CNC Machine Accuracy Enhancement Through Real-Time Error Compensation

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Improving CNC machine tool accuracy has received significant attention recently. This paper intends to provide an introduction of the real-time error compensation methods as applied to reduce both geometric and thermally induced quasistatic machine tool errors. An illustrative example is used to demonstrate the use of error compensation systems for a horizontal machining center. Although several industrial applications of these error compensation systems have achieved significant results, a few major barriers have prevented this promising technology from being applied widely in manufacturing. Several ongoing research activities aimed at overcoming the barriers are also presented.

Introduction

The manufacturing community is in constant pursuit of product quality improvement. In the past, most machined parts were produced on manually operated machines, and the qualities of the parts were controlled by the machine operators. Gauges such as calipers and micrometers were used to measure the features of the parts being machined. Based on these measurements, machine settings were adjusted intermittently to control the dimensions. Therefore, the qualities of the produced parts were highly dependent on the skill level of the operators.

As people rely more and more upon computer numerically controlled (CNC) machines to improve both flexibility and productivity, the dimensional accuracy of the parts produced on these machines has become dependent upon accurate machines and good machining processes. With CNC machines, the primary goal is to automate the machining processes. Operators of these machines, if there are any, are usually responsible for loading parts and monitoring machine conditions but not for part-quality control. Hence, improving machine accuracy and selecting good machining processes are keys to achieving higher quality. The importance of enhancing machine tool accuracy is well recognized due to the increasing demand for accurate machined products. In addition to the awareness from users, machine tool builders have also been in constant search for ways to improve the quality of their products and to reduce the construction costs of the machines that they produce in order to stay competitive.

In general, CNC machine tool inaccuracy is caused by (1) geometric errors of machine components and structures, (2) errors induced by thermal distortions, (3) deflections caused by cutting forces, and (4) other error sources such as servo errors of machine axis (e.g., following or tracking errors) and NC interpolation algorithmic errors. This paper will only address the compensation for the effects of the first three error sources. The effects of other error sources will be addressed by Koren in this special issue.

The accuracy of a workpiece is defined as the degree of conformance of the finished part to dimensional and geometric specifications (Hocken, 1980). Performance of machine tools in terms of accuracy is defined by the error of the relative movement between the cutting tool and the ideal workpiece. For a multiaxis machine, this relative error is called the volumetric error and can vary widely across the machine working zone due to the effect of the angular errors of machine linkages and the time-variant thermal changes of machine tools.

The geometric errors are usually referred to as the errors caused by manufacturing imperfections, misalignments, and structural element static deflection or wear. The thermal errors are thermoelastic deformation and are caused by temperature perturbation resulting from internal or external heat sources. The geometric and the thermal errors are generally categorized as quasistatic errors. In the 1960s, the significance of the thermal error in manufacturing and metrology and its possible solutions were already pointed out by some researchers (McClure, 1967; Bryan, 1968). The methods for testing the geometric and thermal error were summarized by Tlusty and Mutch (1973). By studying a large amount of data, Peklenik (Bryan, 1968) remarked that thermal errors could comprise 40–70 percent of the workpiece error in precision machining.

After geometric and thermal errors, cutting force-induced errors are the next most dominant source of machine tool errors. This problem has become more important recently due to the widespread use of hard machining techniques, where finishing quality is obtained directly from machining heat-treated materials, thus resulting in high cutting forces.

There are two basic approaches for the improvement of machine tool accuracy: error avoidance and error compensation (Hocken, 1980). The error avoidance method is to try to eliminate possible sources of errors through design and manufacturing efforts. Improving machine tool accuracy by careful design and manufacturing has been extensively used (Breev, 1951; Sata et al., 1975; Donaldson and Thompson, 1986; Sugishita et al., 1988). The error compensation methods involve the mapping of machine errors and then correcting for the effect of the errors.

It has been generally accepted that the elimination of the sources of errors through the refinement of the machine tool itself or its environment is more desirable than canceling the error through compensation. However, in many cases, there are physical limitations of machine tool accuracy that cannot be overcome solely by production and design techniques. Also, the further refinement of the machine tool structure for higher accuracy beyond a certain accuracy level is often very costly. Although this approach is indispensable to ensure basic machine accuracy, it is rather mature after many years of development, and the benefits of further refining are sometimes near the point of diminishing returns. In 1980, Sutton studied the costs of machining versus the level of achievable accuracy. His results showed the exponential increase of machining costs as the level of precision requirement tightens.

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Error Avoidance

The reduction of machine tool thermal errors has been researched in precision engineering for a long time. However, it was not widely noticed in the general manufacturing community or by the machine tool industry until the 1980s. The prime example of this effort and its success is the diamond turning center project developed at Lawrence Livermore National Laboratory (Donaldson, 1986), where thermally induced errors have been reduced to below ± 0.0025 μm. In order to achieve this accuracy level, many advanced techniques were applied. These techniques include air bearings for spindles and slides, low-thermal-expansion graphite material for machine structural elements, and high-efficiency cooling systems for the spindle and environment by which temperature variations were controlled to within a 0.05°C band.

In general, the techniques of building highly accurate and thermally stable machines can be classified as: (1) heat source reduction, (2) heat flow control, and (3) thermally robust structural design.

1 Heat Source Reduction. For high-precision applications such as machining optical components, reducing heat sources is almost always the most preferable solution. Usually, the strict control of environmental conditions (e.g., temperature and humidity) is required. If load-carrying demands are not too large, such as in high-precision diamond turning machines and CMMs, air bearings or magnetic bearings can be used for the spindle and guideway (Donaldson, 1986; Woytowiz, 1989) to greatly reduce the friction and thus heat generation.

