Error Compensation in CNC Turning Solely from Dimensional Measurements of Previously Machined Parts

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Abstract

Inadequate shop floor friendliness is a major reason why traditional software based error compensation approaches have failed to be accepted by industry. This paper develops a compensation approach that relies solely on post-process and on-machine measurements of parts previously machined on the same machine. The approach is based on a new method of error decomposition and a simple model of machine deflections induced by the cutting force. The approach is verified by independent measurements of the various model parameters. It is also shown that the machine tool can be made to act as its own dynamometer.

Keywords: Error compensation, Measurement, Computer numerical control (CNC)

1 INTRODUCTION

In practice, the machined part dimension deviates from the desired (programmed) value owing to many quasi-static systematic errors: geometric errors of machine tool (δ_g); thermally induced distortions of machine tool elements (δ_{th}); errors arising from the static deflections of the machine-fixture-workpiece-tool (MFWT) system under the cutting forces (δ_f); and other errors such as those arising from clamping force, tool wear, etc. (δ_{other}).

Software-based error compensation is a method of anticipating the combined effect of the above factors on workpiece accuracy and then suitably modifying the conventionally designed (uncompensated) tool path. Owing to its reliance on modifications to the software rather than hardware, software-based error compensation provides a very economical method of achieving higher machining accuracy without having to resort to higher accurate machinery. It is not surprising therefore that sixty references were quoted in a CIRP keynote paper in 1995 in the context of compensation for geometric errors alone [1]. However, the same paper noted that 'error compensation of machine tools is not common'. Another recent CIRP keynote paper [2] identified machining process modeling for workpiece accuracy as an important pending task.

The authors believe that the reason for the industrial apathy lies in the fact that traditional error compensation strategies have not been shop-floor friendly. The traditional method of compensating for geometric errors requires the collection of voluminous data on each machine using equipment such as a laser interferometer. During such data collection, the otherwise productive machine is forced to be idle. Some (for example [3]) have relied on finite-element modeling of the machine structure to predict thermal errors (an approach likely to be too sophisticated for routine shop-floor use). Others have required temperature distribution data collected from a large number of thermocouples mounted over different parts of the machine. In [4], in-process measurement using a laser based photo-detector was developed. Such methods are expensive in view of the need to outfit each machine tool on the shop-floor with new hardware and signal processing equipment. The present paper aims to meet the criterion of shop floor friendliness by relying solely on data collected from machined part inspection (a normal and routine shop-floor activity). The focus of the paper is on CNC turning.

The premise of the proposed compensation strategy is simple. An error source is recognized as such only by virtue of the fact that it leaves an imprint on every machined dimension of every part. Hence, all one needs to do is to collect and analyze past inspection data in a manner that enables one to anticipate the error on the next part provided, of course, that the inspection database contains enough exemplars of the next part.

2 THE PROPOSED INSPECTION PROTOCOL

The proposed inspection protocol aims to be shop floor friendly. It involves one post-process measurement (PPM) and two on-machine measurements (OMM) of the machined part. PPM is conducted using a CMM—a common inspection device in CNC shops. OMM is performed by using Fine-Touch contact probing in combination with a Q-setter (available on several types of turning centers) as described in [5]. The most attractive feature of Fine-Touch probing is that it does not require expensive and special probes such as the commonly used touch trigger probes. A simple electrical coil wound around the cutting tool or the machine's spindle enables the cutting tool itself to be used as the contact probe while ensuring measurement accuracy of the order of 1 μm [6].

The total error, δ_{tot}, on a dimension, D (a diameter in turning), of the machined part can be determined from a high precision PPM. Let D_{pp} be the magnitude so measured. Then,

$$\delta_{tot} = D_{pp} - D_{des} \quad (1)$$

where D_{des} is the desired magnitude of D.

The total error can be expressed in terms of error components as:

$$\delta_{tot} = \delta_g + \delta_{th} + \delta_f + \delta_{other} \quad (2)$$

Recently, Mou and Liu demonstrated that the 'difference between CMM [D_{pp}] measurement and on-machine measurement [D_{om}] is positioning error' of the machine [7]. The difference is equal to δ_g when OMM is performed while the machine is cool. Otherwise it is equal to (δ_g+δ_{th}) where δ_{th} is the thermal error associated with the particular thermal state of the machine during OMM.

Mou and Liu presented the above arguments while describing a method of error measurement using standard artifacts [7]. The present authors suggest that the above observations are equally applicable when one uses the machined part itself as the artifact during OMM.

