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# Improving machining accuracy in precision line boring

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There is an ever-growing demand for high precision machining to obtain increased accuracy and surface finish, as they are key factors in product quality and performance. Machining operations, in general, are associated with errors of varying magnitude originating from different sources. As a result, the sizes of the machined features usually deviate from their desired, nominal values. Identification of error sources, techniques of measurements (on/off line), and efficient strategies for their compensation are the steps required to minimize, and, in some cases eliminate process errors. This paper focuses on modeling and compensation of geometric errors in machining operations specific to the line boring process. It is part of an undergoing research project focused on design and development of an agile precision line boring station for machining of long bores. After a brief overview of sources of geometric errors and their components, a methodology for their calculation is introduced. In this regard, error equations reflecting the effects of machine tool geometric errors at the tool tip are derived. It is shown that these equations can be further simplified without significantly affecting computational accuracy of the results. This makes the approach more attractive for real-time applications. A set of experimental data obtained from a prototype of the machine is used to study the effectiveness of the proposed approach and the results are reported. The paper concludes with discussions and presentation of different methods and available tools for real time compensation of these errors.

*Keywords*: Machining errors, CNC machines, machining processes, precision machining, geometric errors, error compensation

## 1. Introduction

Rapid changes in technology and globalization of economies have created a new manufacturing environment characterized by competitive market (national and international). Responsiveness (rapid/cost effective response to the demands of the market) of manufacturing firms in producing high quality products is the key to their future success (Jaikumar, 1993; Mehrabi *et al.*, 1997). This competition is more intensified in automotive industry where sharp fluctuations of customer demand for delivery of high quality products can be observed. A major portion of manufacturing processes in the automotive industry is based on machining; therefore, quality of the final products will be largely affected by the accuracy of the machine tools and processes used for their production. Among many machining processes involved in producing automotive parts, precision line boring (used in production of engine heads and blocks) is a very demanding application in terms of both quality and production rate requirements. It is also considered to be one of the most important and difficult machining operations mainly used in manufacturing of cam and crank journals (see Fig. 1); the long bore length, small diameter, and the distance between the journals in the parts contribute to the difficulties involved in performing this type of machining operations.

Machining processes are very complex in nature and there are many parameters that affect the process and the accuracy of the parts produced. As a result, once a part is machined, the actual size of the machined parts differs from desired dimensions specified in design. Although it is not always possible to totally eliminate the dimensional variations, it is desirable to keep these variations within certain limits set by tolerances.

Errors in machining are usually classified into random and systematic errors. Random errors are caused by combination of the machine errors (e.g., bearings, backlash, etc.) and operator errors; as a result, the machined parts errors and their size variations follow usual gausian distribution. Systematic errors, on the other hand, cause a drift in one direction and as a result, the mean value of the sizes of the workpiece deviates in a systematic way (Yandayan and Burdekin, 1997; Ni, 1997). These types of errors are caused by the effects such as tool wear, thermal expansion of machine tool structure, deflection of the tool (during machining) and behavior of clamps/fixtures/workholding devices under the cutting process. Geometric errors of the machine tools fall under the second category. They cause systematic errors of the dimensions of the machined parts. They are inherently position dependent (axis of the machine) and are functions of the axis motions and machine structure. Therefore, they manifest their effects at the tool tip and directly affect the accuracy of the machined part.

Literature survey suggests that there are a number of studies carried out with a focus on a particular aspect of the errors produced in machining. Rivin and Kang (1987) and Tlusty (1971) have reported on the

