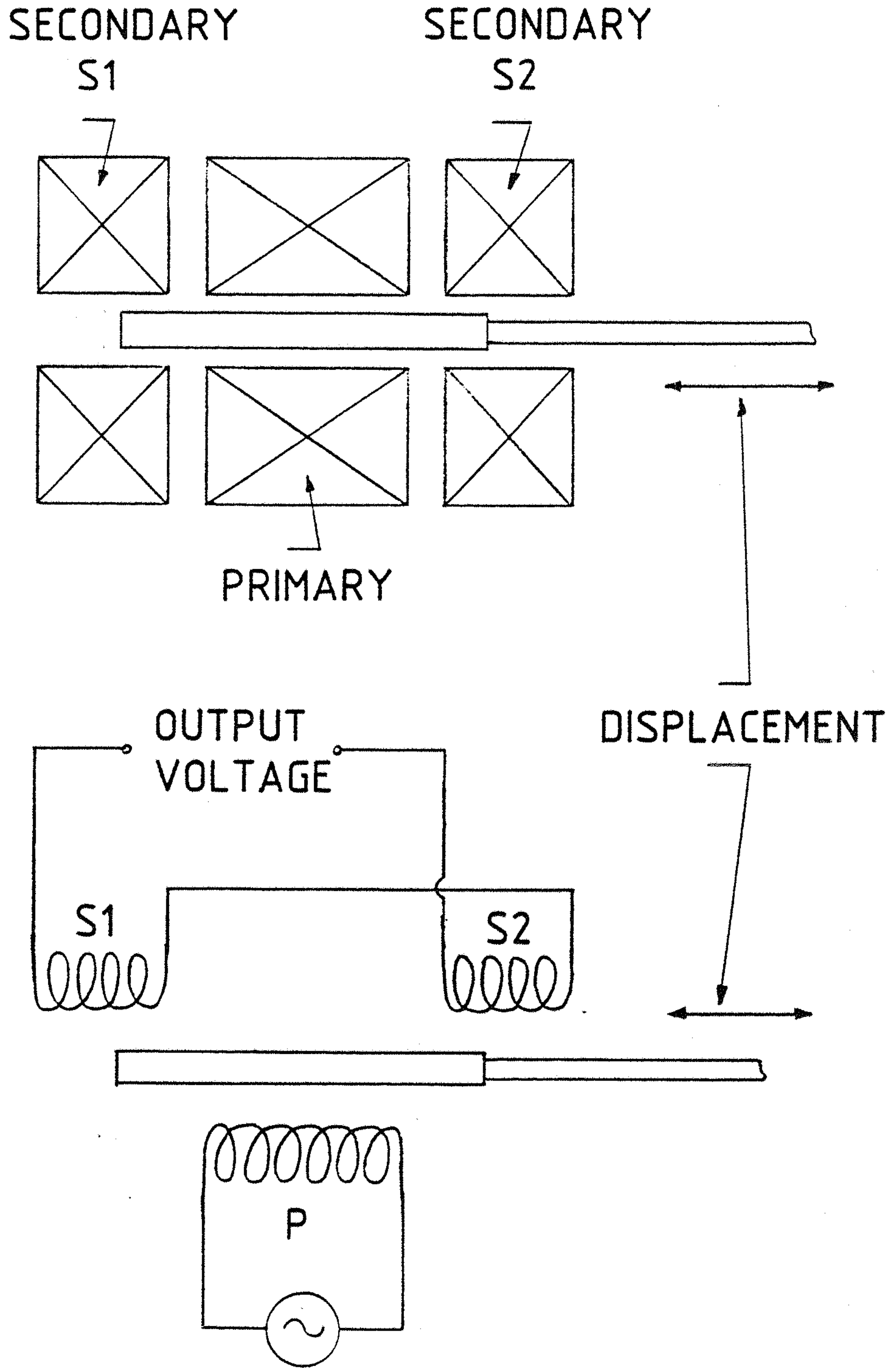

FIGURE 1.4 LINEAR VARIABLE DIFFERENTIAL TRANSFORMER - LAYOUT AND CONNECTIONS

Resistance to hostile environments is excellent (coil is easily hermetically sealed).

Resolution is infinite.

Linearity is good (+/-0.25% of total stroke easily achieved).

Temperature coefficient is good (<100ppm/oC easily achieved).

Output is isolated from input.

The disadvantages must also be considered and include:

Relatively high cost.

Poor stroke to length ratio.

Relatively high input power.

Many of these characteristics are shared by the LVIT, as may be expected by their likeness in construction and operation. The main advantage of the LVDT is its greater versatility of design. In particular several different coil configurations may be used as discussed later. This means that better linearities, temperature coefficients and stroke to length ratios can usually be achieved.

When selecting a displacement transducer all the advantages and disadvantages must be considered for the required application. The LVDTs characteristics must be compared with other transducers which may be suitable (New(1989), Neubert (1975), Sydenham (1972), and Garrett (1979)) in order to select the best transducer for the job.

If an LVDT is selected as the most suitable transducer the values required of the following must be considered:

Stroke length

Linearity

Sensitivity

Input voltage, current and frequency

Load impedance

Phase angle

Space envelope

Weight

Environment - temperature range and coefficient

vibration

humidity

chemical attack etc.

The LVDT design can then begin. The problem of achieving the values selected is normally solved largely by trial and error, drawing on an engineer's experience of similar LVDTs and a few empirical rules. These methods will be discussed in a later section.

1.1.4 The Parts of the LVDT

As described earlier an LVDT consists of a primary winding, two secondary windings which may be in one of a number of configurations and a magnetic core. The windings are usually wound on a bobbin of non-magnetic material which is normally also non-conductive. In some designs the windings are produced such that they are self supporting in which case only a central tube is needed onto which the windings are fitted. In almost all practical LVDT designs the winding assembly will be within a magnetic screen to prevent flux leakage. This will increase the output sensitivity and can improve linearity. Screening is also important to give immunity to interference from external electromagnetic sources. Finally the LVDT will be housed in a case of some non-magnetic material and suitable output cable attached.

The selection factors listed in the previous section are controlled by the design of the LVDT parts briefly discussed here. The design and manufacture of the winding has a large effect on the finished LVDT and hence must be carefully considered. Many factors in the winding design are considered and adjusted to produce an LVDT with the required selection factor values.

1.1.4.1 Choice of Winding Type

The main types of LVDT winding are the three section winding, the graded winding and the complimentary or tapered winding. All three types are described in Appendix A. Other winding configurations have been proposed (Brosh (1961), Herceg(1976)) but almost all modern LVDTs use one of the three main winding configurations.

The type of winding chosen depends on the stroke length and the stroke to length ratio required of the winding. In LVDTs with a short stroke length (< about 25mm) and low stroke to length ratios (< about 0.3) a three section winding (see appendix A) is usually the best choice. The three section winding is the easiest to wind and being the simplest is the most straightforward to develop.

For LVDTs with longer stroke lengths, or high stroke to length ratios an alternative design is usually necessary to obtain acceptable non-linearity over the entire stroke. Small (1988) suggests that for good linearity with long stroke lengths a graded winding should be used. Herceg (1976) states that a high stroke to length ratio can be achieved effectively using a tapered winding. A stroke length of 0.8 can be achieved for a tapered winding compared to 0.3 typically achieved for a three section LVDT with a similar non-linearity value (typically +/-0.5%).

Both the tapered and graded winding can achieve long stroke lengths (upto two metres) and high stroke to length ratios (upto 0.8). The linearity of the graded winding can be optimized by altering the contour of the secondaries. The tapered winding must be used when a constant secondary sum voltage is required. This usually arises when a ratiometric output is used, but may also occur when certain error detection systems are to be used with the LVDT.

1.2 The Importance of Winding Quality

The quality of the winding is one of the most important aspects of LVDT production which affects the finished unit. Several factors are involved in obtaining an ideal winding. The most important are: obtaining a correct turns count; neatly packing the wire in coils (see appendix B); avoiding damage to the insulation and the wire. If these criteria for an ideal winding are not sufficiently well adhered to winding quality will be low and the required LVDT characteristics will not be achieved. For example, if the primary turns count is wrong the sensitivity, primary impedance and resistance and input current will all change from the required values and may be unacceptable.

To satisfy the criteria for an ideal winding it is necessary to have a suitable winding system and use the correct winding techniques.

1.3 Winding Technique

Winding technique can be divided into two areas; setting up the winding system and performing necessary alterations to the system whilst in operation. The area of winding technique requiring most attention will depend to a large extent on the degree of automation of the winding system.

In a mostly manual system in which wire is dispersed over the coil by hand most attention is required whilst in operation. The set up may involve only positioning of wire and bobbin and correct setting of wire tension. However once the system is winding constant care and attention is required by the operator to ensure turns are positioned correctly and the winding is stopped at the current turns count so as to produce a sufficiently accurate winding.

In a more automated system in which wire is positioned automatically and the spindle stopped automatically at the correct turns count, more attention will be required during set up. As with the manual system the wire and bobbin must be positioned and the wire tensioned. The positioning will be more critical because it is more difficult to correct set up errors whilst winding. One problem with an automated system is errors which build up during winding, for example in axial wire position. All the parameters necessary for the system to position the wire accurately must be input. This will include start position, wire size, bobbin width and information on the type of winding required. Once the automatic system is running far less operator intervention is required and the operator may even be free to perform other jobs, such as setting up another machine.

An important part of winding technique is setting the correct tension. Several authors have noted the importance of using the correct tension: Brown (1987) states that dereeling and tensioning of wire must be carefully monitored. Erickson (1980) suggests that adjusting the wire tension is often all that is needed to correct a seemingly unrelated problem. Stevens (1978) goes as far as to suggest that perhaps 50% of all coil winding problems are tension problems and goes on to say that a more stable uniform winding is achieved by proper selection of tension and spindle speed.

In spite of its importance little guidance is available on what is the correct tension to use in a given application. Manufacturers publish tables showing the maximum permissible tension at which copper wire of given diameters should be wound (Aumman technical data). This is the tension at which permanent deformation of the wire starts to occur. Usually best results are obtained at a somewhat lower tension than this. The values chosen are largely the result of experience.

With any winding system the winding technique used will be important. All systems require tension to be set correctly. Set up is most critical with automatic machines while manual machines rely heavily on operator skill whilst winding. This must be considered when selecting a winding system.

1.4 Winding Systems

To achieve the required winding quality a winding system must be developed to achieve, satisfactorily, all the steps in the production of a winding. Mitchell (1983) stated that to wind a coil requires a mechanical system; a feedback system and a control system. Lockwood and Wood (1988) suggested that a motion control system, such as a winding system, typically includes sensors to measure critical parameters, a local supervisory control system and a motor drive system and driven load.

The mechanical system must have a bobbin spindle, a spindle drive, a means of guiding the wire across the bobbin and a device to unspool and tension the wire.

The measurement system measures the turns count, wire guide position and wire tension.

The control system must use information from the measurement system to move and reverse the wire guide and stop the spindle when the correct turns count is reached. It should be noted that the operator may form part or all of the measurement and control systems.

The parts required of the winding system can be put together in a block diagram form to show a generalized winding system (figure 1.5). Further complication may be added by peripheral devices such as bobbin loaders and unloaders, but all the elements necessary to achieve a wound bobbin are shown in figure 1.5.

1.5 Types of Winding System

According to Mitchell (1983) the simplest coil winding system would consist of a hand cranked spindle with a mechanical counter. The operator hand feeds wire onto the mandrel and controls its pitch and tension until the correct number of turns have been wound. In this case many of the elements in figure 1.5 are operator performed. The system elements can be achieved in many other ways to form a complete winding system, such that the number of possible winding systems is potentially vast. However the systems can be grouped under broad types.

Franke (1988) discusses the basic types of machine used by the coil winding industry. The following divisions are made:

Bobbin winder

Fly winder

Stick winder

Toroidal winder.

Bobbin winders are the most common type of winder. The wire is distributed along a winding bobbin between two flanges as the bobbin is rotated on a spindle (figure 1.6). The wire is normally placed side by side, layer on layer with varying degrees of accuracy to form the coil. Fly winders form the majority of other types of winder.

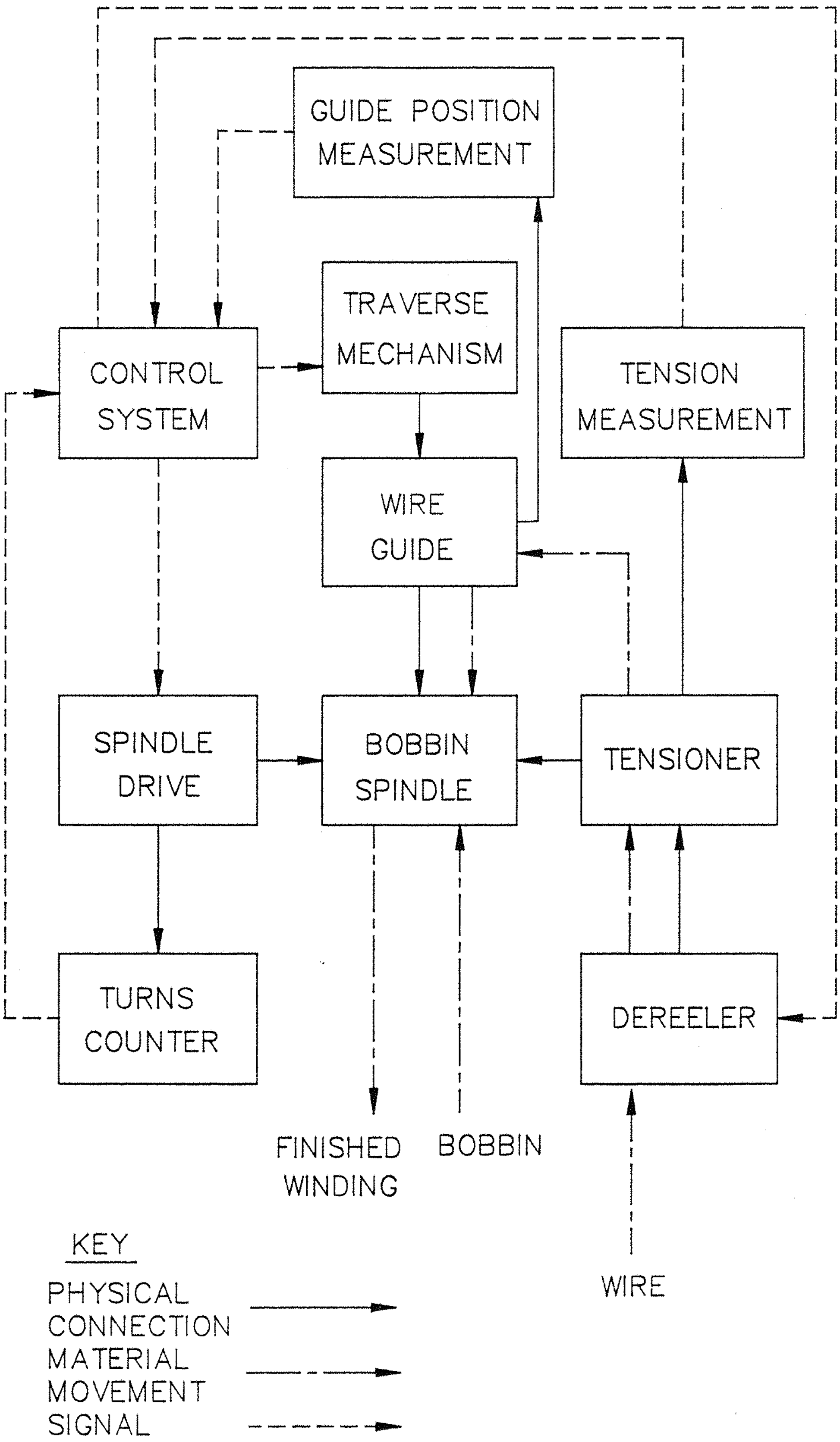

FIGURE 1.5 : BLOCK DIAGRAM OF SIMPLE WINDING SYSTEM

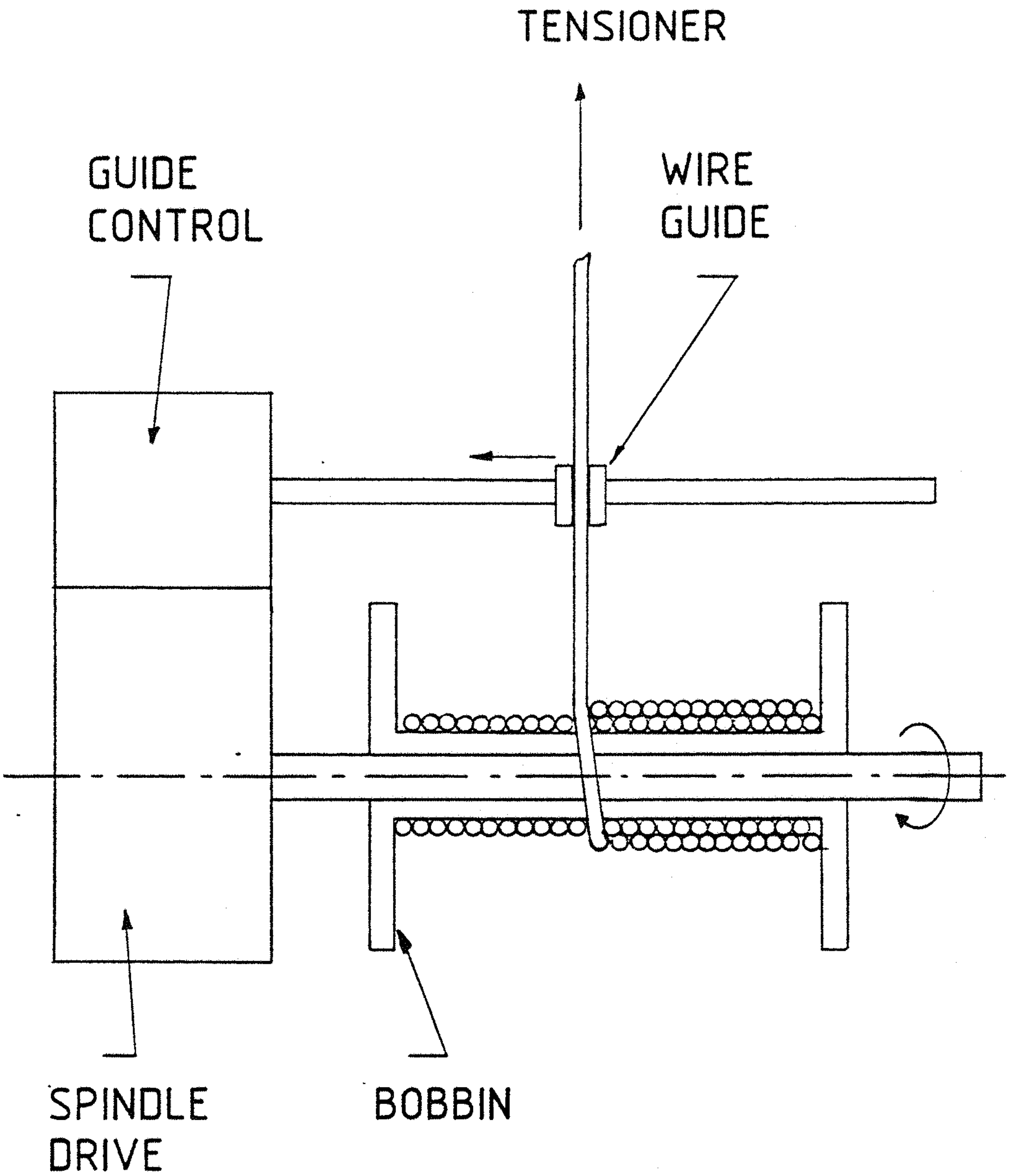

FIGURE 1.6 BOBBIN WINDER

The mandrel holding the bobbin or former remains stationary and wire is distributed by a rotating flyer mechanism attached to the main spindle (figure 1.7).

Stick winders operate in a similar manner to a bobbin winder, but the rotating spindle has a long tube or stick mounted on it. The wire is distributed along its length and the resulting long winding is insulated as required and cut to form individual coils.

Toroidal winders are specifically designed to wind toroidal type windings. The former for these is ring shaped and winding is usually achieved by using a wire shuttle which is guided through the ring and round the outside to form a turn.

Apart from the specialized toroidal winder further diversions can be made into:

Front loading or side loading

Single or multiple bobbin winding

Front loading bobbins are usually easier and quicker for bobbin changeover and securing tails as the bobbin end faces the operator, but they cannot handle long bobbins so well as there is no facility for a tailstock.

Multiple bobbin winding may be achieved in two ways. One method is to produce a system with several spindles having their axes parallel. The other is to place several bobbins side by side on the same spindle axis. In both cases the feed is controlled using a single feed controller with a wire guide for each bobbin. Both systems produce a low accuracy of wire positioning because there is no way of allowing for differences in bobbin or wire dimensions for bobbins being wound simultaneously.

The level of automation was divided by Franke (1988) into:

Manual - machines where the operater controls all functions.

Semi-automatic - some manual operations such as loading / unloading.

Fully automatic - no operator - occasional supervision.

Valente and Manning (1987) categorise machines by complexity and the level of automation, but make the point that it is difficult to make sharp divisions between various types of machine and their uses. The groupings made are:

Basic bench winders

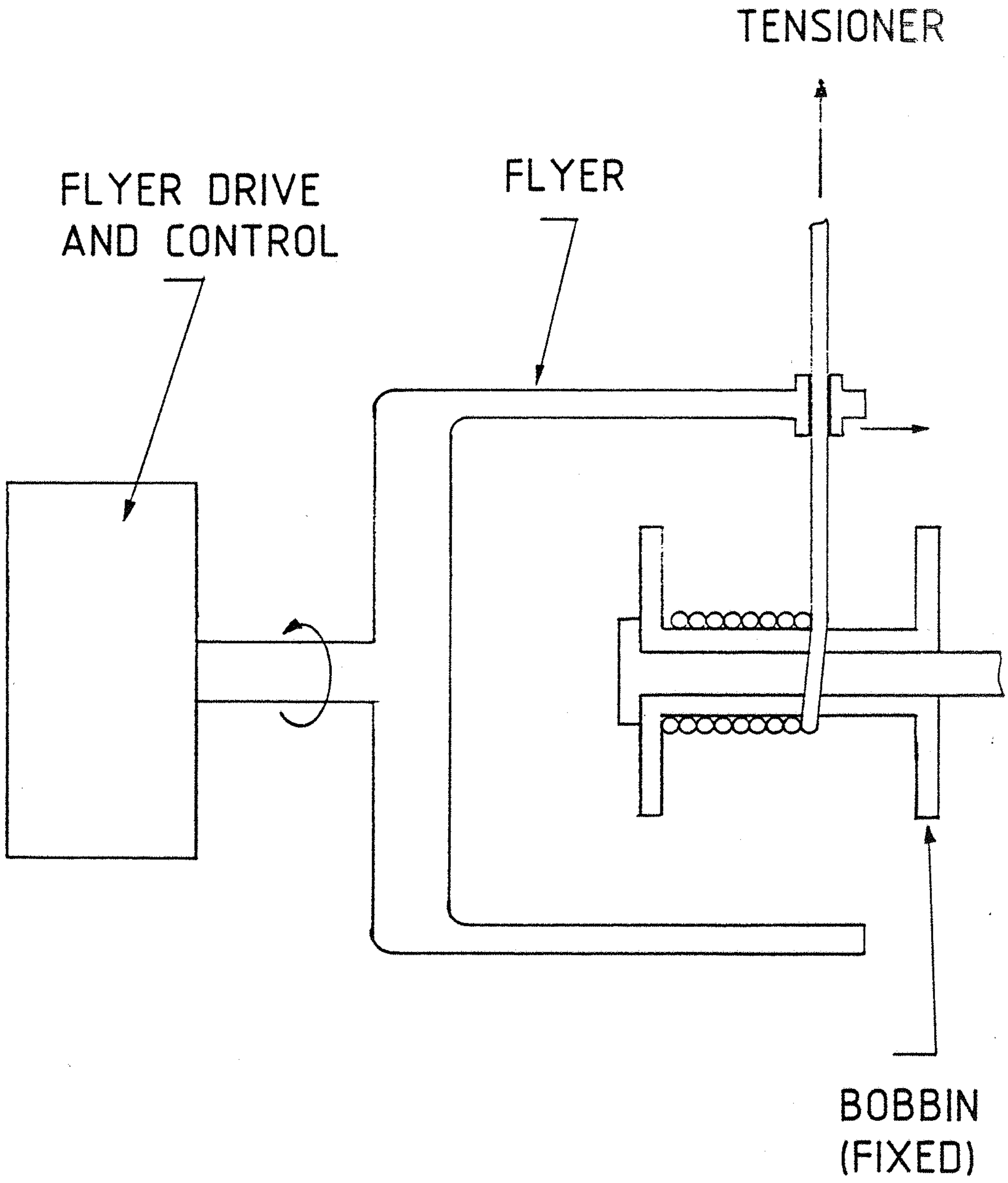

FIGURE 1.7 FLY WINDER

Basic programmable winding machines

Semi-automatic / sophisticated programmable machines

Semi-automatic systems and modular mini-systems

Fully automatic coil manufacturing systems.

