ELECTRONIC BASED ACCURACY ENHANCEMENT OF CNC MACHINE TOOLS

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ABSTRACT

The need for better machine tool accuracy is discussed together with the factors which can affect machine tool accuracy. A study is made of the various techniques adopted for the reduction of errors in machine tools. The concept of error compensation is discussed and the different techniques for error compensation are appraised. A critical appraisal is presented of the work undertaken to date in the field of error compensation. Based on this appraisal a criterion is established for a universally applicable error compensation system. The development of a novel, patented microprocessor based machine tool error compensation system which fulfills this criterion is described. This compensation system, which is based on the precalibrated compensation technique, utilizes a unique geometric compensation algorithm. This algorithm allows the compensation system to compensate for the geometric error components of any machine tool configuration up to three axes. The development of this geometric algorithm is presented. The integration of this compensation system to a large moving column milling machine is described. Measurement tests and cutting tests were performed on this milling machine to establish the effectiveness of the compensation system. The results from these experimental tests are presented, and illustrate the significant improvement in machine tool accuracy achieved through error compensation.

This is the first attempt at producing a machine tool error compensation system with universal applicability, both in terms of the machine geometric model, and the method of applying the compensation to the machine tool. The error compensation system developed gives the potential for compensating for thermally induced and load induced position errors, and will enable further work in this area to be commercially exploited.

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1 INTRODUCTION

1.1 The Need For Greater Accuracy

The purpose of this research is to develop a general purpose compensation system that is capable of enhancing the accuracy of NC and CNC machine tools by correcting for the systematic position errors within the machine tool. In todays modern and competitive manufacturing environment there is an ever increasing need for machine tools of higher precision and greater accuracy. The benefits to be gained from machine tool accuracy enhancement are many, the major benefits being (1):-

- to speed up the process of supplanting, fitting by assembly.

- to ensure better interchangeability of components by manufacturing to higher tolerances.

- to achieve better product performance and reliability.

- to achieve a higher efficiency of manufacture and reduce costs through better machine accuracy capabilities, i.e. reduction of scrap and rework.

This demand for higher precision and greater accuracy has placed a burden on machine tool manufacturers to produce machine tools of a higher overall performance.

The advent of NC and CNC machine tool technology has gone a long way to improving the overall precision of the manufacturing process, by providing a level of consistency that could not be attained from manually based manufacturing. However, the accuracy of manufacturing is still limited by the accuracy capabilities of the machine tool. Any errors in machine tool motion during cutting will be directly reflected in the accuracy of the machined component.

The problem of improving machine tool accuracy is difficult to solve and is greatly compounded by the fact that there are a number of factors contributing to the machine inaccuracy, most of which are completely unrelated.

1.2 The Major Factors Affecting Machine Tool Accuracy

The factors which affect the accuracy of a machine tool and ultimately determine the accuracy of the workpiece are shown in figure 1.1 (2). This diagram shows the complex way in which the components of inaccuracy combine to affect the final accuracy of the workpiece. It can be seen from this diagram that the majority of the sources of error fall into one of three categories, namely errors produced from machine geometrical inaccuracies, errors produced through thermal fluctuations, and errors produced through loading effects. The errors which do not fall into these three categories are those errors associated with the controller, control system and servo system, such as programming error, interpolation error, quantisation error, transducer error etc. However, in a modern machine tool control system which has been correctly set up, these errors should be negligible.

1.2.1 Geometrical Inaccuracies

Geometrical inaccuracies are caused by the mechanical imperfections of the machine tool structure, and the misalignments of the machine tools elements, which are inherent to the production and build of a machine tool. These geometrical inaccuracies will change gradually during the lifetime of a machine due to wear. The effect of the geometrical inaccuracies is to produce errors in the squareness and parallelism between the machines moving elements, and to produce small unwanted motions of each of the machines moving elements.

To define the unwanted error motions produced by the

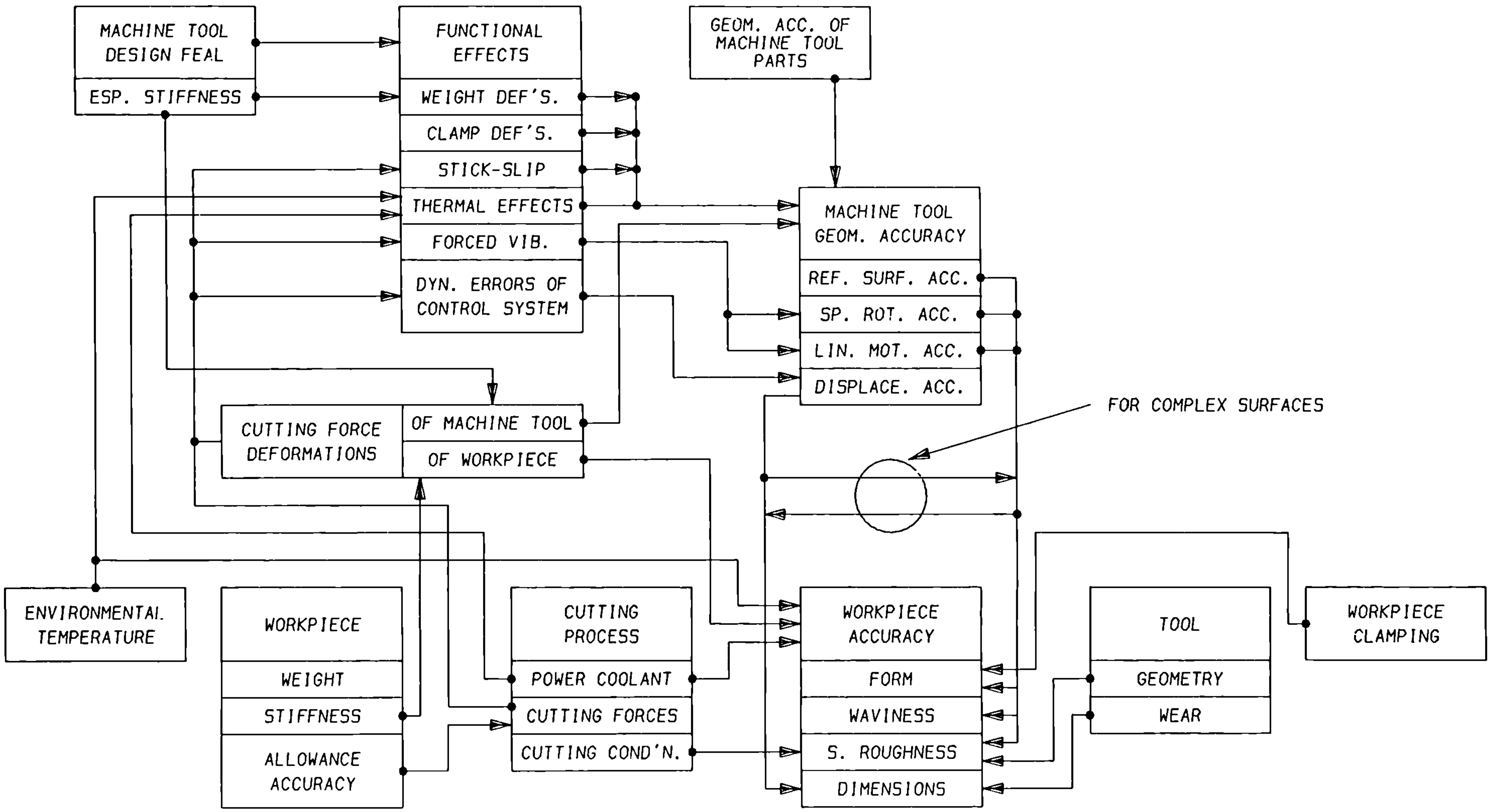


FIGURE 1.1 FACTORS INFLUENCING THE ACCURACY OF THE WORKPIECE

geometrical inaccuracies let us consider a machine tool slide. A perfect slide would be constrained to move in one degree of freedom only so as to produce perfect linear motion. However, as it is impossible to produce a mechanically perfect slide it will, in practice, exhibit movement in all six possible degrees of freedom. This results in three translational error components and three rotational components. These error components are shown diagrammatically in figure 1.2A. The translational error components are known as linear positioning error for positional inaccuracies in the desired direction of slide motion, and horizontal and vertical straightness errors for positional inaccuracies perpendicular to the desired direction of slide motion. The rotational errors are known as roll error for rotations about the desired direction of slide motion, and pitch and yaw errors for rotations about axes perpendicular to the desired direction of slide motion.

The error motions associated with a machine tool's rotational axes, such as a machine tool spindle are analogous to those associated with the translational axis. In this case the rotational axis is constrained to angular motion about its centre line but due to mechanical imperfections it also exhibits small error motions in all six degrees of freedom. The error components for a rotational axis are shown in figure 1.2B. In this case the translational errors are known as axial error for positional inaccuracies along the axis of desired rotation and horizontal and vertical radial errors for positional inaccuracies perpendicular to the axis of desired rotation. The rotational errors are known as angular positioning errors for angular errors about the axis of desired rotation, and horizontal and vertical tilt errors for angular errors about axes perpendicular to the axis of desired rotation.

In the case of a machine tool or workpiece drive axis, the angular position of the axis is generally unimportant

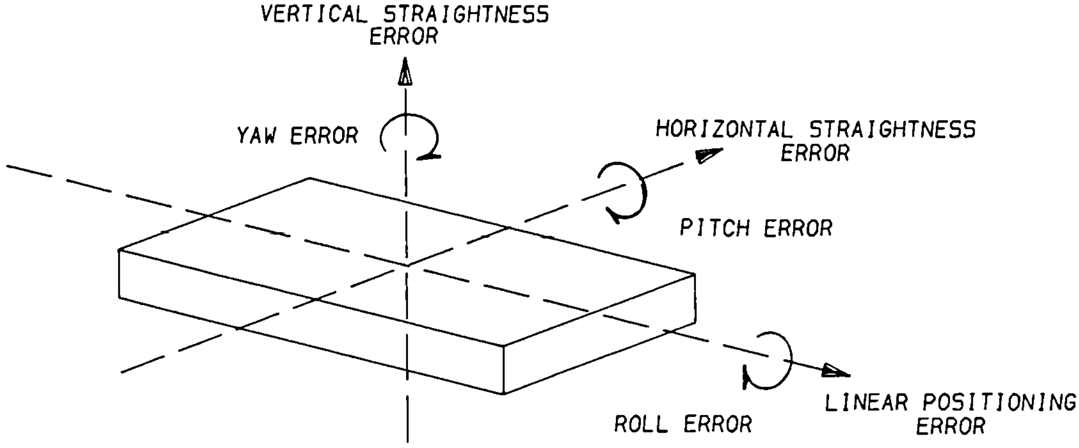


FIGURE 1.2A THE SIX DEGREES OF FREEDOM OF
A MACHINE TOOL SLIDE

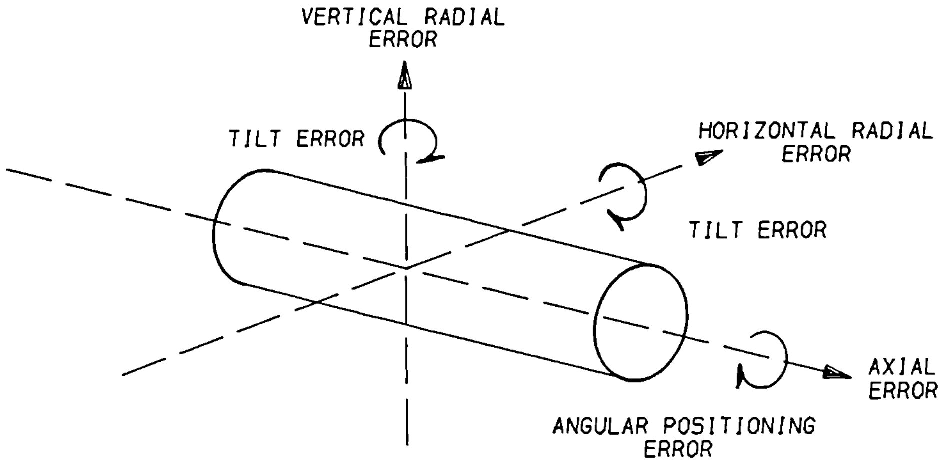


FIGURE 1.2B THE SIX DEGREES OF FREEDOM OF
A MACHINE TOOL SPINDLE

and the angular positioning error is therefore not significant. The angular positioning error is, of course, more important for a rotational positioning axis such as a machine rotary table.

It is apparent that for a practical machine tool the geometrical imperfections of the machine's moving elements will provide a large number of potential sources of positional error between the tool and workpiece. These errors will ultimately affect the workpiece accuracy. As an example consider a machining center with three translatory axes, a rotary positioning table and a tool spindle. This machine will exhibit a total of 32 error components resulting from its geometrical inaccuracies. These 32 error components are listed in table 1. All these 32 error components will interact with each other as the machine tool is in operation producing a varying positional deviation between the tool and workpiece.

TRANSLATIONAL MACHINE AXES	NUMBER OF ERROR COMPONENTS
LINEAR POSITIONING ERRORS	3
STRAIGHTNESS ERRORS	6
ROTATIONAL ERRORS	9
ORTHOGONALITY ERRORS BETWEEN MACHINE AXES	3
ROTATIONAL MACHINE AXES	
ANGULAR POSITIONING ERROR	1
ANGULAR TILT ERRORS	4
AXIAL ERRORS	2
RADIAL ERRORS	4
TOTAL NUMBER OF ERROR COMPONENTS	32

Table 1. The Geometrical Error Components Associated With A 3 Axis Machining Centre

1.2.1.1 The Constituents of the Geometric Error Components

The error components produced by the geometrical inaccuracies of the machine tool structure can be considered to be made up of two primary constituents. These two constituents are termed systematic or repeatable errors, and random or non-repeatable errors. The systematic errors are the dominant error constituent for most machine tools, and may be measured to quantify the accuracy of a machine tool. Due to its repeatable nature it is this type of error which may be eliminated by some form of compensation. For certain error components particularly the linear positioning error component the systematic error constituent can be further subdivided into the three more specific error constituents listed below.

Non-cyclic or progressive error - This error constituent exhibits a non-repetitive pattern of variation, i.e. it is non-periodic in form. This error is generally related to slide displacement and could result, for example, from a constant error in the pitch of a leadscrew.

Cyclic error - This error constituent exhibits a repetitive pattern of variation, i.e. it is periodic in form. The period of the cyclic error is a fraction of the length of travel of an axis and is normally related to the leadscrew pitch. The most common cause of this error is a pitch related inaccuracy in the form of the leadscrew.

Backlash error - This error is caused by mechanical hysteresis in the slide system which manifests itself as a positional deadband during changes in the sense of direction of slide motion. It is measured as the difference in the position error values at any single slide position when approaching that position from two opposite directions. This error may not be constant and can vary over the length of axis travel.

The random error constituent cannot be measured directly, and may only be analysed and expressed statistically. Due to the non-repeatable nature of these errors they cannot be eliminated by compensation, but do provide a useful guide as to the degree of accuracy improvement that may be obtained through compensation for a particular machine tool.

1.2.2 Thermally Induced Errors

The effects of environmental and self induced temerature changes on the accuracy of machine tools is well documented (3-9). Thermal fluctuations of the machine tool structure are caused by changes in environmental temperature, and heat sources local to the machine tool itself. The local sources of heat include, drive motors, gear trains and other transmission devices. These thermal fluctuations will cause expansion, contraction and deformation of the machine tool structure, effectively changing the geometrical errors of the machine tool and resulting in positional errors between the tool point and workpiece.

The effects of thermal fluctuations on a machines positional accuracy are not only dependent upon the degree of temperature variation but also upon the size of the machine tool. A machine member manufactured from mild steel for example will expand by 11.7 microns per metre length for every degree centigrade increase in temperature. The effect of temperature fluctuations on machine tool accuracy are therefore more significant for larger machines.

The effects of environmental temperature change can be greatly reduced by operating a machine tool in temperature controlled conditions, however, in many machine tools the main sources of thermal fluctuations are self generated. A localized source of thermal fluctuation would tend to produce a temperature gradient across the machine tool structure, as opposed to increasing the overall temperature of the machine tool. Two machine elements which are particularly prone to self generated thermal distortion are spindles and leadscrews.

Spindle growth is generally produced by heat generated in the drive transmission, and will vary greatly depending on the type of drive configuration and spindle assembly, the spindle speed and spindle loads. Leadscrew expansion is produced by heat generated in the drive transmission, particularly from friction due to the preload of the ballscrew nut. Leadscrew expansion will vary depending on the method of mounting the leadscrew, feed rates and cutting loads. The effects of leadscrew expansion can be minimised by the use of a linear positioning transducers which can expand in sympathy with the leadscrew and effectively correct for leadscrew growth.

1.2.3 Load Induced Errors

Varying mechanical loads applied to a machine will cause its structure to strain and deform, modifying the geometrical inaccuracies of the machine and resulting in positional errors between tool and workpiece. The varying loads applied to a machine tool during cutting operations provide the main source at this type of error. Load induced errors may also be produced, generally, (depending on the machine configurations) to a lesser extent by the movement of heavy masses (slides etc.) around the working zone of the machine.

In general the load on the machine will vary with a number of factors such as, tool condition, material to be machined, depth of cut and cutting speed. The effect of this load on machine accuracy will depend upon the machines resistance to elastic deformation or stiffness.

1.3 The Responsibilities of the Machine Tool User

All the sources of error discussed can, to a greater or lesser extent, contribute to the inaccuracy of a machine tool, ultimately effecting the final accuracy of the workpiece. However, a number of these error sources can be greatly influenced by the machine tool user in order to minimize their effect on workpiece accuracy. Indeed if a machine is to be used to produce high accuracy components it is the responsibility of the machine tool user to reduce as far as possible all error sources over which he has an influence.

Figure 1.3 shows the prime areas of responsibility for the machine tool user when using a machine to produce high accuracy work. It can be seen from figure 1.3 that the sources of error that can be influenced by the user fall into the categories of thermally induced errors and load induced errors. The machine tool user has no control over the geometrical inaccuracies of the machine, and to a large extent has to live with the effects of such inaccuracies.

To control the thermally induced errors the user can operate the machine in, at best, an environmentally controlled area, or at least in a position of environmental stability (eg, away from the influence of direct sunlight, away from doorways and other sources of direct heat or cold). The machine can be run prior to machining in a 'warm-up' cycle to attain machine thermal stability. The workpiece can be 'soaked' in the machine tool environment prior to machining to produce workpiece stability, and the correct use of coolant, cutting speeds and depth of cut can minimize workpiece expansion during cutting due to friction.

The effects of load induced errors can be reduced by the use of correct tooling together with the choice of the correct cutting speeds and feeds, the use of coolant to reduce friction, and by minimizing the depth of cut.

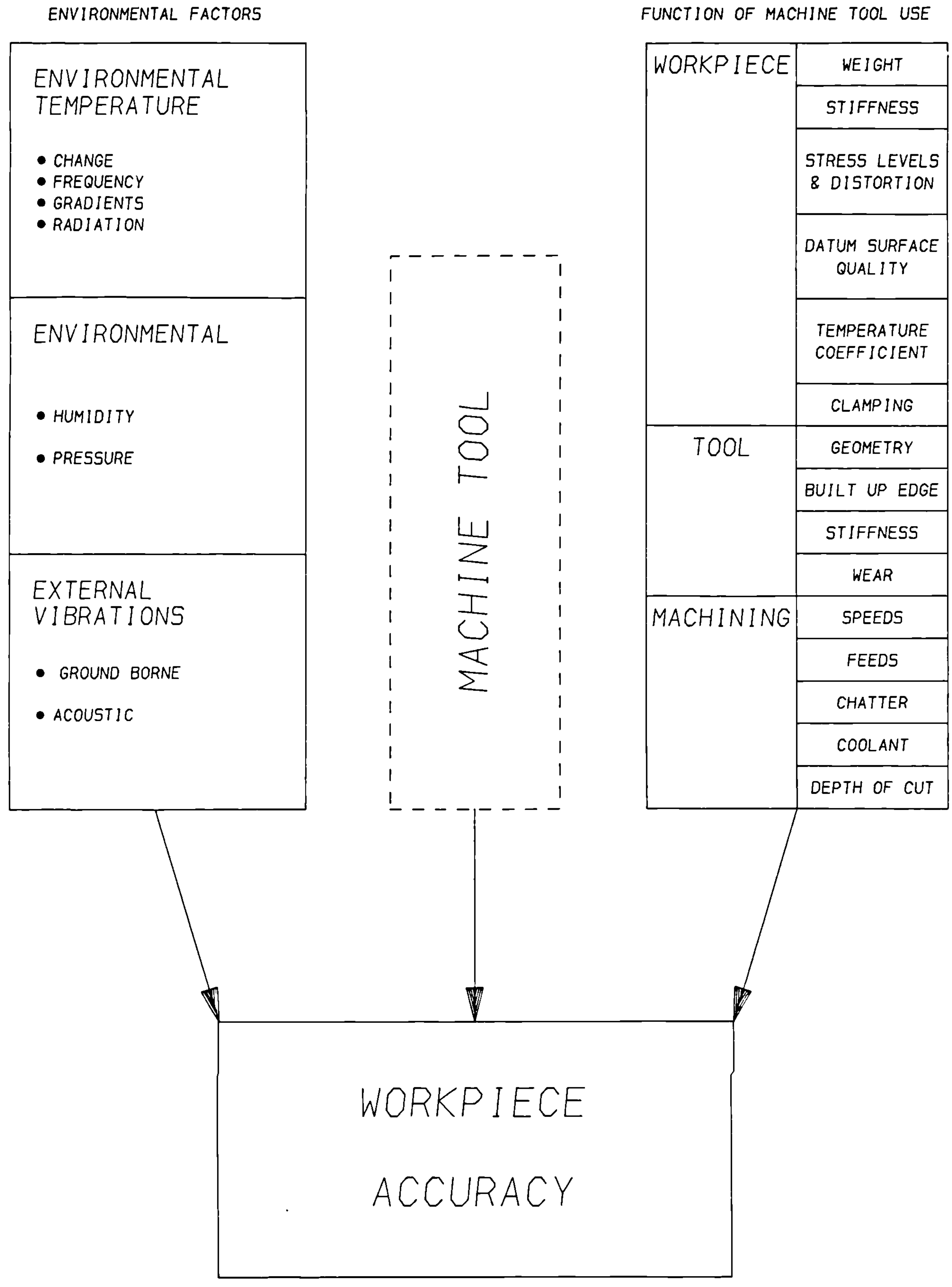


FIGURE 1.3 THE MACHINE TOOL USERS RESPONSIBILITIES

1.4 A Brief Description of Error Reduction Techniques

1.4.1 Error Avoidance

The most obvious technique for reducing machine tool error is error avoidance. Error avoidance attempts to eliminate the source of the error, or to eliminate the effect of the source of the error on the machine tool or workpiece. The preceding section described how the machine tool user could eliminate or reduce some thermally or load induced machining errors by careful and sensible control of the machining process. This approach to error reduction would fall under the category of error avoidance.

The machine tool manufacturer also attempts to control the accuracy of the machine tool by error avoidance techniques. McKeown (1) describes how the geometrical inaccuracies, thermal effects and mechanical loading effects could all be minimised, and machine tool accuracy improved, by better mechanical design, better machine tool construction techniques and the choice of stronger more mechanically and thermally stable materials. The use of better and more sophisticated controllers and transducer systems can also help to reduce error sources. These manufacturing solutions to the accuracy problem, however, would be extremely expensive to implement and would by no means guarantee to eliminate all the possible sources of error. There are therefore very few machining applications where the cost of these manufacturing techniques could be justified.

Blaedel in his paper on error reduction (10) sites a number of examples of error avoidance. The first example is seen in the ruling engine environment of Bausch and Lomb, where lights in the machine room are left off to prevent temperature change during the ruling of the diffraction grating, effectively eliminating a possible source of error. A second example given is that of the Moore Mk.3 jig borer spindle housing. In this case the varying heat source of the spindle bearing produced a dimensional change in the spindle housing. This problem was overcome by producing the spindle housing from a material more thermally stable than the Meehanite used throughout the rest of the jig borer. In this case, although the source of the error still remained, the effects of the source with respect to machine tool accuracy are eliminated.

1.4.2 Error Compensation

The second technique for error reduction is error compensation. Error compensation may be defined as cancelling or correcting for the effect of the error itself. In a number of ways error compensation is more attractive than error avoidance. Firstly, error compensation can be cheaper to implement than using some of the expensive manufacturing techniques of error avoidance. Secondly, error compensation can be more flexible in that it can accommodate changes in sources of error which can not always be accommodated by error avoidance techniques, such as machine wear and tool wear. Finally, error compensation can be used to correct for geometrical induced errors that cannot be eliminated through error avoidance.

In all error compensation techniques the machine errors are identified through some measurement process, and correction is applied to the machine tool to cancel the effects of the error. These error compensation techniques fall into two basic categories known as active compensation and pre-calibrated compensation.

1.4.2.1 Active Compensation

In active compensation measurement of the error and compensation for the error occur simultaneously. In other words the errors are identified on line using some form of measuring system, and corrected for as the machine is operating. Active compensation can be further subdivided into two categories depending upon where the measurement of the errors takes place.

In the first category the workpiece is used as a master and the technique is known as 'in process' error compensation. The geometry of the workpiece is measured at the machine tool during the machining operation. Any deviation from the desired form of the component is identified and the machining process is suitably adjusted to correct for the deviation.

In the second category of active compensation an 'external master' is measured to identify the machine errors. The external master is usually the machine itself. In this case the machines movement is measured and only deviation from the expected motion is corrected for. Examples of active compensation techniques are given in section 2.

Although the philosophy of active compensation is clear and fairly simple, it is often very difficult to implement in practice. The difficulties in implementing active compensation stem primarily from the need for on-line measurement of the errors. Firstly the measuring device has to be very sensitive and accurate (at least an order of accuracy higher than that of the measuring scales of the machine tool), and in all but a few cases there has been a lack of suitable measuring sensors (10). This leads to inconvenience and uncertainty in the measurement of the error. Secondly the cost of any suitable sensors and measuring systems tends to be very high. Finally in many cases the inaccessibility of the required measuring location, together with the hostile environment provided by the machine tool makes the implementation of such active compensation systems difficult and impractical.

1.4.2.2 Precalibrated Compensation

The second category of compensation, pre-calibrated compensation, differs from active compensation in that the error components of the machine tool are measured only once, either before or after a machining operation. The measured error values are then used to generate corrective values that may be applied to the machine tool during a machining operation. As the error components are measured only once for pre-calibrated compensation they are assumed to be repeatable.

Pre-calibrated compensation techniques can be further subdivided depending on whether the error identification and compensation is for the whole machine working zone or just about the contour of a particular component.

If the whole working zone is to be compensated for, the error components of interest are first identified for the whole of the working zone using a measurement master such as a step gauge or laser interferometer. These error components are then stored in hardware or software as an 'error map', and used to correct the machine tool over its entire working zone during cutting operations.

In the second type of pre-calibrated error compensation the error components are identified about a unique workpiece. The compensation which is subsequently applied is obviously only valid about a particular component contour. A technique which falls into this category of pre-calibrated compensation is post process compensation. In this compensation technique the component itself is used as the measurement master. The component is machined until it is just over size or to size and then accurately measured. Any deviations from the desired dimensions are fed back to the machine control system and used to compensate for the final component cut, or for machining subsequent components. The measurement of the component has conventionally taken place off the machine using a C.M.M. This obviously can be time consuming and the process of removing the component from the machine for measurement can lead to error. Recently, however, a commercial system has been developed where the process of measuring the component takes place on the machine tool using a measurement probe in place of the cutting tool (11). This approach speeds up the measurement cycle and reduces the chance of measurement error.

Post process compensation obviously increases the total machining time for a component, and is limited in that the compensation is only valid for a particular component profile, but this technique can be used to produce a component or series of identical components that are more accurate than the machine tool would normally be capable of producing.

All the error reduction and compensation techniques outlined above are explored further in section 2. Here specific examples of compensation systems that have been successfully applied to machine tools are discussed, in order to provide a critical appraisal of the work carried out to date in the field of machine tool accuracy enhancement.

2. LITERATURE SURVEY

The systematic errors of machine tools have been extensively studied (12-21). All these papers deal with the sources, comparative effects, or analysis of the systematic errors that affect machine tool accuracy. A number of compensation strategies and systems have been developed in an attempt to eliminate, or more practically to reduce the effects of the systematic position errors on the machine tools performance. As discussed in section 1 these compensation systems are categorized as being either active compensation systems or precalibrated compensation systems. Precalibrated compensation systems, by the very nature of their operating principle generally make use of electronic or computer technology. This technology has only fairly recently become available, and as a result the early work on machine tool error compensation effort was concentrated on active compensation techniques.

An example of active compensation is provided in the work undertaken by Leete (22). Leete developed a compensation system in which the unwanted rotations, pitch and yaw, and the unwanted vertical and horizontal translations of the machines slides were calculated and corrected from direct measurements on the machine. In order to determine the unwanted rotations and translations of a slide in a particular plane he mounted two displacement transducers on the slide, and used them to measure slide movement with respect to a perfect straightedge reference. A beam of light was used as the straightedge reference. The measurements from the displacement transducers were used to calculate the angular and straightness errors from which the position errors of the machines axes X,Y and Z could be generated. In order to correct for these positional errors compensation was applied to the machine through its N.C. controller, by direct modification to the position registers of the controller. Although this system is still used today the method of implementing compensation through direct modification of the machines controller is impractical for a general purpose compensation system.

Indeed in many modern controllers this approach would be impossible as the position control is implemented entirely in software.

A similar approach for the compensation of machine slide misalignment errors was adopted by Wong and Koenigsberger (23). Again light was used to provide a perfect straightedge reference against which unwanted slide movements could be measured. The optical equipment used to provide the error measurements in both these compensation systems is extremely sensitive and expensive. This is a great disadvantage when it is considered that the equipment is dedicated to a single machine tool.

In an attempt to overcome the problem presented by the high cost associated with sensitive measuring equipment, a modified method of active compensation was adopted by Goodhead et al (24). In this method of compensation, instead of using a perfect straightedge to identify the slide misalignments a precalibrated nonperfect straightedge was used. Instead of the complex and expensive optical equipment a taught fine wire was used. The fine wire was tightly stretched between two points which were parallel to, but isolated from the the moving slide of the machine. The amount of sag experienced by the wire as it was held between the two points was calculated. From this calculation of sag the wire was able to be calibrated in terms of straightness. By placing wires on two sides of the slide, and by using five sensitive displacement transducers attached to the slide a simultaneous measurement could be made of the pitch, yaw, roll, and horizontal and vertical straightness errors. The output signals of the displacement transducers were fed into a mini-computer. This computer using geometric relationships, was used to calculate the position errors of the machines slides from the misalignment values measured by the displacement transducers. The computer also took into account the straightness errors of the wire when calculating the position error values. Although in this example the cost associated with the measuring system has been reduced the measurement system is customized to a particular machine and cannot therefore be applied generally. The technique also requires the processing power of expensive computer technology.

Active compensation systems have also been applied to machines other than machine tools. At the Lawrence Livermore Laboratory in the U.S.A. ,for example, an active compensation system was developed and implemented on a coordinate measuring machine (25). Again the active compensation system was used to correct for slide misalignment errors. The method used to measure the alignment errors was similar to the methods used in the compensation systems described above, in that the straightness errors of the slides were measured as deviations in slide motion with reference to an accurate straightedge. In this system the reference straightedges were positioned parallel to the axes of the coordinate measuring machine, on a separate metrology frame mounted inside the machines base. L.V.D.T's. were used to measure the straightness errors of the machines slides with respect to the reference straightedges. The accuracy of the measurements was further enhanced by precalibrating the reference straightedges and correcting for any inaccuracies during operation. A laser displacement transducer system was also mounted on the metrology frame and used to provide high accuracy linear positioning of the machines axes. Lawrence Livermore Laboratory have adapted this method of compensation for use on two diamond turning lathes that they have built. Again the method was used to compensate for straightness errors. In the earlier of the two machines, the DTM3, the straightness errors are measured by the same method as for the C.M.M., in that L.V.D.T's. were used to measure against reference straight edges. In the latest diamond turning machine, the LODTM, a more sophisticated laser interferometer system is used to measure the straightness of the slides. With the C.M.M. and the two diamond turning lathes the cost and effort required to implement the active compensation methods could only be justified by the extreme accuracy requirements of the machines, and by the high capital cost of the machines.

In all the examples of active compensation given above the compensation has been implemented in real time, and has been effective in reducing particular geometric error components. The main advantage of these active compensation techniques is that the effectiveness of the compensation is dependent only upon the repeatability of the measurement system and not upon the repeatability of the machine. Although the philosophy of active compensation is clear and fairly simple its many disadvantages have resulted in it not being widely used. For instance the techniques require highly sensitive and expensive measuring equipment to be attached to the machines moving elements in a cutting environment. In many cases it is impractical to implement these measuring systems, or impossible to take sensible measurements during machining operations. Active compensation systems are best used when compensating for specific geometric error components. By their very nature they require to be customized to a particular machine. In summarizing it can be said that active compensation systems are expensive and impractical for all but a few machining applications.

The precalibrated methods of compensation do not suffer from the measurement problems associated with the active methods. A dedicated measuring system is not required, and so the problems of measurement system cost, measurement impracticality and measurement system customization are not encountered. Precalibrated compensation can also be more general in that it can be used to compensate for all geometric error components.

Although, as stated earlier, precalibrated compensation has only been exploited since the advent of computer technology, there are early examples where precalibrated compensation systems have been implemented in hardware. These hardware compensation systems are usually used to compensate for linear errors produced by inaccurate transmission devices. An example of such a compensation system is cited by Blaedel (10), in which a cam is used to compensate for position errors in a leadscrew driven table. The following paragraph is a description of the device which was used on a linear dividing engine produced by Sip in 1865.

"The nut, which is apt to turn as a result of the slight friction which it exercises on the screw, is kept in position by means of a finger bearing upon the edge of a steel template fixed at some distance from the screw.

Assuming the template has a sinuous profile reproducing at the required scale the graph of the errors of the thread, the nut will be actuated by a slight rotation movement which, when algebraically added to that of the screw, will compensate the errors"

Hardware compensation systems such as this suffer from severe limitations. The systems are difficult to change once the machine has been assembled and adjusted. The systems are also *limited in what errors they can correct* for, and are not very effective for compensating for large machines. This example, however, does serve to illustrate that error compensation of machine tools is not a new science.

A more recent example of precalibrated compensation is cited by Thompson (26) in his work at Lawrence Livermore Laboratory. The compensation method used in this work was based on the post process compensation technique discussed in section 1. In this example part trace tests were conducted on parts produced on a diamond turning machine type DTM2. The results of these tests were used to calculate the profile errors of the workpiece by comparing the machined part contour with the theoretical contour. New NC tapes were then generated which included corrections for the profile errors. These new NC tapes were then used to recut the component in order to achieve the desired accuracy.

A similar approach was adopted by Kaliskar (27) in his work in error compensation for a copy milling machine. The method involved measuring the profile errors of a part produced on the milling machine and creating a table of errors for a limited number of sections of the workpiece. This table of errors was then loaded into a specially developed "In-line Correction System". When machining further parts in the batch the "In-line Correction System" would automatically introduce the preloaded correction values to the machine at the required position.

A more recent example of a post process compensation system is that of the Profile Grinding Machine developed by Hepworth Engineering Limited (11). As mentioned in section 1, with this machine the post process compensation system is fully automatic. The machine has two sets of planar axes, one set associated with the grinding operation, and one set associated with the measuring operation. The component is machined up to the cut preceding the finishing cut. At this point the measuring axes automatically measure the profile of the component. These measurements are then processed by a computer and compared with the theoretical profile measurements. The computer uses the errors between the actual and theoretical component profile to generate a new part program which includes compensation for the profile errors. The new part program is automatically downloaded to the machine tool controller where it is used for the finishing cut to produce an accurate component. As each component is measured on the machine prior to its finishing cut, the system compensates for tool wear, cutting load and thermal errors as well as the machines geometric errors. This machine has been used in an uncontrolled environment to produce components with a profile accuracy of less than 10 microns. This is, however, a special machine purpose built to produce a single high value component to a high accuracy. This technique could not easily be applied to a general purpose machining situation.

Post process compensation suffers from the major disadvantages that the compensation is only applicable to a single part or series of identical parts, and that the technique can be labor intensive and certainly time consuming to perform.

A more desirable and useful approach to precalibrated compensation is to identify and compensate for the errors of a machine throughout its working volume. In this way the inaccuracies of the machine tool (the cause) are measured and not the inaccuracies of the component (the effect). The compensation is more general and not component specific, and can therefore be applied to a wide range of machine tools, in many applications.

Work has been carried out using this technique at the National Bureau of Standards in the U.S.A. In this work a system was developed to compensate for the effect of the geometric errors of a vertical machining center (28). The translational and rotational errors of the machines axes were measured together with the orthogonality errors between each of the axes. These error components were then used to create an 'error map' for the machine. The 'error map' was stored in the memory of a mini-computer. During point to point drilling operations the mini-computer used the stored error information to calculate the correction values required for the final tool point position. The correction values were applied to the machine tool in order to improve the machine tool accuracy. The system was successful in improving the accuracy of the machining center, however the use of dedicated computer technology to perform the compensation makes this approach far too costly for most machining applications. The system and the mathematical compensation techniques were dedicated solely to the particular machining center, and could not be easily be applied to a machine tool of a different type or configuration even if the economics permitted.

This method of precalibrated compensation has also been implemented on a coordinate measuring machine. In this example Kuntzman and Walde implemented the compensation system on a Zeiss gantry type coordinate measuring machine (29). This research was undertaken to evaluate the effectiveness of precalibrated compensation as applied to a coordinate measuring machine, and in particular to compare the effectiveness of the compensation when using direct and indirect machine calibration techniques. In the indirect technique the individual translatory and rotary error components of the machine are measured using an external measuring device, such as a laser interferometer, and are used indirectly to calculate the machine positional errors. In the direct technique the geometric errors of the machine are directly measured using test bodies placed on the machine, and using the machine itself as the measuring instrument. A more detailed discussion of error identification techniques is given in section 4. In both cases the compensation was implemented inside the machine controller as part of the system software of the coordinate measuring machine. The effectiveness of the compensation was tested by using special test bodies and step gauges. A significant improvement in accuracy was achieved through both measurement techniques, the largest single improvement being from 12.1 microns to 0.9 microns. In conclusion it was stated that the direct calibration technique was the simplest to perform, but the indirect calibration technique produced the more detailed compensation. Again this work shows the effectiveness of precalibrated compensation methods. However this application is specific to the particular coordinate measuring machine, and due to the method of implementation through the controller it can not easily be applied to other machines.

The most notable recent work on precalibrated error compensation is that of Donmez (30). In this work Donmez developed a compensation methodology and system for a Hardinge superslant CNC lathe. As well as compensation for the machines geometric errors, correction was also included for machine generated thermal errors. Using kinematic analysis a mathematical model was developed that described the position errors of the machines axes as a function of the machines geometric error components and temperature. Direct identification techniques were used to measure the geometric error components of the machine tool. The machines thermal errors were determined by monitoring the major heat sources around the machine, such as drive motors and bearings, and directly measuring their effect on the machines geometric errors.

The compensation was implemented using a single board microcomputer. The microcomputer communicated with the machine's Allen Bradley 8200 CNC controller via special interface electronics. The geometric and thermal error data was stored in the microcomputer system memory. The microcomputer used the mathematical model for the machine tool to calculate the compensation values from the stored error and temperature data and the axes positions. The compensation was performed at 20 millisecond intervals, a period equal to the servo update time for the controller. However, due to software limitations the compensation values were injected 40 milliseconds after measurement of the corresponding axis position. This led to reduced compensation system performance if the machine feedrate exceeded 1.5 m/min.

Cutting tests were performed to evaluate the performance of the compensation system and a significant improvement in accuracy was measured. The "warm up" period for the machine tool were reduced and reductions in error of up to 20 times were measured.

From an academic point of view the results of this research work graphically illustrate the improvements in machine tool accuracy that can be achieved through the use of precalibrated error compensation. However, the compensation philosophy, and method of implementation do make the use of this system limited and impractical. For instance the mathematical model developed for the compensation is specific to this particular machine tool and could not be applied to other machine tool types or configurations. Also the method of implementing the compensation through the interface with the CNC controller and the need to modify the controller software makes the system limited to the Allen Bradley 8200 controller and limits its wider use considerably. The method of implementation also limits the performance of the compensation system.

In summarizing the work carried out to date in the field of machine tool error compensation the following important observations can be made:

1. Active compensation techniques require the use of expensive and sensitive measurement equipment. The cost and use of this equipment in the potentially hostile environment of a machine tool makes the use of these compensation techniques impractical for the majority of machining applications.

2. Precalibrated compensation techniques do not require the use of dedicated measuring equipment and are therefore not limited in the same ways that active compensation techniques are. Precalibrated compensation has been shown to produce significant improvements in the accuracy of machine tools, and precalibrated compensation techniques can be used to correct for all the major sources of machine tool error.

3. In all the work carried out to date using precalibrated compensation techniques the emphasis has been on improving the accuracy and performance of specific machine tools. The compensation systems and the methods developed have therefore been dedicated to a particular machine and controller type. Extensive use has also been made of complex and expensive specialized computer technology. As a result of this the compensation systems and methods developed cannot generally be applied to any machine tool other than the one for which they were designed.

Based on these observations, and in order to ensure a general approach to machine tool accuracy enhancement, this programme of work has focused on the development of a universal error compensation system, which can be applied to any type of machine tool. On this basis the following criterion has been established:

1. The compensation system should have the capability to compensate for position errors produced by all the major sources of machine tool inaccuracy.

2. The compensation system should operate in real time and perform dynamic compensation in order to provide true error correction during machining operations.

3. The compensation system should operate without inhibiting or degrading the operation and performance of the CNC controller and machine tool.

4. The compensation system should be transportable so it can be used with a wide range of CNC controllers and servo systems.

5. The compensation system should be flexible and have the capability to be applied to all machine tool types and configurations.

6. The compensation system should be cost effective in order to provide an affordable and therefore acceptable solution to the problem of machine tool accuracy.

This criterion has been adopted in this research project as the outline specification for the development of a general purpose error compensation system which can be applied to any machine tool type and configuration in order to improve its accuracy. Section 3 describes the development of this compensation system, and the compensation methodology used.

3 DEVELOPMENT OF THE COMPENSATION STRATEGY

3.1 Description Of The CNC Test Rig

In order to develop a compensation strategy, and therefore a compensation system that could fulfill the criterion set out in section two, a suitable CNC test machine was required. A single axis CNC system was therefore designed and built. This single axis system, although simple by comparison to a modern CNC machine tool, fully represented in operation and construction a single CNC machine tool axis. As the test machine was a simple single axis CNC positioning system it was extremely low cost in comparison to an actual CNC machine tool. This low cost CNC test rig provided an excellent vehicle for the initial development stage of the research project. A block diagram showing the main elements of the machine, and the machine configuration is shown in figure 3.1. The single axis system comprises of an Allen Bradley 7100 CNC controller, a Bosch servodyn servo amplifier and brushless d.c. motor with tacho generator and optical encoder, and a machine slide driven through a recirculating ballscrew.

In the control loop the CNC controller is a software based digital controller which generates the position demand signal from either a machine part program or from inputs entered manually via the controller keyboard. The position demand signal is summed, by the controller, with a positional feedback signal generated by the optical encoder. A position error signal is produced which is converted to an analogue voltage and output from the controller. This analogue voltage forms the velocity command signal which is used to drive the servo system. The velocity command signal is fed into the servo amplifier where it is summed together with the velocity feedback signal generated by the tacho generator, to produce a velocity error signal. The velocity error signal is used by the servo amplifier to generate a suitable drive signal for the servo motors. The servo motor drives the slide directly through a recirculating ballscrew. This is the

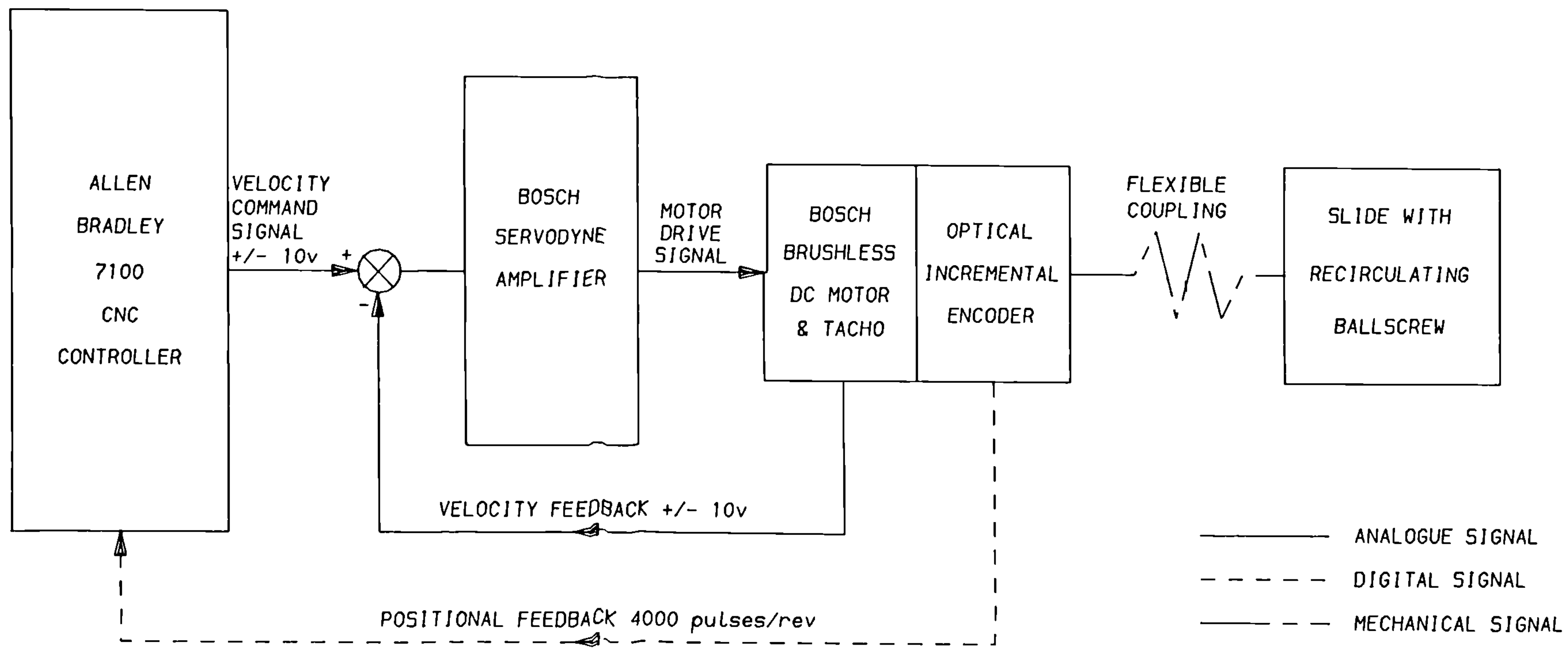


FIGURE 3.1 BLOCK DIAGRAM OF THE SINGLE AXIS MACHINE

basic principle of operation of the majority of CNC machine tool position control systems.

It can be seen from figure 3.1 that the incremental encoder is connected to the brushless d.c. motor, and that the connection between motor and slide is provided by a flexible coupling. The range and magnitude of the errors inherent to this simple single axis system provided a good basis for the development of the compensation strategy and system.

3.2 Simulation Of The CNC Test System

In order to simplify and aid the development of the compensation system a digital simulation of the single axis test machine was developed. The digital simulation of the single axis system provided a flexible design tool which simplified and accelerated the development of the compensation system. This method of design is flexible in that it allows access and manipulation of variables and parameters which would be difficult, if not impossible, to isolate in the real system. It also eliminates the need for a time consuming design and build of compensation hardware before the compensation strategy has been fully proven and tested. The compensation concepts can be quickly and easily implemented in software on the simulated CNC system and can be fully evaluated and proven.

The initial stage in the development of a digital simulation of the single axis test machine involved the formulation of a mathematical model to describe the dynamic operation of the positional servo system.

There were a number of non-linear elements which needed to be considered in accurately modeling the position servo, such as quantisation, friction and mechanical hysteresis. Due to these non-linear effects a general time domain solution for the model was not easily obtainable. An iterative technique has therefore been adopted to simulate the servo system, with the model being implemented in software on a digital computer. The software was written on a Hewlett Packard 9000 personal computer using HP enhanced basic.

3.2.1 Mathematical Analysis Of The Single Axis Machine

A block diagram model for the single axis CNC machine is shown in figure 3.2. This block diagram model shows the mathematical relationships that describe the operation of the positional servo system. Mathematically the operation of the system may be broken down into three sections; the CNC controller, the servo current amplifier and the brushless d.c. motor and slideway.

The 7100 Allen Bradley controller uses the reference pulse technique of position control, a technique adopted by many of the manufacturers of modern CNC controllers, because of its simplicity (31).

The demand position and feedrate are represented by the controller as a stream of reference pulses, the frequency of the pulses representing the required feedrate of the slide, and the number of pulses representing the demanded position of the slide. A second stream of pulses, the feedback pulses, are generated by the incremental encoder. Both pulse streams feed an up-down counter which acts as a comparator and generates the pulse count difference that represents the positional error. This position error count is converted to a voltage by a digital to analogue converter, this voltage being output from the controller to drive the servo system.