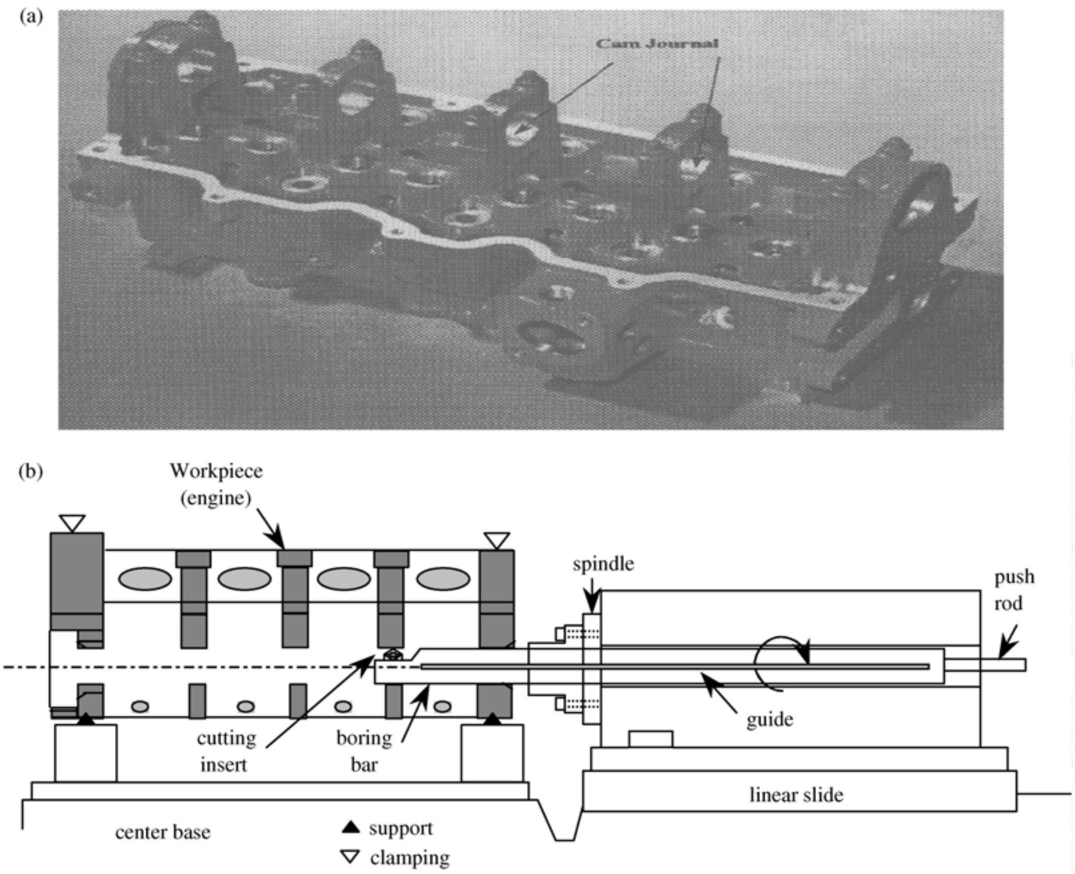


**Fig. 1.** Journals of an overhead cam cylinder head (a) and crank journal boring of an engine block (b).

problems associated with design of the boring bar. They have introduced different approaches to enhance its dynamic stiffness for maintaining geometric accuracy of the machined bore and surface finish. In efforts to better understand machining processes and the parameters involved, modeling of tools and processes are important subjects to be studied. Related to that Iwata and Moriwaki (1981), Araki (1985) and Kashani *et al*. (1993) have developed different models of the tools and machining processes that can be used to study the effects of thermal and mechanical distortions of tools and machine components, cutting forces, bore temperatures, and vibration on the quality of the machined parts. In the studies related to techniques of compensation, Kashani *et al*. (1993), Rasmussen *et al*. (1992) and Crawly *et al*. (1990) have proposed various approaches to minimize the effects of tool vibration on the quality of surface finish. Literature survey also suggests that there are several studies reported that are related to dimensional measurements techniques, workpiece accuracy, and modeling of geometric errors in machining (Ni, 1997; Ferreira and Liu, 1991; Donmez *et al*., 1986; Schultschik, 1977; Yandayan and Burdekin, 1996). Schultschik (1977), French and Humphries (1967) and Leete (1961) have considered volumetric errors in machining and have developed models for systematic evaluation of precision in machine tools. In a report by Ferreira and Liu (1991), a model is developed for estimating geometric errors in machining; the thermal effects of the machine structure are also considered. In their work, they have classified the errors in machining as quasistatic errors (slow time varying errors between the tool and the workpiece) and dynamic errors. Examples of the former are thermally induced errors and machine's structural errors. Dynamic errors on the other hand are caused by sources such as spindle error motion, vibration of the machine structure (self-induced and forced) and deflections under variable loads; these errors have relatively faster time histories. As reported, quasistatic errors are very important and account for almost 70% of the errors attributable to the machine tool.

It might be noticed that although the sources of errors in machining are different, for any practical purposes however, their net effect should be considered at the tool tip. Geometric errors follow the same rule and their overall effects should be considered at the tool–workpiece interface.

In the following sections of this paper, a brief description of geometric errors and their sources is provided and the terminology used is explained. Mathematical models representing the resulting errors at the tool tip are derived. It is shown that these equations can be further simplified without significantly compromising the results. This makes the approach more attractive for real time applications. A set of experimental data obtained from a prototype of the machine is used to study the effectiveness of the proposed approach and the results are reported. The paper concludes with discussions of algorithms for their real time compensation.

## 2. Geometric errors (definitions and notations)

There are seven types of geometric errors in machine tools including angular errors (roll, pitch, and roll), straightness errors, and linear displacement errors (of the slides), and squareness errors of the machine structure (Kim *et al*., 1987). Figure 2 illustrates the six error terms for the *Z*-axis motion of a single axis.

Error mapping of a complete machine is a lengthy and tedious task. For a three axis machine, 21 error terms exist (six error terms for each linear axis, plus three terms related to the squareness of the *XY*-, *XZ*-, and *YZ*-planes) (Kim *et al*., 1987; Ferreira and Liu, 1991; Szuba, 1998; Mehrabi, 1998; Lamb Technicon, 1998). If sufficient degrees of freedom are available, all the errors can be minimized or eliminated. However, degrees of freedom for compensation purposes are usually limited and therefore the errors can be compensated just in directions of travel of the axes.