1.6 Choice of System Elements

All the elements which build up to form the complete winding system must be chosen with the aim of achieving winding of the required quality for the best cost per winding. To produce windings, of the required reliability, the elements must be chosen to wind accurately enough to achieve a finished winding which has the correct output characteristics for all the coil sizes used. Producing windings at the best cost means the cost and winding rate of the system must be considered against the volume of windings needed at present and in the future.

Erickson (1980) has attempted to give some general guidelines on equipment selection considerations. He suggests that the chief criterion in selecting a coil winder is the total cost per coil plus delivery time. However it is pointed out that no one machine possesses maximum efficiency over the wide range of winding specifications which exist. The first basic decision to make involves choosing the most suitable general type of winding system. Another important area of decision which is discussed is the type of control system to use and the degree of its sophistication In Erickson (1980) it is recommended that high levels of sophistication be approached with caution as they can lead to poor reliability and excessive downtime.

From this discussion it can be seen that the choice of the correct winding system is largely one of compromise. The needs of achieving high accuracy must be balanced against cost and the possibility of more downtime. Each element of the complete winding system must be considered with care. However, the elements cannot be considered completely seperately and the effect the solution, used for one element, will have on the rest of the system must be thought through.

1.7 Summary of the Design Need

In this introduction the following points have made:

-Devices to measure displacement and provide information as an electrical signal are widely needed.

-Electromagnetic transducers are an effective and widely used solution to this need.

-The characteristics of the LVDT make it a good choice of displacement transducer in many applications.

-To achieve the desired LVDT characteristics a high quality winding is required.

Hence the need for a winding system to produce accurate windings for use in LVDTs and similar electromagnetic transducers has been established. The introduction then covered the following:

-Categorisation of winding systems.

-Generalized winding system with all necessary elements.

-Considerations to be made when elements are selected.

2. TECHNICAL REVIEW OF LVDTS

2.1 LVDT Users and Uses

In the introduction it was stated that the LVDT is used in many industrial, military and aerospace applications. There are many additions which could be made to this list of application areas including laboratory, medical, automotive and anywhere else where position is measured over a range of 0.25mm to 2m.

Different users choose to use LVDTs for different reasons, but all have a particular need for one of its characteristics. These were briefly discussed in section 1.1.3.

In an aerospace application the LVDT is normally chosen because of the core and coil separation and frictionless core movement. This means the coil can be completely sealed and the unit has excellent life and reliability. Herceg (1976) states that with careful design and assembly LVDTs can be constructed which exceed two million hours MTBF (mean time between failures).

An example of an application where this type of reliability would be essential would be measuring flap positions, for a control system, in a fly by wire aircraft. In this case a failure could be fatal.

In a laboratory application the reasons for choice of an LVDT will most likely be its excellent accuracy and repeatability. An example of a laboratory application discussed by Schaevitz (1975) was for a rupture testing device. In this device an LVDT is mounted alongside the specimen under test so as to measure the elongation as it is pulled at either end (figure 2.1). The features of the LVDT making it ideal for this application are its infinite resolution and its stable and repeatable null, large output over short stroke lengths and the total separation of core and coil. This separation means that if the specimen should rupture suddenly no damage would be done to the LVDT.

Industrial applications are widely varied but a typical example might be measuring a moving part of a CNC machine such as a tool arm. This would be the measurement

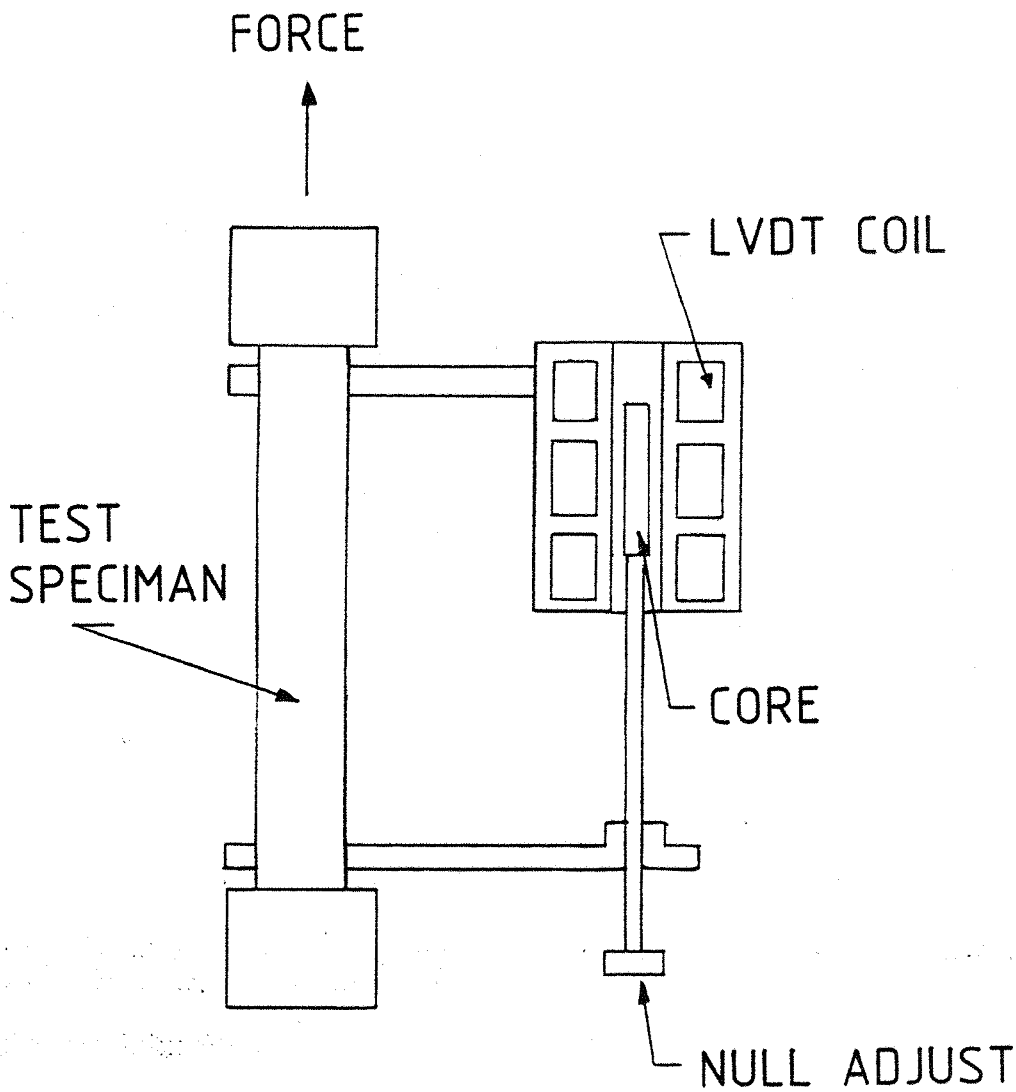

FIGURE 2.1 RUPTURE TEST DEVICE

part of a closed loop control system to guide the tool to the correct position. In this case the features of the LVDT which are desirable might be its hermetic sealing giving it the ability to operate in hostile environments eg. high temperature and chemical attack.

2.2 Input/Output Characteristics

All LVDTs have a set of input and output characteristics and properties to which they are designed. The most important of these are shown in figure 2.2. The values of these characteristics are chosen to meet the requirements of the system in which they will be used. Figure 2.3 shows typical values for some characteristics which might be chosen for the three LVDT applications described in section 2.1. The ability to satisfy this wide range of input / output characteristics is the reason the LVDT is so widely used.

2.3 Design Variables

Achieving the required input / output characteristics discussed in section 2.2 requires the correct choice of the LVDTs design variables. The most important LVDT design variables are listed in figure 2.4. The correct selection of these design parameters normally relies heavily on an engineer's experience of similar LVDTs and the use of a few empirical rules.

Some values of design variables which are fairly typical are given in figure 2.5 for the three applications discussed earlier. In a real design these values would have been selected such that the required input / output characteristics in figure 2.3 were obtained.

2.4 LVDT Design

Having identified the important input / output characteristics and the design variables the problem now is how to select the latter to achieve the required values of the former. As mentioned earlier this is largely a matter for experiment, but with a good understanding of the principles of LVDT operation and design the experimenting

INPUT / OUTPUT CHARACTERISTICS

Linear Range

Output Current

Output Sensitivity

Non-Linearity

Primary Impedance

Secondary Impedance

Primary Resistance

Secondary Resistance

Space Envelope

Weight

Phase Angle

Null Voltage

ENVIRONMENTAL CHARACTERISTICS

Temperature Range

Temperature Coefficient

Pressure Range

Humidity

Figure 2.2 Main LVDT input / output characteristics and properties.

CHARACTERISTIC	APPLICATION		
	AEROSPACE Flap Position	LABORATORY Rupture Testing	INDUSTRIAL CNC Tool Position
Linear Range	+/-25mm	+/-5mm	+/-100mm
Input Current	<10mA	<50mA	<50mA
Output Sensitivity	0.01V/V/mm	0.1V/V/mm	0.01V/V/mm
Non-Linearity	+/-0.25%	+/-0.1%	+/-0.5%
Phase Angle	$<5^{o}$	$<5^{o}$	$<10^{o}$
Null Voltage	<10mV	<5mV	<20mV
Space Envelope (diameter x length)	15mmx100mm	30mmx100mm	30mmx350mm
Weight	<0.05Kg	<0.1Kg	<0.5Kg
Temperature Range	-40 to 150°C	0 to 40°C	-10 to 150°C
Temperature Coefficient	100ppm/°C	200ppm/°C	200ppm/°C

Figure 2.3 Some typical values for the most important characteristics for three LVDT applications.

Winding Configuration

Input Frequency

Input Voltage

Wire Material

Wire Diameter

Enamel Material

Axial Length of Primary

Axial Length of Secondary

Bobbin Diameter

Number of Primary Turns

Number of Secondary Turns

Core Length

Core Diameter

Figure 2.4 Some of the more Significant LVDT Design Variables.

DESIGN VARIABLE	APPLICATION		
	AEROSPACE Flap Position	LABORATORY Rupture Testing	INDUSTRIAL CNC Tool Position
Winding Configuration	Complimentary	3 Section	Contour
Input Frequency	800Hz	10KHz	5KHz
Input Voltage	26V	10V	10V
Wire Material	Copper	Copper	Copper
Wire Diameter	0.1mm	0.14mm	0.14mm
Enamel Material	Polyimide	Polyester	Polyimide
Axial Length of Primary	80mm	15mm	300mm
Axial Length of Secondary	10 x 8mm	15mm	150mm
Bobbin Diameter	15mm	15mm	30mm
Number of Primary Turns	3000	1000	5000
Number of Secondary Turns	5000	2000	1000
Core Length	40mm	20mm	60mm
Core Diameter	3mm	3mm	8mm

Figure 2.5 Some Typical Design Variables for Three LVDT Applications.

necessary can be minimized. This is important as the production of prototype LVDT windings and cores is time consuming and costly.

2.4.1 Achieving the Required Electrical Characteristics

The LVDT can be considered as being similar to an ordinary transformer but with two secondaries and a comparatively poor variable magnetic coupling between primary and secondaries. From this simple consideration an idea of how some input / output characteristics will be altered by the design variables can be developed.

For instance output sensitivity will be affected by the numbers of primary and secondary turns and core size (magnetic coupling). Unfortunately the way one affects the other is not as predictable as with an ordinary transformer. However directions of change can be predicted:- increasing secondary turns or increasing the core length will increase the output sensitivity.

By similar considerations of the LVDTs operation a picture can be built up of which design variables need to be changed and in what directions to move towards the desired input / output characteristics. For example Patranibis (1976) considered an equivalent circuit for an LVDT to devise an equation for the phase angle. It was shown that

$$\text{Phase angle} = 90^{\circ} - \tan^{-1} w P - \tan^{-1} w S$$

where P = Lp / Rp,

S = Ls / (Rs + Rm)

Lp = primary inductance,

Ls = secondary inductance,

Rp = primary resistance,

Rs = secondary resistance,

Rm = load resistance

and w = 2 x Pi x frequency.

Experiments at Penny and Giles showed this equation was useful for deciding which parameters could be altered to obtain the desired phase angle. It was difficult to predict actual quantities because the unpredictable amount of core coupling makes accurate inductance calculations difficult.

2.4.2 Achieving the Required Environmental Characteristics

For many of the environmental characteristics the choice of design variables is similar to most other instrumentation. It is based on the choice of the correct materials for the environment and the best package. As mentioned earlier, the core and coil separation of the LVDT makes it ideal for many environments. The coil can be hermetically sealed in a non magnetic stainless steel for use in high humidity, pressures (to several thousand psi) and under attack by various chemicals.

Operating temperatures up to 200 ^{o}C are easily attained using standard high temperature enamelled copper and bobbins of high temperature plastic. With the use of more specialized materials the limiting factor becomes the temperature at which the cores magnetic properties change. Herceg (1976) describes an LVDT with an operating temperature of 600 ^{o}C.

2.5 Mathematical Models for LVDT Design

Several efforts have been made to model an LVDT to develop expressions which can be used to predict values for output voltage. One of the earliest attempts was by Atkinson and Hynes (1954) who considered a basic three section LVDT. Assumptions were made that leakage flux was constant at the core surface within the secondaries and changed linearly across the primary and the output was proportional with frequency. The following equation for output voltage, e was derived:

$$e = K_1 X (1 - X^2/K_2),$$

where X is the core displacement,

K_1 was described as the transformer sensitivity

and $(1 - X^2/K_2)$ the coefficient of linearity.

The K coefficents were complicated expressions dependent on input frequency, input current, turns and core and winding dimensions. Some limited experimental confirmation of the theory was given in the paper. These results showed the theory was not good at frequencies above about 500 Hertz where sensitivity was no longer proportional to frequency as was assumed. This was attributed to eddy current losses which were not considered.

Work at Penny and Giles is mostly on LVDTs operating near or above one kilohertz meaning little direct use can be made of the Atkinson and Hynes model except as another aid to understanding the LVDTs operation.

Many of the more modern and more complex models use computer analysis. The majority of these methods use finite element analysis to model the flux within the LVDT in a similar way that stresses are modelled in structural engineering. Several papers on this subject have come from the department of Systems Science at City University including Abdullah et al (1977), Rahman (1979) and Rahman and Abdullah (1988). Although the computer packages available seem limited in scope and accuracy at present, it would be foolish of any LVDT manufacturer to ignore developments in this area. As Rahman and Abdullah (1988) state "essentially the computer can replace the costly and time consuming experimental trial and error methods presently employed for design and enhance the general understanding of the device operation."

3. A SYSTEMATIC DESIGN PROCEDURE

The work carried out described in this report has followed a systematic design procedure. This was done to ensure the problem was correctly and fully identified and all suitable solutions considered. This should ensure the optimum solution is obtained.

Several authors have suggested procedures for design which involve a series of steps leading to a design solution. Many of these are similar to that described by Pitts (1973) in which the design process is divided into five steps:

i) Establish requirement or need.

ii) Specification.

iii) Search for alternatives (speculation).

iv) Evaluation of the alternatives.

v) Synthesis to produce the finished solution.

Wallace and Hales (1987) describe the use of a more detailed design process which was translated from Pahl and Beitz (1984) from the German design process guidelines. The main steps in this procedure are similar to those above. However feedback arrows are included with the instructions "upgrade and improve" and "adapt the specification". These highlight the importance of improving work on previous steps in the light of what is learnt later. In describing the use of this procedure the authors stress the need for flexibility saying it should be used as a conceptual framework which may be adapted to suit the problem in hand.

In this work it was decided to follow the general steps described by Pitts using the feedback ideas of Pahl and Beitz and introducing more specialized design procedures such as selection tables and morphological methods whenever their use will help. This was thought to be the best way to maintain proper control over the work so that no potentially useful solutions were missed, but at the same time allow a flexible approach to be taken.

4. OJECTIVES

The main objective was to propose a design for the optimum winding system for the production of windings of a high enough quality for electromagnetic transducers and in particular LVDTs.

To achieve this main objective several other objectives were identified. In order to know what quality and physical parameters the windings required, it was essential to gain a full understanding of the design and functioning of the transducers to be produced using the system. This knowledge would be needed to write the winding system specification.

A step towards the desired optimum winding system would be to study the present winding system used by Penny and Giles. This would enable strengths and weaknesses to be identified and help generate ideas for possible solutions.

Other objectives to help generate ideas were to study the literature to identify how others had produced windings and more generally study similar production systems.

It was also decided to approach winding machine manufacturers and discuss the requirement. This would provide a further source of ideas.

Hence several paths were to be followed to achieve the main objective towards the design of the optimum winding system for electromagnetic transducers.

5. THE SPECIFICATION

5.1 The Need for a Specification

As stated by Pitts (1973) the specification is a listing of all parameters essential to the design. When a possible design solution is being considered it can be compared against the specification to see if all the essential features are present. If they are not, the possible solution must be modified or discarded.

Hence the specification is an essential tool in the design stage of the design process. It is used to compare different possible solutions such that the optimum solution is selected.

5.2 Constructing the Specification

The problem of constructing a suitable specification for a winding system can be divided into two parts. First, the parameters to be specified must be identified and second these parameters must be qualified. For some parameters this qualification would be a value eg. dimensions and for others which cannot be quantified, a brief description of the need is given eg. appearance.

5.2.1 Identifying Parameters

The first specification problem in identifying all the parameters was tackled by splitting the specification into smaller sections; many small problems are easier to solve than one big one. The main division was into functions and characteristics. The system functions were identified by careful consideration of the blocks on figure 1.5. Characteristics were identified by considering the design of the windings and discussion with staff at Penny and Giles. The parameters which required specifying were then identified for each function and characteristic.

The information was best represented on a tree diagram (figure 5.1). The use of the tree diagram aided identification of parameters because as it was constructed gaps in the specification were highlighted. The tree diagram shown

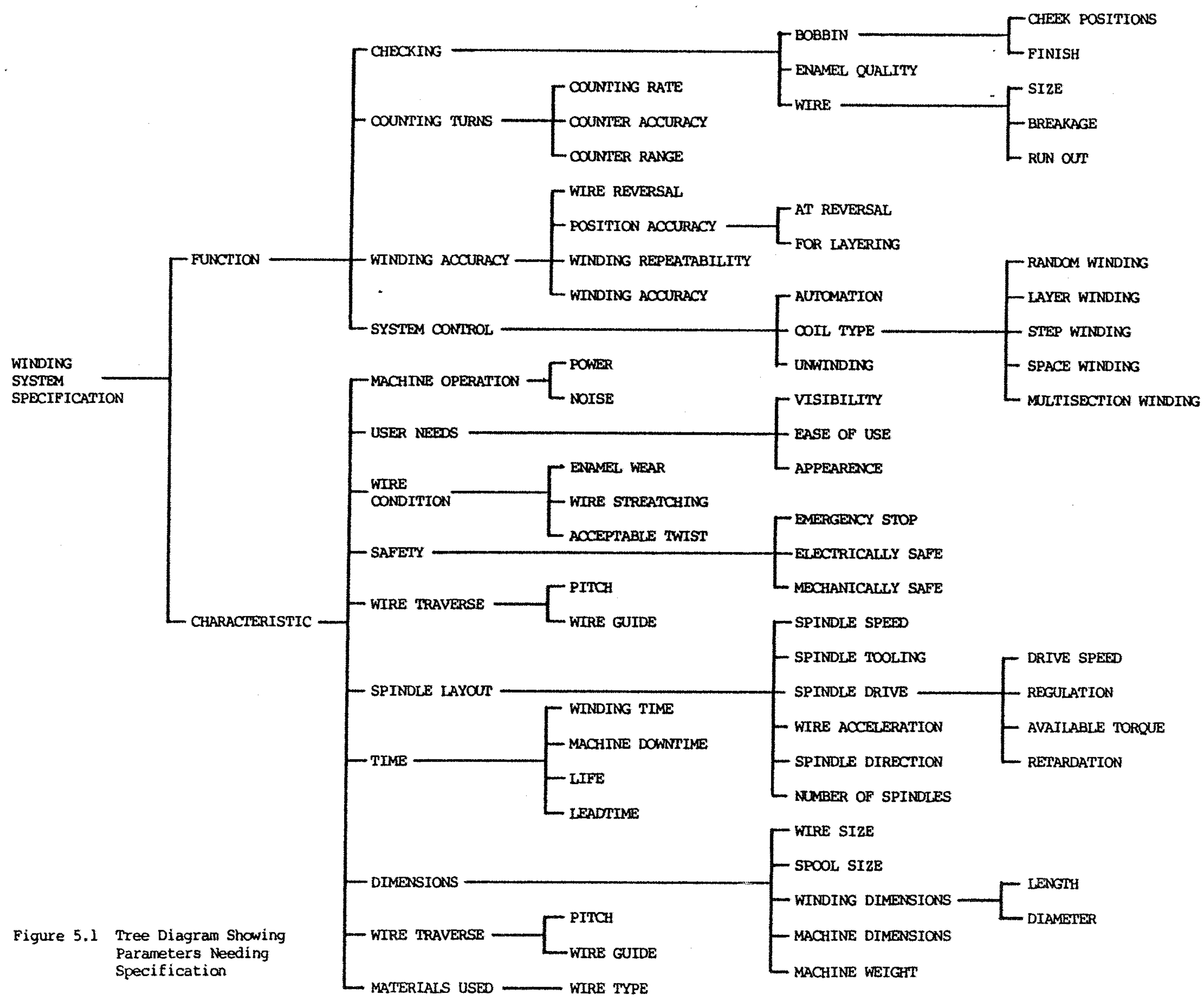

Figure 5.1 Tree Diagram Showing Parameters Needing Specification

in figure 5.1 is the result of several iterations in which parameters not initially identified came to light in later stages of the design process. These were then introduced at the tree diagram stage to produce as complete a specification as possible.

5.2.2 Qualifying Parameters

Having identified, as completely as possible, all the parameters to be specified (figure 5.1) the next stage is to qualify them. The qualifications must be chosen so that a system which satisfies them will wind LVDTs exactly as required. Hence a detailed knowledge of LVDTs and their winding, as discussed in the introduction, was essential. In addition it was necessary to discover the needs of all the people involved with winding.

Specifications from winding machine manufacturers were studied so that, where possible, the same conventions in specifying parameters were employed. It is worth noting that all the manufacturers specifications seen were incomplete.

5.3 The Specification List

The complete specification for a winding system to wind LVDTs of the quality manufactured at Penny and Giles follows. The specification is divided into sections corresponding to the branches of the specification tree diagram (figure 5.1). Appendix C shows the reasoning behind the selection of the qualifications given where this is not trivial or obvious.

5.4 Winding System Specification

Function

1. WINDING

1.1 Winding Accuracy	Layer winding with minimum of voids.
1.2 Wire Reversal	Wire must reverse accurately at bobbin cheeks.
1.3 Position Accuracy	
1.3.1 At Reversal	Position of turn being wound relative to nearest bobbin cheek must be known to +/-0.03mm.
1.3.2 For Layering	Position of wire guide relative to previous turn accurate to +0.00 / -0.05mm.
1.4 Winding Repeatability	Coils of identical specification to be visibly the same and to have matching dimensions and resistance to within +/-10% unless specified for that winding type.