In principle the reference pulse technique should be treated mathematically as a discrete time system with non-uniform sampling, where continuous motion of the servo motor is measured from feedback pulses emitted Ke times per radian of encoder motion. In practice since the encoder pulse count Ke is large (636.6 pulses/rad or 4000

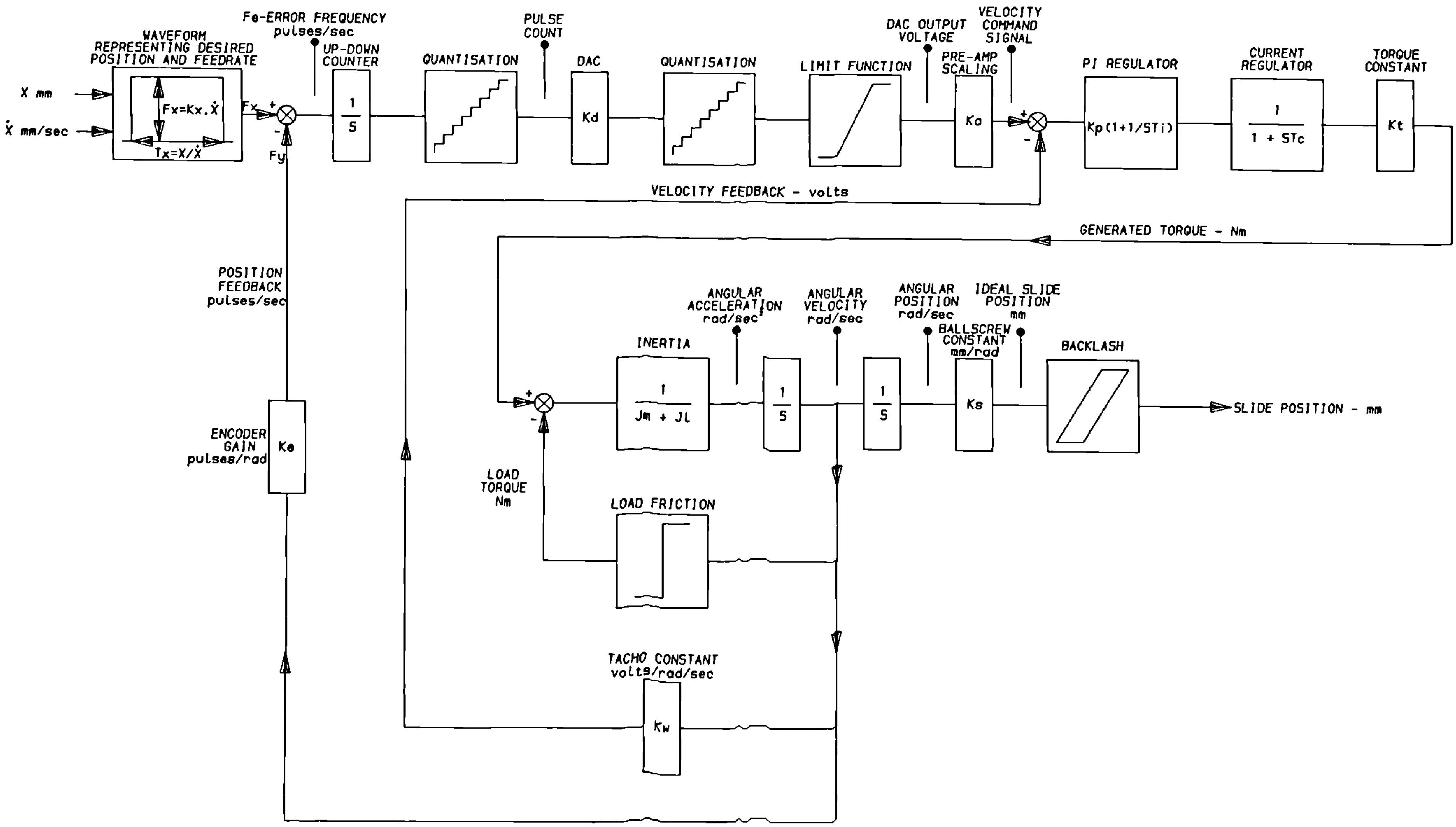


FIGURE 3.2 BLOCK DIAGRAM MODEL OF THE CNC TEST MACHINE

pulses/rev) the reference pulse system may be analysed as a continuous system using Laplace transform methods without loss of accuracy (31).

The demand feedrate and position were represented mathematically as a pulse frequency and a pulse stream duration respectively. The encoder was modeled as a constant, converting motor angular velocity to a pulse frequency. The up-down counter converts pulse frequencies to a pulse number and a phase difference (representing direction of motion), both being the integral of frequency, and was treated as an integrator. However, to be mathematically correct the quantisation effects inherent to the digital nature of the up-down counter have also been considered, and any fractional pulses calculated through the integration of the pulse frequencies have been rounded down to the nearest whole pulse.

The digital to analogue converter was represented by a constant converting the pulse count to a d.c. voltage. Again the quantisation effect exhibited by the DAC has been considered, together with a function limiting the maximum and minimum voltages from the DAC.

The positional control system has an inner "cascaded" velocity control loop which has the effect of improving system stability, permitting a higher overall system gain and so improving system performance (32). For this reason position-velocity cascade control is common to the majority of CNC positional systems.

The velocity feedback is in the form of a d.c. voltage generated by a brushless d.c. tachogenerator housed within the casing of the servo motor. The voltage is considered to be directly proportional the motor angular velocity (the voltage ripple has been assumed insignificant), and the tachogenerator has been modeled as a constant. The feedback voltage and the velocity command voltage from the controller are summed in the first stage of the servo amplifier producing a velocity error voltage.

The PI regulator provides proportional action (an output proportional to the input) and integral action (an output proportional to the integral of the input). Through this proportional plus integral action the response of the servo motor may be controlled in terms of speed of response and damping, allowing the user to optimize the performance of the servo system for a particular application. The PI regulator has been modeled in terms of the summation of a constant term and an integrator function.

The output voltage of the PI regulator forms the current command signal for the current regulator. The current regulator acts as a current control loop, comparing the current command voltage with a voltage representing the actual current, and generating a suitable control signal to drive the current amplifier output stage. This makes it possible to regulate the current in the motor windings and so the torque generated by the motor.

The mathematical analysis of the brushless d.c. motor is the same as for a conventional d.c. motor, the torque produced by the motor being directly proportional to the current supplied by the current amplifier. In the model this relationship has been represented by a torque constant.

The generated torque is required to overcome the inertial effects of the moving parts during motor acceleration, and the load torque produced by friction between moving parts. The total moment of inertia of the system is a function of the dimensions and mass of all the moving parts, and has been analysed in terms of motor moment of inertia, a value for which has been obtained from manufacturers literature, and load moment of inertia which has been calculated from the physical dimensions of the slideway. The friction effects have been simplified to include only constant dynamic friction, stiction having been considered insignificant. The load friction has thus been modeled as a switching function sensitive to the sense of motor rotation. That is positive load friction for a forward motor rotation and negative load friction for reverse motor rotation.

The angular position and angular velocity of the motor have been obtained through successive integrations of the motor angular acceleration.

The ballscrew is the device which transforms the rotary motion of the motor to translatory motion of the slideway, and was represented mathematically as a constant relating angular displacement to ideal linear displacement. By treating the ballscrew in this manner it is assumed to be mechanically perfect. This is an incorrect assumption as all ballscrews exhibit an element of mechanical hysteresis or backlash. Backlash may be considered as a positional deadband which manifests itself when the ballscrew changes its sense of direction. The backlash has been represented in the model as a non linear function relating ideal motor position to actual motor position.

This mathematical representation of the operation of the positional servo system of the single axis test rig was implemented in software in order to digitally simulate the operation of the actual test machine.

The derivation of the system parameters used in the digital simulation, together with a brief description of the numerical analysis techniques used are given in appendix A.

3.2.2 Determination Of The Model Accuracy

Before the model could be used as a design tool to test the compensation strategy, its accuracy had to be determined in terms of how closely it could describe the operation of the actual position servo system. Of primary interest for the development of a position error compensation system was the time response of the position servo system, as it is this response that is modified during compensation. Thus the investigation of model accuracy took the form of a comparison between the time responses of the actual servo system and of the digitally simulated servo system to the same demand inputs.

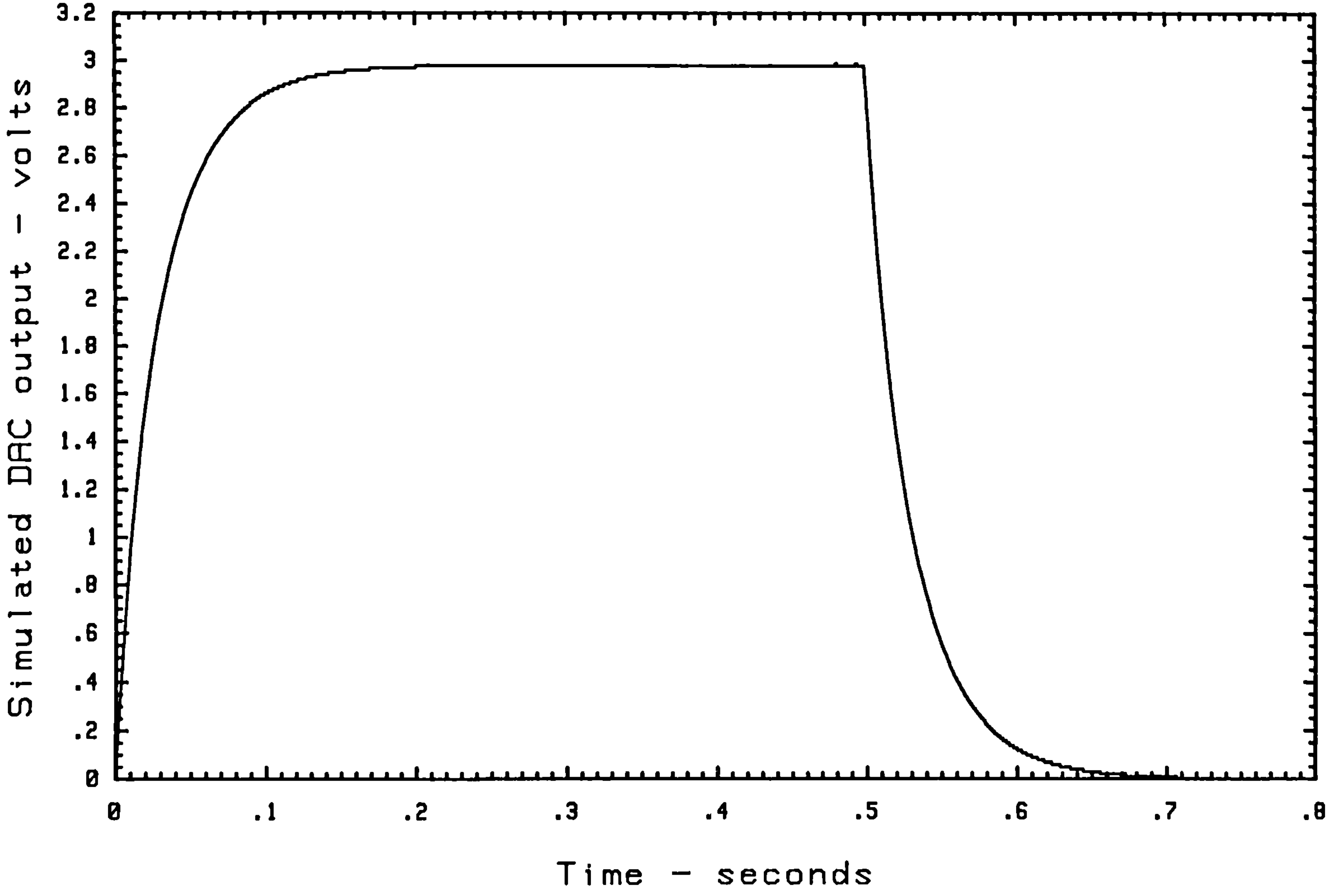
An example of the results obtained from this comparison are shown in figure 3.3 and 3.4. Figure 3.3 shows a plot of the digital to analogue converter output voltage (representative of the position error) calculated from the simulation. Figure 3.4 shows a plot of the DAC output voltage measured at the output from the CNC controller using a storage oscilloscope. In both cases a typical machine tool feedrate of 20mm/sec was selected, and a movement of 10mm demanded. This movement was sufficiently large to provide a clear indication of the systems transient and steady state responses.

It can be seen from figures 3.3 and 3.4 that the simulated and measured responses are similar with regards to both shape and scale. A comparison of the characteristics of each response confirms this similarity. The rise and fall times for both the simulated and actual response curves are 74 milliseconds, the steady state DAC output for both the simulated and actual systems is 3 volts, and the time from the start of the response to the point at which the DAC voltage starts to decrease is 0.5 seconds for both the simulated and actual responses. This shows that the simulation accurately describes the operation of the positional servo system of the test machine. It was, therefore, concluded that the digital simulation of the test machine could be used with confidence to predict the performance of proposed compensation strategies.

3.3 Determination Of The Compensation Strategy

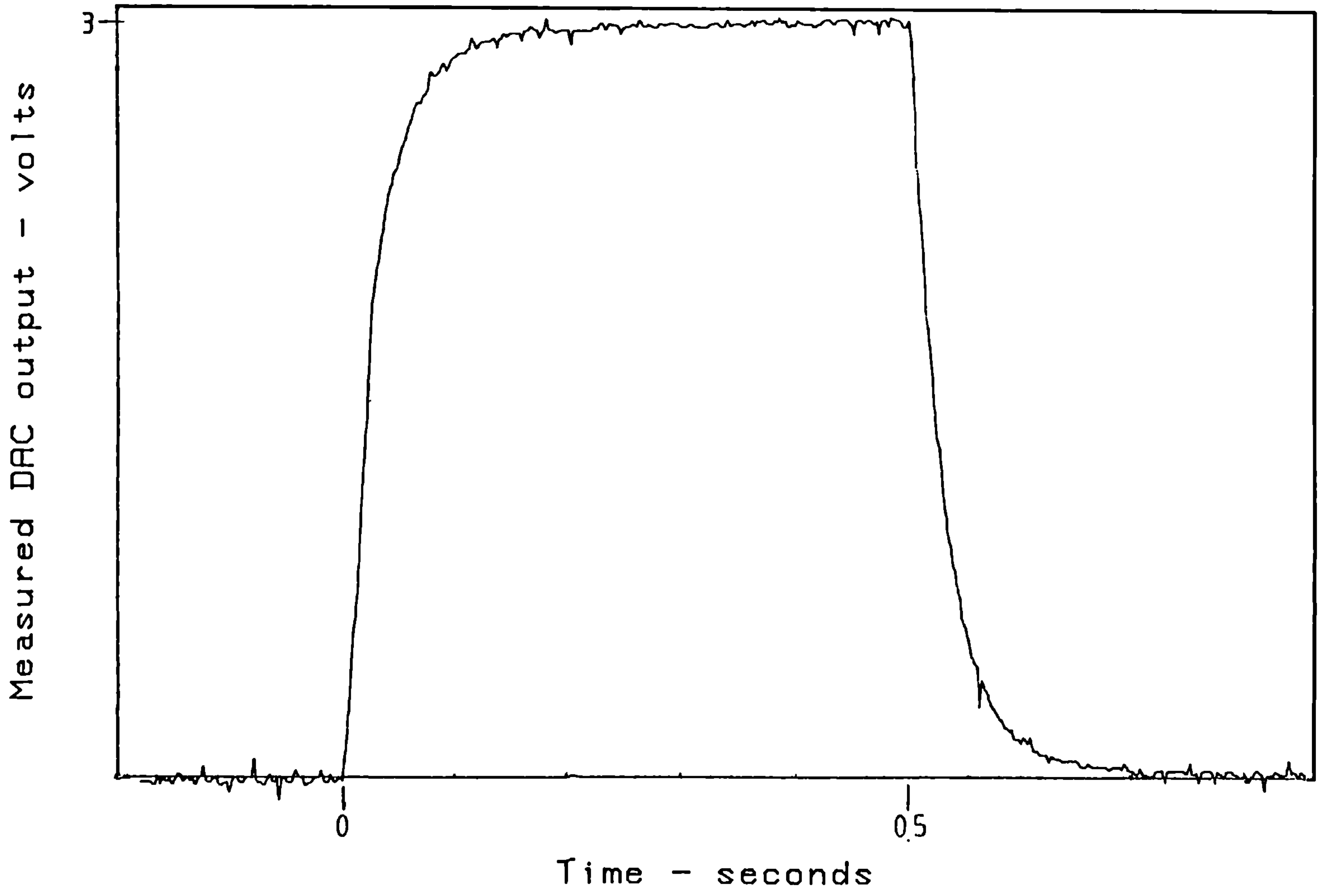
To correct for the positional errors of a machine tool slide a compensation system must obviously physically change the position of the slide. In order to achieve this

FIGURE 3.3 DAC OUTPUT V'S TIME



Desired position = 10 mm   Feedrate = 20 mm/sec

FIGURE 3.4 DAC OUTPUT V'S TIME



Desired position = 10 mm   Feedrate = 20 mm/sec change in slide position the compensation system must interface directly to the position control loop of the machine tool, and add an offset into the positional loop proportional to the amount of correction required. Figure 3.1 shows a typical arrangement of the positional control loop of a CNC machine tool slide. It can be seen from this figure that there are basically 3 points around the position control loop where a position offset could be added, namely through the CNC controller, or as an addition to either the position feedback signal or the velocity command signal. There are therefore three strategies that can be used to implement compensation on a CNC machine tool. These strategies are described below:

1 - Modification to the position control registers of the CNC controller.

The CNC controller generates the position command signal, determines the machines actual position from the position feedback transducer, and generates the position error signal to drive the servo system. Modification to any of these three values within the controller would offset the position of the slide. This method of applying compensation was used in the compensation system developed by Donmez (30) described in section 2.

There are a number of major disadvantages associated with this method of implementing compensation. The interface between the compensation system and the CNC controller would be complex and would be different for each type of controller. A communications link would be required to transfer data and compensation values between the compensation system and the controller in real time, and the timing of the compensation system would have to be closely linked to the timing of the controller. Also modification of the controller software or hardware may be required to allow the compensation system to operate. In short this method of implementing compensation is complex, and the compensation system would have to be customized to suit a particular controller. This method of implementing compensation is therefore impractical and does not fulfill the criterion set out in section 2 for a universal compensation system.

2 - Modification to the position feedback signal.

By suitable modification to the position feedback signal from the position transducer, the position of the machine tool can be offset. This method of implementing compensation overcomes the problem associated with interfacing to the CNC controller, as the position feedback signal can be modified prior to connection to the controller. The problem with this method of compensation is that various types of position transducer such as encoder, resolver and inductosyn can be used on machine tools. Although these transducers are fairly easy to read it could be difficult to accurately modify these positional signals in order to implement compensation. As an example consider a stator excited resolver in which the phase difference between the stator signal and the rotor signal is directly proportional to resolver position. In order to offset the position of an axis the phase shift between the stator and rotor signals would have to be accurately adjusted by the compensation system in real time. This would be difficult to achieve in practice. The problems associated with modifying the output signals of a wide range of position transducers make this method of compensation impractical.

3 - Modification to the velocity command signal.

In almost all CNC machine tools the velocity command signal takes the form of a variable analogue voltage, normally in the range +/- 10 volts. This signal represents the position error of the system (ie, the difference between the actual and desired positions at any instant in time). Adding an offset to this signal will result in a proportional offset in the position of the machine's axis. This signal can be modified outside the CNC controller without consideration to the operation of the controller.

As the signal is a simple d.c. voltage it can be modified easily and accurately. This method of implementing compensation overcomes the problems associated with modification of the controller and modification of the position feedback signals, and fulfills the criterion for a universal compensation system. This method of implementing compensation was therefore adopted for the general purpose compensation system developed during this research project.

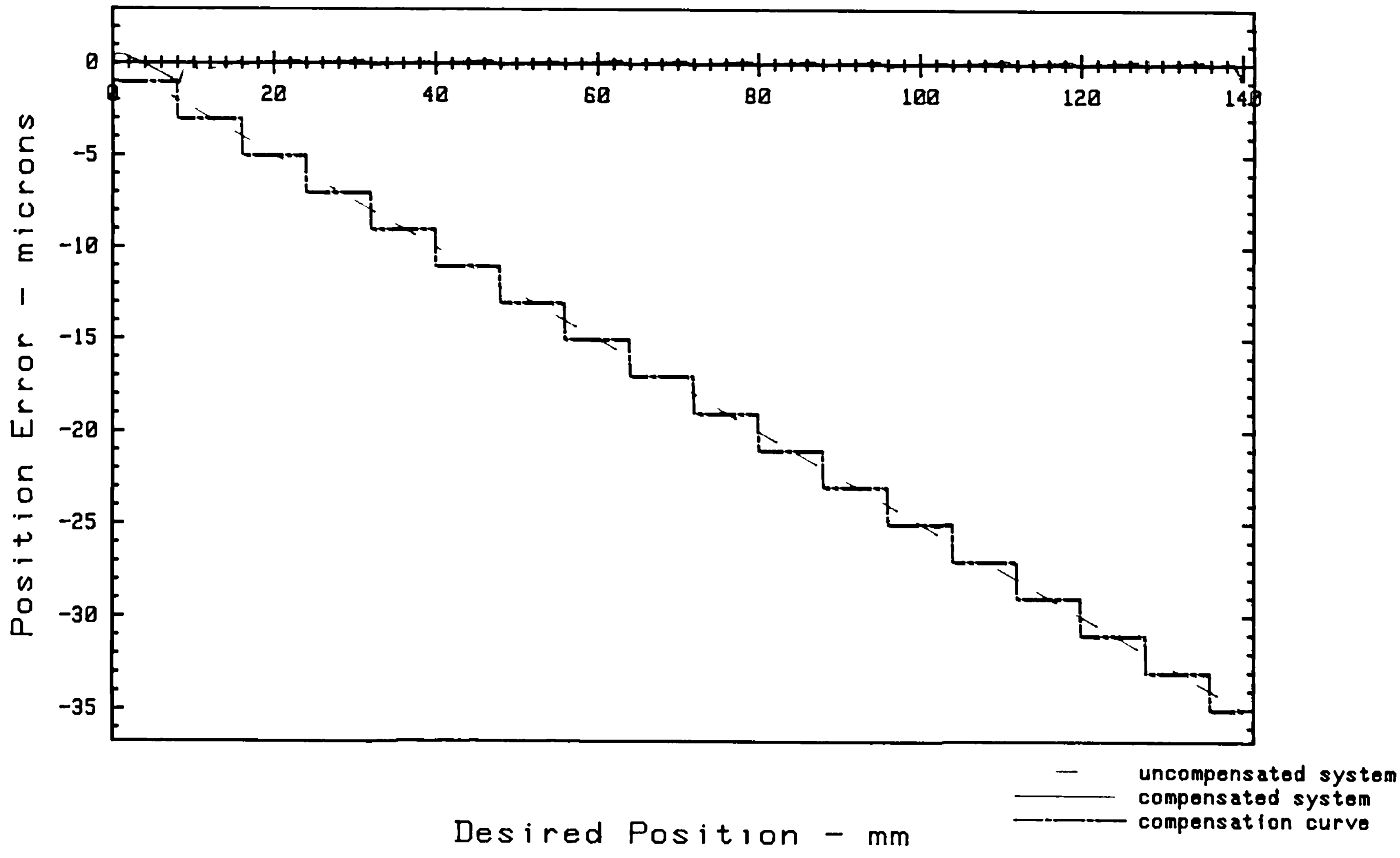
3.4 Simulation Of The Compensation Method

In order to appraise the proposed method of compensation, particularly with regard to its dynamic performance, the compensation method was implemented in software together with the software model of the CNC servo system, and a simulation was performed. It would be difficult to analyze the dynamic performance of the compensation method by any means other than simulation, as this requires the position deviation between the slides actual position and desired position to be monitored while the slide was in motion.

As the test machine is a single axis system only the linear positioning error of the slide could be considered. To simplify this investigation the linear positioning error was assumed to vary linearly from the start position, representing an idealized progressive leadscrew error. The actual linear positioning error within a machine tool would obviously display a more complex pattern of variation, however the reason for this investigation was to appraise the proposed compensation method, and not to accurately model the errors present in an actual machine tool system. The assumed linear error was adequate for this purpose.

Figure 3.5 shows a typical result obtained from a simulation, giving a comparison between the errors for an uncompensated and compensated system. The brown curve indicates the linear variation of the position error for the uncompensated system. The position error is increasing

FIGURE 3.5 SIMULATED COMPARISON OF THE COMPENSATED AND UNCOMPENSATED SYSTEMS



at a rate of 0.25 microns/mm. The blue curve or compensation curve indicates the magnitude of the compensation values in microns and the position at which the compensation values are applied to the servo system. It can be seen from this curve that the compensation values have been added incrementally at 8mm intervals. This interval was chosen as it is the distance required for the linear position error to increase by 2 microns, the resolution of the position transducer. The servo-system cannot accurately position to better than the resolution of the position transducer, and it is therefore not necessary to compensate for position deviations which are less than this resolution. It can also be seen from the compensation curve that the compensation value is applied to the servo system at half an increment (4mm) in advance of the actual position where the compensation is required. This is done for two reasons. Firstly, this strategy would eliminate any lost motion or backlash effects that may be exhibited if the compensation values were to decrease between compensation intervals. Secondly, it allows time for the servo system to respond to the compensation value. The investigation showed that this compensation strategy produced the best dynamic response from the servo system in terms of minimizing the position deviations.

The green curve shows the position error of the servo system with the compensation applied. It can be seen from this curve that the predicted dynamic response of the compensation system is excellent with the position errors well within the resolution of the position transducer (indicated on the diagram by the two light blue lines). Indeed all the predicted responses obtained from this appraisal investigation showed this compensation technique to provide excellent compensation.

3.5 Implementation Of A Prototype Compensation System

3.5.1 Description Of The Prototype Compensation System

Based on the favorable results obtained from the simulation of the proposed compensation method, a prototype compensation unit was developed for use on the single axis CNC test rig. A block diagram showing the compensation unit connected to the CNC test rig is shown in figure 3.6. It can be seen from this figure that the compensation unit is made up of three primary elements; the encoder signal processing circuit, the microprocessor based compensator and the interface hardware.

The position feedback signals from the optical encoder are fed to the encoder signal processing circuit in parallel to the CNC controller. The encoder signal processing circuit converts the two quadrature square wave signals from the encoder into slide position. This positional information is then passed on to the microprocessor unit.

The microprocessor based compensator forms the heart of the system, controlling the operation of the compensation unit. From the slide position, provided by the encoder signal processing circuit, the microprocessor unit selects the corresponding compensation value. The compensation values having been previously stored in the systems memory. This compensation value is applied to the CNC test rig via the interface hardware.

The interface hardware converts the compensation value selected by the microprocessor unit to an analogue offset voltage which is summed with the analogue command signal to produce a compensated command signal. This signal is output from the interface hardware and is applied to the servo system to correct the axis position.

A machine code algorithm is used by the microprocessor to control the compensation process. Machine code provides the fast processing time required for real time compensation. The compensation algorithm is described in simplified form in figure 3.7.

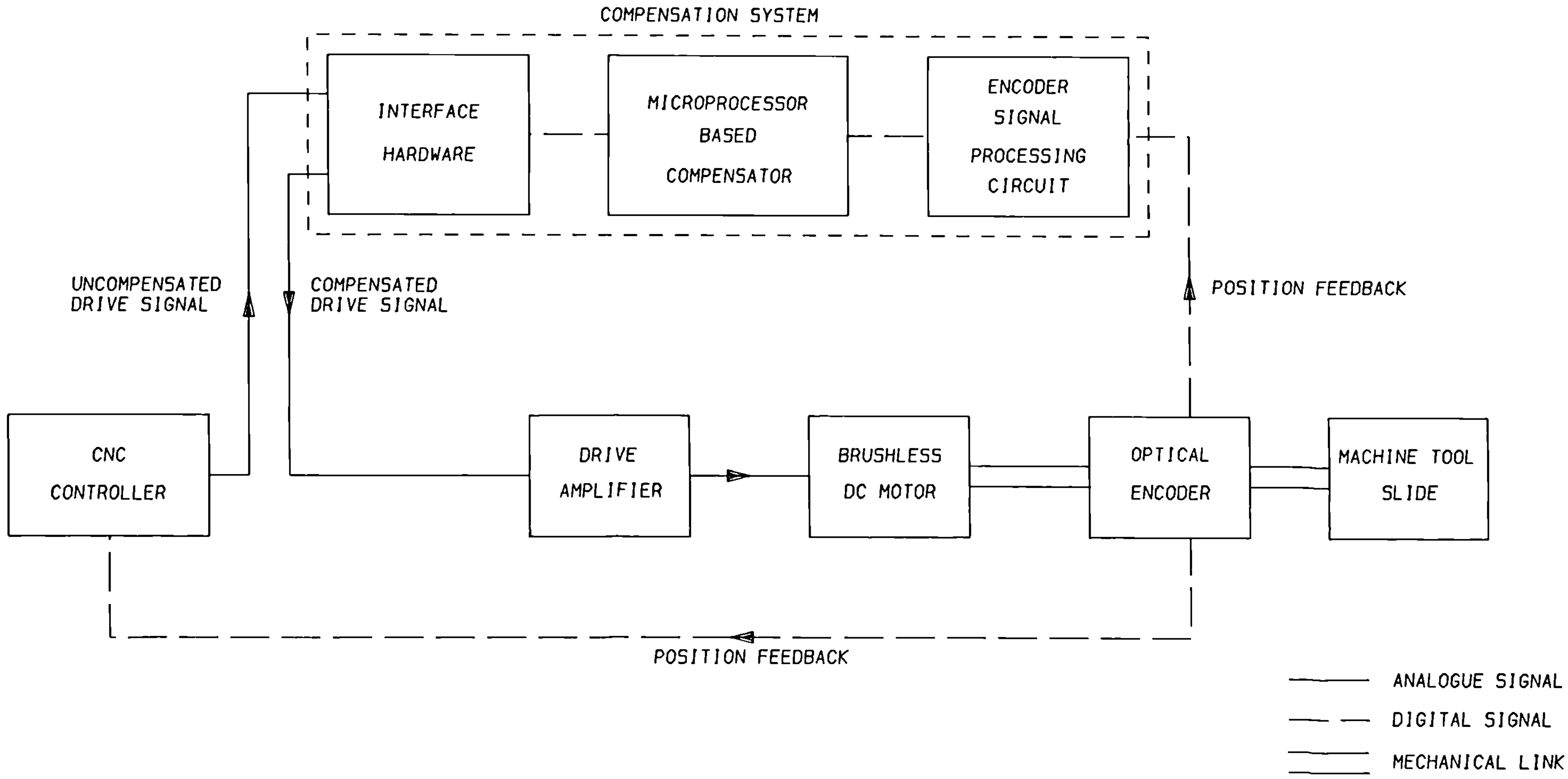


FIGURE 3.6 BLOCK DIAGRAM OF THE COMPENSATION SYSTEM

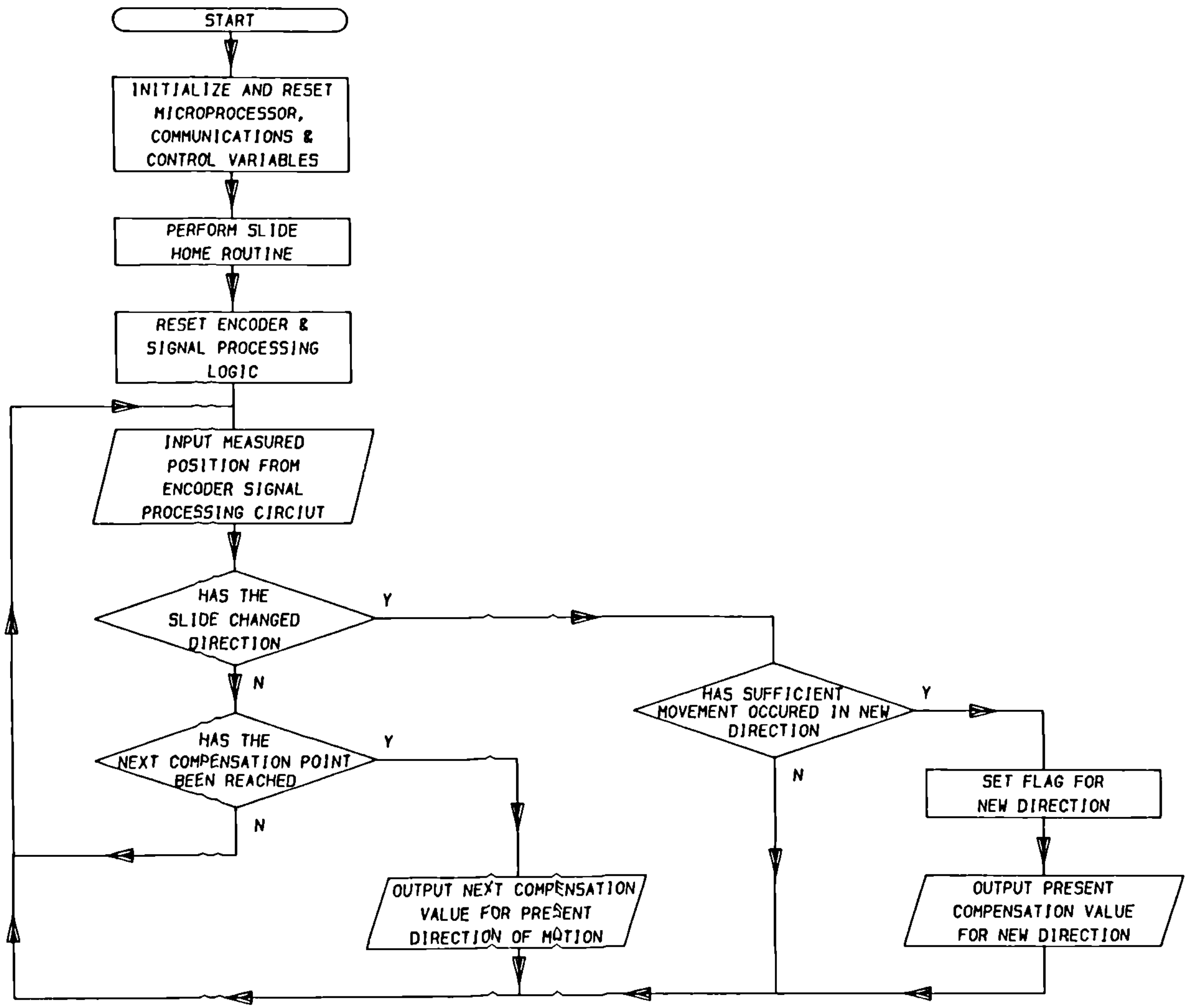


FIGURE 3.7 SIMPLIFIED FLOW DIAGRAM FOR THE COMPENSATION ALGORITHM

During a servo system "power up" the slide is returned to a datum or "home" position. In this way the incremental positional information from the optical encoder is referred to a known reference point and can be interpreted as absolute positional information by the controller. From figure 3.7 it can be seen that upon start up the compensation unit mimics this home procedure. This ensures that the positional information received by the compensation unit is synchronous with the positional information received by the CNC controller, a condition essential for accurate compensation.

Figure 3.7 also shows that separate compensation values have been used for the forward and reverse directions. This strategy has been adopted to provide effective compensation for non-uniform backlash error. The compensation unit switches between compensation values when a change in the sense of direction is detected and movement greater than two microns (the resolution of the encoder) has occurred. This second requirement is necessary to distinguish between a true change in direction and the encoder oscillating between pulses; a condition inherent to encoder based servo systems which manifests itself when the system is "stationary".

3.5.2 Calibration Of The Slideway

Before an actual compensation system could be implemented on the test rig the systematic position errors present within the slideway system had to be identified through a calibration procedure.

As the slide is small in size, has a rigid construction and is not required to perform cutting operations, the load induced errors were assumed negligible. Before a calibration test was performed the servo system was run through a "warm up" cycle for approximately one hour, under the control of part program. This allowed the machine to reach a thermally stable condition. The temperature of the test environment was also monitored and maintained as constant as possible. A laser interferometer system was used as the measurement standard to calibrate the slideway. A feature of this calibration equipment allowed any temperature deviations during or between calibration tests to be compensated for, with all measurements being referred to a standard temperature of 20 degrees Celsius. Therefore, any thermally induced position errors were minimised and could be assumed negligible.

As the servo system comprises of only a single axis the position errors could be identified directly from a linear positioning calibration over the full length of axis travel.

3.5.2.1 The Calibration Procedure

The calibration procedure has been based on the methods described by "British Standard - Accuracy of machine tools and methods of test" (33). Each calibration run involves traversing the slide incrementally to target positions in a linear cycle (as shown in figure 3.8), and recording the actual position measured by the laser interferometer at each target position. The position error at each target position is defined as the difference between the actual position and target position. Five calibration runs are performed in both the forward and reverse directions. This allows the backlash error to be determined and provides a data population of sufficient size to produce acceptable statistical results (34).

The statistical analysis method assumes a Gaussian distribution of data and involves calculating the mean and the standard deviation of the position error values at each calibration point, for both the forward and reverse directions. The mean unidirectional position error at each calibration point gives the representative position error at each calibration point for both directions of travel.

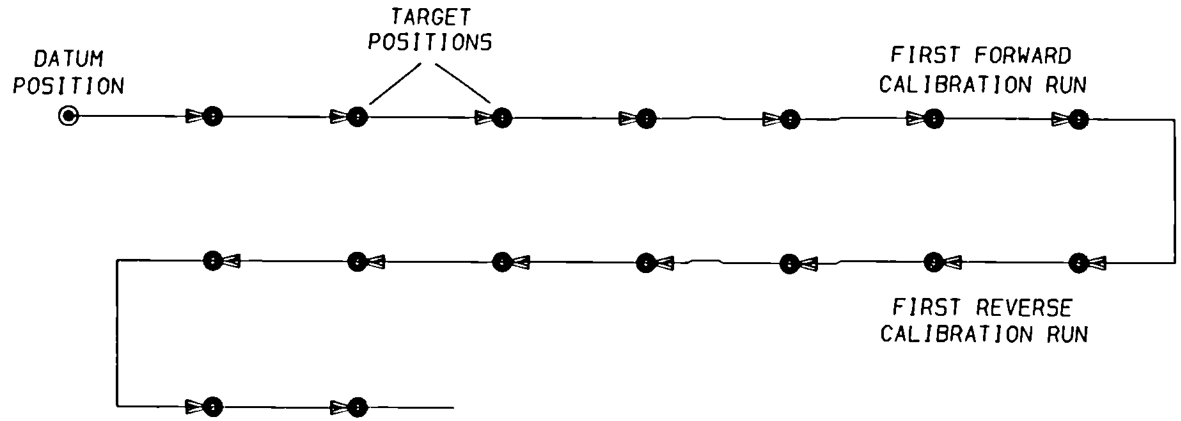


FIGURE 3.8 LINEAR CALIBRATION CYCLE

The reversal error or backlash is calculated as the difference between the forward and reverse mean unidirectional position errors.

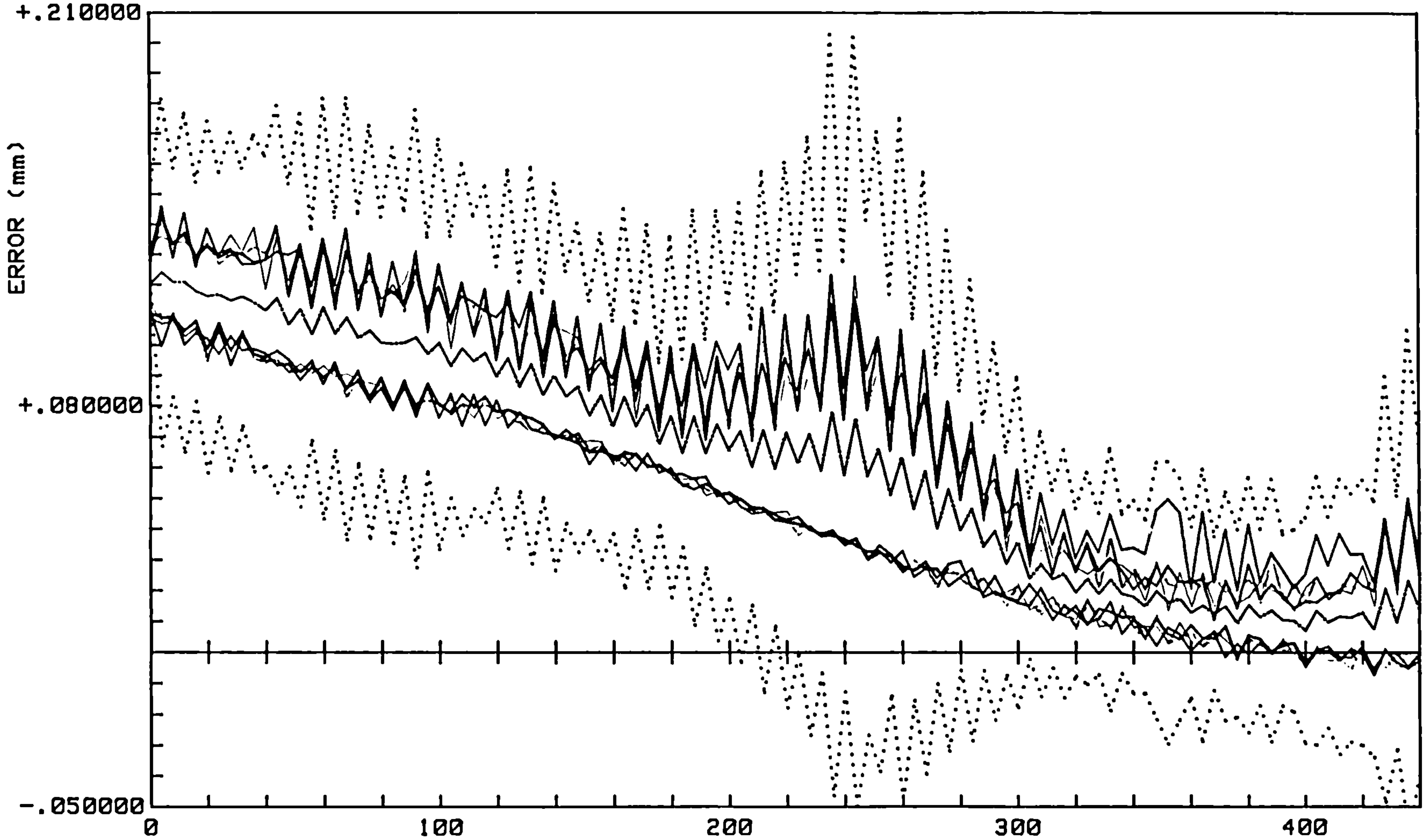
The standard deviation values provide confidence limits for the calibration data. Of particular interest are the +/- 3 standard deviation values which represent 95% confidence limits. These values provide a measure of the error band or positioning accuracy of an axis over the full length of travel, and a measure of the positioning non-repeatability or random error component. The error band is defined as being the difference between the maximum positive three standard deviation value and the minimum negative three standard deviation value, regardless of the direction of motion. The non-repeatability is defined as the maximum difference between the positive and negative three standard deviation bands at any position along the axis.

3.5.2.2 The Results Of The Calibration Tests

To achieve maximum measuring accuracy the measurement system optics require to be positioned close together during a system reset. To accommodate this the datum position for the calibration was set at 450mm, one extreme of axis travel.

Two calibration tests were performed on the slideway. In the first test a calibration interval of 4mm was chosen. This test was performed to identify the progressive and backlash error constituents over the full length of axis travel. The results from this calibration are given in figure 3.9. The plots show the measured slide position errors, with the lower five plots giving the errors for forward motion and the upper five plots the errors for reverse motion of the slide. The single central line indicates the mean of the position errors and the two outer dotted lines indicate the three standard deviation levels. The difference between the position errors for the forward

FIGURE 3.9 SLIDEWAY CALIBRATION RESULTS



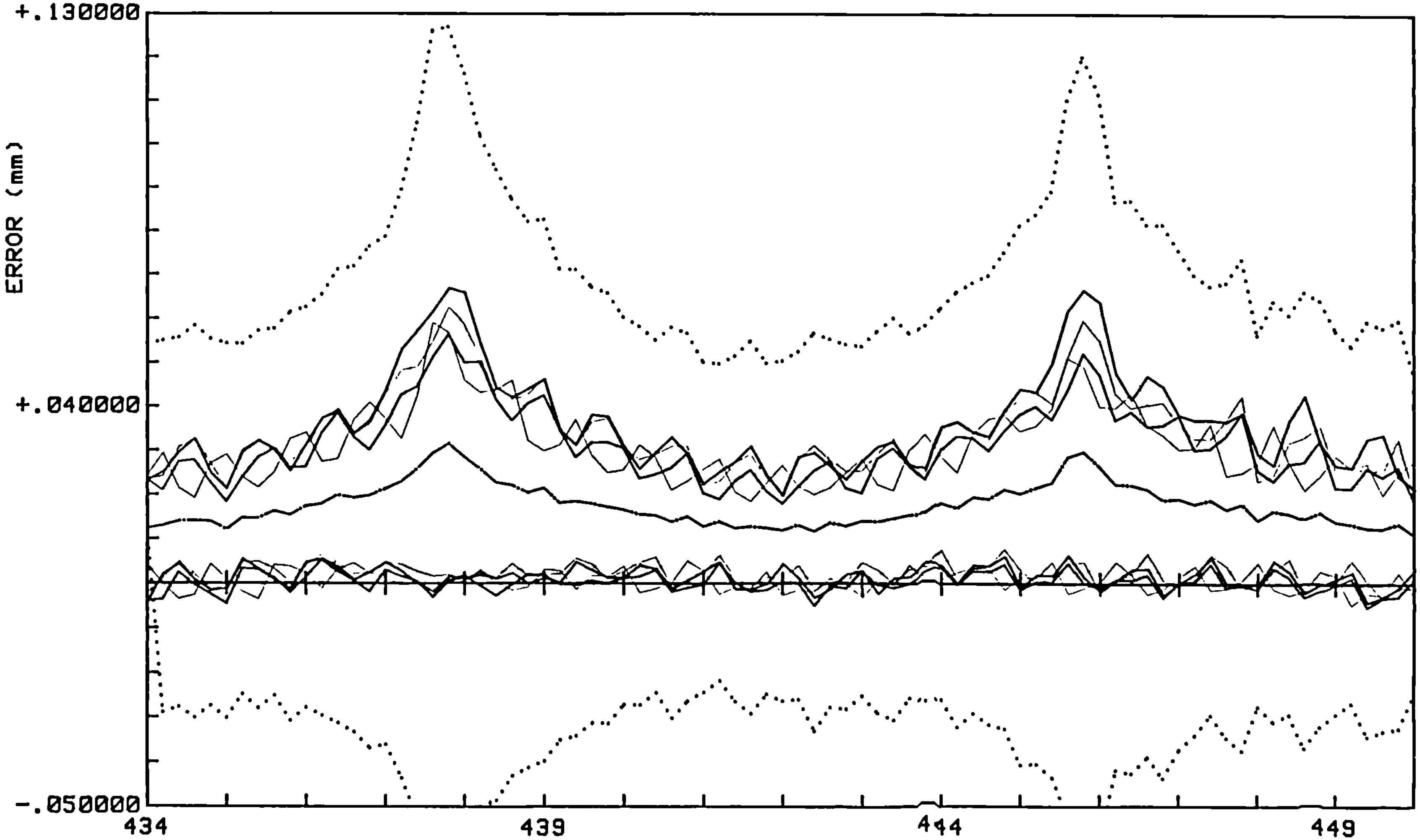
MACHINE: Test Slide NUMBER: CAL. TEST 1 DATE: 20/7/87 BY: S.P. AXIS: Single Axis	LOCATION: Hepworth Eng. 4mm steps, feedrate - 3000mm/min	+/- 3 SIGMA ERROR BAND: .261430 NON-REPEAT: 0.000000

and reverse directions is the backlash error. It can be seen from figure 3.9 that this error is not constant but varies quite markedly over the length of axis travel. Some CNC controllers offer a backlash compensation facility, however, the compensation technique adopted invariably assumes the backlash to be constant over the full range of travel. Obviously this form of compensation is inadequate and could lead to a degrading of positioning accuracy rather than an improvement. The position error plot for the forward direction does not show an obvious cyclic variation, but increases gradually with displacement and may be considered as a wholly progressive position error. The position error plot for the reverse direction clearly exhibits both a progressive, gradually increasing error component and a repetitive cyclic error component.

In the second calibration test a much finer calibration interval of 0.2mm was chosen and the test covered only 16mm, a distance equivalent to twice the leadscrew pitch. This test was performed to provide a clearer picture of the form of the cyclic component of error. The results of this calibration test are shown in figure 3.10. This plot confirms that a cyclic error component is only exhibited during reverse motion of the slide. The period of the cyclic error is 8mm, a distance equal to the pitch of the leadscrew, and is therefore obviously varying in sympathy with the rotation of the leadscrew.

The results of these calibration tests provide a picture of the position errors present within the machine axis. From this calibration data a set of predicitive compensation values for the correction of the slide were calculated. These compensation values were transferred to the memory of the compensation unit for use in the compensation process.

