Error Budget as a Design Tool
For Ultra-Precision Diamond Turning Machines

Form Errors

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Abstract

This paper describes how an error budget can be used as a design tool to enhance the performance of an ultra precision diamond turning lathe. By understanding error sources and their effects on the form of a work piece, it is possible to distinguish specific areas for machine improvement.

Keywords: Error Budget, Diamond Turning, Uncertainty Analysis

Introduction

Two axis diamond turning machines have been utilized for producing high quality, cost effective, axis symmetric, optical and mechanical surfaces. Current trends in diamond turning demand higher accuracy and truth of motion from the machine tool. As a builder of ultra precision machine tools, Precitech is constantly developing improvements that will allow our machines to produce higher quality parts. The following error budget is an analysis of the current state of the art Nanoform® 350 diamond turning lathe. This ultra precision machine tool utilizes a water cooled air bearing spindle and oil hydrostatic slide ways of 250 and 350 mm travel. The Nanoform® 350 has a maximum swing capacity of 350 mm diameter, and is capable of turning 75 mm diameter components to better than 0.1 micron form error. The error budget is used to expose the effectiveness of a proposed design change and it's correlation to the total machine accuracy. Future efforts will study spindle errors as well as surface finish effects in more detail.

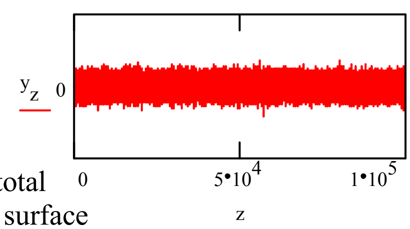

Figure 1 - Gaussian Data

Review types of Error Data

A Gaussian (bell curve) distribution is shown to the right, with data in Figure 1, and a histogram of the data in Figure 2. For this Gaussian type of error, sigma (standard deviation) represents the width of the data, where ±1 sigma about the center point encloses 68 percent of the data, ±2 sigma encloses 95 percent, and ±3 sigma encloses 99.7 percent of the data. Errors with Gaussian distribution include repeatability, reversal, some vibration data, and some thermal errors.

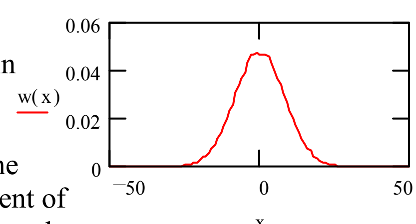

Figure 2 - Gaussian Histogram

Graphs of uniformly distributed data are shown to the right, with the data in Figure 3 and the histogram of the data shown in Figure 4 on the next page. The data is uniformly spread between well defined limits, and a data point has equal probability of falling anywhere within these limits. Uniform data is typical of alignment errors such as squareness, or spindle alignment to the axes.

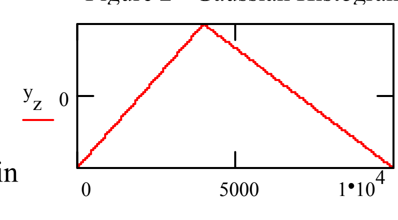

Figure 3 - Uniform Data

In order to add a uniform error with a Gaussian error, some common ground, unit-wise, must be reached. We have chosen to do this by calculating sigma for non Gaussian data sets. This is done by taking the boundary limits (P-V) and multiplying by a conversion factor. In the case of uniform distribution data, the factor is 0.289, which is also $1/\sqrt{12}$. This method allows various types of PV errors to be converted to sigma errors so that they can be added by RSS (root-sum of squares) calculations. [1] [2]

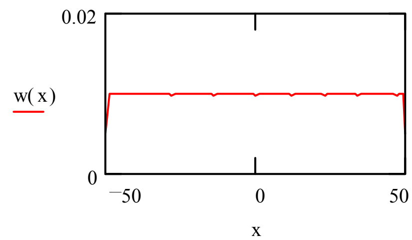

Figure 4 - Uniform Histogram

Another error source exists where the error amplitude changes sinusoidally. Examples of this type of error are scale interpolation error, spindle unbalance, spindle synchronous errors, etc. The sinusoidal form is shown to the right, with the data in Figure 5 and the histogram of the data in Figure 6. As you can see, there are more data points at the edge of the spectrum than in the center. This shifts the conversion factor for this error type to be a larger percentage of the Peak to Valley, namely 0.354 or $1 / \left(2\cdot\sqrt{2}\right)$ times PV equals sigma.

