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An Intelligent Thermal Error Compensation System for CNC Machining Centers

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Abstract

.A measurement and compensation control system for the spindle thermal expansion of machine tools has been developed in this study. The low cost but accurate thermal sensor of AD 590 IC and the tool setting probe MP4 of Renishaw Co. were developed for the measurements of temperature and spindle expansion respectively. Instead of the non-cutting condition as specified by the ISO230-3, the proposed thermal error model is derived from the real cutting condition. With the proper selection of sensor locations, a linear error model with respect to only one or two temperature terms could always be obtained. An embedded error compensation system using an 8051-based single board computer was then developed to compensate for the thermal error in real time. As the error model can be generated in one day under hazard conditions and the whole system is low cost, this system is suitable for industrial use. The intelligent features of this system include: fast model generation, self-malfunction detection, real-time temperature display, EMI removal, automatic compensation, and suitable for most ambient conditions. Experimental tests show the thermal error of a general type CNC machining center can be controlled to within 10μm.

Keywords: Machine Tool, Thermal Error, Real cutting condition, Error compensation.

1. Introduction

The main reasons for dimensional and geometric errors in workpieces produced on machine tools include low static stiffness of the machine structure, low dynamic performance of feed drives, tool wear and thermal deformations of the tool, machine and workpiece. Among which, the thermal error is the most important source, which significantly influences the machining accuracy of the machine tools. Thermally induced deformations in machine tools lead to thermal drift displacements between tool and workpiece, as shown in Fig. 1 [1]. There have been many research reports in this subject over the past years. A reduction of the thermo displacements of more than 80 % of the initial value is possible [2-8]. Some of them utilize various sophisticated models, which do not meet industrial requirements in terms of the cost and simplicity. In addition, many researches follow the current ISO 230-3 international standard that still specifies to experimentally generate the thermal error model of the machine tool under non-cutting (air-cutting) condition [9]. The proposed 5-channel non-contact displacement setup by ISO is shown in Fig. 2. It, in fact, does not exactly reflect the real phenomenon in industrial practice, where any machine tool must cut the metal to produce the part. Therefore, thermal error of the machine tool should be paid with more attention under the real-cutting condition [10-13]. Major considerations are not only to the effectiveness and applicability but also its cost and simplicity in the model generation and error compensation within a very short time.

In this report, a fast and low cost thermal error measurement and compensation system is proposed. The thermal sensor was developed using an AD 590 IC, which performed high accuracy for a long period. The thermal displacement of the spindle was measured using a tool setting probe, which is a standard accessory installed in most machine tools. The thermal error model was generated under real-cutting conditions on steels, which are widely used in machine shops. With the proper selection of sensor locations, the thermal error of any particular machine can be modeled by a linear function with least temperature terms. The diagnosed error model could be stored in a developed single board computer from which the compensation commands could drive the CNC controller to implement real-time error compensation without interrupting the existing NC program.

