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Method for establishing machine tool performance specifications from part tolerance requirements

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Abstract

Design Engineers are accustomed to using tools to evaluate the effect of tolerances on their designs. Valve Designers often calculate the tolerance effects on spring rates and flow paths. Process Engineers, however, have relied on experience or an "educated guess" and trial and error, to meet the design tolerance requirements. The capability of an existing or new machine to produce a given feature to tolerance was essentially unknown. The adoption of two ASME Standards, B5.54-1992 [1] and B5.57-1998 [2], has provided the basis for new process capability tools. These standards use the "Deterministic Method" first described by Donaldson [3] and later by Bryan and Loewen [4]. Machine motions are described by the six degrees of freedom of the linear and rotary axes. The relationships of the axes are defined by the angles between the linear and rotary axis average lines. The motions and relationships or parameters are defined by errors such as angular (roll, pitch and yaw), spindle (radial, axial and tilt), straightness, squareness, parallelism and accuracy (linear and angular). This paper will discuss the method of identifying and describing these errors for a selection of machine designs. A Machine Error Model will be used to evaluate the capability of a machine tool to process a sample part. The concept of Part Tolerance Ratios for establishing the limiting tolerances from a family of parts will be presented. Machine Tolerance Ratio as a measure of machine capability will also be discussed. The methods of measuring, recording and controlling parameters will be addressed.

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1 Introduction

Machine tool test standards have been evolving for nearly one hundred years. In 1927, Dr. Georg Schlesinger published the first of a series of acceptance test specifications for machine tools [5]. This book and the subsequent ISO 230 series of acceptance codes for machine tools [6] state that their aim “is to standardise methods of testing.” An accompanying series of machine tool test conditions, ISO 13041, “establishes the tolerances or maximum acceptable values for the test results” [7]. These methods and tolerances are utilised by machine builders and users, to assess the results of their work or condition of their machines. The tolerances have tightened significantly, to reduce size and improve efficiency. Their complexity, however, has made it difficult for users to establish performance specifications based on their own needs.

The B5.54 [1] and B5.57 [2] Standards for CNC machine tools use methods quite different from Schlesinger. These standards use the "Deterministic Method" first described by Donaldson [3] and later by Bryan and Loewen [4]. Machine motions are described by the six degrees of freedom of the linear and rotary axes. The relationships of the axes are defined by the angles between the linear and rotary axis average lines. The motions and relationships or parameters are defined by errors such as angular (roll, pitch and yaw), spindle (radial, axial and tilt), straightness, squareness, parallelism and accuracy (linear and angular). This revised parametric method of describing machines makes it easier for the Process Engineers to understand the effects of errors.

2 Errors

2.1 Machine errors

2.1.1 Six degrees of freedom – linear motion

Machine elements moving along a linear axis are constrained in space by a variety of bearing systems. These systems consist of sliding elements and rolling elements. Sliding systems use anti-friction methods, including solids, fluids and pressurised fluids. Rolling systems use balls, cylinders and tapered cylinders. The ways on which these systems ride may be flat, round, or contoured. Regardless of the design, the systems all have the same motions relative to the earth. These motions consist of three translation and three rotary motions. These motions can be described as roll, pitch, yaw, straightness 1, straightness 2, and linear displacement accuracy. It should be noted that the bearing system geometry is the primary source of part geometry.

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2.1.2 Six degrees of freedom – rotary motion

Rotating machine elements are constrained relative to the earth, in the same manner as linear systems. The only difference is that the bearing systems are circular instead of linear. Rotating elements exhibit the same three translation and rotation motions. Rotating element motions are described as tilt 1 (pitch), tilt 2 (yaw), axial error (straightness 1), radial error (straightness 2) and angular displacement accuracy (roll).

2.1.3 Multi-axis relationships

Machine elements are connected by a variety of frame designs. The relationships between the bearing systems are defined by the angle between the axis direction lines of linear axes and the axis average lines of rotary axes [2]. These lines are through the average centres of the bearing systems.

2.1.4 Dynamic motion

With the advent of CNC (Computer Numerical Control) and DNC (Direct Numerical Control) the geometry of workpieces can also be affected by the dynamic capability of the machine control system. Tapered, round and contoured features can be produced by a number of different methods. These methods include Linear and Circular Interpolation, managed by the machine control. Tool paths can also be downloaded directly from a CAD/CAM system.

2.2 Thermal and vibration errors

In many material removal processes, temperature can have a significant effect on the geometry of the finished part. The thermal error can lengthen, shorten or distort the part. Vibration errors can affect surface finish. These errors may come from the machine itself, the environment or the material removal process. Four tests in the ASME Standards B5.54-1992 and B5.57-1998 provide tools for measuring and controlling these errors. The TVE (Temperature Variation Error) Test [1] quantifies the effect of the thermal environment around the machine. The Relative Vibration Test [1] quantifies the effect of the vibration environment and the effectiveness of vibration isolation systems. These errors can be reduced by improving the machine environments.