Let D_{omw} be the part dimension determined by OMM immediately after it has been machined so that the thermal state of the machine during OMM is almost the same as that during cutting. Let D_{omc} be the value determined by OMM after the machine has been allowed to cool down. Then, following [7],

$$\delta_g = D_{pp} - D_{omc} \quad (3)$$

$$\begin{aligned}\delta_{th} &= (\delta_g + \delta_{th}) - \delta_g = (D_{pp} - D_{omw}) - (D_{pp} - D_{omc}) \\ &= D_{omc} - D_{omw}\end{aligned} \quad (4)$$

Now, it can be shown by combining equations (1-4) that

$$\delta_f = D_{omw} - D_{des} - \delta_{other} \quad (5a)$$

$$\delta_f \rightarrow D_{omw} - D_{des} \text{ (when } \delta_{other} \rightarrow 0) \quad (5b)$$

As a fist approximation, equation (5b) will be adopted in the rest of the paper.

3 SIMPLE MODELS FOR THE SIGNIFICANT ERROR COMPONENTS IN CNC TURNING

The following simple modeling approach (one with only a few model coefficients) is applicable to turning a workpiece held in a chuck with a centered tool. Axis X is in the radial direction, Y is in the direction of cutting speed and Z is in the feed direction. x, y and z are the coordinates of the nominal (uncompensated) tool tip position, P, with respect to the origin of the machine's axis system.

Note that all the error entities in equation (2) vary as the point P of tool-work contact moves along the tool path prescribed by the part program. In the case of turning, the path of P is confined to the x-z plane so that all the error entities are functions only of x and z.

Traditionally, δ_g distribution is determined by using a laser interferometer while the machine is unloaded ('cool') and fitting the data into an appropriate parameterized model using well-known statistical techniques. δ_{th} is studied by a similar method but focuses on the change in δ_g due to thermal causes. Modeling and prediction of δ_{th} is quite complex because of the large variety of thermal causes and the difficulty in determining the thermal loading parameters.

δ_f can be expressed as follows in turning a workpiece held by chucking at one end only:

$$\delta_f = 2F_x\left(\frac{1}{k_t} + \frac{1}{k_{wp}} + \frac{1}{k_{sp}}\right) \quad (6)$$

where F_x is the radial component of the instantaneous quasi-static cutting force, k_t is the overall stiffness of the tool and the structure supporting it in direction X, k_{wp} is the stiffness of the workpiece on its own, and k_{sp} is the overall stiffness of the chuck/spindle assembly including the headstock-side structure. Note that each of these stiffnesses should be interpreted as the magnitude of F_x required to act at P so as to cause unit deflection in direction X at point P.

k_t and k_{sp} essentially depend upon the machine, fixture, and tool system. These features are relatively constant for a given turning center set up. Note however that k_{sp} continuously changes as P traverses the tool path.

k_{sp} can be estimated from a finite element analysis (FEA). However, FEA is too complex for routine shop floor use. Further, in FEA, it is difficult to account for the contact deflections occurring at the various mating faces in a given machine tool assembly.

In early literature from the former USSR, there were references to the fact that, at least in the case of some sub-assemblies within a machine tool structure, the sub-assembly so behaves under elastic loading as to appear to rotate rigidly about a remotely located but fixed center. Murthy and Venuvinod later demonstrated that this observation is particularly true with respect to the chuck-spindle-headstock sub-assembly of lathes [8]. This observation is used in the present work while modeling k_{sp} for different work holding configurations. In particular, for a workpiece chucked at one end with the other end free,

$$k_{sp} = \frac{K_{csh}}{(R + L - z)^2} \quad (7)$$

where z and L are the instantaneous axial distances between the free end of the workpiece and the cutting point P and the chuck face respectively, R is the axial distance between the chuck face and the plane normal to spindle axis and containing the rotation center (see Figure 1), and K_{csh} is the rotational stiffness (N·mm per radian) of the chuck-spindle-headstock assembly about the rotation center.

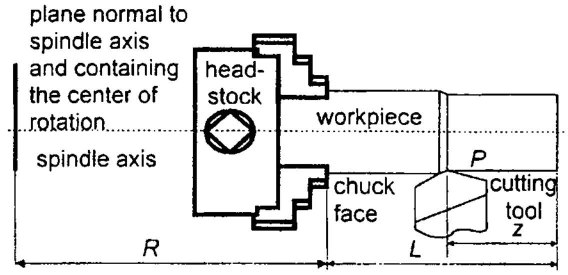


Figure 1: Rotation center of the chuck-spindle-headstock sub-assembly of lathes.

Finally, k_{wp} can be determined by applying well-known principles of theory of elasticity since the instantaneous workpiece shape and the modulus of elasticity of the work material are easily obtained. The authors have written a simple finite difference program for estimating k_{wp} with less than 1% error even while turning complex workpiece profiles.

