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MAGNETIC BEARING SPINDLES
FOR ENHANCING TOOL PATH ACCURACY

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ABSTRACT

Thin rib machining of electronic components or airframe structures can benefit from high speed machining for burr free cutting, improved surface quality and increased metal removal rate. It is suggested that the use of a magnetic bearing spindle can not only successfully provide the benefits of high speed machining but, more importantly, minimize tool path errors. In this paper the various sources of tool path error are discussed as functions of machine tool positioning errors and cutting force errors which are characterized as static, dynamic and stochastic. The operation of high speed magnetic bearing spindles is described and a control scheme whereby the spindle may be translated and tilted for minimizing tool path errors is discussed. This overall research activity is a cooperative effort between the University of Maryland, Cincinnati Milacron, Magnetic Bearings, Inc., The Westinghouse Corporation, and The National Bureau of Standards.

INTRODUCTION

One area of machining which can benefit from improvements in accuracy and higher spindle speeds is the production of thin rib electronic components or airframe structures. Shown in Figure 1 is a typical aluminum microwave guide which is used in mobile radar applications. The path shape is composed of repeating

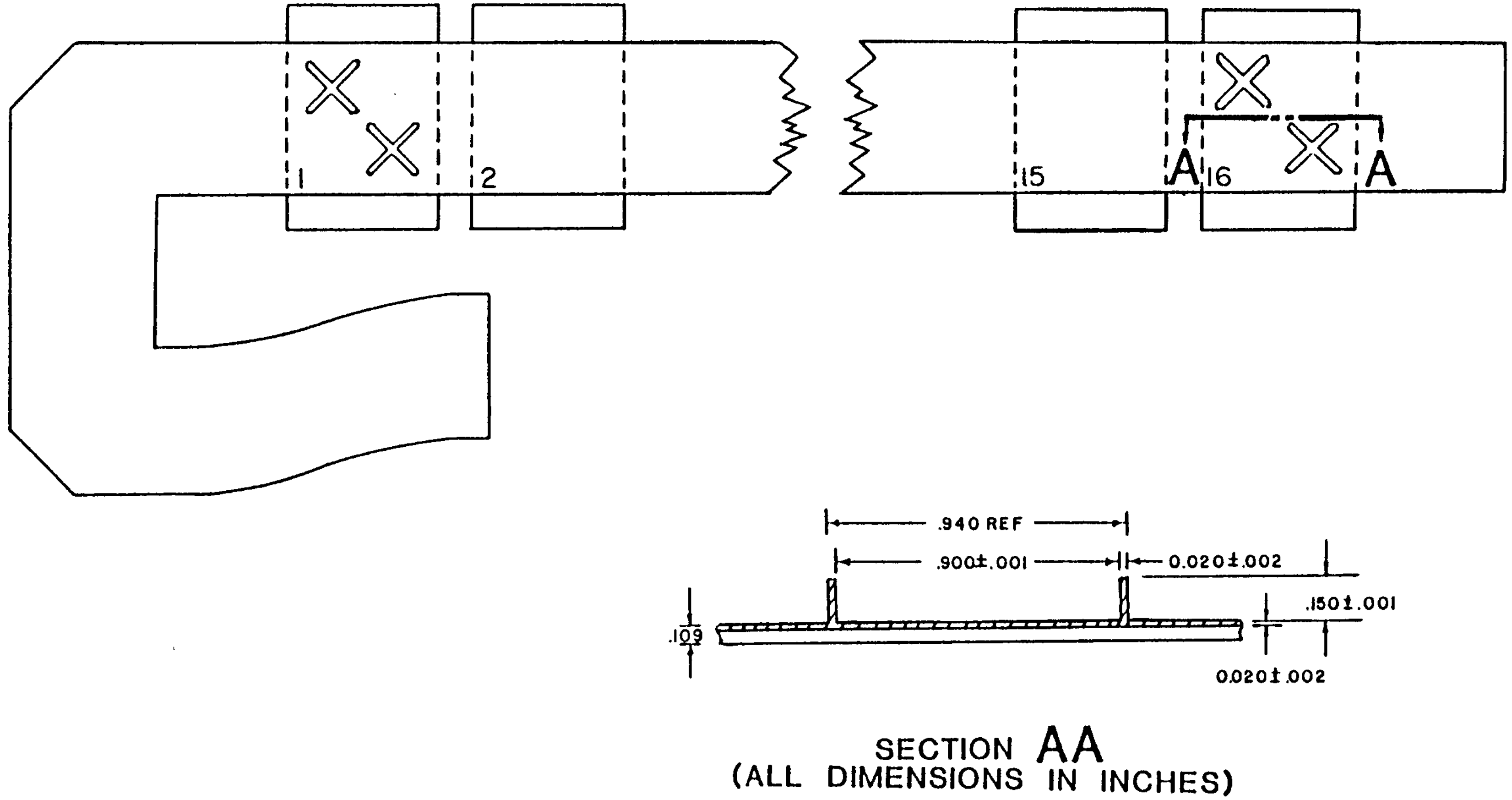


FIG. 1 MICROWAVE GUIDE (Courtesy of Westinghouse Corp.)

sections of extremely thin ribs with "X" shaped openings which go completely through the part base. The economical production of thin ribs has proven troublesome because of the difficulty of controlling part tolerances and surface finish while maintaining high metal removal rates (MRR). A particularly troublesome area has been caused by burrs on the "X" shaped openings. These burrs require the finished piece to undergo a secondary deburring operation resulting in increased production time and costs. Studies have shown that the cost for cleaning and deburring can be quite high and is often unaccounted for in process planning for part production [2].

To improve production efficiency of thin rib components, and to eliminate the secondary deburring operation, it is desirable to increase spindle speeds and table feeds (i.e., to move toward high speed machining) while maintaining part tolerances and surface finish within acceptable limits. In discussions with Westinghouse, Cincinnati Milacron, Magnetic Bearings Incorporated, and the National Bureau of Standards we have concluded that a magnetic bearing spindle can be retrofitted to existing machine tools and, with modification in feed rate, provide a solution to the accuracy, deburring and MRR problems in thin rib machining. Experience by Westinghouse has shown that the deburring operation can be eliminated if the part is machined at higher surface speeds (i.e., higher spindle speeds) provided that part accuracy is maintained. To achieve this goal control of the tool path error via a magnetic bearing spindle is required.