FIGURE 3.10 SLIDEWAY CALIBRATION RESULTS



MACHINE: Test Slide NUMBER: CAL. TEST 2 DATE: 20/7/87 BY: S.P. AXIS: Single Axis	LOCATION: Hepworth Eng. 0.2mm steps,feedrate=3000mm/min	+/- 3 SIGMA ERROR BAND: .194117 NON-REPEAT: 0.000000

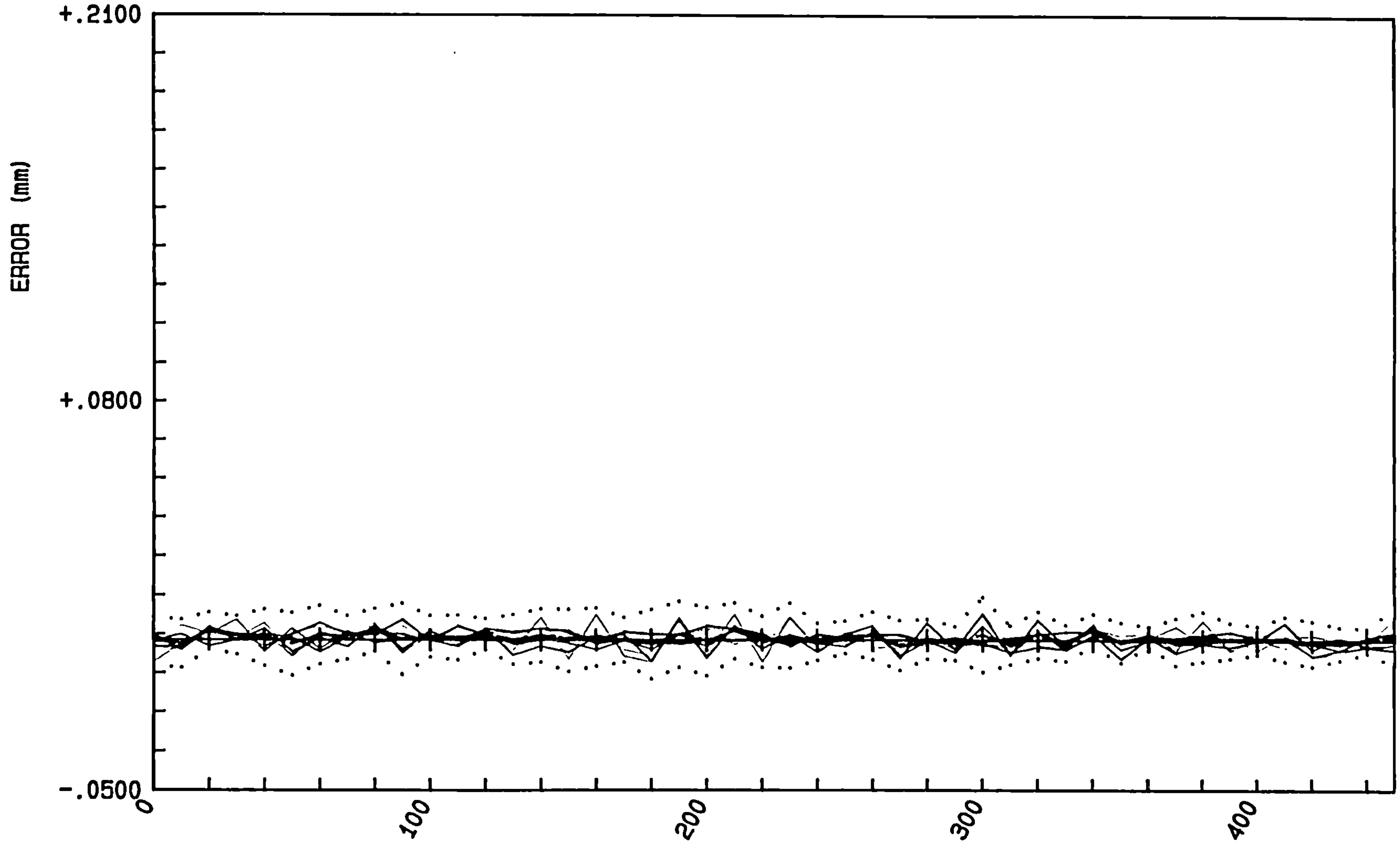
3.5.3 Prototype Compensation Unit Performance

The compensation unit was integrated to the single axis servo system and tested using two separate sets of compensation values. The first set of values were calculated from the results of the first calibration test for the full length of axis travel, shown in figure 3.9, and were used to compensate for the progressive and backlash error components. The second set of values were calculated from results of the second calibration test for part of the axis travel, shown in figure 3.6, and were used to compensate for the cyclic error component.

The performance of the compensation unit was evaluated by re-calibrating the slideway as before, but with the compensation active. The results of these calibration tests with compensation active for the progressive error and the cyclic error are shown in figures 3.11 and 3.12 respectively. These test results are plotted to the same scale as the uncompensated calibration results. This allows an immediate visual comparison to be made between the two sets of test results, and provides an instant appreciation of any improvements that have been made.

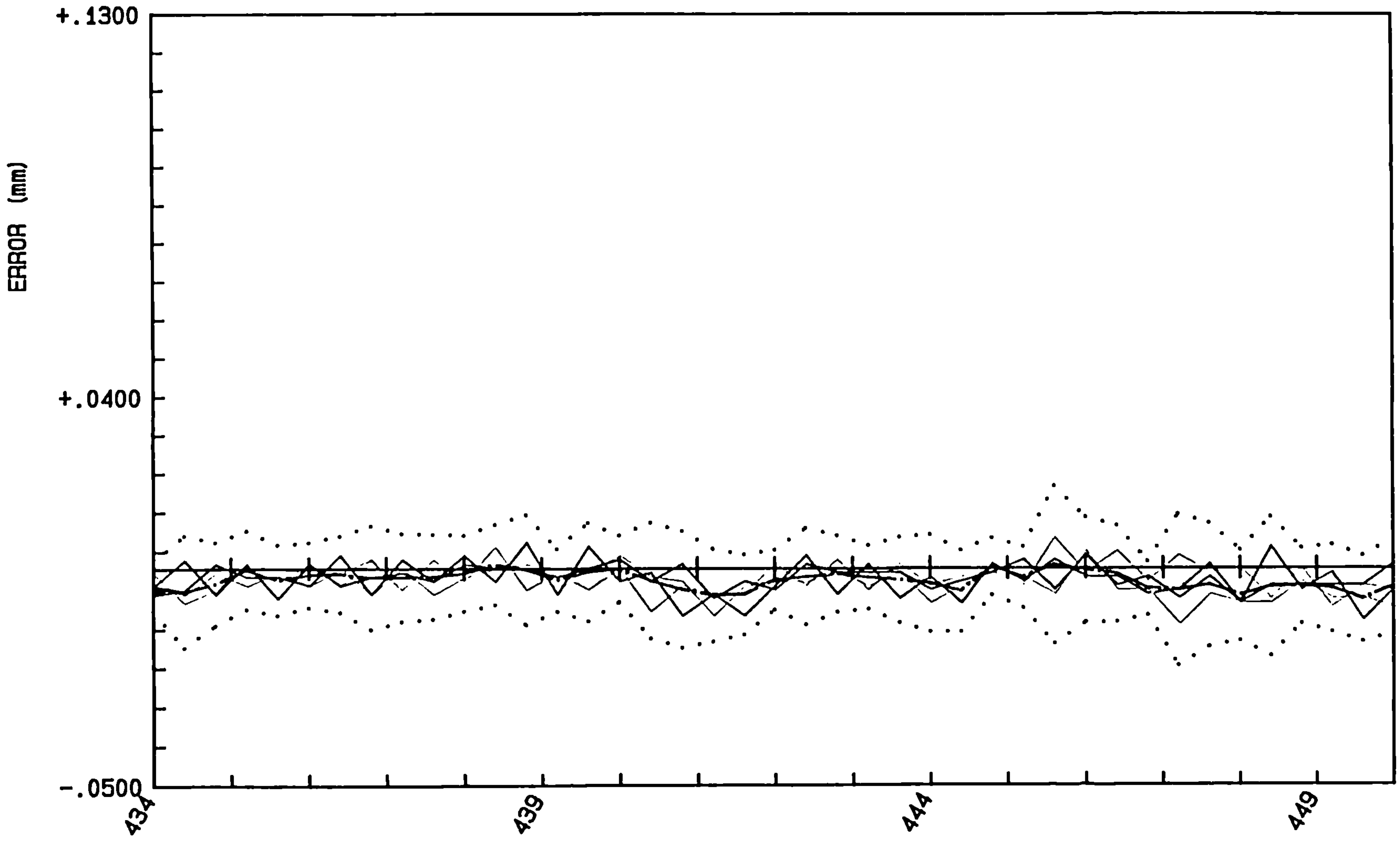
From figure 3.11 it can be seen that a huge improvement has been made in the positioning accuracy of the slideway, with a reduction in the magnitude of the position errors of fourteen to one achieved with the compensation active. This large improvement is of course a reflection of the large position errors present in the uncalibrated system, and a better indication of the performance of the compensation system is given by the error band and non-repeatability values. It can be seen from figure 3.11 that the error band value of 0.027mm, which indicates the total error content, and the non-repeatability value of 0.025mm, which indicates the random error components, are almost equal. This shows that almost all the systematic position errors have been eliminated, and is the best result that may be achieved by any form of pre-calibrated compensation. It can also be seen that the

FIGURE 3.11 CALIBRATION RESULTS WITH COMPENSATION



MACHINE: Test Slide	LOCATION: Hepworth Eng.	+/- 3 SIGMA
NUMBER: CAL. TEST 3	Compensation in both directions	ERROR BAND: .027505
DATE: 12/8/87 BY: S.P.		NON-REPEAT: .025052
AXIS: Single Axis		

FIGURE 3.12 CALIBRATION RESULTS WITH COMPENSATION



MACHINE: Test Slide NUMBER: CAL. TEST 4 DATE: 19/8/87 BY: S.P. AXIS: Single Axis	LOCATION: Hepworth Eng. Compensation over 2 revolutions	+/- 3 SIGMA ERROR BAND: .041467 NON-REPEAT: .036348

non-uniform backlash has been eliminated by compensating separately for the forward and reverse positioning errors.

The results of the calibration with the compensation for the cyclic error active, figure 3.12, also shows a vast improvement over the uncompensated system, with the cyclic error component being eliminated. The error band value of 0.041mm and non-repeatability value of 0.0365mm are very similar, again showing the high performance of the compensation method in compensating for the systematic component of the position errors. The advantages of compensating separately for the forward and reverse positioning errors is again highlighted as the initial cyclic error component was only present for one direction of travel.

The success of these performance tests with the prototype compensation system, and with the simulated compensation system, shows that the systematic errors in CNC machine tools can be eliminated or greatly reduced by the technique of modifying the velocity command signal from the CNC controller. This technique goes a long way to fulfilling the requirements of a universal compensation system set out in section two. The technique can be used to compensate for all systematic position errors if provided with the appropriate algorithm and data. The system operates in real time, and the digital simulation has shown the dynamic performance of the compensation technique to be good. As the compensation technique does not require interaction in any way with the controller it does not inhibit the normal operation of the controller or the machine tool. As the compensation technique uses signals that are common to the majority of CNC machine tools the technique is not controller specific making the system transportable for use with a wide range of CNC controllers and servo systems. However, in order to be flexible the system must be able to compensate for machine tools of all types and configurations. The test system only has a single axis and the only geometric error component that could be considered was linear positioning error. For multi-axis machines other geometric error components must be considered. The effect of the geometric error components on the positioning accuracy of the machine will depend on the configuration of the machine.

In order to provide this flexibility a compensation algorithm is required that can accommodate all machine tool types and configurations. A detailed discussion of the development of this universal compensation algorithm is given in section 4, together with a description of the different techniques used to identify the error components.

4 DEVELOPMENT OF A GENERAL ALGORITHM FOR UNIVERSAL MACHINE TOOL ERROR COMPENSATION

4.1 Error Identification Techniques

In the precalibrated method of error compensation the geometric error components, which contribute to the inaccuracy of the machine tool, require to be precisely identified. It is these error components that are used to generate the corrective values that are applied to the machine tool. The methods used to identify the geometric error components in multi-axis machines (both coordinate measuring machines and machine tools) fall into two categories, namely direct identification techniques and indirect identification techniques.

4.1.1 Direct Identification Techniques

In these identification techniques the positioning error at the tool point is measured directly, with reference to a fixed point. Either a standard or master part, or a space grid can be used to perform the measurement (35,36).

The standard part can take the form of a length standard, an area standard or a volume standard, depending on the number of dimensions that are required to be measured. The standard part of accurately known dimensions is placed upon the machines table, and the tool (usually a probe) is moved around the periphery of the part. The position errors are calculated as the difference between the tool position, as indicated by the machine's read-out, and the true dimension of the part. This method of measurement can be carried out quickly, but it can only indicate the machine errors about the contour of the standard part. This measurement technique can give a good indication of the machine's overall accuracy, but because it does not give a full picture of the errors throughout the whole of the machine working zone it is not suitable for use in precalibrated error compensation.

With the space grid technique the tool (probe) of the machine is moved along a series of straight parallel lines which form a grid or lattice throughout the working space of the machine. A length standard of known accurate dimension is used to indicate the true position of each point along the straight parallel lines. The error at each point in the lattice is calculated as the difference between the indicated position of the tool and the true dimension of the length standard, as with the standard part. In this way a comprehensive picture of the errors throughout the working zone of the machine is generated. The major drawback of this technique is that it takes an extremely long time to perform the measurements, especially if a complete map of the machine errors is to be generated at a reasonable resolution, as is required if compensation is to be performed. This can lead to measurement errors due to temperature changes over long test periods. This method of measurement is also impractical for identifying error constituents that change rapidly with respect to position such as cyclic errors.

Both these direct identification techniques require the use of standard parts or artifacts that need to be dimensionally stable, and which need extreme care when handling, transporting and storing. Direct identification techniques by their very nature lend themselves to machines that have a probing capability and are therefore most suitable, and most widely used, for accuracy evaluation of coordinate measuring machines.

4.1.2 Indirect Identification Techniques

In these techniques, also known as synthesizing techniques, the fundamental geometric error components of the machine, such as linear positioning error, straightness and roll, pitch and yaw errors are measured. These individual error components are then used to determine the positioning errors throughout the working zone of the machine indirectly. In order to do this a geometric model for the machine tool is required. This geometric model defines the actual motion of the machine tool's axes as a function of its fundamental geometric error components, with respect to a reference coordinate frame. The model can therefore be used with the geometric error components to synthesize the actual positioning error at the tool point for any location in the working zone.

This method only requires the measurement of the relevant error components of each of the machine axes along single measurement lines. The number of measurement lines corresponds to the number of machine axes. As a result the time required to complete the measurement of the machine is short when compared to the direct measurement techniques such as the space grid method. However this indirect measurement still provides the comprehensive picture of the machine errors required for error compensation. This method also allows rapidly changing error constituents to be measured, as the measurement increment is not constrained as with the use of standard parts.

Rigid body kinematic analysis methods are used to generate the geometric models required to synthesize the machine positioning errors. As the name suggests, in this method of analysis the machines axes are assumed to be rigid bodies which are unaffected by variations in load and thermal fluctuations. As a result the model only describes the positioning errors due to the geometric imperfections of the machine. However the effects of load and thermally induced error can be considered as modification to the geometric errors of the machine. By determining the relationship between the load and thermal variations and the machines geometric error components, the geometric model can be enhanced to include for load and thermal variations.

The use of the synthesizing technique for determining the position errors of machine tools and coordinate measuring machines has been well documented. One of the most notable examples of the use of the synthesizing technique is given by Schultschick (37). In this work the method was used to identify the errors of a horizontal jig boring machine. The error components of the machine were measured with the machine in an unloaded condition, and at a steady temperature state. A geometric model was generated for the machine and was used to synthesize the position errors at the tool point for any location within the working zone. In order to test the accuracy of the synthesized error values a double ball gauge having an offset of 400mm was used to provide a direct measurement of the position errors. The results of the comparison showed that the synthesized values agreed with the directly measured values to better than 84%.

Another example of the use of the synthesizing technique is given by Voutsadopoulus and Burdekin in their work carried out at U.M.I.S.T. (38,39). They successfully developed a system for the efficient computer aided calibration of coordinate measuring machines. The geometric errors of the C.M.M. are first measured. A suite of software routines which utilize the synthesizing technique are then used to determine the error map throughout the whole of the machine volume, allowing the overall machine accuracy to be evaluated.

The Synthesizing technique has been shown to provide an accurate and reliable picture of the geometrically induced position errors of a machine throughout the whole of its volume. It can provide all the information required for the compensation of the machine's geometrically induced position errors. The measurement technique does not require the use of standard or master parts which are sensitive to handling, transporting and storage, and which are prone to inaccuracies due to temperature variations over long test periods. The synthesizing technique requires a greatly reduced number of measurements when compared to direct measuring techniques, and as a result is far more time efficient. For these reasons it is the synthesizing technique which has been used in this research work.

4.2 Rigid Body Kinematic Analysis Of A Machine Tool

It has already been stated that to use the fundamental geometric error components of a machine tool for error compensation, a geometric model is required. The geometric model describes the actual movement of the machine tool as a function of its fundamental geometric error components. The geometric model will vary in form depending on the configuration of the particular machine tool. In order to develop the geometric model for a particular machine tool configuration kinematic analysis techniques may be used.

Using kinematic analysis each of the machines moving elements, such as slides, are depicted as vectors. Using vectors to represent the movement of the rigid bodies making up the machines structure, the motion of the machine can be represented by a kinematic chain. The kinematic chain can be represented graphically in the form of a vector diagram. As an example, consider a machine with three orthogonal axes controlling the movement of the tool as shown in figure 4.1.

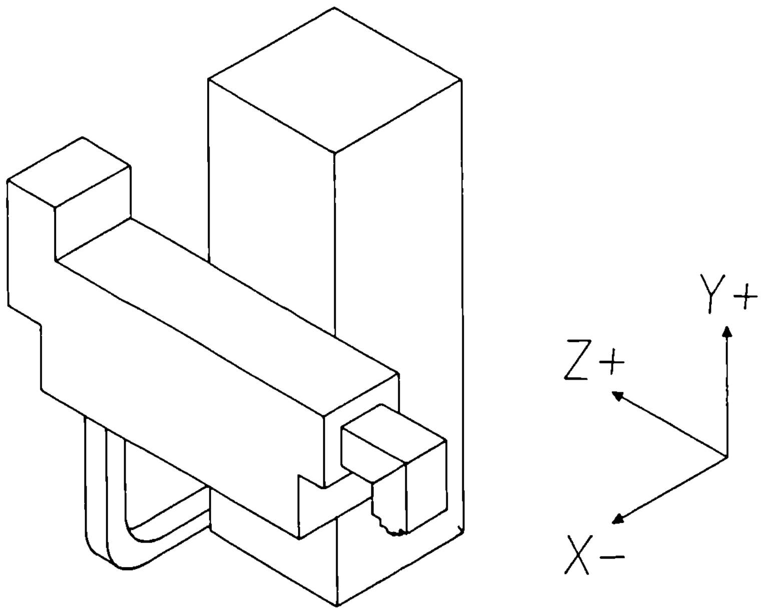


FIGURE 4.1 SCHEMATIC DIAGRAM OF A THREE AXIS MACHINE TOOL

The coordinate frame for this machine can be represented by a system of three orthogonal axes X,Y,Z which are parallel to the machines axes, and which intersect at the point O (coordinate 0,0,0), the machines datum position. This coordinate frame is shown in figure 4.2.

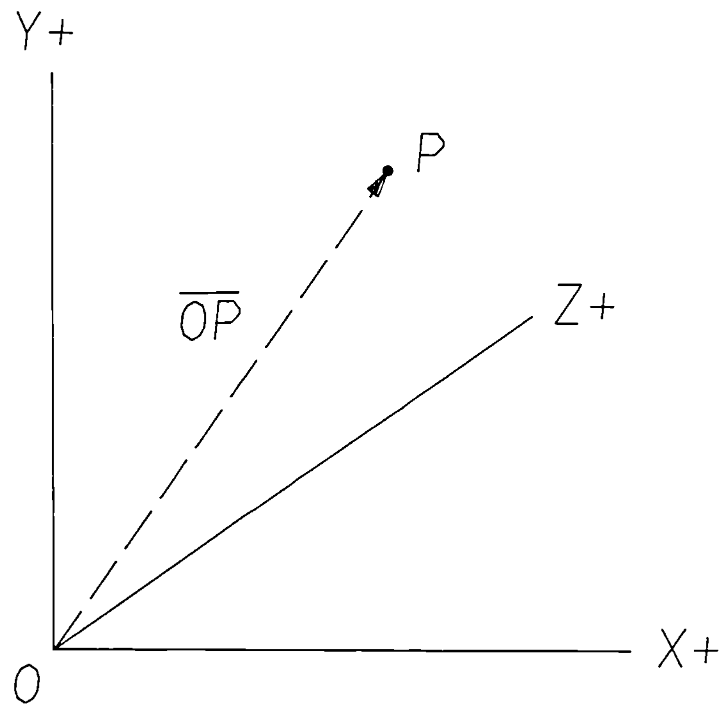


FIGURE 4.2 THE COORDINATE FRAME FOR THE MACHINE TOOL

In figure 4.2 point P represents the present position of the tool at an arbitrary position within the working volume of the machine. The point P can be represented as a single vector $\overline{OP}$ as shown in figure 4.2. The vector $\overline{OP}$ may be written as;

$$\overline{OP} = \begin{vmatrix} Xop \\ Yop \\ Zop \end{vmatrix} \quad \text{-------------- (1)}$$

where,

Xop is the actual X coordinate of the point P
Yop is the actual Y coordinate of the point P
and Zop is the actual Z coordinate of the point P

Alternatively the vector $\overline{OP}$ can be expressed as a sum of a chain of three vectors. Each vector in the chain is parallel to one of the axes in the coordinate frame. The vector chain represents the individual movement (or offset) of each of the machine axes involved in the tool attaining its present position. This three link kinematic chain of vectors representing the motion of the machines axes in moving the tool to the point P is shown in figure 4.3.

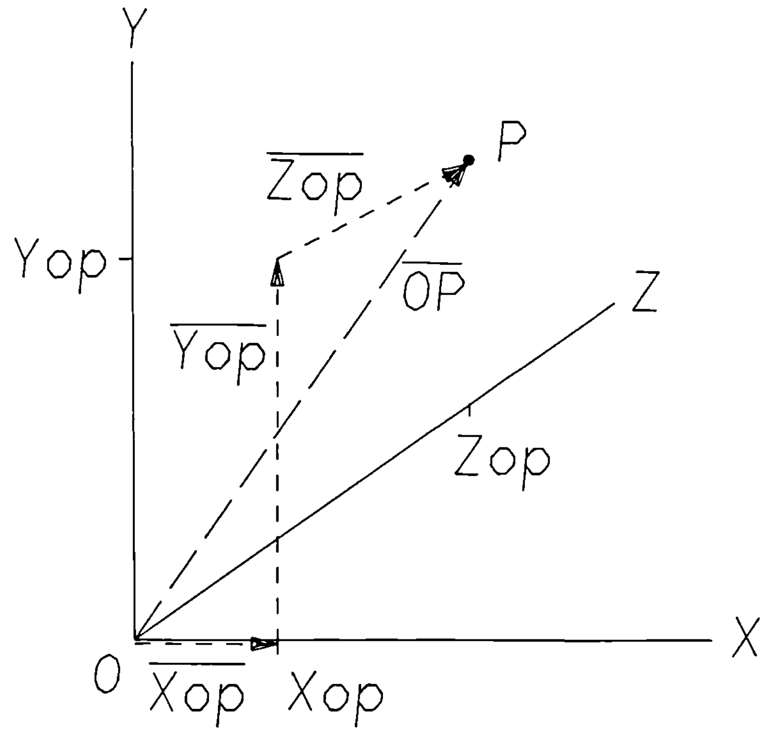


FIGURE 4.3 VECTORIAL REPRESENTATION OF THE MACHINE'S MOTION

The order of the summation of the three vectors is obviously irrelevant as the end vector $\overline{OP}$ will be the same irrespective of the order of movement of the machines axes. The vector $\overline{OP}$ may now be expressed in terms of this kinematic chain as;

$$\overline{OP} = \overline{Xop} + \overline{Yop} + \overline{Zop} \quad \text{-----------------(2)}$$

As discussed in section 1, the actual motion of each of the machine's axes consists of three pure translations and three pure rotations, corresponding to the six possible degrees of freedom of a moving body. The vectors $\overline{Xop}$, $\overline{Yop}$ and $\overline{Zop}$ can therefore each be expressed in terms of these six translatory and rotary constituents of motion. In order to do this each of the vectors $\overline{Xop}$, $\overline{Yop}$ and $\overline{Zop}$ will be considered individually.

The vector $\overline{Xop}$ represents the movement of the X axis required for the tool to attain the position Xop. The three rotational constituents of the movement can be assumed to be infinitesimal angles, and as such their effect on the final position of the X axis is negligible. The vector $\overline{Xop}$ is therefore described by the three translatory motions of the X axis only, and is expressed as;

$$\overline{Xop} = \begin{vmatrix} X + ex(x) \\ ey(x) \\ ez(x) \end{vmatrix} \quad \text{----------------(3)}$$

where,

X is the desired or nominal position of the X axis as indicated by the machines coordinate display.

ex(x) is the translational error of the X axis in the X direction or X linear positioning error.

ey(x) is the translational error of the X axis in the Y direction or X straightness error in the X,Y plane.

and ez(x) is the translational error of the X axis in the Z direction or X straightness error in the X,Z plane.

Although the infinitesimal rotations of the X axis do not directly effect the movement of the X axis, they will have an effect on the movement of the Y and the Z axes as they are mounted upon the X axis. The effect of the three infinitesimal rotational motions of the X axis will be to establish a new trajectory for the Y and the Z axes. This can be represented graphically in the vector diagram by three orthogonal rotations of the reference coordinate frame X,Y,Z through the point Xop to produce the new coordinate frame X_x, Y_x, Z_x as shown in figure 4.4.

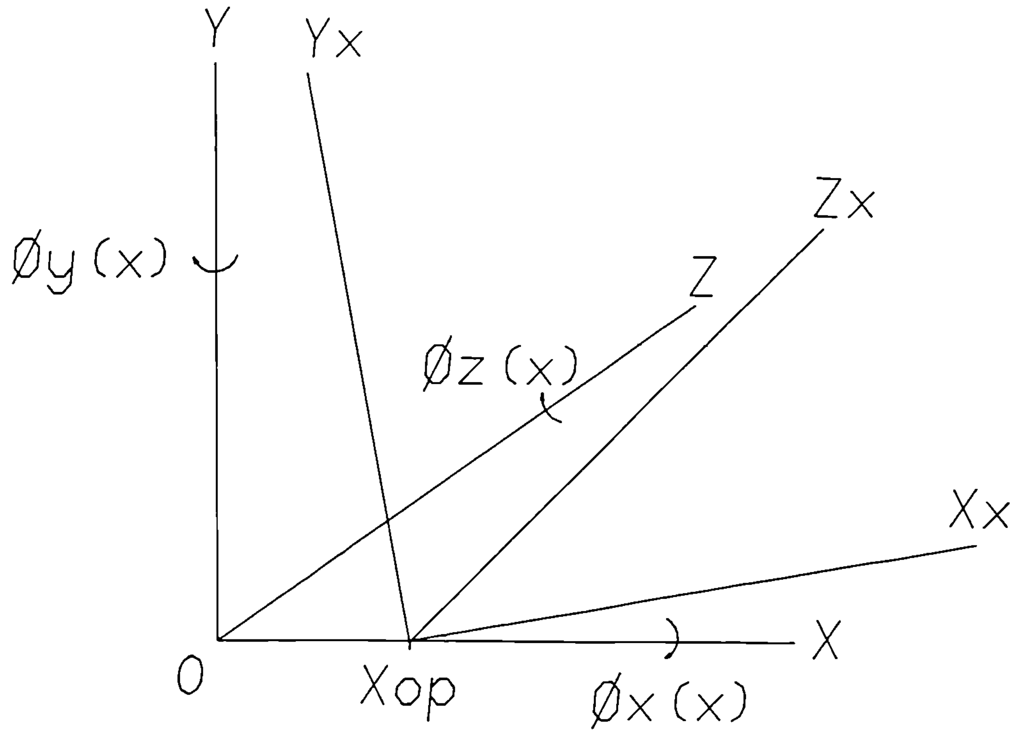


FIGURE 4.4 ROTATION OF THE REFERENCE COORDINATE FRAME

In order to quantify the effects of these three rotations in terms of actual machine position, we need to describe the new Y and Z trajectories in terms of the reference coordinate frame. In order to do this the well known three dimensional transformation matrix can be used (37). This matrix can be used to transform the new coordinate frame X_x, Y_x, Z_x into the reference coordinate frame X,Y,Z. The transformation matrix expressed in terms of the three infinitesimal rotations is given below.

transformation matrix R(x) =

$$\begin{vmatrix} \cos\varnothing y(x)\cos\varnothing z(x) & -\cos\varnothing y(x)\sin\varnothing z(x) & \sin\varnothing y(x)\cos\varnothing z(x) \\ \cos\varnothing x(x)\sin\varnothing z(x) & \cos\varnothing x(x)\cos\varnothing z(x) & -\sin\varnothing x(x)\cos\varnothing z(x) \\ -\sin\varnothing y(x)\cos\varnothing x(x) & \sin\varnothing y(x)\cos\varnothing x(x) & \cos\varnothing y(x)\cos\varnothing x(x) \end{vmatrix} \quad -(4)$$

where,

$\varnothing x(x)$ is the rotational error of the X axis about the X axis or X roll error.

$\phi y(x)$ is the rotational error of the X axis about the Y axis or X yaw error.

and $\phi z(x)$ is the rotational error of the X axis about the Z axis or X pitch error.

Using the assumption that the roll, yaw and pitch angles are infinitesimal the following approximations can be used;

$$\sin \phi = 0$$

and $$\cos \phi = 1 - \phi^2/4 = 1$$

where ϕ is expressed in radians.

Substituting for these approximations in equation 4 allows the transformation matrix R(x) to be greatly simplified as shown below.

$$R(x) = \begin{vmatrix} 1 & -\phi z(x) & \phi y(x) \\ \phi z(x) & 1 & -\phi x(x) \\ -\phi y(x) & \phi x(x) & 1 \end{vmatrix} \text{ ---------(5)}$$

Next consider the vector $\overline{Yop}$ which represents the movement of the Y axis required for the tool to attain the position Yop. The vector $\overline{Yop_x}$ also represents the motion of the Y axis in moving to position Yop, but with respect to the modified coordinate frame X_x, Y_x, Z_x. Again if the rotational motions of the Y axis are assumed to be infinitesimal, the motion of the Y axis within the coordinate frame X_x, Y_x, Z_x can be expressed in terms of its three translatory motions only. This is expressed as;

$$\overline{Yop_x} = \begin{vmatrix} ex(y) \\ Y + ey(y) \\ ez(y) \end{vmatrix} \text{ ---------------(6)}$$

where,

ex(y) is the translational error of the Y axis in the X direction or Y straightness error in the X,Y plane.

Y is the desired or nominal position of the Y axis as indicated by the machines coordinate display.

ey(y) is the translational error of the Y axis in the Y direction or Y linear positioning error.

and ez(y) is the translational error of the Y axis in the Z direction or Y straightness error in the Y,Z plane.

The transformation matrix R(x) can now be used to transform the vector $\overline{Yop}x$ in the coordinate frame X_x, Y_x, Z_x into the vector $\overline{Yop}$ in the coordinate frame X,Y,Z. This gives;

$$\overline{Yop} = R(x) \cdot \overline{Yop_x} \quad \text{-----------------(7)}$$

and substituting with equations 5 and 6 in equation 7 we get;

$$\overline{Yop} = \begin{vmatrix} 1 & -\varnothing z(x) & \varnothing y(x) \\ \varnothing z(x) & 1 & -\varnothing x(x) \\ -\varnothing y(x) & \varnothing x(x) & 1 \end{vmatrix} \cdot \begin{vmatrix} ex(y) \\ Y + ey(y) \\ ez(y) \end{vmatrix} \quad \text{-----(8)}$$

Although the three infinitesimal rotations of the Y axis do not directly effect the movement of the Y axis, they will effect the movement of the Z axis as it is mounted upon the Y axis. The effect of the three rotations of the Y axis is to produce yet another new trajectory for movement of the Z axis. Again this can be represented in the vector diagram as three orthogonal rotations of the coordinate frame X_x, Y_x, Z_x through the point Yop to produce the coordinate frame X_y, Y_y, Z_y.

A transformation matrix can again be used to transform the coordinate frame X_y, Y_y, Z_y into the coordinate frame X_x, Y_x, Z_x. This transformation matrix when simplified using the assumptions of infinitesimal angles can be expressed as,

$$R(y) = \begin{vmatrix} 1 & -\not{0}z(y) & \not{0}y(y) \\ \not{0}z(y) & 1 & -\not{0}x(y) \\ -\not{0}y(y) & \not{0}x(y) & 1 \end{vmatrix} \text{ ----------(9)}$$

where,

Øx(y) is the rotational error of the Y axis about the X axis or Y yaw error.

Øy(y) is the rotational error of the Y axis about the Y axis or Y roll error.

and Øz(y) is the rotational error of the Y axis about the Z axis or Y pitch error.

Finally consider the vector $\overline{Zop}$ which represents the movement of the Z axis required for the tool to attain the position Zop, with reference to the reference coordinate frame. In order to express the vector $\overline{Zop}$ in terms of the machines fundamental geometric error components the vector $\overline{Zop_y}$ must be considered. The vector $\overline{Zop_y}$ represents the same motion of the Z axis in moving to position Zop but with reference to the coordinate frame X_y, Y_y, Z_y. Again if the three rotational errors of the Z axis are assumed infinitesimal the vector $\overline{Zop_y}$ can be expressed in terms of the three translations of the Z axis only. This is expressed below.

$$\overline{Zop_y} = \begin{vmatrix} ex(z) \\ ey(z) \\ Z + ez(z) \end{vmatrix} \text{ -------------------(10)}$$

where,

ex(z) is the translational error of the Z axis in the X direction or Z straightness error in the X,Z plane.

ey(z) is the translational error of the Z axis in the Y direction or Z straightness error in the Y,Z plane.

Z is the desired or nominal position of the Z axis as indicated by the machines coordinate display.

and, ez(z) is the translational error of the Z axis in the Z direction or Z linear positioning error.

The transformation matrices R(y) and R(x) may be used to transform the vector $\overline{Zop}_y$ in the coordinate frame X_y, Y_y, Z_y into the vector of interest, $\overline{Zop}$ in the reference coordinate frame. This transformation is shown below.

$$\overline{Zop} = R(x) \cdot R(y) \cdot \overline{Zop}_y \quad \text{-----------(11)}$$

Substituting with equations (5), (9) and (10) in equation (11) gives;

$$\overline{Zop} = \begin{vmatrix} 1 & -\varnothing z(x) & \varnothing y(x) \\ \varnothing z(x) & 1 & -\varnothing x(x) \\ -\varnothing y(x) & \varnothing x(x) & 1 \end{vmatrix} \cdot \begin{vmatrix} 1 & -\varnothing z(y) & \varnothing y(y) \\ \varnothing z(y) & 1 & -\varnothing x(y) \\ -\varnothing y(y) & \varnothing x(y) & 1 \end{vmatrix}$$

$$\cdot \begin{vmatrix} ex(z) \\ ey(z) \\ Z + ez(z) \end{vmatrix} \quad \text{------------------------------(12)}$$

The vectors $\overline{Yop}$ and $\overline{Zop}$ in equation (2) can now be replaced by equations (8) and (11) respectively, in order to describe the vector $\overline{OP}$ in terms of the machines fundamental motions. This gives;

$$\overline{OP} = \overline{Xop} + R(x) \cdot \overline{Yop}_x + R(x) \cdot R(y) \cdot \overline{Zop}_y \quad \text{-----(13)}$$

4.2.1 Consideration of the Machines Orthogonality Errors

In the kinematic analysis presented above the implicit assumption is made that the axes of the machine are perfectly square to each other. This is of course not the case in practice and there will be errors in orthogonality between mutually perpendicular axes, as discussed in section 1. The orthogonality errors associated with the machine of this example are shown graphically in figure 4.5.

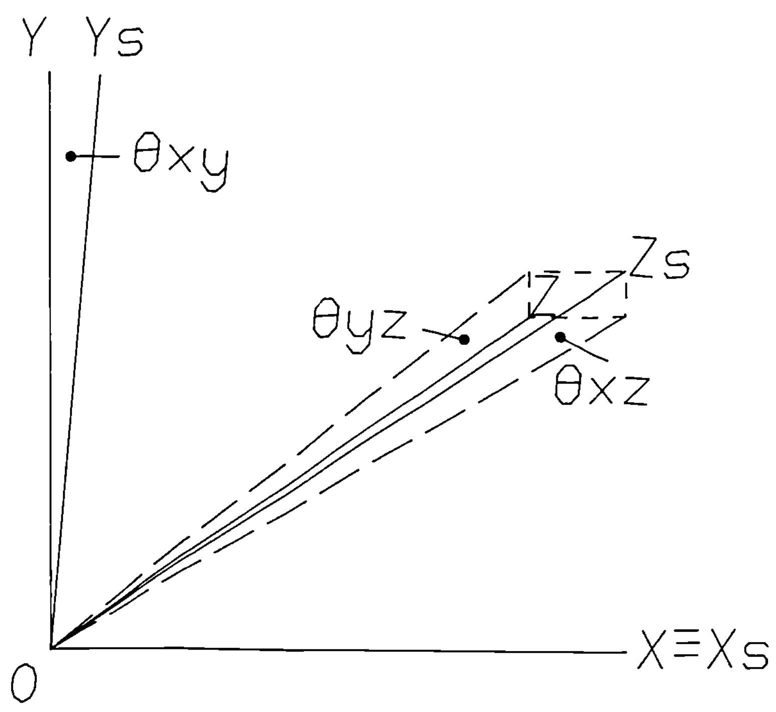


FIGURE 4.5 GRAPHICAL REPRESENTATION OF THE MACHINE TOOL'S ORTHOGONALITY ERRORS

In figure 4.5 the reference coordinate frame of the machine is depicted by the axes X,Y,Z as before. The actual coordinate frame of the machine when the orthogonality errors are considered is depicted by the axes X_s,Y_s,Z_s. It can be seen from figure 4.5 that the reference axis X has been chosen to coincide with the actual axis X_s, and that the reference plane XOY has been chosen to coincide with the actual plane X_sOY_s. This allows the orthogonality errors of the machine to be expressed by just three angles, and greatly simplifies the kinematic analysis of the machine. The three angles that represent the orthogonality errors of the machine are θxy, θxz and θyz. θxy is the squareness error in the plane XOY. θxz is the squareness error in the plane XOZ. θyz is the squareness error in the plane YOZ.

In order to determine the effects of the three orthogonality errors on the positioning accuracy of the machine we must transform the actual coordinate frame X_s, Y_s, Z_s into the reference coordinate frame X,Y,Z. Again a transformation matrix provides the relationship between the two coordinate frames. The form of this transformation matrix, R(s), is shown below (37).

$$R(s) = \begin{vmatrix} 1 & -\sin \theta xy & \dfrac{\tan \theta xz}{1 + \tan \theta yz + \tan \theta xz} \\ 0 & \cos \theta xy & \dfrac{-\tan \theta yz}{1 + \tan \theta yz + \tan \theta xz} \\ 0 & 0 & \dfrac{1}{1 + \tan \theta yz + \tan \theta xz} \end{vmatrix} \quad \text{--(14)}$$

If we assume that the squareness errors θxy, θxz and θyz are infinitesimal then the following approximations can be made.

$$\sin \theta = 0 \qquad \cos \theta = 1 \quad \text{and} \quad \tan \theta = 0$$

using these approximations the transformation matrix R(s) can be greatly simplified as shown below.

$$R(s) = \begin{vmatrix} 1 & -\theta xy & \theta xz \\ 0 & 1 & -\theta yz \\ 0 & 0 & 1 \end{vmatrix} \quad \text{-----------------(15)}$$

This transformation matrix R(s) can now be used to transform the translational movements of the machine's axes from the actual coordinate frame X_s, Y_s, Z_s to the reference coordinate frame X,Y,Z. The transformation matrix R(s) can be included in equation (13) in order to quantify the effects of the orthogonality errors on machine positioning. This is shown below.

$$\overline{OP} = R(s).\overline{Xop} + R(x).R(s).\overline{Yop_x} + R(x).R(y).R(s).\overline{Zop_y} \quad \text{--(16)}$$

In expanded form this equation becomes,

$$\begin{vmatrix} Xop \\ Yop \\ Zop \end{vmatrix} = \begin{vmatrix} 1 & -\theta xy & \theta xz \\ 0 & 1 & -\theta yz \\ 0 & 0 & 1 \end{vmatrix} . \begin{vmatrix} X + ex(x) \\ ey(x) \\ ez(x) \end{vmatrix} +$$

$$\begin{vmatrix} 1 & -\varnothing z(x) & \varnothing y(x) \\ \varnothing z(x) & 1 & -\varnothing x(x) \\ -\varnothing y(x) & \varnothing x(x) & 1 \end{vmatrix} . \begin{vmatrix} 1 & -\theta xy & \theta xz \\ 0 & 1 & -\theta yz \\ 0 & 0 & 1 \end{vmatrix} . \begin{vmatrix} ex(y) \\ Y + ey(y) \\ ez(y) \end{vmatrix}$$

$$+ \begin{vmatrix} 1 & -\varnothing z(x) & \varnothing y(x) \\ \varnothing z(x) & 1 & -\varnothing x(x) \\ -\varnothing y(x) & \varnothing x(x) & 1 \end{vmatrix} . \begin{vmatrix} 1 & -\varnothing z(y) & \varnothing y(y) \\ \varnothing z(y) & 1 & -\varnothing x(y) \\ -\varnothing y(y) & \varnothing x(y) & 1 \end{vmatrix} .$$

$$\begin{vmatrix} 1 & -\theta xy & \theta xy \\ 0 & 1 & -\theta yz \\ 1 & 0 & 1 \end{vmatrix} . \begin{vmatrix} ex(z) \\ ey(z) \\ Z + ez(z) \end{vmatrix} \quad \text{-----------------(17)}$$

Equation (17) represents the geometric model for the machine tool of this example. In this expression the vector $\overline{OP}$ represents the actual position of the machine's axes at any point in the machines working volume. Here $\overline{OP}$ has been expressed in terms of the fundamental geometric error components of the machine, all of which can be easily identified using established measurement techniques.

4.3 The Development Of A Geometric Model For All Machine Configurations

The geometric model which has just been developed in the above example describes uniquely the relationship between the actual position, and the geometric error components of a three axis machine of the configuration shown in figure 4.1. In this particular machine configuration all three axes of motion are associated with the tool, the workpiece being stationary. For any other machine tool configuration the relationship between axis position and the machine's geometric errors would be different, and a new geometric model would be needed to describe this relationship. This presents a potential problem for a general purpose compensation system that needs to be flexible. In section 2 the requirements for a general purpose compensation system were developed, and stated that in order to be flexible a system should be able to compensate for all machine tool types and configurations. In order to accommodate this requirement a geometric model is needed that can be used for all machine configurations.

Any three axis machine may be classified as being of one of four configurations(40). These four basic configurations are shown diagrammatically in figure 4.6. In figure 4.6 the machines are classified as being of either TXYZ, XTYZ, XYTZ or XYZT configurations. The notation indicates whether an axis is associated with tool movement or workpiece movement. Letters following the T refer to axes associated with tool movement and letters preceding the T refer to axes associated with workpiece movement.

Machines of configuration XYZT, in which the tool is stationary and all three axes of motion are associated with the workpiece, are relatively rare. Therefore,in order to simplify the analysis machines of the XYZT configuration are not considered.

The geometric model developed in the above worked example is obviously for a machine of the TXYZ configuration. Using the same kinematic analysis technique, geometric models can be developed for machines of the XTYZ and XYTZ configurations. The resulting geometric models for these three machine configurations are given below.

For TXYZ machine configurations;

$$\overline{OP} = R(s).\overline{Xop} + R(x).R(s).\overline{Yop} + R(x).R(y).R(s).\overline{Zop} \quad \text{----(16)}$$

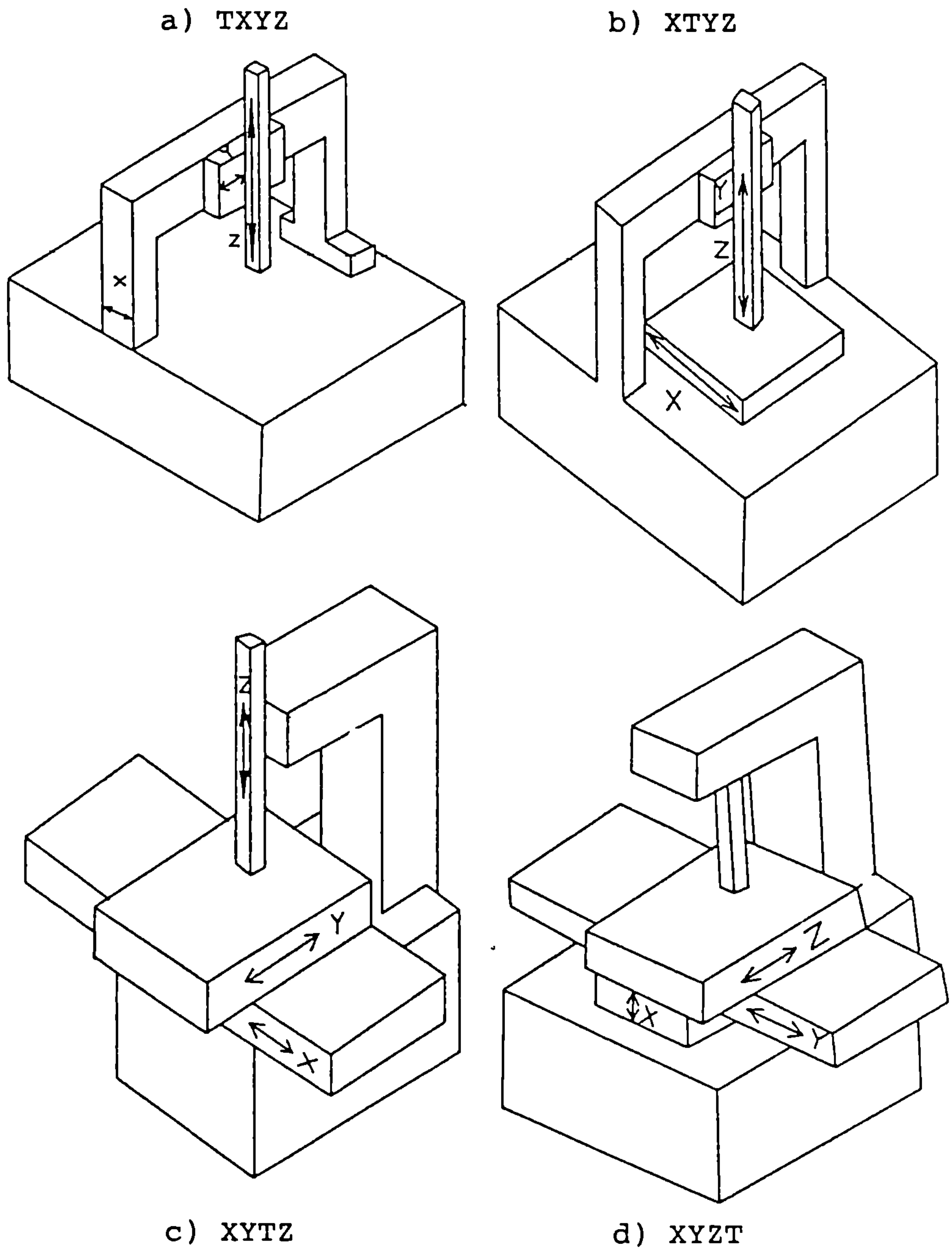


FIGURE 4.6. THREE AXIS MACHINE TOOL CONFIGURATIONS

For XTYZ machine configurations;

$$\overline{OP} = R(x)^{-1}.R(s).(-\overline{Xop} + \overline{Yop}) + R(x)^{-1}.R(y).R(s).\overline{Zop} \quad \text{--(18)}$$

For XYTZ machine configurations;

$$\overline{OP} = R(y)^{-1}.R(x).(-\overline{Xop} + \overline{Zop}) - R(y)^{-1}.R(s).\overline{Yop} \quad \text{----(19)}$$

After expanding, and simplifying these three matrix equations, they can be rearranged to express the X,Y and Z axis position errors in terms of the machines fundamental error components. The geometric model is used in this form by the compensation system to calculate the amount of correction needed for each of the machine's axes. These error equations for the three basic machine configurations are given below.

For TXYZ machine configurations;

$$Xop - X = Ex = ex(x) + ex(y) + ex(z) + \emptyset y(x).Z + \emptyset z(x).Y + \emptyset y(y).Z + \theta xz.Z + \theta xy.Y \quad \text{----(20)}$$

$$Yop - Y = Ey = ey(y) + ey(x) + ey(z) + \emptyset x(x).Z + \emptyset x(y).Z + \theta yz.Z \quad \text{----(21)}$$

$$Zop - Z = Ez = ez(z) + ez(x) + ez(y) - \emptyset x(x).Y \quad \text{----(22)}$$

For XTYZ machine configurations;

$$Ex = ex(x) + ex(y) + ex(z) + \emptyset y(y).Z + \emptyset y(x).Z + \emptyset z(x).Y + \theta xz.Z + \theta xy.Y \quad \text{----(23)}$$

$$Ey = ey(y) + ey(x) + ey(z) + \emptyset x(x).Z - \emptyset z(x).X + \emptyset x(y).Z + \theta yz.Z \quad \text{----(24)}$$

$$Ez = ez(z) + ez(x) + ez(y) - \emptyset x(x).Y - \emptyset y(x).X \quad \text{----(25)}$$

For XYTZ machine configurations;

$$Ex = ex(x) + ex(y) + ex(z) + \emptyset y(x).Z + \emptyset y(y).Z + \emptyset z(y).Y +$$

```
     θxz.Z + θxy.Y                                        ----(26)

Ey = ey(y) + ey(x) + ey(z) - Øz(x).X + Øx(x).Z + Øx(y).Z +
     θyz.Z                                                ----(27)

Ez = ez(z) + ez(x) + ez(y) - Øy(x).X - Øy(y).X - Øx(y).Y
                                                          ----(28)
```

It can be seen from these three sets of equations that the expressions for common axes are very similar. In fact it can be seen that most of the error terms are common to all three sets of equations. It is therefore easy to combine these three sets of equations to provide a single geometric model that can be used for all three machine configurations. The resulting equations are shown below.

```
Ex = ex(x)+ex(y)+ex(z)+Øy(y).Z+Øy(x).Z+Øz(x).Y+θxz.Z+θxy.Y
     -----------------------------------------------------
     ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
     ********************************        ************
     +Øz(y).Y                                       ----(29)
     ********


Ey = ey(y)+ey(x)+ey(z)+Øx(x).Z+Øx(y).Z+θyz.Z-Øz(x).X -(30)
     ---------------------------------------
     ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
     **********************************************


Ez = ez(z)+ez(x)+ez(y)-Øx(x).Y-Øy(x).X-Øy(y).X-Øx(y).Y (31)
     ------------------------
     ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
     ****************        ***********************
```

In the above equations the terms underlined with ---- are associated with machines with a TXYZ configuration, the terms underlined with ^^^^ are associated with machines with a XTYZ configuration, and the terms underlined with **** are associated with machines with a XYTZ configuration.