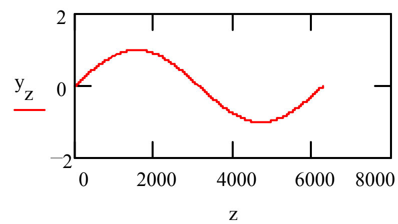

Figure 5 - Sinusoidal Data

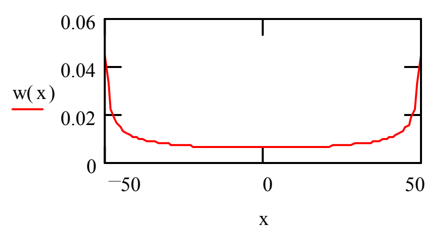

Figure 6 - Sinusoidal Histogram

We also calculated sigma for a banana curve shaped data set. In this case the histogram is not symmetric about the mean, and both sides of data must be considered to calculate a sigma. In this case sigma is 0.342 times PV. This is nearly the same as the sinusoidal factor. These factors are used in combining the errors from various sources at the end of this paper.

Errors in a two axis lathe [3]

Form errors in a lathed part come from either the tool or workpiece not following an ideal prescribed contour in space and time. We have chosen to group the error sources into four categories: Stability errors, Length based errors; Time based errors, and Other errors. While stiffness (machine compliance) is not an error source by itself, cutting force deflects the machine, and variations in cutting force introduce additional part form errors. Some of the following data is preliminary and subject to change.

Nanoform 350 Stability Errors					
Source	Specification	Actual X	Actual Z	Units	Type
Home Repeatability	0.25 PV	0.180	0.100	PV microns	Gaussian
Slide positioning repeatability, reversal		0.012	0.012	sigma microns	Gaussian
Feedback Scale Interpolation Error	0.10 PV	0.002	0.002	PV microns	Sinusoidal
Tool setter repeatability		0.200	N/A	PV microns	Gaussian
Tool setter reaction to temp fluctuations		0.2 / C	N/A	PV microns	Gaussian
Machine reaction to air temp fluctuations		0.2 / C	1.0 / C	PV microns	Sinusoidal
Machine reaction to spindle coolant variations		0.2 / C	1.0 / C	PV microns	Sinusoidal
Round off error		0.004	0.004	PV microns	Uniform

• The home position repeatability is the ability of the slide to 'home' to the same position of the slide travel. These errors are zero if the machine is not re-homed during a production cycle. These values are the PV (Peak to Valley) errors that are allowed and measured. • The slide positioning repeatability is the deviation of position of the slide when repeatedly positioned to one location from both directions. Sigma errors represent one standard deviation of the Gaussian curve, or 1/6 of the equivalent PV errors.

• Scale Interpolation error: The position feedback devices are glass scales with holographic gratings. These scales have a grating pitch spacing of 0.55 microns but a resolution of .0086 microns. The fine resolution is obtained by interpolation (mathematical subdivision) of the sinusoidal output of the read head into divisions that are finer than the original grating pitch. This process depends upon the sinusoidal shape being true. If the sinusoid is imperfect, then the interpolation process will result in a slide position error that repeats every 0.55 microns. This error is present regardless of the interpolation level, i.e. changing the interpolation from 50X to 400X makes it look like there are 8 times more counts for the same distance; however the sinusoid imperfection is the same for both cases.

• The tool setter repeatability is the variation in offset values from the tool set routine, including removing and reseating the tool setter and examining the same tool repeatedly.

• The room temperature surrounding the machine can have a disturbing influence on the machine stability. • Similarly, if water cooling is used to maintain temperature of the machine components, temperature variations of this cooling source can be a disturbing influence on the machine.

• Round Off: The slide position is measured in counts from the encoder, each count representing 0.0086 microns. The desired machine position may be different from a multiple of the encoder count spacing by up to 0.0043 microns. The motion control board used in the Precitech Ultrapath machine tool controller sub divides the resolutions into finer increments, minimizing this type of error.

Nanoform 350 Length Based Errors					
Source	Specification	Actual X	Actual Z	Units	Type
Slide scale length based error 0.4*L/100	1.4, 1.0	0.41	0.14	microns	Sinusoidal
Slide scale length error temp not 20C	-0.70	-0.70	-0.70	PPM / C	Uniform
Axis straightness horizontal	0.30, 0.20	0.23	0.13	microns	Sinusoidal
Axis straightness vertical	0.70, 0.50	0.53	0.48	microns	Sinusoidal
X slide Abbe error calculated and measured	9.55	5.50		microns	Uniform
Z slide Abbe error calculated and measured	2.72		4.50	microns	Uniform
Vertical straightness bimetallic change with temp				microns	Uniform
Spindle to Z parallelism (horizontal)	0.50	0.24		arc sec	Uniform
Spindle to Z parallelism (vertical)	10.00	3.00		arc sec	Uniform
Spindle to X perpendicularity (horizontal)	0.50		0.30	arc sec	Uniform
Spindle coning error	0.28		0.08	arc sec	Uniform
Spindle droop under load (vertical)	0.03	0.03		arc sec / in-lb	Uniform

