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Real-Time Prediction of Workpiece Errors for a CNC Turning Centre, Part 1. Measurement and Identification

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This paper analyses the error sources of the workpiece in bar turning, which mainly derive from the geometric error of machine tools, i.e. the thermally induced error, the error arising from machine–workpiece–tool system deflection induced by the cutting forces. A simple and low-cost compact measuring system combining a fine touch sensor and Q-setter of machine tools (FTS_Q) is developed, and applied to measure the workpiece dimensions. An identification method for workpiece errors is also presented. The workpiece errors which are composed of the geometric error, thermal error, and cutting force error can be identified according to the measurement results of each step. The model of the geometric error of a two-axis CNC turning centre is established rapidly based on the measurement results by using an FTS_Q setter and coordinate measuring machine (CMM). Experimental results show that the geometric error can be compensated by modified NC commands in bar turning.

Keywords: Dimension measure; Error identification; Geometric error; Turning

1. Introduction

In recent years, ultraprecision machining has made remarkable progress. Some special lathes have been able to make ultraprecision machining, to less than a submicron and nanomicron tolerances a possibility. A common second approach is that the grinding is used to achieve a high level of dimensional accuracy after turning. However, the condition of the cutting tool (diamond) and workpiece (aluminium) have restricted the application of ultraprecision lathes. The second approach increases the number of machine tools and machining processes used [1], which results in an increase in the manufacturing cost.

At present, most CNC lathes are equipped with a positioning resolution of 1 μm. Various machining errors in finish turning, however, degrade the accuracy to a level of approximately 10 μm, so that when turning carbon steel, a machining error predictably arises in excess of 20–30 μm. For improving machining accuracy, the method of careful design and manufacture has been extensively used in some CNC lathes. However, the manufacturing cost based on the above method will rapidly increase when the accuracy requirements of the machine tool system are increased beyond a certain level. For further improving machine accuracy cost-effectively, real-time error prediction and compensation based on sensing, modelling and control techniques have been widely studied [2], so ultraprecision and finish tuning can be performed on one CNC lathe.

The positioning resolution of the cutting tools and workpiece is reduced so that it cannot maintain high accuracy during machining because of the cutting-force-induced deflection of the machine–workpiece–tool system, and the thermally induced error, etc. In general, a positioning device using a piezo-eletric actuator is used to improve the working accuracy, but the method introduces some problems, such as, the feedback strategy, and the accuracy of sensors, which add to the manufacturing cost of the products. However, if the workpiece error can be measured by using a measuring instrument, or predicted by using a modelling, the turning program produced by modified NC commands can be executed satisfactorily on a CNC machine tool. Thus, a CNC turning centre can compensate for the normal machining error, i.e. the machine tool can machine a product with a high level of accuracy using modified NC commands, in real time.

The workpiece error derives from the error in the relative movement between the cutting tool and the ideal workpiece. For a two-axis turning centre, this relative error varies as the condition of the cutting progresses, e.g. the thermal deflection of the machine tool is time variant, which results in different thermal errors. According to the various characters of the error sources of the workpiece, the workpiece errors can be classified as geometric error, thermally induced error, and cutting-force-induced error. The main affecting factors include the position errors of the components of the machine tool and the angular errors of the machine structure, i.e. the geometric error. The thermally induced errors of the machine tool (i.e. the thermal error), and the deflection of the machining system (including the machine tools, workpiece, and cutting tools) arising from cutting forces, are called the cutting-force error.

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This paper analyses the workpiece error sources in turning. The errors of a machined workpiece are mainly composed of the geometric error of the machine tools, the thermally induced error, and the error arising from machine–workpiece–tool system deflection induced by the cutting forces. A simple and low-cost measuring instrument for the workpiece dimensions, which combines a fine touch sensor and machine tool Q-setter (FTS_Q), is described, and applied to measure the workpiece error. A new method for identifying the geometric error, the thermal error, and the cutting-force error is also presented for a two-axis turning centre. Finally, the modelling of the geometric error of a CNC turning centre is presented, based on the measurement results using the FTS_Q and CMM. The geometric error can be compensated by the modified NC command method.

2. Error Sources in Turning

The machine tool system is composed of the drive servo, the machine tool structure, the workpiece and the cutting process. The major error sources derive from the machine tool (thermal errors, geometric errors, and forced vibrations), the control (drive servo dynamics and programming errors) and the cutting process (machine tool and cutting tool deflection, workpiece deflection, tool wear, and chatter) [3].

