Error Compensation of Multi-axis Manufacturing Center

Yiding Wang, Kee S. Moon, John W. Sutherland
Dept. of Mechanical Engineering--Engineering Mechanics
Michigan Technological University
Houghton, MI 49931. USA

Guoxiong Zhang, Yanfen Zang, Xiaohua Chu, Junwen Du
Dept. of Precision Instruments Engineering
Tianjin University
Tianjin, 300072. P.R.China

ABSTRACT

In this paper, the practice of error compensation of multi-axis manufacturing center is presented. The general geometrical error model of the machine is developed using homogeneous matrix method. The geometrical error compensation of a Cincinnati-Milacron manufacturing center was realized using this model and the compensation result is checked by measuring different diagonals in the machine working volume. For the thermal error compensation, a new thermal error model is put forward which use the "grey system" theory. This model has the ability to describe the long-term, internal characteristic of the non-linear system. The practice of the thermal error compensation of the spindle displacement is presented. A theory for the selection of the locations for the transducers is put forward. This theory not only can be used in the selection of optimal locations for transducers in thermal error compensation, but can also be used in the temperature control practice of the machine.

Keyword: error compensation, machine tool, accuracy, volumetric error, thermal deformation, grey system.

INTRODUCTION:

The combination of metrology with production control techniques is an important new characteristic of modern production engineering. With the development of computer and high precision sensors, more and more attentions have been paid to the improvement of manufacturing accuracy. Generally speaking, there are two factors which affect the manufacturing accuracy of the machine tools [Hocken,1980]: (1) quasi-static errors: which are the errors of the relative position between the tool and the workpiece that are slowly varying in time and are related to the structure of the machine tool itself. These errors may be divided into three general classes: those due to the geometry and kinematics of the machine, those due to static and slowly varying forces such as the dead weight of the machine components, over-constrained slides, workpiece weight, and the like, and those due to the thermally induced errors in the machine tool structure. These errors cause the actual position to differ from the desired position which result in dimensional errors of the workpiece. 

(2) Dynamic errors: these errors are very complicated. They mainly affect some micro characteristic of errors of the workpiece, such as surface finish, etc.

Only quasi-static errors of the machine are studied in this paper and compensated in the research.

There are generally two concepts for the accuracy enhancement of machine tools [Hocken 1980]: (1) Error avoidance: this is a means of error reduction in which the source of the error or its coupling mechanism is eliminated. It usually needs a large amount of investment on the hardware of the machine. (2) Error Compensation: this is a means of error reduction whereby the effect of the error is cancelled. Error compensation method is a very cost effective method.

GEOMETRIC ERROR MODEL OF THE MACHINE

Because we desired to make the error model of the machine as simple as possible, we used the rigid body assumption to obtain the error model of the machine [Zhang,1985]. In defining their errors, we always assume there are only six errors for each axis: one positioning error, two linearity errors, one pitch error, one roll error, and one yaw error. For a 3-axis machine tool we studied, there exists three squareness error between each axis. So the total error sources are 21.

In most cases, 3-axis machine tools can be classified into four groups. They are FXYZ, XFYZ, XYFZ, XYZF [Hocken,1980]. The letters before F denote available motion direction of the workpiece with respect to the fixed frame, and the letters after F denote the available motion directions of the tool with respect to the fixed frame. For example, in group FXYZ the workpiece is fixed and in group XYZF the tool is fixed.

The displacement of any point on a rigid body can be regarded as the combination of the linear displacement
of the point and the angular displacement of the point. In analyzing
volumetric movement of rigid body, homogeneous matrix is a very efficient tool. The
homogeneous matrix of a 3 dimensional volume is a 4x4
matrix[Donmez.1986], that is:

\[
Q = \begin{pmatrix}
(C)_{n \times 3} & (P)
\end{pmatrix}
\begin{pmatrix}
0 & 0 & 0 & 1
\end{pmatrix}
\]

(1)

(C)\(3\times3\) denotes the angular error motion of x'y'y'
coordinate system from the xyz coordinate system. (P)
denotes the displacement of the reference point.