Length based errors are those that will change value depending upon the dimensions of the part that is to be machined. It is easy to see that a smaller part will be made more accurately than a larger part in some respects. • The scale length based error is the error between the moved distance (measured at the scale) and the scale reading. • There is also a length based thermal error due to running the machine at a temperature different from 20C, where the scale is calibrated. • The straightness is measured using an electronic indicator at the tool height, and as a result, roll errors of the slide do not need to be measured. Vertical error sources are not critical to the performance of the machine and are left out of further analyses.

• Abbe errors are the difference between the slide travel at the scale and at the tool tip or workpiece. These are calculated using pitch and yaw motions of the slide coupled with the distance between the scale feedback device and the tool or part. The measured values were done using a laser distance measurement interferometer.

• When the machine temperature changes, a bimetallic effect can be seen between components with different coefficients of thermal expansion. For example, this causes a change in the vertical straightness in the X and Z axes since the slides are metal and the base is granite. Since vertical straightness has a second order effect on the accuracy of the work piece, the contribution of this error is small. This will affect the pitch angle error for the slide, and the axis compensation (if used).

Nanoform 350 Time Based Errors					
Source	Time Constant	Steady State X Amplitude	Steady State Z Amplitude	Units	Type
Hydro system, scale electronics, work light	TBD	TBD	TBD	microns	Exponential
Linear motor servo active	TBD	TBD	TBD	microns	Exponential
Spindle	TBD	TBD	TBD	microns	Exponential
Spraymist	TBD	TBD	TBD	microns	Exponential

Time based errors are due to the thermal effects during the warm up period for the machine. In this case, the drift of the machine due to temperature gradients is determined from the time period required for the finish pass machining and input as a uniform distribution error. Each component of the machine that is powered or driven heats the machine, with an associated thermal time constant and resultant change of machine shape. Understanding this reaction helps the operator to estimate the error if the machine is not fully warmed up.

Nanoform 350 Other Errors					
Source	Specification	Actual X	Actual Z	Units	Type
Spindle axial synchronous error	0.05		0.025	PV microns	Sinusoidal
Spindle radial synchronous error	0.05	0.017		PV microns	Sinusoidal

Other errors contain the error sources that do not fall easily into the previous categories. In this case, there is an error which is always the same, non-varying value. This could be a zonal defect in the tool edge. This zone will create an error of the same amplitude in the part, regardless of part size, feed rate, or dwell time. The spindle axial synchronous error shows up as a pattern at the center of the part. This may be a step or once per rev, or could have a pattern of spokes radiating from the center.

Typical diamond turning tool forces range from nearly zero up to perhaps 1 Newton. The machine stiffness in the Z direction is 40 Newtons per micron, so the deflection under these forces is less than 0.025 microns and typical finish pass deflections are less than 2 nanometers, making the deflection insignificant to this error budget.

Error Sources during Machine Operation

All of the following errors are dependent upon the operator to minimize where possible.

Tool out of roundness or worn zones
Tool placement / offset values in X and Z
Tool radius scallop height surface finish effect
Straight line motion error to desired curve (poor interpolation in programming)
Work piece centering, and balance / unbalance
Part distortion when mounted, part resonance or chatter, and distortion when at RPM
Thermal disturbance due to cutting coolant or operator involvement

Error Budget Summary

The stability PV errors are multiplied by a factor as outlined earlier depending upon the type of error distribution in order to create a sigma, or standard deviation for the error (see chart below). These are then RSSed together in order to provide a sigma for the spread of all of this type of error. In a similar fashion, the length based errors are combined using equal units of microns per mm of angle, to create a total error for each direction of travel. Typical time based errors are shown for a machine that has been fully warmed up. Because the final cut duration is often much shorter than the dominant thermal time constants, these errors can be treated as having a uniform distribution.

