ERROR COMPENSATION IN CNC TURNING SOLELY FROM DIMENSIONAL MEASUREMENTS OF PREVIOUSLY MACHINED PARTS

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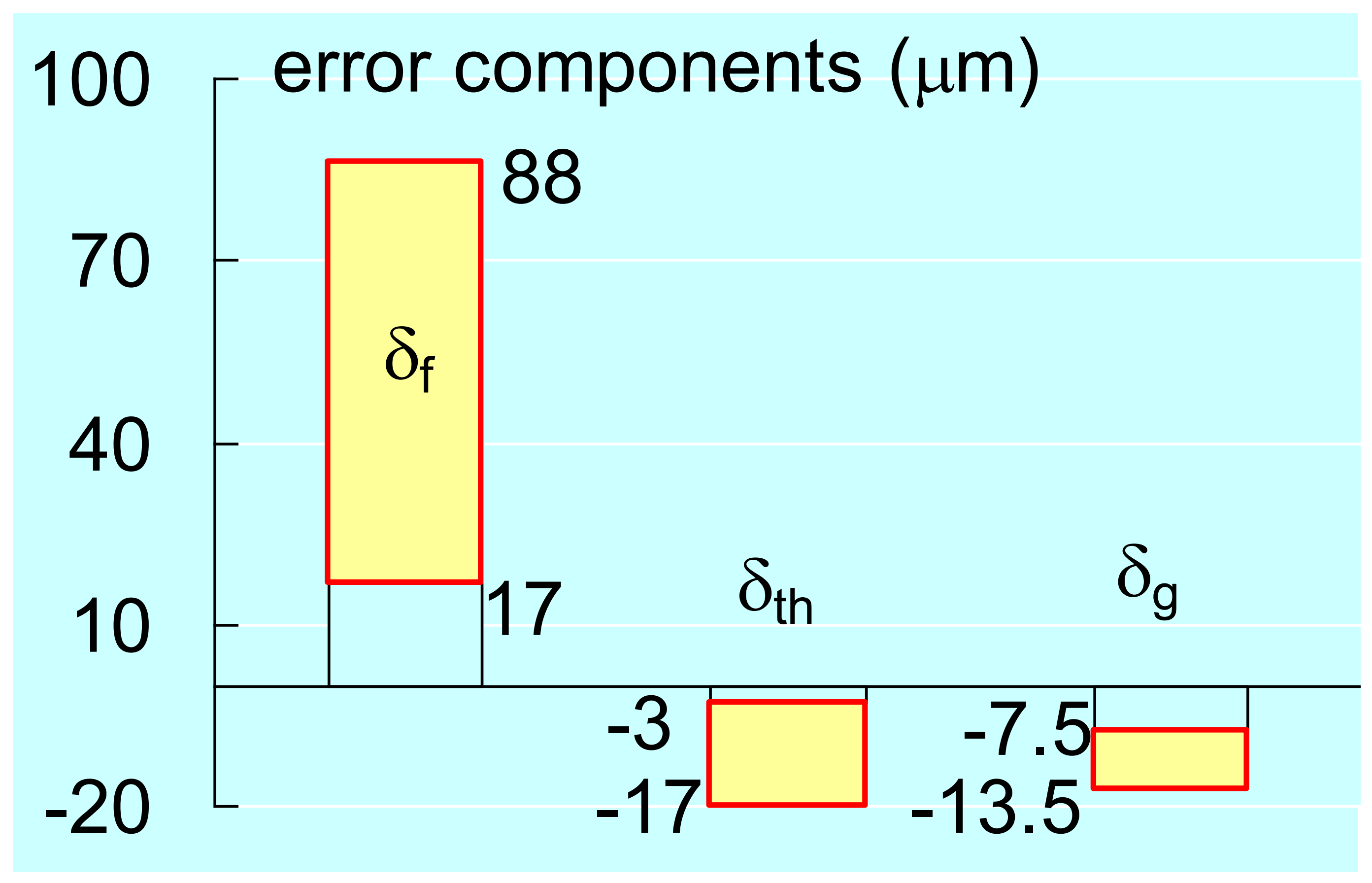
Sources of Dimensional Errors during Machining

δ_g	geometric errors of machine tool;
δ_{th}	thermal distortions of machine tool;
δ_f	static deflections of the MFWT system under cutting force, and
δ_{other}	other errors (clamping, tool wear, etc.).