2. SYSTEM CONTROL

2.1 Automation	The level of automation must be sufficient to achieve the required accuracy and diversity of winding types.
2.2 Unwinding	The machine should have the facility to unwind a coil or part thereof so that it can be reworked.
2.3 Coil Type	Must produce random winding, even layer winding, step windings, space winding and multisection windings.
2.3.1 Random Winding	Section filled to even level but with unlimited crossing of wire.
2.3.2 Layer Winding	Section filled to even layer with no crossing of wire within same layer and fewest possible voids.
2.3.3 Step Winding	Shortening of successive layers to defined length from bobbin cheek for up to 30 layers.
2.3.4 Space Winding	Even size gaps between successive turns in a layer.

2.3.5 Multisection Winding	Winding in successive sections or with sections missed. Upto 30 (required). Upto 100 (desired).

3. COUNTING THE TURNS

3.1 Counter Range	0 to 10000 turns. (clockwise and counterclockwise).
3.2 Counter Accuracy	+/-0.02 turns - following spindle direction.
3.3 Counting Rate	To count at the required spindle speed.

4. DEREELING

4.1 Dereeling Rate	1m/s maximum.

5. CHECKING

5.1 Wire breakage	Warning necessary if a breakage occurs.
5.2 Wire Run Out	Warning necessary when wire is about to run out.
5.3 Wire Size	Check for correct wire size loaded.
5.4 Bobbin Cheek Positions	Position of bobbin cheeks needs to be known for accurate layer winding.
5.5 Bobbin Finish	Bobbin must be clean and free from burrs.
5.6 Enamel Quality	To be no beading or other defects in the enamel.

<u>Characteristic</u>

6. COSTING

6.1 Investment	Capital outlay = £5000 to £20000 expected. Capital to be paid back over a period of 5 years. Cost of investment = £1000 to £4000 / year + interest = £750 to £3000 at 15%.
6.2 Running Cost	For present system:- Operator cost = £11000 / year (including supervision). Maintenance = £300 / year. Downtime cost = minimal (4 machines).

6.3 Cost / Winding	For present system:- Cost / hour = £7 + overheads. Winding time = 15 mins to 8 hrs (typical 1.5 hrs).
7. TIME	
7.1 Winding Time	To give improvement on present cost / winding. Expect <5 mins for simple windings. about 30 mins for complex windings.
7.2 Lead Time	Improve on present system.
7.3 System Downtime	There should be a total of < 1 week / year unplanned downtime.
7.4 Life	> 5 years.
8. WIRE TRAVERSE	
8.1 Wire Guide	Must guide wire accurately enough to achieve the required position accuracy.
8.2 Pitch	0.05 to 10mm. Should also have sideways wire motion without spindle rotation.
9. WIRE TENSION	
9.1 Tension Control	Selectable at the start and monitored during winding.
9.2 Tension Range	0.05 to 4N.
9.3 Tension Accuracy	+/-10% under steady running conditions.
10. SPINDLE LAYOUT	
10.1 Number of Spindles	One.
10.2 Spindle Tooling	The method of attaching bobbin to spindle should be quick and easy to operate.
10.3 Spindle Speed	To achieve the required winding time. This is expected to be 1000 to 6000rpm.

10.4 Spindle	
Direction	Direction of winding to be selectable.
10.5 Linear Wire	6 to 25m/s^2 depending on wire size.
Acceleration	Wire not to drive supply spool.
10.6 Spindle Drive	
10.6.1 Drive Speed	To achieve required spindle speed.
10.6.2 Regulation	To maintain speed and acceleration at the required level to +/-5%.
10.6.3 Available	In steady state 1.5×10^{-4} to 0.3Nm.
Torque	Under acceleration 0.95 to 1.25Nm.
	Additional torque will be required to overcome friction.
10.6.4 Braking	To slow spindle to stop accurately at the required
Retardation	number of turns.

11. MACHINE OPERATION

11.1 Power	Electric - single or three phase.
	Pneumatic - pressure = 80psi.
11.2 Noise	Machine should be quiet in operation.
	Measured to BS 4813.

12. DIMENSIONS

12.1 Wire Size Range	0.05 to 0.25mm (44 AWG to 30 AWG).
	To BS 6811(1).
12.2 Supply Spool	Standard wire spool sizes.
Size	To BS 2565 and BS 1489.
12.3 Winding Dimensions	
12.3.1 Diameter	3 to 30mm.
12.3.2 Length	250mm (required).
	650mm (desired).

12.4 System Size	about 1m x 1m x 1m.
12.5 System Weight	50 to 100 Kg.

13. MATERIALS USED

13.1 Wire Type	Round enamelled winding wire.
	Toleranced to BS 6811(1).
	Copper to BS 6017.
	Enamels to BS 6811(3); BS 4738(1); BS 4516(1); and BS 4663(1).

14. WIRE CONDITION

14.1 Acceptable Twist	< 5 twists / 1m spread evenly.
14.2 Enamel Wear	Winding process must not wear or otherwise damage the enamel.
14.3 Wire Stretching	Stretching of the wire to be <2% increase in length.

15. SAFETY

15.1 Emergency Stop	Must have an electrical stop.
15.2 Electrical	To BS 2771(1).
15.3 Mechanical	To BS 5304.

16. USER NEEDS

16.1 Visibility	Bobbin should be visible.
16.2 Ease of Use	Minimum of training should be necessary.
16.3 Appearance	Layout should be clear and uncluttered.
	The machine should not cause glare or be otherwise offensive to look at.
	Should look part of a modem production department.

6. SPECULATION - THE SEARCH FOR OPTIONS

6.1 Identifying Available Alternatives

To identify possible solutions to the problem of improving the winding process and more generally to any design problem it is necessary to provide some form of stimulus. The need for a stimulus is pointed out by Pitts (1973). One obvious stimulus is considering the problem itself. In addition Pitts suggests two methods which may be used successfully: brainstorming and following a logical path.

A version of both these methods was used to identify possible solutions to the problem considered here. Brainstorming was not used in a large group meeting environment, but many individual discussions took place with people throughout Penny and Giles, at Southampton University and with machine manufacturers. These provided ideas for general solutions and solutions to particular parts of the problem.

A tree diagram (figure 6.1) was used to present the ideas in a logical way. The writing out of ideas in a logical manner helped generate additional ideas. As in the specification stage, using a tree diagram helped identify gaps. At this stage these gaps represented areas where more ideas were required.

Another source of ideas and stimulation for ideas was the literature. This often provided new and novel solutions to particular parts of the design problem.

6.2 Using a Brought-in Machine

Perhaps the most obvious way of improving any production process which has been carried out in the same way for many years is to buy new equipment. This option must be considered as one of many and evaluated against all other options.

The number of different winding machines is vast and a lot of time would be wasted considering all of them. In the introduction types of winding system were discussed and it was stated that there are four basic types of winding machine: bobbin winders, fly winders, stick winders and toroidal winders. Of these stick

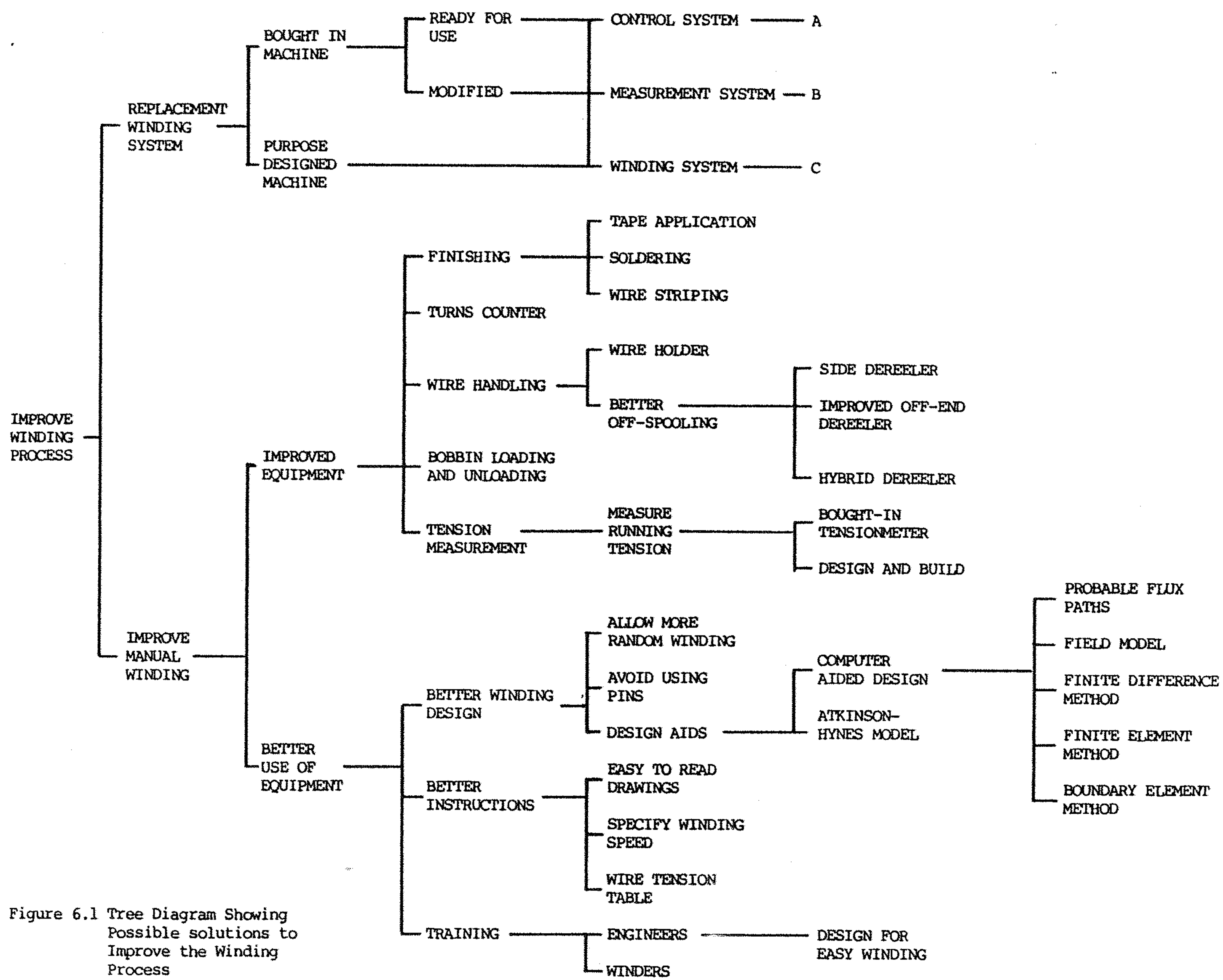

Figure 6.1 Tree Diagram Showing Possible solutions to Improve the Winding Process

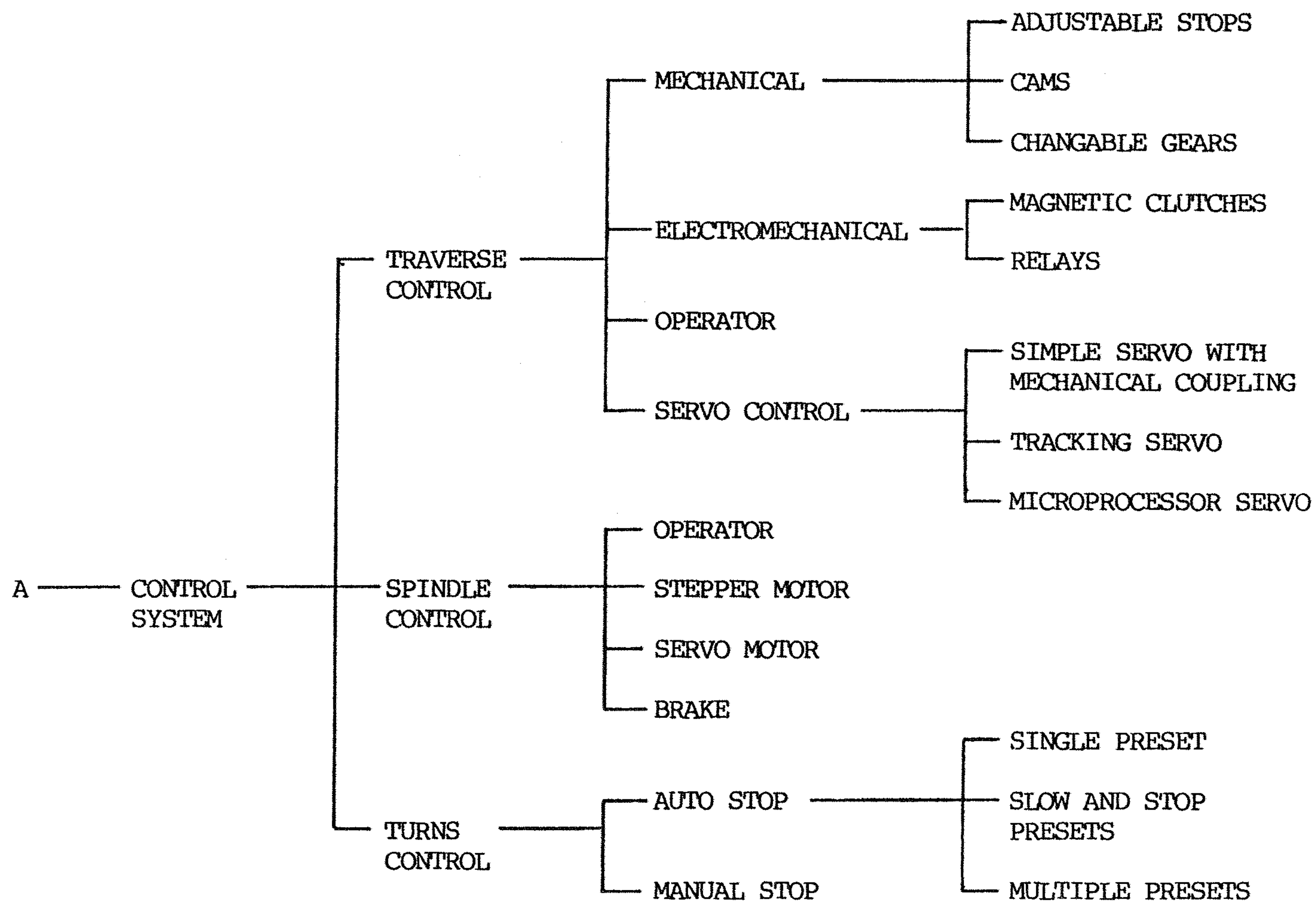

FIGURE 6.1A THE CONTROL SYSTEM

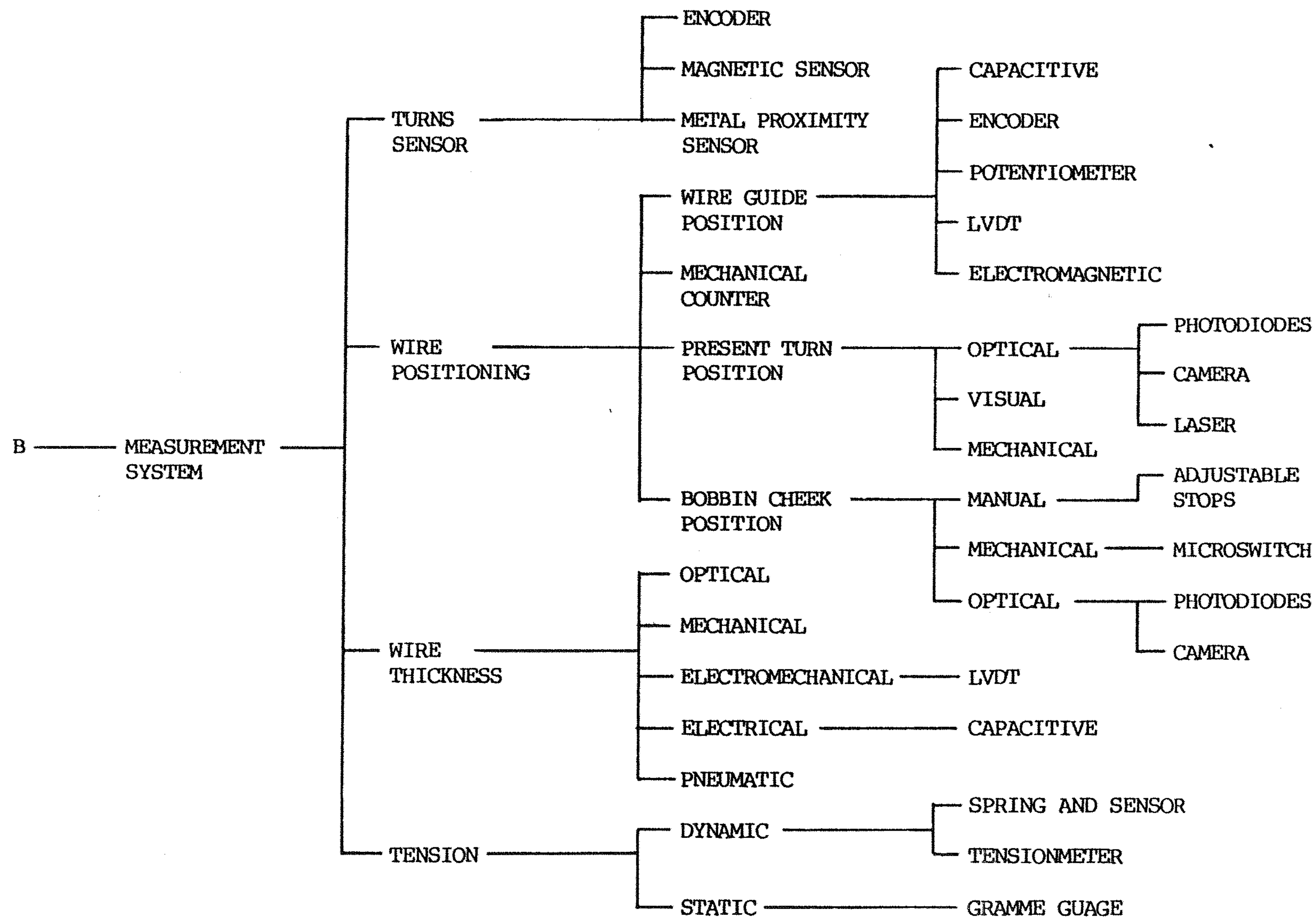

FIGURE 6.1B THE MEASUREMENT SYSTEM

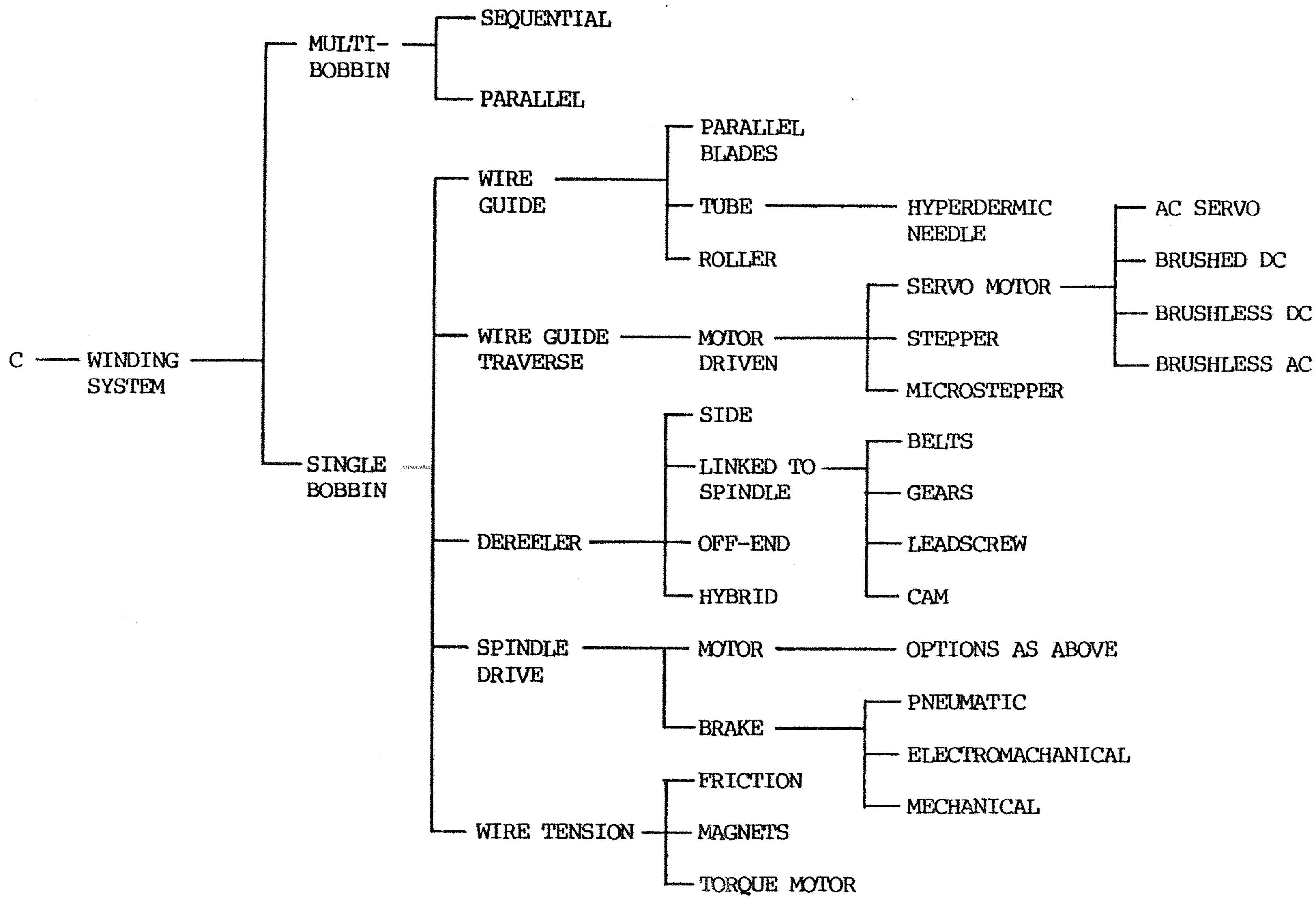

FIGURE 6.1C THE MECHANICAL SYSTEM

and toroidal winders can be neglected immediately as being made to wind completely different types of winding to the LVDT type winding.

A search was carried out to find what possibly suitable machines were available. As far as was possible to tell all manufacturers and suppliers of transformer type winding machines in this country and the main American manufacturers were contacted and information obtained from them on the machines they produced. All machines which could obviously not meet an essential part of the specification were dropped from consideration. The remaining machines which needed further consideration are listed in appendix D.

6.2.1 Modified Bought-in Machine

To find an "off the shelf" machine which fully satisfied the specification would be most fortunate. However, it is likely that there will be at least some scope for modifications and improvements to enable it to meet the specification or to make it a more attractive option.

Any necessary modifications may be carried out by Penny and Giles or by the machine manufacturer. All the manufacturers the project was discussed with were willing to undertake modifications of some sort to their machines.

Considering all possible modifications would be cumbersome and unnecessary. It is far better to consider modifications as a special case of the next section on "purpose designed machines" in which a subpart of the machine is being purpose designed.

6.3 Purpose Designed Machines

Designing and building a machine especially for the desired purpose allows more freedom of ideas than using a bought-in machine. However it will also require greater "in house" effort in its fabrication and is likely to take longer, which must be considered when its cost is calculated.

As discussed in the introduction a winding machine system must have three essential parts. These were called the mechanical system, the measurement system and the control system. Possible design for each part of the system will now be discussed.

6.3.1 The Mechanical System

The mechanical system is any part of the complete system which performs a mechanical operation such as holding, revolving, traversing or guiding. The elements of the machine (figure 1.5) which form the mechanical system are bobbin spindle, spindle drive, spindle brake, traverse mechanism, wire guide, tensioner and dereeler.

Design of the mechanical system of winding machines is probably the most established area of winding machine design. There have been few new innovations in recent years and many machines still have a layout based on that of a small lathe.

The lathe layout satisfies the basic requirements of the mechanical system, which is to have a means of holding and rotating the bobbin to be wound on and a traverse mechanism to disperse the wire across the bobbin as it rotates.

In the simplest winding machine much of the functioning is done by hand in which case the mechanical elements can be very simple. As more automation is required so the requirements of the mechanical system become more complex.

Figure 6.1 gave an overview of the various options available for design of the mechanical system. These options were gathered from a number of sources as discussed earlier. Many of the well established methods of wire dispersal were described in some detail by George (1978). This includes traverses using leadscrews with reversal by cams or end stops. More versatile designs which use clutches for reversal are also described.