Instead of constructing temperature-controlled rooms, recent development has focused on building temperature-controlled boxes which enclose the whole machine (Bosch, 1995). Temperature-controlled boxes use less energy and are cheaper than temperature-controlled rooms. Other advantages are that boxes save space and can be moved with the machine if necessary. In certain applications, heat exchangers have been used extensively to take away the heat generated by electrical motors and other heat sources.

2 Heat Flow Control. Passive heat control was studied by Takada (1987), who inserted insulation pads to control the heat flow between the main structural units (such as the bed or the headstock) and tried to make the thermal deformation of each unit uniform. In passive heat control, the insulation pad not only blocks the heat flow but also shapes the temperature field. With proper installation of the insulation pads, both the temperature field and the thermal sensitivity behavior of the machine structure can be modified.

Active heat control modifies the thermal distortion of a machine by using external heat sources. Bryan et al. (1972) proposed a temperature control scheme by using a liquid shower. Okushima (1973) used a finite element method (FEM) model to predict the thermal deformation of a machine tool and then implemented external heat sources on the critical points of machine structures to control the thermal deformations. Sata (1975) used external heat sources to shorten the time needed for warming up a machine and to reduce variation of the machine temperature distribution after machine warm-up. Otsuka (1977) used a lubrication temperature control system to reduce the thermal deformation. Nishiwaki (1974) used a heat pipe to shape the unsymmetrical temperature distribution of a machine structure into a symmetric one and to decrease thermal bending of the machine structure. Spur (1988) minimized the warm-up time by directly heating the spindle and the spindle housing. In many cases, heating an object is much cheaper than refrigerating it.

3 Thermally Robust Structural Design. This approach tries to eliminate the thermal effect through changes in machine structure and heat source designs. Much effort has been put into studying the thermal behaviors of machine tools since the early 1960s. Researchers have attempted to calculate the thermal expansion and distortion of the machine structure by analytical and numerical methods (finite element methods). In general, the concepts behind thermally robust structure design are based on the following considerations:

(i) design thermally symmetric structures,
(ii) design symmetric heat sources,
(iii) minimize thermal sensitivity of machine structures.

McClure (1967) researched the significance of thermal effects in machine tools. Yoshida and Honda (1967) investigated the relationship between thermal deformation and the temperature distribution using the analytical method and experimental verifications. Strain gauges were used to measure the deformation on a machine bed. In the 1970s, much work had been done to study the thermal behavior of machines using FEM. In 1973, Sata et al. used FEM to calculate the thermal deformation of machine tools and experiment data were used to evaluate the accuracy of predictions made with numerical methods. Okushima and Kakino (1975) used FEM calculations to optimally design a machine tool. Weck and Zangs (1975) used FEM to calculate the thermal behavior of a machine at the design stage to ensure optimal accuracy. Camera (1976) calculated the thermal deformation of a machine tool table using FEM. Spur et al. (1988) calculated the temperature distribution by using a simplified model of the spindle, thus optimizing the thermal behavior of a machine tool at the design stage. They also discussed alternative material for constructing machines. In a later work, Jedrzejewski et al. (1990) used numerical methods to optimize the design of a machine tool based on FEM. Wang and Moriwaki also presented an approach to dynamic analysis of thermal problems for machines under operating states (1994).

Although the FEM is a powerful tool in dealing with objects' complex geometry, it is usually not possible to use it to precisely model boundary conditions and heat sources of machine tools (Bryan, 1990). Therefore, computations to determine the thermal deformation behavior of machine tools provide no more than predictions of qualitative trends, due to the inadequacy of information on heat sources and boundary conditions at assembly joints. The inaccuracy of estimating boundary conditions and heat sources greatly affects the calculation accuracy of the FEM. Attia and Kops (1978) attempted to improve the accuracy of the thermal deformation calculation by investigating the thermal resistance of fixed joints. The effects of contact pressure and configuration were accounted for in this work. In a later paper (Attia and Kops, 1981), they used the FEM approach to model the relationship between contact pressure and thermal resistance and verified the results by experiments.

Error Compensation

Error compensation methods can be applied after a machine tool is constructed to compensate for the effects of machine error sources. The concept of error compensation is not new. A very good description on error compensation can be found in reference (Hocken, 1980). Error compensation methods had been used in many of the older generation precision machine tools. For example, mechanical compensation devices such as a compensation bar had been used to correct for inaccuracy in mechanical lead screws.

Error compensation involves either the direct mapping of machine errors or indirect kinematic modeling of machine errors. The direct mapping of machine errors can be obtained through the use of precision artifacts and/or measurement instruments. The map can be obtained with reasonable effort for geometric errors. It becomes rather difficult to obtain an accurate thermal error map because it is highly dependent on a

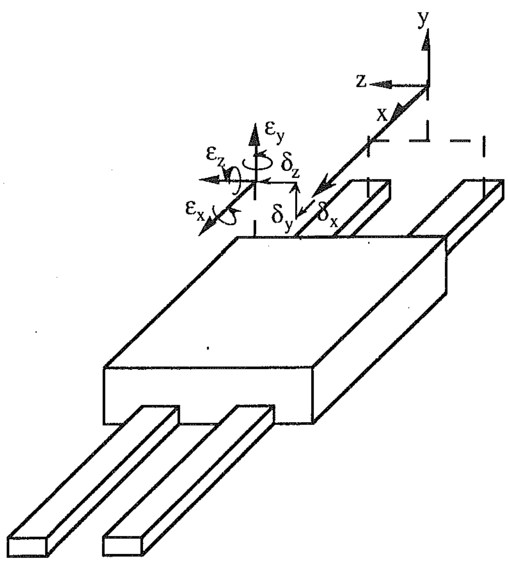


Fig. 1 Error components associated with a prismatic joint

number of factors such as machine working cycles, the use of coolants, environmental conditions, etc.