Errors derived from the machine tool include thermal errors (machine thermal error and workpiece thermal errors), geometric errors, and forced vibrations, which dominate machining accuracy. The thermal errors and geometric errors are the dominant factors with respect to machining accuracy in fine cutting. However, machine tool errors can be decoupled from the other error sources and compensated [4]. The error derived from forced vibration can be reduced through balanced dynamic components and vibration isolation [3].

The errors derived from the controller/drive dynamics are related to the cutting force disturbances and the inertia of the drive and the machine table. These errors can be reduced by an interpolator with a deceleration function [5] or by an advanced feed drive controller [6], these errors, reduced by using the above methods, are small when compared with other error sources.

Owing to the demand for high productivity, high feedrates and large depths of cut are required, which result in large cutting forces. Therefore, the cutting-force induced deflections of the machine tool (spindle), tool holder, workpiece, and cutting tool make significant contributions to machining accuracy during the cutting process. In addition, tool wear and machine tool chatter are also important error sources in the cutting process. However, these effects are neglected here so as to focus on the main error sources.

In short, the error of a machined workpiece, i.e. the total machining error (δ_{Tot}), is composed mainly of the geometric errors of the machine tool(s) (δ_G), the thermally induced error (δ_T), and the error (δ_F) arising from the deflection of the machine–workpiece–tool system induced by the cutting forces. Hence,

$$\delta_{Tot} \approx \delta_G + \delta_T + \delta_F \tag{1}$$

In the next section, we present a novel compact measuring instrument and a new analytical approach for measuring and identifying workpiece errors in turning.

3. A Compact Measurement System

Contact sensors, such as touch trigger probes, have been used to measure workpiece dimensions in machining. In machining practice, the measuring instrument is attached to one of the machine's axes to measure a surface on the workpiece. A TP7M or MP3 associated with the PH10M range of motorised probe heads or a PH6M fixed head have been used widely in the automated CNC inspection environment owing to their high level of reliability and accuracy and integral autojoint. Though the probeheads are of adequate accuracy (unidirectional repeatability at stylus tip (high sensitivity): 0.25 μm; pre-travel variation 360 (high sensitivity): ±0.25 μm), and versatile in application, they have clear drawbacks, including complexity of construction, high price ($4988), and the need for careful maintenance.

To overcome these drawbacks of touch trigger probes, Ostafiev et al. [7] presented a novel technique of contact probing for designing a fine touch sensor. The cutting tool itself is used as a contact probe. The sensor is capable of yielding measurement accuracy comparable to that of the best touch trigger probe in use. Moreover, the principle of operation and construction of the sensor is extremely simple, the cost of the sensor is low, and the maintenance is very easy. In this paper, this sensor will be used to measure the diameter of a workpiece associated with the Q-setter.

A touch sensor is mounted on a CNC turning centre. When we manually bring the tool nose into contact with it, an interrupt signal is generated for the NC unit to stop an axis. Moreover, it can write in an offset and a workpiece coordinate shift automatically. This function facilitates set-up when replacing a tool, and this convenient function is called the "Quick Tool Setter" or "Q-setter". Based on the above principle, we can operate a switch, which is controlled by fine touch sensor, between the Q-setter and NC unit. When the tool tip touches the workpiece surface, the fine touch sensor can send a control signal to the switch, to turn it to the "off" state. See Fig. 1, the fine touch sensor replaces the Q-setter function, to stop an axis and write in an offset and a workpiece coordinate shift automatically. Therefore, the fine touch sensor associated with

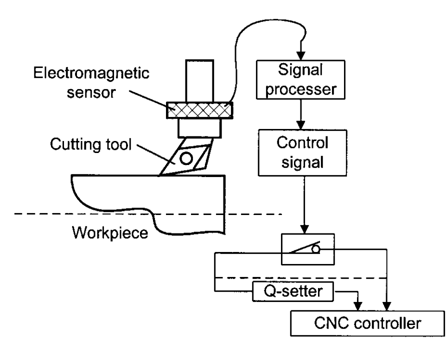

Fig. 1. Flow diagram of a fine touch sensor fixed on a CNC controller.

a Q-setter (FTS_Q) can be used to inspect the diameter of the workpiece, the method is shown in Fig. 2.