Total error on diameter:

$$\delta_{\mathrm{tot}} = \delta_g + \delta_{th} + \delta_f + \delta_{other}$$

Example of error distribution in CNC Turning



Accuracy improvement strategies

- Error avoidance via hardware—accurate machining with an accurate machine; (EXPENSIVE)
- Error compensation via software—accurate machining with an inaccurate machine. (INEXPENSIVE)

However, error compensation is not common in industry:

- Inadequate shop floor friendliness;
- Expensive measuring devices & methodology;
- Inadequate adaptation of error models to changing conditions.

The Need

A shop-floor friendly compensation strategy:

- ↓ not require sophisticated hardware (e.g. laser interferometer, dynamometer)
- ↓ based only on activities that are fairly normal and routine on most shop floors

The Challenge

- Modeling the total error, δ_{tot}, is complex.
- Can we 'divide and conquer'?

  Can we find a shop-floor friendly way of resolving δ_{tot}, into component errors

  (δ_g, δ_{th}, δ_f,,,)?
- Can we model the individual error components in a simple manner?
- Can we enable the machine tool to **<u>learn</u>** to compensate for the next part on the basis of knowledge gained from its past machining experiences?

Some normal shop floor activities

- Post-process measurement (PPM), typically performed on a CMM.
- More recently, on-machine measurement (OMM) has become popular with the advent of touch trigger probing.

  But, touch trigger probes are delicate and expensive.

Our shop-floor friendly OMM

- Ostafiev has recently developed a ‘Fine Touch (FT)’ technique that enables the cutting tool itself to be used as the contact probe with accuracy ≈ 1 µm.
- In 1998, we combined the FT technique with Q-setter available on many turning centers to enable a shop-floor friendly method of on-machine measurement.

Realization of a new principle

- $\delta_{tot} = \delta_g + \delta_{th} + \delta_f + \delta_{other} = D_{pp} - D_{des}$
- Mou and Liu showed in 1994 that