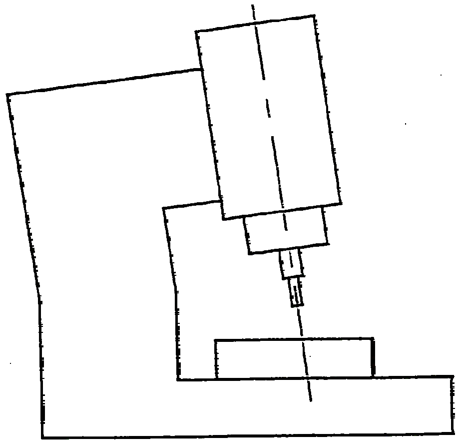


Figure 1: Sketch of C shape machine tool with thermal distortion

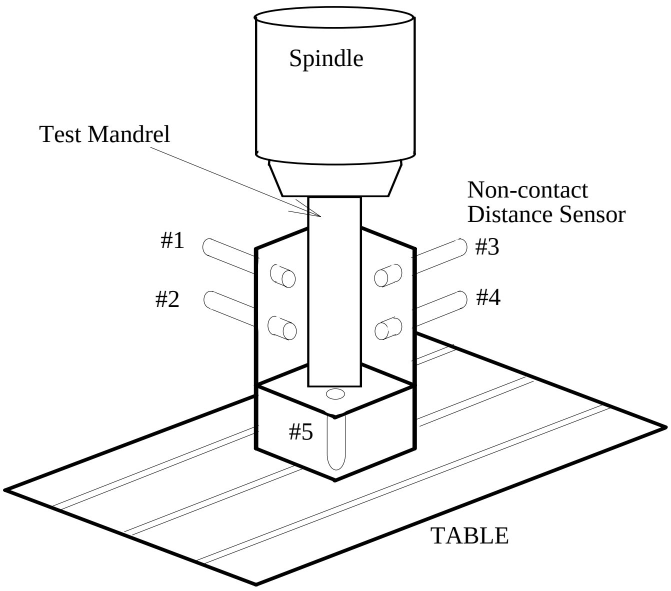


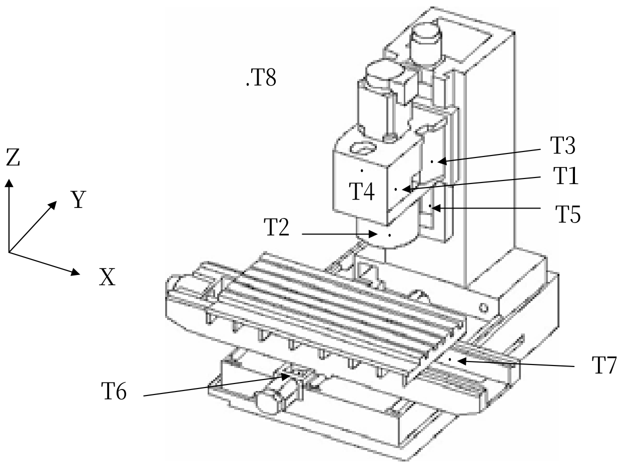
Figure 2: Non-cutting test of spindle thermal drift

2. The Measurement System

2.1 Temperature measurement

In general, thermal couples and thermistors are widely used for the temperature detection on the machine structures. Its characteristics of epoxy bonding, however, brings disadvantages to the machine tool applications since the actual temperature rise is small and the best sensor locations are unknown in the early stage. This research selected a low cost IC-AD590 (US$2 per piece, range to 150℃) and packaged it into a magnetic ring so that it can adhere to the detected metal part and become a portable temperature detector. An

8-channel A/D converter board was also designed to simultaneously detect eight temperatures located around the machine, as shown in Fig. 3(a). Figure 3(b) shows the exploded view of the compact sensor. The sensor positions should be close to the heat sources and sensor amount is dependent on the complexity of the machine tool to be investigated. In this Figure, the eight sensor locations are listed in Table 1. It is noted that the ambient temperature (T8) will also influence the thermal behavior of the machine tools. Calibration results of eight AD-590 sensors using the HP 2804A Quartz Thermometer have proved that all sensors performed very good linearity with accuracy all within 0.7 ℃, and resolution to 0.1℃, as shown in Fig. 4.



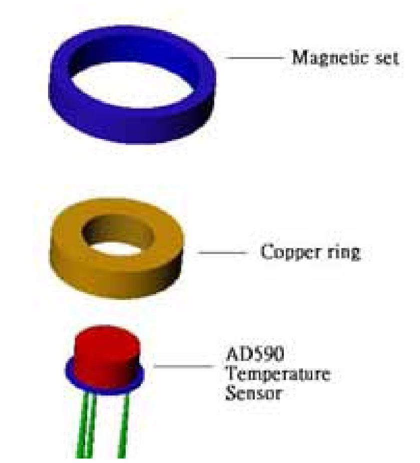


Figure 3: (a) Initial locations for temperature sensors, (b) Exploded view of the sensor.

