ON-LINE REDUCING MACHINING ERRORS IN BORING OPERATION BY FORECASTING COMPENSATORY CONTROL TECHNIQUE

W. M. Chiu[†], D. Gao[†], F. W. Lam[†], and Z. J. Yuan[††]

[†]*Dept. of Manufacturing Engineering, The Hong Kong Polytechnic University, Hong Kong*
[††]*Dept. of Mechanical Engineering, Harbin Institute of Technology, Harbin, P. R. China*

Abstract: This paper presents a new structural micro-boring servo system with the function of on-line compensating machining errors in the small hole boring operation. The forecasting compensatory control technique is employed in this work as the on-line control algorithm.

Keywords: Micro-boring bar, error compensation, forecasting compensatory control

1. INTRODUCTION

Although a substantial volume of research work has been devoted to on-line active error compensation in turning operations for the last decade [1], only a few attempts had been targeted at overhang boring under large length/diameter ratios. Unlike other processes, the implementation of active error compensation for over-hang boring poses some real challenge in modern day machine control technology because suitable sensors for error real-time measurements are practically non-existent for monitoring boring in smaller holes. Besides, even piezoelectric actuators which are popularly employed in the active error compensation systems are sometimes too large to be fitted in the small holes to be bored, thus preventing them being directly attached to the cutting tool [2]. Hence conventional sensors and active actuators which are successful for external machining are of little use when internal surfaces are encountered. A micro-boring servo system with a piezoelectric actuator for on-line reducing the machining errors is developed.

2. MICRO-BORING BAR SERVO SYSTEM

2.1 Principle of Operation

A schematic diagram of the micro-boring servo system is shown in Fig. 1. The micro-boring servo system is consisted of a boring bar, strain gauge meter, active low-pass filter & amplifier, control computer, piezoelectric actuator and its driver. In order to bore small holes, the micro-boring bar is designed with two concentric bars, the outer bar being used for error compensation and the inner for error measuring. The control bar is made into a lever structure, which can rotate around a flexural hinge pivot, and a piezoelectric actuator and boring cutter is installed at the two ends of the lever bar respectively. The measuring bar is of a cantilever structure with two strain gauges attached for measuring the machining error. As a result, the micro-boring bar can be made with relatively smaller outer diameter after the piezoelectric actuator and strain gauges have been incorporated.

As shown in Fig. 2, when the cutting force F =0, the control bar and measuring bar both remain level (Fig. 2a). When the control bar is deflected downwards as the cutting force, F > 0, acts on it, the measuring bar is also deflected downwards (Fig. 2b) and the error signal measured by the strain gauge meter increases. This error signal is input to the computer through the A/D converter and compared with the expected value. The piezoelectric actuator then expands by increasing the applied voltage to the PZT driver through the D/A interface. As a result, the control bar rotates around the flexural hinge in clockwise direction, and the downward deflection of the cutter is suppressed, and the measuring bar becomes level again (Fig. 2c). On the other hand, when the boring cutter deflects upward as the cutting force is reduced, the deflection is then compensated by decreasing the applied voltage to the piezoelectric actuator. Hence, the deflection of the boring cutter can be compensated by the computer-controlled piezoelectric actuator system and the resulting accuracy be improved.