$$\delta_{pos} = D_{pp} - D_{om}$$

$\delta_{pos} = \delta_g$ when the machine is cool

$\delta_{pos} = \delta_g + \delta_{th}$ when the machine is warm

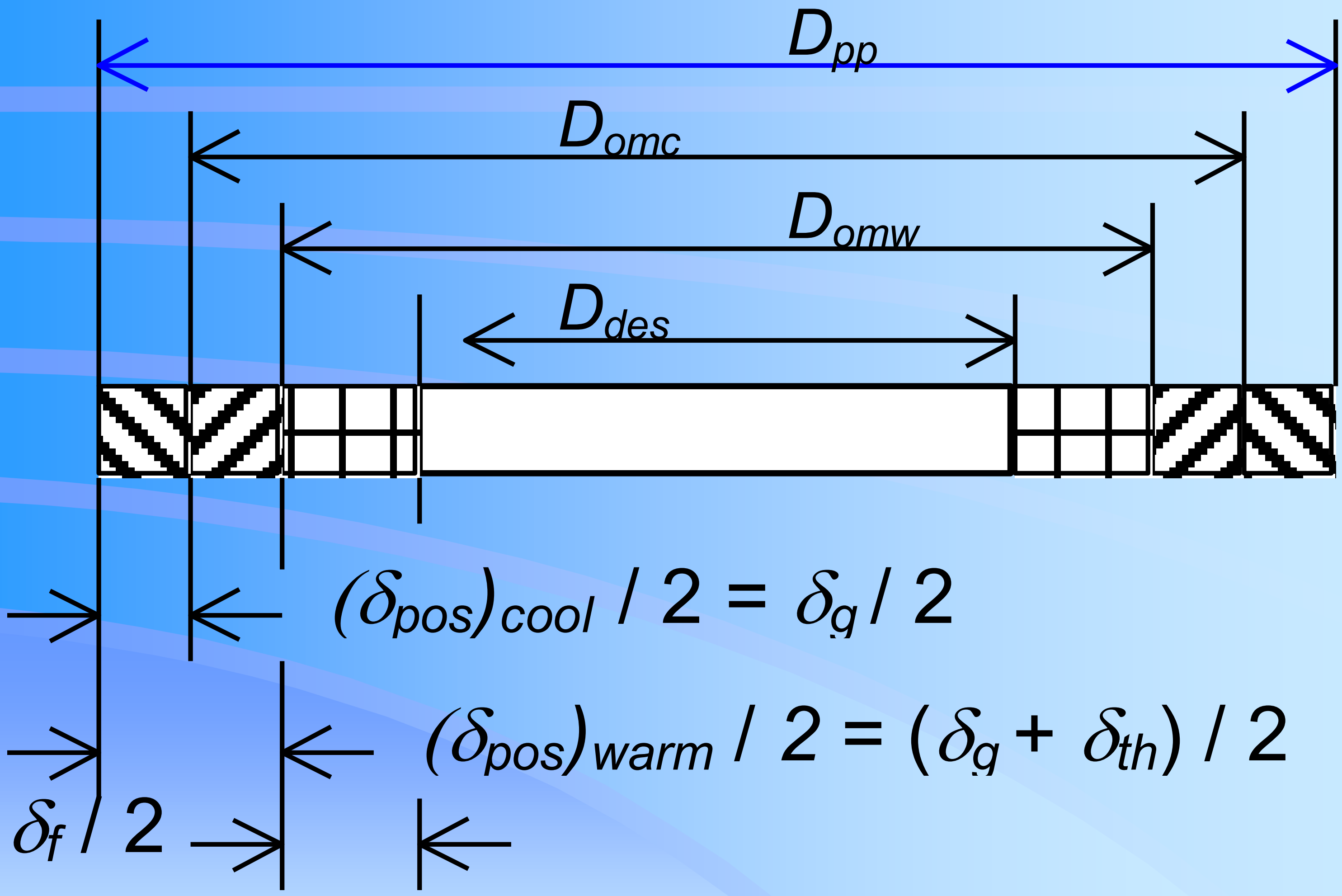
- Hence, if $\delta_{other} \rightarrow 0$,

$$\delta_g = D_{pp} - D_{omc}$$

$$\delta_{th} = D_{omc} - D_{omw}$$

$$\delta_f = D_{omw} - D_{des}$$

Errors and inspected dimensions: Relationships



$$(\delta_{pos})_{cool} / 2 = \delta_g / 2$$

$$(\delta_{pos})_{warm} / 2 = (\delta_g + \delta_{th}) / 2$$

The Principle

The problem of error decomposition can be solved merely by making three measurements of dimension D:

- A Post-Process Measurement, D_{PP}
- An On-Warm-Machine Measurement, D_{omw}
- An On-Cool-Machine Measurement, D_{omc}

PPM and OMM are

fairly normal on many shop floors.

Model for δ_f : Workpieces chucked at one end

F_x	radial cutting force
k_t	tool-side system stiffness
k_{wp}	workpiece stiffness
k_{sp}	overall stiffness of the chuck-spindle-headstock sub-system

$$\delta_f = 2F_x(1/k_t+1/k_{wp}+k_{sp})$$

Predicting $\delta_g(x,z)$ and $\delta_{th}(x,z)$

- Magnitudes of $\delta_g(x,z)$ at different (x,z) derived from previous machining experiences, then modeled to facilitate prediction for the new (x,z).