## 3. Development of the error equations

The primary objective of a machining operation is to ensure that some of the important geometric attributes of the process are kept within certain tolerances which vary with type of machining process. Geometric attributes which are characteristics of the boring process are (Szuba, 1998; Mehrabi, 1998; Lamb Technicon, 1998):

- *circularity:* the degree to which all the points on the intersection of the surface and a plane perpendicular to the axis of revolution are equidistant from the axis;

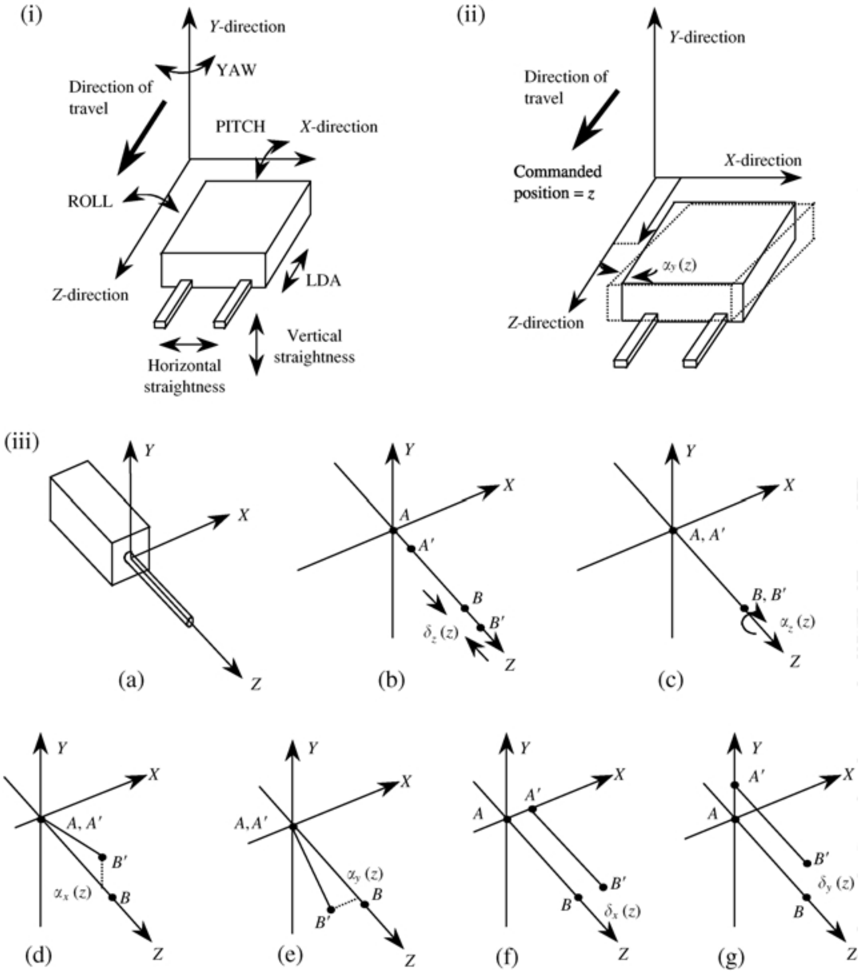


**Fig. 2.** Six basic axis errors (i), example of yaw error (ii) and their resultant components (iii) example of *Z*-axis.

- *concentricity:* the degree to which any two or more part features, such as cylindrical surface and a circular hole have a common axis;
- *cylindricity:* the degree to which all points on a surface or revolution such as a cylinder are equidistant from the axis of revolution;
- *perpendicularity:* the degree to which all points on a part feature, such as a surface, line, or axis are equidistant from a reference plane, line, or axis; and
- *surface roughness:* surface irregularities inherent in the production process; e.g., grooves plowed by a cutting tool.

These attributes are mostly affected by the accuracy of the tooltip position in *XY*-plane and the tooltip orientations. Therefore, compensation of the errors in *X*- and *Y*-axis is particularly important.

As a general practice if the function of the platen (see Fig. 3) is to carry the workpiece, these errors are measured with respect to a nominal cutting tool position; otherwise measurements are made with respect to a nominal workpiece position. In a boring operation, the cutting tool is the moving element and therefore a fixed set of reference axes is required at the center line of the fixture. Also, a separate fixed set of reference axes is required at the center of the platen to define the position of the cutting tool tip (see Fig. 3).