When the cutting tool tip touches the workpiece surface, a "beep" sound is heard and the switching "OFF" signal appears and the axis stops automatically, as far the Q-setter. A new "tool offset" $X_{T\text{-}W}$ is obtained by the NC unit (display of CNC). Before touching the workpiece surface, the cutting tool tip touches the Q-setter, and the "tool offset" $X_{T\text{-}Q}$ is obtained. Thus, the on-machine workpiece diameter $D_{on\text{-}machine}$ is given by the following Eq.:

$$D_{on\text{-}machine} = 2 \times H + |X_{T\text{-}Q}| - |X_{T\text{-}W}| \tag{2}$$

where

$X_{T\text{-}Q}$ is the tool offset when the cutting tool contacts the Q-setter

$X_{T\text{-}W}$ is the "tool offset" when the cutting tool contacts the workpiece surface

H is the distance from the centre of the Q-setter to the centre of the spindle in the x-axis direction and is provided by the machine tool manufacturer, for the Seiki-Seicos L II Turning centre, it is 85.356 mm.

Ostafiev and Venuvinod [8] tested the measurement accuracy of the fine touch sensor, performing on-machine inspection of turned parts, and found that the method was capable of achieving a measurement accuracy of the order of 0.01 μm under shop floor conditions. However, the measurement accuracy of the fine touch sensor together with the Q-setter obtained an accuracy of about μm because the results of the measurement system are displayed by the CNC system, and the readings accuracy of the CNC system is up to 1 μm.

4. Identification of Workpiece Errors

From the above analysis of error sources of the workpiece, the total error δ_{Tot} of machined parts is mainly composed of the following errors in a turning operation:

- δ_G the geometric errors of machine tools.
- δ_T the thermally induced error.
- δ_F the cutting force induced error.

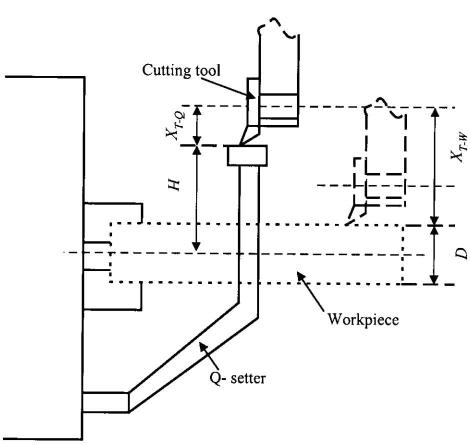

Fig. 2. Inspection for the diameter of a workpiece by using the fine touch sensor with the Q-setter of a machine tool.

To analyse the error sources of a machined workpiece, Liu & Venuvinod [9] used Fig. 3 to illustrate the relationship amongst dimensions associated with different error components in turning.

In Fig. 3, D_{des} is the desired dimension of the workpiece; D_{omw} is the dimension obtained by on-machine measurement using FTS_Q immediately after the machining operation; D_{omc} is the dimension obtained by on-machine measurement using FTS_Q after the machine has cooled down; and D_{pp} is the dimension obtained by post-process process measurement using a CMM after the workpiece has been removed from the machine.

When the workpiece has been machined, and removed from the machine tool system, it is then sent for inspection of the dimensions using a CMM. This procedure is called post-process inspection, by which we obtain it D_{pp} value. As the positioning error of the CMM is very much smaller than the desired measurement accuracy, the total error is

$$\delta_{Tot} = (D_{pp} - D_{des})/2 \tag{3}$$

The dimension D_{omw} is obtained through on-machine measurement using FTS_Q immediately after machining, i.e. the machine is still in the same thermal state as at the time of machining. The measurement is made with the same positioning error as that which existed during machining. Hence, the positioning error in this state would be equal to ($\delta_G + \delta_T$), i.e.

$$(D_{pp} - D_{omw})/2 = \delta_G + \delta_T \tag{4}$$

When the machine has completely cooled down, i.e. without thermal error, the dimension D_{omc} can be obtained by on-machine measurement using FTS_Q. The measurement has a positioning error equal to the geometric error of the machine at the location of measurement. Hence, the positioning error in this state would be equal to (δ_G), i.e.

$$(D_{pp} - D_{omc})/2 = \delta_G \tag{5}$$

Combining Eqs (4) and (5), the thermally induced error δ_T is

$$(D_{omc} - D_{omw})/2 = \delta_T \tag{6}$$

Hence, taking Eqs (1), (3), and (4) into account, the cutting-force-induced error owning to the deflection of the machine–workpiece–tool system δ_F is

$$(D_{omw} - D_{des})/2 = \delta_F \tag{7}$$

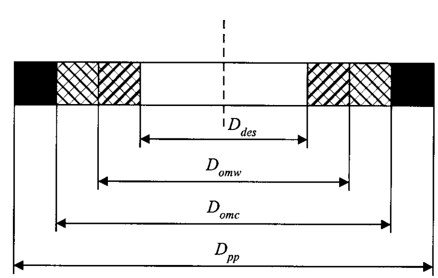

Fig. 3. The relationships among dimensions.