Kinematic modeling uses synthesis methods to estimate the position and/or orientation errors of cutting tools relative to parts based on the error components associated with each joint on a machine. These error components need to be identified through actual measurement, then modeled as functions of machine position and temperature field by empirical modeling techniques. During compensation, a compensation system predicts the final errors of a machine based on the kinematic model, the error component models, and real time feedback (such as temperature reading, axis positions, and cutting forces, etc.) and then compensates for the final errors in real time.

Early work on machine error compensation concentrated on modifying NC part programs based on the results of post-process inspection. Kolistor (1971) measured profile errors of machined parts and modified new NC codes for successive parts to correct the measured errors. During the 1970s and early 1980s, error compensation techniques were successfully developed for coordinate measuring machines (CMMs) (Hocken, 1977; Zhang et al., 1985). Today, almost all CMMs use in one way or another software-based error compensation methods to correct for the geometric inaccuracy inherent to the mechanical construction of the machines, such that the manufacturing costs have been drastically reduced (Kunnzmann et al., 1995).

1 Kinematic Modeling for Machine Errors. Figure 1 shows the structure of a machine prismatic joint. Theoretically, a translational machine axis (say, the x axis) has six error components associated with it—three translational errors in the x, y, and z directions (i.e., linear displacement error, δ_x, vertical straightness error, δ_y, and horizontal straightness error, δ_z), and three rotational errors about the x, y, and z axes, (roll error, ϵ_x, yaw error, ϵ_y, and pitch error, ϵ_z). Besides the six error components of each joint on a machine, there is also a perpendicularity or parallelism error between every two joints on a multi-axis machine.

The final errors between the tool and the part on a machine can be calculated using kinematic modeling techniques. To derive the kinematics of machines with complex configurations, homogenous coordinate transformation techniques have been used.

There has been extensive research on the modeling for the volumetric errors of 3-D machines. Early research utilized trigonometric relationships to derive geometric error models (Leete, 1961; French and Humphrier, 1967; Love and Scarr, 1973). Schultschick (1977) formulated a volumetric error model of a three-axis jig boring machine using vector chain expression. Three-dimensional measurement accuracy of CMM was enhanced by using a multi-dimensional error matrices model (Hocken, 1977). In 1986, Ferreira and Liu presented an analytical quadratic model for the geometric error of a three-axis machine tool based on the assumption of rigid body kinematics and small angle approximations. In order to simplify the analysis, the two straightness errors were treated as dependent variables of two associated angular errors in a single transformation matrix and the angular error components were assumed to be linear functions only. The advantage of using the quadratic model is that the resultant machine errors were presented directly in a parametric form. In a related study, Donmez et al. (1986) derived a generalized error synthesis model for turning machines. This model considered both the geometric and the thermal errors.

Other work in this area includes a study by Anjanappa (1988), who developed a kinematic model to synthesize all the geometric errors of a vertical turning center. Kurtoglu (1990) compensated for the volumetric errors of a milling machine by using a kinematic model which included 18 joint errors but not the perpendicularity errors. In 1992, Soons et al. presented a methodology to obtain an error model for multiaxis machines, including rotation axes. However, the model is not formulated in a systematic way.

Another innovation was illustrated by Chen et al. (1992). In this study, the rigid body assumption was removed and compensation was made for nonrigid body errors (Chen et al., 1992). Again, both geometric and thermally induced errors were modeled through a unified homogeneous coordinate transformation method, where 32 error components, instead of the conventional 21, were considered.

Lin and Ehmann (1993) presented a direct volumetric error analysis method for the evaluation of the position and orientation errors in the workpiece of a multi-axis machine. Their work provided a basis for the automatic derivation of error synthesis models for arbitrary machine configurations.

2 Error Identification Techniques. Because a kinematic error model calculates the final position and orientation errors based on the individual error components of a machine, it is necessary to identify the error components accurately and efficiently. Error identification methods can be categorized into (a) direct error component measurement and (b) indirect error component estimation. The direct error component measurement is performed by measuring the error components at different machine positions and under different temperature distributions, using measuring devices such as a laser interferometer or other mechanical or optical methods (Herreman et al., 1980; Ni et al., 1992). The indirect error estimation is realized by measuring the part profile error or the final volumetric errors of a machine, using measuring devices such as a telescopic (or laser) ball bar and estimating error components based on inverse kinematics techniques (Ziegert and Mize, 1994; Hai et al., 1994). The direct error component measurement is more accurate and straightforward, but sometimes more time-consuming. The indirect method offers a fast and efficient estimation of the machine error components.

A third approach involves the measurement of machined parts. Measurement of part size and form errors can be used to estimate the machine tool errors. Mou et al. (1995) developed an adaptive error identification method, which uses a feature-based comparison method to correlate the dimensional and form errors of a manufactured part to the systematic machine tool errors. Inverse kinematic techniques and statistical methods are used to identify and characterize the contribution of individual machine error components to imperfect part features.