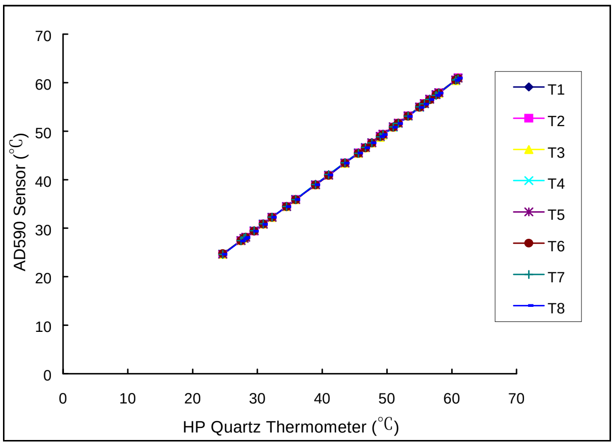


Figure 4: Temperature sensors calibration results

Table 1: Locations of mounting thermal sensors

Sensor number	Location

T1	Side of headstock
T2	Spindle case
T3	Side of Z-slide
T4	Spindle motor
T5	Ball screw nut of Z-axis
T6	Ball screw nut of Y-axis
T7	Ball screw nut of X-axis
T8	Room temperature

2.2 Thermal displacement measurement system

There are several means of spindle thermal drift measurement vs. workpiece table, such as 5-channel displacement transducer equipment [9] and the laser ball bar [14]. Such equipments are only suitable for the measurement under air cutting condition. This research, therefore, directly utilized the function of the tool-setting probe (MP4 of Renishaw Co.), which is a common accessory for the settings of the tool length and the cutter radius. Fig. 3 shows if we detect the touch-triggered positions of spindle in Z direction at cold start and after a machining cycle the positional change will be the amount of spindle expansion. This technique can actually apply to the thermal drift in three dimensions, as shown in Fig. 5. The repeatability of the touch-triggered probe was found only 1 μm. It is deemed as a very useful tool for this purpose.

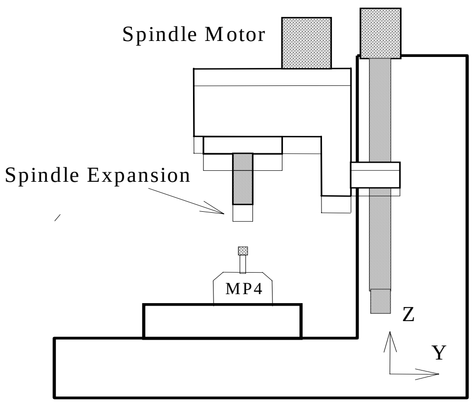


Figure 5: Spindle thermal expansion

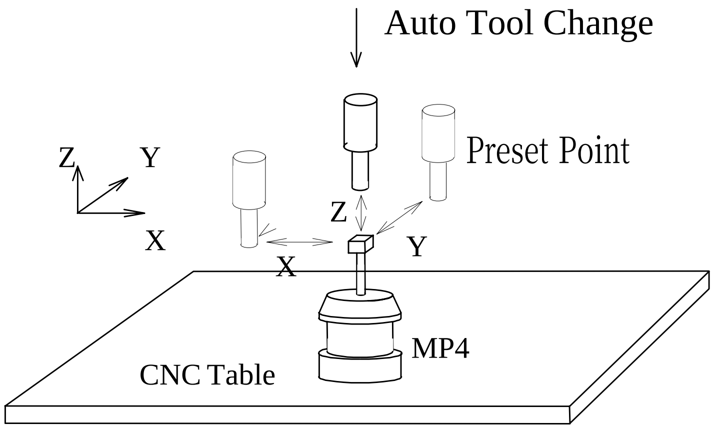


Figure 6: 3-D touch triggering

3. Thermal Model Generation

3.1 Experimental setup for real cutting tests

The procedure of temperature and spindle expansion measurements under real cutting condition is illustrated in Fig. 7. A DNC command is sent to the machine tool controller via RS232 interface by a personal computer. The real cutting process will be carried out on a steel block, such as S50C or the mold steel SKD61. These steels are commonly used in the machine shops. After a prescribed time the cutter will be replaced by a standard bar at the tool changer. An in-cycle gauging is implemented by touching the bar to the MP4 probe. The triggered position in Z-direction together with the current temperature detected by each AD590 sensor will be automatically recorded. It then continues to the next cutting cycle. The NC tool path can be as simple as a zig-zag planar motion.

