A REAL-TIME ERROR COMPENSATION SYSTEM FOR A COMPUTERIZED NUMERICAL CONTROL TURNING CENTER

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ABSTRACT

A real-time compensation scheme for geometric and thermally-induced errors of a computerized numerical control (CNC) turning center is described. The compensation system predicts these errors using a combination of data taken from various sensors on the machine tool and previously established relationships (transfer functions). The system translates these errors into servo counts and injects them into the control loops of the machine tool controller in real-time. A single-board microcomputer interfaced to the machine tool controller and the sensors is the workhorse of the system. The system control software written in PLM, a high level programming language, is modular, flexible, and easily maintainable. To evaluate the capabilities of the compensation system, a series of cutting tests have been performed, and the results are presented. Along with the elimination of machine warmup periods of 8 to 12 hours, significant geometric accuracy improvements in straightness and squareness have been achieved. An additional accomplishment is a dimensional accuracy improvement of up to 20 times over that of uncompensated workpieces.

INTRODUCTION

Reducing the errors of machine tools used in metal cutting operations is a key requirement for improving workpiece accuracy. The elimination of the nonproductive warm-up cycle commonly used to reach thermal equilibrium would greatly improve productivity when machining precision parts. The purpose of this study is to develop a method that can be used to compensate for the quasistatic geometric and thermally-induced errors of a computerized numerical control (CNC) turning center, in real-time, in order to improve the accuracy of turned parts. This compensation is accomplished by a modular, easily maintainable software system, implemented in a dedicated, low cost, single-board microcomputer. The purpose of this paper is to describe the interface requirements and the hardware implementation of the error compensation algorithms and to present some results of the implementation. A rigorous treatment of the mathematical analysis necessary to develop the software as well as a description of the measurements required for the implementation is given in reference 1.

Error compensation is defined as a method of canceling the effect of systematic errors either by directly or indirectly measuring these errors, or by predicting them using a model previously established for the process[2]. Early works on error compensation of machine tools concentrated on active error compensation, in which the error was monitored and compensated for during machining operation. Leete[3] developed a method for compensation of unwanted rotations and translations of machine tool slides by measuring them against a reference plane. Later, Goodhead et al.[4] modified this method using a nonperfect, but precalibrated straightness reference. A Lawrence Livermore Laboratory team used similar techniques in their designs of a coordinate measuring machine and diamond turning machines[5 6].

All the active error compensation techniques mentioned above are in real-time and are very effective for reducing the errors. However, the requirement of attaching highly sensitive measuring instruments to moving machine elements in a cutting environment, and in some cases the impossiblity of making a measurement during machining operation, make this approach very difficult and impractical for many machining operations.

Efforts by Thompson[7] and by Koliskor et al.[8] used the technique of modifying the NC program tapes based on the measured profile errors after the machined part was traced. This method does not compensate for thermal errors and is impractical for small batch sizes. With the increased capability of computers, there is a new trend toward predicting errors by using models and/or previously determined error maps[9 10]. Although most of the efforts are still toward updating NC programs[11 12], some pioneering applications exist using computers in real-time compensation of predicted errors during machining operation[13 14]. None of these applications appears to deal with the changes in the geometric errors due to the changes in the thermal characteristics of the machine tool during the warm-up period. Furthermore, the computers used in these systems are minicomputers, which have high computing power but prohibitively high cost for such applications.

Even if one can determine workpiece errors there is one additional problem. A large minicomputer can be used to predict the errors in real-time but it is difficult to interface the computer to the CNC controller because the controller has little to no provisions available for interfacing. In a typical machine tool, the axis servo motor drives the leadscrew based on the error signal derived from the position command, the position feedback, the velocity feedback, and motor current feedback signals. The position feedback signal comes from a feedback element such as a glass scale, an encoder, an inductosyn, or a resolver. There are two approaches to apply the computed error compensation. One method is to apply error compensation in real-time to the position feedback signal by injecting the compensation signal into the servo control loop hardware in the form of an analog voltage. A compensation system using this technique has been implemented on a CNC controller on a machining center at National Bureau of Standards (NBS)[14]. In some machine tool controllers, due to the fact that the axis servo control is implemented in a software algorithm, it is not possible to break into the servo control loop electronics to properly inject a compensation signal. In this case, the compensation signal must be injected into the controller, in digital form, through input/output (I/O) ports to be manipulated by the control software. However, no matter which of the two techniques are used, the injection of the compensation signal does not interfere with the normal operation of the machine tool controller and requires no extensive modifications to the controller electronic hardware.