- Magnitudes of $\delta_{th}(x,z)$ at different (x,z) derived from previous machining experiences, then pattern matched against corresponding thermal loading parameters using an ANN to facilitate prediction for the new (x,z).

k_{sp} varies along workpiece length

Invoked the long forgotten concept of center of rotation:

> "Some sub-assemblies seem to exhibit a center of rotation."

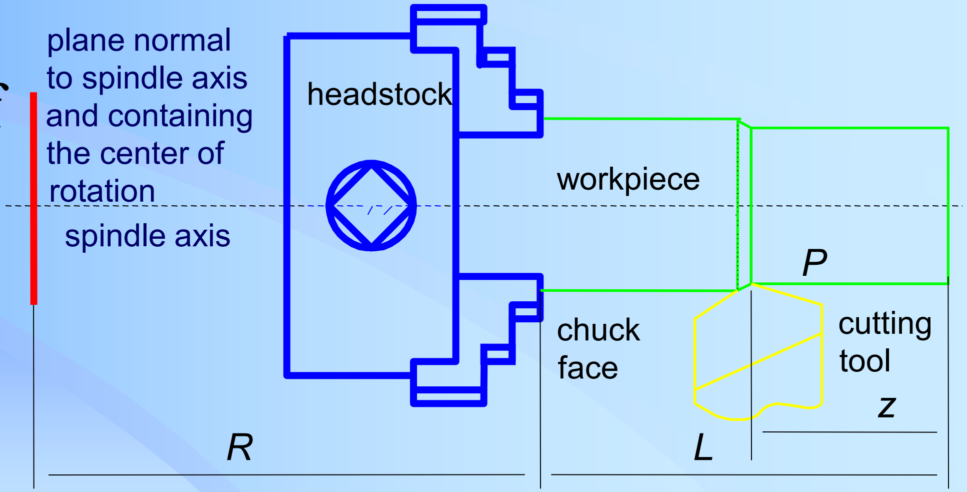
Verified for lathes: e.g. [Murthy & Venuvinod '69]

Verified again by us for our CNC turning center.

$$k_{sp} = K_{csh}/(R+L-z)^2].$$

K_{xcsh} is rotation stiffness of chuck-spindle-headstock assembly,

R, L, z are shown in Figure



On-line estimation of the radial force, F_x

A new approach to on-line F_x estimation:

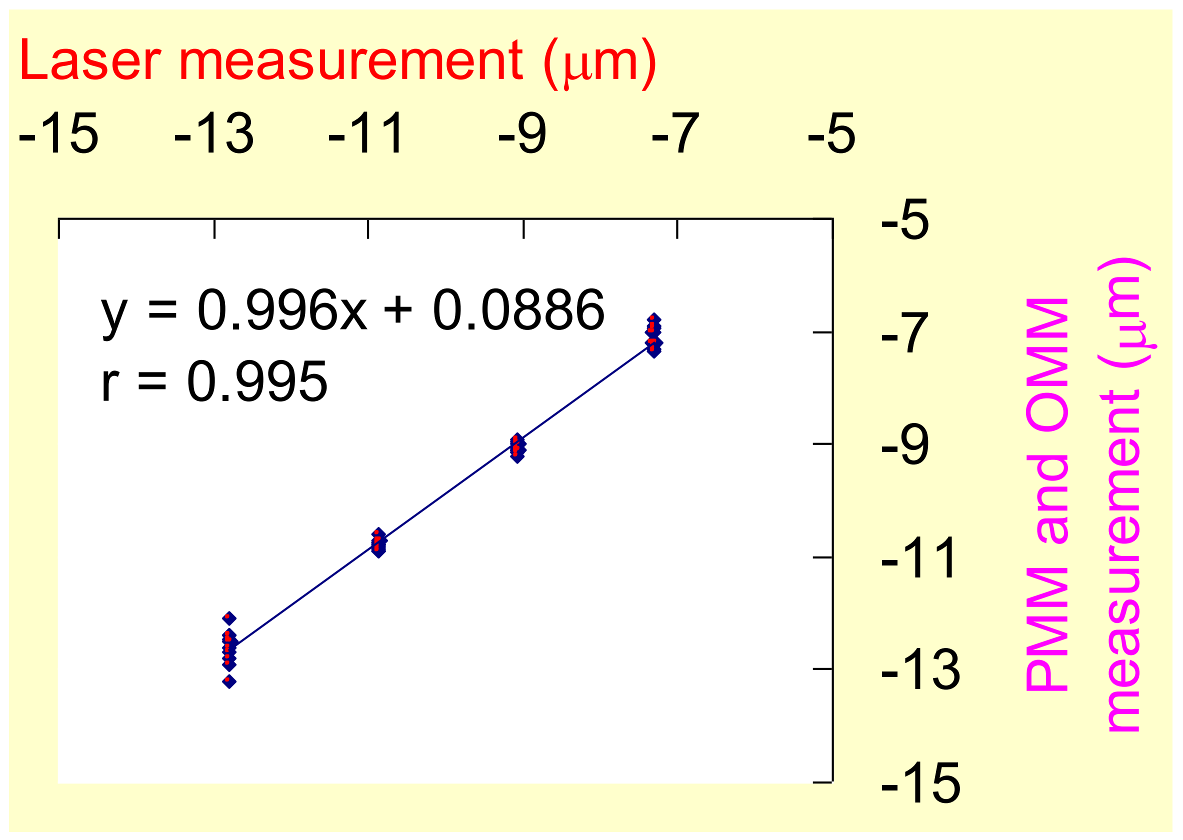
- δ_f can be expressed as an explicit function of seven parameters: F_x, k_t, k_{wp}, K_{csh}, R, L and z.
- (k_t, K_{csh}, R) and F_x can be estimated just by performing on-warm-machine-measurements of **four** diameters and then simultaneously solving the corresponding equations for δ_f .

Thus, it is possible to make the machine tool itself to act as its own dynamometer.