During high speed machining the forces at the interface of the cutting tool and workpiece can cause the tool to chatter. When chatter occurs the effect can not only degrade surface finish and part tolerance but can also damage the tool. Generally, tool chatter is avoided by controlling both the feed rate and spindle speeds of the tool and does not appear to be a limiting factor in improving the metal removal rates in thin rib machining.

In the absence of chatter, dimensional accuracy and the surface finish of the machined part control metal removal rate and, thus, production efficiency. Both effects can be considered as the result of tool path errors. The tool path error in computer numerical control machine tools is defined as the distance-difference between the required and actual tool path. The magnitude of tool path error is both deterministic and stochastic in nature since it depends on both repeatable static and dynamic errors and randomly varying dynamic parameters. This paper addresses the specific problem of identifying and controlling tool path error as it effects dimensional accuracy and surface finish in thin rib machining. Specifically, interest is centered around high speed end milling operations with particular interest on the use of a magnetically suspended spindle for controlling the tool path error.

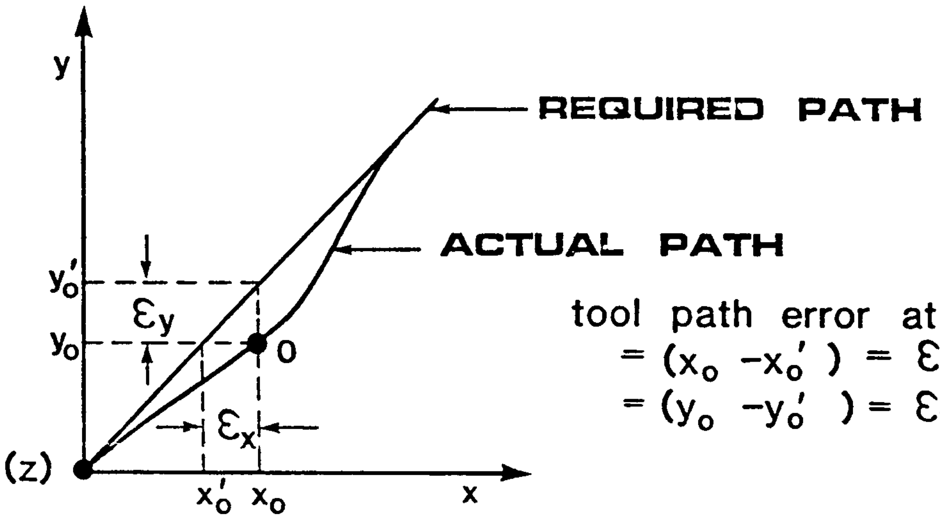
TOOL PATH ERRORS

Tool path error in two-dimensional cutting can be represented as shown in Figure 2. In the more general case of 3-dimensional cutting (i.e., end milling), the tool path error includes the deviation in the z-direction in addition to that shown in Figure 2.

Tool path error (in the absence of chatter) can be classified into the following four categories, based on the source or the error for each category;

- deterministic position errors
- deformation due to heat sources
- deformation due to weight forces
- deformation due to cutting forces.

These four error sources can cause three types of tool path errors, viz: static deterministic, dynamic deterministic and stochastic. Shown in Figure 3 is a listing of the errors which are applicable to end milling, in general, and the machining of

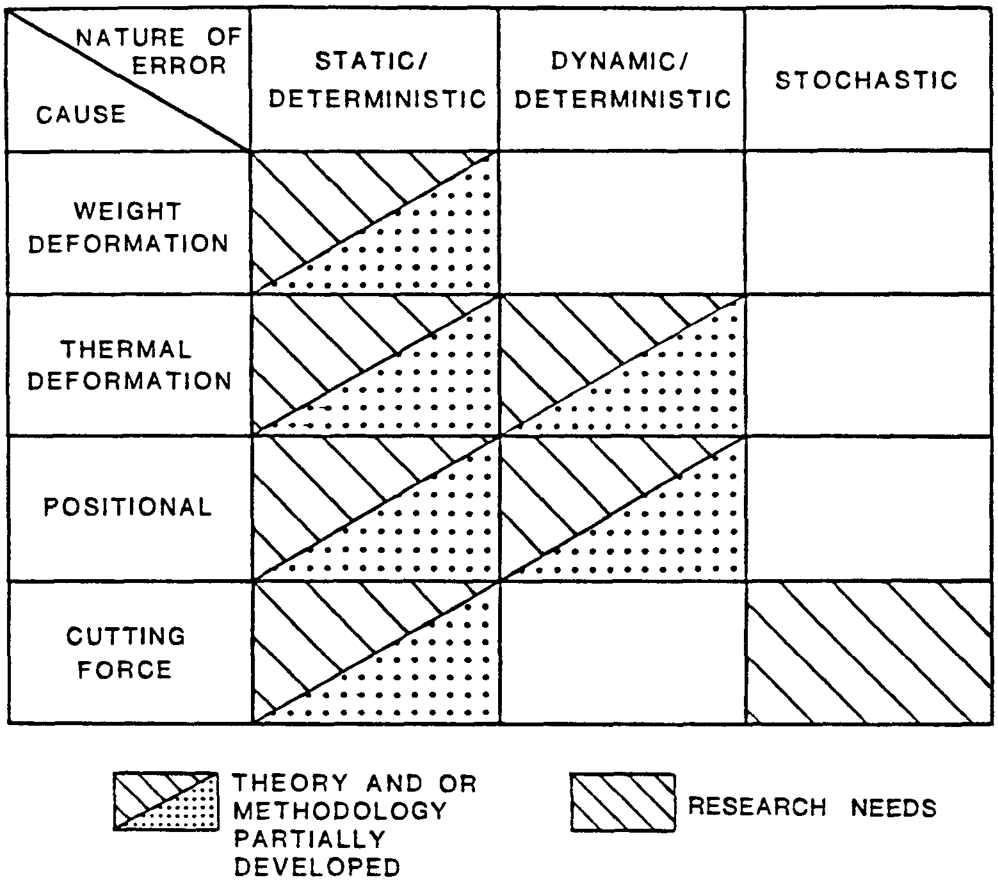


tool path error at 0

$= (x_o - x_o') = \varepsilon_x$ in x-coord.