A very useful observation follows from equations (6) and (7). Note that, for a workpiece held just by chucking at one end, δ_f can be expressed as an explicit function of seven parameters: F_x, k_t, k_{wp}, K_{csh}, R, L and z. Of these, L and z are known *a priori* from the CNC part program; k_{wp} can be directly estimated by using the finite difference program referred to earlier, k_t, K_{csh} and R should be constants for a given machine tool with given work holding set up; and F_x should be constant for a given combination of tool/work material pair, tool geometry, and cutting conditions.

It follows from the above discussion that the three machine constants (k_t, K_{csh} and R) and the radial cutting force (F_x) can be estimated just by performing on-warm-machine-measurement of four diameters (D_{omw}) distributed along the machining length during a single cylindrical turning operation and then simultaneously solving the corresponding equations for δ_f.

4 EMPIRICAL VERIFICATION OF THE APPROACH

Cylindrical turning tests were conducted on aluminium and carbon steel workpieces using a common type of CNC horizontal turning center equipped with a Q-setter and a six-tool turret. Four commercial types of carbide tool inserts with and without chip formers were used to cut over a fairly wide speed and feed range. The depth of cut was however kept small since error compensation is of importance only in finish cutting.

The machined diameters were subjected to post-process and on-machine measurements following the methods described in section 2. From these measurements, the error components (δ_g, δ_{th}, and δ_f) were estimated using equations (3), (4), and (5b). Figure 2 shows that δ_f has resulted in an increase in the machined diameter whereas δ_g and δ_{th} have led to a decrease in the diameter. Next, using the error component δ_f, the three magnitudes of the machine constants (k_t, K_{csh}, and R) and F_x were determined by applying the procedure described in section 3. Several independent tests were conducted to verify the estimates of the various parameters obtained from PPM/OMM measurements: δ_g and δ_{th} were verified using a laser interferometer; k_t, K_{csh} and R were verified by loading the chucked workpiece with a load cell and monitoring the deflections with a dial gauge; and F_x was verified using a piezo-electric cutting dynamometer.

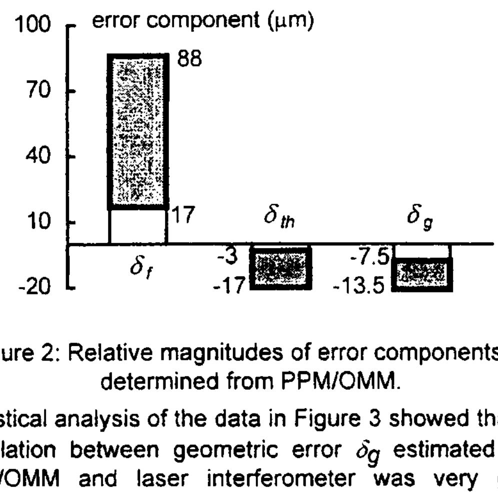


Figure 2: Relative magnitudes of error components as determined from PPM/OMM.

Statistical analysis of the data in Figure 3 showed that the correlation between geometric error δ_g estimated from PPM/OMM and laser interferometer was very good: regression line slope = 0.996, regression line intercept = 0.0886, correlation coefficient r = 0.995.

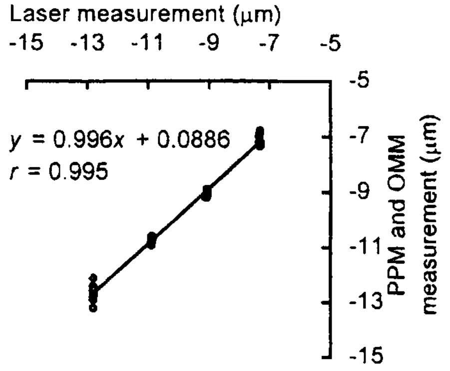


Figure 3: Correlation between δ_g estimates from PPM/OMM and laser interferometer.

The following table compares the mean and standard deviation estimates of k_t, K_{csh} and R as derived from the load cell and OMM based tests along with the confidence levels of agreement following the application of the Student t-Test to the raw data (note that the agreement is very good).

	Estimates from PPM/OMM		Estimates from Load Cell		Confidence (t-test)
	Mean	Std. Dev.	Mean	Std. Dev.	
$k_t \times 10^4$ (N/mm)	1.771	0.056	1.799	0.031	91.2%
$K_{csh} \times 10^8$ (N·mm/rad)	5.878	0.039	5.867	0.030	97.6%
R (mm)	191.1	9.8	202.5	11.7	97.3%

Table 1: Comparison of the estimates of k_t, K_{csh} and R from OMM and load cell measurements.

Figure 4 compares the two estimates of F_x. It can be seen that, notwithstanding the assumption that $\delta_{other} \approx 0$, the correlation is acceptably high (r-value is 0.956).