The Thermal Distortion Caused by Moving Linear Axes [2] and Spindle Thermal Stability Tests [2] quantify the errors coming from the machine. These errors can be reduced by process changes.

3 Machine error descriptions

3.1 Machine

The manner in which machine errors combine to affect the part tolerance is dependent on the machine design. Error Models are custom-designed based on axis configurations since the offsets used to convert angular errors to displacements are dependent on the machine construction. Fundamental differences in machine designs are reflected in the manner in which the axes are arranged or "stacked." There are several schemes in the standards for describing the stacking of machine axes. Most of them involve the use of numbering systems, which are difficult to remember. The most convenient method uses a simple axis, frame (or fixed structure) and spindle nomenclature, first suggested by Charlton [8]. The order in which machine axes are stacked relative to each other determines the machine description. The part is located first and a sequence of axes, frames and spindles is used to describe the machine design. For example, the 3 Axis Vertical Spindle Machining Centre (Gantry Mill) shown in Figure 1 is designated by fXYZS because the Part sits on the Frame (f), which is fixed to the earth, with the X Axis (X) stacked on f, the Y Axis (Y) on X, the Z Axis (Z) on Y and the Spindle (S) on Z.

3.2 Errors

The direction and sign of machine errors is significant when considering the effects due to wear or electronic error compensation. None of the performance standards provides adequate definitions of direction or sign. ISO 841 [9] standardises the variations in axis designation for motion control. This standardisation permits the use of the same Part Program on a variety of machines. The description of machine errors is a similar problem to the axis control. The resulting solution is to use the same axis and sign conventions for machine errors as are used for machine motions. This may seem confusing, since some machine motions are opposite to the error direction. The result however, is that the errors appear in the part, in the proper direction.

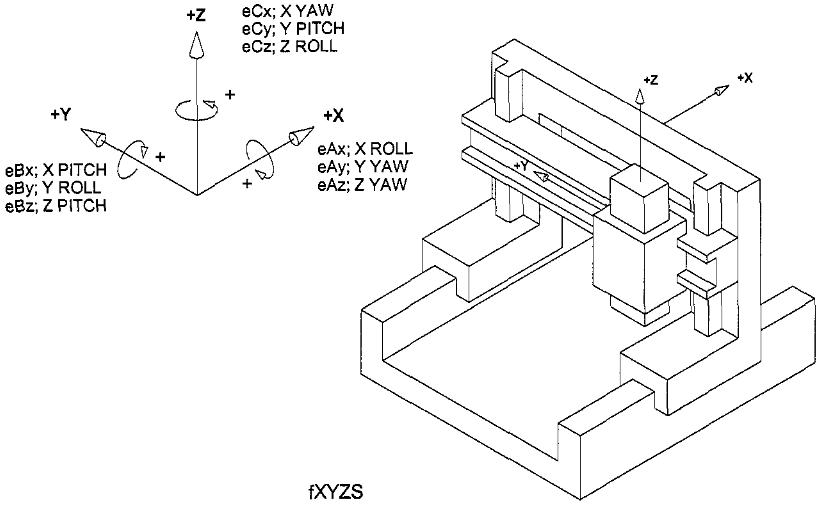

Figure 1: Vertical spindle gantry mill fXYZS

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4 Establishing machine tool performance specifications

4.1 Part feature assessment

Part features and tolerances are well defined by ASME Y14.5M-1994 [10]. The organisation of tolerance symbols used in this standard is a convenient way to break down part features. The definitions of size, form, profile, location, orientation, and run-out are used to relate features with processes.

Part feature tolerance is limited by a machine's capability to produce that tolerance over a given distance. It is well known that even large machines can produce better tolerances over shorter distances. This capability can be established by using the Feature Tolerance Ratio (FTR).

The FTR is determined by dividing the feature tolerance bandwidth by the distance over which it is applied. The FTR can be expressed in inch/inch or mm/mm. The FTR can be used to evaluate the limiting tolerances on a single part or a family of parts. An analysis of FTR is illustrated in Table 1 below. The part having the smallest FTR for size, form, profile, location, orientation or run-out is selected for modeling. The Full Volume and Process Models are based on the processes and the machine axes in motion used to create these features.

Table 1: Feature tolerance ratio

FEATURE TOLERANCE RATIOS																	
Drawing#	Loc.	Individual Features		Related Features			Both	Dist.	Axes					FTR			
		Size	Form	Location	Orientation	Runout	Profile		X	Y	Z	B	#	1 Axis	2 Axes	3 Axes	4 Axes
Part	1/A5			0.150				390	✓	✓			2		0.0004		
12345-1	1/A5			0.500				260	✓	✓		✓	3			0.0019	
	3/D3			0.500				350	✓	✓	✓	✓	4				0.0014
	3/D6		0.050					108	✓	✓			2		0.0005		
	1/B7		0.800					47	✓	✓			2		0.0170		
	1/B7				0.200			604	✓		✓		2		0.0003		
Part	1/B4			0.150				390	✓	✓			2		0.0004		
12345-2	2/B6			0.500				260	✓	✓		✓	3			0.0019	
	2/B3			0.500				350	✓	✓	✓	✓	4				0.0014
	6/F2		0.050					108	✓	✓			2		0.0005		
	6/F2		0.200					604	✓	✓		✓	3			0.0003	
	6/F2		1.200					193	✓	✓	✓	✓	4				0.0062