$= (y_o - y_o') = \varepsilon_y$ in y-coord.

FIG. 2 TOOL PATH ERROR



thin rib structures in particular. Deterministic position errors (both static and dynamic) are defined as those repeatable errors which will reoccur when an identical set of input parameters exist on a given machine tool structure. Stochastic errors, on the other hand, are defined as those errors which occur when a random input is presented to the machine tool. The main source of stochastic error will occur in the cutting process itself. All the errors are further discussed below.

Deterministic Position Errors

Static deterministic position errors are reproducible machine dependent positioning errors which show up as the difference between the absolute position that the machine is commanded to go to (e.g. 4.0000 inches) and where it actually arrives at (e.g. 4.0002 inches), in the absence of cutting chips.

Dynamic deterministic position errors are reproducible machine dependent errors which show up as the difference in path between where a machine is commanded to go (ie., make a 90 degree turn) and where it actually transverses.

These errors will depend on table feed rate but not on time. One technique for the measurement of deterministic position errors involve using a high precision laser measurement system (such as the Hewlett-Packard laser metrology system) and calibrating the individual machine tool. In using this technique the machine tool table is treated as a rigid body with 6 degrees of freedom. The errors of the rigid body (in translation and rotation) as the table moves along the three coordinate directions is then experimentally determined. As an example of applying this technique Hocken and Nanzetta of the National Bureau of Standards reports on its successful implementation on a precision coordinate measuring system [3], and later on a machining center [7,11]. Once the error measurements for a given machine tool are obtained they must be used to correct the machine tool movement. Based upon discussions with Cincinnati Milacron and other machine tool manufacturers no machine tool manufacturer at present incorporates provisions for position error correction to be included in their controller.

Deformation Due To Heat Sources

Heat source errors are reproducible thermal deformation errors due to heat sources which are both internal and external to the machine tool. These errors show up as position differences in spindle/table position as a function of temperature and time. In typical applications the machine tool structure is thoroughly warmed up and the spindle itself is the major source of this error. Heat source errors can be quantified by assessing the possible constant and variable heat sources of a machine tool and experimentally determining the effect of their thermal cycles on spindle/table position. Again, the laser metrology system can provide the experimental tool whereby this error can be measured and mapped. At present no manufacturer incorporates provisions for correction of this error in either their controller or programming software.

Deformation Due To Weight Forces

Deformation due to weight forces are caused by changes in the weight of stationary objects (e.g., workpieces) which are firmly positioned on the machine tool table. These errors show up as reproducible static position differences in spindle/table position and occur in addition to deterministic position errors. These errors may be measured using a laser metrology system and then put in the form of an error map. Again no manufacturer incorporates provisions for correction of this error in either their controller or programming software.

Deformation Due To Cutting Forces

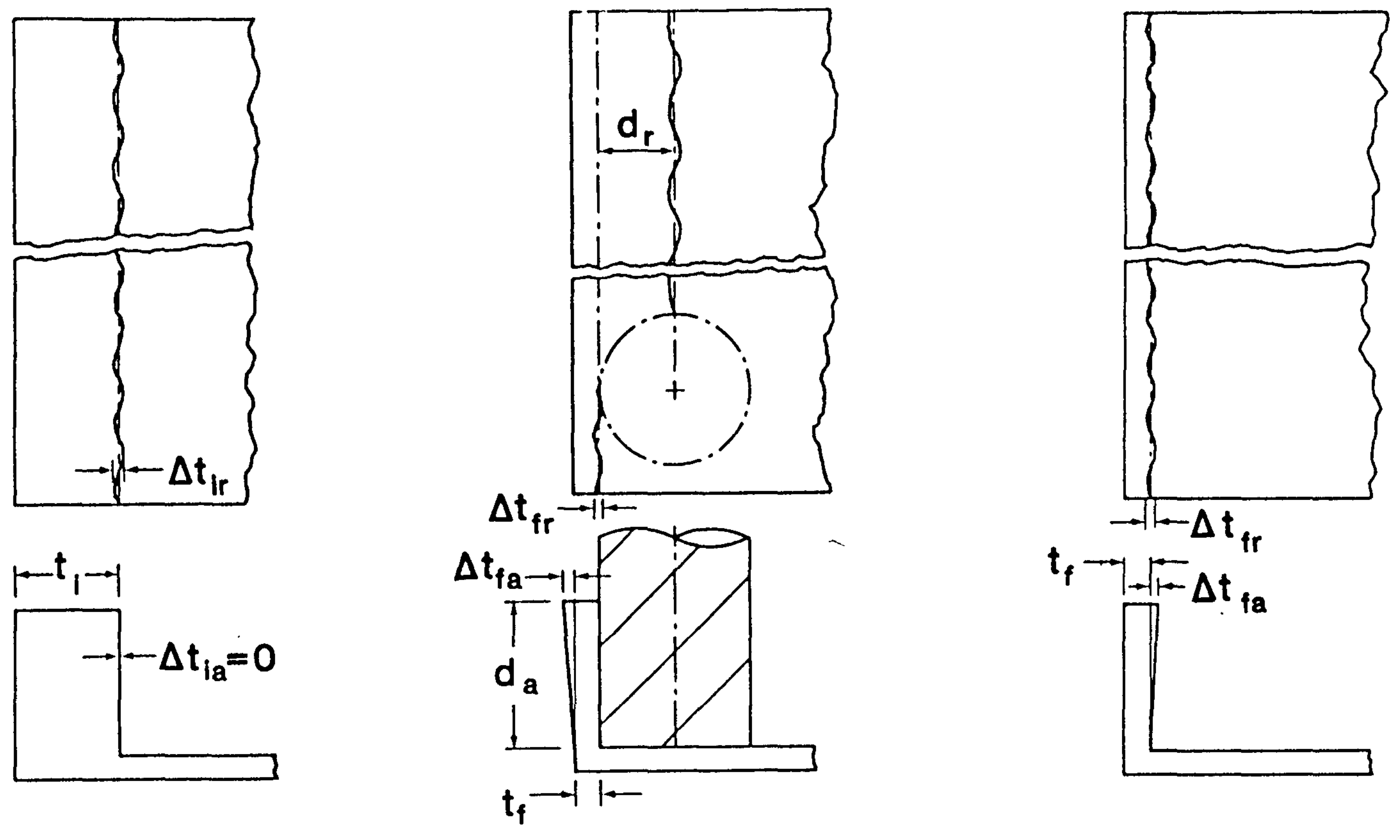
The deformations due to cutting forces are both static deterministic and stochastic in nature [1,12,13]. These errors are best understood by considering typical thin rib machining with a straight teeth cutter as shown in Figure 4. After the cut has been completed the thickness of the rib should be a theoretically perfect t_f. However, because of steady state and stochastic cutting forces the final rib shape is ramped in the vertical direction (characterized by the error Δt_{fa}) and has dimensional variations (characterized by the error Δt_{fr}) in the longitudinal direction. The ramp variations, Δt_{fa}, are deterministic and are due to the cantilever deflection of the thin rib (i.e., compliance between the tool and workpiece). The remaining workpiece deflection error is along its longitudinal length and is identified as Δt_{fr}. This error, caused by stochastic fluctuations in the cutting force, cannot be characterized by conventional means and must be treated by stochastic methods. The cutting force errors can therefore be considered as:

a. Deterministic tool path errors due to compliance between the tool and workpiece.

b. Stochastic tool path errors due to variations in the depth of cut.

The errors due to cutting forces show up as position differences between the required and actual tool/workpiece position and result in workpiece shapes which are not perfect. The departure from perfect shape is considered acceptable if workpiece tolerances and surface finish are within user defined limits.

The tool path error due to the static deterministic deformation caused by varying compliance between tool and workpiece is in general a combination of the compliance of tool and workpiece structures. However, in end-milling operations, of thin ribbed parts (e.g., microwave components), the variation in compliance is principally that due to the workpiece. The



(a) BEFORE FINISH CUT (b) DURING FINISH CUT (c) AFTER FINISH CUT

FIG. 4 THIN RIB MACHINING

variation in compliance between tool-workpiece in this situation is therefore due to the variation in workpiece geometry, which is deterministic. No method of correcting these errors is currently available but, through the use of a magnetic bearing spindle, it will be possible to tilt the spindle to compensate for these errors. This method of error minimization is currently under study and will be reported at a later date.

The deformation due to variations in depth of cut is caused by stochastic cutting force variation. These variations are a combination of cutting an imperfect blank shape, and the influence of machine dynamics on the cutting process. Depth of cut errors can be understood by considering the case of end milling as shown in Figure 5.

The imperfect blank shape consists of a nominal depth of cut which has superposed on it random variations in thickness (x_0). The nominal depth of cut gives rise to steady state cutting forces which act on the tool/workpiece structure to cause deformations. These deformations can be considered static deterministic and may be predicted by applying chip cutting mechanics [1]. The random variations in rough machined blank thickness give rise to stochastic variations in cutting forces which, in turn, give rise to stochastic variations in part shape or, alternatively, cause stochastic tool path error.

The tool path errors due to variations in depth of cut are termed "copying errors" and occur as follows. The random blank error (x_0) is 'copied' on to the machined surface (as x_1) to a reduced scale. The 'rate of copying' of form error can be written as $i = x_1/x_0$, where i varies from 0 to 1. The resultant cutting force F at the instant of generating a finished surface with a straight tooth cutter can be written as,

$$F = r_a x_a \tag{1}$$

where r_a = proportionality constant called cutting stiffness and

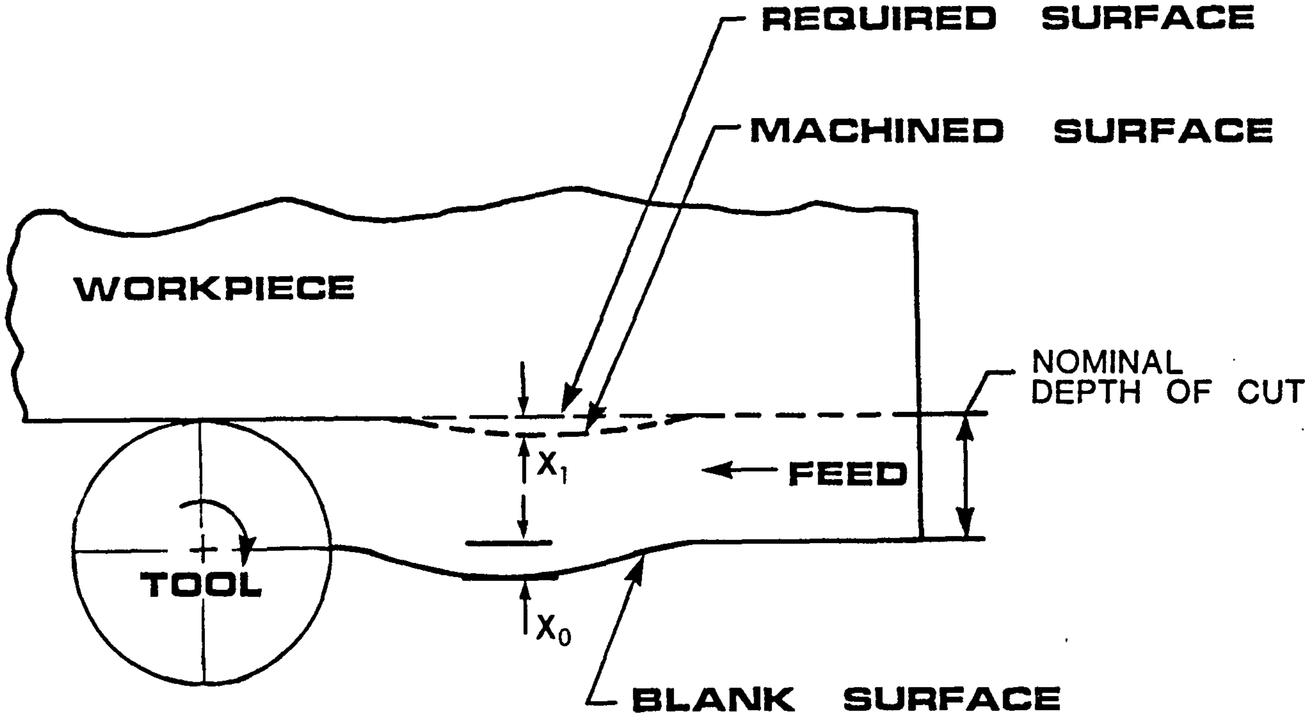


FIG. 5 VARIATION OF DEPTH OF CUT IN END MILLING

x_a = depth of cut in the direction normal to finished surface.