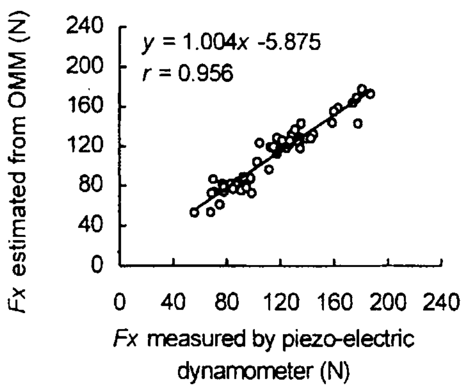
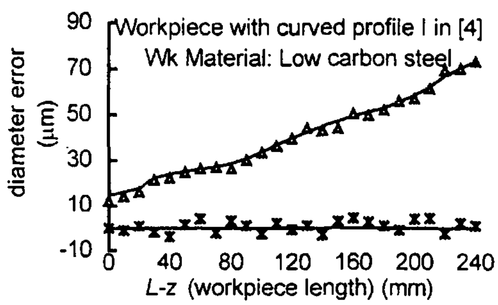


Figure 4: Correlation between F_x estimates from OMM and piezo-electric dynamometer.

The above results indicate that F_x can be estimated solely from workpiece measurements, i.e., the machine tool can be made to act as its own dynamometer at least with respect to the radial force and the dynamometer constants are determinable from workpiece measurements performed on the same machine!

5 ERROR COMPENSATION

Section 2 has outlined a method for estimating the major error components from PPM/OMM results from historical data derived from previously machined components. Section 3 has described a method for modeling the machine structure so that the deflection error associated with the next workpiece can be predicted from the data obtained from a similar cutting situation. A method for predicting F_x from data obtained with the same tool/work material pair, tool geometry and cutting conditions has been outlined. Thus it is straight forward to apply Case Based Reasoning (CBR) to predict the total error on the next part. All one needs to do is to retrieve cases similar to the next part from a progressively compiled case base and adapt the data to the new situation. Note that (i) little adaptation is needed with regard to the prediction of δ_g, k_t, K_{csh}, R; (ii) k_{wp} is easily determined for the new part by the finite difference program, (iii) adaptation of F_x can be done by suitable interpolation or extrapolation of previous force data by means of a suitable analytical model of turning forces (models are quite good at predicting trends although not so at absolute quantities [2]). However, with regard to δ_{th}, further research is needed to resolve some difficulties concerning the characterization of thermal loading to facilitate case retrieval.



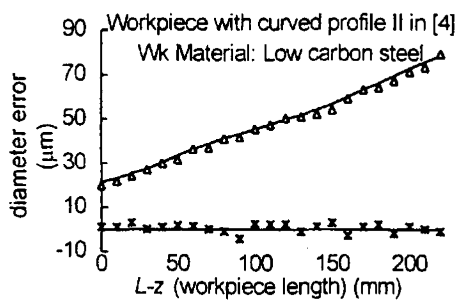


Figure 5: The performance of the proposed method of error compensation (— model prediction; Δ PPM - without compensation; • PPM - with compensation).

The new method of error compensation has been tested against a range of workpiece profiles using steel and aluminum workpieces. For each workpiece, tests were conducted with uncompensated and compensated parametric CNC programs, respectively. It was found that, in all cases, the PPM/OMM based compensation method could bring the error magnitudes down to below 5 µm. Figure 5 shows two sets of benchmark results obtained while using complex curved profile segments which are identical to those adopted in [4]. However, unlike in [4] where the workpieces were supported by the tailstock, our workpieces were held by chucking at one end only. Further, the tool insert (DNMG 150604-QM), the toolholder (PDJNL 2525N-15) and, of course, the machine tool are different. However, the cutting conditions (depth of cut = 0.5 mm, feed = 0.1 mm/rev, cutting speed = 240 m/min, and dry cutting) in the final pass were quite close to those used in [4]. It is seen from Figure 5 that the maximum diametral error could be brought down to about ±3-4 µm (which is much better than the ±10 µm obtained in [4] while testing the effectiveness of a non-contact in-process measurement using a laser based photo-detector) even when the maximum error associated with the uncompensated program was over 70 µm.

6 CONCLUSION

A new method of error compensation has been developed for CNC turning. The method is based solely on post-process and on-machine inspection of parts previously machined on the same machine. Since inspection is a normal and routine shop-floor activity, when compared to prevailing compensation methods, the new approach is much more shop-floor-friendly. The approach has been verified by independent measurements. An important discovery is that the new approach enables the machine tool to act as its own dynamometer.

7 ACKNOWLEDGMENTS

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