Stability	PV	Factor	X Sigma	Z Sigma	Type
Slide positioning repeatability, reversal			0.0120	0.0120	Gaussian
Feedback Scale Interpolation Error	0.005	0.354	0.0018	0.0018	Sinusoidal
Machine reaction to 1C air stability	0.100	0.289	0.0058	0.0289	Uniform
Machine reaction to 0.1 C coolant stability	0.050	0.289	0.0029	0.0145	Uniform
Round off error	0.004	0.289	0.0012	0.0012	Uniform
RSS of Stability Errors			0.0138	0.0345	um RMS

Length Based	PV	Length	X Sigma	Z Sigma	Type
	microns	mm	um/mm	um/mm	
X slide scale length based error	0.41	350	0.000415		XX Sinusoidal
X slide scale length error temp 29C	2.31	350	0.001907		XX Uniform
X axis straightness horizontal	0.23	350		0.000233	ZX Sinusoidal
Z slide scale length based error	0.14	250		0.000198	ZZ Sinusoidal
Z slide scale length error temp 29C	1.65	250		0.001907	ZZ Uniform
Z axis straightness horizontal	0.13	250	0.000184		XZ Sinusoidal
X slide Abbe error	5.50	350	0.004541		XX Uniform
Z slide Abbe error	4.50	250		0.005202	ZZ Uniform
Spindle to Z paralellism (horizontal)	0.24	arc sec	0.000336		XZ Uniform
Spindle to X perpendicularity (horizontal)	0.30	arc sec		0.000420	ZX Uniform
Spindle coning error	0.08	arc sec		0.000112	ZX Uniform
RSS of X direction errors with X movement			0.0049		um RMS/mm
RSS of Z direction errors with Z movement				0.0055	um RMS/mm
RSS of X direction errors with Z movement			0.0004		um RMS/mm
RSS of Z direction errors with X movement				0.0005	um RMS/mm

Time Based	PV	Factor	X Sigma	Z Sigma	Type
Hydro System, scale electronics, work light	0.02	0.289	0.0012	0.0058	Uniform
Linear Motor Servo Active	0.02	0.289	0.0012	0.0058	Uniform
Spindle	0.1	0.289	0.0058	0.0289	Uniform
Spraymist	0.02	0.289	0.0012	0.0058	Uniform
RSS of Time Based Errors			0.0061	0.0306	um RMS

Other					
Spindle Axial Synchronous error (affects Z)	0.025	0.354		0.0089	Sinusoidal
Spindle Radial Synchronous error (affects X)	0.017	0.354	0.0060		Sinusoidal

Example	X	Z	
Travel required to machine part	50	5	mm
Stability	0.014	0.035	um RMS
Length, 50 * 0.0049 (for X)	0.247	0.025	um RMS
Length, 5 * 0.0004 (for X)	0.002	0.028	um RMS
Time	0.006	0.031	um RMS
Other	0.006	0.009	um RMS
Total RSS	0.248	0.060	um RMS

If the length of travel needed to machine a part is known, a predicted error can be calculated. The above example uses 50 mm of X travel and 5 mm of Z travel. This shows the expected RMS error band for the machine in making this part. In this case, the X error is 0.248 microns RMS, and the Z error is 0.060 microns RMS.

The work piece error is measured normal to the surface, so for a flat part, the X error is not significant, regardless of amplitude. In reality, the X and Z values must be mapped against the surface normal to the part in order to determine the impact of the machine errors on the work piece. [1]

Also, the length based errors are repeatable, and thus can be reduced using error correction routines, such as the Ultracomp accessory for on-machine measurement and error correction of the work piece. These procedures can also correct for tool waviness, tool placement error, and the repeatable part of spindle growth errors. Removing the length based errors leaves a residual error of 0.047 microns RMS in the Z direction, but the accuracy limitations of the correction procedure must also be included in the error estimate. In the case of Ultracomp, a typical accuracy is 0.025 microns RMS, which gives a resulting part accuracy of 0.053 microns RMS.

Examine where to concentrate efforts to improve accuracy

It is now possible to compare the errors associated with each source. This indicates that positioning accuracy compensation of the axes would be the most productive place to improve machine accuracy. This method is limited in that it is only valid for one tool location and one workpiece length. It also assumes that pitch errors are repeatable, and the machine can change pitch with temperature as noted above. Accuracy can also be improved by entering the scale compensation value for the temperature of the machine in use instead of the calibrated values at 20C. Thermal stability effects are expected to also be a significant contribution to total error. Since thermal effects are more difficult to compensate, this may be the most important area to focus on in improving machine accuracy.

Conclusions

This paper summarizes the error budget process for a cost effective, state-of-the-art, ultra-precision diamond turning lathe. Furthermore, typical error values along with a method for combining errors has been displayed. This error budget has been found to be consistent with actual machine cutting results. Finally, advancements in ultra precision machining are occurring as a result of a fundamental understanding of machine tool error sources and their consequences.

References

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