The cutting force F acting in any plane will produce a deflection of the tool-workpiece system. Let x be the component of the deflection normal to the finished surface which affects the dimension.

The cutting force in terms of the deflection is,

$$F = k_a x \tag{2}$$

where k_a = stiffness between tool and workpiece called machine stiffness.

From equations (1) and (2);

$$x = \mu x_a \tag{3}$$

where, $\mu = ra/ka$.

The deflection x at any instant can also be written as

$$x = s - x_a \tag{4}$$

where s = required depth of cut and

x_a = actual depth of cut.

Substituting equation (3) in equation (4),

$$x = s\,[\mu/(1+\mu)] \tag{5}$$

For an incremental case, equation (5) becomes

$$\Delta x = \Delta s\,[\mu/(1+\mu)] \tag{6}$$

where Δs = incremental required depth of cut and

Δx = incremental deflection normal to finished surface.

From Figure 4, $\Delta s = x_0$ and $\Delta x\ x_1$. Thus

$$x1/xo = i = \mu/(1+\mu)$$

In most machining operations $\mu << 1$ so that $i \cong \mu$, and the copying error does not propagate between passes.

End milling does not follow the normal behavior and a typical value of μ for end milling is about 2.67 for cutting steel [12], which gives a value of $i = 0.73$. Therefore for every consecutive pass, the error only reduces by a factor of about 1.4. The cutter teeth are helical in practice and therefore make the relationships more complicated [12,13].

No method of correcting the stochastic errors is currently available but, through the use of a magnetic bearing spindle, it will be possible to translate the cutting tool to minimize these errors. The techniques for this approach to error minimization are currently under study and will be reported at a later time.

MAGNETICALLY CONTROLLED SPINDLES

The magnetic spindles for use on machine tools are fairly experimental at this time. The only spindles currently available for use on machine tools are developed and built by Societe Mecanique Magnetique (S2M) of France. In 1984 Magnetic Bearings Inc. (MBI) of Radford, Virginia (a division of Kollmorgan) obtained the patents from S2M and is currently distributing the S2M spindle in the United States. At present there are three models of magnetic spindles available for milling purposes. These 3 models cover the speed range between 30,000, and 60,000 rpm with a rated horsepower between 20 and 34 [16,17].

Magnetic spindles consist of a spindle shaft supported by contactless, active radial and thrust magnetic bearings, as is shown in Figure 6. In operation, the spindle shaft is magnetically suspended with no mechanical contact with the spindle housing. Position sensors placed around the shaft continuously monitor the displacement of shaft in three orthogonal directions. The sensor information is processed by a control unit and any variation in the position of the shaft are corrected by varying

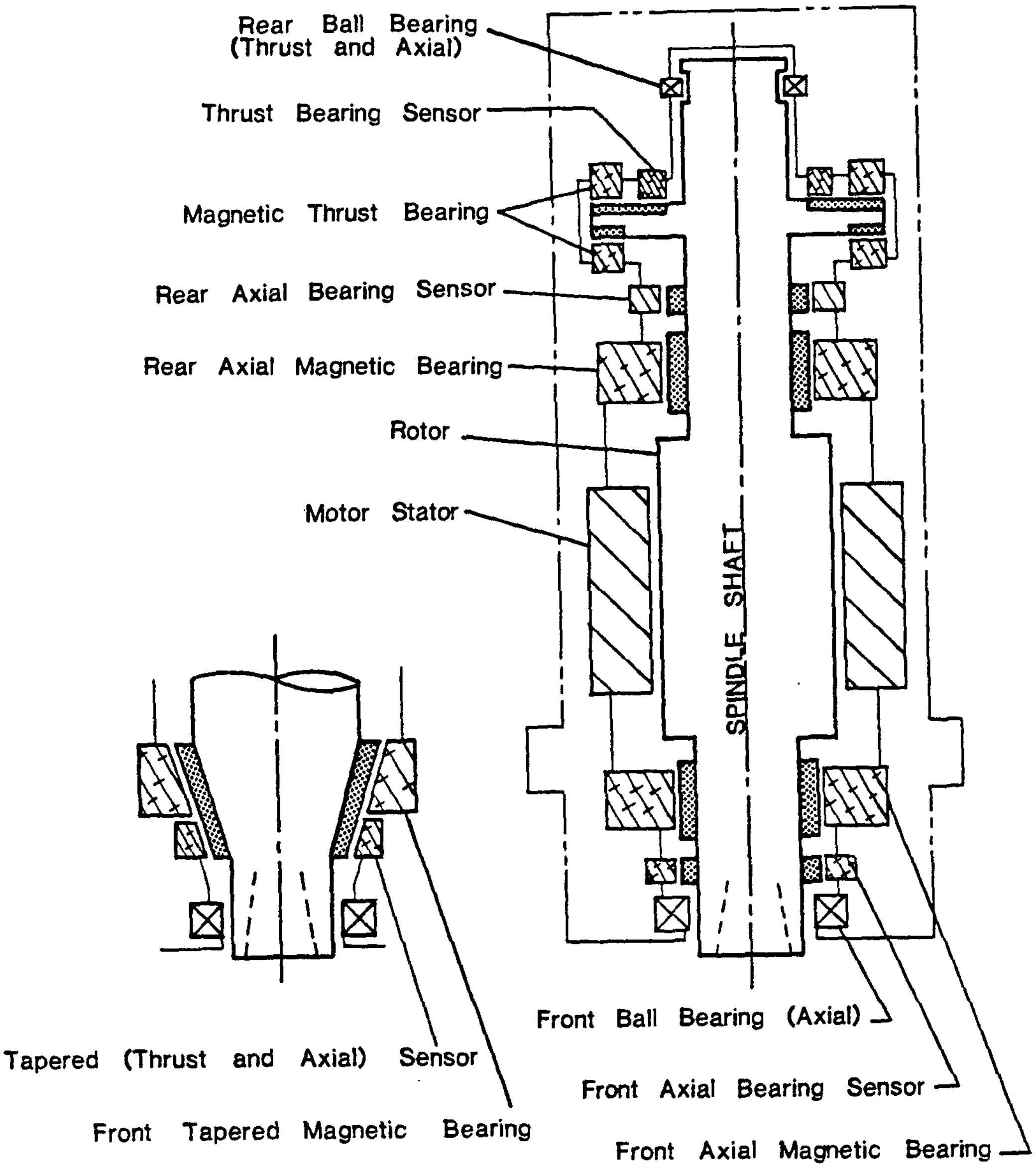


FIG. 6 MAGNETIC SPINDLE CONFIGURATION (REF.1 7)