Error equations can be derived by using matrices for rotation of a vector about an axis (Groover *et al.*, 1986) such as:

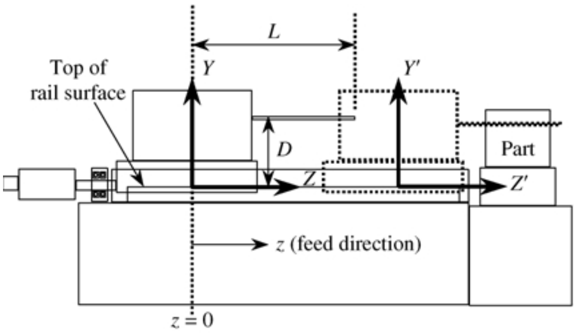


**Fig. 3.** Schematic diagram of a single axis machine.

$$\begin{bmatrix} \cos\alpha_i(j) & -\sin\alpha_i(j) & 0 & 0 \\ \sin\alpha_i(j) & \cos\alpha_i(j) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha_i(j) & -\sin\alpha_i(j) & 0 \\ 0 & \sin\alpha_i(j) & \cos\alpha_i(j) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} \cos\alpha_i(j) & 0 & \sin\alpha_i(j) & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\alpha_i(j) & 0 & \cos\alpha_i(j) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

for roll, pitch, yaw, and homogeneous transformations for linear translations such as:

$$\begin{bmatrix} 1 & 0 & 0 & \Delta a \\ 0 & 1 & 0 & \Delta b \\ 0 & 0 & 1 & \Delta c \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

for straightness errors.

In the above equations, $\alpha_i(j)$ are the roll, pitch, and yaw errors; and $\Delta a$, $\Delta b$, and $\Delta c$ are the straightness errors of $X$-, $Y$-, and $Z$-axes. To calculate total errors at the tool tip, Equations 1–4 for each axis should be multiplied by similar matrices describing the errors for other axes in a successive manner which makes the volume of computations relatively large. Also, squareness errors (the errors between the axis of the machine) need to be included in these calculations. However, since the angles involved are very small (on the order of arcsec), the second order terms resulting from these transformations can be neglected. This is equivalent to independently treating the effects of each individual error and superposing them to get the total errors at the tool tip. For example, referring to Fig. 2, it can be seen that the net effect of a small roll error on $Z$-axis (i.e., $\alpha_z(z)$) creates two error components in $X$- and $Y$-axis. This is true for other angular errors, straightness errors and squareness errors of the machine structure. The total error at the tool tip can be obtained by superposing these error components. Furthermore, trigonometric approximations (i.e., $\sin\alpha \approx \alpha$ and $\cos\alpha \approx 1$) can be used to further simplify these relations. For the machine under consideration and its kinematics (see Figs 2 and 4), the following equations are obtained for the errors in three directions (Szuba, 1998; Mehrabi, 1998):

$$\begin{aligned} \Delta x = &+ (z+L)[\alpha_y(x)+\alpha_y(y)] + L\alpha_y(x) - D[\alpha_z(x) \\ &+ \alpha_z(z)] - D\alpha_z(y) + y\,\varepsilon_{xy}\,(Y) + z\varepsilon_{xz}\,(Z) \\ &+ \Sigma\,[\delta_x(z), \delta_x(y), \delta_x(z)] \end{aligned} \quad (5)$$

$$\begin{aligned} \Delta y = &- (z+L)[\alpha_x(x)+\alpha_x(y)] - L\alpha_x(z) \\ &+ x\alpha_z(y) + z\varepsilon_{xz}\,(X) + x\varepsilon_{xy}\,(X) \\ &+ \Sigma\,[\delta_y(x), \delta_y(y), \delta_y(z)] \end{aligned} \quad (6)$$

$$\begin{aligned} \Delta z = &D[\alpha_x(x)+\alpha_x(z)] + D\alpha_x(y) - x\alpha_y(y) \\ &+ x\varepsilon_{xz}\,(X) + y\varepsilon_{yz}\,(y) + \Sigma\,[\delta_z(x), \delta_z(y), \delta_z(z)] \end{aligned} \quad (7)$$

The following notations are used in the above equations: $\Delta x$, $\Delta y$, and $\Delta z$ are the components of the