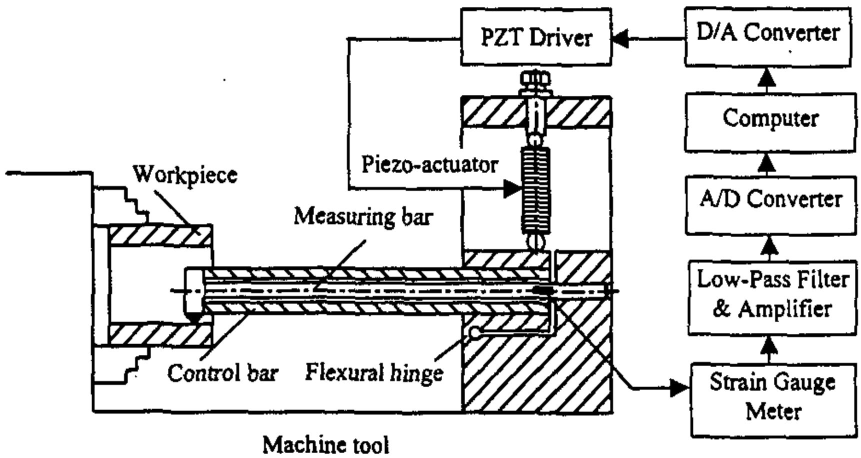


Fig. 1 The schematic diagram of the micro-boring servo system

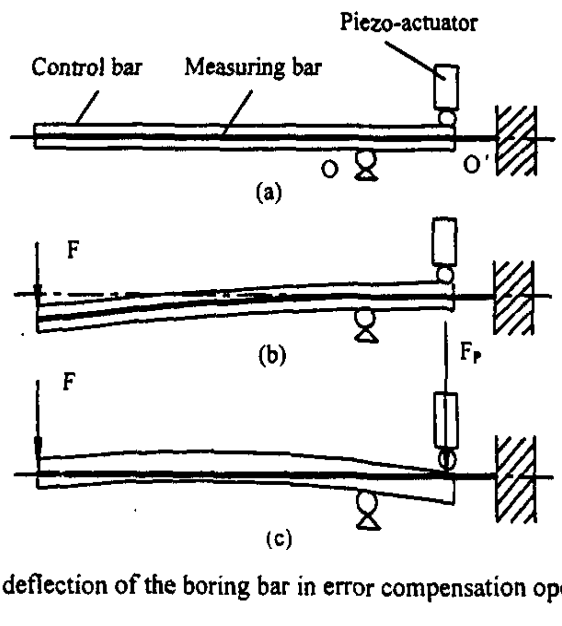


Fig. 2 The deflection of the boring bar in error compensation operation

2.2 Dynamic model

The equation of motion model for the micro-boring system is shown in Fig. 3. For this purpose, the piezoelectric actuator is modeled as a single degree of freedom system with lumped mass, stiffness and viscous damping coefficient denoted as M_p, K_p, and C_p respectively. The variable y stands for the radial deflection of the cutter, θ for the angular rotation about point O of the control bar, for the angle rotation about point O′ of the measuring bar. I_θ stands for the moment of inertia of the control bar about point O, I for that of the measuring bar about the point O′. C_θ, K_θ are the damping coefficient and stiffness of the control bar and C , K for measuring bar. F_c and F_p represent the radial cutting force and the pushing force of the piezoelectric actuator respectively. Assuming that the angles and θ can further be simplified as equal quantities for small departures from the equilibrium positions, the equation of motion describing this micro-boring system can be approximated as

$$M\ddot{y} + C\dot{y} + Ky = F_c + \frac{L_1}{L_2}F_p \qquad (1)$$

Where

$$M = (I_\theta + I_\psi + L_1^2 M_p)/L_2^2$$
$$C = (C_\theta + C_\psi + L_1^2 C_p)/L_2^2$$
$$K = (K_\theta + K_\psi + L_1^2 K_p)/L_2^2$$

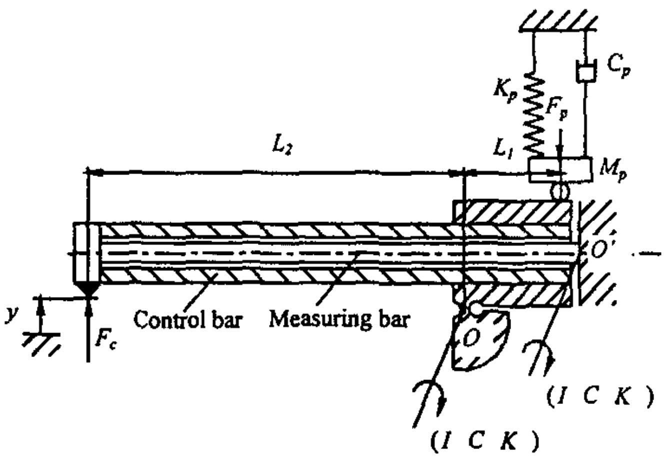


Fig. 3 Dynamic model for the boring bar

2.3 Control algorithm

To carry out on-line form error control, it is evident that a combination of on-line error measurement and active error compensation is necessary. Furthermore, the implemented control method should be able to compensate for the deterministic as well as random form error components. The Forecasting Compensatory Control (FCC) method which has been successfully implemented for the control of many form error problems has been adopted in this work.