The compensation system developed in this study, which is implemented on a Hardinge Superslant CNC Turning Center†, injects the compensation signals into the axis-servo control-loop software. The details of this system as well as the results of the error correction are presented here.

THE PRINCIPLES OF THE COMPENSATION SYSTEM

The errors for which the system compensates are quasistatic geometric and thermally-induced errors. These errors are predicted by using relationships previously established between systematic errors and the errors associated with a particular machine tool temperature profile. In the process of building these relationships, the geometric errors were measured using a laser interferometer and high precision capacitance probes. The errors associated with a particular temperature profile are determined by monitoring thermocouples placed in critical locations: the leadscrew nuts and bearing housings, the spindle bearing housings, the headstock, the bed, several points on the cross slide and the carriage bodies.

†Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

The relationships for each type of error, such as linear displacement, straightness, yaw, and orthogonality, are established by applying least-squares curve fitting techniques to the error data and the corresponding temperature profiles for each element of the machine. The error data was taken automatically by a desk-top computer over a warm-up period of two days in order to cover the whole operating temperature range of the machine tool. While temperature was being monitored, geometric error data was collected. The locations at which the temperature readings were best correlated with the geometric errors were selected as the best representative locations at which to predict thermally-induced errors. After predicting each error component, the system uses the principles of rigid body kinematics to combine the error components in order to find the error at the cutting tool. The overall system uses three types of independent parameters to calculate the error: 1) the nominal axis position, 2) the direction of motion, and 3) the temperatures of the previously selected locations. The selected locations for temperature measurements are: the spindle rear bearing housing, the leadscrew rear bearing housings for the cross slide and the carriage, the cross slide slideway, and the carriage body. In addition to the direct temperature measurements, a tool-setting station is used to measure drift of the machine reference points due to the machine tool frame migration during operation.

The actual error compensation is achieved by sending the error values to the machine controller. The machine tool controller acts on the compensation values in software, thus, no modification to the machine control hardware is necessary. The schematic of the software servo control loop is shown in Figure 1. In the turning center, the machine tool controller updates the axis position data every 20 milliseconds. Meanwhile, the compensation microcomputer, which runs in synchronization with the machine tool controller, receives the position information from the machine tool controller at the same rate. Based on the current position, direction of motion, thermal data, and the information obtained from the tool setting station, it calculates the errors along both machine axes corresponding to the current position and sends them to the machine tool controller. The controller receives these values via parallel I/O ports and adds them to the registers containing the following errors. The following error is defined as the lag of actual axis position from the commanded position by an amount proportional to its velocity. The position command signal summed with the following error will be the error signal used to drive the axis servo in the next servo cycle. Using this technique the servo control timing of the machine tool controller is unchanged and, best of all, the basic servo control algorithm is undisturbed.

SYSTEM HARDWARE

The overall compensation system, which is shown in Figure 2, consists of the following components:

1. Remotely controlled digital temperature measurement system
2. Turning center keyboard interface module
3. Tool-setting station
4. Multibus†, 8086-based single-board microcomputer for the compensation controller
5. Machine Tool Controller interface

The temperature measurement system is used to monitor the temperatures at the previously described points on the machine. This system consists of signal conditioning and digitizing electronics, and a 10-channel scanner. It communicates with the single-board microcomputer through an RS-232 interface. Upon receiving a command from the microcomputer, it digitizes the appropriate channels, and returns the temperature information.

The keyboard interface module, designed and built by NBS, is based on an 8048 single component microcomputer. The function of this module is to translate commands from the compensation controller and enter it into the machine tool controller by emulating the keyboard operation. This module is necessary for moving the machine tool axes to the proper positions so that the tool-setting station can determine the offsets of the machine reference points.

The tool-setting station, also developed by NBS, is a linear variable differential transformer (LVDT) displacement measuring device. It is mounted on the spindle and controlled by an 8088 microprocessor to linearize its output and reduce the nonlinearity of the LVDT from ±0.25% to ±0.024%. The algorithm and the technique for linearization is described in reference 15. The tool-setting station is used to measure the displacement along both x and z machine axes. A special gauge bar is mounted on the tool turret. The bar is used with the tool-setting station to determine the machine reference drift over time.