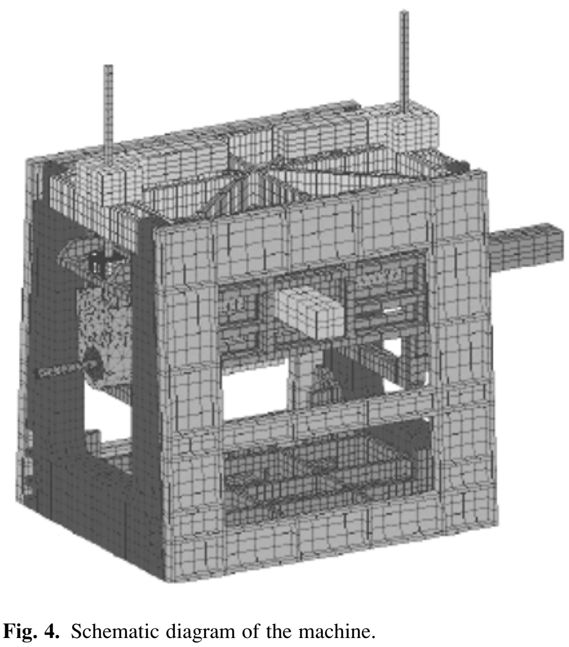

**Fig. 4.** Schematic diagram of the machine.

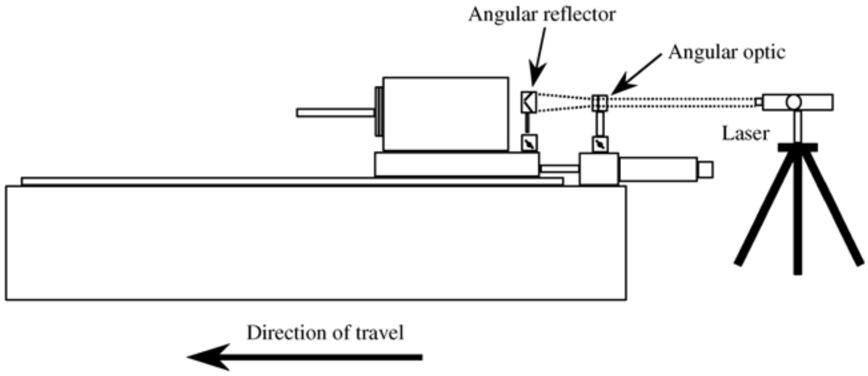


**Fig. 5.** Schematic of the experimental setup for measuring yaw error of a horizontal axis.

total errors at the tool tip (i.e., required motion on each axis to be compensated by the controller); $\alpha_i(j)_{(i,j=x,y,z)}$ are the angular errors of the axis; $\varepsilon_{ij}(j)_{(i,j=x,y,z)}$ are the squareness errors of the machine structure; $\delta_i(j)_{i,j=x,y,z}$ are the straightness errors of the axis, $x$, $y$, and $z$ are the axis coordinates; $L$ and $D$ are the length of the tool bar (see Fig. 2) and its center height (in $Y$-axis); and $\Sigma$ is the summation symbol.

These equations (namely Equations 5–7) provide instantaneous magnitude of the errors produced on the 3-axis of the machine that need to be compensated by the controller. A closer look at these equations reveals that from computational point of view, they are fairly straightforward and all computations can be done in real-time. One can readily see the benefits of this approach as compared to typical computations and matrix operations involved when Equations 1–4 are used in error calculations. The angular errors involved can be obtained through (on/off-line) measurement; the same is true for the linear errors (e.g., squareness and straightness).

## 4. Experimental results and discussion of algorithm for compensations

In order to study the effectiveness of the approach, a set of data (total of 21 sets) was obtained from the machine. Experiments were carried out based on the ASME guidelines for error measurements in machining (ASME Guidelines, 1992). The machine was running at its rapid traverse speed (1.0 m/s) and acceleration was the machine's maximum acceleration (1.08 m/s$^2$). The data was collected after warm up period of the machine. The laser interferometer was used to measure straightness errors and electronic levels were used to measure angular errors (see Fig. 5). Samples of experimental data for angular and straightness errors are shown in Fig. 6; details of experimental setup and measurement data can be found in Szuba (1998) and Mehrabi (1998). Fig. 7 shows the ranges of the computational errors obtained by using exact equations (i.e., using Equations 1–4 for each axis) and simplified versions (i.e., Equations 5–7). It is seen that generally speaking, the errors (due to computation) at the tooltip in all three axis are within $\pm$ 0.0014 $\mu$m. This is quite sufficient to achieve the required accuracy in a typical boring machining. Therefore, the proposed approach while provides very compatible results in terms of error calculations, it has a more compact form which is very suitable for real-time applications.

### 4.1. *Error correction techniques*

As mentioned previously, error compensations are limited to the directions of axis motion. To fully compensate for the errors (angular and linear), additional degrees of freedoms are required which are usually difficult to generate. A proposed solution is accomplished by using ''Smart Tooling'' designed as a part of this project (Koren and Pasek, 1998; Pasek and Szuba, 1998; Lamb Technicon, 1998). The idea behind the design of smart tool (see Fig. 8) is that moving the tool tip in the radial direction with the help of an actuator, such as a piezoelectric actuator, can compensate for boring bar deflections and part of geometric errors.