One method which uses clutches is shown in figure 6.2. The belt is driven

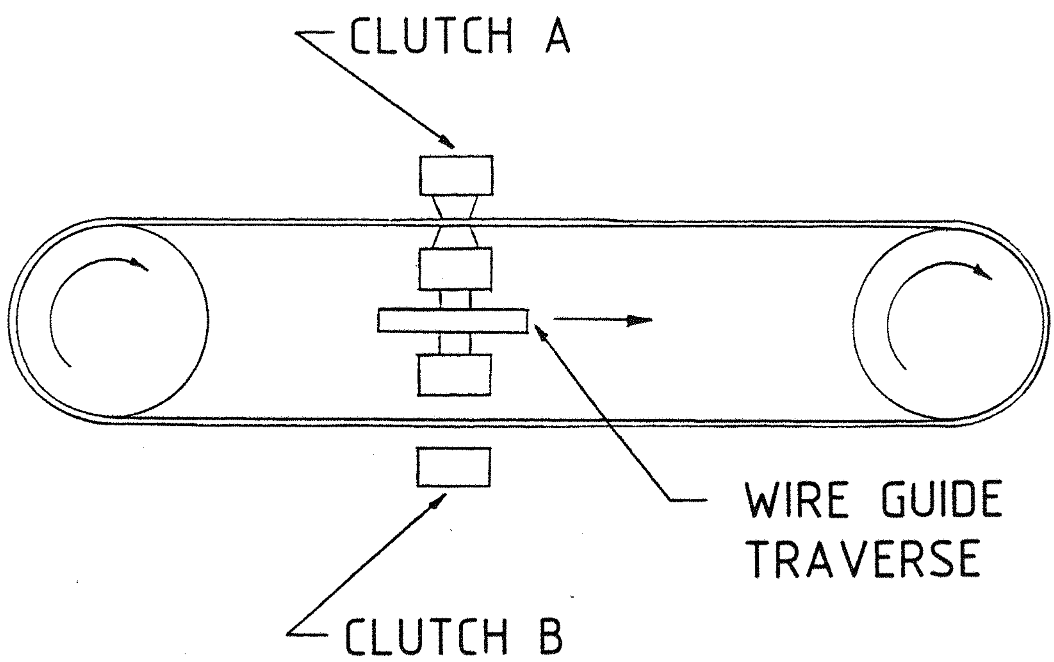

FIGURE 6.2 CONTINUOUS BELT TRAVERSE AND REVERSAL MECHANISM

continuously in one direction and clutches A and B alternately engage and disengage to drive the wire guide to and fro.

In the mechanisms described by George the pitch is varied by the use of change gears or infinitely variable feed rate systems. Several designs of systems were described.

All the mechanical systems discussed so far are based on established mechanical coupling techniques. Much more versatility can be introduced to the system by using separate drives for spindle and traverse. This reduces the mechanical coupling complexity, but will substantially increase the control system complexity. The control system will need to synchronise the speeds of both drives to achieve accurate winding. This will be discussed in a later section.

Various motors which could be used for both spindle and traverse drives are listed on figure 6.1. The types and choice of drive motor are discussed in detail by Kelloway and Green (1990). Many other authors have discussed the use of motors for spindle and traverse drives. Holt (1982) suggested the use of separate stepper motors. Stepper motors also featured in an assessment of motors and controls for coil winding equipment by Mitchell (1983). Characteristics and short-comings of stepper motors were listed and the observation was made that they may not be a good choice for a spindle drive because of disadvantages such as low speed, torque and acceleration. Mitchell recommended DC servo motors for the spindle drive because of their smooth operation, high speed and power.

DC servo motors for use in coil winding applications are discussed in greater detail by Persson (1984). Detailed discussions of stepper motors and microstepping motors which have improved resolution are given by De Sa E Silva (1972) and Ording (1984) respectively.

6.3.1.1 The Tension and Dereeling System

A very important sub-system of the mechanical system performs dereeling and tensioning of the wire. This must enable wire to be transferred from a supply reel to the bobbin being wound while under a controlled amount of tension. The importance of maintaining the correct tension has been stressed earlier in the report and the system must be designed with this in mind.

Dereeling from the wire supply reel can be achieved in two ways. The supply reel can be rotated and the wire removed from the side or the supply reel kept stationary and the wire uncoiled from the end. Side dereeling isfurther divided into systems which power the supply reel to rotate and those which rely on the pull of the wire to rotate it.

Methods of tensioning the wire can also be divided into two broad categories. Tension is created by impeding the motion of the wire. This can be achieved by impeding the wire motion directly such as by friction or in the case of side dereeling by impeding the rotation of the reel from which the wire is being unspooled.

Dereeling and tensioning methods were discussed by Brown (1987). In particular some advantages and disadvantages of the two methods of dereeling described above (side and off-end) were noted. The main problem with side dereeling is that of inertia of the rotated supply reel which can cause breakage of finer wires. One method which is often used to alleviate this problem is dancer arms. Dancer arms are discussed by Faresse (1988) and consist of a sprung arm which moves during acceleration of the reel so as to reduce the force on the wire. Although dancer arms can reduce the effects of supply reel inertia they will not prevent wire breakage altogether as there is inertia in the arm itself.

Problems with supply reel inertia are avoided by using off-end dereeling. However other problems can occur. One potential problem is that damage can occur to the wire enamel due to snagging on the supply reel flange of other turns of wire as the wire is unspooled. In extreme cases this can even lead to wire breakage. However this is not usually a major problem and is minimized by good housekeeping to prevent damage to supply reels. A second problem is the spinning away from the reel when uncoiled quickly (figure 6.3). This is fairly easily overcome by the use of a suitable cover (figure 6.4). The other main potential problem is that the unspooling will twist the wire once for each turn taken from the supply spool. Brown (1987) states that this is not generally a significant problem with round wires which is probably true unless the twists bunch leading to kinks in the wire.

An alternative method of dereeling is described by Brown which is designed to overcome the problems of off-end dereeling. This dereeler incorporates many features of the side and off-end dereelers and is called a hybrid dereeler (figure 6.5). This also has many of both the advantages and disadvantages of the side and off-end dereelers.

Tensioners have been discussed by a few authors. Conway (1975) describes tensioners for use with side dereelers. The simplest tension system is one in which the wire drives the supply reel and tension is produced by the force needed to rotate the reel. The limitations of this system are the huge variations in torque which occur with wire speed changes. An improvement is obtained by applying a fixed drag torque to the supply reel shaft. However a far from constant tension is obtained. Variations in tension are caused by changes in the supply reel diameter as wire is removed. This is overcome by use of slip devices which follow the reel diameter and vary drag torque to give a more constant tension.

The tension system recommended by Conway (1975) is similar to the system used by Penny and Giles at present. It used a variable speed drive which is controlled to provide the correct torque on the supply reel spindle to produce a constant tension. The main drawback of this type of system is that the supply reel

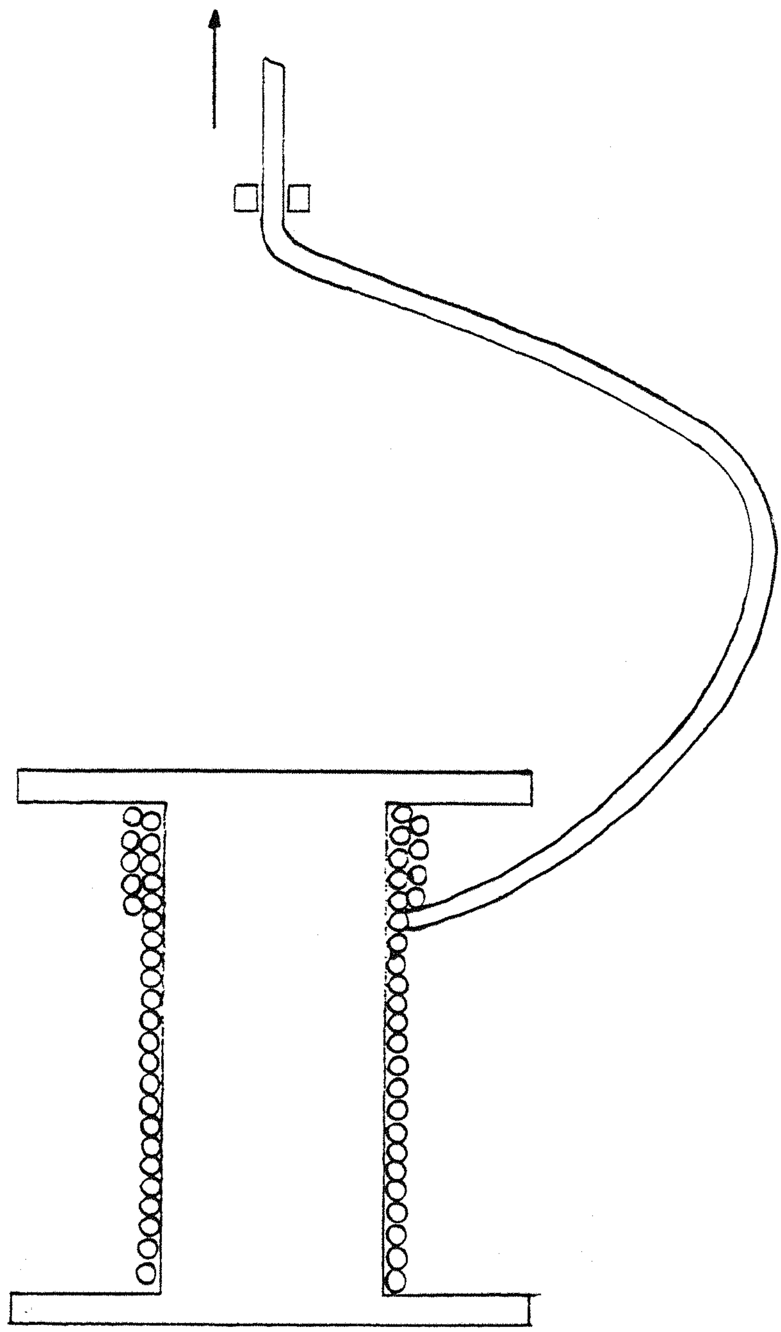

FIGURE 6.3 SPINNING OF WIRE AWAY FROM SUPPLY REEL

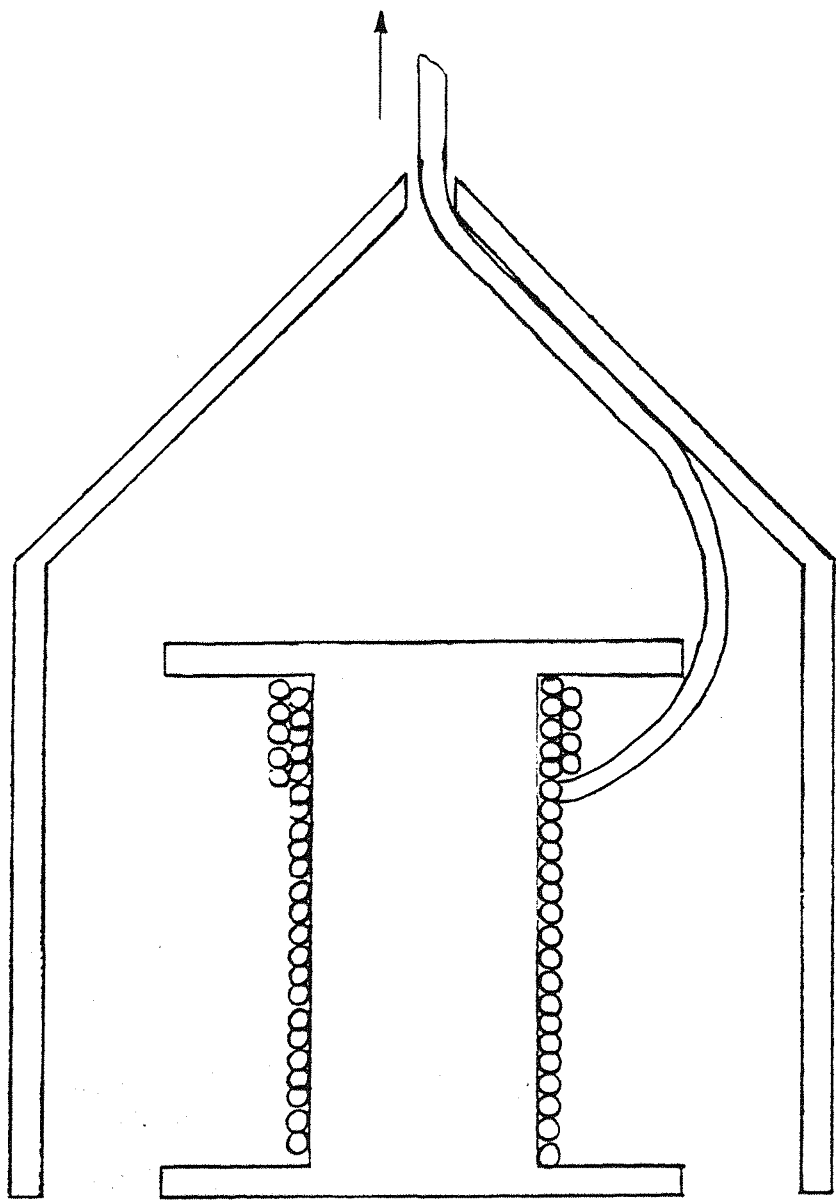

FIGURE 6.4 OFF-END SPOOLING COVER FOR IMPROVED WIRE CONTROL

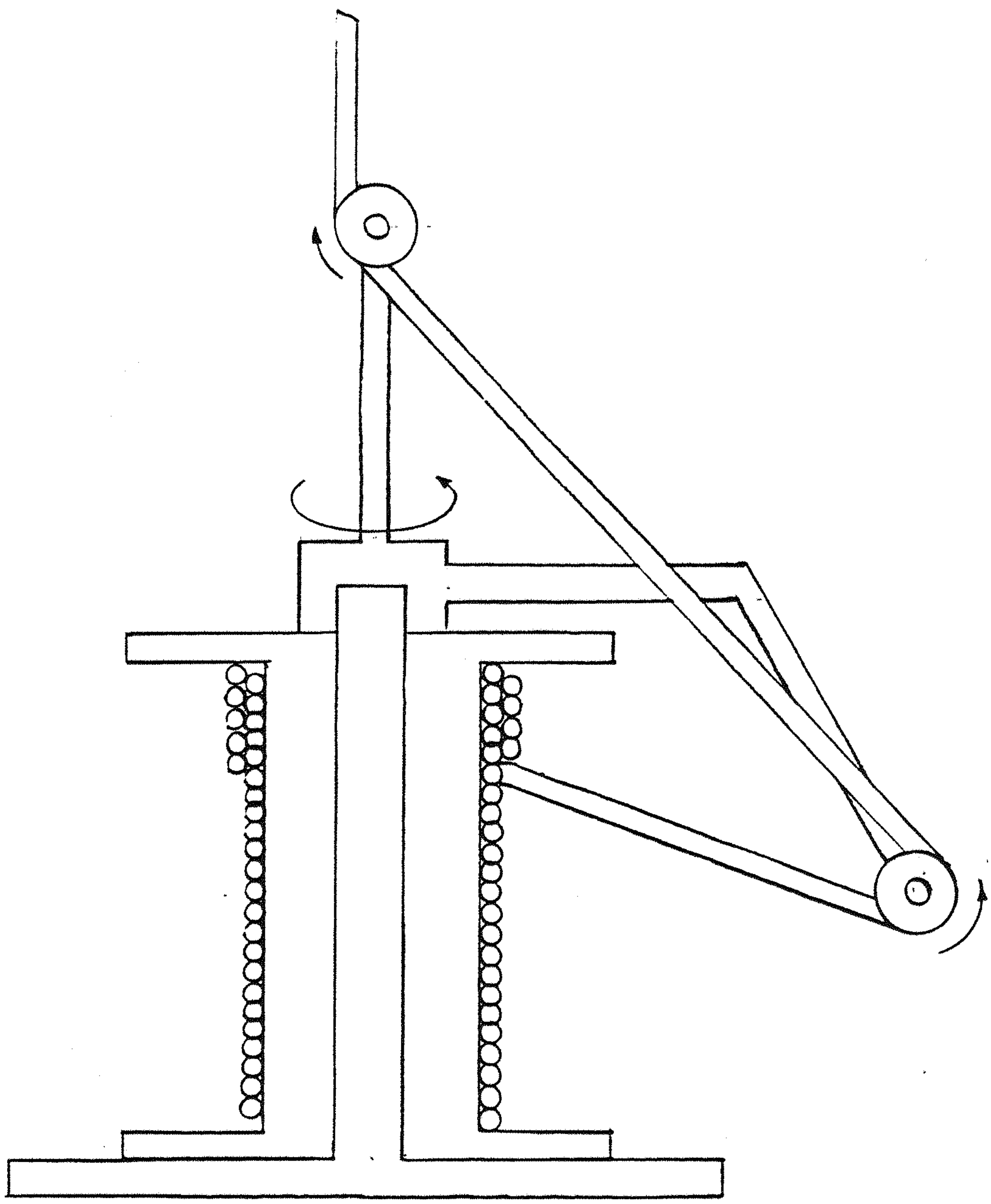

FIGURE 6.5 HYBRID DEREELER

size is limited to that which the motor can control.

In devices which produce a tension on the wire as a separate system from the dereeling system, as is the case with all off-end dereelers, the most common method is to apply a friction force to the wire. The most obvious method is to use two pads between which the wire passes. The tension is varied by altering the gap between the pads. In fact this method is widely used.

An alternative is to apply a braking action to a pulley around which the wire runs. This brake may be a simple rubbing device or of more novel design. One manufacturer uses magnets to provide a non-contact braking action (Tenaka (1988)).

6.3.2 The Measurement System

The measurement system measures quantities on the mechanical system. These measurements are then output for the information of the operator or more importantly are fed to the automatic control system such that the control system can use the information to decide what instructions to give to the mechanical system.

The elements of the machine (figure 1.5) which form the measurement system are the tension measurer, turns counter and guide position measurer.

6.3.2.1 Turns Counter

Although it is possible for the operator to count turns by eye, this is not practical for all but the simplest windings. Mitchell (1983) lists a turns counter as one of the basic requirements for "the least expensive winding system", in which all the functions are operator controlled.

Many of the different types of turns counter available are described by Goan (1981). Counters can be divided into mechanical and electrical and also into visual (manual), single preset (auto-stop), dual preset (slow and stop) or multiple preset (several stops).

Mechanical counters are usually found on older designs of machine or the less automated bench winders. The counters are normally of a straight-forward design being connected to the bobbin spindle by gears or belts.

Goan (1981) suggests that electrical counters are now favoured, offering higher accuracy, faster speeds, lower maintenance costs and much greater flexibility than mechanical counters. He goes on to suggest six criteria which should be considered when designing electronic counters:-

1. Number of digits - highest required turns count.
2. Single or bidirectional.
3. Up counting (0 to required turns count) or down counting (required turns count to 0).
4. Method of turns pick up - eg. photoelectric, metal proximity, hall effect, metal vane pick up etc.
5. Number of presets.
6. Need for slow preset before stop preset.

In nearly all situations a bidirectional counting mode is preferable. A bidirectional counter counts up when the spindle is turned one way and down when turned the other. Unidirectional counters do not follow the spindle direction in this way, but count up whichever sense the spindle is rotated in. Hence unidirectional counters will introduce errors when the direction of spindle rotation is changed.

The merits of up counting and down counting are less one sided. Down counters have the small advantage that it is possible to see at a glance that winding is finished (zero count). The decision is largely one of personal preference.

All the methods of detecting rotation of the bobbin spindle listed in criteria 4 above have been demonstrated and used successfully in commercially available turns counters. All can operate sufficiently quickly to measure high winding speeds.

The number of presets required will depend on the application. The simplest preset counter would have only one preset to disengage the spindle motor when the required number of turns is reached. This method will result in some run on which is often compensated for by disengaging some turns before the required number. Alternately the accuracy can be improved by applying a brake as the motor is disengaged. The limit to which accuracy can be improved by this method comes when the braking force becomes so great that wire breakage occurs. To improve accuracy further and reduce the danger of wire damage a two preset counter can be used. The first preset is set several turns short of the required turns count. At this preset the motor is disengaged or slowed, so when the second preset is reached the spindle can be stopped quickly at the correct turns count.

Multiple preset counters allow several stops or direction reversals to be made on the same winding. This allows complex winding shapes to be built up as with the contour wound LVDT or other functions such as taping to be carried out at specific points during the wind.

6.3.2.2 Guide Position and Wire Position Measurement

To obtain ideal layer winding it is necessary to know the position of the last turn wound, the wire guide position, the wire diameter and the bobbin cheek positions. These quantities are needed so the wire guide can be moved one wire diameter per spindle diameter relative to the previous turn and must reverse direction at the bobbin cheeks.

In theory all these quantities are known or can be calculated directly from known quantities. The nominal wire size will be known and the bobbin will be moulded and / or machined to a specified dimension. The theoretical wire position can be calculated from the number of turns and wire size and the wire guide position known by moving one wire diameter per turn.

Many machines operate in exactly this way relying on using these theoretical values. Unfortunately there are tolerances on the wire size and bobbin dimensions which can lead to large errors. This is best demonstrated by a simple calculation:

Enamelled winding wire is supplied to BS6811. Barmaper (1988) has used this specification to give the tolerance on the sizes of wire available. Consider 0.1mm diameter grade 2 enamelled wire which has a given tolerance of +/- 0.006mm. A typical winding may have up to 5000 turns. The tolerance on the wire over this number of turns gives a maximum error from the position expected using the nominal enamelled wire size of 0.006mm x 5000 ie. 30mm! In practice the error is not found to build up to this level but it illustrates the danger of using theoretical calculations.

Hence to obtain more accurate windings it is necessary to measure some or all of the quantities listed earlier. Of these the earliest and most commonly measured is wire guide position. This can be achieved by any of the methods shown on figure 6.1 of which optical encoders are probably the most common. Methods by which the other quantities may be measured are also given on figure 6.1. Many of these are techniques which are used widely for mechanical measurements such as in inspection but which could be applied to this need.

6.3.2.3 Tension Measurement

The importance of obtaining accurate wire tension has been stressed often in this report. To achieve this it is essential to measure tension accurately.

Tension may be measured statically or dynamically. Static tension is measured during machine set up and can be easily and accurately be carried out using a simple force measuring device such as a gramme gauge. Unfortunately, when winding is started the tension will increase. This was demonstrated by experiment (Leigh (1989)) which showed tension increased roughly proportionally with winding speed. Hence, to obtain repeatable windings, when using static tension measurements, it is necessary to use the same winding speed each time.

A better method is to measure the tension whilst winding is in progress. Methods of measuring dynamic tension are shown on figure 6.1. All these methods rely on taking the wire around a pulley and measuring the force exerted on the pulley. There are several methods by which this force can be converted to a useable tension measurement. The simplest is to measure the movement of a spring (figure 6.6).

The term tensionmeter on figure 6.1 refers to any bought-in ready to use tension measuring device. All tensionmeters tried at Penny and Giles were of the type of design described above.

6.3.3 The Control System

To produce a layered winding the system must control rotation of the bobbin spindle, motion of the wire guide traverse and the number of turns. Other quantities such as wire tension which must be adjusted to produce good windings are not included here, because they are set at the start of winding and need not be controlled throughout the winding process.

In the past, most winding machine control systems were fairly simple, relying on mechanical linkages such as: cams, gears and leadscrews, as discussed earlier. Alternately the operator was responsible for some, or even all, aspects of machine control. With the recent growth in machine automation the range and complexity of winding machine control has widened markedly. Shah (1985) discussed trends in winding control and in particular the implementation of microprocessors.