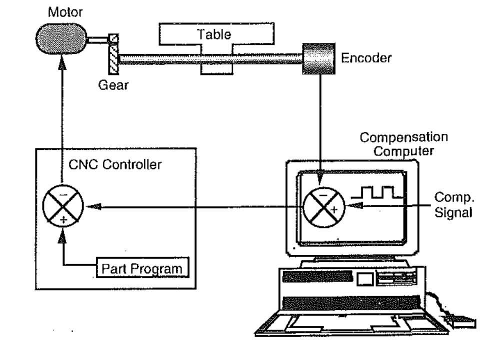


Fig. 2 Compensation by feedback interception of servo loops

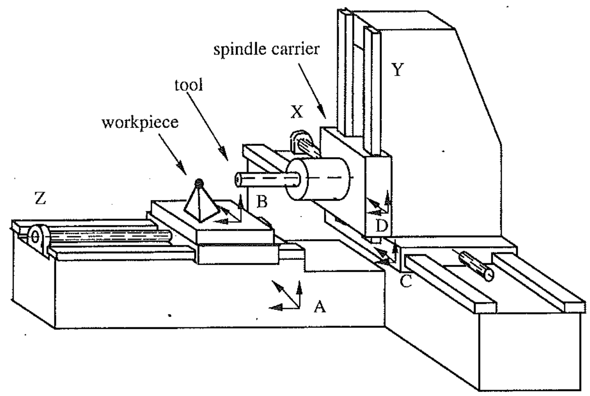


Fig. 4 Coordinate assignment for a three-axis CNC machining center

3 Implementation of Error Compensation Control. Error compensation is usually realized by moving the joints of a machine such that the tool and the part have a relative motion in the reverse direction of the machine volumetric error. For example, on a three-axis machining center, if the volumetric errors in the x, y, and z directions are ΔW_x, ΔW_y, and ΔW_z, respectively, then the x, y, and z axes need to be moved by the amounts $-\Delta W_x$, $-\Delta W_y$, and $-\Delta W_z$.

In early error compensation research, the compensation action was done through off-line NC code modifications. This method is rather tedious and assumes that the off-line identified errors would remain the same during actual machining. Recently, two different techniques have been developed to achieve real time error compensation: (i) a feedback interception method and (ii) an origin-shift method.

The feedback interception technique is implemented by injecting quadrature signals into the feedback loop of a servosystem. As shown in Fig. 2, encoder feedback signals are intercepted by a compensation computer. The computer calculates the volumetric error of a machine and injects or removes pulses which are equal to the calculated volumetric error into or from the quadrature signals. The servosystem will adjust the position of the slide accordingly in real time (Yee et al., 1990). The advantage of this technique is that it requires no modifications of CNC controller software. It can be applied to any CNC machine, including some old types of CNC machines, with position feedback of machine joints. However, specially developed electronic devices are needed to insert quadrature signals into the servoloops. These insertions can sometimes be very tricky and require extreme caution such that they do not interfere with the feedback signals of a machine.

The origin-shift method is illustrated in Fig. 3. The compensation computer calculates the volumetric error of a machine, then the amounts by which the machine axes need to be moved to compensate for the error. These amounts are sent to the CNC controller as compensation signals to shift the reference origins of the control system through an I/O interface, and are added to the command signals for the servoloop. This function is usually transparent to operators because compensation does not affect either the coordinate readings or the part program being executed on a CNC controller (Chen et al., 1993). The origin-shift method does not modify any CNC machine hardware; however, it requires modification of the programmable logic controller (PLC) unit of a CNC controller so that compensation values can be received at the CNC end, which may not be possible on some older CNC controllers.

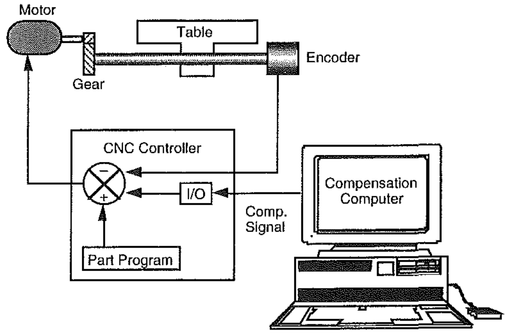


Fig. 3 Compensation by shifting the origins of machine axes

An Illustrative Example of Error Compensation Systems

Figure 4 illustrates a three-axis CNC machining center. To develop an error compensation system, the positional errors of a cutting tool relative to a workpiece should be estimated, based on the kinematic error synthesis model. For this three-axis machining center, there are 32 geometric and thermal error components, which include (1) errors associated with each moving axis, (2) orthogonality errors between any two machine axes, (3) spindle thermal growth and tilt, and (4) axis reference origin drifts (Yang et al., 1996a). To determine the tool tip errors relative to the workpiece in a three-dimensional space (i.e., volumetric errors), both the tool and the workpiece will be expressed using homogeneous coordinate transformation methods as follows:

$$\tau_A^C \tau_C^D \vec{T}_D(t) = \tau_A^B (\vec{W} + \Delta\vec{W})_B$$

where

$(\vec{W} + \Delta\vec{W})_B$: the ideal workpiece dimension vector $\vec{W}$ and the workpiece error vector $\Delta\vec{W}$ in the z-axis slide coordinate system B,

τ_A^B: the transformation matrix from the z-axis slide coordinate system B to the machine coordinate system A,

$\vec{T}_D(t)$: the vector of the tool tip in the spindle carrier coordinate system D,

τ_C^D: the transformation matrix from the spindle carrier coordinate system D to the x-axis slide coordinate system C,

τ_A^C: the transformation matrix from the x-axis slide coordinate system C to the machine coordinate system A.