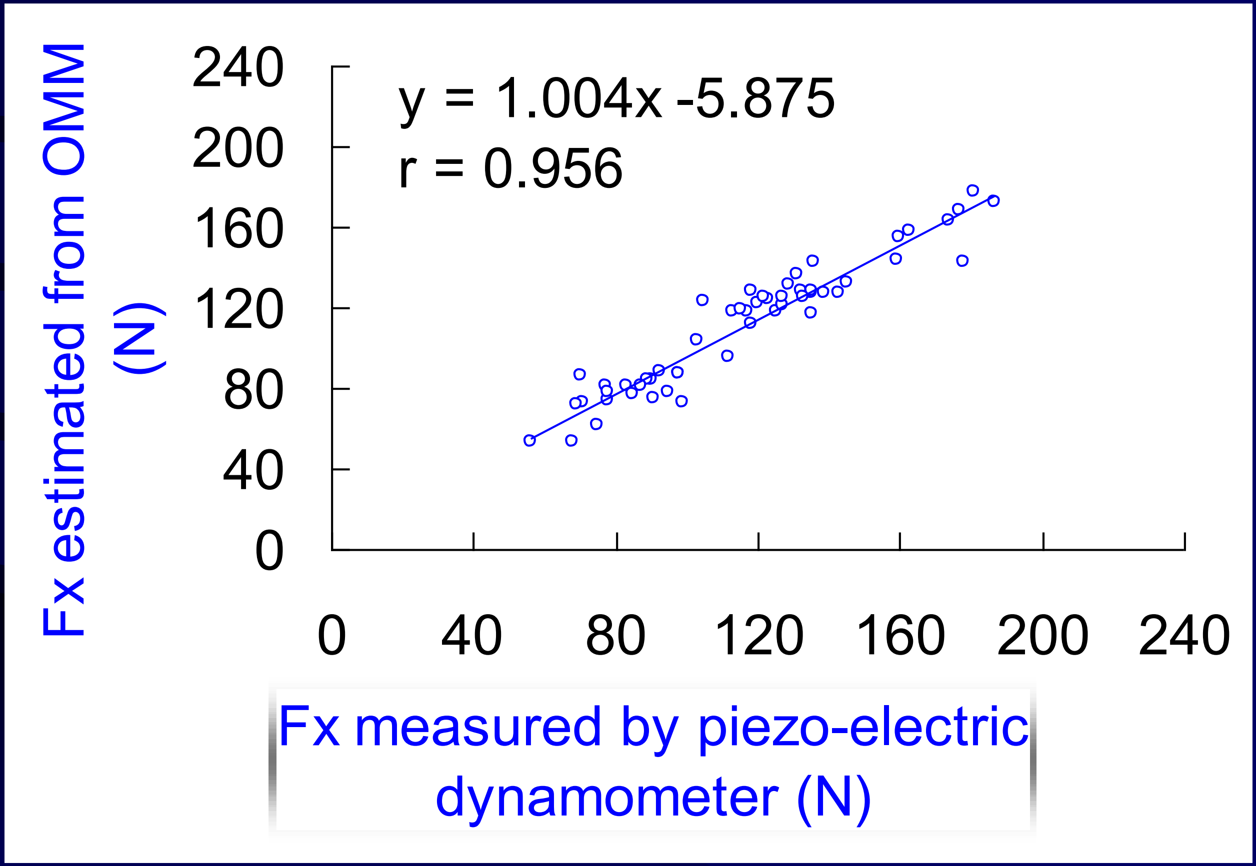
Experimental verification

- Geometric and thermal error distributions verified through independent measurements using a laser interferometer.
- Machine's structural stiffness parameters verified through independent measurements using a load cell and dial gauges.
- Radial cutting force estimates verified through independent measurements using a piezo-electric dynamometer.

Comparison between δ_g estimates from PPM/OMM and laser interferometer



Comparison between F_x estimates from OMM and piezo-electric dynamometer



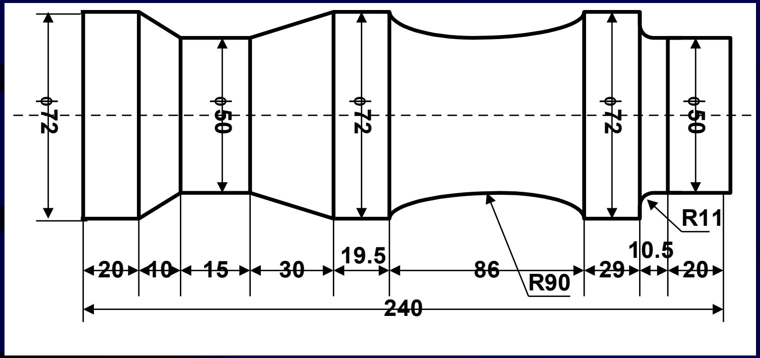
Comparison between k_t, K_{csh} and R estimates from OMM and load cell measurements

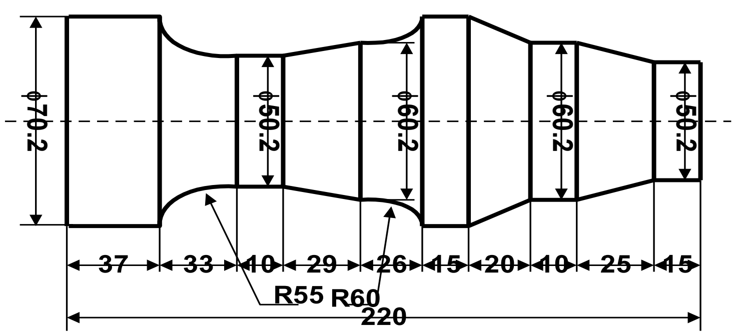
	Estimates from PMM/OMM		Estimates from Load Cell		Confidence (t-test)
	Mean	Std. Dev.	Mean	Std. Dev.	
$k_t \times 10^4$ (N/mm)	1.771	0.056	1.799	0.031	91.2%
$K_{csh} \times 10^8$ (N·mm/rad)	5.878	0.039	5.867	0.030	97.6%
R (mm)	191.1	9.8	202.5	11.7	97.3%