Several other authors have discussed the control of winding including Mitchell (1983), Manning (1986), Adams (1984) and Lockwood and Woods (1988). The

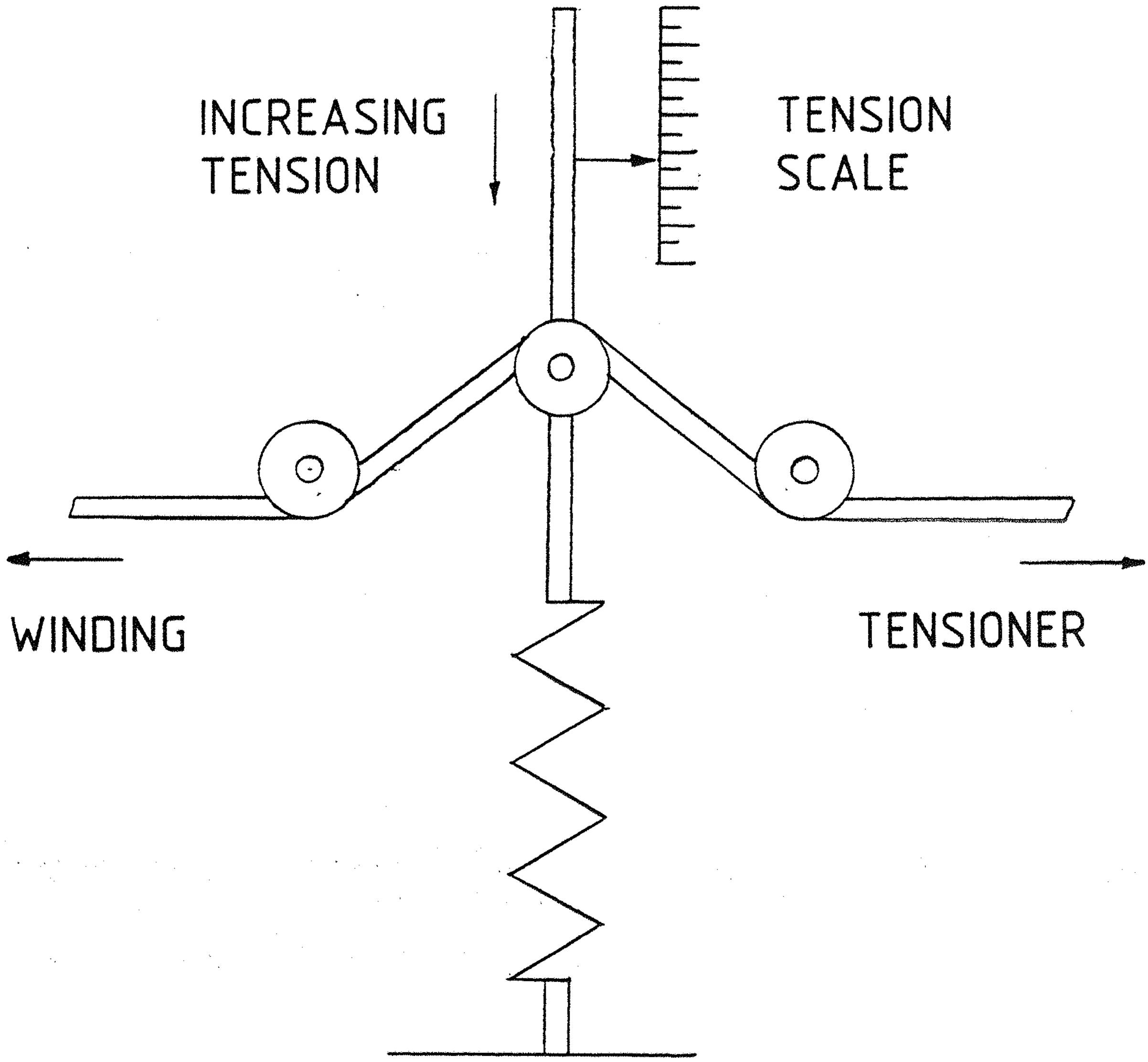

FIGURE 6.6 MEASUREMENT OF TENSION

last authors concluded that "with the use of a sophisticated,wide bandwidth control system the operating speed and accuracy of coil winders could potentially be increased."

Figure 6.1 shows methods by which each of the controlled parameters could be achieved. Altough these have been considered separately it is important to note that they are interactive.

6.3.3.1 Traverse Control

The simplest method of controlling the traverse of the wire is to use the operator. This is how the present Penny and Giles machine operates. It relies on the operator watching the position of the turn being wound and adjusting the bias of the incoming wire to position the next turn. With a suitably skilled and alert operator this method produces excellent results as a person makes an extremely flexible control system. The main drawbacks are that the training period required can be long and the maximum winding speed possible is quite low.

Mechanical and electromechanical systems have been discussed earlier. These rely on well tried and understood mechanics and electronics. The main drawback is their lack of flexibility. In particular the ability to produce accurate layer windings in spite of wire and bobbin tolerances is very limited.

Servo control of the type discussed by the authors mentioned in the previous section is becoming more and more common. The various types of servo control applicable to coil winding are described well by Mitchell (1983).

6.3.3.2 Spindle and Turns Control

The control of spindle revolution and number of turns are closely interactive. The spindle drive and brake must be controlled so as to produce the correct turns count. In the present Penny and Giles systems these functions are carried out by the operator. The spindle is driven by an AC motor and an electronic turns counter and when the correct turns count is reached the operator disengages the motor and brakes the spindle by hand.

The different types of turns counter were discussed earlier. The mechanical counters are mainly used with operator control. Electronic counters may also have electronic or microprocessor control. In a similar way to the traverse control the microprocessor control is becoming more common.

6.4 Using Improved Equipment

Improved equipment includes improvments of the present winding machine such as replacing part of it and additions to it such as devices for preforming work presently done by the operator. As the machine is of a very straight-forward design there is little scope for replacing parts without reaching a point where it would be more advantageous to design a new system. The most important exception to this is the dereeling and tension system.

The dereeling and tensioning system could be replaced with any of those discussed in section 6.3.1.1. This section discussed tensioners as part of a purpose designed machine, but the same criteria apply in the case of replacing the existing system.

The scope for add-on devices is somewhat broader and ranges from methods for holding the wire while setting up the bobbin to a bought-in taping machine.

6.4.1 Bought-in Add-on Devices

Two areas were seen as possibly benefiting from commercial devices. These were measuring devices and aids to finishing operations.

The quantities measured at present are turns count and wire tension. The turns counter used at present is a bidirectional up counter which has proved adequate for the job.

Wire tension is measured using a gramme gauge. The main improvement which could be made here is to use a device to measure dynamic tension. This would avoid failures due to the wrong tension being used because a winding speed other than the design speed has been used. Tension measurements equipment of this type was discussed in section 6.3.2.3.

The only finishing operation which was identified as possibly benefiting from a bought-in device was that of applying tape over the winding. Tape may be applied over a finished winding, or between primary and secondary windings. Information was gathered on several makes of taping machines. The main problem was finding a device which could handle the broad range of tape widths required. This was only possible at a very high purchase cost.

6.4.2 Purpose Designed Add-on Devices

Many of the purpose designed devices which could be usefully added to the present winding machine are the same as those described for the purpose designed winding machine (section 6.3). For instance, one of the tension and dereeling systems described may be suitable for improving the present system. All parts of the machine can be considered for possible improvement in this way.

Purpose designed add-on devices, which do not fall into the category above tend to be more minor modifications. These are often the result of a solution to a problem perceived by the winding operator. Modifications of this type usually occur throughout a machine's life. Possible areas of modification are listed on figure 6.1.

6.5 More Efficient Use of Equipment

Using equipment more efficiently is a method of improving any production system which must always be considered. This is the case whether new equipment is to be installed, or the present equipment kept, or modified.

Methods by which greater efficiency may be achieved include better training and instructions and improved winding design. Improving training and instructions are areas which should be looked at constantly as ways of improving quality, output and morale. Winding design may be impoved so as to make winding easier and quicker and so improve the overall winding system.

6.5.1 Improved Training and Instructions

Areas in which training and instructions may be improved include easier to read drawings and more information on tension and winding speed. Winding drawings could usefully be made a standard format so that winding operators could quickly and accurately pick out the information required.

Much more insructions and training will be needed if all, or part, of the winding machine is modified or redesigned. The necessary additional training and instructions must be considered alongside the electromechanical design.

6.5.2 Improving Winding Design

When designing an LVDT the main objective is to satisfy the required input / output characteristics as described earlier. In conjunction with this they should also be designed for economic manufacture and an important aspect of this is to make the LVDT winding easy to produce quickly and accurately.

The basics of LVDT winding design were discussed in an earlier section in some detail. To achieve an easy to wind LVDT the design parameters must be chosen to minimize complication. A set of suggested rules for achieving an easy winding is given in appendix E, together with a summary of the reasoning used to obtain these guidelines.

A second method by which improvements in LVDT design may be achieved has also been discussed earlier. That is the use of theoretical design aids and computer modelling.

7. EVALUATION OF THE ALTERNATIVES

7.1 The Purpose of Evaluation

The purpose of evaluation is fairly obvious. That being to select from the alternatives, which have been generated, the solution which best satisfies all the technical and economic design needs. It is important that evaluation is done with care as poor or hasty assessment may result in discarding many hours of work carried out to generate the alternatives.

7.2 Methods Used for Evaluation

The search for alternatives should have generated a broad range of many different solutions which are presented for evaluation. The first step in the evaluation stage is to discard solutions which obviously fall short of the systems requirements. Many solutions can be discarded as being technically insufficient without any need for calculations. Some evaluation of this type is carried out during the search for alternatives stage. For example when considering bought-in machines toroidal and stick winding machines were discarded from consideration at an early stage, as being unable to wind LVDT coils. This type of ongoing evaluation is essential to stop the number of solutions under consideration becoming unmanageable.

Having discarded all "obviously unsuitable" solutions the next step is to gather information on the remaining solutions. This information is then used to do some initial rough calculations to allow the solution to be compared with the specified requirement.

The specification is central to the evaluation design stage. It can be considered the "benchmark" against which the possible solutions are compared to establish their technical and economic worth.

When all the solutions which can be discarded at the logical arguement and rough calculation stage have been removed the remaining solutions must be considered using more accurate calculations and sensitive comparisons. One of the recognized design evaluation methods is useful at this stage.

7.3 Design Optimization

Design optimization is a method which can be usefully employed at the evaluation stage. Optimization involves progressively improving a design until the optimum is reached. This is usually achieved by some form of hill climbing. This involves looking at how parts of the system can be changed to improve the design (move up hill). This is continued until no further improvement is possible (hill summit) and the optimum design should be achieved. One major pitfall is that more than one summit may be present and the highest is not the one found. It is necessary to choose initial conditions carefully to avoid this danger.

A good description of optimization is given by Beveridge and Schechter (1970). This includes a general procedure for design optimization. The most important steps in this procedure are to:

1. Define a suitable objective.
2. Choose a system or systems for study.
3. Examine the system structure and the interelationships of system elements.
4. Construct a model for the system.
5. Examine internal and external restrictions placed on the system variables.
6. Develop an objective function for the system by expressing the objective in terms of the system variables.
7. Determine the optimum solution for the system using the objective function.
8. Using the information obtained, repeat the procedure until a satisfactory result is obtained.

7.3.1 Using Design Optimization

An attempt was made to use the Beveridge and Schechter optimization procedure to evaluate the winding machine system. The model used was based on the diagram in figure 1.5. This was used with the objectives discussed in section 4 to try and construct a suitable objective function. 15 system variables were identified as follows: spindle speed, counter accuracy, counter complexity, tension accuracy, measurement accuracy, wire position accuracy, traverse motion accuracy, traverse rate, traverse control flexibility, control automation, control speed, control accuracy, winding accuracy, winding repeatability and winding time. The interrelation between these variables was considered. Unfortunately the only way found of expressing these relationships was to use graphs showing expected trends. It was ~~found un~~ NOT feasible to combine these graphs such that an objective function could be formed and this method was not pursued further. However, the method is useful in helping develop an understanding of what is important in the system design.

To use this procedure of optimization to its full potential it is necessary to be able to express the relationships between system variables in a functional way. Its use is still complicated if the number of system variables is large.

7.4 The Morphological Method

7.4.1 Description of the Morphological Method

The morphological method is a design process with similar general steps to those used in this report. However, its main strength is the conscious and logical way in which it presents possible design solutions. This allows accurate comparisons to be made between these solutions.

Probably the earliest discussion of morphological methods is by Zwicky (1948) who describes the principles of the method and claims:

1. The morphological method provides for a check of completeness of the answers given to a specific problem.

2. If it is found that answers already available are incomplete, the method

serves as a powerful incentive toward the invention of things as yet unrealized or untried.

A detailed discussion on how the morphological method can be applied to engineering design is given by Norris (1963). The most important aspect of the method is the construction of a morphological chart. This is a design table in which parameters essential to design are listed in the left hand column and in rows to the right of each parameter are the possible ways of achieving that particular element.

To use the morphological chart for evaluation it is essential to have a carefully established specification. This should list what is needed of the same parameters as in the morphological chart. The possible solutions in the chart can then be compared in an orderly way against the specification.

Norris (1963) states that to perform this evaluation the 'basis of comparison' must be determined. These 'basis of comparison' should then be made quantitative by feeding in suitable factors and assumptions. The quantitative basis of comparison was likened to a sieve or filter which removes unsuitable solutions.

7.4.2 Using the Morphological Method

The method used is a modified version of the Morphological method. The morphological chart is drawn up with the quantities as listed in the specification down the left hand side. The possible solutions are then listed in adjacent columns with their specifications. This provides a convenient form for presenting and comparing the possible solutions.

The method devised for quantitative evaluation was to calculate a value for each solution, which was to be a measure of how well the solution satisfied the specification. These values could then be compared to identify the most worthy solution.

To determine this worthiness value each specified quantity was assigned a factor (0 to 5) as a measure of its importance (figure 7.1). The specification for each possible solution is then considered and a score (0 to 5) given for how well each specified quantity is satisfied by that solution (figure 7.2). A worthiness value can then be calculated by summing the products of these two scores (figure 7.3).

Many possible solutions can be discarded without the need to go through this calculation. If a specified quantity for a possible solution has a very low score (0 or 1), but has a high importance factor (4 or 5), it indicates that the possible solution is lacking in one of the essential areas of its operation. This should be considered further and if this fault cannot be corrected, such as by a modification, the solution should be discarded.

After this scoring method had been tried for a range of possible solutions a shortfall with the method was identified. It was found that poor scores for particularly important specified quantities, which may make a possible solution undesirable, can be swamped when the total worthiness value is calculated. The large number of specified quantities could easily hide one poor score, however important it was. This is demonstrated by the fact that the Aumann PW Meric machine scores higher than the present system (figure 7.3). This machine was the subject of a detailed study (Cannon and Holt (1982)) which showed it to be unsuitable for Penny and Giles needs. The reason was its very low accuracy and repeatability. The low scores for accuracy and repeatability were outweighed by higher scores elsewhere for less important quantities.

7.4.2.1 Weighting Methods

A method for weighting the most important quantities was needed. Three methods by which this might be achieved were identified:

1. A non-linear importance factor could be used such that the more important

Figure 7.1 Individual Parameter Importance Factors

Parameter	Importance Factor of Parameter
1. WINDING	
1.1 Winding Accuracy	5
1.2 Wire Reversal	5
1.3 Position Accuracy	
1.3.1 At Reversal	5
1.3.2 For Layering	5
1.4 Winding Repeatability	4
2. SYSTEM CONTROL	
2.1 Automation	3
2.2 Unwinding	4
2.3 Coil Type	
2.3.1 Random Winding	2
2.3.2 Layer Winding	3
2.3.3 Step Winding	3
2.3.4 Space Winding	3
2.3.5 Multisection Winding	3
3. COUNTING THE TURNS	
3.1 Counter Range	2
3.2 Counter Accuracy	3
3.3 Counting Rate	3
4. DEREELING	
4.1 Dereeling Rate	3

5. CHECKING	
5.1 Wire breakage	2
5.2 Wire Run Out	2
5.3 Wire Size	3
5.4 Bobbin Cheek Positions	4
5.5 Bobbin Finish	1
5.6 Enamel Quality	3
6. COSTING	
6.1 Investment	5
6.2 Running Cost	3
6.3 Cost / Winding	5
7. TIME	
7.1 Winding Time	5
7.2 Lead Time	3
7.3 System Downtime	3
7.4 Life	3
8. WIRE TRAVERSE	
8.1 Wire Guide	3
8.2 Pitch	3
9. WIRE TENSION	
9.1 Tension Control	2
9.2 Tension Range	3
9.3 Tension Accuracy	4
10. SPINDLE LAYOUT	
10.1 Number of Spindles	1
10.2 Spindle Tooling	3
10.3 Spindle Speed	3
10.4 Spindle Direction	2

10.5 Linear Wire Accelleration	3
10.6 Spindle Drive	
10.6.1 Drive Speed	1
10.6.2 Regulation	3
10.6.3 Available Torque	2
10.6.4 Braking Retardation	3
11. MACHINE OPERATION	
11.1 Power	2
11.2 Noise	3
12. DIMENSIONS	
12.1 Wire Size Range	3
12.2 Supply Spool Size	3
12.3 Winding Dimensions	
12.3.1 Diameter	3
12.3.2 Length	4
12.4 System Size	1
12.5 System Weight	1
13. MATERIALS USED	
13.1 Wire Type	1
14. WIRE CONDITION	
14.1 Acceptable Twist	4
14.2 Enamel Wear	3
14.3 Wire Stretching	3
15. SAFETY	
15.1 Emergency Stop	1
15.2 Electrical	2
15.3 Mechanical	2

16. USER NEEDS

16.1 Visibility	3
16.2 Ease of Use	4
16.3 Appearance	3

Figure 7.2 Possible Solution Specification

Solution : Present Winding System

Parameter	Solution Specification	Score
1. WINDING		
1.1 Winding Accuracy	Accurate layer winding ~30 layers	4
1.2 Wire Reversal	Manual	4
1.3 Position Accuracy		
1.3.1 At Reversal	Resolution of eye - a few wire diameters	3
1.3.2 For Layering	Resolution of eye - a few wire diameters	4
1.4 Winding Repeatability	Many units require reworking	2
2. SYSTEM CONTROL		
2.1 Automation	All manual	0
2.2 Unwinding	Whole coil easily unwound	4
2.3 Coil Type		
2.3.1 Random Winding	Easily achieved	4
2.3.2 Layer Winding	Accurate layer winding	4
2.3.3 Step Winding	Step control with manual measurement	2
2.3.4 Space Winding	Manually spaced turns	2
2.3.5 Multisection Winding	Possible with a large number of sections ~100	4
3. COUNTING THE TURNS		
3.1 Counter Range	10^6 turns	4
3.2 Counter Accuracy	+/- 0.01 turns	4
3.3 Counting Rate	Adequate for fastest speed	3
4. DEREELING		
4.1 Dereeling Rate	Adequate for fastest speed	2

5. CHECKING

5.1 Wire breakage	Operator check	3
5.2 Wire Run Out	Operator check	3
5.3 Wire Size	Operator check	2
5.4 Bobbin Cheek Positions	Operator check	2
5.5 Bobbin Finish	Operator check	3
5.6 Enamel Quality	Operator check	2

6. COSTING

6.1 Investment	Already written off	5
6.2 Running Cost	Operator + Maintenance ~#8000	3
6.3 Cost / Winding	Long winding time	2

7. TIME

7.1 Winding Time	~20 mins - 7.5 hrs / winding	1
7.2 Lead Time	Long development time ~2 months	2
7.3 System Downtime	Very low - 4 machines	4
7.4 Life	5-10 years	3

8. WIRE TRAVERSE

8.1 Wire Guide	Manually biased	2
8.2 Pitch	Upto ~10mm - poor accuracy	2

9. WIRE TENSION

9.1 Tension Control	Torque motor	2
9.2 Tension Range	0 - 2.8 Newtons	3
9.3 Tension Accuracy	Poor response	2

10. SPINDLE LAYOUT

10.1 Number of Spindles	One	3
10.2 Spindle Tooling	Collet for each bobbin type	3
10.3 Spindle Speed	Typically 1000 rpm	1

10.4 Spindle Direction	Bidirectional	3
10.5 Linear Wire Acceleration	~0.055 - 0.13 ms^{-2}	2
10.6 Spindle Drive		
10.6.1 Drive Speed	Upto 2000 rpm	3
10.6.2 Regulation	No control on acceleration	2
10.6.3 Available Torque	0.36 Nm	3
10.6.4 Braking Retardation	By hand	3
11. MACHINE OPERATION		
11.1 Power	240 volts	4
11.2 Noise	Quiet at low speeds used	3
12. DIMENSIONS		
12.1 Wire Size Range	0.05 - 0.25mm	4
12.2 Supply Spool Size	60mm diameter x 60mm long	1
12.3 Winding Dimensions		
12.3.1 Diameter	60mm	3
12.3.2 Length	650mm	5
12.4 System Size	1070 x 3640mm floor space for two machines	2
12.5 System Weight	~50 Kg	
13. MATERIALS USED		
13.1 Wire Type	Round enamelled winding wire	3
14. WIRE CONDITION		
14.1 Acceptable Twist	Twisting introduced by downspooling	2
14.2 Enamel Wear	Smooth surfaces but some operator damage	3
14.3 Wire Stretching	Some caused by poor tension control	3

15. SAFETY

15.1 Emergency Stop	Foot pedal operated	3
15.2 Electrical	Safe	3
15.3 Mechanical	Safe	3

16. USER NEEDS

16.1 Visibility	Clear	4
16.2 Ease of Use	Considerable practice for some windings	1
16.3 Appearance	Simple	2

Specified Quantity	Importance Factor		Present System Sc	Pr	To	Aumann PW Meric Sc	Pr	To
1.1	5		4	20		2	10	
1.2	5		4	20		3	15	
1.3.1	5		4	15		2	10	
1.3.2	5		4	20		2	10	
1.4	4	120	2	8	83	2	8	53
2.1	3		0	0		3	9	
2.2	4		4	16		0	0	
2.3.1	2		4	8		4	8	
2.3.2	3		4	12		1	3	
2.3.3	3		2	6		3	9	
2.3.4	3		2	6		4	12	
2.3.5	3	105	4	12	60	3	9	50
3.1	2		4	8		4	8	
3.2	3		3	9		3	9	
3.3	3	40	3	9	26	3	9	26
4.1	3	15	2	6	6	2	6	6
5.1	2		3	6		4	8	
5.2	2		3	6		3	6	
5.3	3		2	6		2	6	
5.4	4		2	8		2	8	
5.5	1		3	3		3	3	
5.6	3	75	2	6	35	2	6	37
6.1	5		5	25		3	15	
6.2	3		3	9		3	9	
6.3	5	65	2	10	44	3	15	39
7.1	5		1	5		3	15	
7.2	3		3	9		3	9	
7.3	3		2	6		2	6	
7.4	3	70	4	12	32	3	9	39
8.1	3		2	6		4	12	
8.2	3	30	2	6	12	3	9	21
9.1	2		2	4		2	4	
9.2	3		3	9		3	9	
9.3	4	45	2	8	21	2	8	21
10.1	1		3	3		3	3	
10.2	3		3	9		3	9	
10.3	3		1	3		3	9	
10.4	2		3	6		3	6	
10.5	3		2	6		5	15	
10.6.1	1		3	3		3	3	
10.6.2	3		2	6		5	15	
10.6.3	2		2	4		4	8	
10.6.4	3	105	3	9	49	3	9	77
11.1	2		4	8		3	6	
11.2	3	25	3	9	17	3	9	15
12.1	3		4	12		4	12	
12.2	3		1	3		1	3	
12.3.1	3		3	9		4	12	
12.3.2	4		5	20		3	12	
12.4	1		2	2		4	4	
12.5	1	75	3	3	49	3	3	46
13.1	1	5	3	3	3	3	3	3
14.1	4		2	8		2	8	
14.2	3		3	9		4	12	
14.3	3	50	3	9	26	4	12	32
15.1	1		3	3		3	3	
15.2	2		3	6		3	6	
15.3	2	25	3	6	15	3	6	15
16.1	3		4	12		3	9	
16.2	4		1	4		3	12	
16.3	3	50	2	6	22	2	6	27
SCORE		900			500			507

Figure 7.3 Example of a Winding System Comparison Table Sc=Score Pr=Product To=Total

quantities could be assigned a value of more than 5.

2. A second importance factor could be introduced which would be a measure of the importance of the specified quantity for comparison between solutions. This would allow important quantities to be more heavily weighted.

3. A separate morphological chart could be constructed containing only the most important specified quantities. This could than be used to calculate a worthiness value for these quantities, which could be used for comparison in conjunction with the worthiness value for all quantities.

The specified quantities which have been identified as the most important are listed in figure 7.4. Each of the above methods was tried as a way of highlighting these quantities.

Figure 7.5 shows values out of 20 for the selected quantities. These values were then used to redraw the morphological chart (figure 7.6). With the important quantities highlighted in this way the Aumann PW Meric scores less than the present system.