By expanding all the matrices, the estimated workpiece volumetric errors can be solved for as follows:

$$\Delta W_x(t) = \Delta z x_x(t) + \Delta x y_x(t) + \Delta S_x(t) + \delta_{xx}(t) + \delta_{xy}(t) - \delta_{xz}(t) + L\epsilon_{\beta s}(t) + (T_z + L + Oxy_z)\epsilon_{\beta x}(t) + (T_z + L)\epsilon_{\beta y}(t) - (T_z + L + Ozx_z + Oxy_z - z)\epsilon_{\beta z}(t)$$

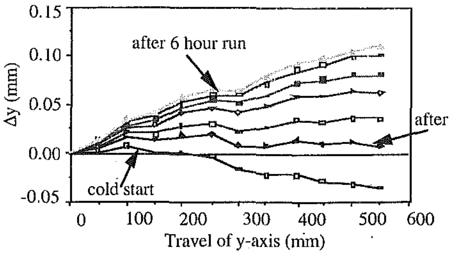


Fig. 5 An example of position- and temperature-dependent machine error components

$$- (T_y + Oxy_y + y)\epsilon_{\gamma x}(t) + T_y\epsilon_{\gamma y}(t)$$
$$+ (T_y + Oxy_y + y + Ozx_y)\epsilon_{\gamma z}(t) - yS_{xy}(t)$$
$$\Delta W_y(t) = \Delta zx_y(t) + \Delta xy_y(t) + \Delta S_y(t) + \delta_{yx}(t) + \delta_{yy}(t)$$
$$- \delta_{yz}(t) - L\epsilon_{\alpha s}(t) - (T_z + L + Oxy_z)\epsilon_{\alpha x}(t)$$
$$- (T_z + L)\epsilon_{\alpha y}(t) + (T_z + L + Oxy_z + Ozx_z - z)\epsilon_{\alpha z}(t)$$
$$+ (T_x + Oxy_x)\epsilon_{\gamma x}(t) + T_x\epsilon_{\gamma y}(t)$$
$$- (T_x + Oxy_x + x + Ozx_x)\epsilon_{\gamma z}(t)$$
$$\Delta W_z(t) = \Delta zx_z(t) + \Delta xy_z(t) + \Delta S_z(t) + \delta_{zy}(t) + \delta_{zx}(t)$$
$$- \delta_{zz}(t) + (T_y + Oxy_y + y)\epsilon_{\alpha x}(t) + T_y\epsilon_{\alpha y}(t)$$
$$- (T_y + y + Oxy_y + Ozx_y)\epsilon_{\alpha z}(t) - (T_x + Oxy_x)\epsilon_{\beta x}(t)$$
$$- T_x\epsilon_{\beta y}(t) + (T_x + Oxy_x + x + Ozx_x)\epsilon_{\beta z}(t)$$
$$- xS_{zx}(t) - yS_{zy}(t)$$

Detailed nomenclatures can be found in reference (Yang et al., 1996a). The above error synthesis models can be used to estimate the workpiece volumetric errors based on the information about individual error components. The error components can also be grouped into several categories according to the nature of the errors. These include: (1) pure position dependent errors, (2) pure temperature dependent errors, and (3) errors that depend upon both temperature field and axis positions. They can be modeled by the following models.

1 Pure Position Dependent Errors. The geometric error component of an individual machine axis can generally be represented by a high-order polynomial function of the machine axis position:

$$E_k(p) = \sum_{i=0}^{k} a_i p^i \quad p \subset \{x, y, z\}$$

2 Pure Temperature Dependent Errors. Temperature dependent errors such as spindle thermal growth are usually determined by the temperature field of the machine structure and, therefore, can be represented by the following equation:

$$E(t) = e_0 + \sum_{i=1}^{k} b_i\Delta T_i + \sum_{i=1}^{m}\sum_{j=1}^{n} c_{ij}\Delta T_i\Delta T_j + \ldots$$

3 Position and Temperature Dependent Errors. For certain machine error components such as the one shown in Fig. 5, the errors vary not only along the machine axis, but also according to different temperature fields. Fortunately, most of these errors do not change their basic profiles but only vary the slopes of the error profiles. Therefore, the separation of the geometric and thermal errors is done by estimating the variation of the slopes of the error profiles.

$$E(\mathbf{p}, \mathbf{t}) = E_k(p) + E_t(p, t) = \sum_{i=1}^{k} a_i p^i$$
$$+ p \cdot \left(s_0 + \sum_{i=1}^{m} s_i\Delta T_i + \sum_{j=1}^{n}\sum_{k=1}^{l} d_{jk}\Delta T_j\Delta T_k + \ldots \right)$$

To determine the model parameters for these error components, large amounts of experimental measurement data will be generated by running the machine through various working cycles. Under each thermal condition, individual machine errors and temperature field data are measured simultaneously. From the experimental data, the error component models can be estimated using multivariate regression analysis. The coverage of the working cycles should be as wide as possible such that all potential machine working conditions are taken into account.

A different approach, based on artificial neural networks, can also be used to model the machine volumetric errors (Narayan et al., 1993; Moriwaki et al., 1995; and Yang et al., 1996b). In this case, machine axis positions and temperature field data are used as input variables and fed into the input nodes. The tool positional errors relative to workpiece references are considered as output variables. This approach requires a significant amount of experimental data to train the neural network parameters.

Using the above error component models and the error synthesis models, estimated tool volumetric errors can be calculated from the axis feedback as well as temperature field measurements. The compensation for the predicted errors is implemented using the software CNC origin-shift method. One of the typical experimental test results is given in Fig. 6. The results are obtained with the application of real-time error compensation. Comparing this to the data in Fig. 5, it clearly shows that thermally induced errors can be controlled to a small range with compensation.