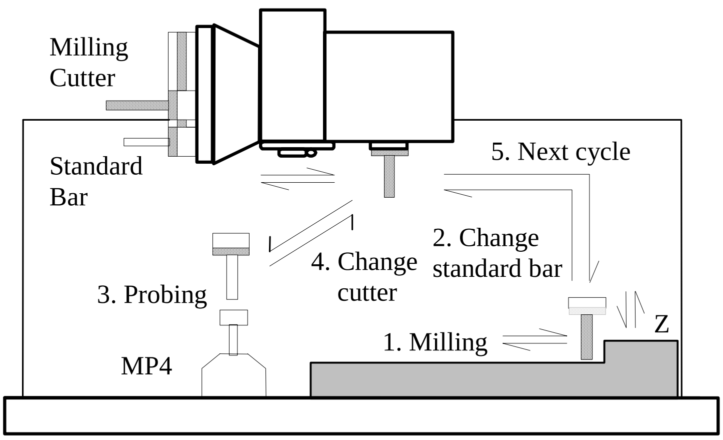


Figure 7: Procedure of in-cycle spindle expansion measurement

3.2 The best conditions for error model generation

(1) Optimum Temperature Sensor Locations

During machining all sensors respond the temperature rises in different rates. Proper selection of effective temperature terms is very essential to represent an accurate error model. The thermal displacement to temperature change could be as simple as a linear function if the optimum sensor locations could be found [15, 16]. A linear error equation with least variables must be the best model for error compensation. This is the key point of the thermal model generation. Fig. 8 shows an example that selecting T4 (spindle motor) of Figure 3 performs a nonlinear relationship between the spindle expansion and the T4 temperature rise. However, if selecting T2, it performs a pretty good linear curve under different depth of cut, as shown in Fig. 9.