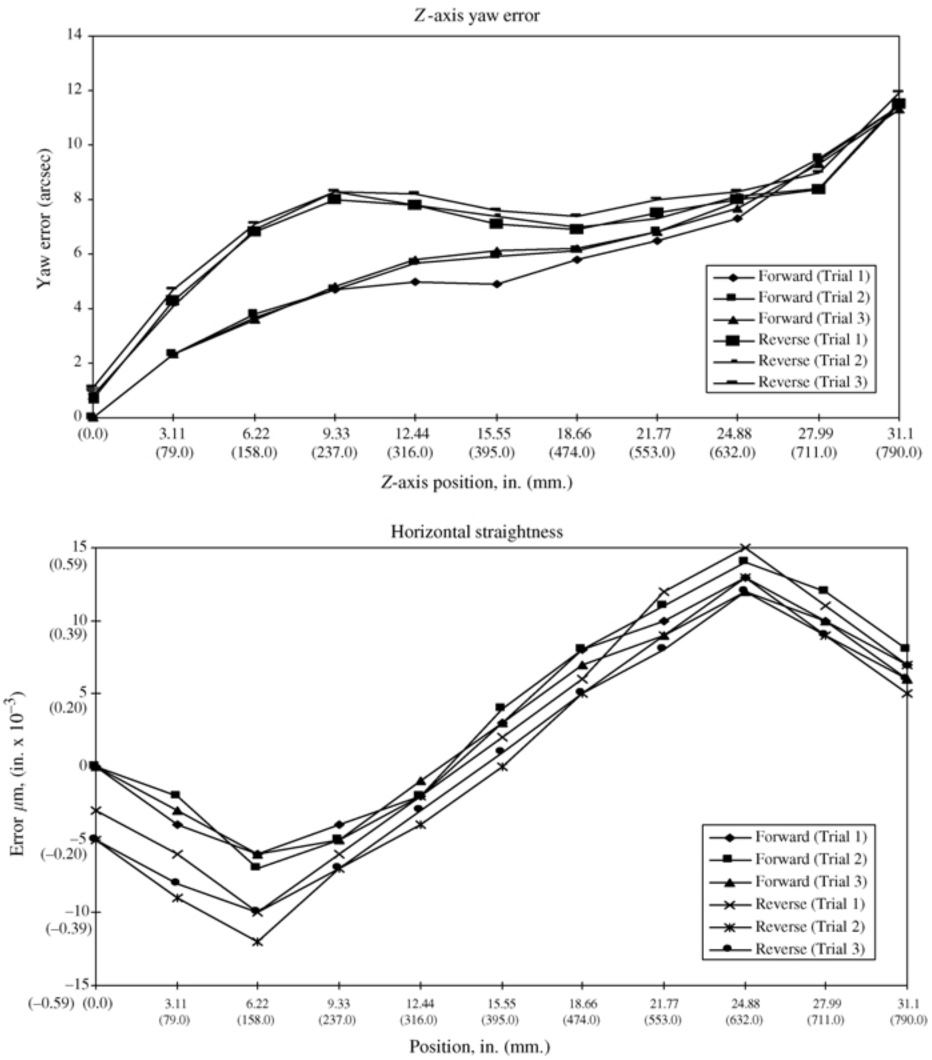


**Fig. 6.** Typical experimental data for yaw and straightness errors ($Z$-axis).

In line boring process, the overhang of the boring bar is relatively large. Therefore several guide pads riding on the subsequent journals are used for its support. These guides limit the radial movement of the tool bar once inside the engine block. The application of smart tool is one method for increasing the number of degrees of freedom for compensation as well as overcoming this limitation. The smart tool allows for precise tool tip movements in the radial direction, compensating for boring bar deflections and part of geometric errors. By noting that the smart tool motion in radial direction is limited (less than 50 $\mu$m), a combination of axis motions and smart tool radial motion should be used to compensate for the linear errors in $XY$-plane (obtained by solving Equations 5–7).

It should be mentioned that different techniques are proposed by other researchers to compensate the errors in machining. For example, Kaiji *et al*. (1995) have introduced the design principle of an active leadscrew mechanism that can control or eliminate backlash in the leadscrew. As reported, ultra-precision positioning can be achieved by combining the axis motion (for relatively coarse motions) and piezoelectric actuators for fine motions. However, the focus of their work has been on eliminating backlash which is one component

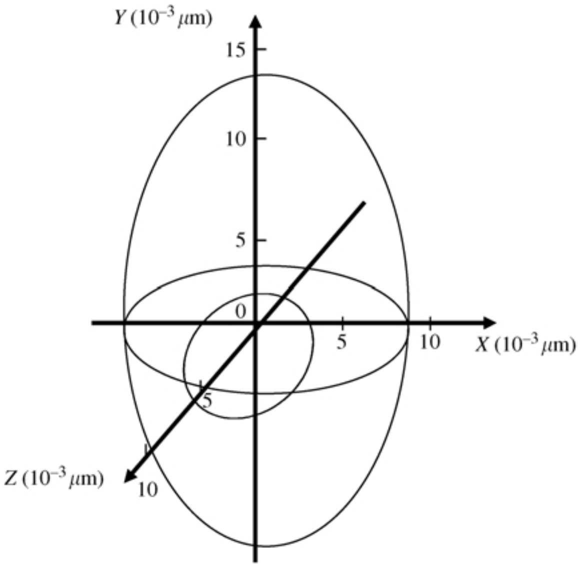


**Fig. 7.** Range of errors due to computation (approximate and exact).

of the errors in machining. In this study, piezoelectric actuators are used to accurately position the tool tip relative to the workpiece. Therefore, with this approach, the combined effects of the errors reflected at the tool tip are effectively compensated.