A second importance factor was introduced by giving each of the specified groups an importance factor as well as each specified quantity (figure 7.7). This was then used to construct figure 7.8 which again has highlighted the important quantities.

Constructing a second morphological chart of only the more important specified quantities involves simply taking the values from the original chart. This has been done in figure 7.9. This can now be used in conjuction with the original chart (figure 7.3).

7.4.3 Using the Revised Morphological Method

Three methods of weighting the most important specified quantities have been tried. These were all an improvement on the original Morphological method. This is demonstrated by the observation that the Aumann PW meric now scores

1.1 Winding Accuracy

1.2 Wire Reversal

1.3 Position Accuracy

1.3.1 At Reversal

1.3.2 For Layering

1.4 Winding Repeatability

2.2 Unwinding

6.1 Investment

6.3 Cost / Winding

7.1 Winding Time

9.3 Tension Accuracy

16.2 Ease of Use

Figure 7.4 Important Specified Quantities

Parameter	Importance Factor of Parameter
1.1 Winding Accuracy	20
1.2 Wire Reversal	18
1.3 Position Accuracy	
1.3.1 At Reversal	18
1.3.2 For Layering	20
1.4 Winding Repeatability	18
2.2 Unwinding	15
6.1 Investment	20
6.3 Cost / Winding	20
7.1 Winding Time	18
9.3 Tension Accuracy	15
16.2 Ease of Use	15

Figure 7.5 Weighted Importance Factors

Specified Quantity	Importance Factor		Present System Sc	Pr	To	Aumann PW Meric Sc	Pr	To
1.1	20		4	80		2	40	
1.2	18		4	72		3	54	
1.3.1	18		3	54		2	36	
1.3.2	20		4	80		2	40	
1.4	18	470	2	36	322	2	36	206
2.1	3		0	0		3	9	
2.2	15		4	60		0	0	
2.3.1	2		4	8		4	8	
2.3.2	3		4	12		1	3	
2.3.3	3		2	6		3	9	
2.3.4	3		2	6		4	12	
2.3.5	3	105	4	12	104	3	9	50
3.1	2		4	8		4	8	
3.2	3		3	9		3	9	
3.3	3	40	3	9	26	3	9	26
4.1	3	15	2	6	6	2	6	6
5.1	2		3	6		4	8	
5.2	2		3	6		3	6	
5.3	3		2	6		2	6	
5.4	4		2	8		2	8	
5.5	1		3	3		3	3	
5.6	3	75	2	6	35	2	6	37
6.1	20		5	100		3	60	
6.2	3		3	9		3	9	
6.3	20	215	2	40	149	3	60	129
7.1	18		1	18		3	54	
7.2	3		3	9		3	9	
7.3	3		2	6		2	6	
7.4	3	70	4	12	45	3	9	78
8.1	3		2	6		4	12	
8.2	3	30	2	6	12	3	9	21
9.1	2		2	4		2	4	
9.2	3		3	9		3	9	
9.3	15	100	2	30	43	2	30	43
10.1	1		3	3		3	3	
10.2	3		3	9		3	9	
10.3	3		1	3		3	9	
10.4	2		3	6		3	6	
10.5	3		2	6		5	15	
10.6.1	1		3	3		3	3	
10.6.2	3		2	6		5	15	
10.6.3	2		2	4		4	8	
10.6.4	3	105	3	9	49	3	9	77
11.1	2		4	8		3	6	
11.2	3	25	3	9	17	3	9	15
12.1	3		4	12		4	12	
12.2	3		1	3		1	3	
12.3.1	3		3	9		4	12	
12.3.2	4		5	20		3	12	
12.4	1		2	2		4	4	
12.5	1	75	3	3	49	3	3	46
13.1	1	5	3	3	3	3	3	3
14.1	4		2	8		2	8	
14.2	3		3	9		4	12	
14.3	3	50	3	9	26	4	12	32
15.1	1		3	3		3	3	
15.2	2		3	6		3	6	
15.3	2	25	3	6	15	3	6	15
16.1	3		4	12		3	9	
16.2	15		1	15		3	45	
16.3	3	50	2	6	33	2	6	60
SCORE		900			934			850

Figure 7.6 Example of a Winding System Comparison Table Sc=Score Pr=Product To=Total

Parameter Group	Second Importance Factor
1. Winding Accuracy	4
2. System Control	3
3. Counting the Turns	3
4. Dereeling	3
5. Checking	2
6. Costing	5
7. Time	4
8. Wire Traverse	3
9. Wire Tension	3
10. Spindle Layout	3
11. Machine Operation	1
12. Dimensions	2
13. Materials Used	1
14. Wire Condition	3
15. Safety	4
16. User Needs	3

Figure 7.7 Second Importance Factors

Specified Quantity		Importance Factor		Present System Sc	Pr	To	Aumann PW Meric Sc	Pr	To
1.1	(x4)	5		4	80		2	40	
1.2		5		4	80		3	60	
1.3.1		5		4	60		2	40	
1.3.2		5		4	80		2	40	
1.4		4	480	2	32	332	2	32	212
2.1	(x3)	3		0	0		3	27	
2.2		4		4	48		0	0	
2.3.1		2		4	24		4	48	
2.3.2		3		4	36		1	9	
2.3.3		3		2	18		3	27	
2.3.4		3		2	18		4	36	
2.3.5		3	315	4	36	180	3	27	174
3.1	(x3)	2		4	24		4	24	
3.2		3		3	27		3	27	
3.3		3	120	3	27	78	3	27	78
4.1	(x3)	3	45	2	18	18	2	18	18
5.1	(x2)	2		3	12		4	16	
5.2		2		3	12		3	12	
5.3		3		2	12		2	12	
5.4		4		2	16		2	16	
5.5		1		3	6		3	6	
5.6		3	150	2	12	70	2	12	74
6.1	(x3)	5		5	75		3	75	
6.2		3		3	27		3	45	
6.3		5	195	2	30	132	3	75	195
7.1	(x4)	5		1	20		3	60	
7.2		3		3	36		3	36	
7.3		3		2	24		2	24	
7.4		3	280	4	48	128	3	36	156
8.1	(x3)	3		2	18		4	36	
8.2		3	90	2	18	36	3	27	63
9.1	(x3)	2		2	12		2	12	
9.2		3		3	27		3	27	
9.3		4	135	2	24	63	3	27	78
10.1	(x2)	1		3	6		3	6	
10.2		3		3	18		3	18	
10.3		3		1	6		3	18	
10.4		2		3	12		3	12	
10.5		3		2	12		5	30	
10.6.1		1		3	6		3	6	
10.6.2		3		2	12		5	30	
10.6.3		2		2	8		4	16	
10.6.4		3	210	3	18	98	3	18	154
11.1	(x1)	2		4	8		3	6	
11.2		3	25	3	9	17	3	9	15
12.1	(x2)	3		4	24		4	24	
12.2		3		1	6		1	6	
12.3.1		3		3	18		4	24	
12.3.2		4		5	40		3	24	
12.4		1		2	4		4	8	
12.5		1	150	3	6	98	3	6	92
13.1	(x1)	1	5	3	3	3	3	3	3
14.1	(x3)	4		2	24		2	24	
14.2		3		3	27		4	36	
14.3		3	150	3	27	78	4	36	96
15.1	(x4)	1		3	12		3	12	
15.2		2		3	24		3	24	
15.3		2	100	3	24	60	3	24	60
16.1	(x3)	3		4	36		3	27	
16.2		4		1	12		3	36	
16.3		3	150	2	18	66	2	18	81
SCORE			2740			1545			1534

Figure 7.8 Example of a Winding System Comparison Table Sc=Score Pr=Product To=Total

Specified Quantity	Importance Factor		Present System			Aumann PW Meric		
			Sc	Pr	To	Sc	Pr	To
1.1	5		4	20		2	10	
1.2	5		4	20		3	15	
1.3.1	5		4	15		2	10	
1.3.2	5		4	20		2	10	
1.4	4	120	2	8	83	2	8	43
2.2	4	20	4	16	16	0	0	0
6.1	5		5	25		3	15	
6.3	5	50	2	10	35	3	15	30
7.1	5	25	1	5	5	3	15	15
9.3	4	20	2	8	8	2	8	8
16.2	4	20	1	4	4	3	3	3
SCORE	255		151			118		

Sc=Score Pr=Product To=Total

Figure 7.9 Winding System Comparison Table - Most Important Quantites lower than the present system (figures 7.6, 7.8 and 7.9).

However there are some problems with all three. Using the first method (non-linear importance factor) the amount by which the score is increased for the most important quantities is rather arbitary. This means some trial and error is likely to be necessary to get the value right. Too low a value will mean the problem of important quantities being masked will remain. Too high and only the important values will have a noticed effect on the final score. The scoring out of 20 used here seems to be at the right level, as it gives a sensible ratio in the scores for the present system and the Aumann PW meric.

The second method of introducing a second importance factor has two main problems. One is that the extra importance factor makes the Morphological chart more complicated. The other is that it has not served its purpose very well. The score for the Aumann and the present system are very close. Some further adjustment of the second importance factor would probably improve this, but it was thought better to concentrate on a less complex method.

The third method is the method favoured. It provides a simple way of highlighting the important specifies quantities. It does not have the problems of requiring trial and error to get values right as long as the important quantities have been chosen correctly. The only potential problem is that there are now two Morphological charts for each possible solution. It is possible that too strong a conclusion can be drawn from one chart without considering the other. This danger must be borne in mind when using the Modified Morphlogical method.

7.4.4 Results from the Morphological Method

Figure 7.2 showed an example of a specification for a possible solution (in this case the present system) and the solution scores given. These scores have then been used to form the first column of the various morphological charts (figures 7.3, 7.6, 7.8 and 7.9). To determine the worthiness score for each possible solution a similar specification must be listed and additional columns formed on the morphological chart. This is the procedure followed to form the other columns shown in the figures listed.

The major drawback with carrying out the evaluation in this way is that a lot of work is required to fill out the chart for each possible solution considered. For this reason it was decided to use the smaller morphological chart with only the most important quantities (as figure 7.9). Many of the less promising possibilities could than be removed from consideration and those remaining considered in greater detail. Figure 7.10 shows a morphological chart for the important specified quantities. This determines comparison scores for several possible solutions which are complete systems. Figure 7.11 shows a similar chart for partial solutions. The values for these parts are for the solution being added to the present winding machine. The scores also give a measure of how well the part solution will perform as part of a purpose designed machine.

Figure 7.12 lists some general design outlines along which a purpose built machine might be designed. Most of the design ideas for a purpose built machine, which were generated in the last section, are included. Figure 7.13 shows the important quantity morphological chart for these solutions.

7.4.5 Discussion of Results

In figure 7.10 the morphological chart for a variety of manufactured winding machines has been drawn up. These were the machines identified as at least having the basic necessary facilities. For example, toroidal and stick winders have been eliminated as discussed earlier. From figure 7.10 it can be seen that the only machines which score higher than the present system are the Marsilli WM 06 PC and the Meteor M20. These machines both have a high degree of automation using computer control. This suggests that to replace the skill of the operator in the present system requires sophisticated automation.

Specified Quantity	Importance Factor		Present System			Aumann PW Meric			Marsilli WM 06 PC			Tenaka AW-853V			Adams-Maxwell 1200			Aumann CW/T			Meteor M20		
			Sc	Pr	To	Sc	Pr	To	Sc	Pr	To	Sc	Pr	To	Sc	Pr	To	Sc	Pr	To	Sc	Pr	To
1.1	5		4	20		2	10		4	20		3	15		2	10		2	10		3	15	
1.2	5		4	20		3	15		3	15		3	15		3	15		3	15		3	15	
1.3.1	5		4	15		2	10		3	15		2	10		2	10		2	10		3	15	
1.3.2	5		4	20		2	10		4	20		3	15		3	15		3	15		3	15	
1.4	4	120	2	8	83	2	8	43	4	16	86	3	12	67	2	8	58	3	12	62	4	16	76
2.2	4	20	4	16	16	0	0	0	3	12	12	1	4	4	1	4	4	2	8	8	1	4	4
6.1	5		5	25		3	15		3	15		3	15		4	20		3	15		2	10	
6.3	5	50	2	10	35	3	15	30	3	15	30	3	15	30	4	20	40	2	10	25	4	20	30
7.1	5	25	1	5	5	3	15	15	5	25	25	3	15	15	2	10	10	2	10	10	4	20	20
9.3	4	20	2	8	8	2	8	8	3	12	12	3	12	12	2	8	8	3	12	12	3	12	12
16.2	4	20	1	4	4	3	3	3	4	16	16	4	16	16	4	16	16	3	12	12	4	16	16
SCORE		255			151			118			181			144			136			129			158

Sc=Score Pr=Product To=Total

Figure 7.10 Winding System Comparison Table - Most Important Quantities

Specified Quantity	Importance Factor		Present System			Schmitt ZD 100 Tensionmeter			Tenaka MT 300 Tensioner			Fisher-Baker 100 Tensioner			Altic GR 64 Tensioner			Midland TW 300 Taper			Improved LVDT Design		
			Sc	Pr	To	Sc	Pr	To	Sc	Pr	To	Sc	Pr	To	Sc	Pr	To	Sc	Pr	To	Sc	Pr	To
1.1	5		4	20		5	25		4	20		3	15		4	20		4	20		5	25	
1.2	5		4	20		4	20		4	20		4	20		4	20		4	20		4	20	
1.3.1	5		4	15		3	15		3	15		3	15		3	15		3	15		3	15	
1.3.2	5		4	20		4	20		4	20		4	20		4	20		4	20		4	20	
1.4	4	120	2	8	83	3	12	92	2	8	83	2	8	78	2	8	83	3	12	82	3	12	92
2.2	4	20	4	16	16	4	16	16	1	4	4	1	4	4	3	12	12	4	16	16	4	16	16
6.1	5		5	25		3	15		3	15		4	20		3	15		1	5		4	20	
6.3	5	50	2	10	35	2	10	25	3	15	30	3	15	35	3	15	30	1	5	10	3	15	35
7.1	5	25	1	5	5	2	10	10	2	10	10	3	15	15	2	10	10	2	10	10	2	10	10
9.3	4	20	2	8	8	4	16	16	4	16	16	2	8	8	3	12	12	2	8	8	3	12	12
16.2	4	20	1	4	4	2	8	8	1	4	4	1	4	4	1	4	4	2	8	8	2	8	8
SCORE		255			151			167			147			144			151			139			179

Sc=Score Pr=Product To=Total

Figure 7.11 Winding System Comparison Table - Most Important Quantities

Machine Part	Solution			
	1	2	3	4
Bobbin Spindle	Lathe bed	Lathe bed	Lathe bed	Lathe bed
Spindle Drive	Electric Motor	Stepper Motor	Servo Motor	Servo Motor
Turns Counter	Mecanical	Electric	Electric	Electric
Control System	Mechanical	Electrical	CNC	CNC
Tensioner	Friction	Friction	Friction	Torque Motor
Dereeler	Off end	Off end	Off end	Side
Tension Measurement	Scale	Hand held Meter	Hand held Meter	Fixed Meter
Guide Position Measurement	Potentiometer	Encoder	Encoder	Encoder
Traverse Mechanism	Spindle driven leadscrew	Seperate stepper motor	Seperate servo motor	Seperate servo motor

Figure 7.12 General Design of Purpose Built Machine

Specified Quantity	Importance Factor		1			2			3			4		
			Sc	Pr	To	Sc	Pr	To	Sc	Pr	To	Sc	Pr	To
1.1	5		1	5		3	15		4	20		4	20	
1.2	5		2	10		4	20		4	20		4	20	
1.3.1	5		2	10		3	15		3	15		3	15	
1.3.2	5		1	5		3	15		3	15		3	15	
1.4	4	120	2	8	38	3	6	71	3	6	76	3	6	76
2.2	4	20	2	8	8	2	8	8	2	8	8	2	8	8
6.1	5		2	10		1	5		1	5		1	5	
6.3	5	50	1	5	15	2	10	15	2	10	15	2	10	15
7.1	5	25	4	20	20	4	20	20	4	20	20	4	20	20
9.3	4	20	2	8	8	2	8	8	2	8	8	3	12	12
16.2	4	20	4	16	16	3	12	12	3	12	12	3	12	12
SCORE		255			105			134			139			143

Sc=Score Pr=Product To=Total

Figure 7.13 Winding System Comparison Table for figure 7.12 Designs - Most Important Quantities

Figure 7.11 shows the morphological chart for methods which may be used to improve on the present system. Of these methods improved LVDT design and the Schmitt ZD 100 tensionmeter give a higher score than the present system. The tensionmeter improvement is due to the more accurate measure of tension which can be achieved. As stated several times throughout this report and elsewhere controlled tension is an essential element in obtaining good quality windings.

Improving LVDT design involves designing LVDTs to be as simple to wind as possible with the available equipment. This is a technique which with careful consideration could lead to shorter winding times and improved quality and repeatability. It is something which should be considered whatever the winding equipment in use.

Figure 7.13 is the morphological chart for the general designs of purpose designed winding machine. All have scored lower than the present system. The main reason for this is the long times required to design a machine capable of producing sufficiently high quality windings. This leads to very high design and production costs.

All the possible designs which scored better than the present system on the important quantity morphological charts have been tabulated for all the specified quantities (figure 7.14). This table confirms the higher value of these options compared to the present system. The highest scores are for the two CNC manufactured machines. However it should be remembered that the other possible solutions in the table would be easier to implement and could form part of a solution which may also include a manufactured machine.

Specified Quantity		Importance Factor		Present System Sc	Pr	To	Marsilli WM 06 PC Sc	Pr	To	Improved LVDT Design Sc	Pr	To	Meteor M20 Sc	Pr	To	Schmitt ZD 100 Sc	Pr	To
1.1	(x4)	5		4	80		4	80		5	100		3	60		5	100	
1.2		5		4	80		3	60		4	80		3	60		4	80	
1.3.1		5		4	60		3	60		3	60		3	60		3	60	
1.3.2		5		4	28		4	80		4	60		3	60		4	80	
1.4		4	480	2	32	332	4	64	344	3	48	368	4	64	304	3	48	368
2.1	(x3)	3		0	0		4	36		1	9		4	36		2	18	
2.2		4		4	48		3	36		4	48		1	12		4	48	
2.3.1		2		4	24		5	30		4	24		5	30		4	24	
2.3.2		3		4	36		4	36		4	36		3	27		4	36	
2.3.3		3		2	18		4	36		2	18		4	36		2	18	
2.3.4		3		2	18		5	45		2	18		5	45		2	18	
2.3.5		3	325	4	36	180	4	36	255	4	36	189	4	36	222	4	36	198
3.1	(x3)	2		4	24		4	24		4	24		4	24		4	24	
3.2		3		3	27		4	36		4	36		4	36		3	27	
3.3		3	120	3	27	78	3	27	87	3	27	87	2	27	87	3	27	78
4.1	(x3)	3	45	2	18	18	3	27	27	2	18	18	3	27	27	2	18	18
5.1	(x2)	2		3	12		3	12		3	12		3	12		3	12	
5.2		2		3	12		3	12		3	12		3	12		3	12	
5.3		3		2	12		2	12		2	12		2	12		2	12	
5.4		4		2	16		2	16		2	16		2	16		2	16	
5.5		1		3	6		3	6		3	6		3	6		3	6	
5.6		3	150	2	12	70	2	12	70	2	12	70	2	12	70	2	12	70
6.1	(x5)	5		5	125		2	50		5	125		2	50		3	75	
6.2		3		3	45		3	45		3	45		3	45		3	45	
6.3		5	325	2	50	220	4	100	195	3	75	245	4	100	195	2	50	170
7.1	(x4)	5		1	20		5	100		2	40		4	80		1	20	
7.2		3		3	36		3	36		3	36		3	36		3	36	
7.3		3		2	24		3	36		1	12		3	36		2	24	
7.4		3	280	4	48	128	3	36	208	4	48	136	3	36	188	4	48	128
8.1	(x3)	3		2	18		4	36		2	18		4	36		2	18	
8.2		3	90	2	18	36	4	36	72	2	18	36	4	36	72	2	18	36
9.1	(x3)	2		2	12		3	18		2	12		2	12		3	18	
9.2		3		3	27		3	27		3	27		3	27		3	27	
9.3		4	135	2	24	63	3	36	81	3	36	75	3	36	75	3	36	81
10.1	(x2)	1		3	6		3	6		3	6		3	6		3	6	
10.2		3		3	18		3	18		3	18		4	24		3	18	
10.3		3		1	6		5	30		1	6		5	30		1	6	
10.4		2		3	12		3	12		3	12		3	18		3	12	
10.5		3		2	12		5	30		2	12		5	30		2	12	
10.6.1		1		3	6		4	8		3	6		4	8		3	6	
10.6.2		3		2	12		5	30		2	12		5	30		2	12	
10.6.3		2		2	8		3	12		2	8		3	12		2	8	
10.6.4		3	210	3	18	98	4	24	170	3	18	98	4	24	182	3	18	98
11.1	(x1)	2		4	8		3	6		4	8		3	6		4	8	
11.2		3	25	3	9	17	3	9	15	3	9	17	3	9	17	3	9	17
12.1	(x2)	3		4	24		4	24		4	24		4	24		4	24	
12.2		3		1	6		4	24		1	6		4	24		1	6	
12.3.1		3		3	18		4	24		3	18		4	24		3	18	
12.3.2		4		5	40		3	24		5	40		4	32		5	40	
12.4		1		2	4		3	6		2	4		3	6		2	4	
12.5		1	150	3	6	98	3	6	108	3	6	98	3	6	116	3	6	98
13.1	(x1)	1	5	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
14.1	(x3)	4		2	24		2	24		2	24		2	24		2	24	
14.2		3		3	27		4	36		4	36		4	36		3	27	
14.3		3	150	3	27	78	4	36	96	3	27	90	3	27	87	3	27	78
15.1	(x4)	1		3	12		3	12		3	12		3	12		3	12	
15.2		2		3	24		3	24		3	24		3	24		3	24	
15.3		2	100	3	24	60	3	24	60	3	24	60	3	24	60	3	24	60
16.1	(x3)	3		4	36		3	27		4	36		4	36		4	36	
16.2		4		1	12		4	48		2	24		4	48		2	24	
16.3		3	150	2	18	66	5	45	120	2	18	78	5	45	129	2	18	78
SCORE			2740			1545			1911			1668			1834			1579

Figure 7.14 Winding System Comparison Table for Best Solutions Sc=Score Pr=Product To=Total

8. CONCLUSIONS

8.1 The following conclusions are made about winding technique:

8.1.1 The most critical quantities to control are tension and wire guide position.

8.1.2 Winding design must be considered carefully to allow quick and accurate winding.

8.1.3 Computer models for LVDT design can aid understanding but none are sufficiently accurate to produce designs for the majority of LVDTs.

8.2 The following conclusions are made about the present windings machines:

8.2.1 The present winding machines produce windings of sufficient quality and accuracy for Penny and Giles needs provided the operator has sufficient training, experience and concentration and the correct settings for tension and winding speed are recorded and used.

8.2.2 The main shortfalls of the present system are: it requires a fairly high degree of operator skill; many windings require reworking and it is slow.

8.2.3 There is little scope for improving the present winding machine with the important exception of better tension measuring equipment.

8.3 The following conclusions are made about a replacement machine:

8.3.1 The most suitable type of machine would be a bobbin winder.

8.3.2 To replace the operator's skill requires a high degree of automatic control. ~~sophistication~~.

8.3.3 The bought-in machines most likely to satisfy Penny and Giles' reqirements are the Marsilli WM 06 PC and the Meteor M20.

8.3.4 Designing and building a machine from scratch should provide the most suitable design, but the large amount of work involved in its design and manufacture makes it too expensive to be justified.

8.4 The following conclusions are made about using the Morphological method:

8.4.1 The Morphological method provides a convenient and logical method for presenting the possible design solutions.

8.4.2 The ~~value~~ analysis carried out using the Morphological charts provided a convenient method of comparing the many and varied possible solutions.

8.4.3 For the best results from the value analysis the specification must be as complete and accurate as possible.

8.4.4 The accuracy of the method of assigning values to each parameter is greatly improved by weighting the most important quantities.

8.4.5 The best weighting system is to draw up a second Morphological chart of the most important quantities. The use of this Modified Morphological method has been demonstrated.

8.4.6 If the specification is complete and importance factors and parameter values are asigned correctly then the results from the Modified Morphological method can be used with a good degree of confidence.