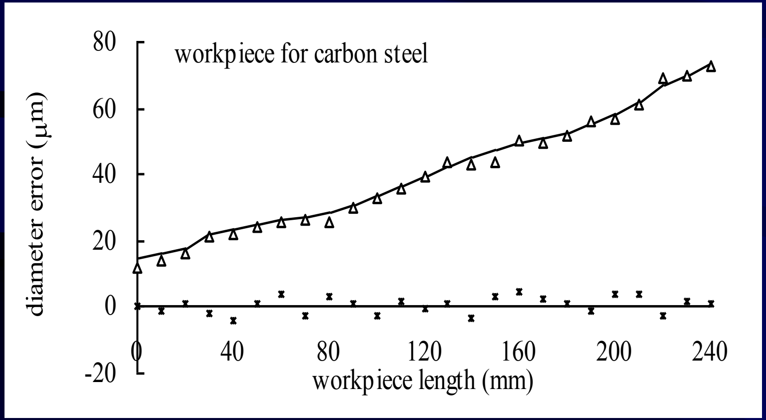
The error compensation strategy

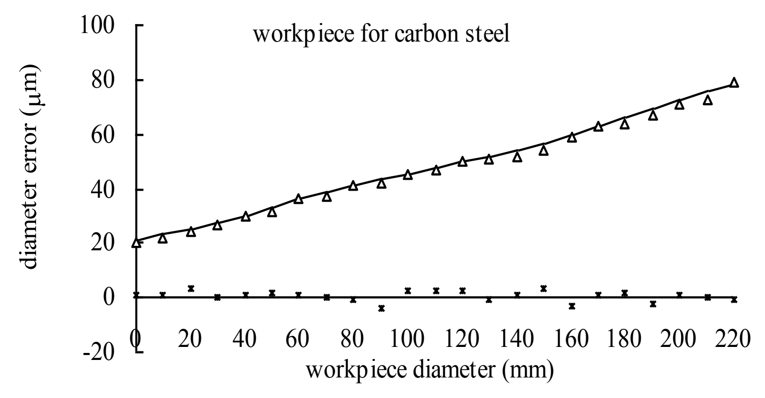
- For the method of error compensation based on PPM/OMM, it is straight forward to apply CBR to predict the dimensional error on the next part:
- Little adaptation of the prediction of $\delta_{g,}$ k_t, K_{csh} and R for the new MFWT system;
- k_{wp} is determined for the new part by the FD program;
- Adaptation of F_x is done through suitable interpolation or extrapolation of previous force data by an analytical model of turning forces.

Error Compensation Results









The maximum diameter error could be reduced from 72-91 μm down to 5~7 μm.

After due implementation of the CBR systems

One would be able to take a visitor round one’s shop floor and say:

- “This machine is new. He is still dumb. He hasn’t yet learnt to compensate.
- Ah! Look at this machine! She has been with us for 8 months and has learnt to compensate quite well. She is correct 95% of the time.”

THANK YOU

Conclusion

A new method of error compensation has been developed for CNC turning. The method is based *solely on two OMMs and further one PPM* of previously machined parts on the same machine. Hence, when compared to prevailing compensation methods, *the new approach is much more shop-floor-friendly*. The approach has been verified by independent tests. An important discovery is that *the new approach enables the machine tool to act as its own dynamometer.*

Contents

Our inspection protocol

- Carry out the first OMM to obtain D_{omw}.
- Calculate δ_f by using: $\delta_f \approx D_{omw} - D_{des}$
- Repeat OMM to obtain D_{omc}.
- Calculate δ_{th} by using: $\delta_{th} = D_{omc} - D_{owm}$
- Carry out PPM to obtain D_{pp}:
- Calculate δ_g by using: $\delta_g = D_{pp} - D_{owc}$

Inspection protocol (I)

The proposed inspection protocol requires only *one* PPM and *two* OMMs of machined parts:

PPM is conducted using a CMM.