The smart tool consists of the following components (Koren and Pasek, 1999; Koren *et al.*, 1999; Pasek and Szuba, 1998; Szuba, 1998): (i) tool tip translation mechanism, (ii) laser measurement system, (iii) computer controller, and (iv) wireless transmitter for communication (see Fig. 8). The tool tip translation mechanism uses a piezoelectric actuator to provide up to 50 $\mu$m of displacement relative to the boring bar. Position sensitive optical detectors provide the real-time XY-plane feedback signals for the tool tip and end of boring bar position. The controller is implemented on a PC/104 computer with a 133 MHz AMD $5 \times 86$ CPU and an analog interface. All control algorithms are embedded in the controller using a memory IC and the control loop has a 0.15-ms sampling period. The smart tool controller communicates with the machine controller using a standard serial data port, through a wireless inductive rotary transmitter, which also transmits electrical power for the actuator and electronics. The main controller can start and stop the control loop, and upload and download data and parameters to/from the

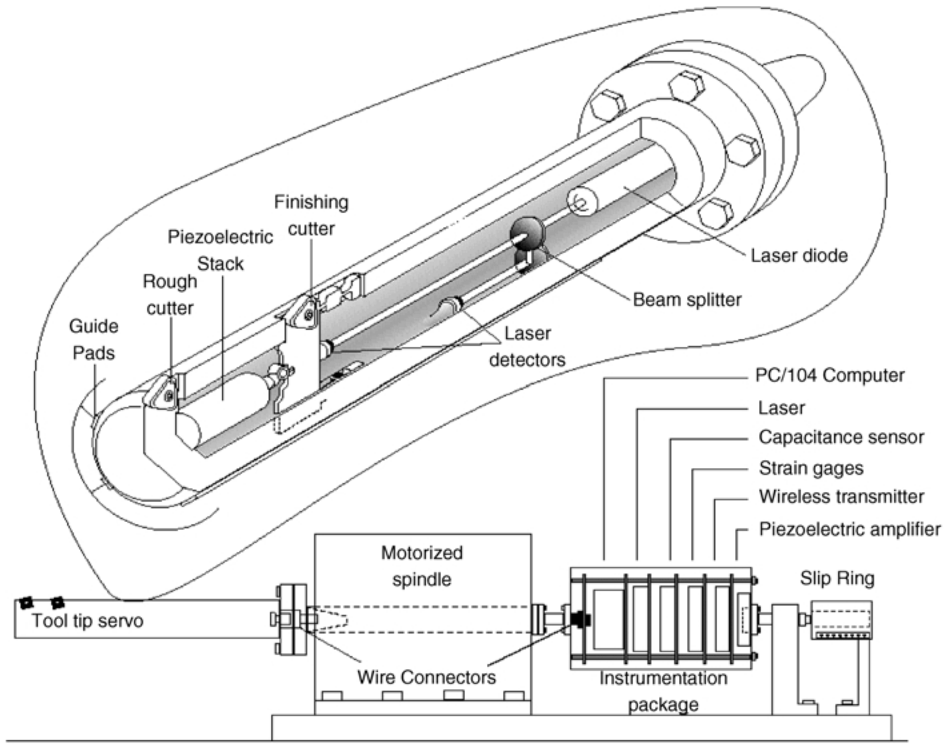


**Fig. 8.** Schematic diagram of the smart tool.

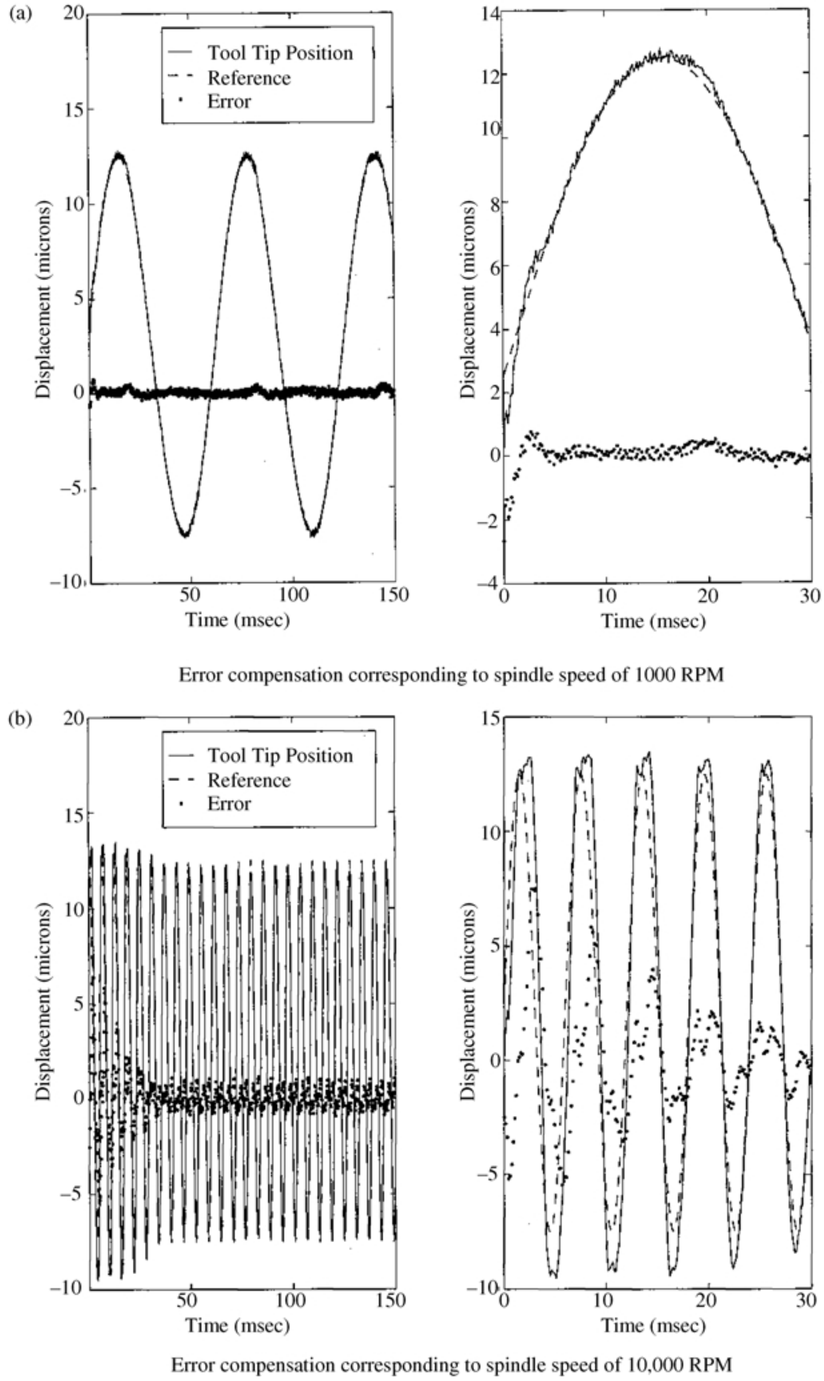


**Fig. 9.** Experimental results for error compensation when the smart tool is utilized. Spindle speed (a) 1,000 rpm, (b) 10,000 rpm.

smart tool. Figure 9 shows step response of the smart tool and experimental results illustrating smart tool tracking performance. Typical time histories of the errors resulting from tool tip offsets in center location of bore holes relative to spindle axis at different spindle speeds (in this case 1000 rpm and 10,000 rpm) and real time performance of the smart tool in compensating them are shown on the same figure. It

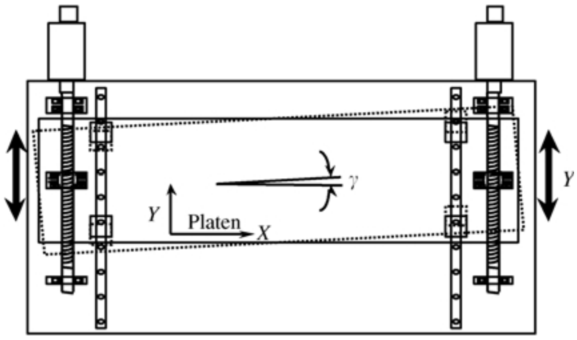