the current level in electro-magnetic coils, thereby forcing the spindle shaft to its original position. The magnetically floating spindle shaft can be rotated freely about its mass center even if the mass center deviates from the geometric axis. Conventional ball bearings (called touchdown bearings) are also provided on both ends of the spindle for supporting the shaft when the spindle is stopped and for serving as the touchdown bearings in case of a power failure.

It is particularly important to note that the spindle shaft can be translated up to ±.005 inches and tilled up to 0.5° with no effect on the performance of the spindle system. This unique feature of magnetically controlled spindles can have significant impact in correcting tool path errors.

The unique design of magnetic spindles provides significant advantages over conventional spindles with regard to tool path error correction. These advantages are:

1. Built-in 3-dimensional force sensors are available for adaptive control of the cutting process.
2. Built-in 3-dimensional position sensors are available for adaptive control of cutting process.
3. Ability to translate and tilt the spindle shaft (within air gap restrictions) for tool path error minimization. Applicable for minimizing both deterministic compliance error and stochastic errors due to variation in depth of cut and machine tool dynamics in thin rib machining.
4. High rotational speeds with reduction in cutting forces and improved surface finish (i.e., burr free cutting).
5. Ability to control the stiffness of the spindle which can be particularly beneficial for chatter control.
6. High material removal rate (MRR) available with increased table feed rates.

Additional advantages of the magnetic bearing spindle include no lubrication requirements and high thermal stability due to the absence of friction.

In the United States two manufacturers have implemented magnetic bearing spindles in machine tools, Turchan and TMI-Forest, Inc. The inability to deal with different cutting tools made them unsatisfactory for universal machines while somewhat satisfactory operation was obtained using them on dedicated machines. Currently manufacturers of machine tools are concerned with the excessive cost and sophisticated electronics involved in terms of reliability and maintenance. However, numerous manufacturers appreciate the definite advantages that magnetic bearings have over conventional ones and would encourage their use should the technology become feasible.

Several investigators have used magnetic spindles [8,9,10] by retrofitting them on existing machine tools. Their primary focus was to use the magnetic bearing spindle to improve metal removal rate. In the approach suggested in this paper, the many other advantages of using magnetically controlled spindles to improve tool path errors can take precedence over the advantage of high metal removal rate. This approach exploits the full capabilities of the magnetic spindles and will be useful for retrofitting existing machine tools for tool path error minimization.

ERROR MINIMIZATION

In general, tool path error consists of machine tool errors and cutting force errors. These errors can be static and dynamic deterministic and/or stochastic. The machine tool static and dynamic deterministic errors can be quantified using a laser metrology system and put in the form of an error map for use in software correction. Cutting force errors are both static deterministic and stochastic and can be minimized by utilizing a magnetically controlled spindle and a control strategy which takes advantage of the spindles ability to tilt and translate, while continuing to rotate at high speeds. In this section the current state of the art of tool path error correction is discussed.

Hocken, et al. [3] have shown that a laser metrology system [18] can be used to evaluate static positioning errors and demonstrate their repeatability. Use of the laser involves instrumenting a machine tool with optical elements attached to the spindle and table as is shown in Figure 7. With proper optical elements the laser position measurement system is adaptable to measure all static and dynamic errors which occur without any cutting taking place. Once the errors have been determined it is possible to generate error maps (i.e., error matrix) in which the true position becomes the input to the map and the output (i.e., looked up value) is the machine controller coordinates which generate the true position. Error map correction can be implemented in either the part program software or in the machine tool controller itself. At present neither implementation exists commercially.

When the machine tool is cutting chips the laser metrology system is not adaptable to measure the additional tool path errors caused by cutting forces. Current work has concentrated on minimizing the chip cutting error by either improving machine tool structure dynamics or compensating the error through software correction at the part programming stage.

One method of improving the deterministic tool path error in conventional speed machining has been discussed by Koren [6] who showed that, cross-coupled biaxial control between machine tool axes is preferable instead of individual-axis control of CNC machines. In conventional machines each axis has a separate closed loop control, so that the control loop of one axis received no information regarding the other. However, any load disturbance error in one of the axes is corrected only by its own loop, while the other loop experiences no change resulting in path error or contour error. Hence, Koren has found that cross-coupling the axis will improve the accuracy of the tool path in contour cutting. The drawback of this approach is the reduced velocity

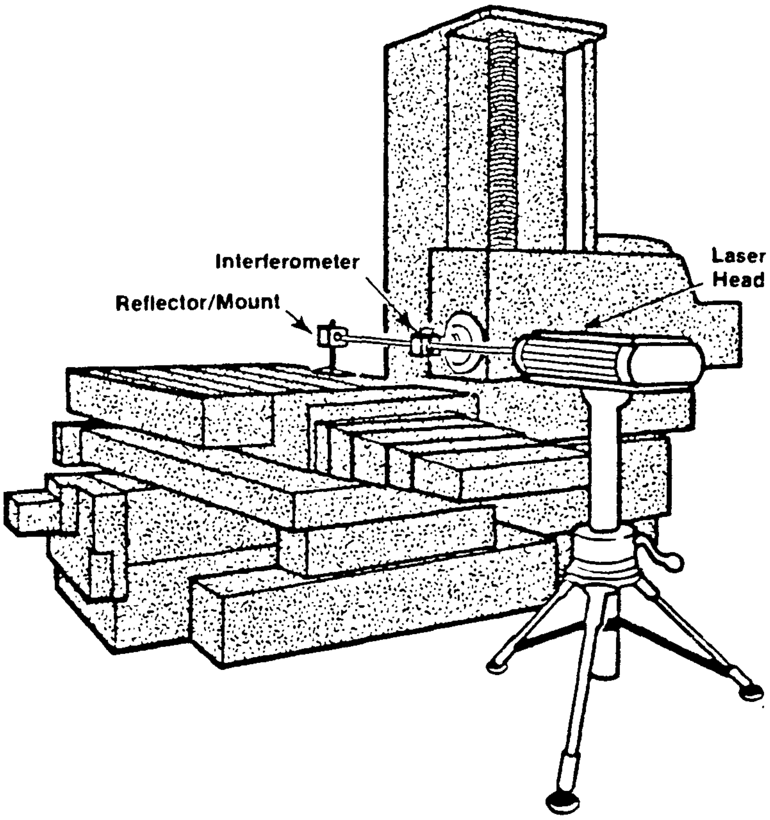


FIG. 7 LASER POSITION MEASUREMENT

response which might make it difficult for high speed machining applications. This approach, however, has no impact on stochastic tool path error.