The proposed FCC control system in this research forms the core of the feed-back control system, with a special feature that the compensating sign is based on a forecasted value rather than a directly measured value, which has shown some delay. A block diagram of the overall FCC control structure is presented in Fig. 4. The time lag between the moment of measurement and that of control action caused by the piezoelectric actuator system and the strain gauge measurement system in the boring operation can be compensated through the FCC control model.

The deflection errors of the cutter occurring at different instances of time are considered as a stochastic process which can be represented by autoregressive and moving average (ARMA) models. The advantage of the time series approach is its ability to predict the future values without the necessity of obtaining the complex cause-and-effect relationships between various errors and their sources. More importantly, it is possible to account for the random parts of the error as well as their deterministic parts. For real-time implementations, autoregressive (AR) models are often used due to its simplicity in computations. On the basis of time series analysis, deflecting errors can be modeled by [3]

$$y_t = \phi_1 y_{t-1} + \phi_2 y_{t-2} + \dots + \phi_p y_{t-p} + \delta \tag{2}$$

where y_t stands for the tool deflecting error observed at different time of t, and ϕ_j stands for the autoregressive parameters, and, δ is a white noise series representing non-correlated random errors (note that the errors of the measuring system are also considered in this series). An AR(p)model can be developed recursively on-line. After each sampling of measurement, the parameters of the model will be updated. This allows the stochastic model to closely follow the process variations

One of the most important features of the FCC technique is forecasting capability. Based on the past and current measurements as well as the developed models, the behavior of errors at a compensation point will be predicted before a cutter actually cuts at the point. The forecasting function attempts to overcome the time lag between the moment of measurement and that of control action. It gains extra time for a controller to generate compensatory command and for the piezoelectric actuator to respond in advance. From equation (2), the q-step ahead forecasting made at time t, $y_t(q)$, can be expressed as [4]

$$\hat{y}_t(q) = \sum_{i=1}^{q-1} \phi_i \hat{y}_t(q-i) + \sum_{i=q}^{p} \phi_i y_{t+q-i} \tag{3}$$

the forecasting $y_t(q)$ made at time t for q=1, 2, 3,...can be updated when a newly observed y_{t+1} becomes available.

For this system, the prediction of deflecting errors of the cutter was made by using a 1-step ahead forecasting of the developed AR(3) model. Fig.5 shows the deflecting errors and the error of this 1-step ahead forecasting. It is indicated that the forecasting errors is uncorrelated and distributed normally about zero.

In the model being setup, the deflecting error is sequentially sampled and stored in the computer. The predicted position of the cutter is forecasted by the AR model the parameter of which are updated recursively on-line. Then, the forecasted value is used to control the expansion/contraction of the piezoelectric actuator to effect compensation. Fig. 6 shows the deflecting errors of the cutter with and without the FCC compensation system indicating that the machining accuracy can be improved effectively by the developed control model.

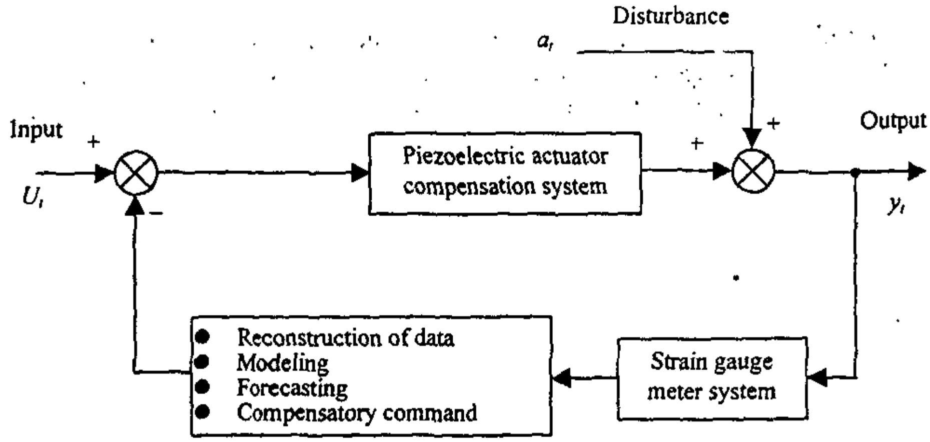
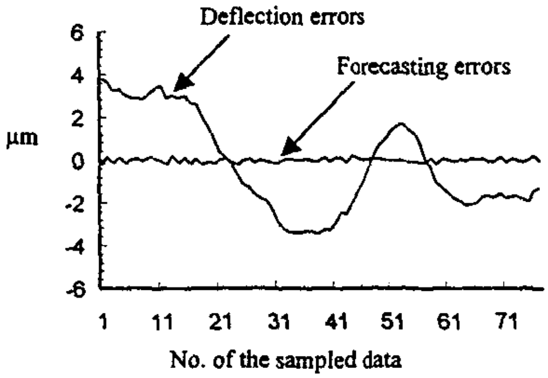