This universal geometric model forms the heart of the algorithm, used by the compensation system, to generate the correction values that are applied to the axes of the machine tool. For a particular machine configuration the relevant error components are stored in the memory of the compensation system, any redundant error terms being set to zero. In this way all redundant error terms are effectively removed from the geometric model.

As well as being used for all three axis machines this geometric model can also be applied to two axis machine configurations. For example the Y and Z axes of a XTYZ type of machine are of the same configuration as a lathe. By setting all error terms associated with the X axis to zero the geometric model can be applied to a lathe configuration. Used in this way this universal geometric model can be applied to most machine configurations.

A production version of a universal compensation system has been developed, which utilizes this universal geometric model, and the compensation techniques developed during this research and described in section 3. This production compensation system is described in section 5.

5 DESCRIPTION OF THE PRODUCTION COMPENSATION SYSTEM

5.1 Introduction

In section 3 the development of a compensation strategy was described that broadly fulfilled the requirements of a universal compensation system. Simulation techniques were used to prove the viability of the compensation strategy and to assess its performance. Based on the results of these simulation tests a prototype compensation system was designed and built. This prototype system was integrated to a single axis test machine and its performance evaluated. The results of these evaluation tests showed that the compensation strategy was extremely effective at correcting for systematic position errors.

In section 4 a general geometric model was developed that describes the relationship between axis positional error and the geometric error components, for all machine tool types and configurations up to three axes. This geometric model can be used in a precalibrated compensation system to predict the amount of compensation required to correct for the systematic position errors of a wide range of machine types and configurations.

In this section the compensation strategy and the general geometric model are combined to produce a compensation system that fulfills completely the criterion for for a universal compensation system. This compensation system provides a cost effective and flexible solution to the accuracy problem, and thus provides a product with a good market potential. The production compensation system was developed using the strategy and principles derived from the prototype compensation system, and utilizing the general geometric model. The hardware configuration, although more complex for multi-axis operation, is basically the same as for the prototype system. It consists basically of a position decoding circuit, a central processing circuit and a compensation interface circuit.

In order to protect the innovative nature and novel aspects of this compensation system patents were applied for. Patents were applied for in the following countries, Great Britain, Europe, U.S.A., Japan and Taiwan. The patent application in the U.S.A. has been granted (patent no. 323,652), the other patent applications are currently at the patent pending state.

The following sections give a description of the hardware and software that make up the production compensation system.

5.2 Compensation System Hardware Description

The production error compensation system (known as E.C.S.) is made up of a number of hardware modules which are located in a system rack, and connected together via a common 96 way bus. This modular structure provides the system with flexibility allowing the hardware configuration to be customized to suit a particular machine tool type and configuration. For example, the amount of compensation memory can be chosen to suit the size and condition of the machine, and the number of axis interface modules can be chosen to suit the number of machine axes. Figure 5.1 shows the modular construction of the E.C.S., and shows the seven module types that can make up a system. These are the microprocessor module, the system memory module, the communications module, the axis memory module, the encoder axis module, the resolver axis module and the power supply module. It can be seen from figure 5.1 that the modules connect together via a common backplane. This backplane supports the 96 way bus that provides the communications link for the flow of signals throughout the system. The construction of the E.C.S. is based on the eurocard standard, with each module consisting of up to two 3U eurocard size circuit boards. The modules are mounted in a standard 19 inch sub-rack assembly, and connect to the backplane via a 96 way connector. An E.C.S. unit set up for a three axis machine configuration is shown in figure 5.2.

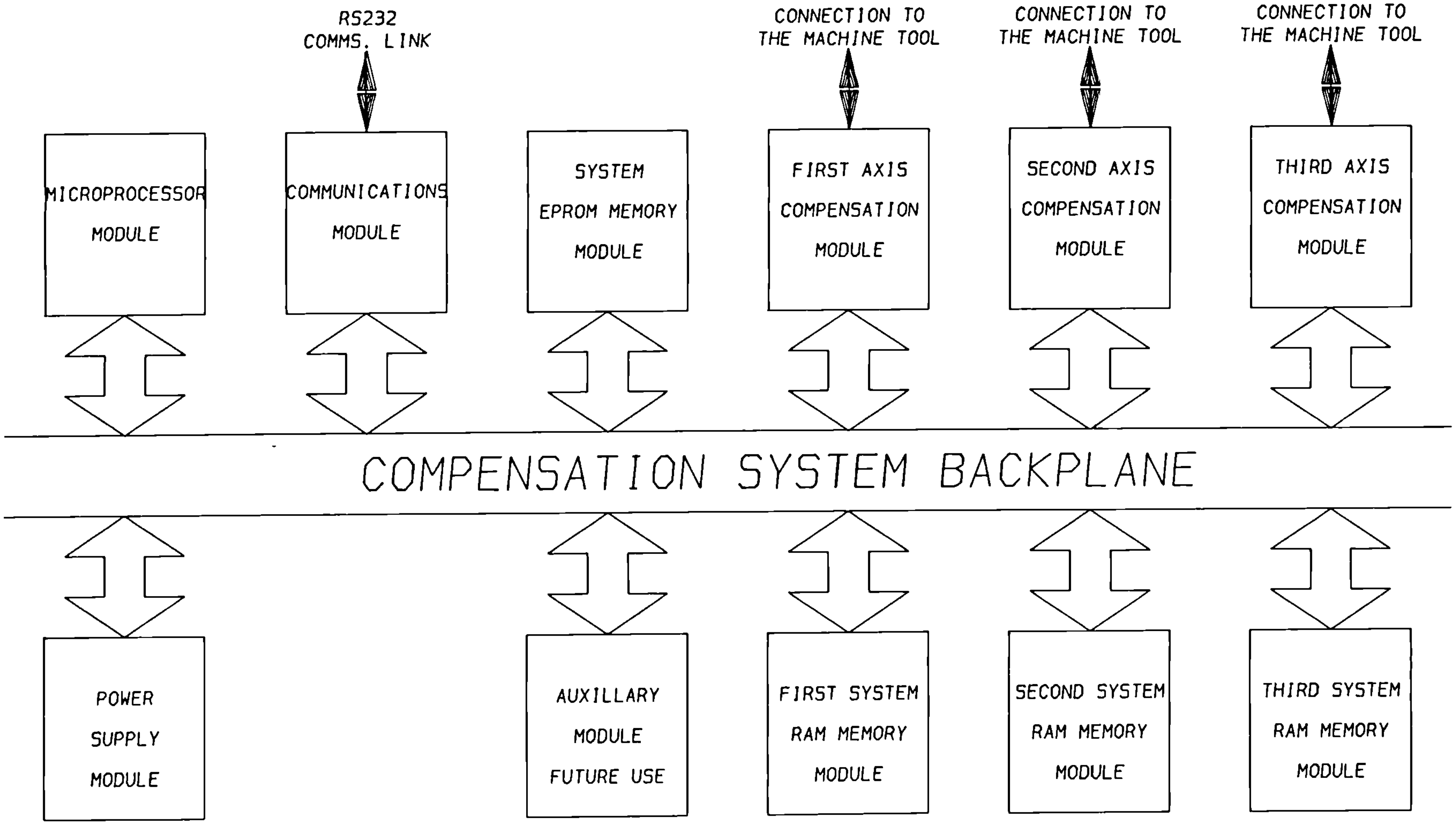
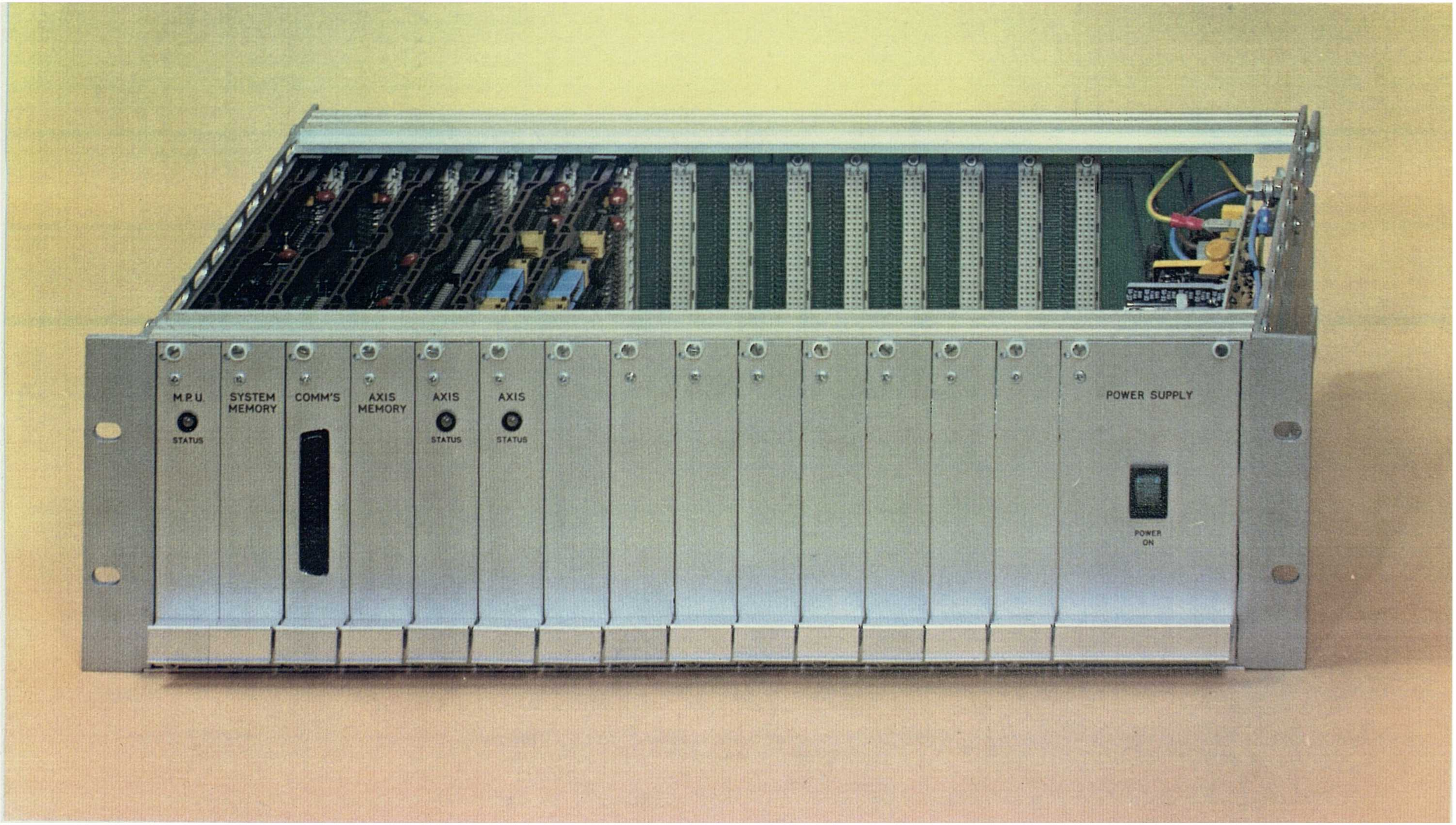


FIGURE 5.1 THE MODULAR ERROR COMPENSATION SYSTEM

FIGURE 5.2 - THE E.C.S. UNIT FOR A TWO AXIS MACHINE TOOL



This figure shows the modules in position in the 19 inch sub-rack.

The microprocessor module is at the heart of the E.C.S., controlling the operation of the compensation process and providing the processing power required to calculate the compensation values in real time. The microprocessor itself is the 16 bit Motorola 68000. The microprocessor runs at 8 megahertz and has a 32 bit internal architecture. These two features ensure the fast processing that is required for real time compensation of multi-axis machines. The microprocessor has a 24 bit address bus which provides an addressable range of 16 megabytes. This extensive addressable range allows a large memory capacity for the storage of geometric error values. A watchdog circuit is incorporated on the microprocessor module. This circuit monitors the operation of the E.C.S. and ensures that in the event of a failure the E.C.S. fails safe by electrically isolating the E.C.S. from the machine tool.

The system memory module, as the name suggests provides the memory required for the operation of the microprocessor system. The module is made up of a small amount of volatile RAM and a larger section of EPROM. The RAM provides scratch pad memory required for the routine operation of microprocessor, such as storage for the stack. The EPROM holds the system firmware. The firmware is the system program controlling the compensation process and general operation of the E.C.S.

The communications module provides the internal and external communications required for operation of the E.C.S. A dual RS232 serial interface is provided for communication with external devices. Connection to this serial interface is made via a 36 way 'D' type connector mounted on the front panel of the communications module. The serial interface allows the E.C.S. to communicate with an external computer. This is necessary for commissioning, testing and fault finding of the E.C.S. This interface also allows the data required for compensation, such as geometric error values, machine customization data and E.C.S. status data, to be transferred to the E.C.S. A limited number of digital I/O signals are also provided for external use, and can be accessed through the 36 way connector. These digital signals are not generally used, but are included to provide flexibility in the event of special applications where simple digital control signals may be required. This module also provides digital signals for internal use. These internal digital control signals are used to control the operation of the E.C.S. A timer is also provided on the communications board which again is used to control the operation of the E.C.S.

The axis memory module is a RAM based module which holds the machine tool specific information that is required by the E.C.S. in order to perform compensation. This machine specific information includes the geometric error data for the machine tool that is obtained through the error identification process, and the machine tool compensation parameters. One of the main attributes of the E.C.S. is its ability to be applied to a variety of machine tool types and configurations. In order to do this the E.C.S. requires machine specific information such as number of axes and axis configuration. The compensation parameters are parameters used to provide the E.C.S. with this information, and so customize an E.C.S. unit for use with a particular machine tool. The geometric error values are used by the microprocessor to calculate the compensation values to be applied to the machines axes. A single axis memory module can hold a maximum of approximately 32,000 geometric error values. An E.C.S. unit can accommodate a maximum of 5 axis memory modules providing a maximum system storage capacity of approximately 160,000 geometric error values. The axis memory is not preassigned to a particular axis or error type, resulting in optimum efficiency and flexibility of the memory. The integrity of the ram is maintained by a lithium battery located on the axis memory module. This battery provides power to the RAM through a battery backup control circuit when the main power supply to the E.C.S. is switched off. As well as keeping the RAM 'live' the battery backup circuit provides write protection, preventing corruption of the stored data. The estimated life of the lithium battery is 10 years.

The encoder axis module provides the interface between the E.C.S. and the machine tool axis. As the name suggests this module is used with machines that have incremental optical encoders as position transducers. The signals from the encoder, the two quadrature signals and the marker signal are fed into the axis module through an opto-isolator stage. The opto-isolators provide electrical isolation between the encoder and the E.C.S. The encoder quadrature signals are processed by the axis module to produce a meaningful position count that can be used by the microprocessor. The axis module effectively counts the edges of the two quadrature waveforms, providing a four fold increase in resolution over the fundamental resolution of the encoder. The microprocessor module calculates the compensation value based on the current axis position supplied by the axis module, and the stored geometric error values. The compensation value is then applied to the machine tool axis through the axis module. A digital to analogue converter on the axis module converts the digital compensation value calculated by the microprocessor module to an analogue compensation signal. This analogue signal is then fed into an operational amplifier circuit where it is summed with the axis command signal from the CNC controller. The output from the operational amplifier circuit is a compensated drive signal. This compensated drive signal is output from the axis module and used to drive the axis servo amplifier. A relay on the axis module is used to electrically isolate the E.C.S. from the machines servo system under certain conditions. These conditions include, if the E.C.S. is in a fault state, if the E.C.S. is not in compensation mode and if the power to the E.C.S. is lost. An E.C.S. unit can hold up to 8 encoder axis modules.

The resolver axis module provides the same function as the encoder axis module, but for machine tools that have resolver position transducers. Functionally this module is the same as the encoder axis module in that it decodes the position signals from the position transducer into the form required by the microprocessor, and applies the compensation value calculated by the microprocessor to the machines axis. In machine tool applications resolvers are normally used in one of two modes of operation, either the stator excited mode or the rotor excited mode. In the stator excited mode of operation the phase relationship between the stator signal and the rotor signal changes in direct proportion to the rotor position. In the rotor excited mode of operation the amplitude of the two stator signals change in direct proportion to the rotor position. Although these two modes of resolver operation are fundamentally different the single axis module can be used for either mode. Transformers are used to provide electrical isolation between the E.C.S. and the resolver. These transformers can also be used to attenuate the resolver signals if required. The resolver module is made up of two printed circuit boards 'piggy backed' together. The resolver axis module therefore takes up two slot positions in the 19 inch sub-rack, and as a result the E.C.S. can only hold up to 5 resolver modules.

The majority of machine tools use either incremental optical encoders or resolvers as position transducers. Therefore the encoder and resolver axis modules provide the E.C.S. with the potential to be used with almost any CNC or NC machine tool.

The power supply module supplies the d.c. voltages required for the operation of the E.C.S. The power supply module accepts a nominal input voltage of either 110V or 240V a.c., and supplies 5V, 12V and -12V d.c. The power supply is of the switched mode type, and is able to supply the required current while being relatively small in size. The power supply is specifically designed for use in microprocessor systems.

The E.C.S. must have one microprocessor module, one system memory module, one communications module and one power supply module. These modules make up the basic microprocessor system. The number of axis memory modules is chosen to suit the number of geometric error values required to be stored, and is normally a function of the size and condition of the machine tool. One axis memory module is sufficient for the majority of machine tools. One axis module is required per machine axis (either encoder or resolver type to suit the machine). All the modules are based on original designs except the power supply module which is a commercially available module.

5.3 Compensation System Software Description

Two piece's of software are associated with the operation of the E.C.S. These are the system firmware and the integration software. Both these software packages have been specifically designed and written for the E.C.S.

The system firmware has already been briefly mentioned. This software has been written in Motorola assembly language and is stored as machine code in EPROM on the system memory module. This software is run by the microprocessor and completely controls the operation of the E.C.S. unit. A simplified flow diagram indicating the primary operation of the system firmware is shown in figure 5.3. Upon power up or reset of the E.C.S. the firmware performs an initialization of the system. This involves resetting all software flags and pointers to their initial values, re-setting the electronics and initializing all digital control signals. The E.C.S. has two modes of operation, either compensation mode or integration mode. The mode of operation of the E.C.S. is determined by the state of the external communications socket on the front of the communications module. After initializing the system the firmware interrogates the communications port to determine if an external device is connected to the E.C.S. If no device is connected the the firmware puts the E.C.S.

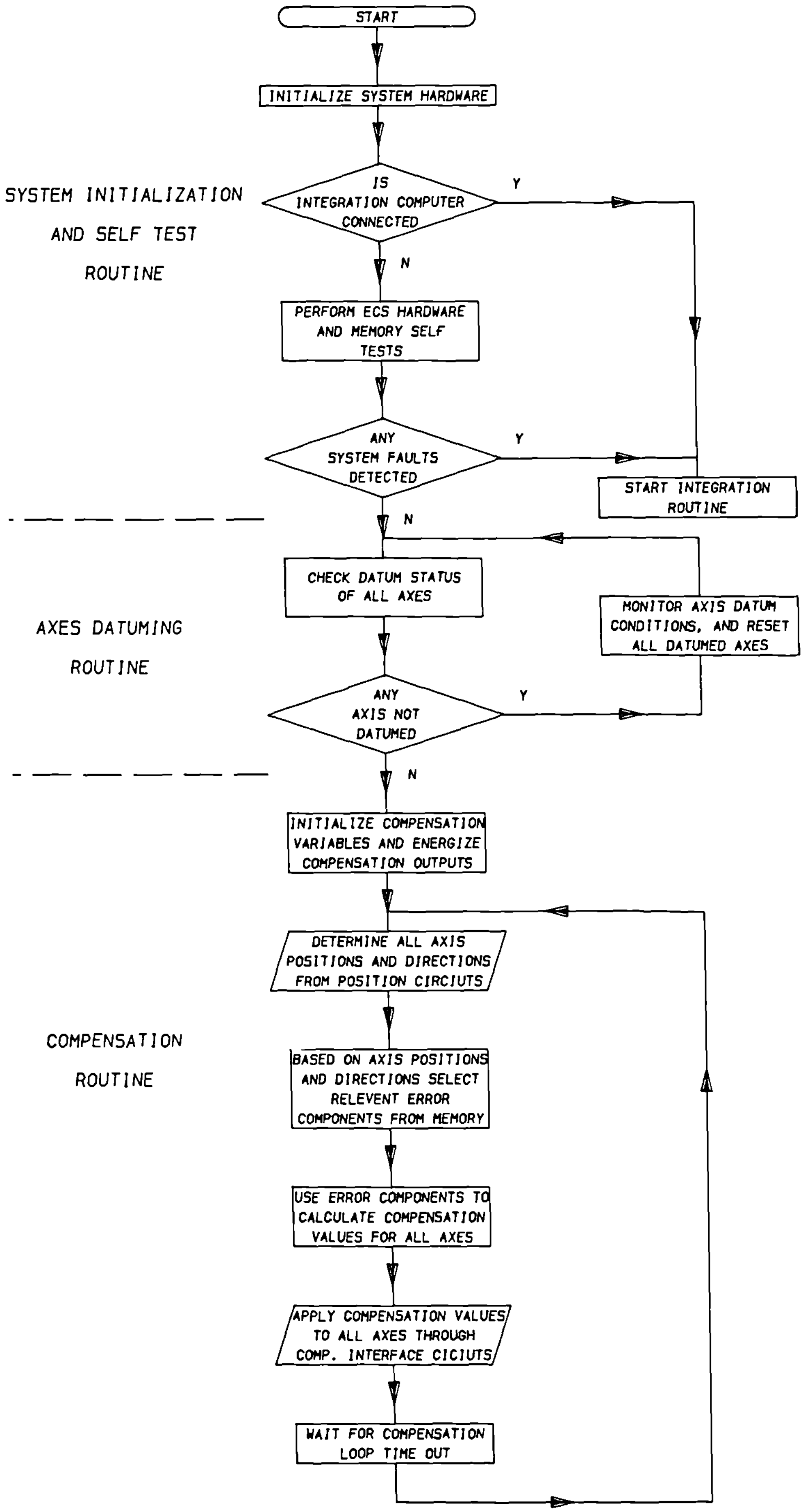


FIGURE 5.3 FLOW DIAGRAM FOR THE E.C.S. FIRMWARE

into compensation mode. If a device is connected the firmware puts the E.C.S. into integration mode.

In compensation mode the firmware controls the compensation process. Upon entering compensation mode the firmware first checks the integrity of the axis memory and its contents. As stated earlier the axis memory holds the machine specific data required by the E.C.S. in order to perform compensation. Any corruption of this data would completely invalidate the compensation. In order to check the integrity of the axis memory the firmware performs two tests. In the first test each memory location is checked to ensure it can be written to and read from correctly. In the second test a block check character is calculated for the memory contents and is compared with the block check character calculated when the memory was initially loaded. This test ensures that no corruption of the axis memory data has occurred. If either of these tests fail the firmware takes the E.C.S. out of compensation mode and into integration mode, where the fault can be reported. If the memory tests are successful the firmware performs the datuming operation. The positional information produced by both the incremental encoder and the resolver is incremental and not absolute. Upon initial power on of the machine tool, therefore, all the machines axes must be returned to an absolute reference position. From this reference point the absolute position of each axis can be determined from the incremental information provided by the position transducers. This operation is known as machine referencing or datuming. The E.C.S. unit also requires a datum from which to measure absolute position, and must therefore mimic the datuming operation to the machine tool. The datuming operation will vary depending upon the type and make of the CNC controller. In order to overcome this problem the datuming routine is defined by the datuming parameters, which are stored as part of the machine specific data on the axis memory board. Once all the axes have been successfully datumed, the E.C.S. is able to perform compensation. At this stage the firmware resets all the axis positions to their reference values, sets the initial compensation values and energizes the isolation relays in order to connect the E.C.S. to the machines axes. The firmware now performs the cyclic process of compensation. This involves firstly processing the positional information from the axis modules in order to determine the positions of all the axes. Based on these positions the relevant geometric error values are selected from the axis memory module. The axis positions and geometric error values are then used with the geometric model to calculate the compensation values for each axis. These compensation values are finally applied to the machine tool axes through the axis modules. The compensation loop time is constant and controlled by the timer on the communications board. This compensation loop time is set by a machine specific parameter, and is normally chosen to suit the servo update time of the CNC controller. If while in the compensation mode a fault were to occur the E.C.S. would immediately drop out of compensation mode and would electrically isolate itself from the machine tool. If a non-fatal fault were to occur the E.C.S. would drop into integration mode under the control of the system firmware. The E.C.S. could then be interrogated to determine the cause of the fault.

In integration mode the firmware allows the E.C.S. unit to communicate with an external IBM type personal computer. The communications link is provided by the RS232 serial interface on the communications module. In integration mode the firmware controls the operation of the E.C.S. based on instruction codes received from the external computer. This mode, as the name suggests, is primarily used during the integration and commissioning of an E.C.S. to a machine tool. The integration mode provides two primary functions. Firstly it allows data to be transferred to and from the E.C.S., and secondly it allows the functionality of the E.C.S. to be tested. The data that can be transferred between the E.C.S. and the external computer includes, the geometric error values which can be transferred to the E.C.S., the machine specific data which can be transferred to or from the E.C.S. and the E.C.S.

status and fault flags which can be transferred from the E.C.S. in order to aid fault finding. Certain functions of the E.C.S. can be tested while in the integration mode in order to test the operation of the E.C.S., and to aid in the setting up of the E.C.S. These functions include reading an axis position, applying a compensation value to a machine axis and testing and recording the axis datuming routines.

The integration software is a high level program written in the C language. This software runs on the external IBM type personal computer, and provides the interface between the engineer and the E.C.S. It is the integration software that controls the operation of the E.C.S. when the E.C.S. is in integration mode. The integration software has three primary functions. Firstly the integration software provides the means for customizing the E.C.S. unit for use with a particular machine tool. This customization is achieved through a set of software parameters that provide the E.C.S. with machine specific data. These software parameters are set through the integration software and transferred to the E.C.S. by the integration software. Secondly the integration software is used to process the geometric error data that has been measured from the machine tool during the error identification process. This processing converts the error data to the form that is required by the E.C.S. The processed error data is also transferred to the E.C.S. by the integration software. Thirdly the integration software provides a test and fault finding function. A number of routines are provided by the integration software that allow the functionality and status of the E.C.S. to be tested. These routines greatly aid the setting up and integration of the E.C.S. and in fault finding.

The integration software is menu driven, and interactively takes the engineer through the process of setting up, testing and integration of an E.C.S. unit. The menu tree for the integration software is shown in figure 5.4, and each menu is discussed below.

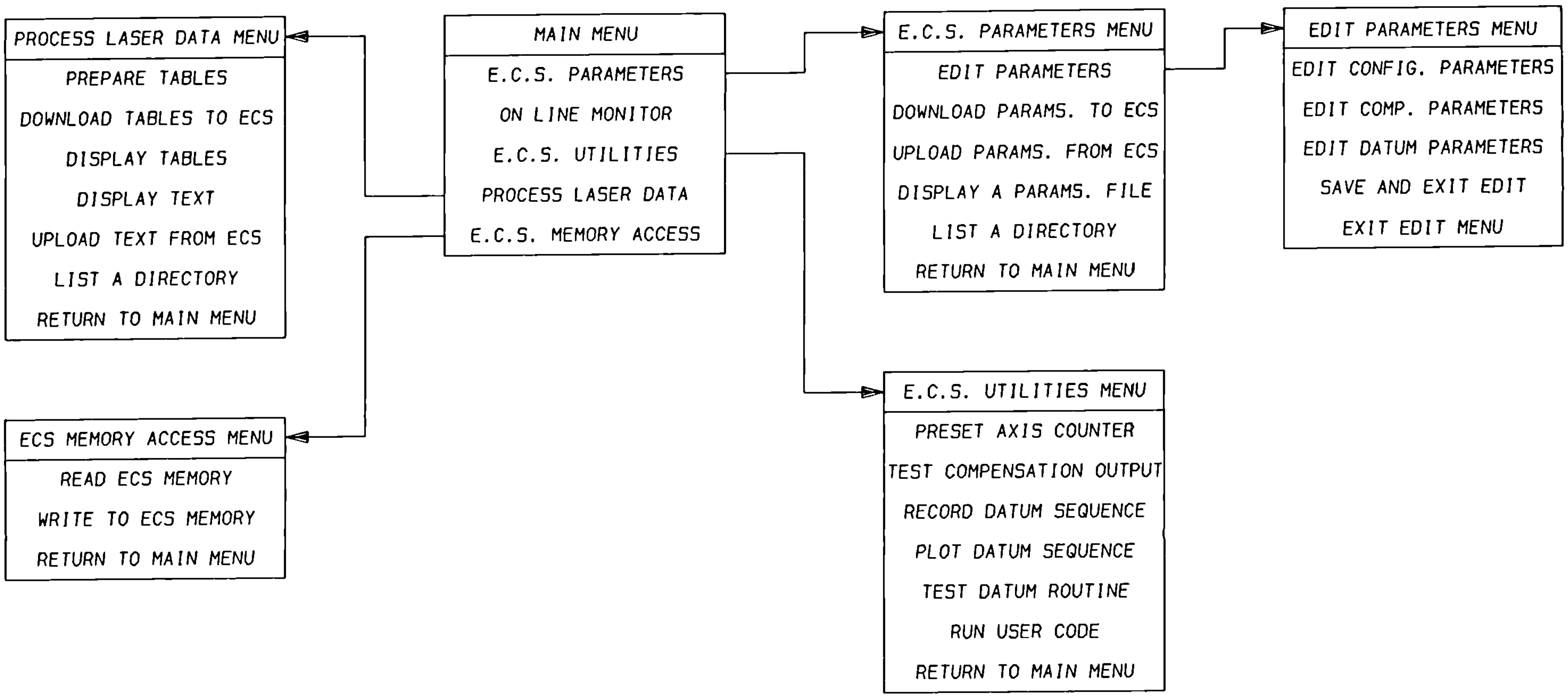


FIGURE 5.4 INTEGRATION SOFTWARE MENU TREE

The E.C.S. PARAMETERS menu provides the functions for setting, editing and transferring the machine specific data. Through this menu the parameters can be set or edited and stored to disc, transferred to the E.C.S., transferred from the E.C.S. and stored on disc or displayed on the screen. These parameters fall into three groups, namely configuration parameters, compensation parameters and datuming parameters. The configuration parameters are associated with the type and configuration of the machine tool and are listed below.

number of machine axes
axes names (X,Y,Z)
axis configuration
machine measurement system (imperial or metric)
type of position transducer (encoder or resolver)
position feedback scaling factor

The compensation parameters are associated with the compensation process and are listed below.

number of axis memory modules required
compensation required (linear, planar or volumetric)
compensation loop iteration time
minimum distance to qualify as move (encoder deadband)
compensation output value scaling factor
compensation polarity
angular scaling factor
squareness offsets

The datuming parameters are associated with the machine tool datuming routine and some examples are listed below.

datum type (e.g. Fanuc, Allen Bradley, Siemens)
reference switch polarity
reference switch initial state
reference switch final state
reference switch approach speed
reference switch approach direction

null offset value

The ON LINE MONITOR is a utility that displays the current status of the machine tools axes on the external computer. In this state the E.C.S. is continuously monitoring the status of the machine tools axes and transferring this information to the external computer. The following information is displayed by the ON LINE MONITOR; the axes names, the axes positions, the axes speeds, the axes reference status, reference switch status and encoder marker signal status. This feature is very useful for testing and setting up the E.C.S. The position and speed information indicates the correct operation of the transducer signal processing circuit on the axis module. It can also aid in checking that the polarity of the transducer wiring is correct, and that the position scaling parameter is correct. The reference and marker signal status can help in determining the datum routine parameters.

The PROCESS LASER DATA menu provides all the functions necessary for the processing and transferring of the geometric error data required by the E.C.S. The geometric error data is collected and stored in data files on the computer during the error identification process. This data is stored on the computer in ASCII format, and the data is in a 'raw as measured form'. This data must therefore be processed to extract the required information, and to convert it into the binary format required by the E.C.S. For example the straightness error data requires processing to remove any slope error introduced by the measurement process. The integration software takes the engineer through this processing stage by only asking for the geometric error data associated with the type of compensation set up in the compensation parameters. Once processed the binary error data is stored on disc ready for transfer to the E.C.S. The error data can now be displayed on the computer, or transferred to the axis memory module of the E.C.S. The integration software will only allow the data to be transferred to the E.C.S. if all of the error components required for the chosen type of compensation are present in the data file. This is to ensure that the E.C.S. receives all the information it requires to perform correct compensation. A file header is include as part of the E.C.S. data file. This header provides general information associated with the E.C.S. integration such as; customer name, machine tool type and serial number, date of installation and name of installation engineer. Also included in the file header is a list of all the individual geometric error data files processed to produce the E.C.S. data file. All this information is useful for reference and and for servicing. The integration software allows a file header stored in an E.C.S. to be transferred to the computer and displayed on the screen.

The ECS UTILITY menu provides a number of utility routines which can help the engineer in testing the operation of the E.C.S., and in setting up the E.C.S. parameters, and in locating and diagnosing any faults. A brief description of the function of each of the utilities is given below.

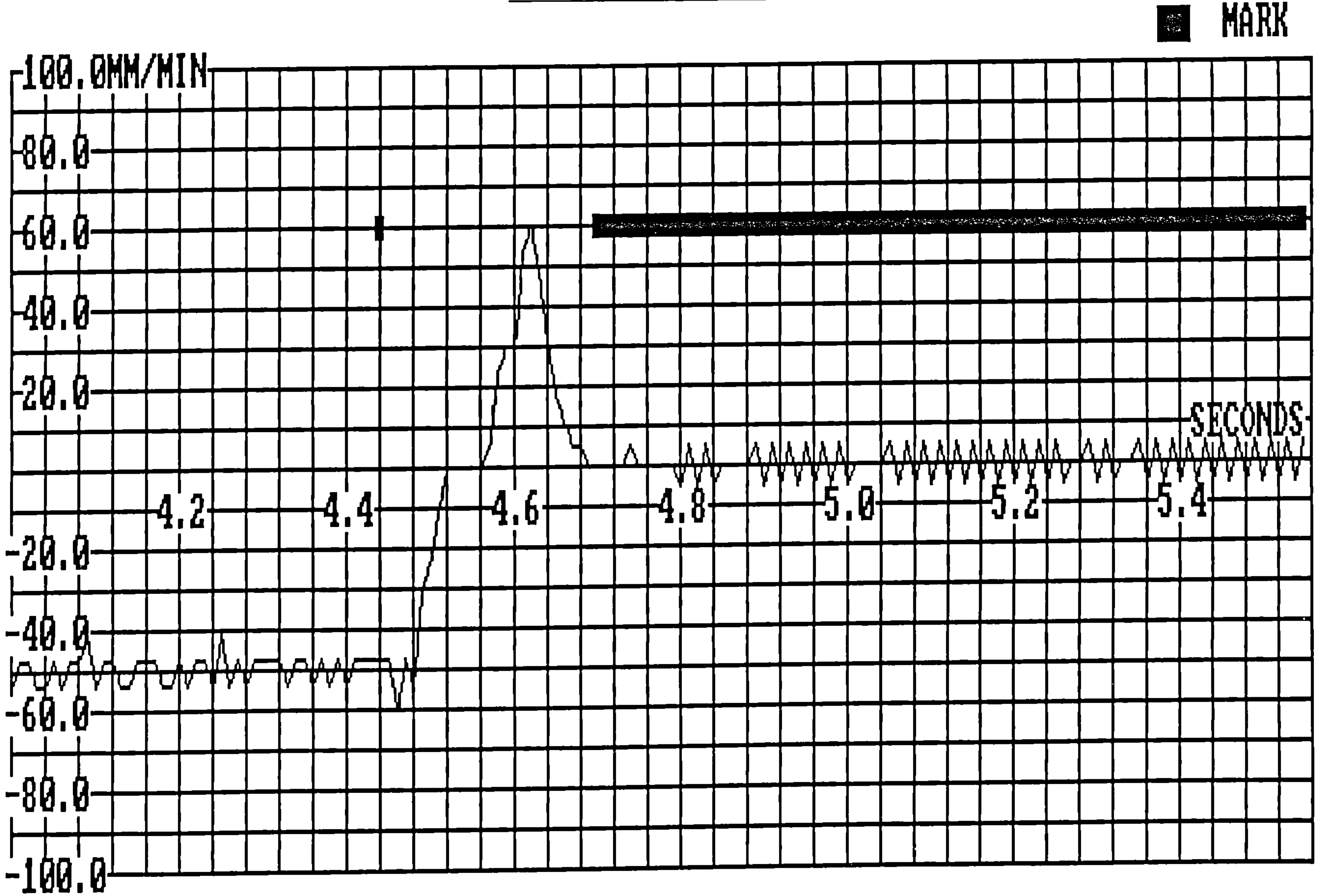
SET AXIS POSITION allows the position of any of the machine tools axes, as indicated by the E.C.S., to be preset to any value. This feature is useful for testing the operation of the position transducer decoding circuit, and in diagnosing any faults with this circuit.

OUTPUT COMPENSATION VALUE allows any analogue compensation value (entered in microns) to be output via the digital to analogue converter on the axis module for any of the machines axes. The relay that connects the axis module to the machines axis can be energized if desired. When energized the compensation value is applied to the servo system of the machine tool. This feature allows the digital to analogue converter circuit to be set up and tested. The relay is not required to be energized for this function. This feature can also be used to set and test the compensation output scaling factor, and to test the performance of the E.C.S. when connected to the machines axis. The relay is energized for this function. This feature is axis specific and can therefore only be applied to one axis at a time.

RECORD DATUM SEQUENCE, DISPLAY DATUM SEQUENCE and TEST DATUM ROUTINE are all features which aid the setting of the datuming parameters, and in the testing of the E.C.S. datuming routine. RECORD DATUM SEQUENCE allows the datuming operation of any of the machine tools axes to be recorded in terms of axis velocity and reference switch and marker signal status. When using this feature the E.C.S. continuously monitors and records the axis position and reference switch and marker signal status over a ten second period. At the end of this period this information is transferred to the external computer where it can be stored or displayed. The computer displays this datuming information in the form of a velocity time graph, from which a complete picture of the datum operation can be seen. An example of a recorded datum operation is shown in figure 5.5. This feature is axis specific. DISPLAY DATUM SEQUENCE allows a datum operation that has been previously recorded and saved to be displayed on the screen. Using these two features the datuming operation for each axis can be completely defined, and this greatly aids in the setting of the datuming parameters. Once the datuming parameters have been set TEST DATUM ROUTINE allows the E.C.S. datum routine to be tested. Through this feature the integration software instructs the E.C.S. to run through its datuming routine for all the machines axes. This requires all the machines axes to be returned to their reference positions. If the datuming routine is successfully completed the E.C.S. returns to integration mode under the control of the integration software.

DISPLAY ECS STATUS provides information on the current status of the E.C.S., and diagnostic information in the case of an E.C.S. fault. All the compensation address pointers are displayed in tabular form using this feature. These pointers indicate the last geometric error values selected by the system firmware, and their location in the

FIGURE 5.5 - AN AXIS DATUM OPERATION RECORDED BY THE INTEGRATION SOFTWARE



axis memory. This feature can help in fault finding by indicating the position of the firmware at the time of a fault. The results of the tests on the E.C.S. memory can also be displayed using this feature. If a memory test were to fail, the address of the memory location producing the failure is indicated. Other diagnostic messages are given such as, axis memory corrupt, compensation output error and axis module fault.

RUN USER SOFTWARE is a special feature that allows a machine code program that resides in the E.C.S. memory to be executed. The start address of the program in the E.C.S. memory is entered and the program is executed. This feature provides the engineer access to the processing power of the microprocessor. Machine code routines can be written to perform, for example, system tests . These routines can then controlled from the integration software.

The MEMORY ACCESS menu allows the contents of any part of the E.C.S. memory to be displayed by the computer, and any part of the E.C.S. RAM to be written to from the computer. With the memory read function the start and end address of the memory to be transferred are entered. The contents of that particular section of memory are then transferred to the computer and displayed on the screen. With the memory write function the start and end address of the memory to be assigned are entered, followed by the data to be transferred. This feature allows data and code for user defined programs to be transferred to the memory of the E.C.S. , and can be used in conjunction with the RUN USER SOFTWARE utility.

5.4 E.C.S. Installation Requirements

The installation of an E.C.S. unit to a machine tool can be split into two distinct stages. Firstly mechanical installation of the E.C.S., and secondly electrical connection of the E.C.S. to the relevant machine tool signals and power supply.

The E.C.S. can be physically located either inside or outside the electrical cabinet of the machine tool. The preferred location for the E.C.S. is inside the electrical cabinet of the machine tool, where the unit is protected and in a controlled environment. If installed inside the electrical cabinet of the machine tool, then no further enclosure is required for the E.C.S. The 19 inch sub rack of the E.C.S. is designed to fit into a standard 19 inch rack. If such a rack is available within the electrical cabinet the E.C.S. can be mounted directly into it. If a rack is not available the mounting of the E.C.S. is customized to suit the particular electrical cabinet. If the E.C.S. cannot be accommodated within the electrical cabinet of the machine tool it must be mounted externally. In this case the E.C.S. is mounted within a purpose built enclosure that affords the system the required protection. When mounting the system externally consideration is given to; the surrounding environmental conditions, the accessibility and proximity to the required electrical signals and the accessibility of the system for the user.

The signals that are required for operation of the E.C.S. are; the position transducer signals, the analogue command signals from the CNC controller and the axis reference signals from the axis reference switches. Electrical connections are required between the machine tool and the E.C.S. in order to provide these signals. Connection of the E.C.S. to an appropriate power supply is also required.

The position signals are obtained directly from the position transducers. The E.C.S. is connected to the position transducers in parallel with the CNC controller. In this way the E.C.S. and controller receive exactly the same positional information. If the transducers are incremental optical encoders then connection is also made to the marker signals. The marker signals are used in datuming operation.

The analogue command signals from the machine tools

CNC controller are connected directly to the E.C.S. These command signals are modified by the E.C.S. during the compensation process to produce the compensated command signals. The compensated command signals from the E.C.S. are connected directly to the command inputs of the axis servo amplifiers.

The axis reference signals are obtained directly from the reference switches. The E.C.S. is connected to the reference switch of each axis in parallel with the CNC controller. This ensures that the E.C.S. and controller receive exactly the same referencing signals.

The E.C.S. requires connection to a suitable 110V or 240V power supply. The power supply to the E.C.S. must be interlocked to "power on" circuit of the CNC controller. This is to ensure that power to the E.C.S. is only supplied when the position transducers of the machine tool are powered. In this way the E.C.S. is forced to perform a datuming operation every time position feedback is lost. This power interlock is provided by a relay which is energized by the "power on" circuit.

In order to evaluate the effectiveness of this compensation system it has been integrated to a large three axis horizontal milling machine. The integration to this machine tool, together with the error identification techniques used, are described in section 6.

6 INTEGRATION OF THE E.C.S. TO A MACHINE TOOL

6.1 Introduction

With the compensation strategy decided, and the E.C.S. developed, the next stage in the research was to provide a rigorous means for evaluating the performance of the compensation system. In order to test the full volumetric capability of the E.C.S. in a practical environment it was decided to integrate the E.C.S. to a large three axis machine tool. A large machine tool was favoured as many of the error components, particularly the angular errors, become increasingly significant the larger the machine. A large machine tool would therefore provide the best platform for the complete objective testing of the E.C.S. The geometric model, as described in section 4, can be used to compensate for many machine tool configurations with one, two or three axes. In testing the E.C.S. on a three axis machine the capability for compensating on machine tools with less than three axes would also be implicitly tested. The machine tool used for these evaluation tests is described below.

6.2 Description Of The Machine Tool Used In Evaluating The E.C.S.

The machine tool used in the evaluation of the E.C.S. was a large moving column milling machine. The machine tool is a moving column machine with a cantilever configuration. The column of the machine, the X axis, is connected to the side of the stationary bed by a saddle. The back of the column is supported by a separate narrow rail, which is fastened to the foundation and runs parallel to the machine bed. The head slide, the Y axis, moves vertically up the column, and supports the machine's ram, the Z axis. The ram moves in the horizontal plane and carries the machine spindle and tool. A schematic diagram showing this machine configuration is shown in figure 6.1. The machine has an X axis stroke of approximately 4 metres, a Y axis stroke of

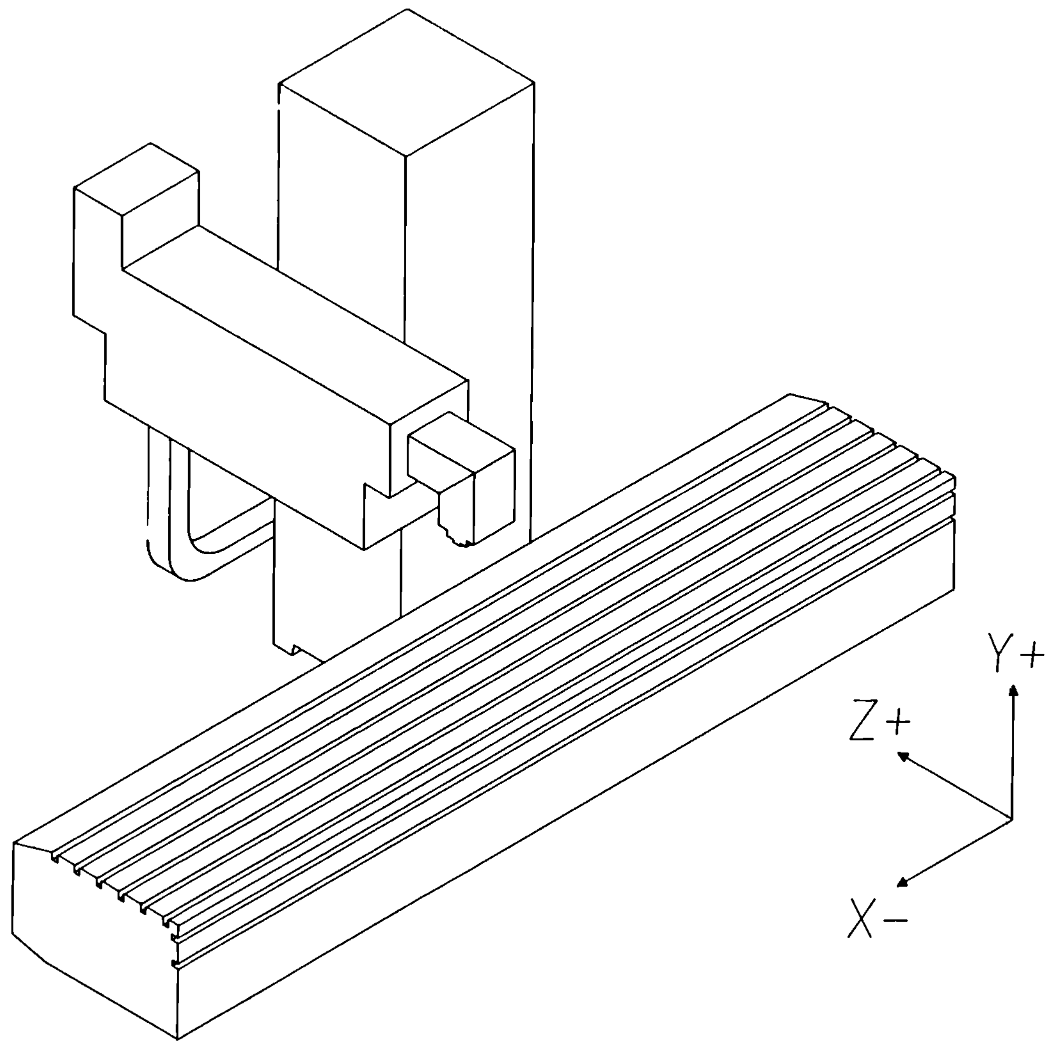


FIGURE 6.1 SCHEMATIC DIAGRAM OF A MOVING COLUMN MILLING MACHINE

approximately 1.4 metres and a Z axis stroke of approximately 1 metre, providing a working volume of approximately 5.6 cubic metres. Linear incremental encoders are used as the position transducers for all three of the machines axes. These transducers ensure that the pure linear positioning accuracy of the machines axes is good. Indeed, as a result, the pure linear positioning errors are not the most significant source of error in the machine. Due to the size and configuration of the machine tool the straightness and angular error components tend to be the most significant error components.

There are two main advantages for a machine tool of this configuration. Firstly, as the bed is stationary it can be made sufficiently stiff and long to support heavy, large or awkward components. Secondly, the cantilever construction, when used in conjunction with an appropriate "universal head", allows many aspects of the workpiece to be machined with a single setup. For example, if a cube were placed on the machine bed, four out of its six sides could be machined with a single setup. However, the penalty for these useful machining assets is that this configuration can produce some significantly large straightness and angular error components. The column and the ram are the axes that are particularly effected by these error components. As mentioned above the back of the column is supported by a separate narrow rail. Any misalignments or errors in straightness and flatness of this rail will result in minute rotations of the column as it moves down the bed. These minute rotations of the column manifest themselves as an X axis roll error, and an X axis vertical straightness error. Due to the cantilever configuration of this machine tool the ram shows a tendency to "droop" as it extends away from the column. This can result in a significant Z axis vertical straightness error.