Kline, et al [4] developed a mechanistic model for the prediction of feed rate on the force system characteristics in end milling. The model was developed based on the experimentally obtained average force data for a given cutter geometry and workpiece material. The computer model gives the force distribution as a function of axial depth of cut and rotation of cutter. The program developed for end milling gives as output, such characteristics as, force profiles as a function of rotation, force center profiles, force distribution along the axis of cutter, cutter deflection profiles, etc. The model is verified on cornering cuts in end milling as shown in Fig. 8. During cornering the radial depth of cut varies and hence the cutting force. The model has been reported to be successful in predicting the forces during cornering to within 5-20% of the actual cutting force. The mechanistic model is therefore useful in programming the feed rate variation required during cornering to limit the cutting force within a threshold value. However, this method does not account for workpiece deflection under cutting forces, on for dynamic deterministic position errors. In addition this algorithm is not designed to account for stochastic variation in blank thickness.

Kline, et al [5] later did work on the effect of runout of cutters held in set screw type tool holders in end milling. It was shown that cutter runout in end milling leads to changes in the amplitude and frequency of cutting force. A mathematical model was developed to include this effect into the previously developed mechanistic model [4]. Successful experimentation of the above model has been carried out for 7075 Aluminum.

Watanabe and Iwai [15] have reported successful application of adaptive control to increase the accuracy of finished surface in

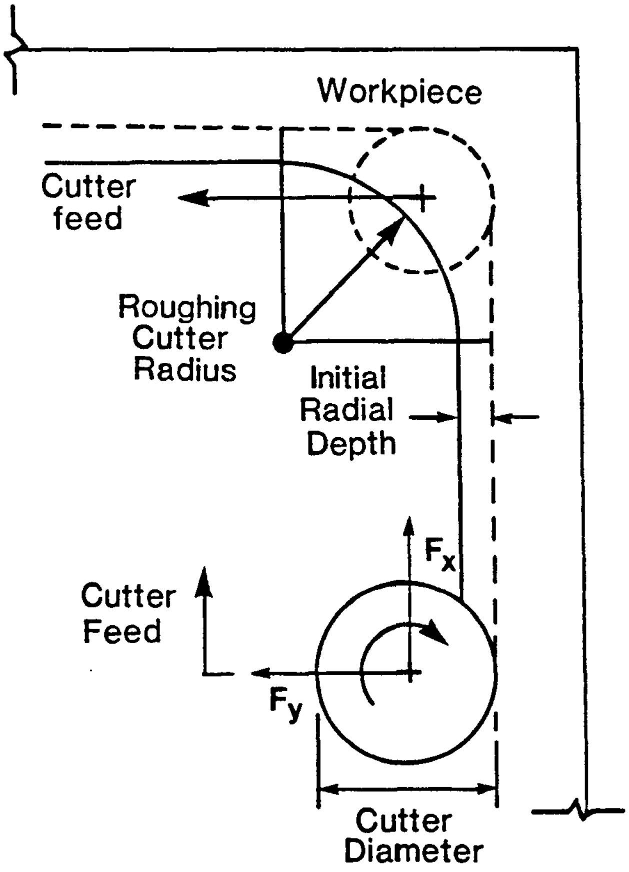


FIG. 8 CORNERING CUTS IN END MILLING (REF. 4)

conventional end milling. The deflection of the spindle nose is used to compute the cutting force and tool deflection at the tool-workpiece interface. The tool position normal to the cutting surface is shifted to compensate for the tool deflection. The cutting force is also used to alter the feed rate to maintain the error within limits in the direction parallel to the depth of cut. The feed rate control is achieved by the interpolation program of the machine controller. The motion normal to the cutting surface is, however, obtained by servo-programs since they need less compilation compared to interpolation programs. However, this method is not designed to account for workpiece deflection, stochastic variation in blank thickness and thermal deformation.

In the work done at General Dynamics-Convair Division [14] a technique called 'Net Machining' is used to minimize the ramp error in thin rib machining. Using this technique, multiple cutting passes are made on each side of a free standing rib with each pass alternating the side of the rib on which deeper amounts of material are removed. This technique is reported to have successfully reduced the ramp error due to deflection of thin ribs but with the penalty of greatly increased part machining time.

The review of the literature suggests that a systems approach to quantification and control of tool path errors will yield extremely beneficial results. For the most part it appears that although the positioning errors of a machine tool can be measured with a laser metrology system, the minimization of these errors in an actual machine tool has not been carried out in practice.

ERROR MINIMIZATION METHODOLOGY

The benefits of using a magnetic bearing spindle for error correction in thin rib machining include the inherent advantages of high speed machining and the imlementation of error correction methodologies for improving part shape and surface finish.

The University of Maryland in cooperation with Magnetic Bearings Incorporated, Cincinnati Milacron, Westinghouse, and the

National Bureau of Standards has undertaken a program to implement an error correction methodology in a vertical machining center. The strategy is to utilize an experimentally determined error matrix of a test machine, along with models of cutting force errors, and to implement a corrective control scheme to significantly reduce overall part errors in thin rib machining.