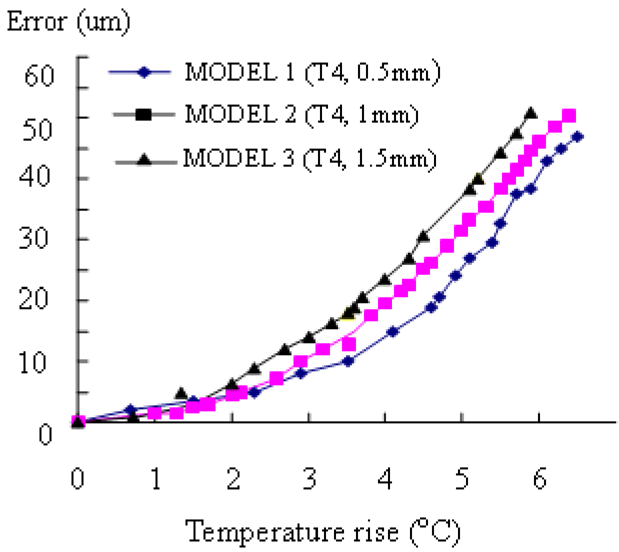


Figure 8: Nonlinear behavior between T4 and the spindle thermal expansion

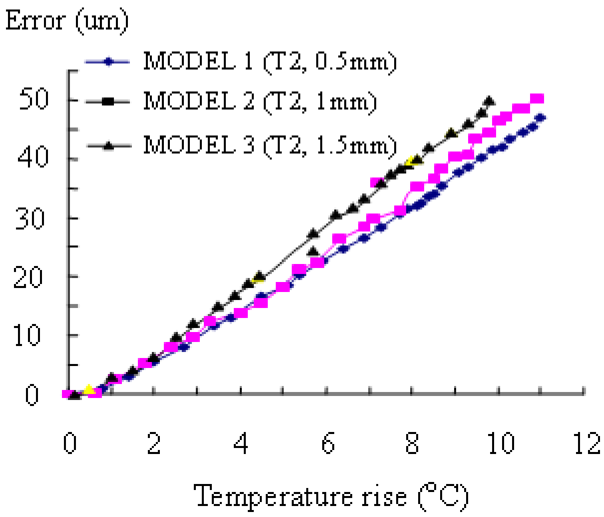


Figure 9: Linear behavior between T4 and the spindle thermal expansion

(2) Fast Error Model Generation

Like a human body, every individual machine tool has its own error model, which has to be diagnosed and cured at a regular time interval. The time required to testing and predicting a simple, accurate and reliable thermal error model is also a major concern since most managers would not tolerate to leave the machine from the production line for long. Consequently, any acceptable solution of error model generation must be as fast as possible. To this point, this research has found that to increase the depth of cut is the most effective way to reduce the experimental time while maintaining the linearity of the error model. Moreover, due to the weather change all the year round the working environment of the investigated machine also induces serious disturbance to the generated model. Having had a long time experiments, this study has also found that, regardless of the daily outdoor temperatures, if the room temperature could be controlled to a small variation the thermal error model of the investigated machine tool could still be stable.

Combining the efforts of the above two best conditions, Fig. 10 shows a very satisfied results. The work material is S50 carbon steel. The depth of cut is 1 mm with feedrate 216 mm/min and an end mill at 2390 rpm. The temperature rise at the spindle front housing (T2 in Fig. 3) has a very good linear relationship with the spindle expansion. Experiments were carried out in different days with room temperatures controlled at ±0.5℃. It is seen the repeatability is very good. Since the total time for each experiment lasted only 3.5 hours, it was not difficult to control the room temperature as long as the testing environment could prevent the air flowing in from outdoor.

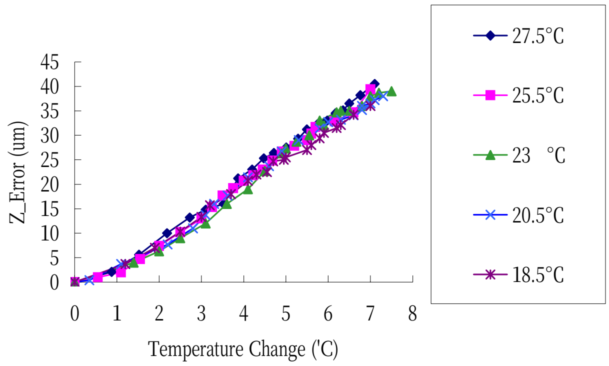


Figure 10: Linear error model generated at different room temperatures

4. Error Compensation Board

An Intel 8051-based single board computer was developed to implement the error compensation process. As shown in Fig.11, the linear error function was initially stored in the 8051 processor. During the real cutting process AD590 sensor kept reading the T2 temperature for every 5 minutes and sending data to 8051 IC. This processor then output a compensation command via the I/O B2 interface card into the CNC controller so as to automatically shift the origin of the machine coordinate. The special feature of this strategy is that the compensation board is a stand alone one which can be placed in the CNC controller box, and the NC commands for the part machining will not be interrupted. The machine tool does not need to equip an external computer as required by most of other researches. Meanwhile the cost of the compensation board is rather cheap, which is the primary requirement.