A multibus single-board microcomputer with 128k RAM memory is the main controller of the overall system. This microcomputer board contains a 16-bit 8086 microprocessor as the CPU, and a high-speed version 8087A numeric coprocessor for floating point arithmetic operations. The architecture of this board is designed for high speed floating point numeric computations which are necessary for real-time operations. The combination of 8086 and 8087A makes it possible to run the computer at an 8-MHz clock rate to meet the requirement of high servo bandwidth for contouring cuts. This microcomputer uses a multibus serial I/O board with four RS-232 serial I/O ports to communicate with the other components of the system, such as the temperature measurement system, the tool setting station, the keyboard module, and a CRT terminal that is used for data entry and control. Communications and control for the Allen-Bradley 8200 CNC† machine tool controller are obtained via three multibus parallel I/O boards, one for each axis and one for command-status protocol.

SYSTEM SOFTWARE

The main criteria for the system software are flexibility, modularity and easy maintainability. To meet this criteria, a high level language, Programming Language for Microcomputers (PLM), was selected as a programming language for the compensation system. PLM is a structured language, similar to PL1, which has facilities for such data structures as structured arrays and pointer based dynamic variables; this helps in building modular software. Using these facilities, the calculations for different error components are carried out in modular fashion so that it is possible to include modules to correct for other error sources which might be found in the future.

This system, of which the flow chart is shown in Figure 3, performs three major operations. The first is to measure the machine reference offsets, which are obtained by activating the tool-setting station with the reference gauge bar mounted in the turret. The second operation is to measure the tool offsets. Due to current limitations of the tool-setting station, this part of the software is left to be developed at a later stage. Currently, tool offset parameters are manually entered into the compensation controller. The third operation is to calculate the systematic errors and those caused by thermal changes and to inject the servo counts corresponding to these errors. This operation requires that the compensation controller be in continuous communication with the machine tool controller. Based on the nominal x and z positions obtained from the machine tool controller and the temperatures obtained from the temperature measurement system, the compensation software calculates the resultant error along both machine axes. After the resultant errors are calculated, the values are converted into servo resolution counts, and then fed to the machine tool controller. The details of this operation are explained in the following paragraphs.

Instead of traditional relay or solid-state logic panels for machine/control interfacing, this CNC machine-tool controller uses a software feature, Programmable Application Logic (PAL). This software synchronizes all the control functions with the machine tool's logic. PAL programs are written in a programming language that consists of a set of ladder diagram instructions. With these instructions, it is possible to create rungs of logic that can perform a variety of functions such as basic relay logic, timer counters, and double precision arithmetic operations. It is also possible to access data tables within the controller, which contain information about the status of machine tool (active miscellaneous preparatory codes, tool function codes, and spindle codes) and to write to some of these tables in order to modify their contents.

Obtaining the nominal position information and injecting the compensating servo counts are done through these tables. The PAL program can monitor the information contained in a data table and control outputs to the machine tool in response to this data. The operation of the machine requires the iterative execution of the PAL instructions periodically. The PAL program cycle is 20 milliseconds. PAL inputs data as the instruction is being executed, but all the outputs are executed at the end of the PAL cycle. Other machine tool controller manufacturers achieve similar functions by different methods.

In order to synchronize the compensation controller with PAL, handshaking is established between the compensation controller and the machine tool controller. To do this, along with the updated error servo counts, the compensation controller sends an incremented index code to PAL, to differentiate between the old and the new sets of servo counts. Since the error calculation takes about 10 milliseconds, the new set of servo counts corresponding to a current position is received by PAL in the next cycle. Therefore, there is a maximum of 2 cycles (40 milliseconds) time lag between a nominal position and the compensation execution corresponding to that position. The timing diagram of this operation is shown in Figure 4. The 40 milliseconds time lag does not cause any problem in the machining operation due to the fact that the tool motion is slow in comparison. For example, for a typical 6 inches per minute feed rate, the machine moves only 0.004 inches during such an interval. The difference of the systematic errors between two points 0.004 inches apart is negligible. Due to this limitation, the compensation system works more accurately at slower feed rates. Feed rates up to 60 inches per minute, however, will not significantly decrease the accuracy of the system.