Fig. 4 The block diagram of the overall FCC control structure



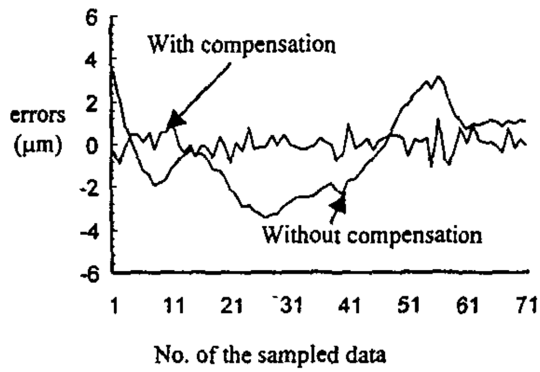


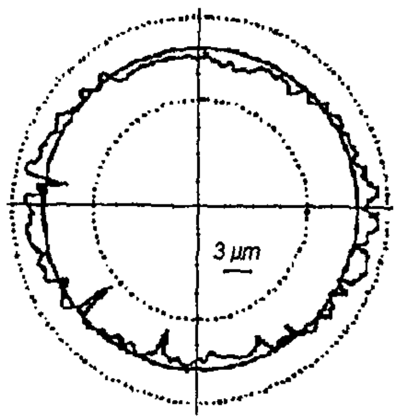
Fig. 5 Deflection errors and forecasting errors Fig.6 Improvement of machining accuracy

3. ON-LINE CUTTING EXPERIMENTAL RESULT

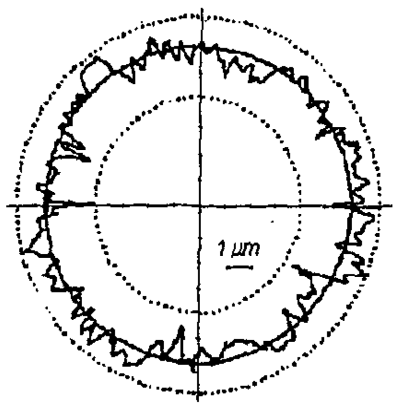
The effectiveness of the micro-boring bar system was also tested through actual cutting experiment. The results were based on boring a 35mm diameter aluminum workpiece. The cutting test was conducted in the CNC lathe (MAZAK QUICK TURN 8N) under the cutting conditions of 0.2 mm depth of cut, 500rpm. The workpiece was machined with and without the compensation system. The roundness of the cut specimens under the before-said conditions is measured on a coordinate measuring machine (OPTON, UMC850S). The roundness results are shown in Fig.7 which clearly indicates that the roundness of the workpiece was significantly improved by the developed micro-boring servo system.

4. CONCLUSION

A micro-boring servo system has been developed for on-line compensating the machining errors in small hole boring operation. In order to bore small and deep holes, the micro-boring bar is designed with a new structure, which is composed of two concentric bars, one as control bar and the other as the measuring bar. The boring bar system is shown to function successfully under a relatively large length to diameter ratio. The "Forecasting Compensatory Control" method was employed in the micro-boring servo system as the on-line control algorithm. Both analytical and experimental studies suggest that the micro-boring system can be used to reduce form errors for micro-boring operations.



(a) without compensation



(b) with compensation

Fig. 7 The roundness curves of the workpieces machined with and without compensation

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