So far, the machining error is composed of the geometric error, the thermal error, and the cutting-force-induced error and can be identified using the above procedure. The thermal error and the force-induced error modellings is addressed in Li [10]. Here, the geometric error of machine tool is measured and modelled.

5. Modelling of Geometric Error

The geometric error of a workpiece is mainly affected by the offset of the spindle, and the linear error and the angular errors of the cross-slide for a two-axis CNC turning centre. Here, only the geometric error of workpiece in the x-axis direction is taken into account for a bar workpiece. This is expressed by the following formula.

$$\delta_G = \delta(s) - \epsilon(x)\, h_{T\text{-}Q} - \delta_x(x) \tag{8}$$

where

$\delta(s)$ is the spindle offset along the x-axis direction
$\epsilon(x)$ is the angular error (yaw) of the cross-slide in the x, y-plane
$\delta_x(x)$ is the linear displacement error of the cross-slide along the x-axis direction

The spindle offset is a constant value independent of the the machining position. The angular error term and the linear error term are functions of the cross-slide position x.

In this paper, the FTS_Q is mounted on a Hitachi Seiiki, HITEC-TURN 20SII two-axis turning centre. The FTS_Q calibration instrument was developed to measure rapidly the dimension of the workpiece in the x-axis direction on the two-axis CNC turning centre when the machine has completely cooled down, i.e. without the effect of thermal error. The geometric error can be computed by using Eq. (5) according to the measured results. First, the diameter of a precision ground test bar is measured at 10 positions, 20 mm apart, by a CMM, their values D_{ppi} (i = 1, 2, . . ., 10) are recorded. Then, the test bar is mounted on the spindle, and its diameter is also measured at 10 positions, 20 mm apart, by the FTS_Q. The measurement arrangement is shown in Fig. 4, the readings are D_{omcl} (i = 1, 2, . . ., 10). Thus, the geometric error at each point along the x-axis for the bar workpiece are computed as follows:

$$\delta_{Gi} = (D_{ppi} - D_{Gi})/2 \tag{9}$$

From starting point B to point A, the results are shown in Fig. 5 for diameters of 30, 45, 60, and 75 mm. The workpiece

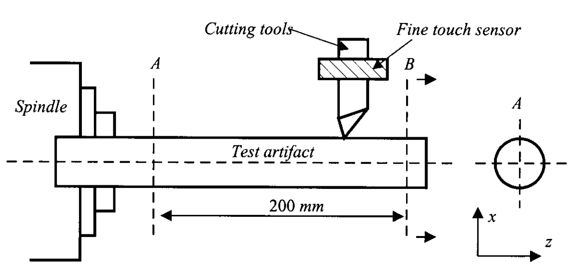

Fig. 4. Diagram of the geometric error measurement of the workpiece using FTS_Q.

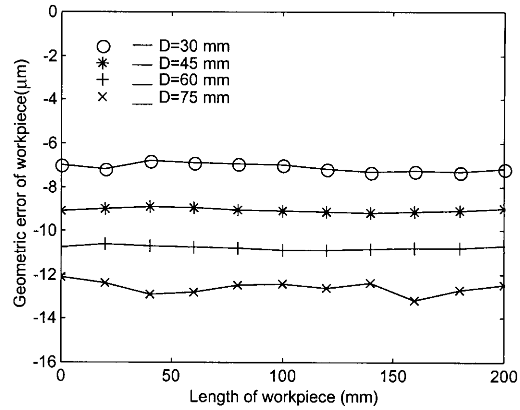

Fig. 5. Geometric errors of the workpiece along the z-axis.

geometric errors in the z-axis direction are the same. The workpiece geometric errors, however, increase along the x-axis direction, as shown in Fig. 6. These average geometric errors are −7.1036, −9.0636, −10.7764, −12.5955 (μm) for diameters 30, 45, 60, and 75 mm, respectively. Hence, the geometric errors of the two-axis CNC turning centre can be calculated by the following Eq.:

$$\delta_G(x) = -0.121x - 3.519 \tag{10}$$

where x is the diameter of the workpiece (mm), $\delta_G(x)$ (μm) is the geometric error of the workpiece.