PERFORMANCE TESTS AND RESULTS

To test the capability of the error compensation system, a series of cutting tests have been performed. These tests are based on the comparison of the dimensional and the geometric accuracies of parts machined under similar conditions with and without error compensation. The machine requires about 8 to 10 hours to reach thermal equilibrium from a cold start. It is important for the system to be able to respond to such a thermal transition condition. A batch of parts is machined without error compensation over this thermal transition period with a waiting time between each part. While the machine is not cutting, it continues running to warm up. Another batch of parts is machined, from a cold start, under the same conditions with error compensation applied.

In these experiments, cutting is carried out by turning and facing two types of workpieces. The first type is turning of a cylinder 1-5/8 inch in diameter and 8 inches long. This piece is used to check the accuracy on the diameter, the taper, and the straightness of the cylindrical profile. The second type, which is used to check the squareness and the length accuracy, is a 4-inch diameter, 3.5-inch long cylinder which is faced.

AISI 1018 mild steel is selected as the workpiece material for its good machinability and low thermal coefficient of expansion. To minimize the static cutting force and to obtain the best possible finish, the combination of 1100 feet per minute surface speed, 0.0025 inch per revolution feed rate, and 0.005 inch depth of cut is selected as the cutting conditions. A 15-degree positive rake tool holder with 80-degree diamond shaped titanium nitride (TiN) coated insert is used in the tests.

The measurements of the machined parts were carried out on a coordinate measuring machine with a measurement uncertainity of 60 microinches. The results of these measurements are summarized in Tables 1 through 4. In these tables the data is given in the temporal order in which the parts are machined. The first set of data in these tables correspond to the parts machined when the machine was cold, while the last set correspond to the parts machined when the machine was warmed up at the end of approximately 8 hours of running. As seen from these tables, the ratio of the dimensional accuracy improvement using error compensation over the uncompensated parts increases as the machine warms up. In the last machined pairs the accuracy on the diameter improved from 2230 microinches oversize to 150 microinches undersize, and the length improved from 6390 microinches oversize to 450 microinches oversize. Alternately, error compensation for tapers is not as essential once steady-state temperature is reached as it is for dimensional accuracy. Figure 5 shows the comparison of cylindrical profile straightness of two parts machined under similar conditions with and without error compensation. The significant increase in geometric and dimensional accuracies of the machined parts demonstrates that the real-time error compensation approach is achievable and results in an increase in precision of the machined part of up to 20 times in length and up to 15 times in diameter.

CONCLUSION

Based on previously established relationships for geometric and thermally-induced errors of the machine tool, a real-time compensation system has been developed. Two main components of the system are an inexpensive single-board microcomputer and modular and easily maintainable software written in a high level language. The performance tests carried out under the transient thermal conditions showed significant geometric and dimensional accuracy improvements of up to 20 times over the parts machined without error compensation. While attaining high accuracy at a low cost, the system also eliminated the machine warm-up periods which are common practice in a typical machine shop environment for precision parts, thereby improving equipment utilization.

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Table 1. Error in Diameter
(Nominal diameter: 1.605 in.)

Compensated (μin.)	Uncompensated (μin.)	Improvement (ratio)
650	1300	2.00
530	1050	1.98
270	1030	3.81
-130	1470	11.31
-150	2230	14.87

Table 2. Error in Length
(Nominal length: 3.44 in.)

Compensated (μin.)	Uncompensated (μin.)	Improvement (ratio)
-150	570	3.80
390	4410	11.31
-250	5240	20.96
-90	-480	5.33
450	6390	14.20

Table 3. Error in Taper
(On diameter of 1.605 in.; along 2.7 in. length)

Compensated (μin/in)	Uncompensated (μin/in)	Improvement (ratio)
26	85	3.27
18	88	4.89
-44	95	2.16
-8	-7	0.88
4	17	4.25

Table 4. Error in Squareness
(On the radius of 1.99 in)

Compensated (μin/in)	Uncompensated (μin/in)	Improvement (ratio)
33	44	1.33
39	9	0.23
26	37	1.42
54	79	1.46
32	58	1.81