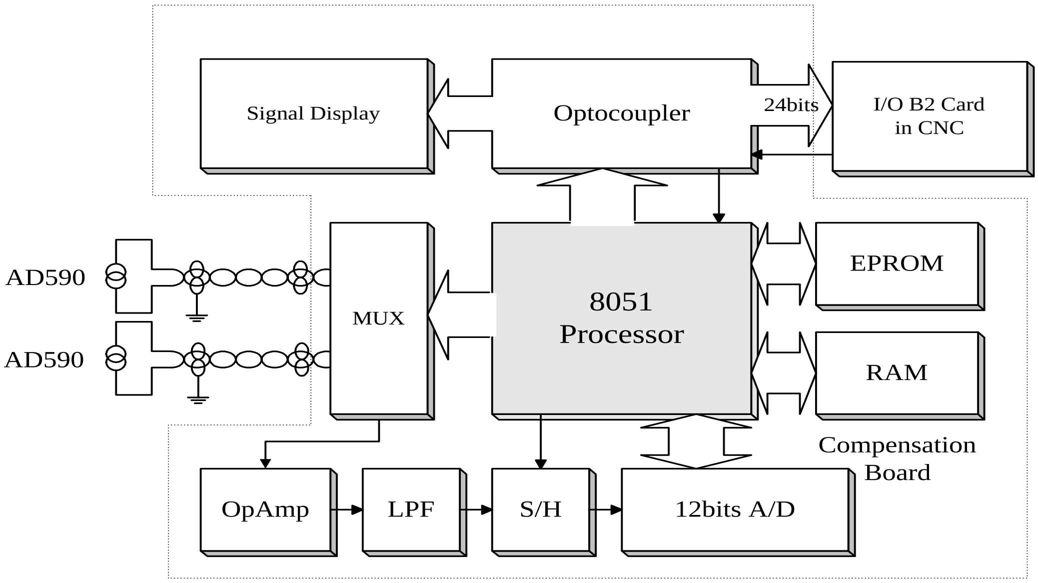
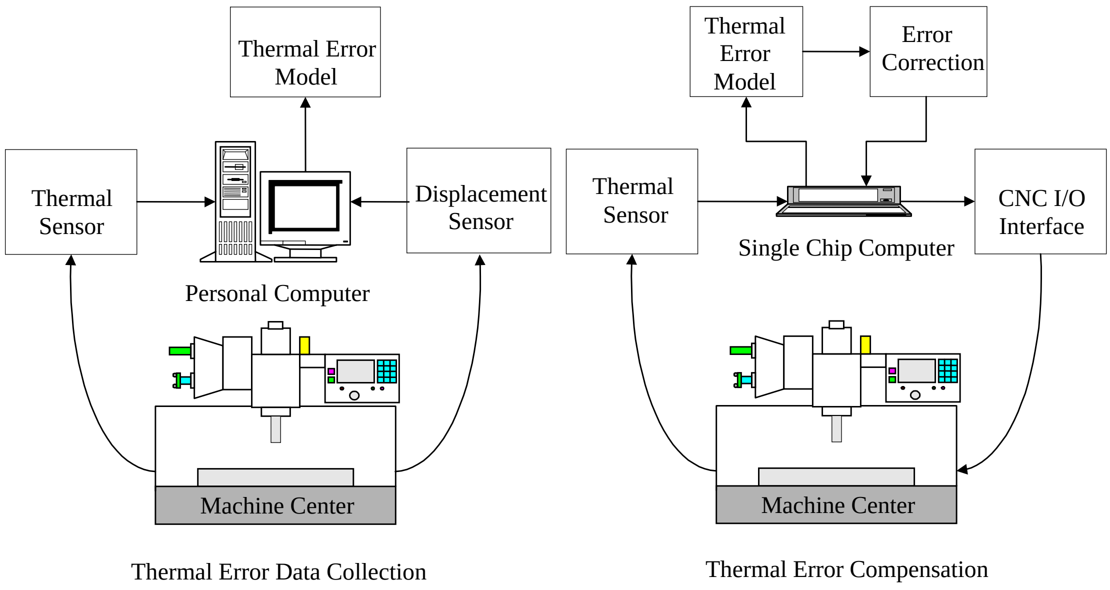


Figure 11: Block diagram of the error compensation board

5. System Integration

The whole system integration method is implemented by two steps. The first step is to generate the thermal model of the spindle expansion due to cutting condition. Temperature sensors (AD590) and displacement sensor (MP4 tool setting probe) are measured during direct cutting condition, shown in Fig. 12(a). The best linear curve among the sensors (in this case is T2) can be found and fitted as the thermal error model of this machine. The second step is then store the error correction model in the single chip computer and direct link to the CNC controller for real time error compensation process during cutting of any other material, as shown in Fig. 12(b).