We regard X axis as the reference axis, XY plane as the
reference plane. Thus, when the bridge moves a nominal
distance x, the homogeneous matrix of this vector is:

\[
Q(x) = \begin{pmatrix}
1 & -E(x) & E(x) & x - \Delta(x)
\end{pmatrix}
\begin{pmatrix}
E(x) & 1 & -E(x) & \Delta y(x)
\end{pmatrix}
\begin{pmatrix}
-E(x) & E(x) & 1 & \Delta z(x)
\end{pmatrix}
\begin{pmatrix}
0 & 0 & 0 & 1
\end{pmatrix}
\]

(2)

When the bridge moves to a nominal distance y, the
homogenous matrix of the vector is:

\[
Q(y) = \begin{pmatrix}
1 & -E(y) & E(y) & \Delta y(y) - a_y y
\end{pmatrix}
\begin{pmatrix}
E(y) & 1 & -E(y) & \Delta z(y)
\end{pmatrix}
\begin{pmatrix}
-E(y) & E(y) & 1 & \Delta x(y)
\end{pmatrix}
\begin{pmatrix}
0 & 0 & 0 & 1
\end{pmatrix}
\]

(3)

When the bridge moves to a nominal distance z, the
homogeneous matrix of the vector is:

\[
Q(z) = \begin{pmatrix}
1 & -E(z) & E(z) & \Delta x(z) - a_x z
\end{pmatrix}
\begin{pmatrix}
E(z) & 1 & -E(z) & \Delta y(z)
\end{pmatrix}
\begin{pmatrix}
-E(z) & E(z) & 1 & \Delta y(z)
\end{pmatrix}
\begin{pmatrix}
0 & 0 & 0 & 1
\end{pmatrix}
\]

(4)

where E denotes the function of angular error, \(\Delta\) denotes
the function of positioning error, \(\alpha\) denotes the
squareness between axises.

We assume at the beginning of motion, all coordinate
systems of the machine (fixed frame, workpiece, axes,
tool) are aligned. In the actual manufacturing process,
the vector of the tool tip must be coincided with the
vector of the point to be machined on the workpiece.
of the position accuracy of this machine.

THERMAL ERROR OF THE MACHINE.

The effects of thermal error loom so large in modern precision manufacturing. Many specialist world wide share a common view that the errors caused by the thermal effect are at least equal to the errors caused by the geometry imperfections if not larger [Bryan, 1990]. Thermal errors have the potential threat to the quality of the production and also cause some troubles in improving the efficiency of production. So the benefit of reducing the thermal errors is remarkable.

In theory, the thermal error is directly related to the temperature rise of the thermal source. The temperature field of the thermal source can be described by [Okushima, 1974]:

\[ [C] \frac{dT}{dt} = [h][T] + [P] \tag{12} \]

[C]: thermal capacity matrix.
[h]: thermal impedance matrix
[p]: thermal load matrix.
[T]: temperature matrix

From thermal elastic theory, we have:

\[ [F] = [G][T] \tag{13} \]
\[ [F] = [K][U] \tag{14} \]

[F]: node force matrix.
[C]: transformation matrix of deformation-temperature.
[K]: rigidity matrix
[U]: thermal deformation matrix.

From (12), (13), (14) we can obtain the thermal deformation of the machine. So the thermal deformation can be obtained indirectly by measuring the temperature field changes of the machine.

THERMAL ERROR COMPENSATION MODEL OF THE MACHINE

The thermal deformation process of the NC machine is a non-linear, time varying, complicated system [Hocken, 1980]. The finite element method used by many scholars showed unsatisfactory result. One reason is that there are many assumptions in FEM which might not be true to the fact. The other reason is that it is very hard if not impossible to define the boundary conditions of this method. Besides, this method is time consuming and is hard to be used on line. Further more, thermal deformation has a sort of time-lag effect, that is, the current thermal deformation not only relates itself to the current state but also to the previous states (historical value). Hocken [Hocken, 1980] called this "memory of previous environment". FEM can not describe this phenomena.