6.2.1 The Machines Geometric Error Components

This machine tool is of course of the TXYZ configuration, as described in section 4. In this configuration all three axes of movement are associated with the tool, the workpiece being stationary. The geometric model that describes the axial positioning errors of the machine in terms of its fundamental error components was developed in section 4, and is shown again below.

$$Ex = ex(x)+ex(y)+ex(z)+\phi y(x).Z+\phi z(x).Y+\phi y(y).Z+\theta xz.Z+\theta xy.Y \quad ----(20)$$

$$Ey = ey(y)+ey(x)+ey(z)+\phi x(x).Z+\phi x(y).Z+\theta yz.Z \quad ----(21)$$

$$Ez = ez(z)+ez(x)+ez(y)-\phi x(x).Y \quad ----(22)$$

The E.C.S. uses this geometric model to calculate the position errors of the machine's axes, Ex, Ey, Ez, based on the position of the machine's axes, X, Y, Z, as indicated by the position transducers. In order to do this the relevant geometric error components of the machine, which are assumed constant for a given axis position, need to be identified. The relevant geometric error components for this machine are listed below.

ex(x) - X axis linear positioning error.
ey(x) - X axis straightness error in the XY plane.
ez(x) - X axis straightness error in the XZ plane.
Øx(x) - X axis roll error.
Øy(x) - X axis yaw error.
Øz(x) - X axis pitch error.

ey(y) - Y axis linear positioning error.
ex(y) - Y axis straightness error in the XY plane.
ez(y) - Y axis straightness error in the YZ plane.
Øy(y) - Y axis roll error.
Øx(y) - Y axis yaw error.

ez(z) - Z axis linear positioning error.
ex(z) - Z axis straightness error in the XZ plane.
ey(z) - Z axis straightness error in the YZ plane.

θxy - Squareness error in the XY plane.

θxz - squareness error in the XZ plane.
θyz - Squareness error in the YZ plane.

These seventeen error components all contribute, to a varying extent, to the positioning inaccuracy of this machine at the tool point. The accurate identification of these error components is a critically important stage in the integration of an E.C.S. to a machine tool. This is because the integrity of this error data will be directly reflected by the effectiveness of the resulting compensation.

6.3 Identification Of The Machine's Geometric Error Components

6.3.1 Description Of The Measurement System

A laser interferometer measuring system is the main tool used in identifying the geometric error components (41). The laser measurement system is quick and easy to set up, and provides a reliable and extremely accurate measurement standard. The laser interferometer, when used with the appropriate optical components, is capable of measuring linear positioning error, pitch and yaw error, straightness error and squareness error. The laser interferometer is quickly becoming the accepted equipment for machine tool accuracy evaluation and calibration. Indeed a number of Standards specify or recommend the laser interferometer as the preferred measuring instrument. When used in conjunction with a computer these systems become a powerful tool for the collection, storage and analysis of error data. The computer also provides a convenient media for communication between the E.C.S. and the measurement system.

A Renishaw laser interferometer system has been used in this work (42). This system has been specifically developed for the calibration and accuracy evaluation of machine tools. Figure 6.2 shows a schematic diagram of the

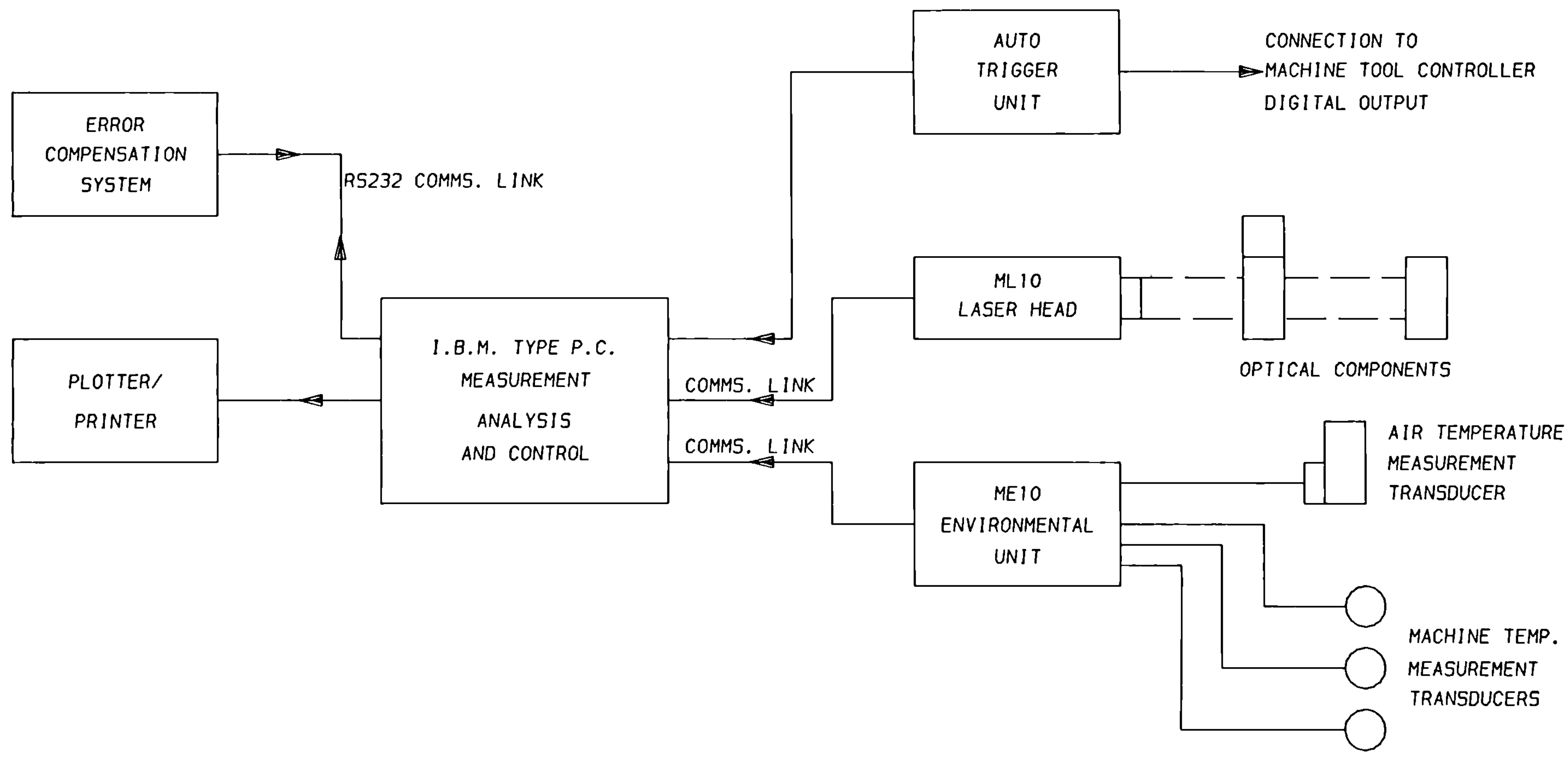


FIGURE 6.2 SCHEMATIC DIAGRAM OF THE LASER INTERFEROMETER MEASUREMENT SYSTEM

laser measurement system. It can be seen from this diagram that an I.B.M. type p.c. is at the heart of the measurement system. This computer forms the controller for the measurement process. A Renishaw software package controls the collection, storage and analysis of the error data.

The ML10 laser head is connected to the computer via a communications link. The laser head incorporates a Helium Neon laser that provides the source of the laser light, and houses the interferometry electronics. The laser head is mounted off the machine on a purpose built tripod, which provides a stable platform. The optical components provide a closed optical path for the laser light. The position and type of optical component is chosen to suit the measurement to be made, i.e. linear optics, angular optics or straightness optics. One of the optical components acts as a reference for the measurement and is mounted on a stable, stationary part of the machine tool. The second component is mounted on an appropriate moving member of the machine tool.

The ME10 environmental unit is used to monitor relevant environmental parameters in the vicinity of the machine tool. The philosophy of the interferometry process hinges about the fact that laser light is of a single, known frequency and therefore wavelength. However the wavelength of light does vary slightly with changes in air pressure, air temperature and relative humidity. The ME10 unit monitors these environmental parameters and allows the the computer to compensate for any measurement errors that could result from changes in these parameters. The ME10 unit can also accommodate up to three surface temperature transducers. These transducers are slow acting, and incorporate a magnetic base, and are designed for mounting on the machine tool structure. These transducers monitor the temperature of the machine tool structure and allow the computer to refer all measured data to standard temperature of 20 degrees Celsius. In machine tool calibration this is done for two reasons. Firstly, if all data is referred to a standard temperature then a meaningful comparison can be made between data that has been recorded for a single machine at different times. True variations in the machines accuracy due to wear can be made and appropriate action taken. Secondly, in machine calibration and acceptance testing a comparison is normally sought between the machines actual accuracy and the machines specified accuracy. As the machines specified accuracy is referred to a standard temperature of 20 degrees Celsius, the machines actual accuracy must also be referred to this standard temperature for a fair comparison to be made. There can, however, be problems with this philosophy when data is being measured for the purpose of compensation. A simplistic approach is used in the laser measurement system to compensate for variations in temperature from 20 degrees Celsius. A single, simple linear scaling factor, the coefficient of expansion, is used to calculate the compensation. For the complex structure of a machine tool, which may be made up of a number of different materials, this simplistic approach to temperature compensation can be grossly inadequate. Also, if a machine is to be used in an environment that has a stable temperature that is not 20 degrees Celsius it may be more appropriate to measure the error components at the machines normal environmental temperature.

An "auto trigger unit" has been developed that allows the error data to be collected automatically. This unit connects to the Renishaw laser interface board, which is located in the computer, and triggers the computer to take a measurement. The trigger unit can be controlled manually via a push-button mounted in its casing, or automatically via a high going logic signal. This logic signal can be supplied by a digital output from the machine tool's P.L.C. An existing digital output can be used, such as the output for machine coolant control. In this way triggering can be controlled by machine tool M codes such as M08 and M09. A part program can then be used to increment the machine's slide and trigger the measurement system, controlling the complete measurement process automatically. This speeds up the measurement process, and reduces the possibility of errors in what would otherwise be a tedious manual operation. An example of a part program used to automatically collect the error data is shown in appendix B.

The E.C.S. hardware is connected to the computer via an RS232 serial interface. This communications link allows information and error data to be transferred between the computer and the E.C.S. The "integration software" described in section 6 is used for this purpose.

Auxiliary equipment such as plotters and printers can be connected to the computer via a parallel interface. This allows hard copies of the measured error data to be obtained for recording and analysis.

6.3.2 Description Of The Measurement Procedure

In order to accurately identify the error components of the machine tool required for compensation a rigorous measurement procedure was required. When measuring a machine tool with a view to compensation great care is required in positioning the optical components and in selecting the correct line for the measurement. The choice of the correct measurement line is particularly important for linear positioning errors and straightness errors. The measured value of these error components can vary dramatically depending on the choice of measurement line. This is because the value of the error component being measured can be influenced by the effect of other error components. As an illustration consider the X axis linear positioning error of this machine tool. This error component, measured at the tool point, will effectively vary with Z axis position. This is because a component of the measured linear positioning error will be due to X axis yaw, such that;

$$\text{measured } ex(x) = \text{actual } ex(x) + \emptyset y(x).Z$$

In this case the X axis linear positioning error should be measured with the Z axis fully retracted, to ensure the integrity of the measured data. In general the philosophy for the choice of measurement line should be to ensure that the measured error component is as "pure" as possible. If this philosophy is not adhered to the measured data will be incorrect and the effect of the compensation could be to compound the accuracy of the machine tool rather than improve it. This measurement philosophy can conflict with the conventional, established philosophy for machine tool calibration. This is because conventional measurement philosophies cater for the need of machine tool accuracy evaluation and specification testing rather than for machine tool compensation. The conventional measurement line for X axis linear positioning measurement of this machine would be down the center of the bed.

The coordinate frame for this machine tool is shown in figure 6.3. This figure shows the sense of all the axes, and indicates the datum point of the machine.

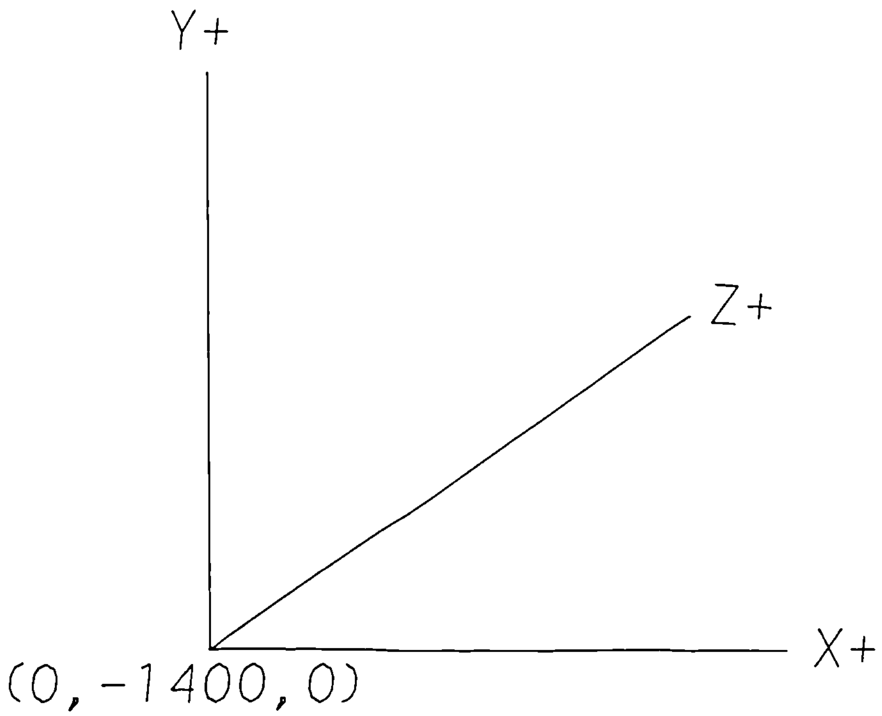


FIGURE 6.3 THE COORDINATE FRAME OF THE TEST MACHINE

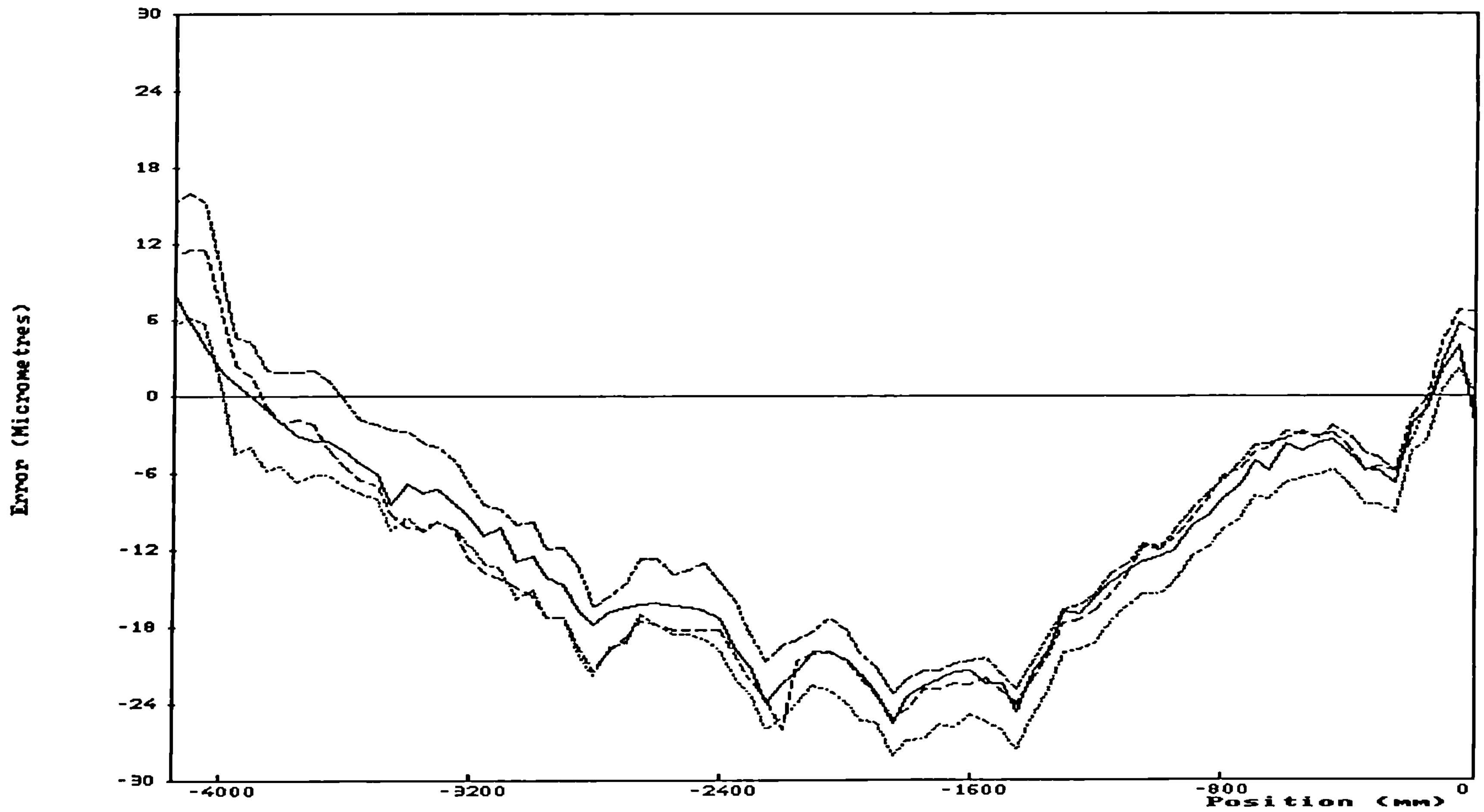
The datum point for all the measurements is the coordinate X0mm, Y-1400mm, Z0mm, and represents the extreme positive position of the X and Z axes and the extreme negative position of the Y axis. The reference measurement line for all X axis measurements is from the coordinate X0mm, Y-1400mm, Z0mm to the coordinate X-4100mm, Y-1400mm, Z0mm. The reference measurement line for all the Y axis measurements is from the coordinate X0mm, Y0mm, Z0mm to the coordinate X0mm, Y-1400mm, Z0mm. The reference line for all Z axis measurements is from the coordinate X0mm, Y-1400mm, Z0mm to the coordinate X0mm, Y-1400mm, Z-1000mm. Before any measurements were taken the machine was returned to its home or reference position. This position is the ultimate reference position for both the machine tool and the compensation system. For all measurements made with the laser interferometer system the stationary optics were positioned on the bed of the machine, and the moving optics were placed on the end of the ram as near as possible to the center line of the machine spindle. This is to ensure that as far as is possible the error is measured with reference to the tool point.

The machine was not in a temperature controlled environment, but the environmental temperature was monitored and as far as possible temperature effects were minimised. Prior to any measurement being taken the machine was run through a warm up cycle, allowing the machine to attain a stable operating temperature. The measurement tests were, as far as was possible for these specialized tests, carried out in accordance with the British Standard for machine tool measurement and test (33).

6.3.2.1 Measurement Of Linear Positioning Error

X axis linear positioning error, ex(x) - This error component was measured along the X axis reference measurement line, and was measured at 50mm increments. Figure 6.4 shows the results of this measurement. It can be seen from this figure that the accuracy band for this

FIGURE 6.4 X AXIS LINEAR POSITIONING ERROR



measurement is 40 microns, which is not excessive considering the long stroke of this axis. The reversal error is fairly constant and small in magnitude over most of the axis travel, the average being 2.5 microns. This low reversal error is due to the use of a linear encoder as position transducer.

Y axis linear positioning error, ey(y) - This error component was measured along the Y axis reference measurement line, and was measured at 50mm increments. Figure 6.5 shows the results of this measurement. The linear positioning accuracy of this axis is 40 microns. The reversal error is fairly constant over the length of the axis at approximately 8 microns. This reversal error is probably a function of the angular motion of the headslide during axis reversal, and the distance between the tool position and the linear transducer (Abbe effect).

Z axis linear positioning error, ez(z) - This error component was measured along the Z axis reference measurement line, and was measured at 20mm increments. Figure 6.6 shows the results of this measurement. The linear positioning accuracy of this axis is 30 microns. The reversal error is not constant for this axis but varies from a maximum of 10 microns to a minimum of 2 microns. This non-uniform reversal error could not be corrected by the reversal error compensation resident in most machine tool controllers. This is because controllers normally consider the reversal error to be constant with reversal error correction being based on a single value.

6.3.2.2 Measurement Of Straightness Error

X axis straightness error in the XY plane, ey(x) - This error component was measured along the X axis reference measurement line, and was measured at 10mm increments. Figure 6.7 shows the results of this measurement. The small measurement increment was required as the error component was relatively large and changed rapidly with respect to X

FIGURE 6.5 Y AXIS LINEAR POSITIONING ERROR

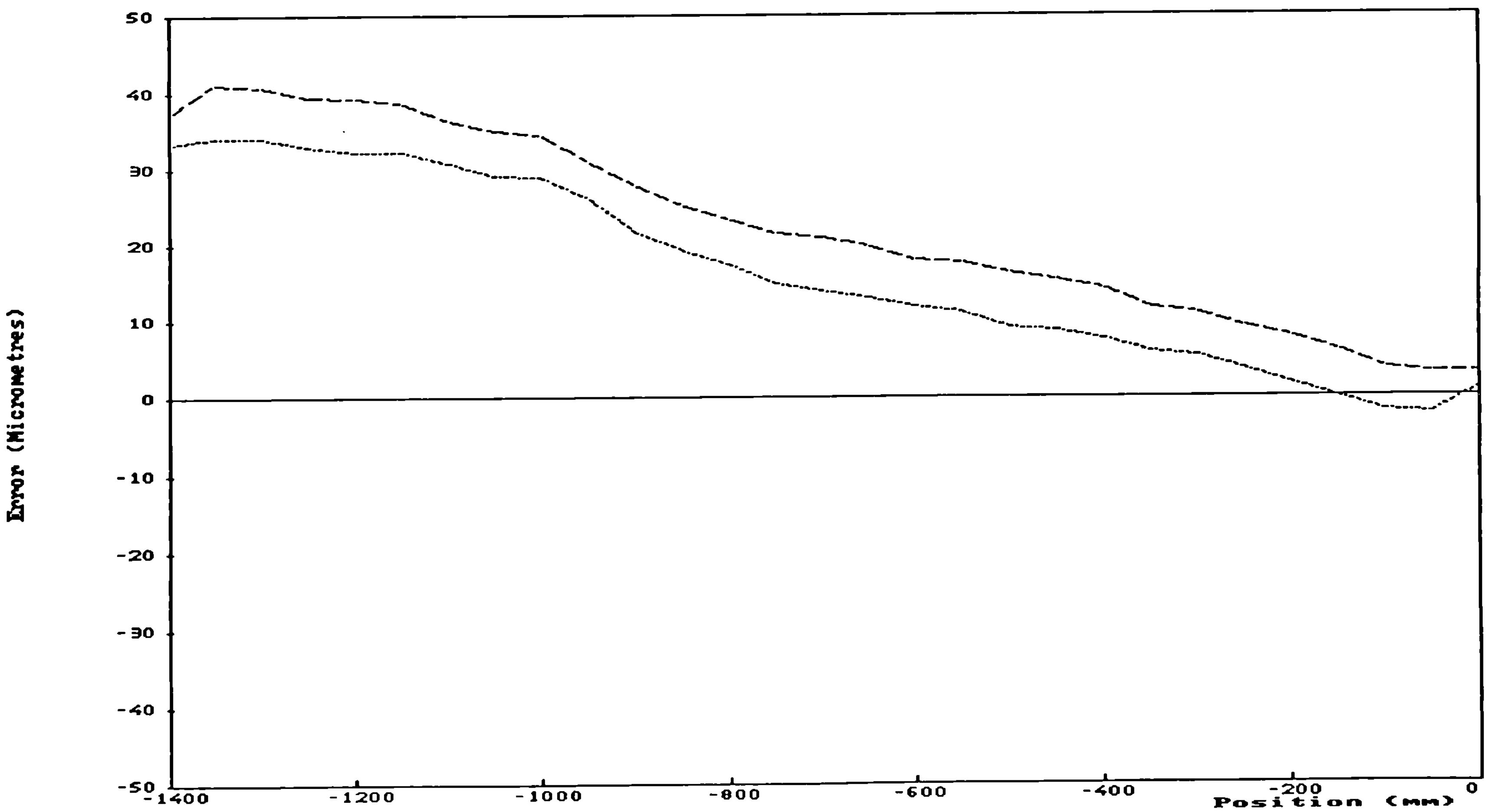


FIGURE 6.6 Z AXIS LINEAR POSITIONING ERROR

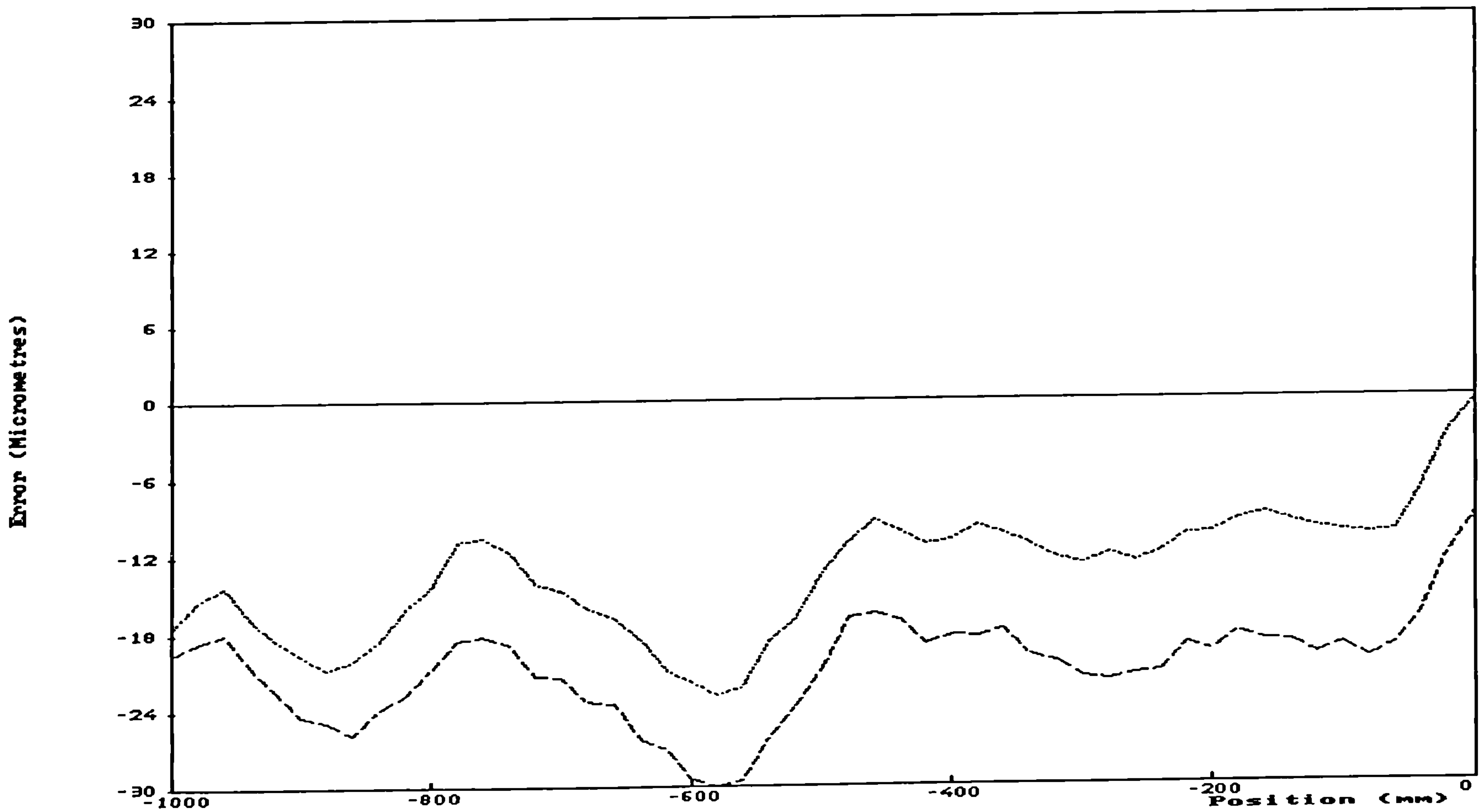
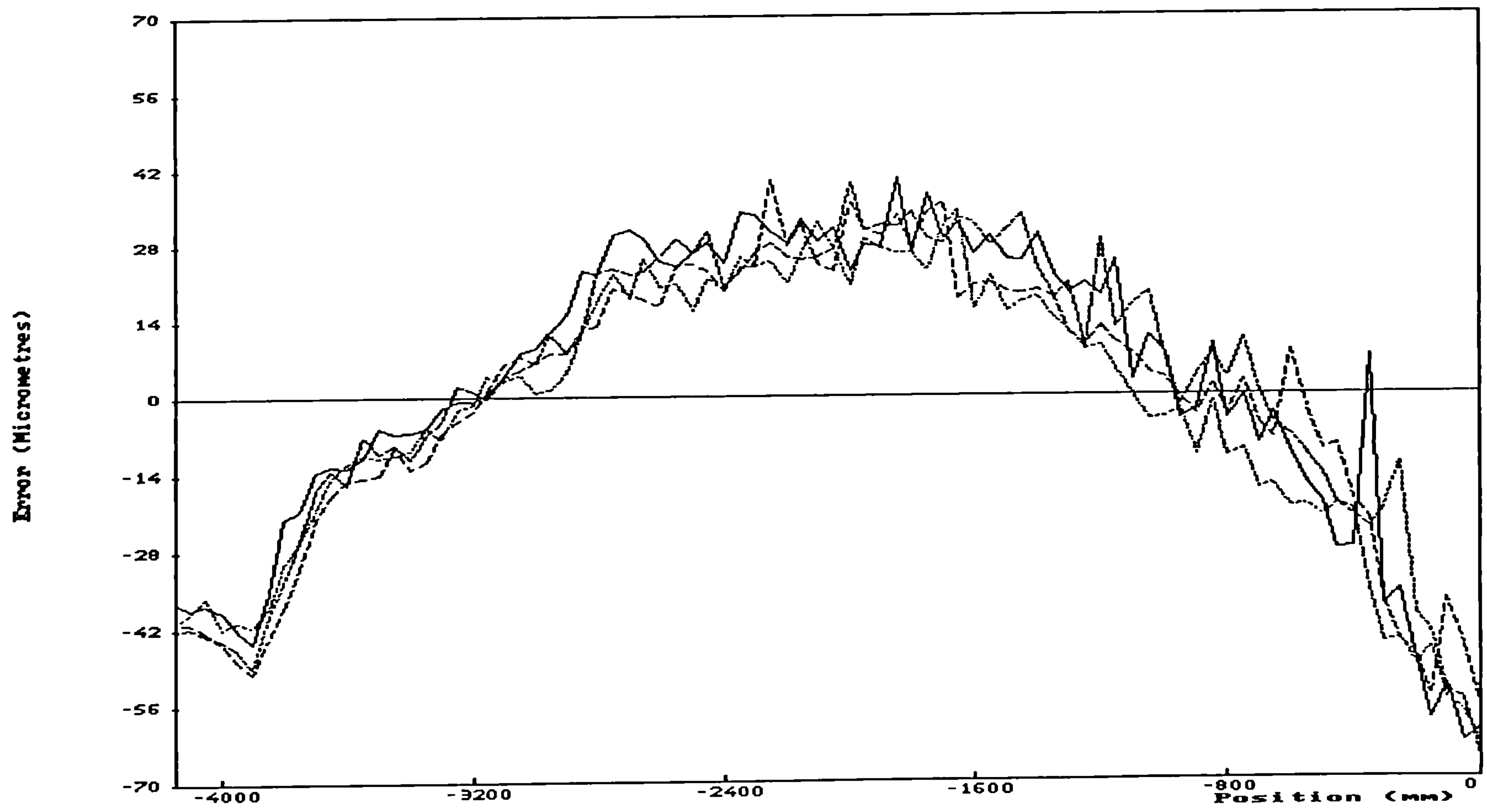


FIGURE 6.7 X AXIS STRAIGHTNESS ERROR IN THE XY PLANE



axis movement. As the straightness error is perpendicular to the axis travel it was found not to be critically sensitive to X axis position. As a result there was no need to stop the axis before taking a reading, and the measurements were taken on the fly. Collecting the data on the fly greatly increased the speed and efficiency of the measurement process, thus providing a significant benefit when measuring such a large machine tool. It may also be argued that data collected on the fly better represents the dynamic performance of the machine tool, and provides more representative data for compensation purposes. It can be seen from figure 6.7 that this straightness error is significantly large, the error band being approximately 100 microns. As explained earlier in this section the X axis straightness errors where expected to be large due to the cantilever construction of the machine. This error is primarily produced as a result of small imperfections in the form and alignment of the narrow rail that supports the back of the column. These imperfections will tend to pivot the column about the machine bed resulting in large X axis angular and straightness error components. It can also be seen from the figure that the reversal error is insignificant, and that the repeatability of the measurement is fairly poor. Poor repeatability of the straightness data may not necessarily mean that the error component itself is unrepeatable. This is because the repeatability of straightness measurements can be greatly effected by thermal currents and vibration. In this case the unrepeatable straightness data is primarily due to the unrepeatability of the measurement system. For the purpose of compensation the general form of the data is therefore the most important. Indeed during this investigation it was found that in order to provide data that would produce accurate compensation the raw measured data should be "smoothed" and averaged over a number of runs. The sign convention for this error component corresponds to the sign convention of the Y axis, with a positive straightness error corresponding to positive movement in the Y direction.

X axis straightness error in the XZ plane, ez(x) - This error component was measured along the X axis reference measurement line, and was measured at 10mm increments. Figure 6.8 shows the results of this measurement. Again this measurement was taken on the fly. As expected the magnitude of this straightness error is significantly large, the error band being approximately 85 microns. The unusual shape of the straightness error is probably produced as the error follows the form of the columns narrow guide rail. The reversal error for this measurement is small; the mean value being 2 microns, and the repeatability is good. The sign convention for this error component corresponds to the sign convention of the Z axis, with a positive straightness error corresponding to positive movement in the Z direction.

Y axis straightness error in the XY plane, ex(y) - This error component was measured along the Y axis reference measurement line. The Y axis is mounted in a more conventional manner on ground guideways. As a result this error changed gradually, and a measurement interval of 50mm was adequate. The results of this measurement are shown in figure 6.9. This measurement was taken on the fly. As would be expected from an axis of this type this straightness error component is relatively small, the error band being approximately 16 microns. The reversal error for this measurement is small at approximately 4 microns, and constant over the whole of the axis travel. The repeatability of the measurement is good. When an error such as this is so small it is valid to consider the error component as being insignificant, and compensation for the error being unnecessary. The sign convention for this error component corresponds to the sign convention of the X axis, with a positive straightness error corresponding to positive movement in the X direction.

Y axis straightness error in the YZ plane, ez(y) - This error component was measured along the Y axis reference measurement line, at intervals of 50mm with the readings taken on the fly. The results of this measurement are shown

FIGURE 6.8 X AXIS STRAIGHTNESS ERROR IN THE XZ PLANE

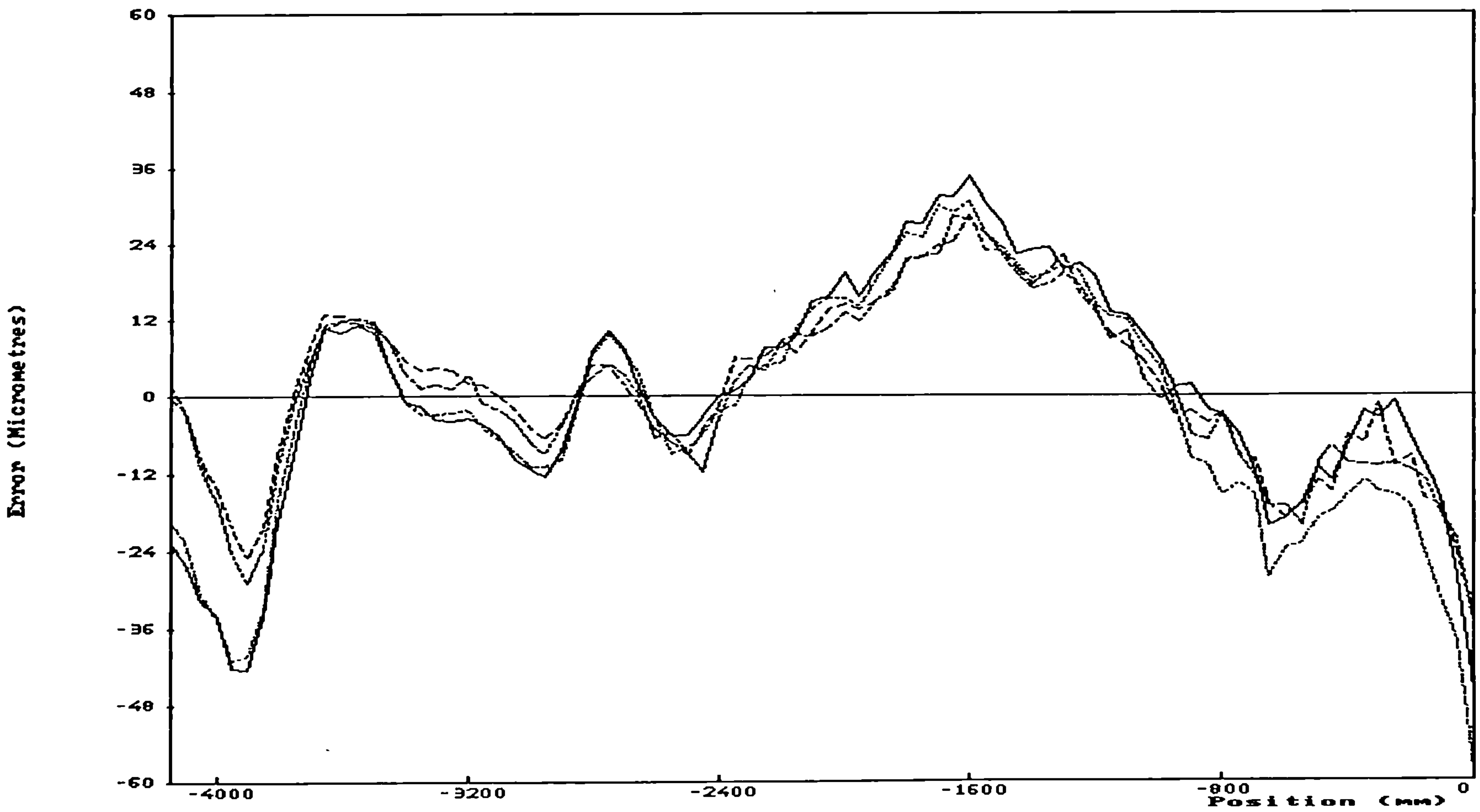


FIGURE 6.9 Y AXIS STRAIGHTNESS ERROR IN THE XY PLANE

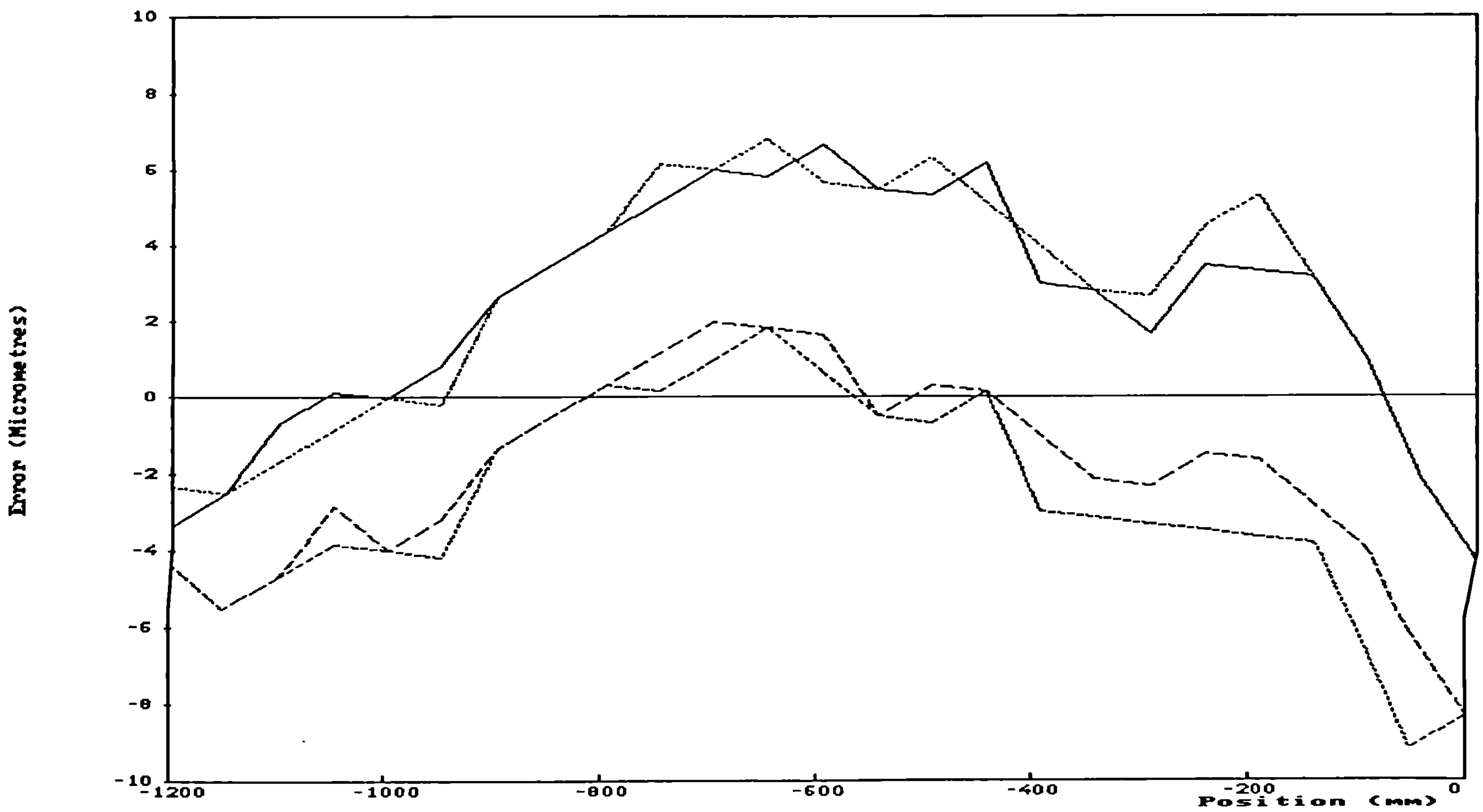
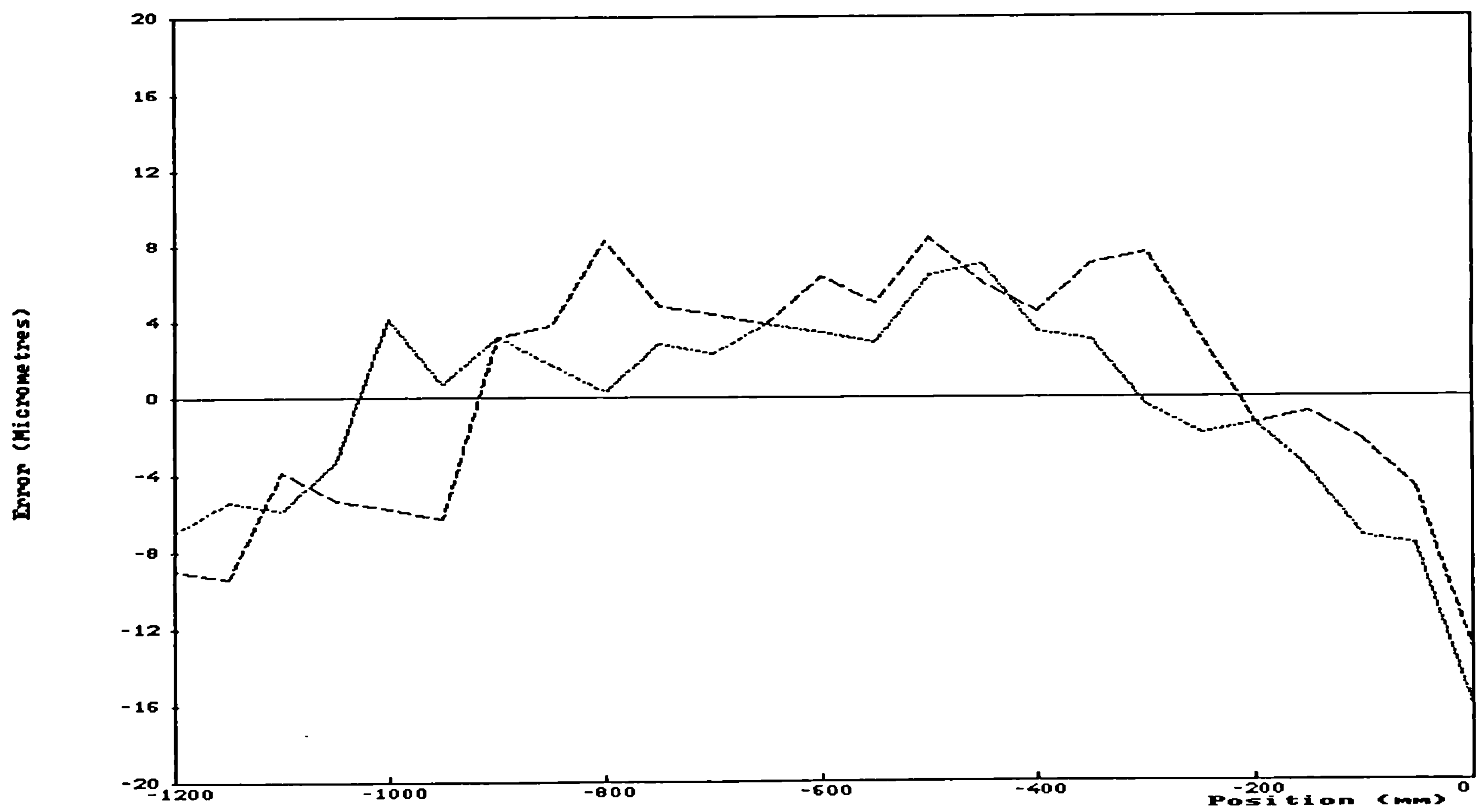


FIGURE 6.10 Y AXIS STRAIGHTNESS ERROR IN THE YZ PLANE

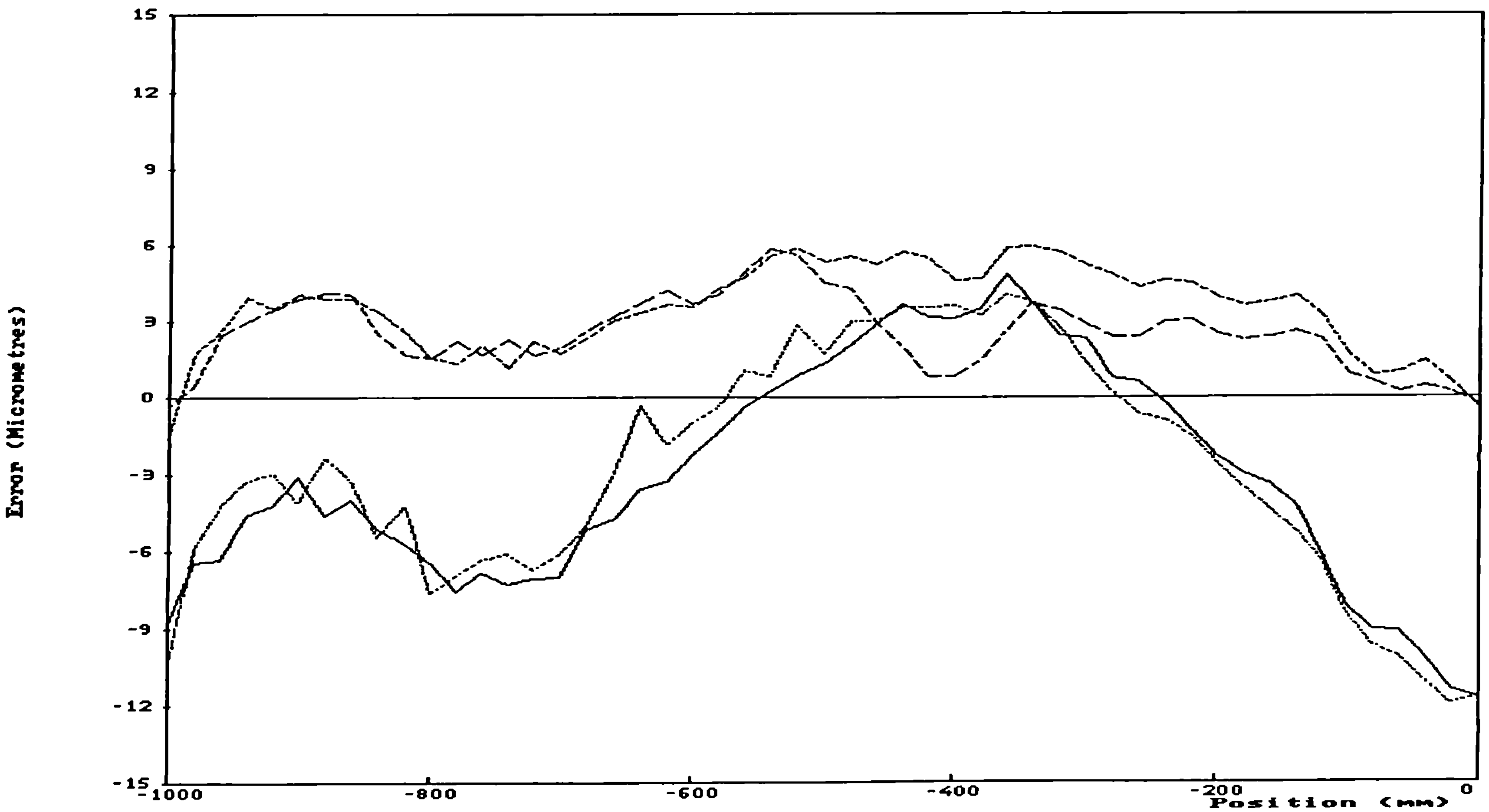


in figure 6.10. As expected this straightness error is relatively small in magnitude the error band being approximately 24 microns. The reversal error for this measurement is small and the repeatability is good. The sign convention for this error component corresponds to the sign convention of the Z axis, with a positive straightness error corresponding to positive movement in the Z direction.