The effectiveness of compensation for both geometric and thermal errors has also been demonstrated in several industrial applications. One machine tool builder has implemented this technology on its twin-spindle CNC turning centers. A major aerospace manufacturer has also applied this technology to a large gantry-type CNC machining center for aircraft wing panel profiling. In another application, one automotive powertrain manufacturer has duplicated this error compensation technology onto multiple CNC turning centers to demonstrate its application in a mass-production environment. In all these applications, consistent error reduction has been achieved from several folds up to one order of magnitude.

Major Barriers of Error Compensation

Although real-time error compensation techniques have been successfully demonstrated in both research laboratories and industrial production facilities, there are still some major barriers before widespread applications are possible. More specifically, the following barriers need to be further researched and removed.

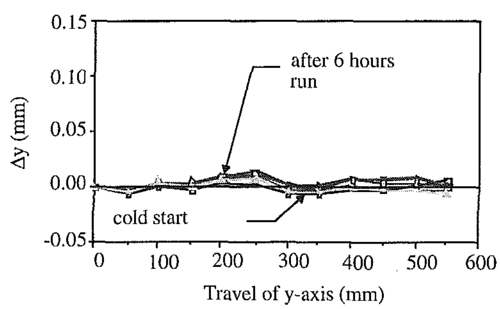


Fig. 6 Illustrative example of error compensation results

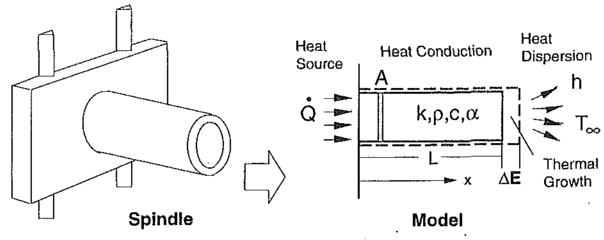


Fig. 7 One-dimensional model of a machine tool spindle

1 Sensor Placement. In almost all current implementations of error compensation systems, the determination of thermal sensor locations is somewhat empirical and through a trial-and-error process. It is usually done by first mounting a large number of sensors at locations determined based on the engineering judgment. Statistical correlation or pareto analysis is then used to select a smaller set of thermal sensors for error component modeling.

This empirical process is more like an art rather than a science. A good selection of thermal sensor locations becomes a key to the accurate modeling of machine thermal errors. The trial-and-error process also results in a significant waste of time and sensors that are not used for the final error modeling.

2 Lengthy Machine Characterization Period. Because of the complex nature of machine thermal behaviors, it usually takes a rather lengthy period of time to characterize these behaviors. As the machine thermal conditions are determined by many interacting factors such as ambient temperature, machine working cycles (spindle speeds and axis feed speeds), cutting conditions, coolant applications, etc., the characterization process requires the simulation of all these conditions. It takes many hours for a machine structure to reach its thermal steady state and then to cool it down to its original state.

Also, almost all thermal error models reported in literature use high order polynomials or nonlinear models such as neural networks. It is well known that nonlinear models or high-order polynomials have relatively good interpolation capability, but very poor extrapolation accuracy. Therefore, to train these thermal error models properly requires experimentation using a wide range of possible working conditions. Many potential users of this error compensation technology shy away because of the long period of time required to characterize a machine.

3 Robustness of the Error Models. A third concern is the robustness of the thermal error models. Whether a thermal error model trained in one season can still be used in another season is a realistic concern. What will happen if a machine's coolant temperature suddenly drops a few degrees? These are difficult questions to answer. The robustness of the thermal error models depends on the thoroughness of the training process, which again is related to the length of characterization time. It also depends on the thermal sensor placement and model structure. Clearly, all these three barriers are coupled together.

Several Ongoing Research Activities

In this section, several ongoing research activities are described. Some specifically address the technical barriers discussed above.

1 Optimal Sensor Placement Strategy. This research investigates a basic hypothesis: if a linear or nearly linear relationship between thermal errors and a selected set of measurements of temperature field could be found, the thermal characterization time could be significantly reduced due to the good interpolation and extrapolation capabilities of linear prediction models. The real questions to be answered are: (1) Is there a linear or nearly linear relationship between machine thermal errors and a selected set of temperature measurements? and, if the answer to (1) is "yes," (2) Under what conditions does this linear relationship exist?

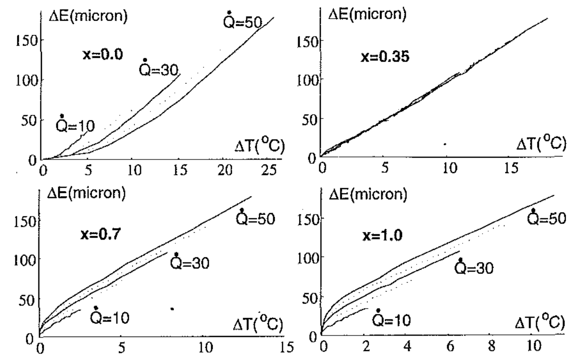


Fig. 8 Temperature-error relationship with different heat fluxes

Through the heat transfer analysis of a simplified one-dimensional spindle model depicted in Fig. 7, it is found that when a temperature sensor is strategically located, there exists a nearly linear transient relationship between the thermal growth of the spindle and the temperature reading at the selected sensor location. As shown in Fig. 8, when a sensor is located approximately around $x = 0.35L$ from the assumed heat source at the base end of the spindle, the total thermal growth at the free end of the spindle can be predicted based on a nearly linear function of the temperature readings taken at $x = 0.35L$. When the sensor is mounted at any other location, it is clear that nonlinear relationships are required to predict the thermal growth (Lo et al., 1996).