6. Compensation of Geometric Error

To compensate for the geometric error in the direction of the depth of cut, the tool path can be shifted in accordance with the error. The NC commands in turning are modified, at a minimum resolution 1 μm, in the direction of the depth of cut. The calculated geometric error exceeded 1 μm according to the equation (10), as illustrated in Fig 7.

Figure 8 shows that the workpiece errors include the geometric error, the thermal error and the cutting force error. The tool path determined by the calculated geometric error, and the workpiece error are compensated for by the modified NC command method. In this example, we used a cutting speed of 4 m s^{-1}, a feedrate of 0.2 mm rev^{-1}, a depth of cut of

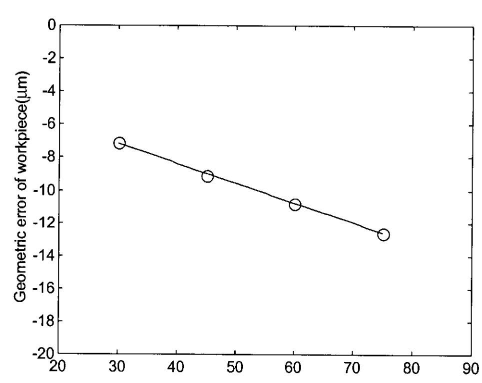

Fig. 6. The average geometric error for the different diameters.

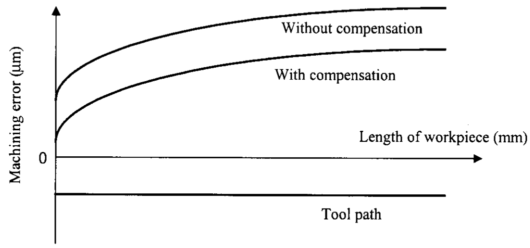

Fig. 7. Compensation of geometric error.

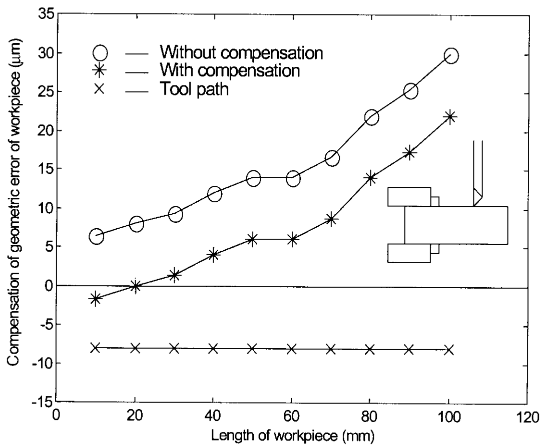

Fig. 8. Compensation of geometric error by a modified NC command.

1 mm (cutting length 100 mm), a diameter of 40 mm, mild steel workpieces, and DNMG 1506 04 QM tools. The workpiece error was measured using our FTS_Q at 10 positions 10 mm apart. The workpiece errors were reduced by means of the compensation of the geometric error. The remaining workpiece error contains the thermal error and cutting force error, these will be discussed in part 2 [10] and part 4 [11]. Experimental results suggest that the geometric error in finish turning can be compensated for by the use of this simple method described above.

7. Conclusions

Owing to increasing demand for higher precision coupled with lower costs in the machining industry, there is a growing need for automated techniques leading to enhanced machining accuracy. In this paper, the workpiece error sources are analysed for a two-axis CNC turning centre, which derive mainly from the geometric error of the machine tool, the thermally induced error, and the error arising from MFWT system deflection induced by the cutting forces. A simple and low-cost measuring system combining a fine touch sensor and Q-setter for machine tools (FTS_Q) is developed to measure the workpiece error on-machine. The workpiece errors can be divided into the geometric error, the thermal error, and the cutting force error from the on-machine and post-process measured results. The geometric error function of a two-axis CNC turning centre can be established rapidly from the measurements by using the FTS_Q and a CMM. Experimental results show the geometric error can be compensated for by the modifying the NC commands in finish turning.

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