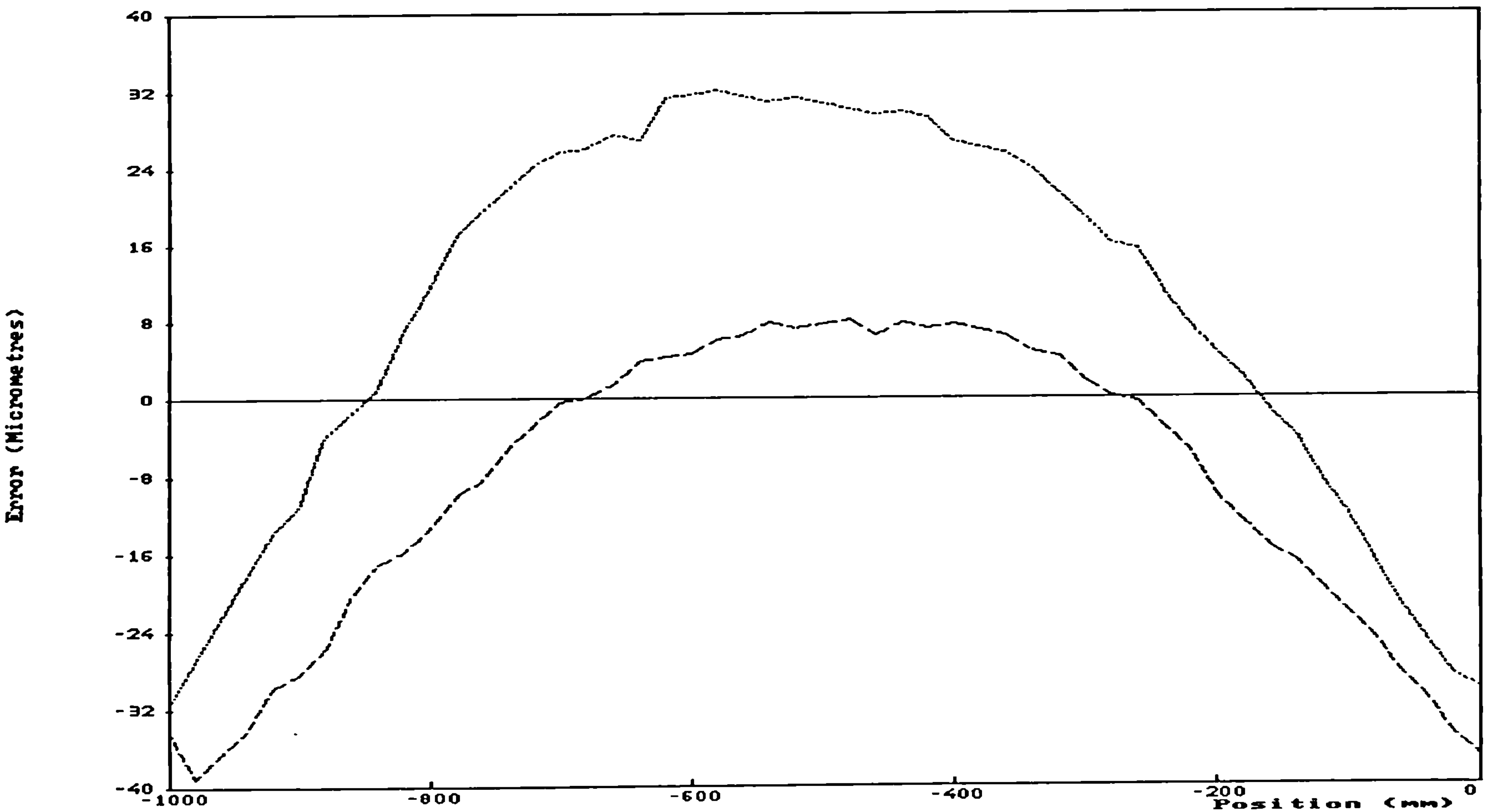
Z axis straightness error in the XZ plane, ex(z) - This error component was measured along the Z axis reference measurement line. The Z axis is mounted on planed guideways which provide good support and alignment in the XZ plane. As a result this error changed gradually, and a measurement interval of 20mm was adequate. The results of this measurement are shown in figure 6.11. This measurement was taken on the fly. Due to the good horizontal support of this axis this error is relatively small (although not insignificant), the error band being approximately 17 microns. The reversal error for this measurement is, however, surprisingly high with a maximum value of approximately 12 microns. The reversal error varies in magnitude significantly of the travel of the axis. The sign convention for this error component corresponds to the sign convention of the X axis, with a positive straightness error corresponding to positive movement in the X direction.

Z axis straightness error in the YZ plane, ey(z) - This error component was measured along the Z axis reference measurement line. Due to the cantilever construction of the machine this straightness error was expected to be significantly large. The mass of the Z axis causes it to fall as it extends from the column, producing an effect commonly known as ram droop. Although the axis guideways are machined in order to minimize this effect the resulting error is invariably large. The magnitude of this particular error is a direct consequence, and a major disadvantage, of this configuration of machine tool. This error was measured at 20mm intervals, with the readings taken on the fly. The

FIGURE 6.11 Z AXIS STRAIGHTNESS ERROR IN THE XZ PLANE



<u>FIGURE 6.12 Z AXIS STRAIGHTNESS ERROR IN THE YZ PLANE</u>



results of this measurement are shown in figure 6.12. The smooth symmetrical bowed form of this error component is classical of ram droop. The error as expected is significantly large, the error band being approximately 70 microns. The reversal error is large with a maximum value of approximately 26 microns. The reversal error varies over the travel of the Z axis, probably due to gravitational effects. The repeatability of the error component is good. The sign convention for this error component corresponds to the sign convention of the Y axis, with a positive straightness error corresponding to positive movement in the Y direction.

6.3.2.3 Measurement Of Rotational Error

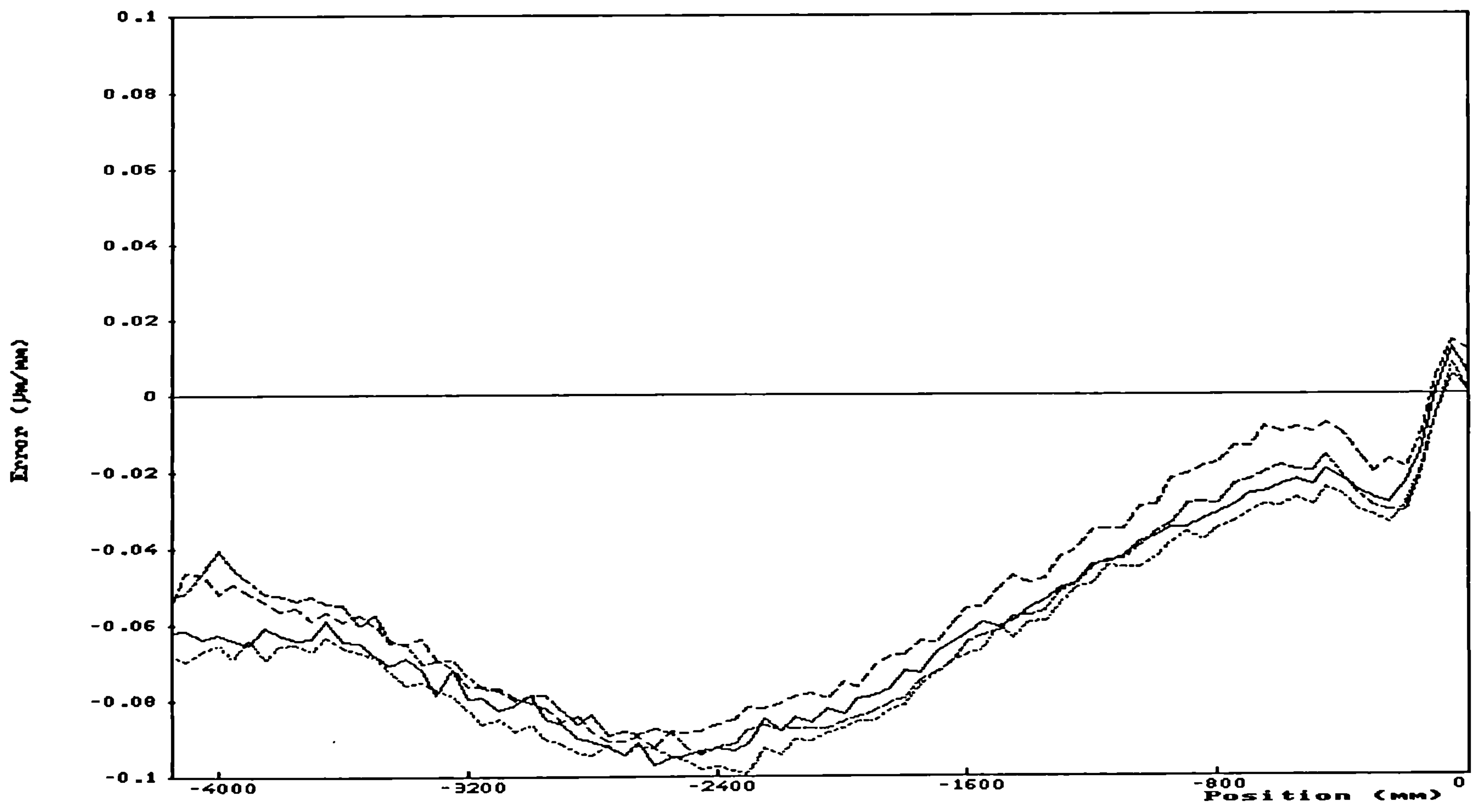
X axis pitch error, $\varnothing z(x)$ - This error component was measured along the X axis reference measurement line. As with the X axis straightness errors the X axis rotational errors were expected to be significantly large. Again this is due to the machine's configuration, particularly the method of support for the column. Although significant the rate of change of the pitch error was gradual and smooth, and a measurement increment of 20mm was found to be adequate. Figure 6.13 shows the results of this measurement. It can be seen from this figure that the error is large, the error band being over 100 microns/m. The effect of this error component, on this machine, is to vary the positioning accuracy of the X axis as a function of Y axis position, such that;

$$X \text{ positional error due to pitch} = \varnothing z(x).Y$$

As the Y axis has a stroke of over 1.4m it can be appreciated that this pitch error can have a great effect on the overall positional accuracy of the machine. The repeatability of this error component is good and the reversal error is small. The sign convention for this error is such that a positive error corresponds to counter clockwise rotation.

X axis yaw error, $\varnothing y(x)$ - It was found to be difficult to

FIGURE 6.13 X AXIS PITCH ERROR



obtain a repeatable and reliable X axis yaw measurement by measuring the error component direct using the laser interferometer with the angular optics. The integrity of the measured error data is of the upper most importance if it is to be used for compensation. This problem was overcome by calculating the X axis yaw error from its effect on the positional accuracy of the X axis. The effect of X axis yaw error, on this machine, is to vary the positioning accuracy of the X axis as a function of Z axis position, such that;

X positional error due to yaw = $\emptyset y(x).Z$

The X axis positional error due to yaw can also be calculated as;

$ex(x)(\text{at Z 0mm}) - ex(x)(\text{at Z 1000mm})$

From these two expressions X axis yaw can be expressed as;

$\emptyset y(x) = ex(x)(\text{at Z 0mm}) - ex(x)(\text{at Z 1000mm}) / 1000$

X axis yaw can therefore be calculated from measurements of the X axis linear positioning error with the Z axis fully retracted, and with the Z axis fully extended. The yaw error measured in this way was found to be more reliable, resulting in better compensation. The results from this measurement are shown in figure 6.14. As expected this error is large, the error band being approximately 65 microns/m. The repeatability of this error component is good and the reversal error is small.

X axis roll error, $\emptyset x(x)$ - Roll error can not be measured using the laser interferometer. As a result this error component was measured using a Talyvel electronic level. This error component was measured along the X axis reference measurement line. The level was placed on top of, and in line with the Z axis, or ram of the machine. Readings were taken at intervals of 20mm. The results from this measurement are shown in figure 6.15. Again this angular error component is significantly large, the error band being 100 microns/m. The unusual shape of the error is produced because the error directly reflects the form of the narrow rail supporting the back of the machines column. The effect of this X axis roll error is two fold. Firstly it effectively changes the X axis horizontal straightness

FIGURE 6.14 X AXIS YAW ERROR

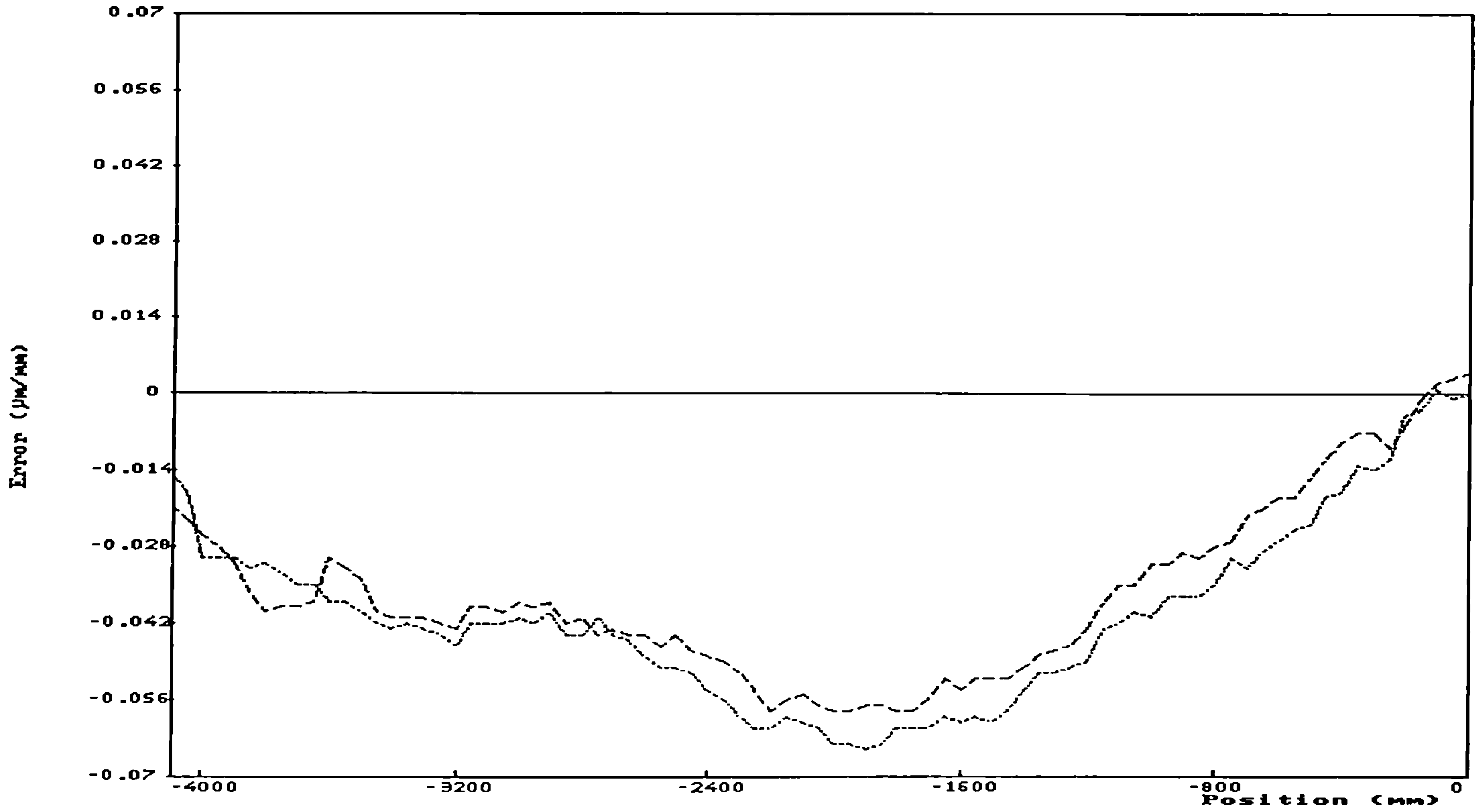
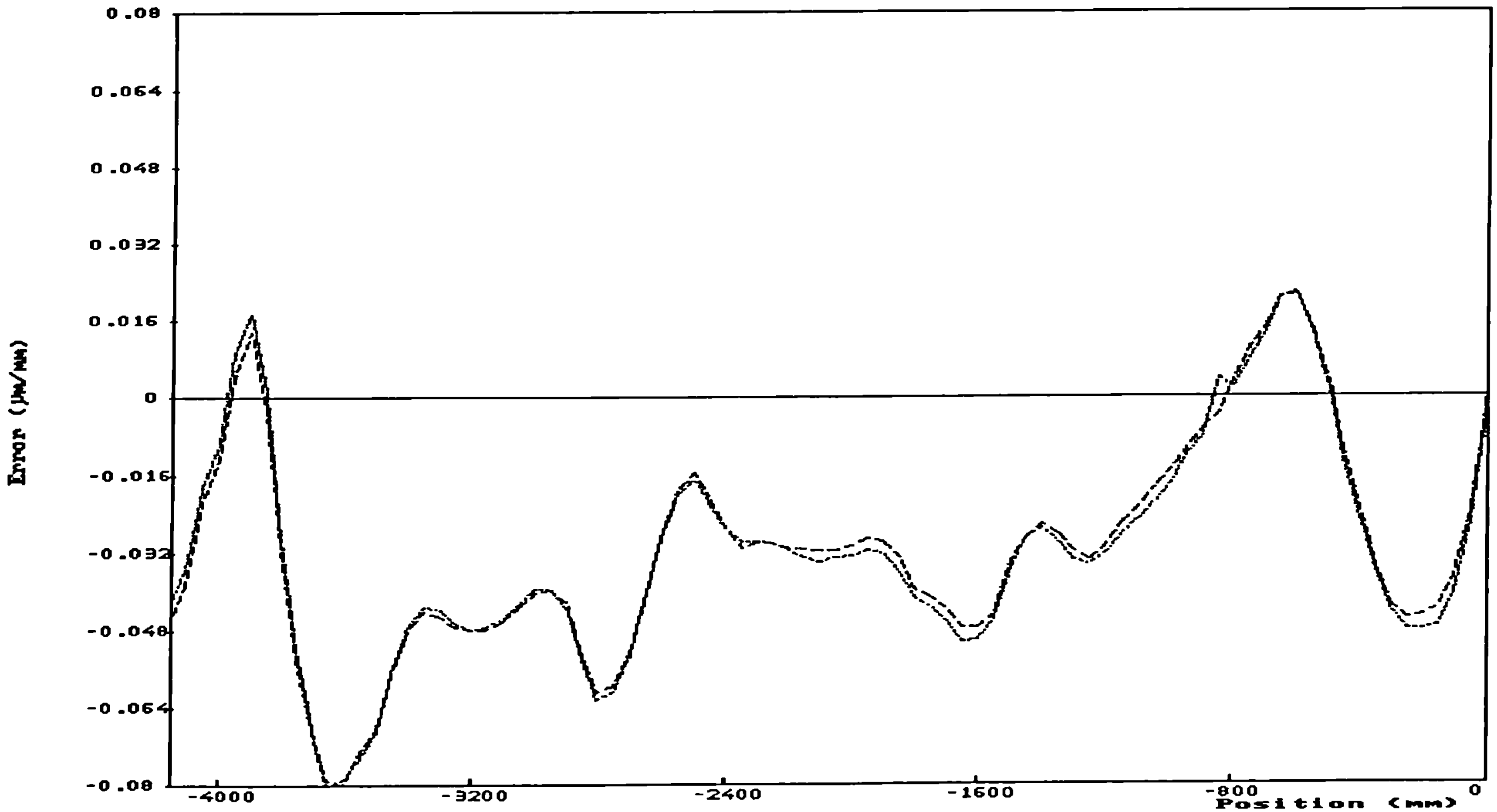


FIGURE 6.15 X AXIS ROLL ERROR



component as a function of Y axis position. Secondly it changes the X axis vertical straightness component as a function of Z axis position. The repeatability of this error component is good and the reversal error is negligible. The sign convention for this error component is such that clockwise rotation of the Talyvel corresponds to a positive error.

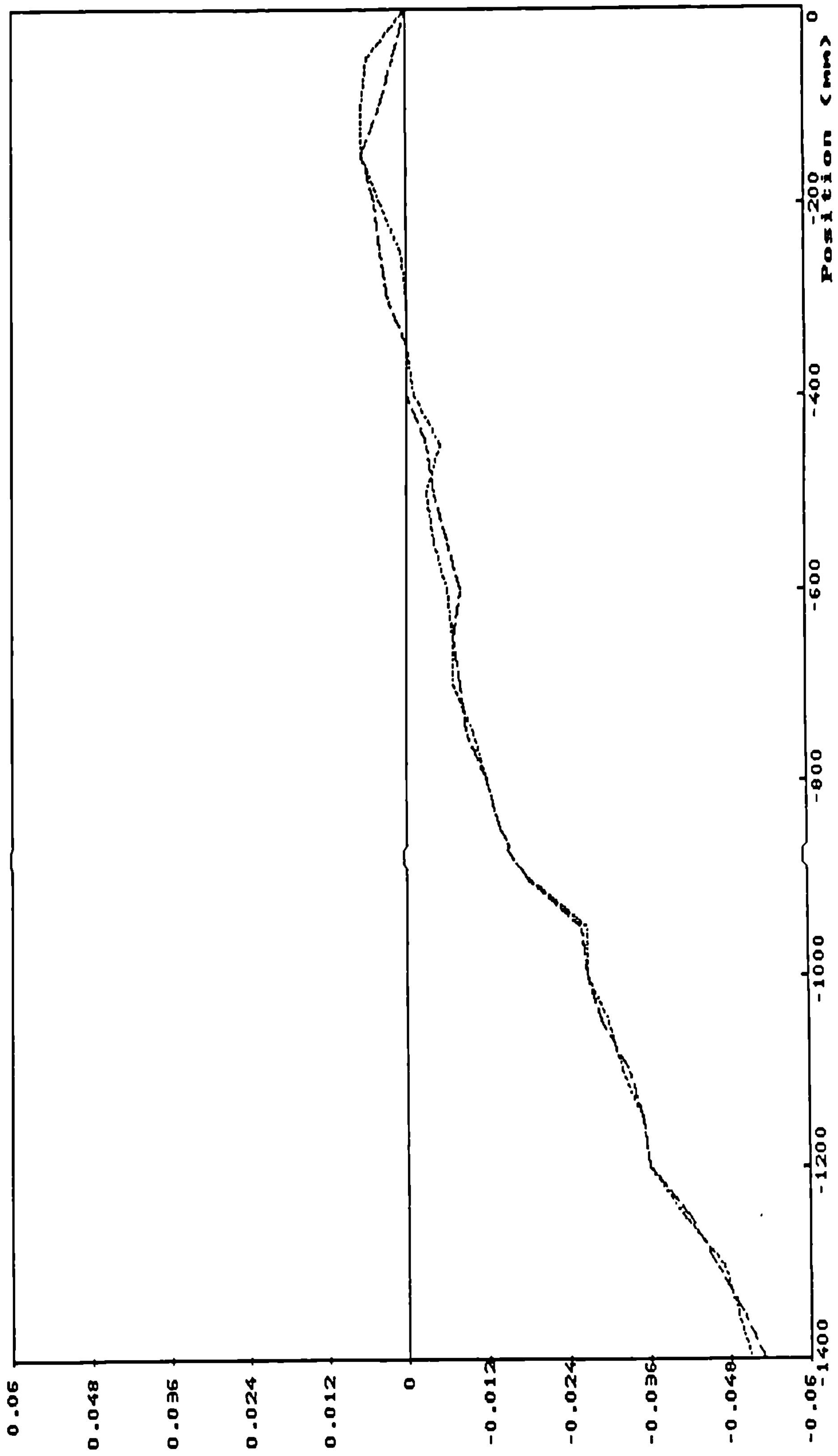
Y axis yaw error, Øx(y) - As with the X axis yaw error it was found to be difficult to obtain a repeatable and reliable Y axis yaw measurement by measuring the error component direct using the laser interferometer. As a result a similar method was used to measure the Y axis yaw error. In this case the effect of the yaw error is to change the positioning accuracy of the Y axis as a function of Z axis position. The Y axis yaw error component can therefore be calculated from;

$$Øx(y) = ey(y)(\text{at Z 0mm}) - ey(y)(\text{at Z 1000mm}) / 1000$$

Y axis yaw error can therefore be derived from two measurements of Y axis linear positioning error. The first measurement with the Z axis fully retracted the second measurement with the Z axis fully extended. As with X axis yaw this method of measurement produced reliable and accurate data. The results of this measurement are shown in figure 6.16. The results show this error component to be significant, the error band being approximately 60 microns/m. This large yaw error is produced as a result of the cantilever construction of the machine, with the overhanging mass of the machine tending to rotate the Y axis. The repeatability of this error component is good and the reversal error is negligible.

Y axis roll error, Øy(y) - It is not possible to obtain a reliable or accurate measurement for Y axis roll. The laser interferometer can not be used to measure roll, and because the rotational error is vertical as opposed to horizontal the electronic level can not be used. It is, however, fair to assume that this error component is insignificant, and that it will not have a significant effect on the positional accuracy of the machine tool. This is because

FIGURE 6.16 Y AXIS YAW ERROR



the supporting guideways of the Y axis provide good and accurate support, which will minimize roll error. This is indicated by the low Y axis straightness error measurements shown in figures 6.9 and 6.10. The Y axis roll error has therefore been considered negligible for this particular machine tool, and has been omitted from the compensation.

6.3.2.4 Measurement Of Orthogonality Error

Squareness error in the X,Y plane, θxy - With a machine tool of this size it is difficult and time consuming to measure squareness error using the laser interferometer. Such a measurement is time consuming because each squareness measurement requires two straightness measurements using a complicated optical arrangement. The correct arrangement of the optical components can also be difficult to achieve without special fixtures. In particular accurate and correct location of the optical square, required to measure squareness, can be difficult. To overcome these measurement problems the three squareness errors of this machine tool were measured using a granite square, a granite parallel and a 1 micron resolution dial test indicator or D.T.I. To measure the squareness error in the X,Y plane the parallel was placed on the machine bed parallel to the X axis. The D.T.I. was placed in the spindle of the machine tool and run along the top of the parallel. The parallel was adjusted until the D.T.I. indicated zero along the length of the parallel. The square was then placed on top of the parallel with the right angle pointing towards the coordinate X0mm, Y-1400mm, Z0mm. The D.T.I. was then traversed up the edge of the square in the Y direction, and the squareness error calculated from;

θxy = total deflection of D.T.I./Y axis movement microns/m

The squareness error in the X,Y plane was measured as -16 microns/m, which would produce a maximum positional error of 22.4 microns at the full extent of Y axis travel.

Squareness error in the X,Z plane, θxz - The granite parallel was not required for this measurement. To measure this squareness error component the granite square was placed on the machine bed in the X,Z plane, with the right angle pointing towards the coordinate X0mm, Y-1400mm, Z0mm. With the D.T.I. located in the machine spindle it was traversed along the edge of the square in the X direction. The square was adjusted until the D.T.I indicated zero along the full length of the square. The D.T.I. was the run along the edge of the square in the Z direction, and the squareness error calculated from;

θxz = total deflection of D.T.I./Z axis movement microns/m

The squareness error in the X,Z plane was measured as -38.8 microns/m, which would produce a maximum positional error of 38.8 microns with the ram fully extended.

Squareness error in the Y,Z plane, θyz - To measure this squareness error component the parallel was placed on the machine bed parallel to the Z axis. The D.T.I. was placed in the spindle of the machine tool and run along the top of the parallel. The parallel was adjusted until the D.T.I. indicated zero along the length of the parallel. The square was then placed on top of the parallel, in the Y,Z plane, with the right angle pointing towards the coordinate X0mm, Y-1400mm, Z0mm. The D.T.I. was then traversed up the edge of the square in the Y direction, and the squareness error calculated from;

θyz = total deflection of D.T.I./Y axis movement microns/m

The squareness error in the Y,Z plane was measured as 66.93 microns/m, which would produce a maximum positional error of 66.93 microns with the ram fully extended.

All these 16 measured error components were used by the E.C.S. system to compensate for the positional errors of this machine tool throughout its working volume, in order to enhance the volumetric accuracy of the machine tool. The results obtained by this compensation are presented and discussed in section 7.

7 RESULTS OF THE INTEGRATION OF THE E.C.S. TO A MACHINE TOOL

7.1 Introduction

The 16 error components that were identified from the measurements of the machine tool, described in section 6, were all processed using the "integration software" and transferred to the memory of the E.C.S. With the E.C.S. activated, and compensating for the effects of these error components, the next stage of the research program was to assess the improvement in accuracy achieved through the compensation procedure, and so determine the effectiveness of the E.C.S. The first stage in assessing the effectiveness of the E.C.S. was to remeasure the error components of the machine tool. For the error components that were directly compensated for by the E.C.S., such as linear positioning error and straightness error, the improvement achieved by the compensation could easily be determined by remeasuring the error components with the E.C.S. active. This method of remeasuring the error component with the compensation active could obviously not be adopted for the angular error components. This is because the angular error components themselves are not compensated for by the E.C.S. but the effects of the angular errors. In this case the angular error components themselves were not measured, but the positional errors that they created. For instance, X axis yaw error produces a positional error in the X axis as a function of Z axis position. In order to determine the effectiveness of compensating for X axis yaw, therefore, the X axis linear positioning error was measured with the Z axis fully extended (the worst case scenario), and with the compensation first inactive and then active. These measurement tests provided the most important indication of the compensations system performance for two reasons. Firstly they provided a direct and fair comparison with the initial measurement data, from which a direct measure of improvement could be gained. Secondly these tests allowed each individual error component to be assessed independently providing more meaningful diagnostic information. Once the effects of compensating for the individual error components had been established more global tests were performed. These took the form of cutting tests, which provided a picture of the dynamic performance of the E.C.S., and gave an indication of the improvements in workpiece accuracy that can be gained (which is of course the ultimate goal). The results from all these evaluation tests are presented and discussed below.

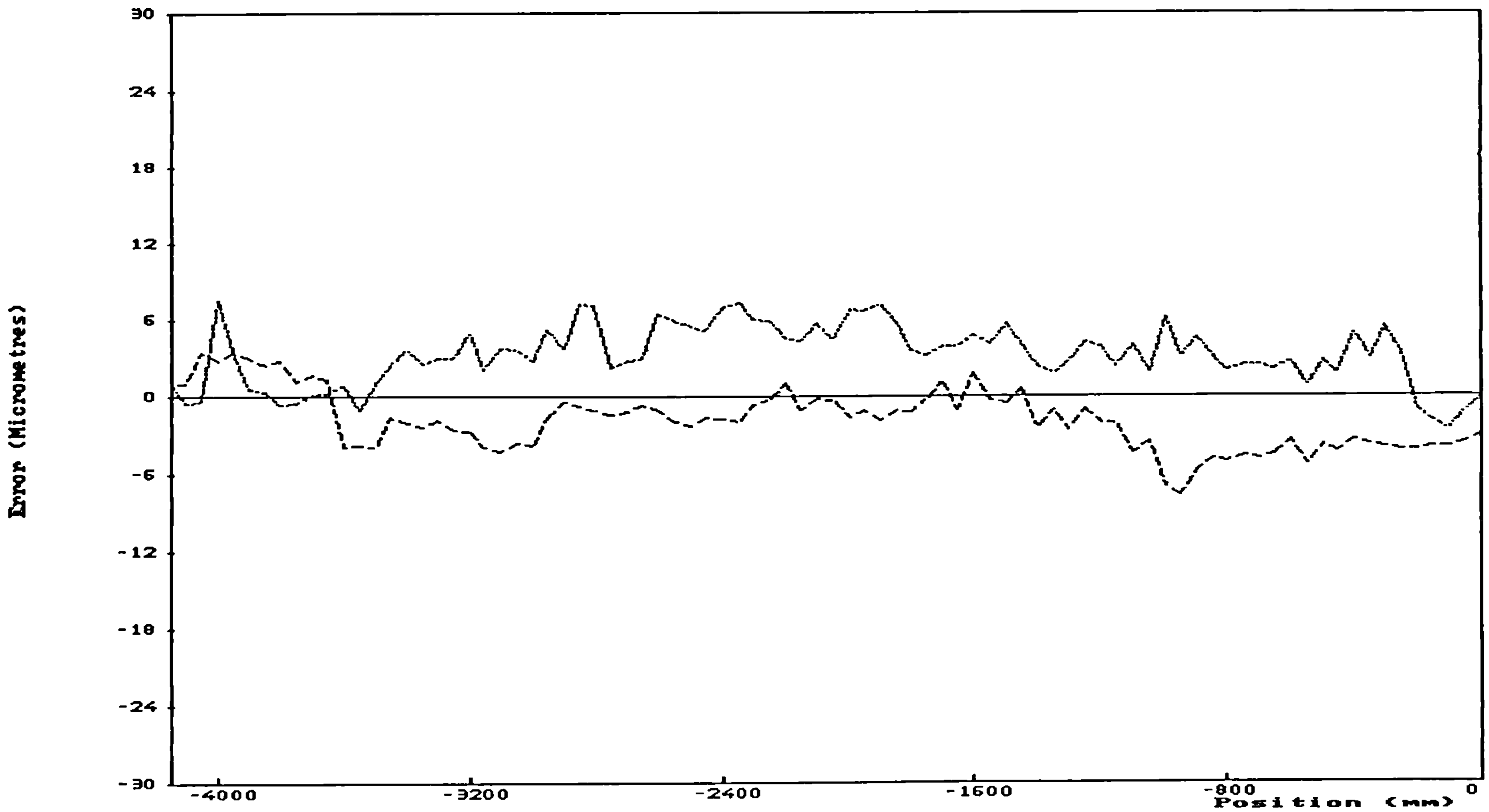
7.2 Remeasurement Of The Machine's Error Components

The error components were remeasured using the same measurement system and techniques as described in section 6. The same axis reference measurement lines were used unless otherwise indicated.

7.2.1 Measurement Of Linear Positioning Error

X axis linear positioning error, ex(x) - The results from this measurement are shown in figure 7.1. The data has been plotted to the same scale as figure 6.4, the uncompensated linear positioning error. In this way an immediate visual comparison can be made between the uncompensated and compensated error component, and an appreciation of any improvement can instantaneously be gained. It can be seen from figure 7.1 that the error has been significantly reduced the error band being approximately 14 microns, a reduction of 26 microns over the uncompensated error. The form of the graph is also significant with the error showing a straight trend about the zero line, indicating effective compensation. The size and form of the compensated data indicate that the systematic component of the error has been significantly reduced leaving only the random component of the error, which of course can not be reduced by this method of compensation. There was very little reversal error measured from the uncompensated machine leaving no room for improvement.

FIGURE 7.1 X AXIS LINEAR POSITIONING ERROR AFTER COMPENSATION



Y axis linear positioning error, ey(y) - The results from this measurement are shown in figure 7.2. The data is plotted to the same scale as figure 6.5, the uncompensated error plot. It can be seen from this measurement that the compensation system has produced a dramatic improvement in Y axis linear positioning accuracy. The error band for this measurement is approximately 6 microns, giving an error reduction of more than 35 microns, and an accuracy improvement of 6.8:1. The form of the compensated data shows that the systematic error component has been dramatically reduced leaving the random error component scattered about the zero line. The initial reversal error although small has also been reduced to negligible proportions.

Z axis linear positioning error, ez(z) - The results from this measurement are shown in figure 7.3. The data is plotted to the same scale as figure 6.6, the uncompensated error plot. Again this result shows a dramatic improvement in the linear positioning error. The error band for this measurement is approximately 6 microns, giving an error reduction of more than 24 microns, and an accuracy improvement of 5:1. Again the form of this measurement indicates a clear reduction in the systematic error component. The slight offset from the zero line is due to the choice of the initial datum position, and is not significant. The reversal error has been reduced to a negligible level. This is important as the initial reversal error shown in figure 6.6 clearly varies over the length of the axis. This result highlights an important advantage of the E.C.S. over conventional compensation methods; namely its ability to compensate for non-uniform reversal errors.

7.2.2 Measurement Of Straightness Error

X axis straightness error in the XY plane, ey(x) - The results from this measurement are shown in figure 7.4. This error component was measured on the fly. The data is

FIGURE 7.2 Y AXIS LINEAR POSITIONING ERROR AFTER COMPENSATION

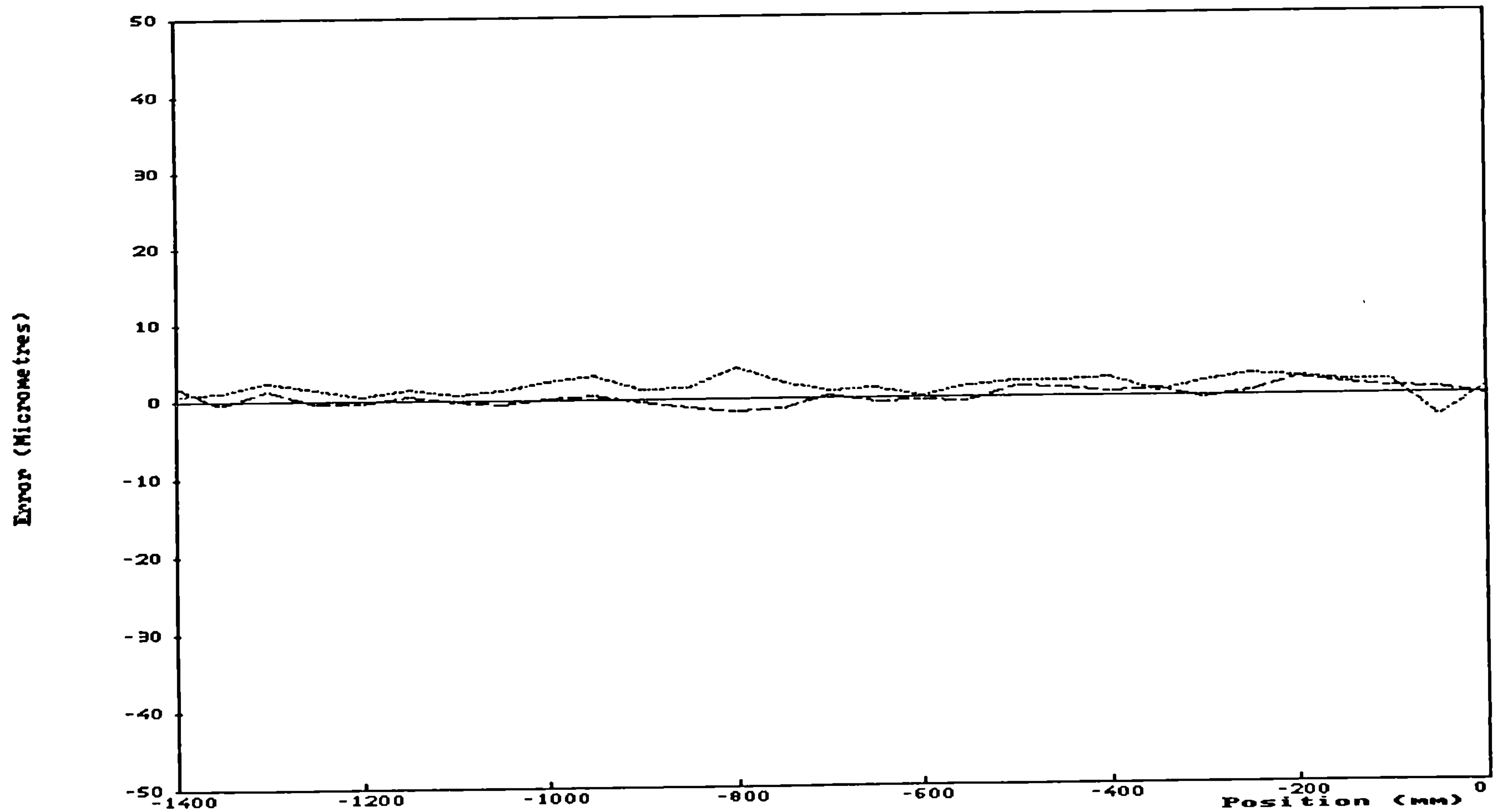


FIGURE 7.3 Z AXIS LINEAR POSITIONING ERROR AFTER COMPENSATION

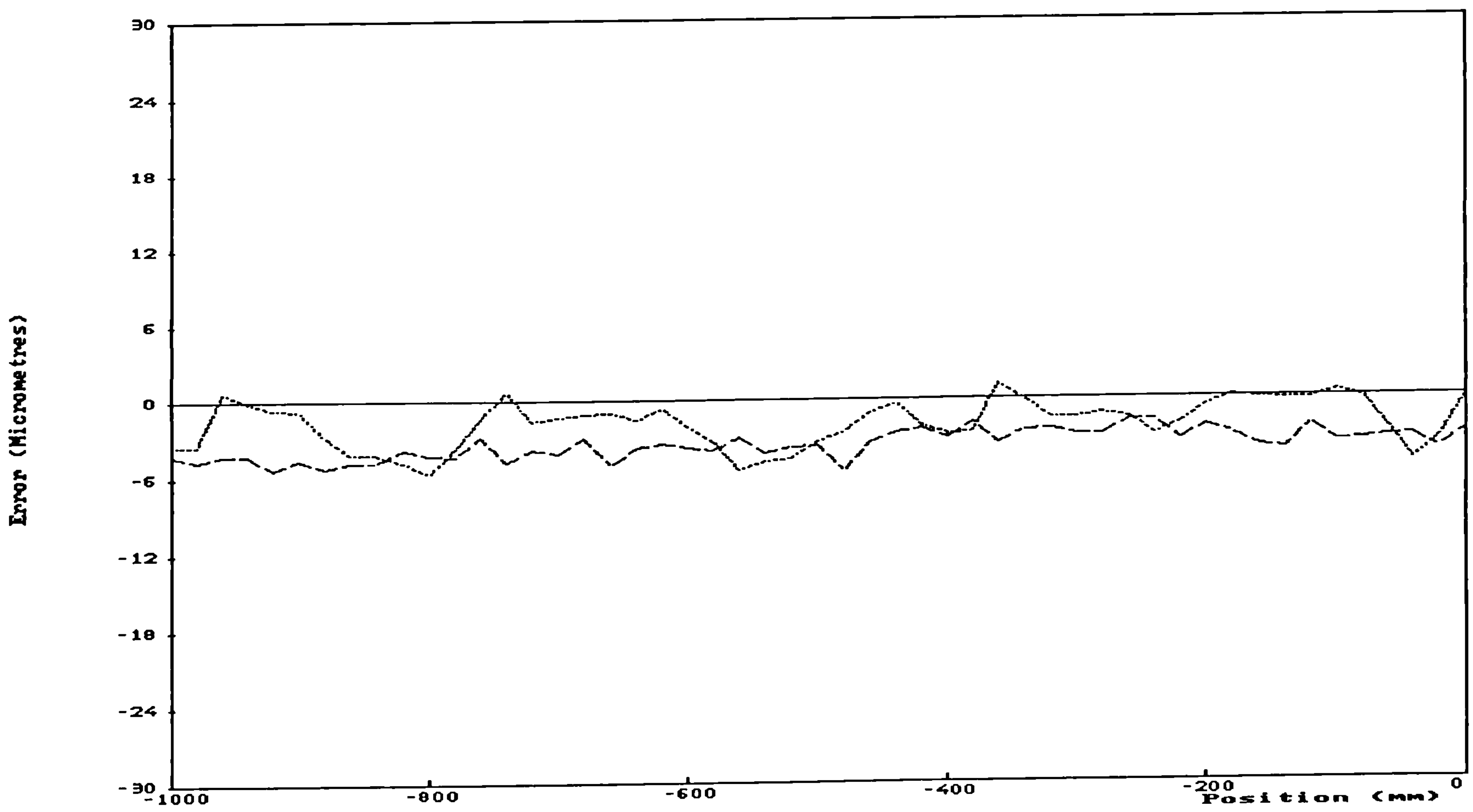
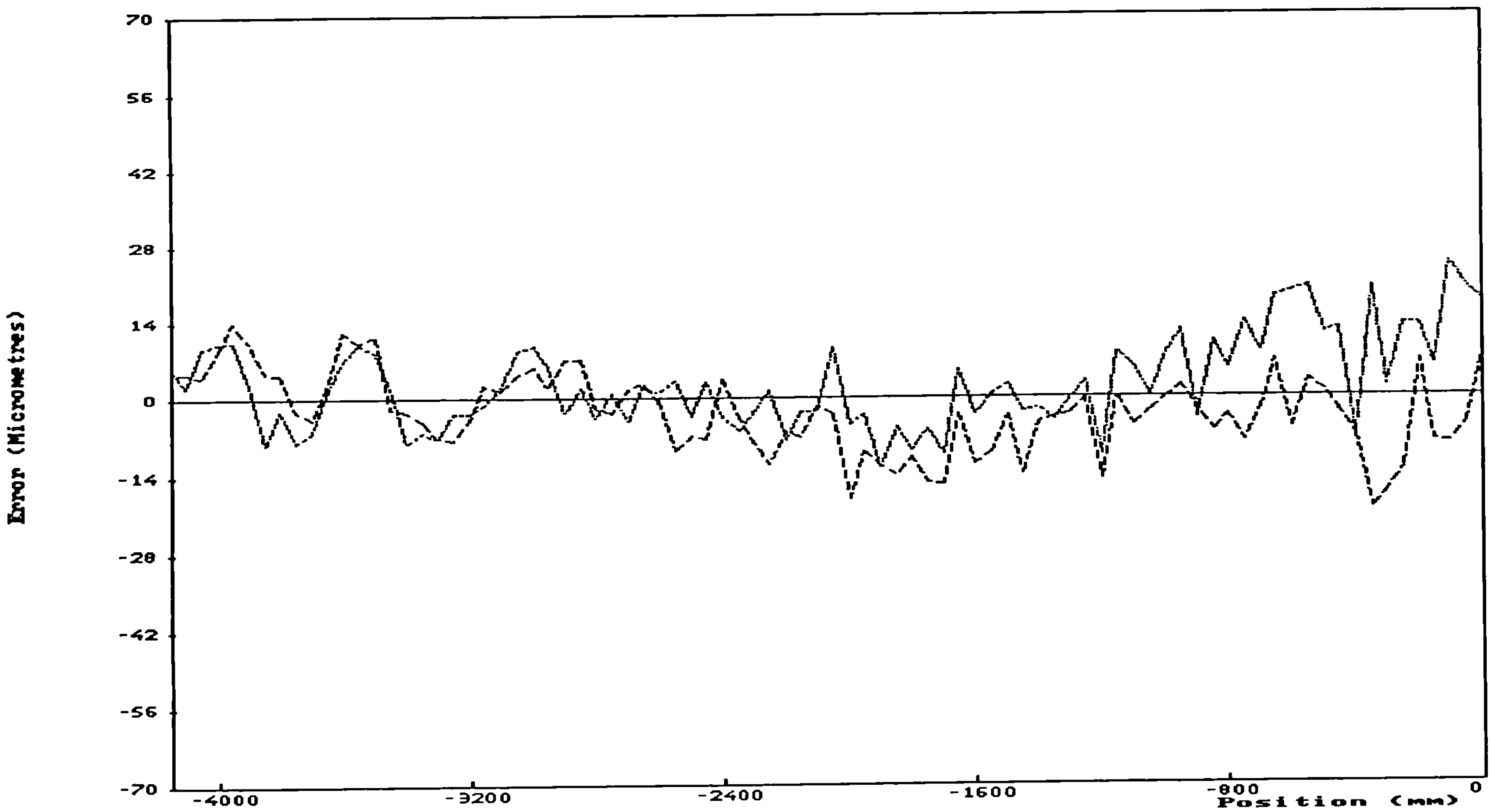


FIGURE 7.4 X AXIS STRAIGHTNESS ERROR IN THE XY PLANE AFTER COMPENSATION

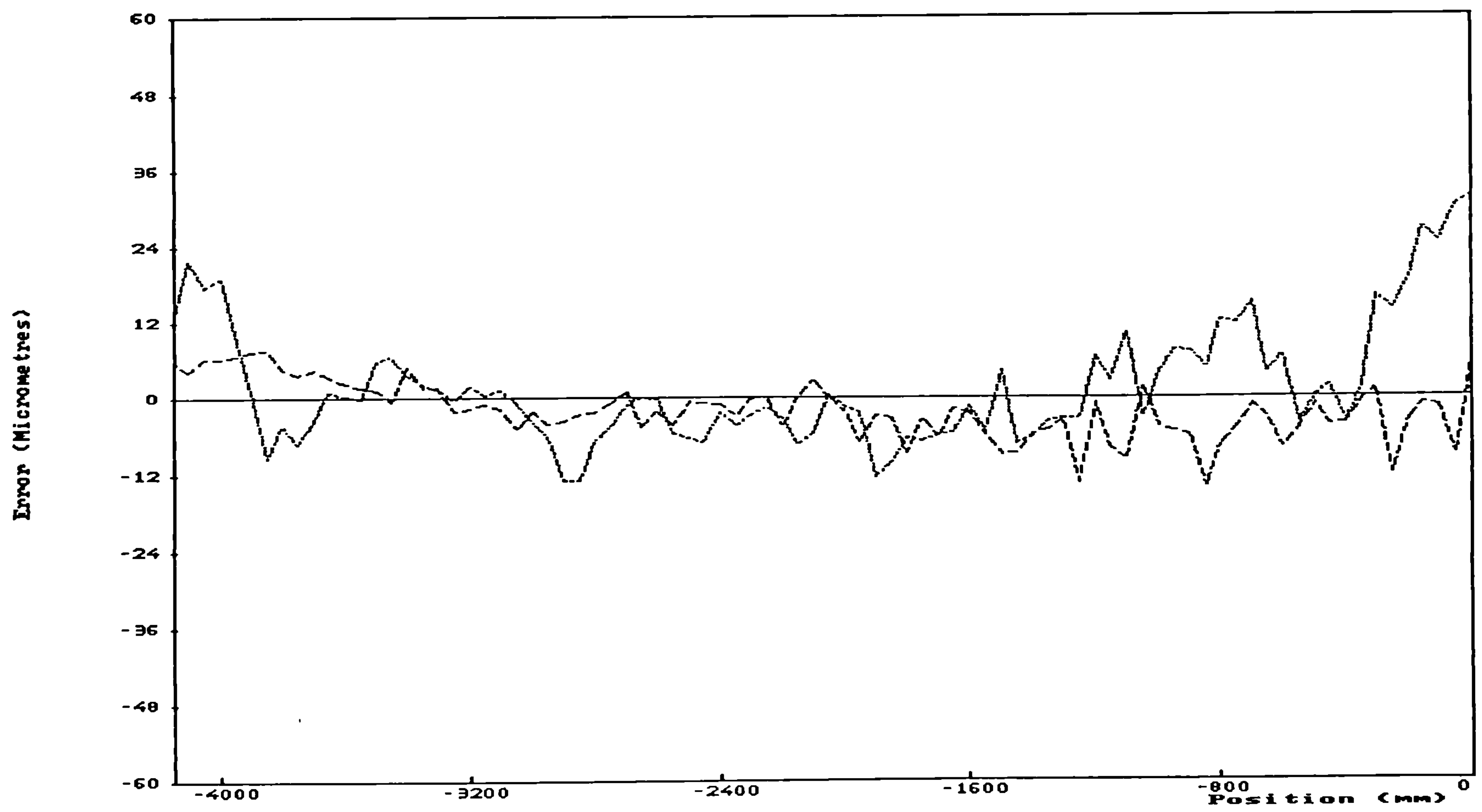


plotted to the same scale as figure 6.7, the uncompensated error plot. This was a significant error in the uncompensated machine tool, and the results show that a good improvement has been made with the compensation active. The error band for this measurement is approximately 40 microns giving an error reduction of 60 microns, and an accuracy improvement of 2.5:1. The size of the error band for this error is a reflection of the relatively poor repeatability of the measurement procedure. Indeed the form of the measured data indicates that most of the residual error is due to the random error component. A more dramatic appreciation of the error reduction achieved can be gained by a visual comparison of figure 7.4 with figure 6.7. As the reversal error of the initial straightness measurement was negligible it is difficult to quantify any improvement.