OMM is performed by using the tool itself as a Fine-Touch (FT) contact probe (a shop-floor friendly approach) in combination with Q-setter.

[Liu, Venuvinod, and Ostafiev, I.J. Mfg. Tech. & Mgmt, 1998].

Experimental Verification (II)

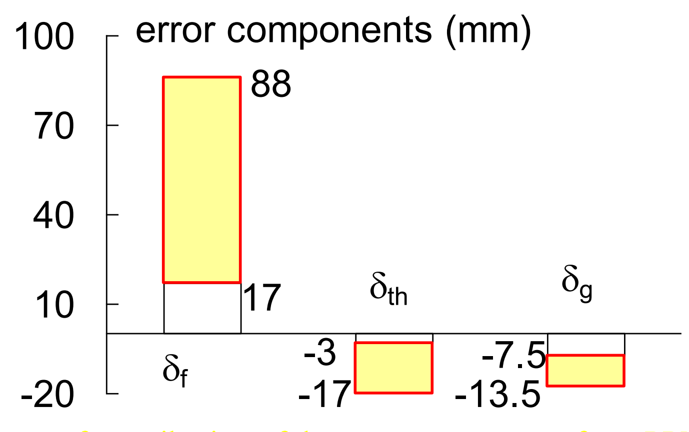
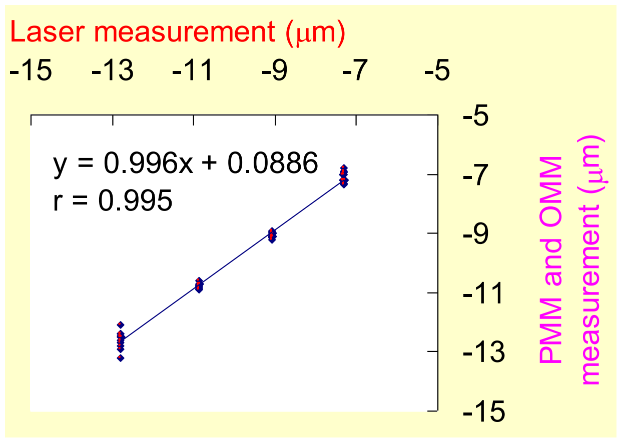


Diagram of contribution of the error components from PPM/OMM.



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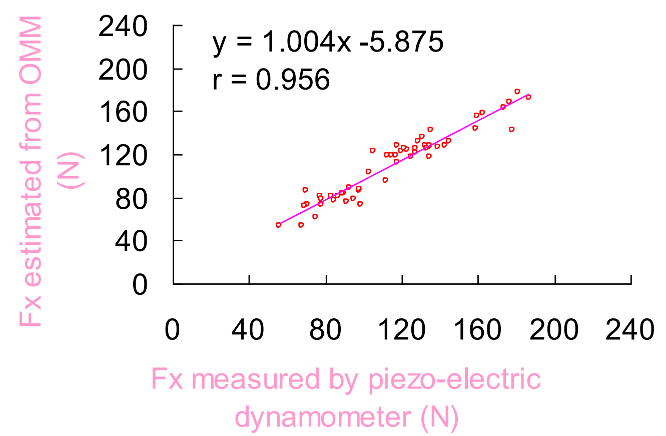
Comparision of the estimations of k_t, K_{csh} and *R* from OMM and load cell measurements:



Comparision between F_x estimates from OMM and piezo-electric dynamometer.