This preliminary finding has also been verified using a three-dimensional machine column structure as shown in Fig. 9. In this case, an analytical solution to the heat transfer problem becomes rather difficult. A finite element method is used to analyze the heat transfer problems. It has been demonstrated both numerically and experimentally that, when temperature sensors are placed at some "strategic" locations, linear models can be used for thermal error components. These linear thermal error models can be trained quickly and have relatively good extrapolation capability as compared with conventional nonlinear multiple regression models.

2 Thermal Sensor Failure Detection and Recovery. If a sensor fails during compensation, it could result in a wrong compensation signal and unacceptable parts could be produced.

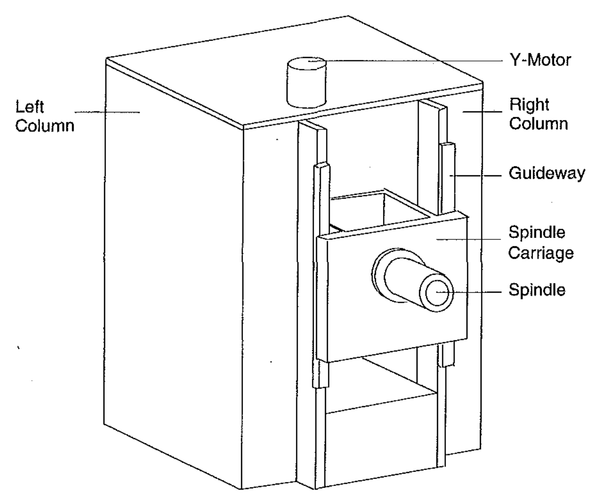


Fig. 9 Sketch of the machine column and the spindle

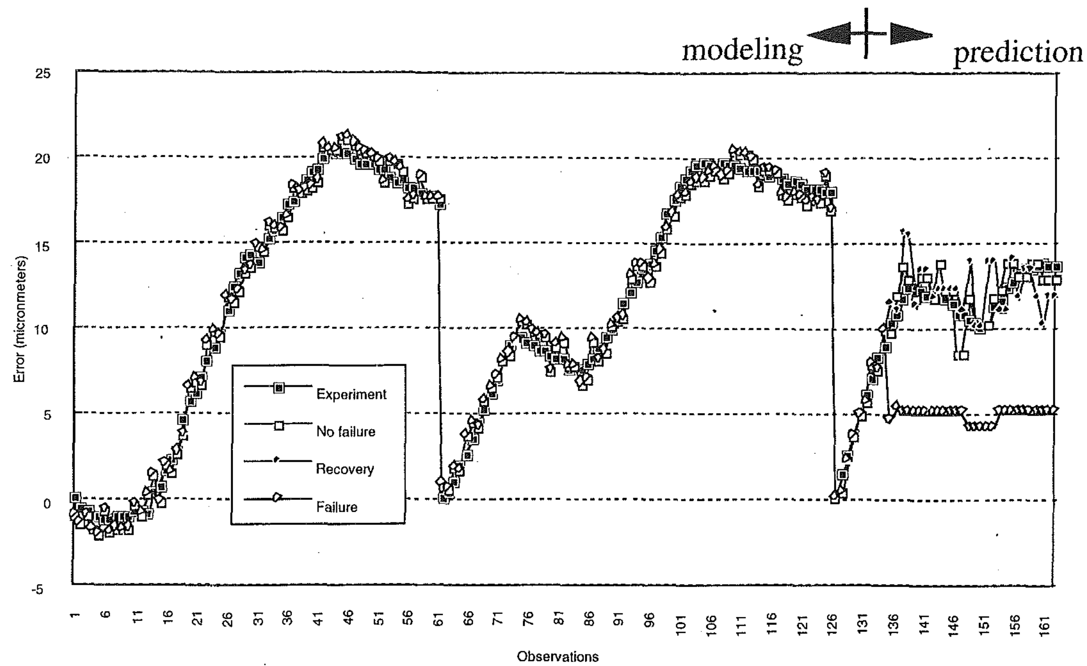


Fig. 10 Prediction of spindle error in the *x*-direction with and without thermal sensor failure recovery

Therefore, the ability to detect sensor failure is crucial. The proposed approach is to establish correlation models between different thermal sensors under normal working conditions (Yang et al., 1996b). The rationale is based on the fact that all the sensors are mounted on the same machine and are related by heat transfer properties (i.e., all the sensors are correlated to each other to a certain degree). Once the correlation of a sensor with others is far from the established range, it will be diagnosed as a defective sensor and the sensor value in the error model needs to be recovered by an estimated value.

The feasibility of sensor reading recovery is verified using four sensors for estimating the spindle drift in the x-direction on a turning center. The spindle drift error in the x-direction can be represented with the following equation.

$$\Delta x = f(\mathrm{T27, T84, T85, T90})$$

where Δx is the spindle drift in the x-direction; and T27, T84, T85, and T90 are the readings from these sensors. During the modeling stage (assuming normal sensor conditions), the spindle drift is modeled as a function of the four temperature readings. The correlation between sensor T27 and two other sensors, T26 and T29, is also established as the following:

$$\mathrm{T27} = g(\mathrm{T26, T29})$$

During the verification simulation (prediction stage in Fig. 10), sensor T27 was assumed to be defective and its reading was set to zero (or any other extreme value). Comparisons are made for three cases: (1) with no sensor failure; (2) with failure of sensor T27 and subsequent prediction based on recovered information from sensors T26 and T29; (3) with failure of sensor T27 and without sensor recovery. Figure 10 shows that recovery of sensor failure using correlated sensor data works well.