X axis straightness error in the XZ plane, ez(x) - The results from this measurement are shown in figure 7.5. This error component was measured on the fly. The data is plotted to the same scale as figure 6.8, the uncompensated error plot. Again in this figure the effect of the E.C.S. can be clearly seen. The error band is approximately 40 microns giving an error reduction of 45 microns, and an accuracy improvement of 2:1. More importantly the erratically shaped straightness error of the uncompensated machine has been reduced to straight and even form. The uncompensated straightness measurement, figure 6.8, clearly shows poor repeatability at the positive end of travel and a large reversal "kick" at the negative end of travel. These two anomalies are also reflected in the measurement of the compensated straightness error, where a slight deterioration in accuracy can seen at the extreme ends of travel. If these extreme ends of travel are omitted, and only the central working section of the axis considered, an even greater improvement in accuracy can be calculated. Again the small initial reversal error makes it difficult to quantify any improvement.

Y axis straightness error in the XY plane, ex(y) - The

FIGURE 7.5 X AXIS STRAIGHTNESS ERROR IN THE XZ PLANE AFTER COMPENSATION



results from this measurement are shown in figure 7.6. This error component was measured on the fly. The data is plotted to the same scale as figure 6.9, the uncompensated error plot. The initial uncompensated straightness error was relatively small, and as a result only a marginal improvement has been made with the compensation active. The error band with compensation is approximately 12 microns giving an error reduction of 4 microns, and an accuracy improvement of 1.3:1. A marginal improvement can also be seen in the reversal error component. The relatively small improvement provided by the compensation is a direct reflection of its initial negligible size.

Y axis straightness error in the YZ plane, ez(y) - The results from this measurement are shown in figure 7.7. This error component was measured on the fly. The data is plotted to the same scale as figure 6.10, the uncompensated error plot. The results of this measurement show an error band of approximately 11 microns giving an error reduction of 13 microns, and an accuracy improvement of 2.2:1. Although the initial size of this straightness error was small, leaving little room for improvement, a definite reduction in this straightness error can be seen.

Z axis straightness error in the XZ plane, ex(z) - The results from this measurement are shown in figure 7.8. This error component was measured on the fly. The data is plotted to the same scale as figure 6.11, the uncompensated error plot. As with the Y axis straightness values this error component was not significantly large. As a result there is little if any improvement in the error band with the compensation active. There is however a slight improvement in the form of the error. The uncompensated straightness error displayed an erratic shape with an unusual reversal error characteristic at the extreme ends of axis travel. With compensation the straightness error is flatter in form with a slight improvement in the reversal error characteristic.

Z axis straightness error in the YZ plane, ey(z) - The

FIGURE 7.6 Y AXIS STRAIGHTNESS ERROR IN THE XY PLANE AFTER COMPENSATION

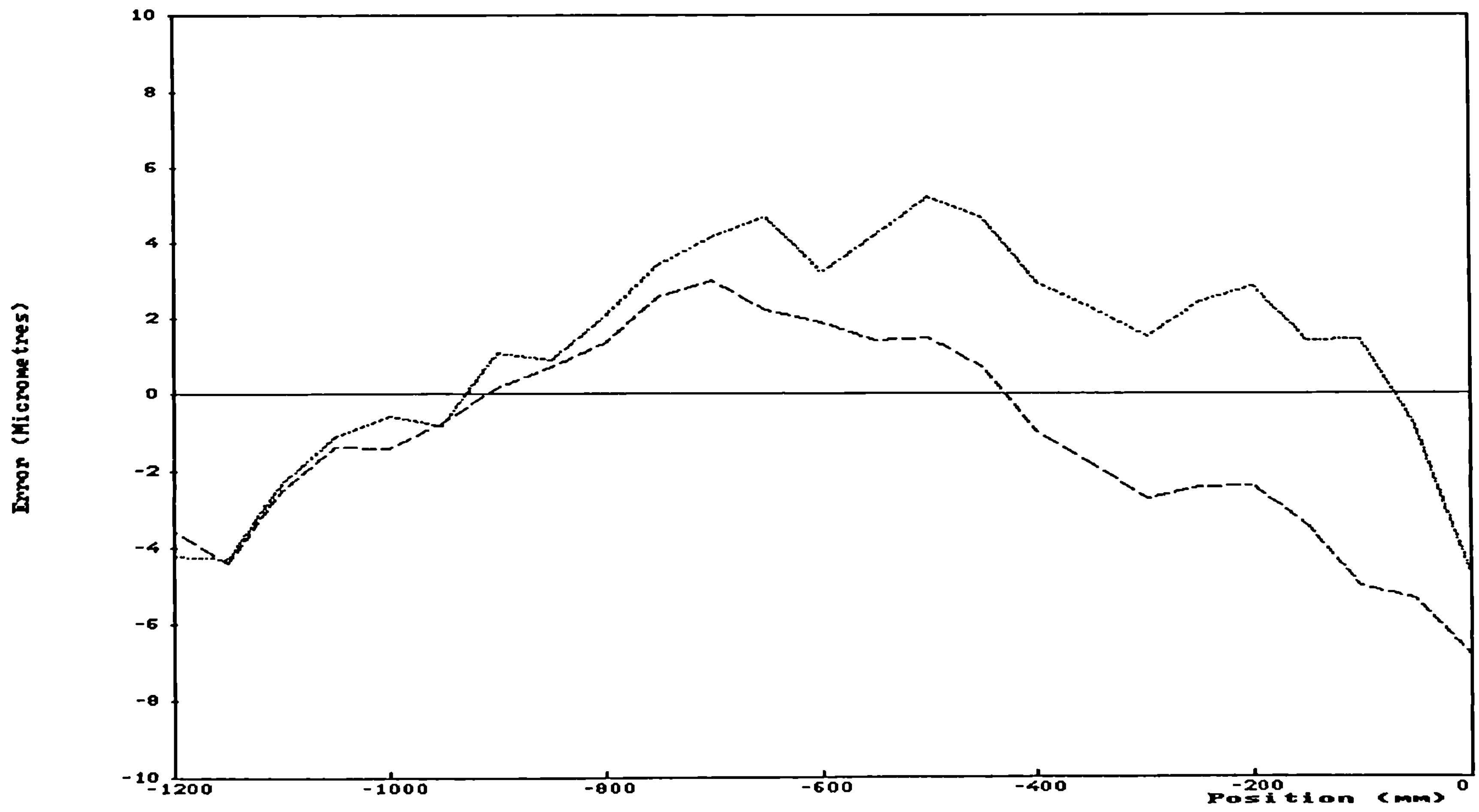


FIGURE 7.7 Y AXIS STRAIGHTNESS ERROR IN THE YZ PLANE AFTER COMPENSATION

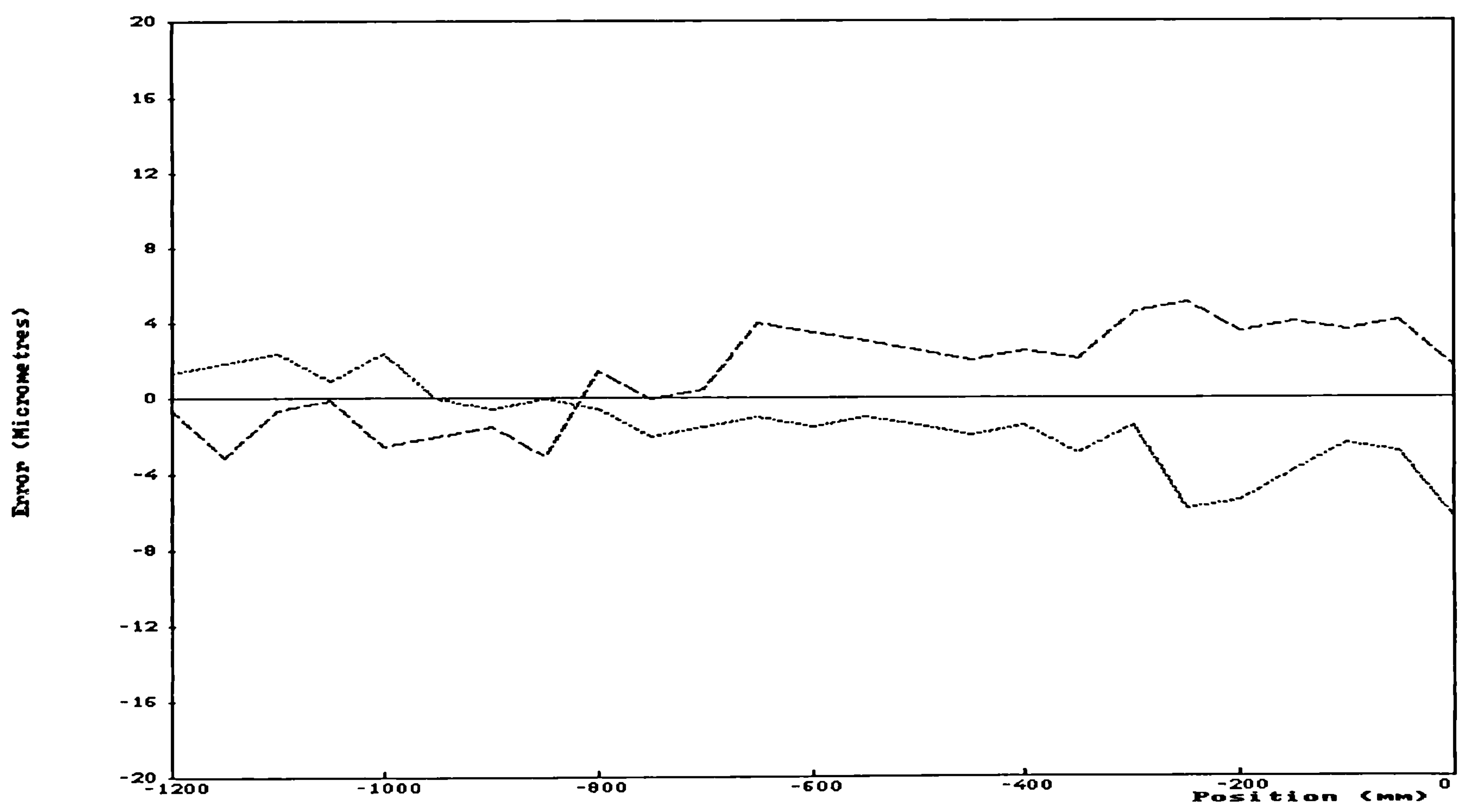
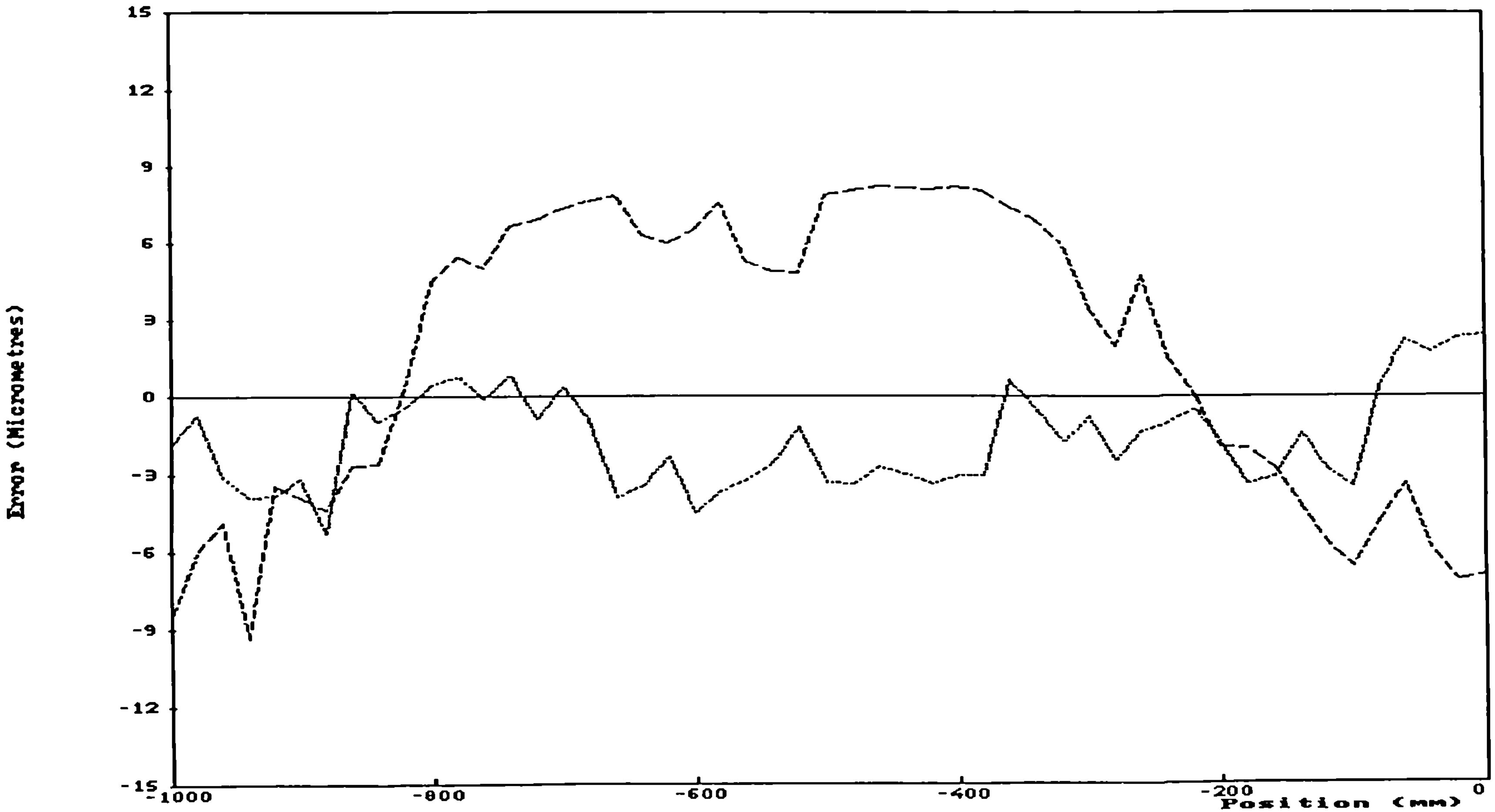


FIGURE 7.8 Z AXIS STRAIGHTNESS ERROR IN THE XZ PLANE AFTER COMPENSATION



results from this measurement are shown in figure 7.9. This error component was measured on the fly. The data is plotted to the same scale as figure 6.12, the uncompensated error plot. As discussed in section 6 this error component, commonly known as ram droop, is a major source of error in a machine of this configuration. The results from this measurement show an excellent improvement in the straightness error. The error band is approximately 16 microns giving an error reduction of 54 microns, and an accuracy improvement of 4.4:1. As significant as the large overall error reduction is the improvement in the form of the straightness error. This can be clearly appreciated by a visual comparison of figures 7.9 and 6.12. The characteristic bow shape of the ram droop has been reduced to a small error evenly distributed about the zero line, indicating excellent straightness of movement of the compensated axis. The even distribution of the compensated error about zero also indicates that the systematic component of the error has been greatly reduced leaving only the random error component. A very good improvement can also be seen in the reversal error characteristic of the error. The uncompensated reversal error is not only large at a maximum of 26 microns, but is also grossly irregular over the axis length. The compensated reversal error has been reduced to a minimal level over the complete axis length, again highlighting the unique benefit of this method of compensation.

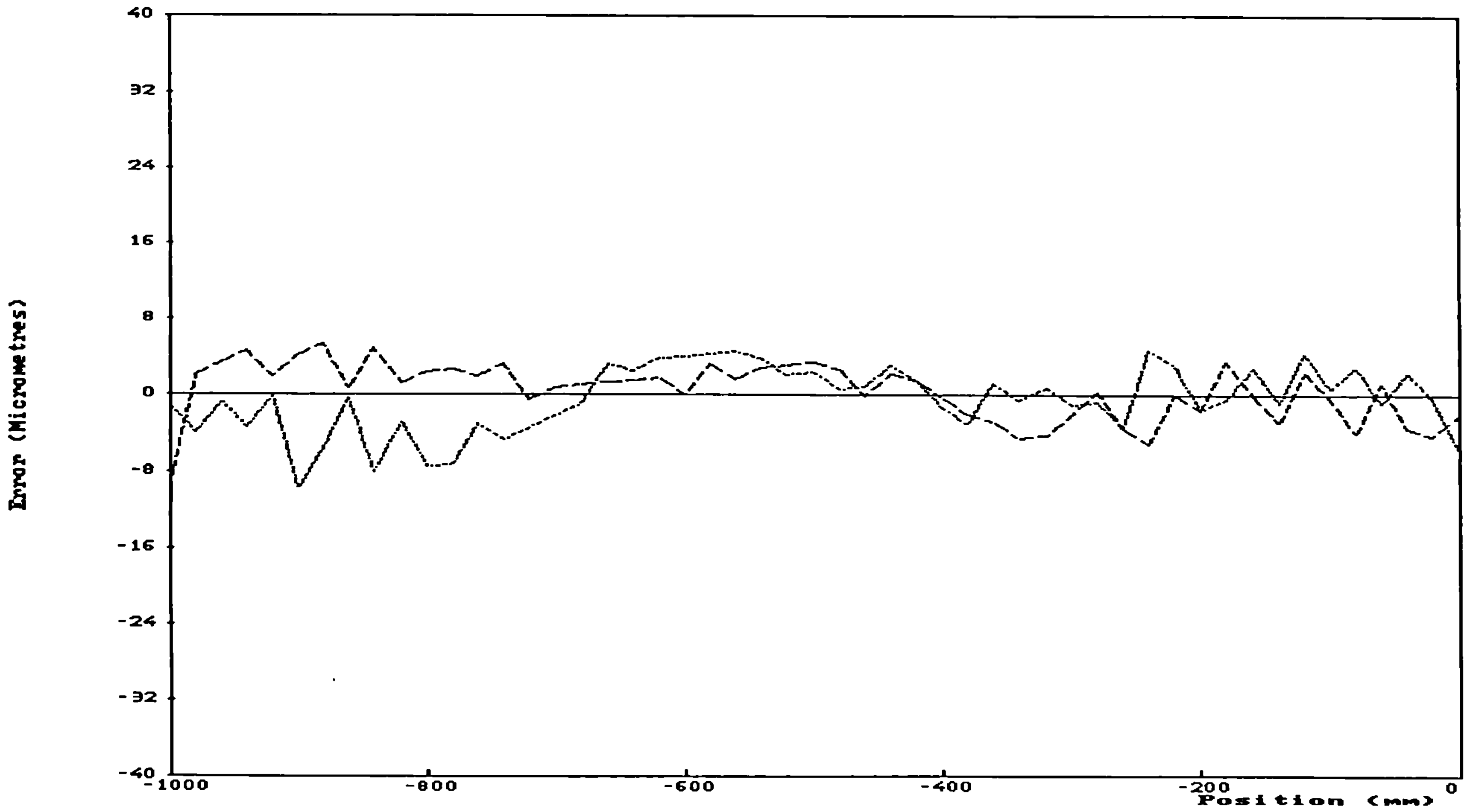
7.2.3 Measurement Of The Effects Of Rotational Error

X axis pitch error, $\emptyset z(x)$ - As discussed in section 6 the effect of X axis pitch error on this machine is to produce an X axis positional error that is a function of Y axis position. The relationship is;

X positional error due to pitch = $\emptyset z(x).Y$

In order to quantify the effect of X axis pitch on the positioning accuracy of the machine, and to quantify the improvement in accuracy gained through compensation for X axis pitch, two measurements were made. The first

FIGURE 7.9 Z AXIS STRAIGHTNESS ERROR IN THE YZ PLANE AFTER COMPENSATION



measurement was of X axis linear positioning error with the Y axis at its extreme end of travel away from the machine's datum coordinate, and with the E.C.S. inactive. This extreme Y axis position is where the effects of X axis pitch are most significant. The results of this measurement are shown in figure 7.10. The second measurement was a repeat of the first measurement but with the E.C.S. active. This second measurement would quantify the effects of compensating for this pitch error, and the results from this measurement are shown in figure 7.11. In figure 7.10 the significant effect of X axis pitch can be clearly seen. The error band for this measurement is 50 microns, which is larger than for the pure linear positioning error of the X axis shown in figure 6.4. At this point the positioning error due to pitch is the dominant error. This can be clearly seen by comparing figure 7.10 with figure 6.13, the X axis pitch error plot. The form of these two plots is similar indicating that the positioning error shown in figure 7.10 is largely produced as a result of the pitch error shown in figure 6.13. In figure 7.11 the results of compensating for this pitch error are clearly seen. The error band for the measurement is 34 microns, giving an error reduction of 16 microns over the uncompensated measurement, an accuracy improvement of 1.5:1. A visual comparison of figures 7.10 and 7.11 gives an even more vivid indication of the improvement in accuracy resulting from the compensation. The comparison shows not only a numerical improvement in accuracy, but also highlights the improvement made in the form of the error.

X axis yaw error, $\emptyset y(x)$ - The effect of X axis yaw error on this machine is to produce an X axis positional error that is a function of Z axis position. The relationship is;

$$X \text{ positional error due to yaw} = \emptyset y(x).Z$$

Again in order to quantify the effectiveness of the E.C.S. in compensating for this yaw error two measurements of X axis linear positioning error were made. The first measurement was of the X axis linear positioning error with the Z axis fully extended, and with the E.C.S. inactive. This extreme Z axis position is where the effects of X axis

FIGURE 7.10 THE EFFECTS OF X AXIS PITCH ERROR BEFORE COMPENSATION

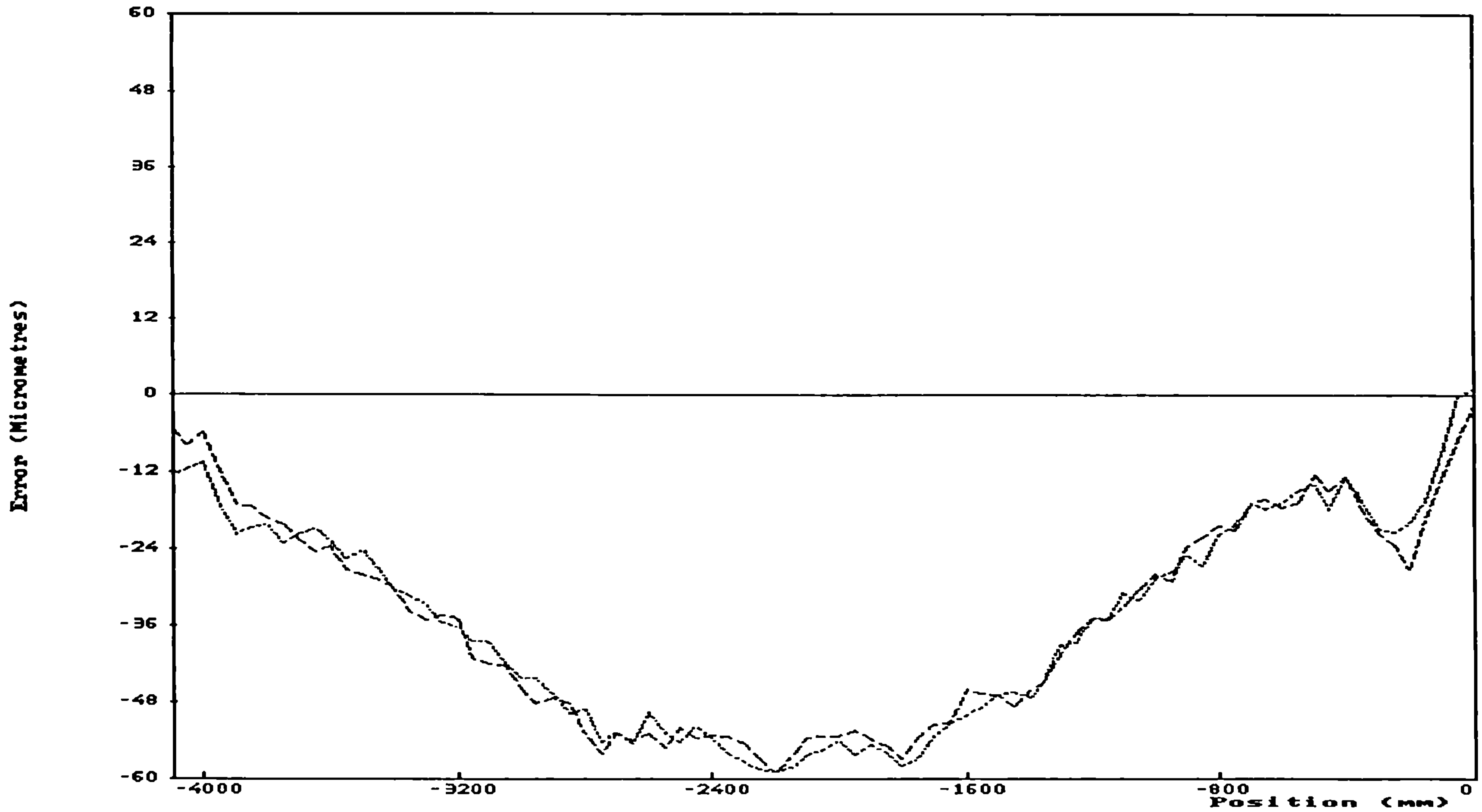
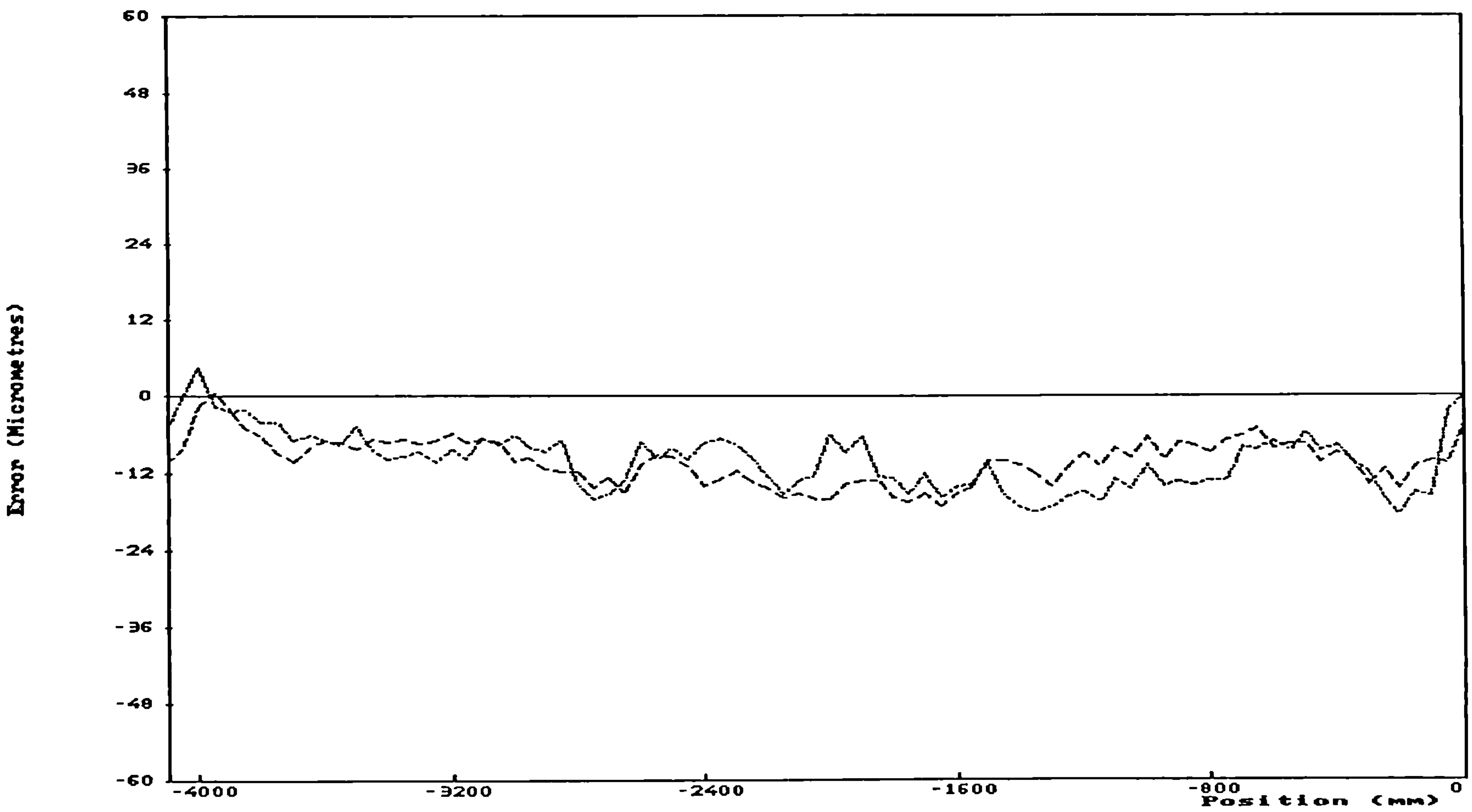


FIGURE 7.11 THE EFFECTS OF X AXIS PITCH ERROR AFTER COMPENSATION



yaw are most significant. The results of this measurement are shown in figure 7.12. The second measurement was a repeat of the first measurement but with the E.C.S. active. The results of this measurement are shown in figure 7.13. The effects of the X axis yaw error can be clearly seen in figure 7.12. The error band for this measurement is 54 microns which is again greater than for the pure X axis linear positioning error. It is interesting to note that the sense of the positioning error produced by X axis yaw is opposite to the sense of the pure X axis linear positioning error. The yaw error tends to produce a positive linear positioning error where as the pure X axis linear positioning error is predominantly negative. The net result of this is that the two errors tend to cancel each other out. If the sense of these two error components had been in the same direction the effects of the yaw error would have been even more dramatic, producing a combined error of over 100 microns. Figure 7.13 clearly shows the effect of compensating for this error. The error band for the measurement is 17 microns, giving an error reduction of 37 microns over the uncompensated measurement, an accuracy improvement of 3.2:1. A dramatic improvement in both the form and magnitude of the error can be seen from figure 7.13.

X axis roll error, Øx(x) - The effect of X axis roll error on this machine is to alter both the X axis horizontal and vertical straightness errors. The X axis horizontal straightness error varies as a function of Y axis position. The relationship is;

X horizontal straightness error due to roll = Øx(x).Y

The X axis vertical straightness error varies as a function of Z axis position. The relationship is;

X vertical straightness error due to roll = Øx(x).Z

The effect of X axis roll on each of these straightness error components was considered separately.

Two measurements were made of X axis horizontal straightness error. The first measurement was made with the Y axis at its extreme of travel away from the measurement

FIGURE 7.12 THE EFFECTS OF X AXIS YAW ERROR BEFORE COMPENSATION

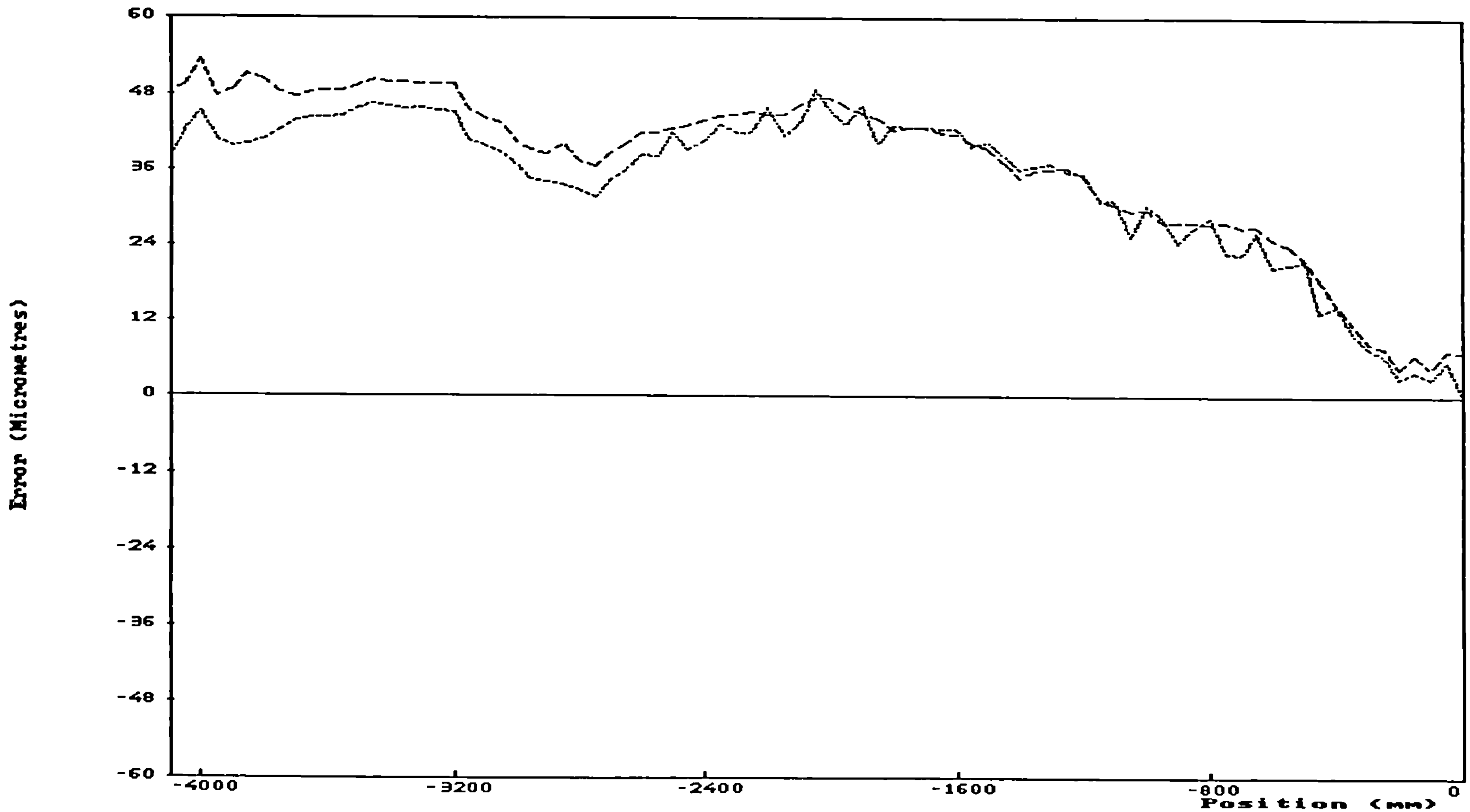
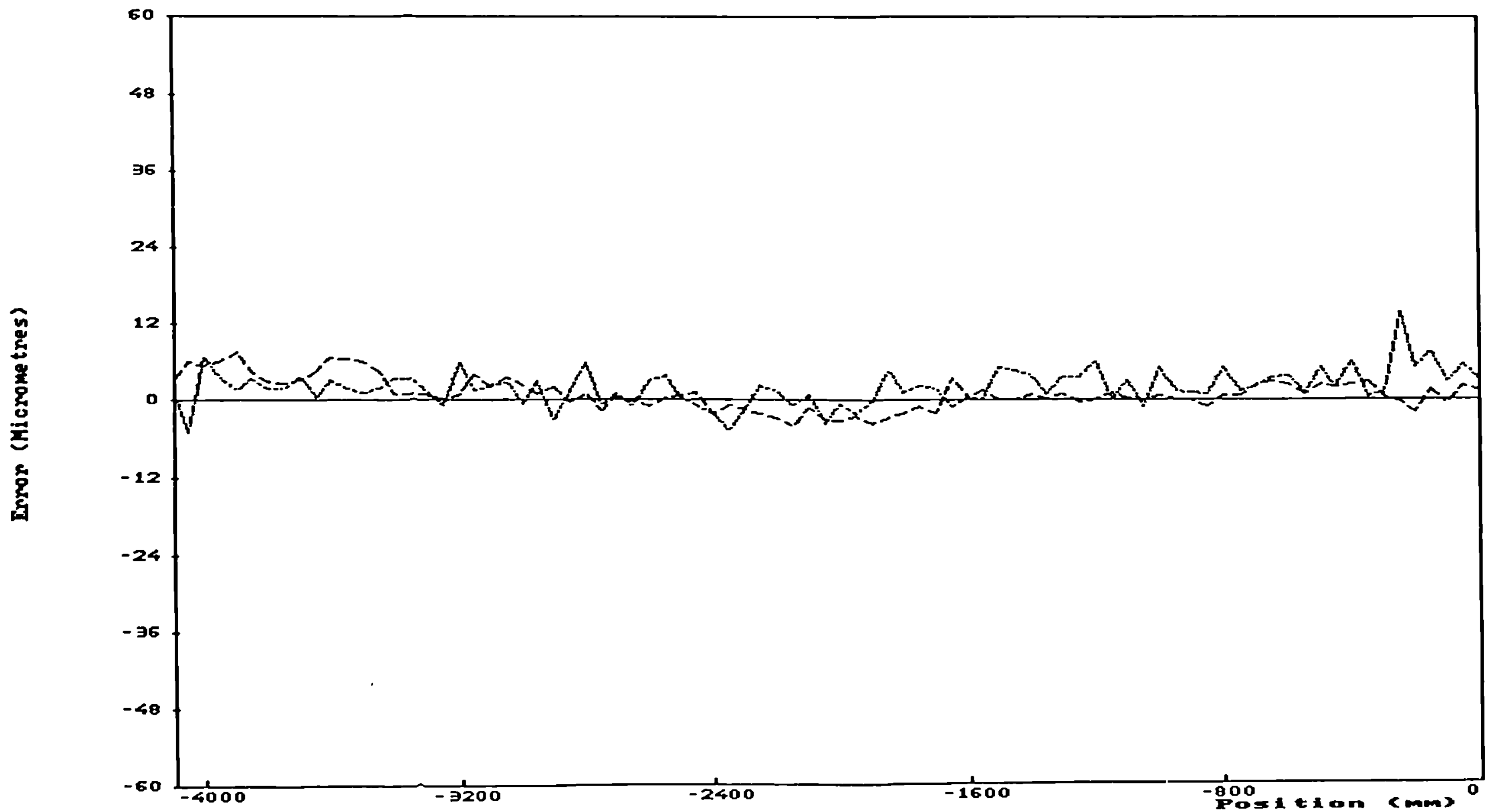


FIGURE 7.13 THE EFFECTS OF X AXIS YAW ERROR AFTER COMPENSATION



datum coordinate, with the E.C.S. inactive. The results of the measurement are shown in figure 7.14. The second measurement was a repeat of the first measurement but with the E.C.S. active. The results of the measurement are shown in figure 7.15. The effects of X axis roll on the X horizontal straightness error can be clearly seen in figure 7.14. The error band for this measurement is over 100 microns. This large value of error band is due to the excessive straightness deviations over the first 800mm of the axis travel. The effectiveness of the compensation can be seen in figure 7.15. The error band for this measurement is approximately 40 microns giving an error reduction of 60 microns, and an accuracy improvement of 2.5:1. A significant improvement in the form of the error can also be seen in this figure.

Two measurements were made of X axis vertical straightness error. The first measurement was made with the Z axis fully extended, with the E.C.S. inactive. The results of the measurement are shown in figure 7.16. The second measurement was a repeat of the first measurement but with the E.C.S. active. The results of the measurement are shown in figure 7.17. In figure 7.16 the effect of the roll error can be seen in the form of this plot. The undulations in the straightness error being produced as the column rotates in sympathy with its narrow rear support rail. The error band for this measurement is large at approximately 100 microns. With the compensation active, figure 7.17, the error band has been reduced to 50 microns. This gives a error reduction of 50 microns and an accuracy improvement of 2:1.

Y axis yaw error, Øx(y) - The effect of Y axis yaw error on this machine is to produce a Y axis positional error that is a function of Z axis position. The relationship is;

Y positional error due to yaw = Øx(y).Z

As with the previous rotational errors in order to quantify the effectiveness of the E.C.S. in compensating for this yaw error two measurements of Y axis linear positioning error were made. The first measurement was of the Y axis