(a) **(b)**

Figure 12: System integration into machine tool, (a) error model generation process, (b) error compensation process

6. Industrial Requirements

The developed prototype system consists of three modules, namely the temperature sensors, the temperature acquisition module, and the error compensation module. All can be packed in a carrying case. The tool-setting probe for the detection of spindle thermal drift is deemed the standard tool used in most machine shops. While the research team brought this portable kit to a machine tool builder in Taiwan, some more requirements were suggested to fit the in-situ practice. Those are:

1. The sensor heads must imbed in the inside of the machine and the cables must be bundled up with the machine's cable strand.

To accommodate this requirement, the AD590 IC can directly insert into the machine body and the magnet mount is no more useful. The toughest job is the EMI disturbance to the sensor cable when all cables are bundled together. It is more serious in high spindle machines. Therefore, noise removal scheme in terms of shielded cable, ground connection, hardware low-pass filter and software data screening is necessary to implement. Through such a strategy the temperature variation could be successfully suppressed.

2. The system must suit for different CNC controllers and different temperature sensors.

To accommodate this requirement, the I/O address from the compensator should make proper adjustment. This should keep close collaboration with the company's controller engineers as they can program the ladder diagram according to our need. Besides, the temperature acquisition circuit should make proper options to fit for both the current input (AD 590) and the resistance input (thermistor). The prototype system has so far work out on Fanuc and Mitsubishi controllers.

3. Operators need the temperature display to ensure the system is in operation.

To accommodate this requirement, a 20x2 LCD for real time temperature display of up to 8 channels with a single chip 8051 processor (ATMEL89C51) was designed and its function was verified.

4. The parameters of the error model should be programmable.

As the error model may drift after a period of run, the machine tool builder should be able to calibrate and update the error model for regular maintenance. To meet this requirement, an extra EPROM was added to connect with the 8051 processor. New parameters are also displayable on the LCD panel for verification.

5. The system should possess the function of self-diagnosis.

Every machine tool is purchased for very long-term use, normally 15 years. Any damage to the system may happen from time to time caused by improper operation or functional decay of the components. Alarm signals should be indicated for the temperature module, LCD module, EPROM module, and I/O module when malfunction arises. To accommodate this requirement, the self-diagnosis software was developed and built in the 8051 processor.

It can be seen that the industrial environment needs more conditions than the laboratory. This prototype system has been put extreme efforts for commercialization. Through close collaboration between academia and industry all requirements have been solved successfully.

6. Experiments

In the experiments, both in the laboratory and factory site, thermal error model of the investigated machine tool was fast generated under various real cutting conditions on steel blocks, namely S50C and SKD61. The effort of error model generation took within 4 hours under proper room temperature control. Fig. 13 shows an example of the spindle position drift with and without error compensation. It is clearly seen that the errors caused by spindle thermal expansion can always be successfully controlled to within 10 µm during an eight -hour run. A reduction of thermal error more than 80% could be achieved.

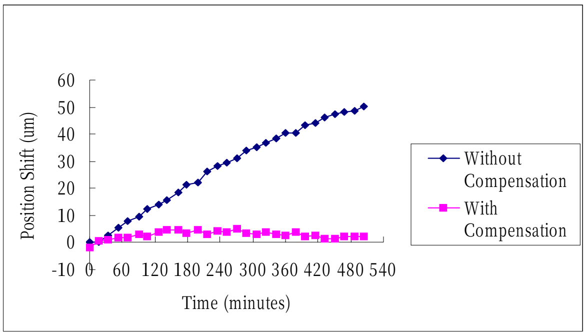


Figure 13: Experimental results, material: SKD61

This system has been tested by the Precision Machine Development Center in Taiwan, (PMC) for four years. The functionality is accepted by a number of machine tool builders. Fig. 14 shows the example that was carried out by PMC with this developed system to an industrial machine tool. Similar achievement is also obtained. The model generation process took 6 hours, while the error compensation completed in one hour. The whole built-in error compensation system can be done in one day.