A control scheme as shown in Figure 9, is the proposed block diagram for control of a magnetic bearing spindle. This scheme, although still being refined, will take the overall machine error matrix and cutting force model data and adjust the spindle location (both translation and tilt) in order to minimize the instantaneous overall tool path errors. The work currently involves the following tasks:

- generate static and dynamic tool path error maps in end milling operations
- develop an expert system for stochastic error correction
- develop and implement control algorithms for controlling magnetically suspended spindles to minimize tool path errors
- experimentally test and validate models and algorithms using a CNC vertical machining center fitted with a magnetically suspended spindle.

The current work is intended to fill a void in the state-of-the-art in end milling machining. In a recent report [19] MTTF recommended research to "develop data on cutting forces and deflections and their effect on accuracy of machined surface in end milling. Include web flexibility. Assume input from the NC program and consider the feasibility of input from cutting force measurement and analysis". The current cooperative effort will address the task suggested in the MTTF report.

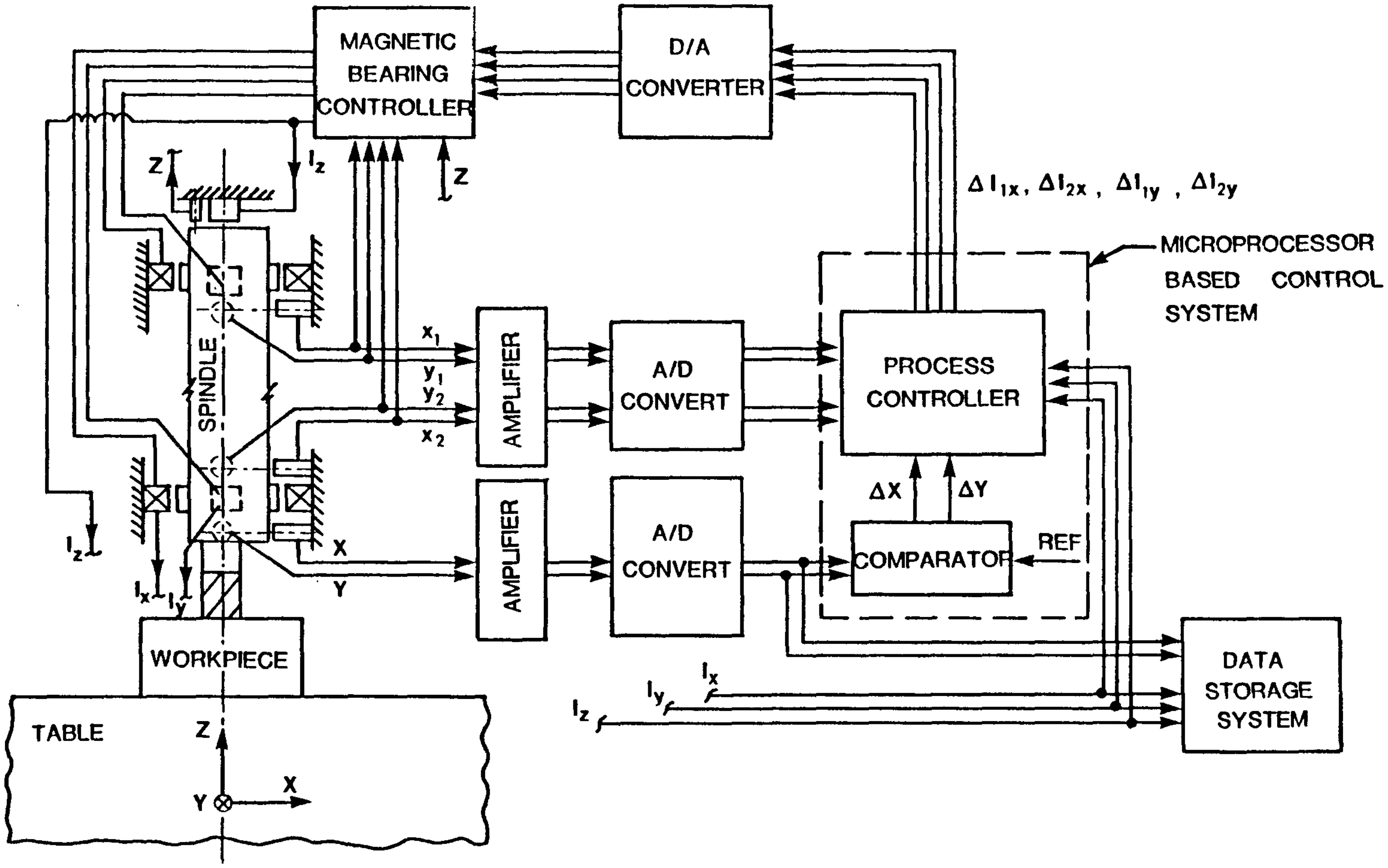


FIG. 9 EXPERIMENTAL SETUP FOR TOOL PATH ERROR MINIMIZATION IN END MILLING

CONCLUSIONS

The present cooperative research direction of the authors and engineers from Cincinnati Milacron, Magnetic Bearings Inc., Westinghouse and the National Bureau of Standards has been presented. The long term research work is in its early stages and involves tool path error minimization through the use of magnetic bearing spindles.

Tool path errors have been characterized as static deterministic, dynamic deterministic and stochastic. The source of each of these errors is either in the machine tool itself or in the nature of the cutting process. Based on the ability of a magnetic bearing spindle to both translate and tilt an initial control scheme for the magnetic bearing has been presented. Furthermore, it is expected that the long term benefits of this cooperative research will be:

- Fundamental understanding of the dynamics and performance of magnetically suspended spindles in a high speed machining environment.
- Generation of a body of fundamental, analytical and experimental knowledge in the high speed machining of parts.
- The enhancement of accuracy by quantifying and controlling tool path error.
- Contribution to the basic knowledge of burr-free machining of thin ribbed microwave guide-like parts.
- Development of a control strategy for tool path error minimization in end-milling that is machine independent.
- Potential for increased MRR.

ACKNOWLEDGMENT

The research discussed here represents a cooperative activity started among engineers from the University of Maryland, the National Bureau of Standards, The Cincinnati Milacron Corporation, Magnetic Bearings Inc., and the Manufacturing Group (Columbis, MD) of Westinghouse Corporation. Input from all these sources is greatly appreciated. Special thanks to Ken Bone (Cincinnati Milacron), Henry McFadden (MBI), Arne Rasmussen (Westinghouse) and John Simpson (NBS) in discussing the technical ideas presented in this paper.

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