FIGURE 7.14 THE EFFECTS OF X AXIS ROLL ERROR ON X HORIZONTAL STRAIGHTNESS BEFORE COMPENSATION

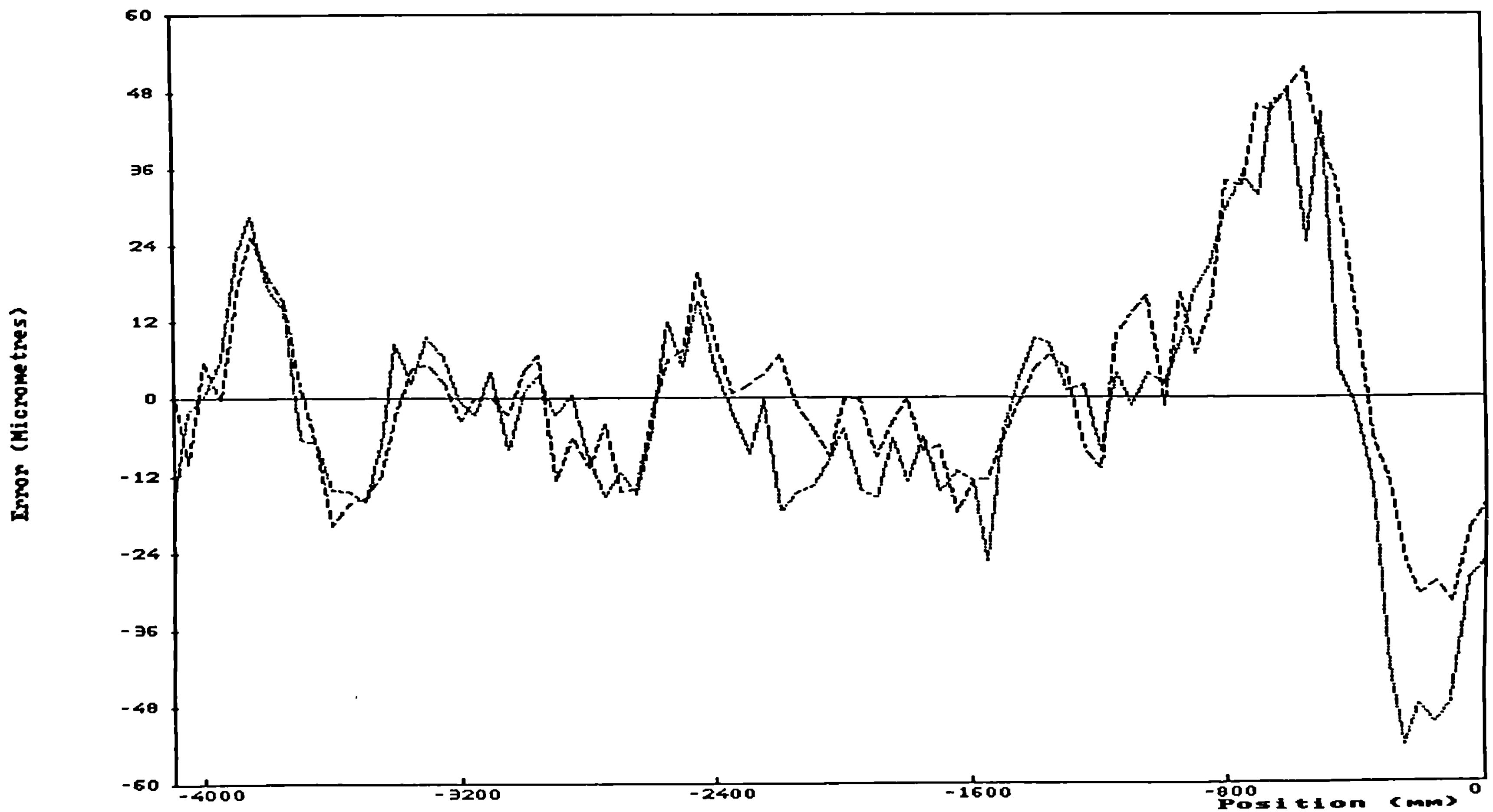


FIGURE 7.15 THE EFFECTS OF X AXIS ROLL ERROR ON X HORIZONTAL STRAIGHTNESS AFTER COMPENSATION

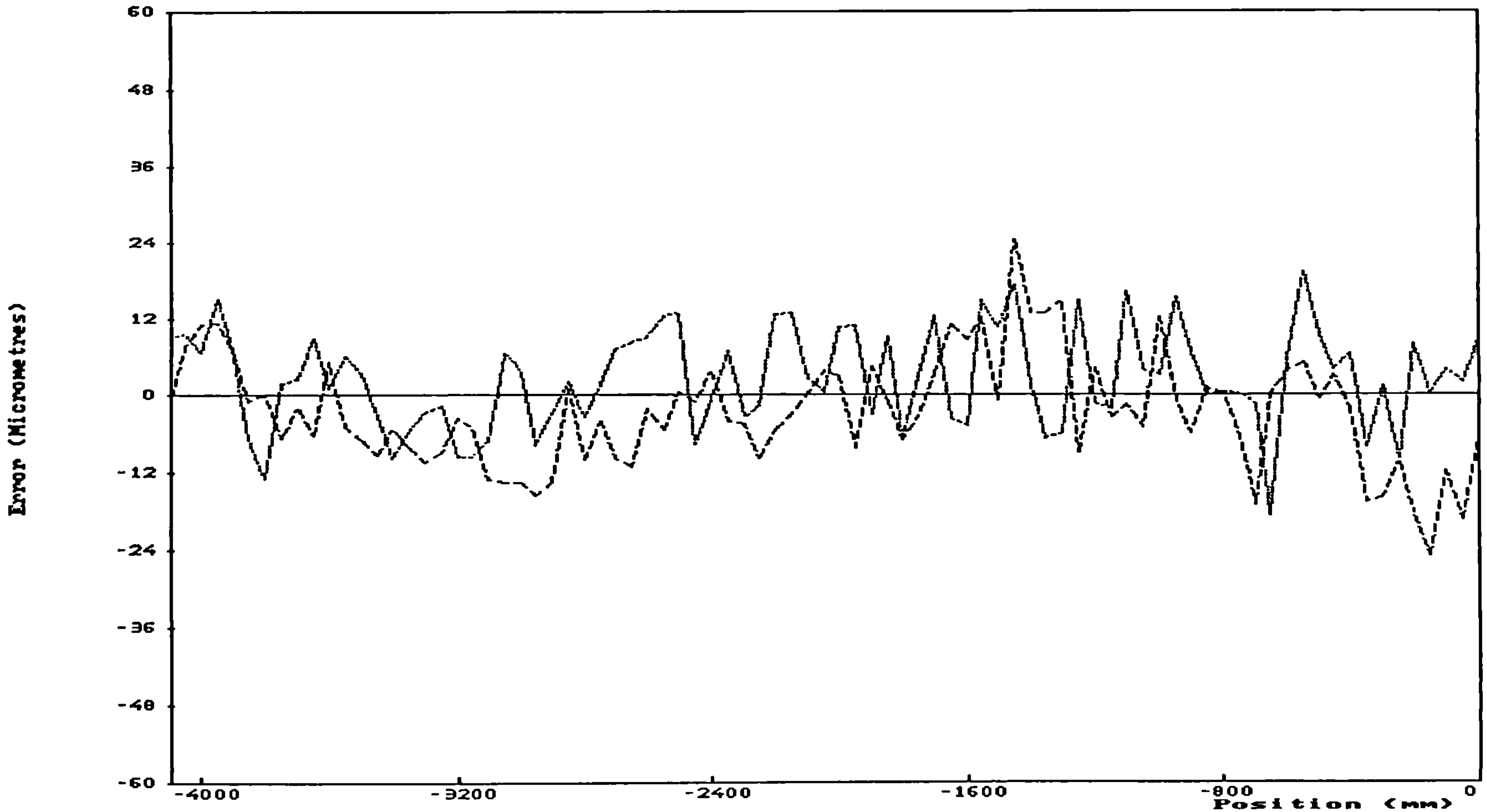


FIGURE 7.16 THE EFFECTS OF X AXIS ROLL ERROR ON X VERTICAL STRAIGHTNESS BEFORE COMPENSATION

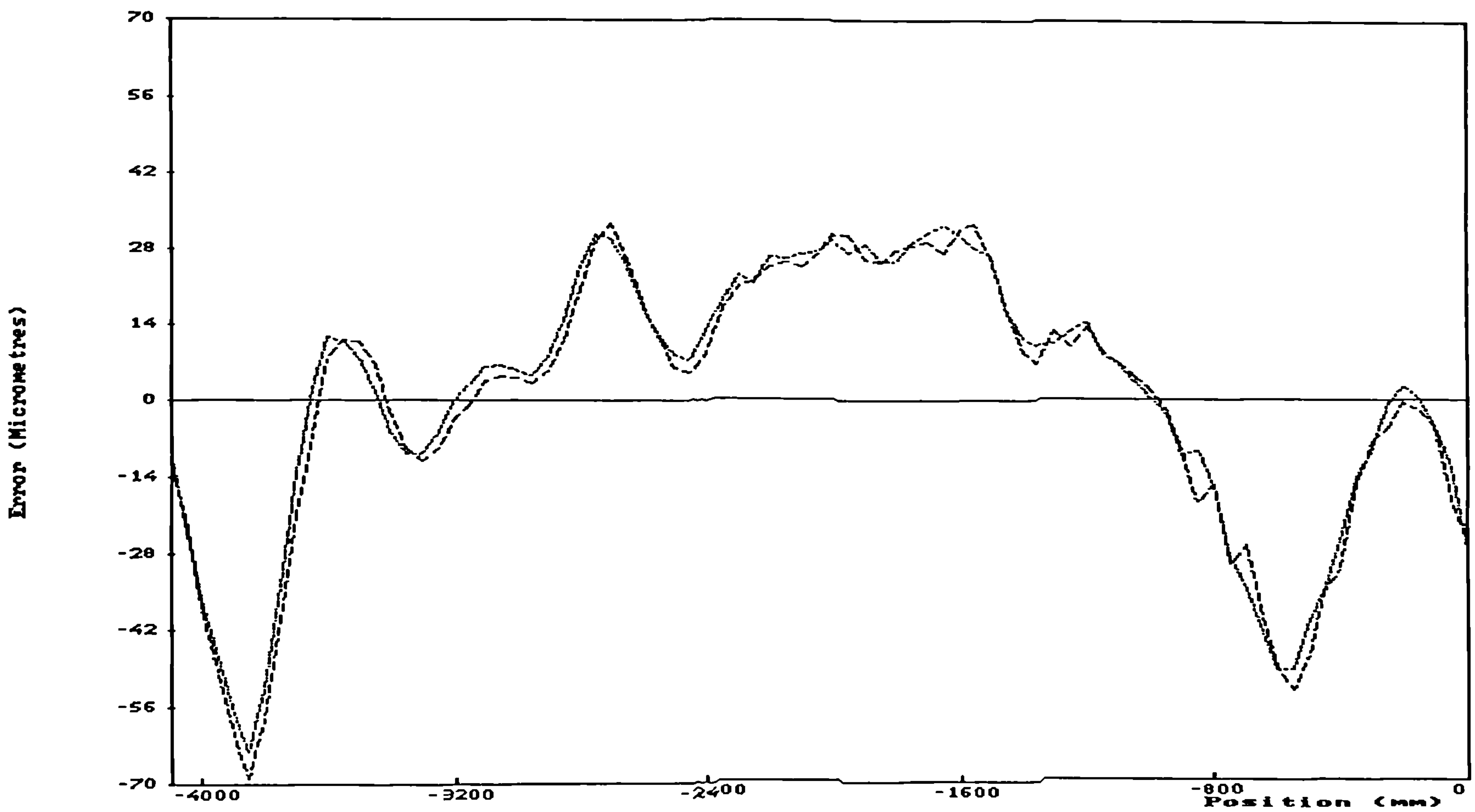
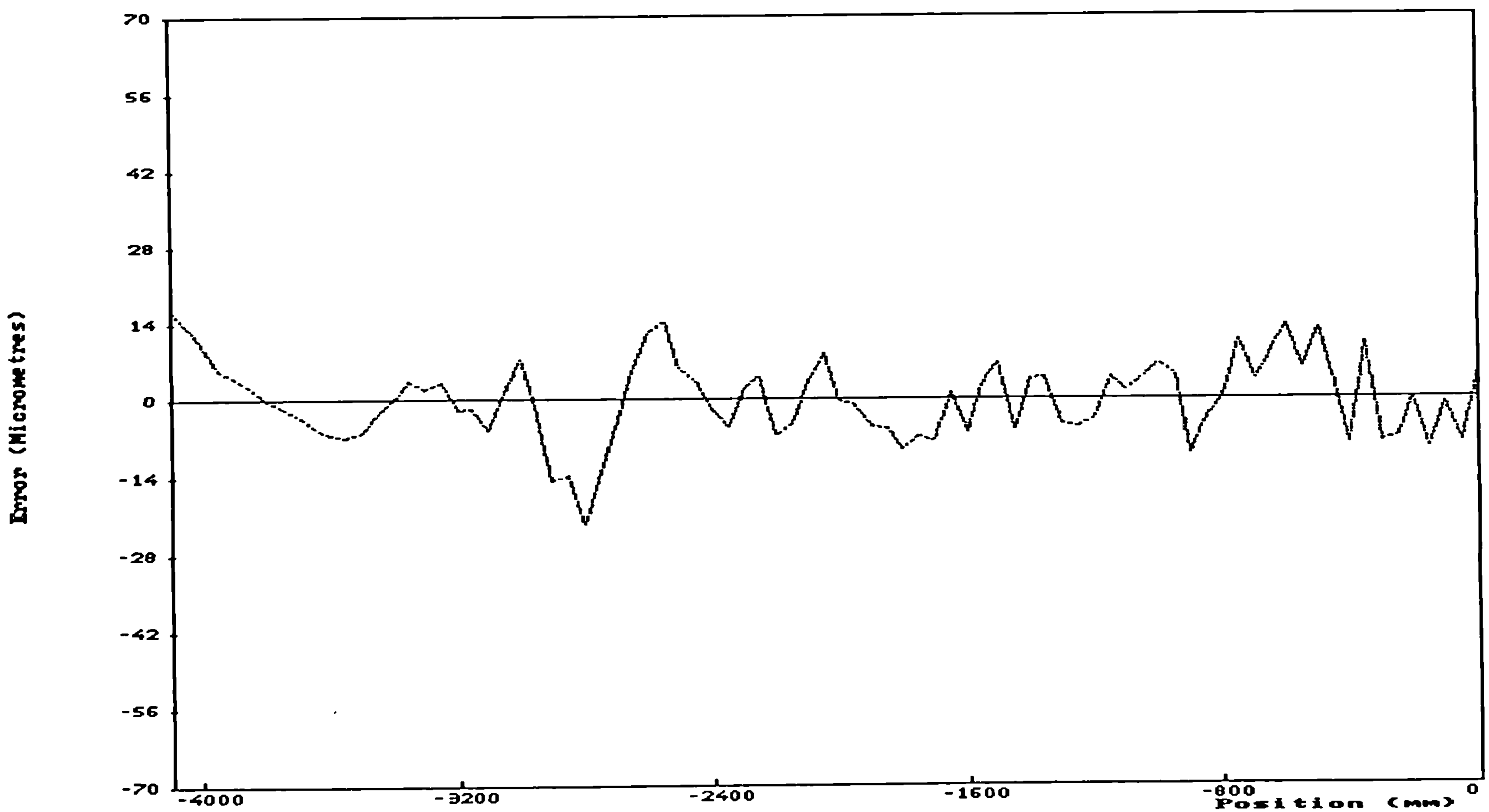


FIGURE 7.17 THE EFFECTS OF X AXIS ROLL ERROR ON X VERTICAL STRAIGHTNESS AFTER COMPENSATION



linear positioning error with the Z axis fully extended, and with the E.C.S. inactive. At this Z axis position effects of Y axis yaw are most significant. The results of this measurement are shown in figure 7.18. The second measurement was a repeat of the first measurement but with the E.C.S. active. The results of this measurement are shown in figure 7.19. From figure 7.18 it can be seen that Y axis yaw has had a dramatic effect on the positioning accuracy of the Y axis, producing an error band of 100 microns. This is more than double the pure linear positioning error of the Y axis shown in figure 6.5. This is because the sense of the positioning error produced by Y axis yaw is the same sense as the Y linear positioning error. The two errors therefore combine to produce the seemingly large positioning error. The effect of the E.C.S., shown in figure 7.19 is equally as dramatic. The error band for this measurement is approximately 15 microns giving an error reduction of 85 microns, and an accuracy improvement of 6.7:1. The size of the error reduction is of course as a consequence of the large initial value of the error, however the result clearly shows the effectiveness of the E.C.S. at compensating for the effects of rotational errors.

7.2.4 Measurement Of Orthogonality Error

All three squareness errors were remeasured in the same way as described in section 6, using a granite parallel, a granite square and a dial test indicator. Small adjustments were made to the squareness compensation values until each squareness errors were effectively eliminated. As the squareness compensation value is represented by a single number adjustments were easily and quickly made.

7.2.5 Summary Of The Measurement Tests

These measurement tests conclusively show that all the significant error components present within this machine

FIGURE 7.18 THE EFFECTS OF Y AXIS YAW ERROR BEFORE COMPENSATION

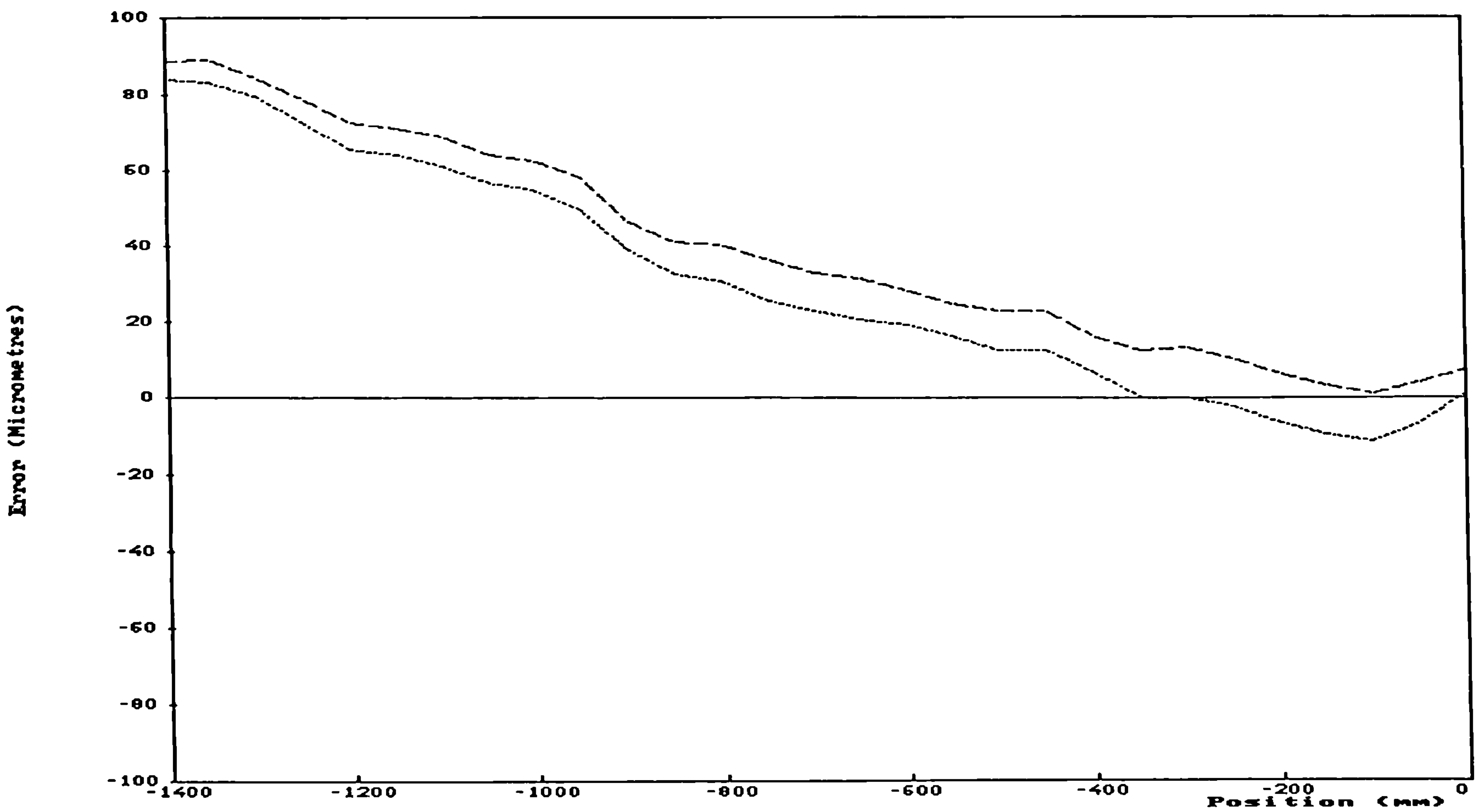
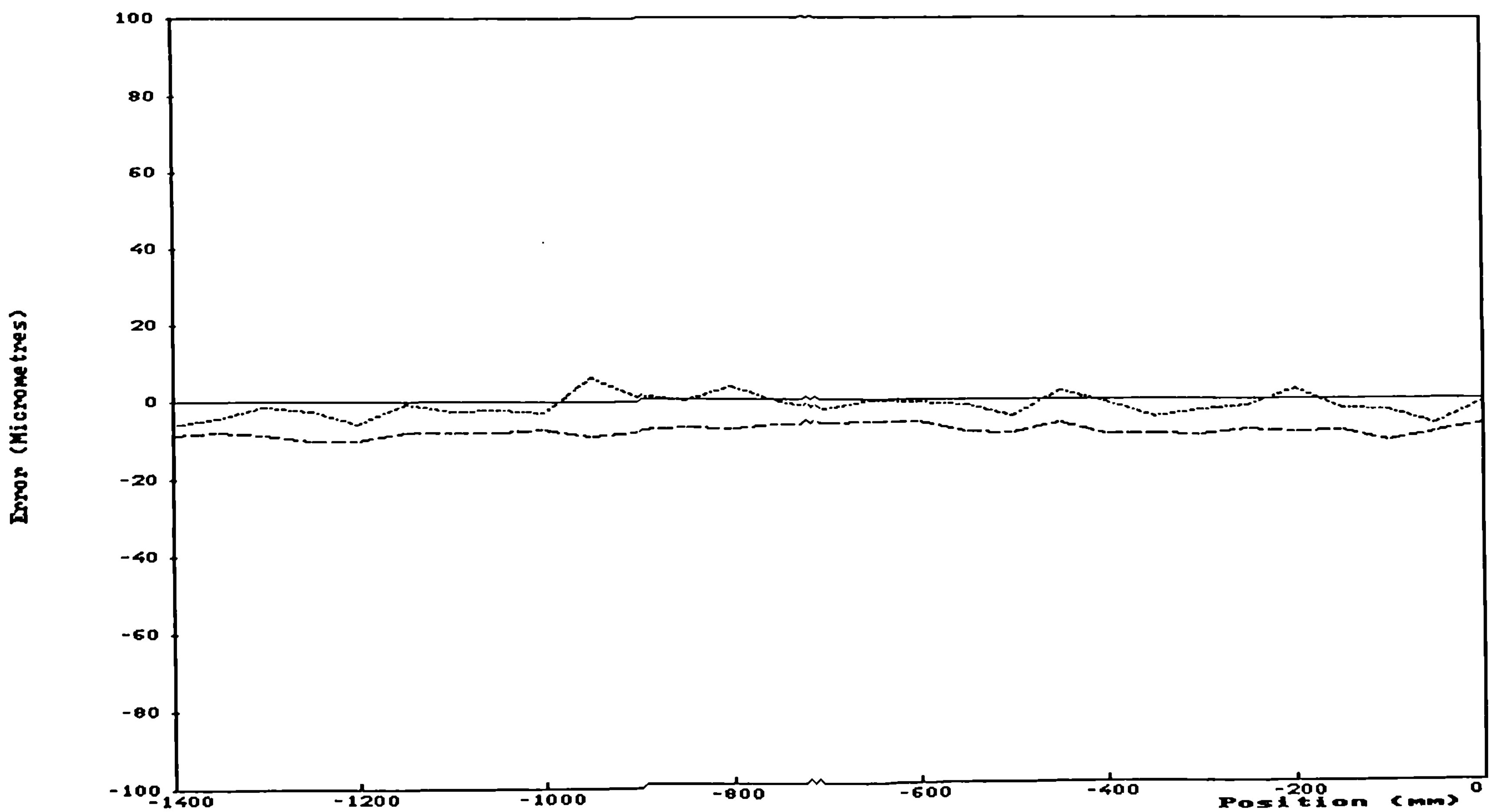


FIGURE 7.19 THE EFFECTS OF Y AXIS YAW ERROR AFTER COMPENSATION



tool were dramatically and effectively reduced or eliminated by the E.C.S. The results also indicate that for most error components the systematic constituent of the error was minimised leaving only a relatively small random error constituent. This highlights the success of the compensation system, as the systematic error is of course the only error constituent that can be effected by this precalibrated method of compensation. A measure of the volumetric accuracy of the machine tool before and after compensation is given in figures 7.20 and 7.21. In these figures the cube represents the working volume of the machine tool. The positional errors at strategic positions within the volume have been calculated from all the measured error components, for the uncompensated and compensated machine. These positional errors are plotted in microns on these diagrams. These diagrams show a large improvement in the accuracy of the compensated machine throughout its working volume. The worst case error with compensation is 36 microns compared to 135 microns without compensation.

7.3 Cutting Test Results

Two cutting tests were performed to evaluate the effectiveness of the E.C.S. during machining. In the first test a circular profile was machined in a block of steel. This cutting test is a standard test for this particular machine type, and provides a measure of the machines interpolation accuracy. The metal block was placed on the machine bed and a circle of diameter 250mm was cut in the XZ plane. Although the circle was not large it was of adequate size to indicate any improvements gained from the compensation, while being of a manageable size for accurate measurement. The results of this machining test are presented in figure 7.22. The polar plots show the error in roundness measured at 10 degree increments around the circumference of the circles. A definite improvement in roundness and accuracy can be seen in the results from the compensated circle, when compared with the uncompensated

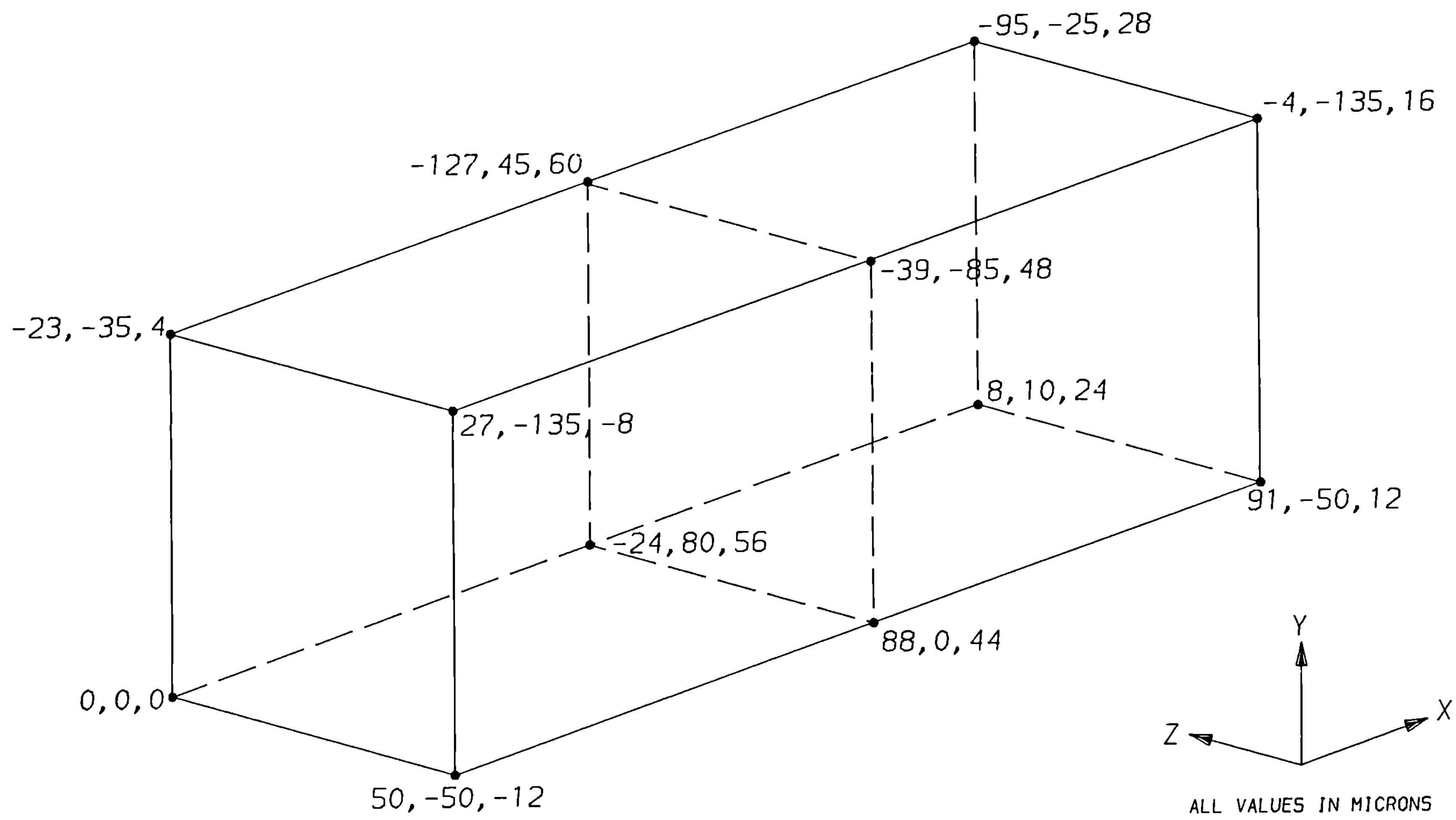


FIGURE 7.20 THE VOLUMETRIC POSITIONAL ACUURACY OF THE MACHINE TOOL BEFORE COMPENSATION

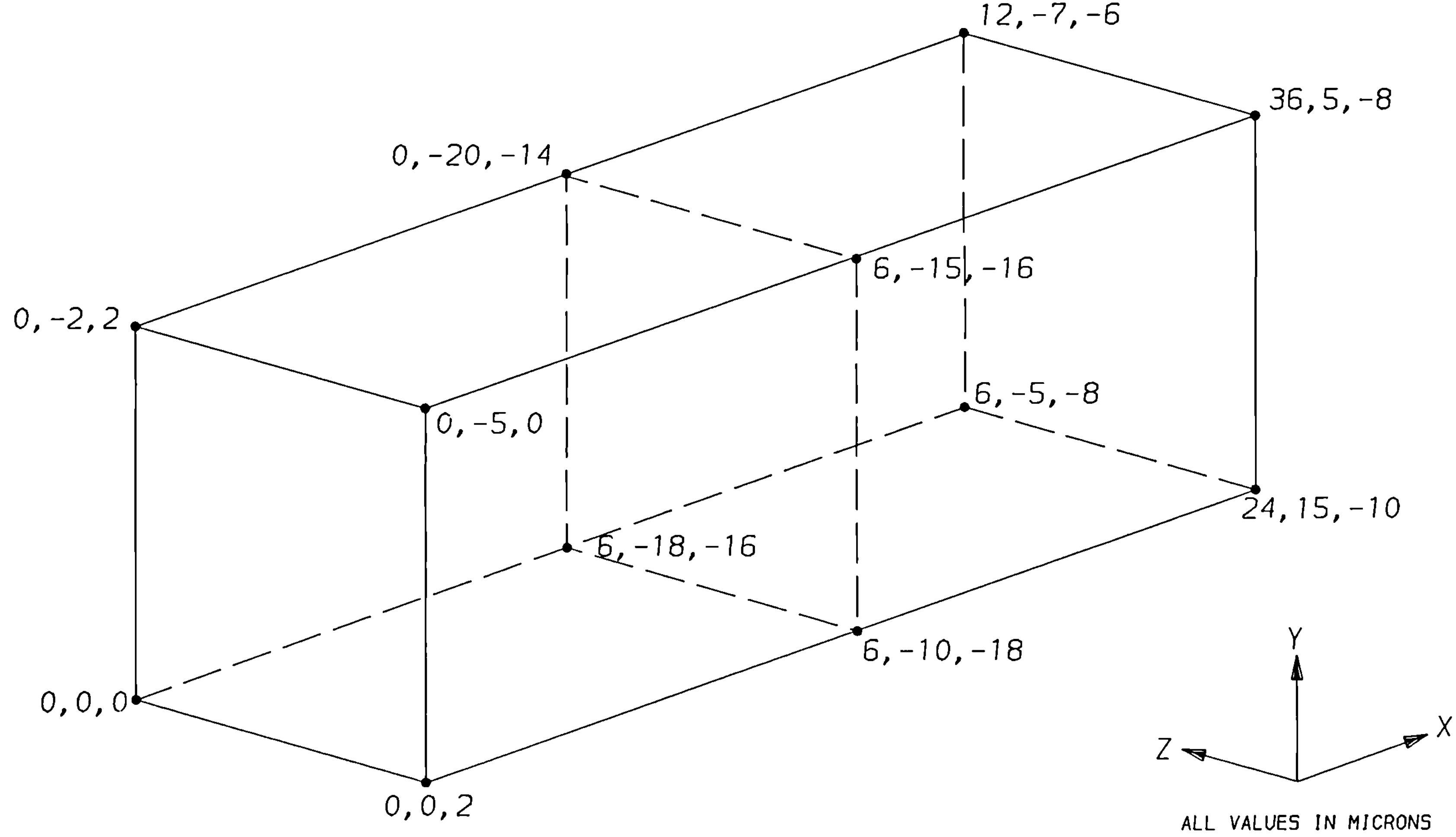
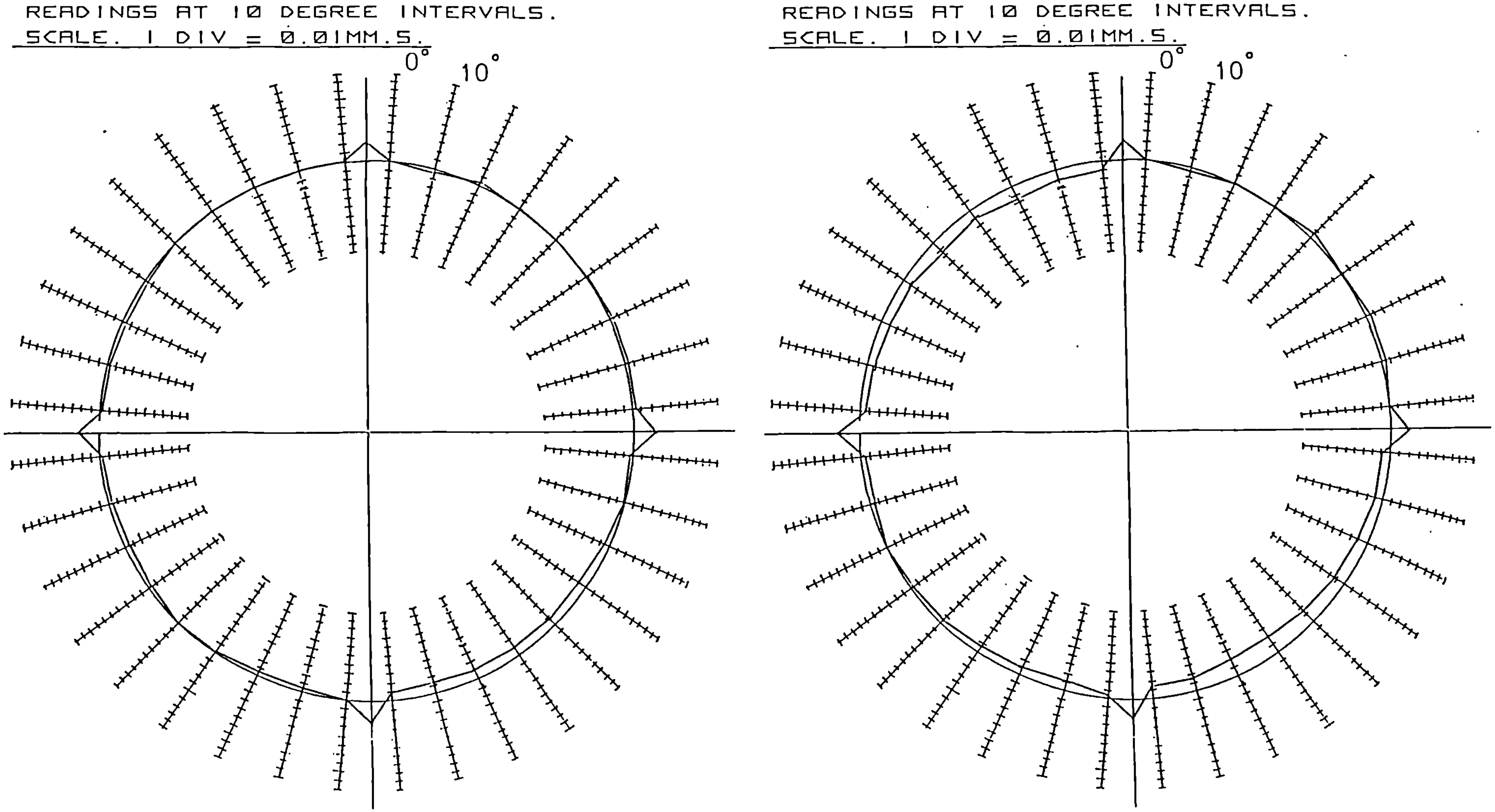


FIGURE 7.21 THE VOLUMETRIC POSITIONAL ACUURACY OF THE MACHINE TOOL AFTER COMPENSATION

FIGURE 7.22 THE RESULTS OF THE CIRCULAR CUTTING TESTS

WITH AND WITHOUT COMPENSATION



circle. The "pips" at the poles of the circles are produced as an axis changes direction. With such large machines the axis drives can not instantaneously reverse the mass of the axes. This problem manifests itself as an apparent reversal error, thus creating the "pips". This problem is a function of the axis drives and can not be overcome by compensation.

In the second cutting test a rectangular block of steel 1800mm long by 800mm wide was placed on the machine bed. The top surface of the block was then machined flat (in the XZ plane) using a 6 inch face cutter. A 0.25mm depth of cut was used in order to minimize cutting forces. Two cuts were taken, the first with the compensation inactive, and the second with the compensation active. This test was performed to measure any improvement in flatness brought about from compensation of the straightness error components. After cutting the block was measured for flatness using a Talyvel electronic level. The results of these measurements are shown in figure 7.23. The form of these two flatness diagrams is not greatly significant. This is because they are not to the same scale and a fair comparison can not be made between them. The form of the diagram will also be effected by factors such as surface finish. The important measurement from these diagrams is the maximum peak value, as it is this value which is used to indicate overall flatness. It can be seen from figure 7.23 that the maximum peak value for the compensated machine is 75.4 microns, which is just over half the maximum peak value of the uncompensated machine of 148.4 microns. Again this shows that a significant improvement in machining accuracy is gained from error compensation.

Both these cutting tests have confirmed the results obtained from measurements of the individual error components, that error compensation can greatly improve the positioning accuracy and so the machining accuracy of machine tools. All these tests have shown that precalibrated error compensation provides an effective, relatively cheap, and efficient solution to the machine tool accuracy problem.

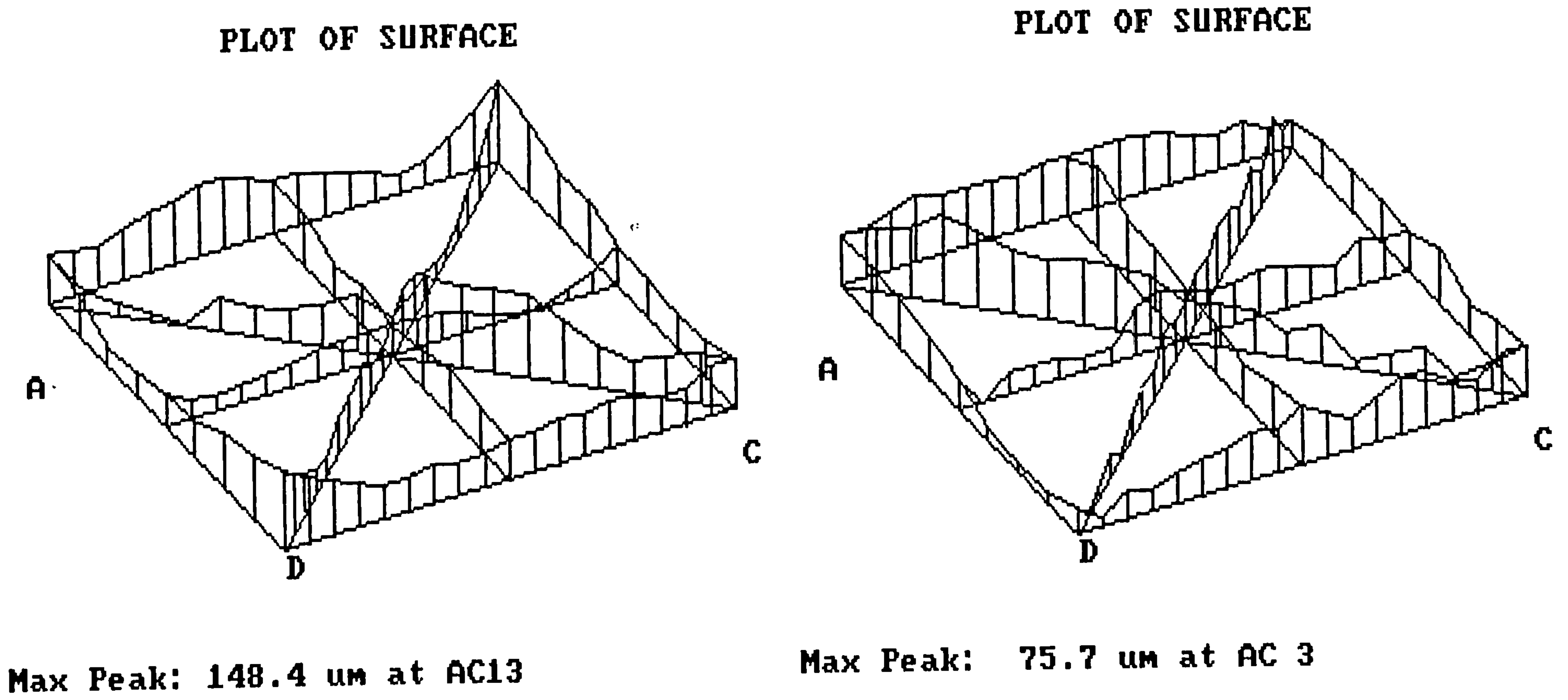


FIGURE 7.23 THE RESULTS OF THE FLATNESS CUTTING TESTS WITH AND WITHOUT COMPENSATION

These performance tests carried out on this large three axis machine tool have clearly and conclusively shown the ability of the E.C.S. to compensate positional errors produced by all geometric error components. A second and unique quality of the E.C.S. is its ability to be applied to machine tools of various configurations, and with various control systems. This important attribute means that the E.C.S. can be almost universally applied. The E.C.S. has been successfully applied to a number of different machine tools, and a summary of the results from these integrations is given in appendix C, with a more detailed discussion of some of these integrations being given in various references (43-49).

8 CONCLUSIONS

1. The work has undertaken a survey of machine tool error reduction techniques, in particular error compensation. It has identified the limitations of the current error compensation systems as applied to machine tools.

2. On the basis of the limitations perceived above, a strategy for error compensation with universal applicability to a wide range of machine tool types and configurations was developed.

3. Based on the above, algorithms have been developed that permit error compensation for the geometric error components of all machine tool configurations with up to three axes.

4. For universal implementation of the error compensation algorithm a flexible, modular, microprocessor based error compensation system was developed. The novel aspects of this system have resulted in patents being granted.

5. A strategy for identification of the machine tool geometric error components to be used for error compensation has been developed.

6. The error compensation system has been integrated to a large three axis moving column milling machine. This integration demonstrated the significant reduction in systematic machine position errors that can be achieved using the error compensation system.

7. The system has been developed into a commercial product, and is currently marketed by Butler Newall Limited. The system has been successfully applied to a number of machine tools of varying types and configurations.

8. The universal applicability of the error compensation system provides a facility for error compensation in retrofit and recondition work as well as giving potential

for reducing build costs on new machines.

9 SUGGESTIONS FOR FURTHER WORK

The flexibility and modular construction of the E.C.S. unit provides scope and potential for further exploring and exploiting error compensation, in order to enhance the accuracy of not only machine tools, but many servo controlled positional system. The main areas of consideration for this further work are listed below.

1. Compensation for thermally induced errors. Thermal effects are widely recognized as being a major cause of errors in machine tools. The E.C.S. can be developed in order to compensate for thermally induced errors. This will require the design and development of new system modules for on line measurement of the relevant variables (temperature etc.). Development of identification techniques in order to quantify the thermal behavior of machines will be required, together with enhancement of the compensation algorithm to accommodate thermal compensation. Work should be concentrated on compensating for self induced thermal errors. These errors, unlike the environmentally induced errors, are largely outside the control of the machine tool user, and are therefore of primary concern. Self induced thermal errors are potentially easier to quantify and compensate for as the cause and effect of these errors can be readily identified. Compensation for these errors then provides a cost effective and commercially viable solution. Analysis of a machine tools behavior with respect to environmental changes can be extremely complex, time consuming and expensive.

2. Investigation of spindle errors. Spindles are an area of particular concern when considering machine tool accuracy. High speed geared spindles can be a major source of heat generation in the machine tool, producing significant errors. As such spindles are an area for particular consideration when studying machine tool accuracy enhancement. Development of measurement systems is required designed specifically for investigating the dynamic

behavior of spindles. Development for algorithms for correction of spindle errors is also required. This work complements the work on thermal compensation.

3. Load induced errors. Load effects can significantly effect the accuracy of a machine tool. Cutting forces and their effects can be minimised by the correct choice of feeds and speeds. The effects of the movements of large masses during the machining operation are more difficult to influence. Research into the identification of, and correction for, load induced errors is required.

4. Development of geometric error compensation. Machine tools are becoming more complex, with machines of five or more axes being commonplace. Enhancement of the geometric model is required to cater for these more complex machine configurations. Tool length will also effect machine tool accuracy as a function of its geometric components. Work is required to compensate for geometric errors produced by varying tool length and orientation, particularly for machines with "positioning heads" and tool changers.

5. Improvement to error identification techniques. With large machines the most time consuming aspect of the error compensation process is the error identification phase. Improvements in the efficiency of the error identification process will make error compensation more cost effective and much more attractive to the machine tool user.

6. Active error compensation. Although this research work has concentrated on the precalibrated compensation technique active error compensation can provide an effective and attractive means of error correction. The availability of relatively cheap, small, and accurate measurement transducers provides an increasing potential for active compensation. With the development of suitable transducer interface modules the E.C.S. provides a vehicle for combining to greatest effect both precalibrated and active compensation techniques.

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APPENDIX A

SPECIFICATION OF THE MATHEMATICAL MODEL PARAMETERS USED IN THE SIMULATION OF THE SINGLE AXIS TEST SYSTEM

A.1 Specification Of The Model Parameters

A.1.1 Parameter Values Obtained From The Manufacturers Specification

DAC voltage limits.	-	- 0 to 10v
Demand voltage pre-amplifier scaling.	- K	- 1/3
PI regulator proportional gain.	- Ka	- 30.06
PI regulator integral action time.	- Ti	- 0.0204 sec
Current regulator time constant.	- Tc	- 0.0003 sec
Motor torque constant.	- Kt	- 0.5 Nm/A
Motor moment of inertia.	- Jm	- 0.00023 kgm^2

A.1.2 Parameter Values Measured from The System

DAC gain. - Kd - 0.0099734 v/p

With the slide travelling at constant velocity the axis following error (position control loop position error) was noted from the CNC controller, and the DAC output voltage was measured. The DAC gain was then calculated as the ratio of the DAC output voltage to the system following error.

$$Kd = \frac{\text{DAC output voltage}}{\text{Following error}} \quad \text{v/pulse}$$

Tachogenerator gain. - Kw - 0.632298 v/rad/sec

With the slide travelling at constant speed the tachogenerator feedback voltage was measured at the input to the axis drive amplifier. The tachogenerator gain was then calculated as the ratio of the velocity feedback voltage to the motor speed.

$$K_w = \frac{\text{Tacho feedback voltage}}{\text{Motor speed}} \quad \text{v/rad/sec}$$

Load friction torque. - Tl - 0.02538878 Nm

The friction force exhibited by the slideway could not be calculated easily, as it was dependent not only on the coefficient of friction between the contact surfaces but also on the influence of the slides gib strips. As a result the slide friction was measured directly using a spring balance calibrated in Newtons. With the slide disconnected from the ballscrew it was pulled along at constant speed using the spring balance. The Motor load torque could then be calculated using the following formula:-

$$T_l = \frac{\text{Measured friction force . Ballscrew pitch}}{\text{Efficiency factor . 6.2832}} \quad \text{Nm}$$

The efficiency factor was used to represent the efficiency of the ballscrew and ballbearing in reflecting the load force through the motor.

A.1.2 Derived Parameter Values

Incremental encoder gain. - Ke - 636.62 pulses/rad

This value was calculated from:-

$$K_e = \frac{\text{Encoder pulse count per rev}}{6.2832} \quad \text{pulses/rad}$$

Ballscrew constant. - Ks - 1.2773 mm/rad

This value was calculated from:-

$$K_s = \frac{\text{Ballscrew pitch}}{6.2832} \quad \text{mm/rad}$$

Load inertia. - Jl - 0.000517711 kgm^2

The mass of the system load was calculated from its volume (calculated from its dimensions), and its density. The moment of inertia of this sliding mass was then calculated from:-

$$\text{MOI sliding mass} = \frac{\text{Sliding mass . Ballscrew pitch}^2}{\text{Ballscrew efficiency . 39.4784}} \; kgm^2$$

The moment of inertia of the rotating mass as seen at the motor was calculated from:-

$$\text{MOI rotating mass} = \frac{\text{Rotating mass.Radius of gyration}^2}{2} \; kgm^2$$

The total load moment of inertia, Jl, was then calculated as the summation of the translatory and rotary inertias.

A.2 Numerical Analysis Methods

A trapezoidal technique was used to perform the numerical integrations required in the simulation. In this integration technique the function is assumed to vary linearly between discrete time intervals. This is a valid assumption provided that the time interval is sufficiently small such that there are no significant transients during the time interval. As an example, consider a function f(t) that varies from a value f(k-1) to a value f(k) in a time interval T. If q(t) is the integral of the function f(t), then in discrete form using the trapezoidal approximation:-

$$q(k) = q(k-1) + T/2(f(k)+f(k-1))$$

A Euler method was used to simulating the first order lag function of the current regulator, in discrete form. Consider a first order lag function of the form:-

$$B(s) = A(s)/(1+STc)$$

which can be expanded to produce:-

$$d\,B(t) = (A(t) - B(t))\,.dt/Tc$$

which in discrete form becomes:-

$$\hat{}B(n) = (A(n) - B(n)).T/Tc$$

where T is the time interval between samples.

Using this equation a first approximation of B(n+1) can be calculated:-

$$B(n+1) = B(n) + (A(n) - B(n)).T/Tc$$

This first approximation of B(n+1) can be used with the discretized fist order lag function to calculate ^B(n+1):-

$$\hat{}B(n+1) = (A(n+1) - B(n+1)).T/Tc$$

Which in turn can be used to calculate an improved second approximation of B(n+1):-

$$B(n+1) = B(n) + (\hat{}B(n) + \hat{}B(n+1))/2$$

Again the accuracy of this method is dependent on the choice of the time interval T. A time interval of 0.1ms was used for the simulation of the single axis test system, and was found to give good results.

APPENDIX B

AN EXAMPLE OF A PART PROGRAM USED FOR THE SEMI-AUTOMATIC CALIBRATION OF A CNC MACHINE TOOL

This part program is similar to the one described in section 6, used to calibrate the moving column machine tool. This particular program was used for the measurement of X axis linear positioning error. Readings are taken at 50mm increments from the position X = 0mm to X = -4150mm. Readings are taken six times at each point. Three times approaching the point from the positive direction and three times approaching the point from the negative direction. At the extreme ends of travel the backlash is removed before a measurement run is commenced. Before each reading is taken a two second dwell is used to allow the axis position to settle. The M codes M08 and M09 are used to trigger a reading. M08 effectively closes a switch to take a reading and M09 resets the switch. A dwell of one second between the M08 and M09 commands ensure a correct reading is taken.

```
$REP 3              ;REPEAT LOOP1 3 TIMES
> G90G00X5.0        ;REMOVE BACKLASH BEFORE FIRST READING
> G90X0F2000
> G04H2             ;DELAY FOR AXIS POSITION TO SETTLE
> M08               ;TRIGGER MEASUREMENT SYSTEM TO TAKE READING
> G04H1
> M09
$REP 83             ;REPEAT LOOP2 83 TIMES
> X-50.0G91         ;MOVE INCREMENTALLY 50mm
> G04H2             ;DELAY FOR AXIS POSITION TO SETTLE
> M08               ;TRIGGER MEASUREMENT SYSTEM TO TAKE READING
> G04H1
> M09
$END                ;END LOOP2
> X-4155.0G90       ;REMOVE BACKLASH BEFORE READING
> X-4150.0G90
> G04H2             ;DELAY FOR AXIS POSITION TO SETTLE
> M08               ;TRIGGER MEASUREMENT SYSTEM TO TAKE READING
> G04H1
> M09
```

```
$REP 83              ;REPEAT LOOP3 83 TIMES
> X50.0G91
> G04H2              ;DELAY FOR AXIS POSITION TO SETTLE
> M08                ;TRIGGER MEASUREMENT SYSTEM TO TAKE READING
> G04H1
> M09
$END                 ;END LOOP3
$END                 ;END LOOP1
```

APPENDIX C

A SUMMARY OF E.C.S. INTEGRATIONS

The E.C.S. has been integrated to a number of machine tools of varying type and configuration. The following tables give a summary of these integrations, showing the improvement in accuracy achieved with the compensation. These results not only demonstrate the effectiveness of the E.C.S., but also highlight its universal applicability. All translatory errors are quoted in microns and all squareness errors are quoted in arc seconds.

1. Swedturn slant bed lathe with Swedturn CNC controller. Linear compensation only was implemented on this machine.

AXIS	LINEAR POSITIONING ACCURACY		MEAN BACKLASH	
	BEFORE COMP.	AFTER COMP.	BEFORE COMP.	AFTER COMP.
X	37	3	27	4
Z	58	3	5	4

2. Colchester Hydro lathe with Fanuc 5 controller. Linear and straightness compensation was implemented on this machine.

AXIS	LINEAR POSITIONING ACCURACY		MEAN BACKLASH	
	BEFORE COMP.	AFTER COMP.	BEFORE COMP.	AFTER COMP.
X	55	10	11	1
Z	60	26	14	1

PLANE	STRAIGHTNESS ERROR BEFORE COMP.	AFTER COMP.
Z(X)	6	4
X(Z)	10	8

3. Tsugami machining centre with Fanuc 6MB controller. Linear compensation only was implemented on this machine.

AXIS	LINEAR POSITIONING ACCURACY		MEAN BACKLASH	
	BEFORE COMP.	AFTER COMP.	BEFORE COMP.	AFTER COMP.
X	30	9	24	7
Y	27	4	12	3
Z	16	8	11	4

4. Beaver VC35 machining centre with Fanuc 6MB controller. Linear compensation and squareness compensation was implemented on the two axis table of this machine.

AXIS	LINEAR POSITIONING ACCURACY		MEAN BACKLASH	
	BEFORE COMP.	AFTER COMP.	BEFORE COMP.	AFTER COMP.
X	39	7	9	1
Y	76	14	33	8

PLANE	SQUARENESS ERROR BEFORE COMP.	AFTER COMP.
X,Y	28	5

5. KTM Modular milling machine with Allen Bradly 8600 controller. Linear compensation and squareness compensation between all the axes was implemented on this machine.

AXIS	LINEAR POSITIONING ACCURACY BEFORE COMP.	AFTER COMP.	MEAN BACKLASH BEFORE COMP.	AFTER COMP.
X	67	22	5	2
Y	94	19	60	10
Z	114	24	40	10

PLANE	SQUARENESS ERROR BEFORE COMP.	AFTER COMP.
X,Y	35	11
X,Z	-49	-4
Y,Z	0.7	0.7

6. Marwin Maxetrace with Kongsberg controller. Linear compensation only was implemented on this machine.

AXIS	LINEAR POSITIONING ACCURACY BEFORE COMP.	AFTER COMP.	MEAN BACKLASH BEFORE COMP.	AFTER COMP.
X	700	170	-	-
Y	220	56	-	-
Z	70	16	40	10

7. Wadkin V8-15 machining centre with GE 2000 controller. Linear compensation was implemented on all axes of this machine and straightness compensation on the X and Y axes only (the machine table).

AXIS	LINEAR POSITIONING ACCURACY BEFORE COMP.	AFTER COMP.	MEAN BACKLASH BEFORE COMP.	AFTER COMP.
X	24	10	18	4
Y	32	6	10	2
Z	80	8	60	6

PLANE	STRAIGHTNESS ERROR BEFORE COMP.	AFTER COMP.
Y(X)	18	8
X(Y)	16	9