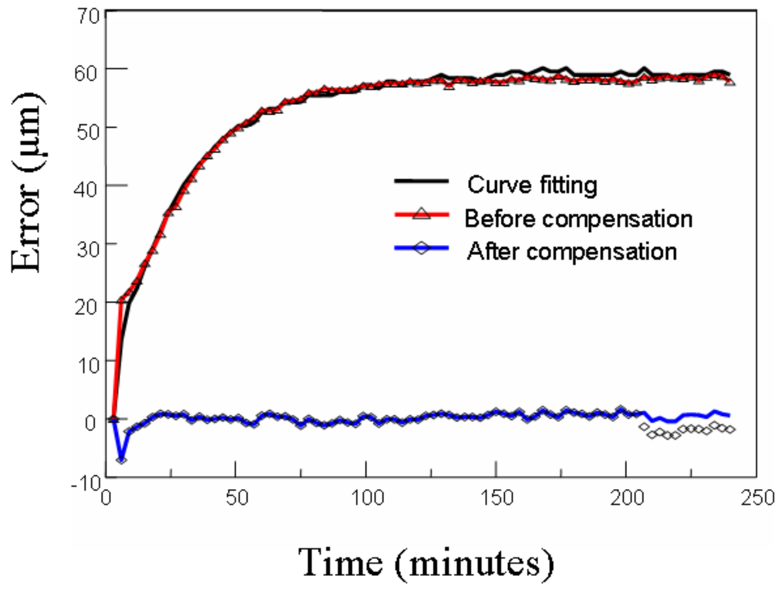


Figure 14: Second test by PMC

7. Conclusions

A very effective method for the thermal error measurement and compensation of CNC machine tools is presented in this article. This system has been verified its applicability in industry. Many special features of this system are summarized as follows.

1. The temperature sensor is made by low cost IC-AD590 with magnetic mount so that the placement location can be changed. An eight-channel sensor card is developed to enable data collection of 8 temperature points simultaneously, either from the developed IC sensor or from the thermistor. If needed, it can be expanded to more channels.
2. The thermal drift of the spindle with respect to the worktable is detected using a general-purpose tool setting probe. Three-dimensional shifts can be easily detected with repeatability to 1 µm.
3. This system is suitable for real cutting condition.
4. The location of temperature sensor mounting is very critical. For an optimum location the thermal error model can be linear.
5. Fast generation of thermal error model can be achieved by increasing the depth of cut.
6. Influence of ambient temperature can be minimized if the outdoor air is prevented from flowing into the machine site.
7. Modifications for factory practice have been made with intelligent functions for commercial purpose.
8. A low-cost error compensation card is developed by employing the 8051-based

microprocessor techniques.

9. Remarkable error compensation results have been achieved.

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一種智慧型綜合加工機之熱誤差補償系統

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本文針對工具機熱誤差補償技術中，熱誤差模型建立的主要困難例如：溫度感測器放置點、長時間的熱誤差建模及熱誤差模型的強健性等進行研究分析。發展溫度感測器最佳放置點原理與方法及快速熱誤差模型建立技術。不同於 ISO230-3 規範所提的空切削熱誤差建模法，本文提出更符合實際的實切削熱誤差建模法。以 AD590 I.C. 型溫度感測器偵測最佳放置點的溫度變化，以標準桿配合觸發式探頭進行切削中熱誤差線上量測。將實驗結果以線性迴歸分析建立切削中熱誤差預測模型。並發展單板電腦硬體補償器，以 8051 微處理器為核心，透過工具機參考原點漂移的方式直接補償預測熱誤差值。實際切削工件驗證的結果顯示，主軸熱變形的誤差經由補償的方式可以大幅降低至 10μm 之內。

關鍵詞: 工具機, 熱誤差, 實切削, 誤差補償