9. FURTHER WORK

The possible solutions which have been identified as most promising should now be tested in detail. This should involve practical testing of each system to ensure the windings produced are satisfactory and that they can be produced economically.

Marsilli and Meteor have been contacted about tests on their machines and both were willing to carry out whatever tests are required. The first test should be to get these manufacturers to wind some of the windings Penny and Giles already produce. They should be supplied with bobbins, wire and detailed winding drawings. The windings the machine manfacturers produce should be compared with the same winding type produced in the present winding machine. The following parameters should be compared:

Visual inspection to note crossovers and voids

Coil resistance

Coil diameter.

The windings should then be built up into LVDTs and all the LVDT parameters listed earlier in this report should be compared. These tests should be carried out on a range of windings of different sizes and winding configurations.

If the windings produced are satisfactory for Penny and Giles LVDTs then the winding time, repeatability and failure rate must be checked to establish the machines are economically viable as predicted in the report.

Tests should also be carried out to establish that the design rules suggested in appendix E will make winding quicker and simpler. This could best be done by redesigning a range of the LVDTs already produced, but implementing these rules to see if windings of similar quality can be produced more quickly. This could be done with the present equipment or with any new machine purchased.

If the present machine is going to be used much longer then a new method of measuring tension should be employed. This should enable dynamic tension to be measured and should be used throughout the winding process including any downspooling which is carried out. The improvement in failure rate can then be measured.

APPENDIX A

Winding Types

The main types of LVDT design are briefly described below.

A.1 Three Section LVDTs

This is the simplest LVDT design with one cylindrical primary coil and two coaxial secondary coils placed symmetrically either side of it (figure A.1). This type of LVDT has been described by a number of sources. The earliest detailed description was by Schaevitz (1946). More recently it has been described by Schaevitz (1975), Herceg (1976) and Alloca and Stuart (1984).

A.2 Graded Winding LVDT

In this type of LVDT the primary is wound all the way along the LVDT length and the secondaries are wound on top, symmetrically about the centre. The geometry is adjusted to give the best linearity which requires more turns at the end than the centre.

There are two ways in which this grading can be achieved:

1. Layer winding - In this each layer on the secondary is shorter than the previous layer to produce the desired contour (figure A.2).
2. Section winding - Each secondary is wound in several sections with more turns in the outer sections (figure A.3).

Graded winding LVDTs are described briefly by Small (1988) and are mentioned by Rahman and Abdullah (1988).

A.3 Complementary or Tapered Winding LVDT

This type of winding is wound such that the total number of secondaries at any point is constant. A change in output occurs because from one side to the other the number of turns on one secondary increases as the number on the other decreases (figure A.4). The primary may be wound in alternate sections (figure

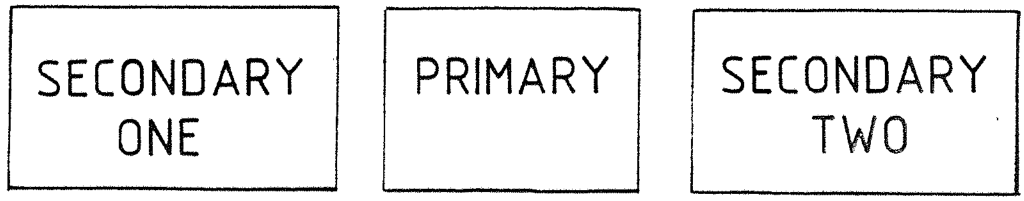

FIGURE A.1 THREE SECTION WINDING LVDT

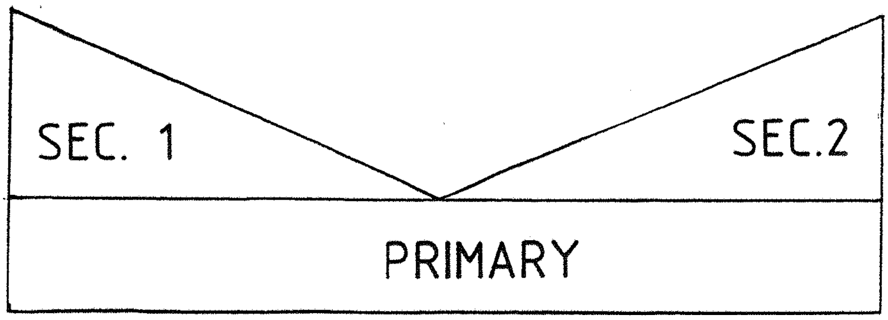

FIGURE A.2 LAYER WOUND GRADED LVDT

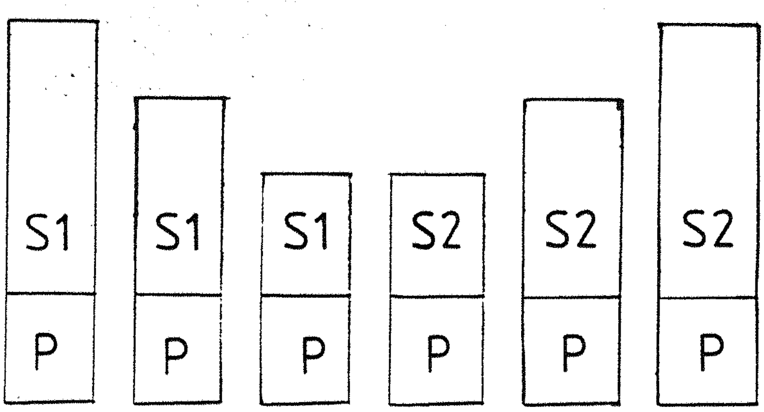

FIGURE A.3 STEP WOUND GRADED LVDT

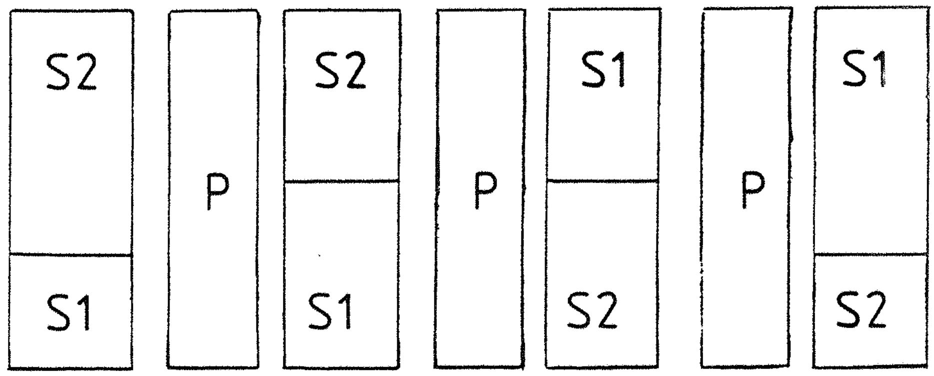

FIGURE A.4a PRIMARIES IN ALTERNATE SECTIONS

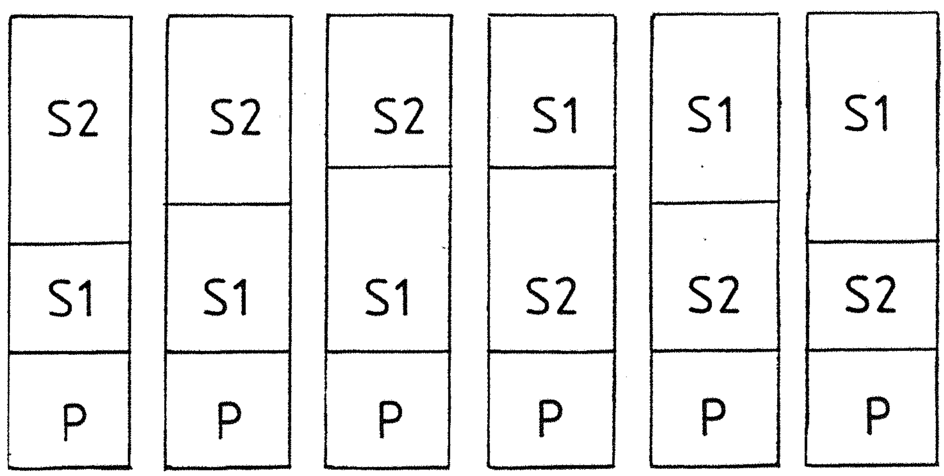

FIGURE A.4b PRIMARIES ALONG BOTTOM

FIGURE A.4 COMPLIMENTARY WINDING LVDT WITH TWO POSSIBLE PRIMARY CONFIGURATIONS

A.4a), along the bottom (figure A.4b) or, rarely, along the top.

Complimentary or tapered winding LVDTs are described by Herceg (1976) and mentioned by Rahman and Abdullah (1988).

APPENDIX B

Understanding Wire Layering

Several authors have highlighted the importance of a comprehensive understanding of the way in which wire forms into a coil in order to produce accurate layer windings. Stevens (1978) states "... the mechanical and electrical problems become more and more pronounced, underscoring the necessity of understanding the complete basics of winding coils". He goes on to suggest "... a successful winding operation cannot be achieved without such comprehensive understanding". George (1978) suggests "The important thing is that one understands the geometry of reversal and for the best results seek a good pattern." In order to gain an understanding he has drawn out the positions of the wire at a bobbin flange as the end of one layer and beginning of the next would appear. By considering the helix angles and hence the position the wire guide would be expected to take he has shown that motion of the wire guide will have no advantage as the wire lifts from one layer to the next. This is because the bobbin flange would interfere with the wire if the guide is moved beyond it. Hence the best winding is obtained by leaving the guide stationary for a turn or two at reversal.

In figures B.1 and B.2 the way in which wire could position itself over three layers is shown. The first layer of wire forms a helix. The next layer will be a helix of equal pitch and equal but negative helix angle. At two points of each turn the turns of the upper layer sit in the grooves between turns in the layer below. Figure B.1 shows a section through the coil at the position where this is the case. Figure B.2 is a section through the same coil but 90^{o} round from figure B.1. It is quickly seen that the appearance of the coil is much less well ordered in figure B.2. From figure B.2 it is clear that obtaining a perfect layer winding is not possible and some voids and cross-overs near the flanges must be accepted. The amount of voids and cross-overs will increase with the number of layers. This also means the number of turns which will fit on a

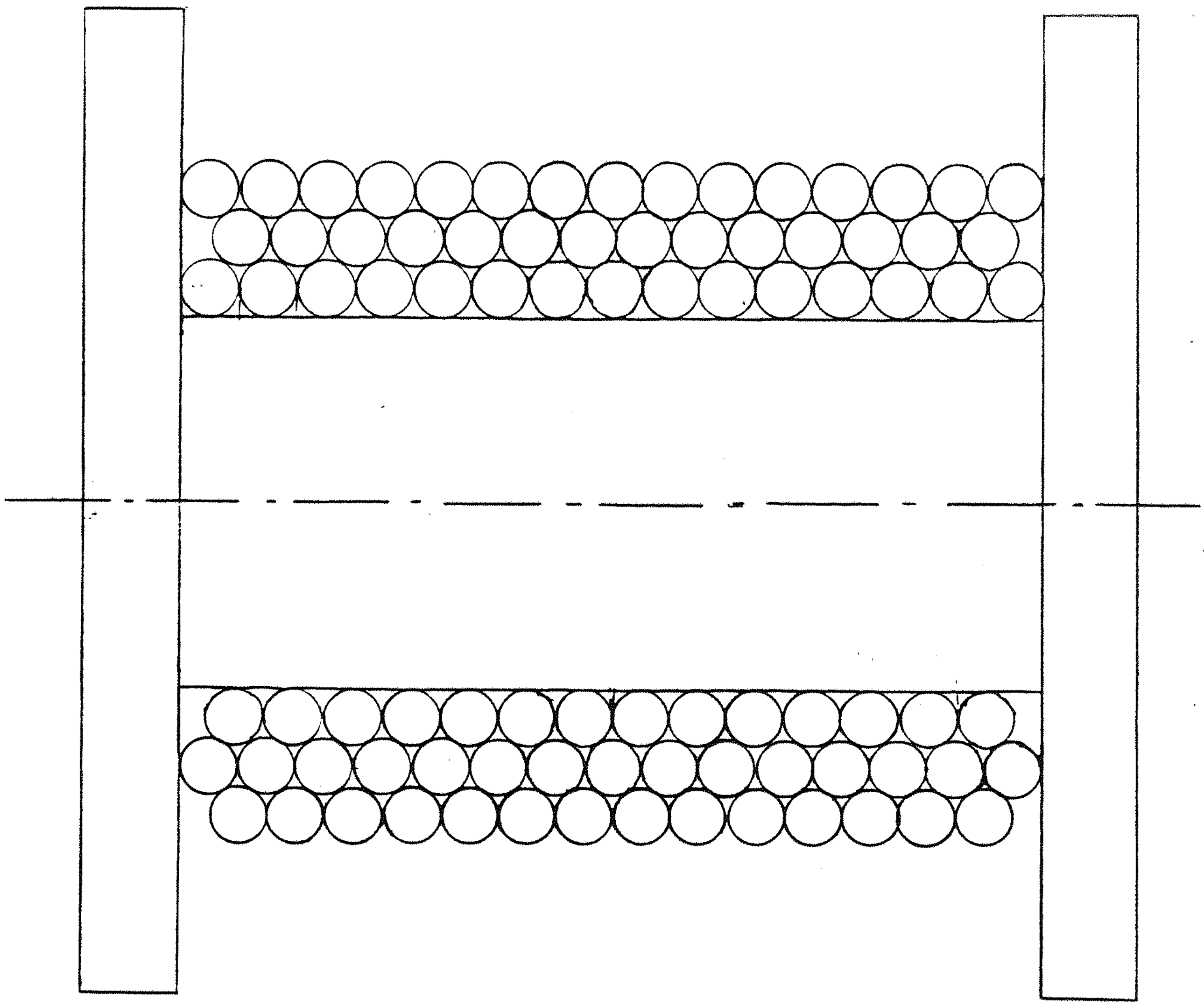

FIGURE B.1 SECTION THROUGH A LAYER WOUND COIL

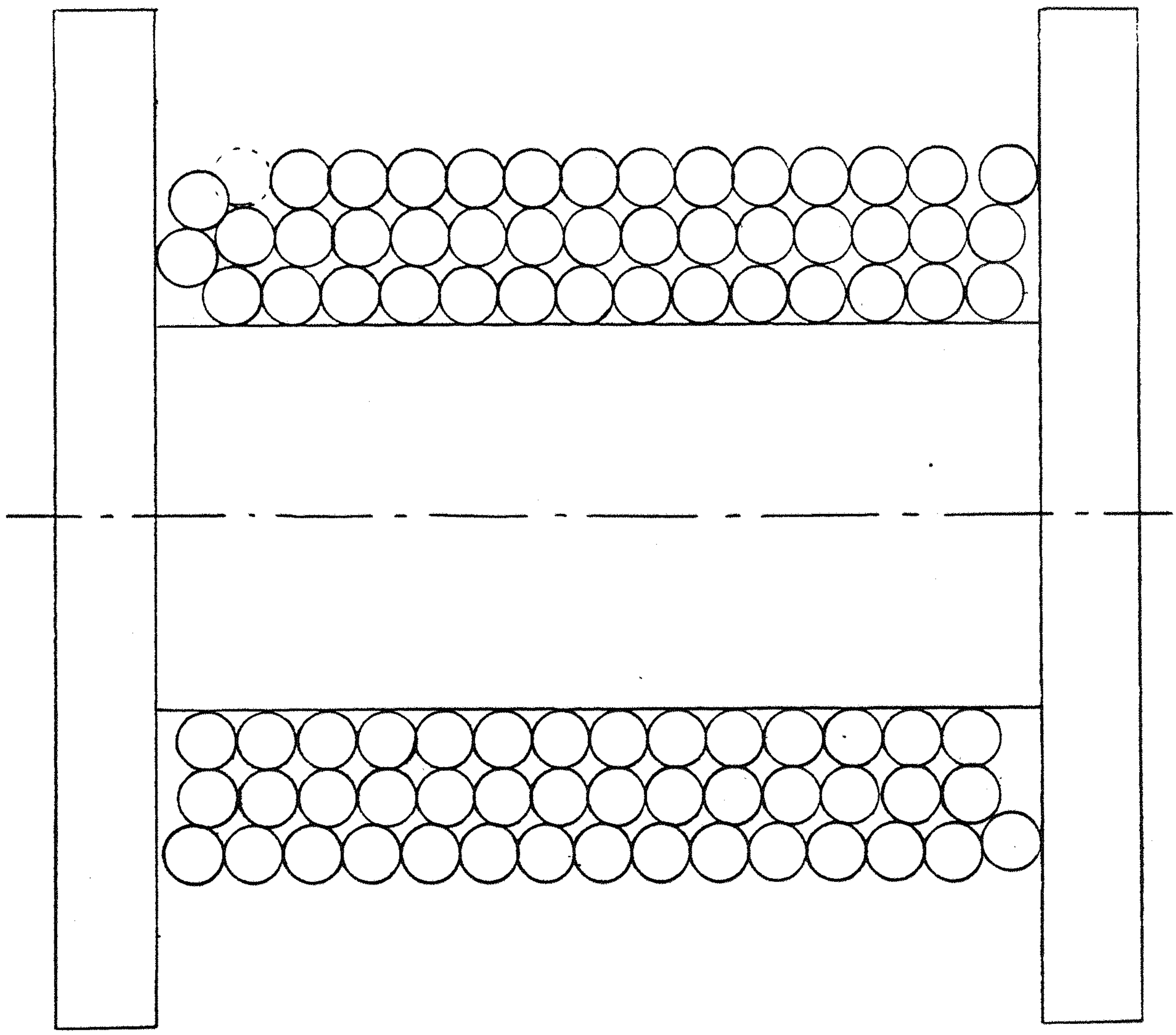

FIGURE B.2 SECTION THROUGH LAYER WOUND COIL bobbin will be somewhat less than might be expected by a calculation analogous to that for cylinders in a rectangular box.

These shortfalls from perfection must be considered when specifying windings and when evaluating winding systems.

APPENDIX C

Selection of Specification Qualifications

There follows a list of the reasoning and calculations made in the selection of qualifications to the winding system specification (section 5.3).

1. Winding Accuracy

1.1 Most LVDTs produced at Penny and Giles at present required layer winding with few voids. This may be for one or both of the following reasons - An even layer winding will provide the best accuracy and it will take up the minimum volume for a given number of turns.

1.2 Accurate reversal is essential for layer winding.

1.3.1 Reversal may occur at a bobbin cheek or on a graded winding, at the end of a layer. The layers on a graded winding are dimensioned from the nearest bobbin cheek to +/-0.075mm or larger (approximately +/-1 wire dimension).

To achieve accurate layer winding the position of the wire being wound in relation to the cheek is required to be better than 1 wire diameter. As the smallest wire size is 0.-5mm the tolerance +/-0.05mm was chosen.

1.3.2 As at reversal, an accuracy of about 1 wire diameter is required for accurate layering. The tolerance was chosen to provide a slight bias against the previous turn to give a tight, neat winding.

2. System Control

2.2 It is very unlikely a system will always produce perfect windings. Time and waste can be saved by having a facility to unwind and rework coils.

3. Counting the Turns

3.1 LVDTs and LVITs typically have from a few hundred to a few thousand turns.

3.2 On a winding with several sections the wire must finish to a known position with sufficient accuracy to be taken through a slot in the bobbin to the next section. An accuracy of +/-0.02 turns (7^{o}) should be sufficient to achieve this without making the slot unnecessarily wide.

To satisfy the unwinding requirement the counter must follow the spindle direction to achieve this accuracy if turns are removed.

4.Dereeling

4.1 1m/s is the amount of wire required to wind a 30mm diameter coil at 6000rpm.

6. Costing

6.3 The cost per winding can be used in comparing the 'actual cost' of different systems as opposed to just using capital outlay. An alternative would be to calculate the cost per hour for the system and hence find how fast the system must wind good coils to represent an improvement on the present system.

The cost per hour will include the following:

General overheads - factory rent, management etc.,

Operator cost,

Supervisor cost,

Running costs - electricity, waste, etc.,

Maintenance costs,

Writing down of capital over pay back period,

Interest on capital.

For two systems used in the same situation the general overheads cost will be the same for both systems, so need not be calculated for comparison.

Calculations for the present system:

Operator cost ~ £8000 / year,

Supervisor cost ~ £3000 / year - supervising several machines,

Running cost ~ £100 / year,

Maintenance ~ £300 / year - 1 to 2 days engineering time, Writing down = £0 - past pay back period,

Interest = £0

Total = £11400 / year plus overheads.

= £7 / hour plus overheads.

Winding time ~ 1.5 hours on average.

Cost per winding ~ £10.50 plus overheads.

7. Time

7.1 See 7.3

7.2 Improvements in lead time of the new LVDTs will mean better profitability for the system.

7.3 System downtime will affect the cost per winding and must be minimized to reduce the cost per winding.

7.4 The life must be greater than the pay back period.

8. Wire Traverse

8.2 The minimum pitch of 0.05mm is required for the minimum wire size. The maximum of 10mm is the largest that is required for space winding the last layer to achieve a uniform wire distribution for maximum accuracy. Sideways wore movement without rotation is required for correctly positioning the tails and for moving between sections particularly on complimentary windings.

9. Wire Tension

9.2 The maximum tension is the lowest useable tension for the minimum wire size and the maximum tension is the maximum permissible tension for the maximum wire size.

9.3 When a wire (particularly copper) is wound under tension it will be stretched by an amount dependant on the tension. by maintaining the tension less than the maximum permissible tension the stretching will be small. If the tension varies the resistance of the finished coil will vary which in turn will have an effect on the LVDTs characteristics. It was found that if the tension was varied by less than +/-10% the

LVDT characteristics were still acceptable.

10. Spindle Layout

10.4 Direction of winding must be selectable to satisfy unwinding demand. Also some types of LVDT and LVIT coils have turns wound in both senses.

10.5 The maximum wire acceleration for a particular wire can be calculated from the wire tension used and the maximum permissible tension. If the Penny and Giles recommended static tensions are used the maximum accelerations are easily calculated (figure C.1).

10.6.2 Angular acceleration is calculated directly from the linear wire acceleration and coil diameter.

10.6.3 The torque required at the bobbin under steady state equals the product of the wire tension and coil radius. The torque,T required to accelerate the bobbin can be calculated using

$$T = I \times A,$$

where I = moment of inertia

and A = angular acceleration.

12. Dimensions

12.1 This is the maximum and minimum wire sizes which have or are likely to be used.

12.3.1 This is the maximum and minimum diameters which have been or are likely to be used.

12.3.2 Most LVDT windings are less than 250mm long. Some special units are up to 650mm. These specials could be wound on the present system if the cost of having the facility for longer coils on a new system was not viable.

14. Wire Condition

14.1 No kinks are to be present as these may cause problems with achieving even layering and may cause enamel damage resulting in insulation failures.

If the number of twists is such that it is approaching 1 per bobbin turn this is also likely to cause problems with achieving even layer winding. 5 twists per metre represents one twist every two revolutions of a 30mm diameter coil.

14.2 Damage to enamel will cause insulation or dielectric failures.

14.3 Stretching of wire is usually caused by too high a tension. It will cause an increase in resistance as described earlier in this appendix. If the stretching is less than a 2% increase the resistance and impedance are found to be within the required limits.

APPENDIX D

Manufactured Winding Machines

There follows a list of all the manufacturers of possibly suitable bobbin winding machines in this country together with the main manufacturers from the US. The address of each manufacturer is given and a brief description of the main machines they produce. These descriptions include an approximate price which was correct at autumn 1989.