3 Cutting Force-Induced Error Compensation. As explained in the introduction, most of the current error compensation research has not considered cutting force-induced errors. It has been assumed that in conventional finish machining, the cutting force is small and the resulting deflection can be neglected. However, with the increased use of hard machining, cutting force-induced errors can become significant. In this study, a unique form of the planar error model is proposed to compensate for all the cutting force induced errors in a turning center (Yang et al., 1996c).

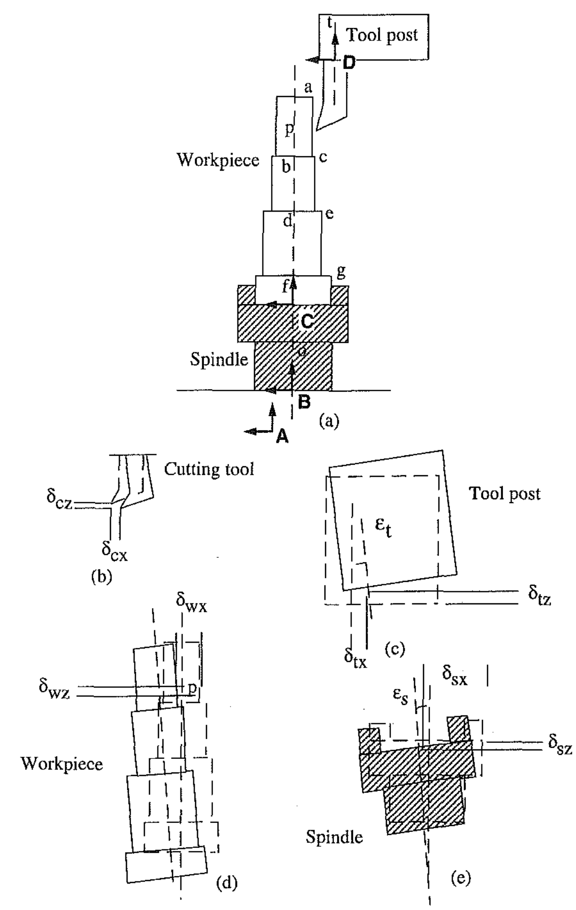
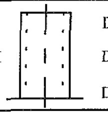
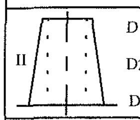
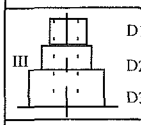


Fig. 11 Cutting force-induced error components in a turning operation

Table 1 Summary of the performance evaluation of the cutting force-induced error compensation

Type		W/O(mm)	With error compensation (mm)			Cutting parameter
			No. 1	No. 2	No. 3	
I 	D1	39.3700	39.3751	39.3751	39.3725	r = 750 rpm f = 190.5 mm/min d = 1.27 mm
	D2	39.3571	39.3725	39.3725	39.3700	
	D3	39.3370	39.3776	39.3751	39.3675	
Error (mm)		0.0330	0.0051	0.0026	0.0050	
II 	D1	38.8087	38.8214	38.8239	38.8188	r = 750 rpm f = 127 mm/min d = 0.254 - 1.524mm
	D2	38.8010	38.8239	38.8264	38.8239	
	D3	38.7858	38.8239	38.8290	38.8239	
Error (mm)		0.0229	0.0025	0.0051	0.0051	
III 	D1	39.3217	39.3243	39.3294	39.3243	r = 750 rpm f = 101.6 mm/min d = 0.508, 1.016, 1.524 mm
	D2	39.3192	39.3294	39.3294	39.3294	
	D3	39.2938	39.3344	39.3268	39.3217	
Error (mm)		0.0279	0.0101	0.0026	0.0077	

There are ten cutting force-induced error components for a two-axis turning center shown in Fig. 11. Six error components, related to the tool post and the spindle, are calibrated using a capacitance sensor system. Two error components related to the cutting tool are calculated theoretically based on the cantilever beam model. The other two error components, which are related to the workpiece, are calculated using a simplified finite element method in order to include all possible part geometry. This simplified finite element algorithm can be executed on-line to estimate the workpiece deflection under the influence of instantaneous cutting forces at different cutter locations.

The error compensation control is implemented on the turning center based on the software origin-shift approach. A compensation control system has been developed by integrating an IBM/PC computer with the existing CNC controller on the turning center. This compensation control system performs the following functions:

- Reads the cutting force information from an imbedded piezoelectric force sensor in real time.
- Reads the current positions of the slides from the rotary encoders or linear scales.
- Calculates all cutting force-induced error components using mathematical models.
- Calculates the planar errors in two directions using the cutting force planar error synthesis model.
- Transfers the planar error signals to the CNC controller to implement the planar error compensation in real time.

A series of cutting tests were conducted to verify the effectiveness of this proposed method. In the tests, three types of cutting were conducted. The results, shown in Table 1, demonstrate that use of this compensation system reduces the maximum diameter error by 85 percent for Type I cutting, 78 percent for Type II cutting, and 67 percent for Type III cutting.

Conclusions

The concept of error compensation to improve machine tool accuracy has been studied extensively for several decades in the research community. This research has reached a certain maturity and is almost ready for commercial applications. Several industrial implementations have demonstrated the effectiveness of software compensation for geometric and thermally induced errors in turning centers and multi-axis machining centers. However, further research is still necessary to remove a number of technical barriers, which include rapid machine characterization and robust modeling of machine thermal behaviors under varying machine cycling conditions and environmental conditions.

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