In our research, a new model which is called "grey system model" is used. We regard the system in which information is completely known as a "white system", and in which the information is completely unknown as a "black system". For the system in which the information is not completely known, we call it "grey system" [Deng, 1987]. The grey system model is a kind of differential equation. It can describe the long term, internal developing trend of the system. The grey system model has the form of

\[ a x_1(t) + a_1 x_2(t) + \cdots + a_n x_n(t) \]

\[ \frac{dx_1(t)}{dt} = a_1 \frac{dx_2(t)}{dt} + \cdots + a_n \frac{dx_n(t)}{dt} \tag{15} \]

The superscript (1) denotes that it is the first order accumulation of the variable. We regard the thermal deformation system of the machine tool as a grey system. In this system, the completely known information include: temperature change of the temperature monitoring points, thermal deformation of the deformation monitoring points, etc. Other information such as how the thermal flow is propagated in the machine etc. is not available. For the machine in our research, because of its symmetric structure, the most significant thermal deformation is the spindle displacement in the Y direction. We mainly discuss this displacement. So we assume the time series of the deformation in Y discription as X1, the time series of the temperature change of the temperature monitoring points as X2, X3, Xn, and obtain the grey system model of thermal deformation—temperature change of the temperature monitoring points. The grey system model was constructed using least square method.

We obtained the grey system model of the thermal deformation—temperature change of the temperature monitoring points using the data in the beginning 30 minutes after the machine started to work. Then predicted the errors of the future using the obtained model, and made numerical correction by the software of the machine. The result showed that the grey system model is accurate in describing the spindle thermal displacement of the machine. The error of the spindle displacement in the vertical direction can be compensated up to 85% from our first stage experiments.

THEORY FOR THE SELECTION OF TEMPERATURE MONITORING LOCATIONS IN THE THERMAL ERROR COMPENSATION

The earliest practices of selecting temperature monitoring locations were solely based on experiences and therefore were not efficient. With the development of transducer technology and data acquisition technology, people tend to use as many transducers as possible with the expectations of obtaining high

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accuracy. But in practice, this is not beneficial to the result. One reason is that with more transducers used, the more the error source of the individual transducer will contribute to the final result. Besides, it is very inconvenient for the machine to operate properly with so many transducers placed on it. Also, it takes more time to process all the information provided by all the transducers, thus it is not good for on-line operation. So optimizing the selection of the locations for the transducers is beneficial to the simplification of the model and improvement of the reliability of the system. Last but not least, it is economical.

Here we briefly describe the theory for the selection of the locations for the transducers.

1. Pattern classification of the thermal behavior of the machine.

Different locations of the machine have different thermal behavior. First, we place as many as possible transducers on the machine to study the thermal behavior of the machine. We obtain the time series of the temperature change of every transducer and the time series of the thermal deformation of the point we want to study. We set up the AR model of the temperature change series as:

$$T(t) = \alpha T(t-1) + e(t)$$  \hspace{1cm} (16)

\(a = (a_1, a_2, \ldots, a_n)\) are the coefficients of the AR model, \(e(t)\) is the white noise.

We set up the second order model and use the coefficient \((a_1, a_2)\) as the characteristic parameter for pattern classification. The pattern classification was realized by using fuzzy ISODATA method. So the various transducers can be classified into a few groups and we can choose one transducer from every group as the characteristic transducer.

2. Optimizing the selection of the locations for transducers

Although the characteristic transducers are obtained, the function of every transducer in describing the thermal behavior of the machine is not the same. Our objective is to select the few points that will best describe the thermal behavior of the machine. In our study, we employ the so-called "B type relevancy" in grey system theory. B type relevancy shows how close the relation is between the change of the process and the cause of the change of the process. We calculate the B type relevancy coefficient of the thermal deformation series to the temperature change series of every characteristic transducer. We select the few locations where the transducers have the biggest B type relevancy coefficient with the thermal deformation as the temperature monitoring points.

CONCLUSION

This paper describes an on-going research for the error compensation of the multi-axis manufacturing center. Error compensation method is a means to improve the accuracy of the machine without making many hardware changes of the machine. It is an economical method in improving the machine accuracy. Besides, error compensation method has a great impact on the design concept, that is the previous pursuit of higher accuracy can be directed toward the pursuit of stability and reliability [Zhang, 1985] so a good error budget can be achieved. Using error compensation methods, we can realize so called "precision machining without precision machinery" [Wu, 1989]. Future work should include: quick method for machine calibration, high quality software for error compensation, thermal error prediction and compensation of the machine in the real workshop conditions.

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