MANUFACTURER	SUPPLIERS ADDRESS	MACHINE	OPTIONS	PRICE	COMMENTS
Adams-Maxwell	1207 No La Brea Av. Inglewood California 90302 USA 213 673-3245	Model 1200		$1200	Single spindle hand fed winders.
			-1		Wire size: 0.025-0.5mm Speed: 5000rpm
			-2		Wire size: 0.025-0.1mm Speed: 3600rpm
			-3		Wire size: Up to 1.6mm Speed: 150rpm
		Model 1200	+1250 Auto-traverse	$3500	Auto-traverse adds Computer control to standard 1200. Pitch increment: 0.001mm
					Wire size: As above Traverse: 250mm Speed: As above
Aumman	(Bill Wallen) 1 Horatius Way Silver Wing Ind Est Croydon CR0 4RU 01 680 3292	WU		£3000	Winding machine for fine and very fine wire. Compact design. Automatic traverse. Electronic counter. Belt driven spindle.
			Longer beds Pneumatic reset		Wire size: 0.04-0.55mm Traverse: 100mm Speed: 12000rpm

MANUFACTURER	SUPPLIERS ADDRESS	MACHINE	OPTIONS	PRICE	COMMENTS
Aumann	As above	WG 300		£3500	Versatile coil winding machine. Automatic traverse. Electronic counter. Easy access for manual operations. Wire size: 0.04-1.7mm Traverse: 150mm Speed: 6000rpm
		PW 300	PW Meric Processor Control	£7050	Basic programmable winding machine. Numeric control. Similar mechanics to WG300.
			PW 500		500mm bed (300mm traverse)
			PW 700		700mm bed (300mm traverse) Wire size: 0.05-1mm Traverse: 300mm Speed: 6000rpm

MANUFACTURER	SUPPLIERS ADDRESS	MACHINE	OPTIONS	PRICE	COMMENTS
Aumann	As above	CW	Conuc controller		Fully computer controlled bench winding machine. Keyboard + VDU operation. Traverse control by servo motors + encoder. Slow running speed availiable.
			/E	£10500	For fine wires and high speed. Wire size: 0.01-1mm Traverse: 200mm Speed: 12000rpm
			/T	£13100	For heavy wire and complicated tasks.
			Extensive accessory range		Wire size: 0.05-5mm Traverse: 200mm Speed: 6000rpm
Blume and Redecker	(Robert Clark) 57-59 Stanley Rd West Croydon CR0 3QF 01 683 1119	CPW 2000		£11500	Computerized precision compact winding machine. Text entry - Menu driven. Floppy disk storage. Teach in facility. Wire size: 0.02-0.8mm Traverse: 250mm Speed: 15000rpm

MANUFACTURER	SUPPLIERS ADDRESS	MACHINE	OPTIONS	PRICE	COMMENTS
Bobifil	Koelectic Ltd Dean Int Ho Thames Ind Est Marlow Bucks SL7 1TB 06284 77266	BE 23		£2250	General purpose basic bench winder.
		ER 33		£3350	Medium fast versatile winder.
			+MP 1	£4850	Adds computer control to traverse and turns counter.
			+CNC 1	£10000	Adds full computer control to all functions. Contol by 2 low inertia motors. Modular construction. Wire size: 0.001-2.5mm Traverse: 200mm Speed: 3100-9400
COWECO	Koelectric Ltd As above	CS		£2900	Basic bench winder. Cam actuated traverse. Change gears for pitch. Auto stop. Speed: 10000rpm
		C		£3000	As CS +longer base. Speed: 5000rpm

MANUFACTURER	SUPPLIERS ADDRESS	MACHINE	OPTIONS	PRICE	COMMENTS
COWECO	As above	DL	Single or Dual preset mechanical Counter Multipreset electrical Counter	£6700	Variable feed coil winders. Wire spacing continuously variable whilst winding. Traverse set by number of turns or adjustable stops. Wire size: 0.025-1.6mm Traverse: 150mm Speed: 8000rpm
		DLS			As DL with short base less tailstock.
		W		£5500	Laboratory Winder. Versatile winding machine. Wides universal, progressive universal and back wound coils. Adjustable cam traverse.
		WX			As W + Variable transmission traverse.
Koelectric	As above	RH/1	Motor sizes 1/15 to 5/8 hp	£210	Low cost powered winder. Manual guiding of wire. Wire size: up to 0.6mm Traverse: 150mm Speed: 1500rpm

MANUFACTURER	SUPPLIERS ADDRESS	MACHINE	OPTIONS	PRICE	COMMENTS
Cranco	Cranleigh Coil Winding Equipment The Common Cranleigh Surrey GU6 8LU 0483 273536	CW 3	with DM1 motor and CS3 counter-shaft	£1300	Simple bench winder. Infinately variable traverse rate. Auto traverse using leadscrew. Wire size: 0.05-0.5mm Traverse: 125mm Speed: 3900rpm
		CW 45	/GTH off end despooled tenioner /RC2 side despooled tensioner	£1600	Basic bench winder. Winding spindle driven from motor shaft. Motor speed electronically controlled. Smooth slow starts. Manual control slow/stop. Traverse as CW 3. Wire size: 0.05-0.5mm Traverse: 125mm Speed: 8000rpm
		CW 46	As CW 45	£2000	Similar to CW 45 + one preset slow/stop. Electromechanical brake. Wire size: 0.05-0.5mm Traverse: 125mm Speed: 8000rpm

MANUFACTURER	SUPPLIERS ADDRESS	MACHINE	OPTIONS	PRICE	COMMENTS
Cranco	As above	CW 66	Wire feed systems RC1 + ST1 for medium/ fine wires	£3700 +£230	Bench winder with pitch continuously variable. 9 fixed speeds. Smooth run up to speed. Auto stop. Adjustable stops for traverse. Wire size: 0.05-2.5mm Traverse: 190mm Speed: 5500rpm
		CW 76	As CW 66 Range of accessories	£4900	Versatile, accurate winding machine. Electronic control. Auto slow/stop. Multi-preset. Bidirectional. Wire size: 0.05-2.5mm Traverse: 320mm Speed: 6000rpm
Deron Electronics	Unit 3 Lisle Rd Hughenden Av High Wycombe Bucks 0494 23485	Spindle-Master D 2000	Variety of Options and accesories: Tensioners Dereelers Jog pedel	£9000	Totally programmable winder for wide variety of coils. Modular construction. Manual facilities availiable. Wire size: 0.02-1.7mm Traverse: 150mm Speed: 6000rpm

MANUFACTURER	SUPPLIERS ADDRESS	MACHINE	OPTIONS	PRICE	COMMENTS
Fisher-Baker Corp	3108 Industrial 31st St Ft Pierce Florida 34936 USA 305 466 0750	Model 351		$7400	Bench bobbin winder.
			Tensioners	$125+	Servo driven electronic control.
			Break Detector	$180	Continuous pitch selection whilst running by pot. Wire size: 0.04-1mm Traverse: 100mm Speed: 16000rpm
Marsilli	(Peter Eddens) Edson Machinery Unit 7 Faraday Pk Ind Est Faraday Way Orpington Kent BR5 3QW 0689 75421	WM 06	PC Controller	£19000	Layer coil winding Machine. Interfaced to PC. Stores in memory relavent information: Speed, pitch, acceleration, turns ect. PC has closed loop control. Change pitch in operation. Manual unwinding. Slow speed for manual use.
			S Controller	£13500	Numerical control. Easier programming. Open loop control. Reversal by turns/layer or limit switches. Wire size: 0.02-1.5mm Traverse: 270mm Speed: 12000rpm Torque: 1.25Nm

MANUFACTURER	SUPPLIERS ADDRESS	MACHINE	OPTIONS	PRICE	COMMENTS
Marsilli	As above	WM 26	PC Controller	£20000	All functions of coresponding WM 06 machine.
			S Controller	£14500	Wire size: 0.03-3.5mm Traverse: 450mm Speed: 6600rpm Torque: 2.3Nm
			Altic dereelers/ tensioners M65F for 0.04-0.25mm wire	£350	
Meteor	(Malcom Bates) Micafil (GB) Ltd 8 Church St Rugby CV21 3PH 0788 73391	ME307-101		£9500	High capacity fine wire winding machine. Adjustable start to selected speed. Electronic counters. 10 presets. Slow and stop - Auto reset.
			Range of accessories		Wire size: 0.01-0.5mm Traverse: 100mm Speed: 15000rpm

MANUFACTURER	SUPPLIERS ADDRESS	MACHINE	OPTIONS	PRICE	COMMENTS
Meteor	As above	M 01B		£10000	Universal high capacity fine wire winding machine. Electonic controller. Speeds and feed infinately variable. Electrodynamic braking.
			Range of accessories		Wire size: 0.01-1.7mm Traverse: 200mm Speed: 12000rpm
		M 20	Standard bed	£16250	Numerically controlled programmable winder. Easily programmed by menu technque.
			Long bed	£17500	Calculates feed. Correction of feed reversing error. Winds multisection and varying winding width.
			Range of accessories		Wire size: 0.01-2mm Traverse: 200mm standard 540mm long Speed: 15000rpm
		M 40	Electric tailstock	£18000	Numerically controlled programmable heavy guage winder for high quality. Similar to M 20 control. Wire size: 0.2-4mm

MANUFACTURER	SUPPLIERS ADDRESS	MACHINE	OPTIONS	PRICE	COMMENTS
Rotawinder	Forest Rd Hainault Ilford Essex IG6 3HJ 01 501 0369	200		£16000	Versatile high speed programmable winder. Cone or flywinding heads. Mocroprocessor control. Nudge keys to correct coil shape. Wire size: 0.02-0.25mm Traverse: 70mm Speed: 45000rpm
Tenaka	CPG equipment Ltd 54 Central Rd Worcester Pk Surrey KT4 8HY 01 330 2323	AW-852V	Tailstock Tensioners Controllers M-56R	£5000	Automatic coil winder. Microprocessor control. M-56R controllers gives 100 step programme. Suitable for coils with taps. Wire size: 0.02-2mm Traverse: 80mm Speed: 10000rpm
		AW-853V	Tailstock Tensioners Controllers M-58R	£10500	Automatic winding machine. Similar to AW-852V + long traverse. M-58R has all features of M-56R + sectional winding capabilities. Wire size: 0.02-2mm Traverse: 300mm Speed: 3000rpm

MANUFACTURER	SUPPLIERS ADDRESS	MACHINE	OPTIONS	PRICE	COMMENTS
Tenaka	As above	AW-850			General purpose processor contolled coil winders. Front loading.
			M-55 controller	£3600	One stage winding - one pattern at a time.
			M-55R controller	£3900	As M-55 + spindle speed change.
			M-56R controller	£4400	Up to 100 step program. Multi-step coils. Variable width, pitch, turns.
			M-58R controller	£4900	As M-56R + sectional winding capabilities.
					Wire size: 0.02-1mm Traverse: 80mm Speed: 10000rpm
			850V		For thicker wire. Induction motor replaced by DC motor.
					Wire size: 0.02-2mm Traverse: 80mm Speed: 3000rpm

MANUFACTURER	SUPPLIERS ADDRESS	MACHINE	OPTIONS	PRICE	COMMENTS
Universal Mfg Co Inc	(Geoff Wilkinson) Gear Link Unit 21 Matrix Ho 18 Constitution Hl Leicester LE1 1PL 0533 623532	Model 2.5UB		£	Microprocessor controlled bobbin winding machine. Micro control of all winding functions. Servo motor drives. Footswitch jogging of spindle. Wire size: 0.025-1.6mm Traverse: 200mm Speed: 10000rpm
Frank Whitelegg	Curtis Rd Dorking Surrey RH4 1EJ 0306 881337	AL1		£2300	Coil winding machine. Automatic wire guide driven by leadscrew. Single phase motor. Foot activated clutch and brake. Wire size: 0.05-1.5mm Traverse: 220mm Speed: 3200rpm
			AL2	£2600	3 phase motor. Wire size: 0.12-3mm Traverse: 240mm Speed: 2200rpm
			AL5	£3300	Wire size: 0.12-4mm Traverse: 400mm Speed: 1560rpm

APPENDIX E

Winding Design Rules

E.1 Suggested LVDT Design Rules for Achieving Straighforward Windings

The following conclusions and recommendations are made:-

1. Where choice is possible the type of winding used should be chosen in the following preferred order:

i. Three section winding.

ii. Sectional graded winding.

iii. Complementary winding.

iv. Layering graded winding.

2. Random winding should be allowed when it does not adversely affect performance.

3. The tolerances on the layer lengths of a layered graded winding should be made as large as will still achieve the required output quantities and in particular linearity.

4. The order in which sections of a complimentary winding are filled should be considered carefully. The quickest and easiest route for the wire can then be found.

5. The largest wire size which will achieve the required performance should be used.

6. i. Select tension carefully to suit wire size and bobbin design and hence to give the optimum winding.

ii. The maximum permissible tension for the wire size being used must never be exceeded.

iii. The tension selected must be stated clearly on the winding drawing together with whether it is measured statically or dynamically. The latter is always preferable.

7. i. Tension is spindle speed dependent and hence the winding speed must also be selected to give the optimum winding.

ii. The selected winding speed must be shown clearly on the winding drawing.

8. The bobbin cheeks must be thick enough not to be distorted by the wire.

9. The bobbin slot must go right to the base of the bobbin cheeks.

10. i. The bobbin must be clean, deburred and free of any steps on the surface to be wound on.

ii. The bobbin surface should be rough enough that the coil of wire will not slide around.

11. All the information necessary to produce a completed winding must be included on the winding drawing.

12. In the future the use of computer aided design to allow analysis of different windings without building them, should be considered.

Care must be taken that the performance of the LVDT does not suffer because of efforts to make the winding simple to produce.

E.2 Reasoning for Design Rules

1. The order shown is the order of difficulty of winding, and therefore winding time, from the easiest and quickest to the most complex and time consuming.

2. It is much quicker and easier to perform random winding than layer winding.

3. A larger dimensional tolerance makes winding operations quicker.

4. The methods of winding complementary windings are best demonstrated by an example. Consider five adjacent sections which are to be wound with 1 layer of wire in the first, 2 in the second etc. If the sections are wound consecutively a pin must be used to reverse direction in certain sections. This is because with even numbers of layers the wire finishes at the wrong side of a section. The wire is normally looped around a pin to allow the direction to be reversed. The pin is removed after winding the next section. This leaves a loop of wire which is prone to damage.

By winding the sections in the order 1,3,4,2,5 the wire always finishes going towards the next section to be wound (figure E.1).

5. Larger wire is easier to handle, easier to wind and is less prone to stretching and breakage.

6. The correct selection and use of tension has a major effect on the winding quality.

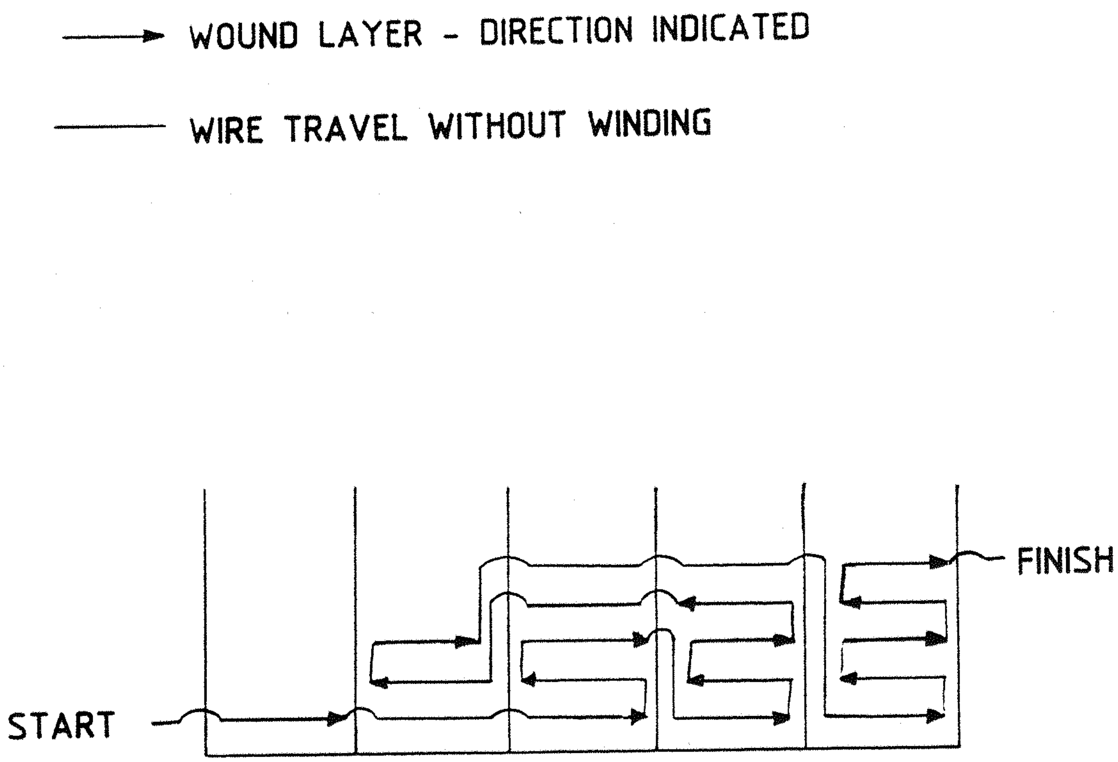

FIGURE E,1 METHOD FOR MULTISECTION WINDING AVOIDING REVERSAL BETWEEN SECTIONS

This has been discussed in the introduction and elsewhere in this report.

7. The effect of spindle speed on tension has also been discussed elsewhere in this report.

8. Thin bobbin cheeks can be pushed outwards as a section is filled with wire. This makes accurate layer winding very difficult in adjacent sections.

9. If the slot through the bobbin cheeks does not go to the base of the cheek the wire will stick out proud of the first layer and introduce voids into subsequent layers.

10. i) Dirt, burrs or steps on the winding surface will all impede the disired layering of wire.

ii) If the winding surface is too smooth the coil of wire can slide around after winding and damage to the wire is likely to occur.

11. Including all necessary information on the winding drawing is obvious, but some important information such as winding speed can often be overlooked if its importance is not realised.

12. The potential of computer aided design and analysis has been discussed elsewhere in this report.

REFERENCES

Abdullah, F.; Finkelstein, L.; Rahman, M.M. (1977): "The Application of Mathematical Models in the Evaluation and Design of Electromechanical Instrument Transducers", Journal of Applied Science and Engineering A, V.2, pp. 3-26.

Adams, R.J. (1984): "The Evolution of Winder Control", Tappi Journal, V.67, n.10, pp. 72-75.

Alloca, J.A. and Stuart, A. (1984): "Transducer - Theory and Applications", Reston Publishing Co. Inc., Reston, Virginia

Atkinson, P.D. and Hynes, R.W. (1954): "Analysis and Design of a Linear Differential Transformer", The Elliott Journal, V.2, pp. 144-151.

Aumann Technical Data: "Wire Size and Tension Information", Aumann (UK) Ltd., Croydon.

Barmaper Ltd. (1988): "Technical Data - Enamelled Copper Winding Wire", Barmaper Ltd., Stanmore, Middx.

Brosh, A. (1961): "Differential Transformer", US. Patent 2,985,854, May 23.

Brown, A.D. (1987): "Universal Winding: A Review of Basic Theory and a Discussion of Modern Winding Techniques", ICWA Proceedings 1987, Rosemont, Il., pp. 52-57.

Cannon, G. and Holt, N. (1982): "Evaluation of Aumann PW Meric Winding Machine", Penny and Giles Test Report No. 371, Oct 1982.

Carden, P.J. (1988): "Initial Design Study of Coil Winding Process", BSc Project, Dept. of Mech. Eng., Southampton University.

Conway, J. (1975): "Tension Control in Fibre Filament and Wire Winding", Wire Industry, V.42, n.497, pp. 369-370.

De Sa Silva, C. (1972): "What Size Stepper?", Machine Design, Dec. 1972, pp. 1-8.

Erickson, D. (1980): "Coil Winding Report", Electronic Packaging and Production, V.20, n.9, pp. 161-171.

Faresse, F.B. (1988): "Controlling Precision Winders with Clutches and Brakes", Power Transmission Design, V.30, n.10, pp. 25-27.

Franke, F. (1988): "The Basic Types of Machine in the Coil Winding Industry", ICWA Proceedings 1988, Cincinnati, Ohio, pp. 20-21.

Garrett, J.D. (1979): "Survey of Displacement Transducers below 50mm", Journal of Physics E, V.12, pp. 562-573.

George H.A. (1978): "Coil Winding Machine Design: An Analysis of Current Practices and their Effect on Coil Quality", Coil Winding International, V.2, n.1, pp. 23-29.

Goan, J. (1981): "Counters for Coil Winding Machines", ICWA Proceedings 1981, Chicago, Il., pp. 59-61.

Heddle, T.A. (1952): "A Method of Designing a Compensated Solenoid giving Approximately Uniform Field", British Journal of Applied Physics, V.3, p. 95.

Herceg, E.E. (1976): "Handbook of Measurement and Control", Handbook HB-84, Schaevitz Engineering, Pennsauken, N.J.

Holt, N. (1982): "The Inductor Transducer", Project No. 1506, Penny and Giles, Christchurch.

Kellaway, M. and Green, R. (1990): "Making the Right Power System Choice", Eureka, V.10, n.4, pp. 67-74.

Leigh, C.R.A. (1989): "Test Report on the Schmitt ZD100 Tensionmeter", Test Report No. 402, Penny and Giles, Christchurch.

Lockwood, M. and Woods, A.W. (1988): "Equipment Control: The Status of Hardware Development and Control Techniques", Coil Winding Iternational 1988, London, pp. 3.1-3.1.11.

Manning, T.A. (1986): "Advantages of Programmable Winding Machines in a Low Cost Labour Market", ICWA Proceedings 1986, Hong Kong, pp. 43-46.

McKenzie, P. (1988): "Production of Special Inductive Transducer Coils", BSc Project Report, Dept. of Mech. Eng., Southampton University.

Mitchell, P. (1983): "Counters, Steppers, Servos and Computers as Applied to the Coil Winding Industry", ICWA Proceedings 1983, Chicago, Il., pp. 96-101.

Moore J.H. (1988): "Linear Variable Inductance Position Transducer for Suspension Systems", IMechE paper C428/88, pp. 75-81.

Neubert, H.K.P. (1975): "Instrument Transducers - An Introduction to their Performance and Design - 2nd Ed.", Oxford University Press, London.

New, R.E. (1989): "A Non-Contacting Transducer for use in Hydraulic or Pneumatic Cylinders", Transducer Technology, April 1989, pp. 11-13.

Norris, K.W. (1963): "The Morphological Approach to Engineering Design", Conference on Engineering Design, Permagon press, Oxford, pp.115-140.

Ording, J.J. (1984): "Microstepping Motion Control", ICWA Proceedings 1984, Chicago, Il., pp. 100-105.

Pahl, G. and Beitz, W. (1984): "Engineering Design", The Design Council, London.

Patranibis, D. (1976): "Principles of Industrial Measurement", McGraw-Hill, New Delhi.

Persson, E.K. (1984): "Brushless Motor Systems for Coil Winding Applications", ICWA Proceedings 1984, Chicago, Il., pp. 171-174.

Pitts, G. (1973): "Techniques in Engineering Design", Butterworths, London.

Rahman, M.M. (1979): "Mathematical Modelling and Computer Aided Design of Field Coupled Electro-Mechanical Transducers", PhD Thesis, Dept. of Systems Science, City University, London.

Rahman M.M. and Abdullah, F. (1988): "Computer Aided Modelling of Unconventional Coils for Inductive Sensors", Coil Winding International Conference, London, pp. 2.1-2.1.13.

Schaevitz, H. (1946): "The Linear Variable Differential Transformer", Proceedings of the Society of Experimental Stress Analysis, V.4, pp. 79-88.

Schaevitz, H. (1975): "LVDTs Provide High Resolution Displacement Measurement", Electronic Products Magazine, V.17, n.10, pp. 53-61.

Shah, M.K. (1985): "Trends in Coil Winding Controls", ICWA Proceedings 1985, Boston, Ma., pp. 118-123.

Small, G.D. (1988): "A Survey of Precision Linear Displacement Measurement", ERA Report 87-0347R, ERA Technology, Leatherhead.

Stevens, J. (1978): "The Secrets of Good Coil Winding", Electronic Packaging and Production, V.18, pp. 225-228.

Sydenham, P.H. (1972): "Microdisplacement Transducers", Journel of Physics E, V.5, pp. 721-735.

Tenaka (1988): "Tenaka Technical Data", Tenaka.

Valente, G.M. and Manning, T.A. (1987): "Types of Coil Winding Machine and their Applications", ICWA Proceedings 1987, Rosemont, Il., pp. 62-68.

Wallace, K.M. and Hales, C. (1984): "Some Applications of a Systematic Design Approach in Britian", Konstruktion, V.39, n.7, pp. 275-279.

Zwicky, F. (1948): "The Mophological Method of Analysis and Construction", Courant Anniversity Vol. 1948, pp. 461-470.