**Fig. 10.** Pitch error compensation by using dual linear actuator system.

is seen that the smart tool can compensate for the errors in a very fast and consistent way.

While the linear errors can be compensated by the techniques just described, angular errors are more difficult to compensate since most of machines do not provide any angular motion. One possibility for angular error compensation is to take advantage of the special structure of this machine which allows for additional (but limited) degree of freedom to be generated (Koren *et al*., 1999). By using a dual linear actuator system (see Fig. 10) for the *Y* or *Z* directions, pitch error can be partly compensated. Analysis of the results (Szuba, 1998; Mehrabi, 1998) show that the pitch error of the *Z*-axis has a dominant effect on the tool tip errors. It should be noticed that the control structure (software/hardware) of machines plays a key role in successful implementation of any compensation scheme. Real time error compensation of machines with proprietary controllers is usually difficult as they need some extra hardware and interfacing components (Ni, 1997; Donmez *et al*., 1986). But in machines with open-architecture controllers various schemes can easily be implemented (Koren *et al*., 1996). The machine under design has an open-architecture controller; therefore access to its controller and addition/removal of extra software/hardware is rather convenient.

## 5. Conclusions

This paper is focused on geometric errors associated with the line boring process and methods for their compensations. A general procedure for computations of the errors is provided. It is shown that it is possible to simplify the equations by using trigonometric approximations without significant changes in the results. Algorithms for error compensation by using the smart tool and the dual ballscrew method for angular error corrections are discussed and experimental results are presented.

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