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Table 2: Machine full volume model

FULL VOLUME ERROR MODEL

	X	Y	Z
Start	-289.0000	0.0000	-55.6700
End	0.0000	161.0000	0.0000
Travel	289.0000	161.0000	55.6700

	Error	Description	Error Dir	Comments	Ang (AS)	Error (in/ft)	Offset (in)	Full Error (in)
1	eXx	Lin Acc	x	Systematic Deviation (E)				0.001600
2	erXx	Repeat	x	Unidirectional Repeatability (R↑)				0.000200
3	eYx	Str Y	y					0.002300
4	eZx	Str Z	z					0.002100
5	eAx	Roll	z	Offset Y Travel	8.0	0.00047	90	0.003492
6	eBx	Pitch	x	Offset Z Travel+ W Travel - Tool Length	4.8	0.00028	90	0.002095
7	eCx	Yaw	x	Offset Y Travel	4.1	0.00024	31	0.000616
8	eoCxy	Sq	x	Offset Y Travel	6.0	0.00035	90	0.002625
9	eYy	Lin Acc	y	Systematic Deviation (E)				0.003200
10	erYy	Repeat	y	Unidirectional Repeatability (R↑)				0.000100
11	eXy	Str X	x					0.000300
12	eZy	Str Z	z					0.000400
13	eBy	Roll	x	Offset Z Travel+ W Travel - Tool Length	12.4	0.00072	31	0.001864
14	eAy	Pitch	y	Offset Z Travel+ W Travel - Tool Length	8.1	0.00047	10	0.000393
15	eCy	Yaw	y	Offset Scale Distance from S C/L	10.6	0.00062	10	0.000514
16	eoAyz	Sq	y	Offset Z Travel - Tool Length	-55.0	-0.00320	90	-0.024000
17	eZz	Lin Acc	z	Systematic Deviation (E)				0.000600
18	eZz	Repeat	z	Unidirectional Repeatability (R↑)				0.000100
19	eYz	Str Y	y					0.000100
20	eXz	Str X	x					0.000400
21	eCz	Roll	x	No Offset	2.3	0.00013	90	0.001004
22	eBz	Pitch	x	Offset Z Travel - Tool Length	2.5	0.00015	31	0.000376
23	eAz	Yaw	y	Offset Z Travel - Tool Length	1.6	0.00009	31	0.000241
24	eoBxz	Sq	x	Offset Z Travel - Tool Length	4.6	0.00027	31	0.000698
25	eXs	Rad Err X	x					0.000100
26	eYs	Rad Err Y	y					0.000093
27	eZs	Axial Err Z	z					0.000110
28	eoAxs	Sq SX	x or z	Offset Tool Length	4.3	0.00025	8	0.000167
29	eoBys	Sq SY	y or z	Offset Tool Length	5.3	0.00031	8	0.000207
							Sum =	0.005514

4.2 Machine full volume models

Machine errors are modeled here using a Microsoft® Excel® spreadsheet. The nomenclature of the errors uses an e (displacement), er (repeatability), eo (orthogonality), ei (interpolation), or et (thermal) to describe the type of error. A capital letter defines the direction of the error, including rotation. A small letter defines the moving axis or axes. The magnitude of the errors is determined by the performance measurements of similar sized machines. An example for the fXYZS Gantry Mill is shown in Table 2.

The Models described in this paper assume linearity and use the bandwidth of bi-directional errors. The use of bi-directional errors considers the effect of machining in two directions and datums that may be established in directions opposite to machining. Angular and multi-axis errors are converted to displacements by using offsets. Errors are weighted for travel and summed to determine the worst error in the volume.

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4.3 Process models

The development of a Process Model (Table 3) from the Full Volume Model involves several steps. The first is to use the FTR to identify the features and tolerances, which will govern the capability limits of the machine. The second is to determine which of the machine axes are moved and how far they travel using the datum reference frames. The errors from the axes not moved in the process are removed from the Model. Third, the contributions to part error from the machine's angular and orthogonal errors are determined using tooling and machine offsets. The weighted sum of all errors contributing to a feature is compared to the tolerance bandwidth, resulting in the Part Tolerance Ratio (PTR). The PTR should be greater than 4 to assure that the machine is consuming only 25% of the part tolerance. Machine performance specifications can be adjusted to improve the PTR. If the PTR is between 1 and 4, an in-process inspection should be made to assure part quality. If the PTR is less than 1, the machine/process should not even be specified for producing the part feature.

Table 3: Process model

FLAT SURFACE MILLED WITH 12 INCH DIAMETER SHELL MILL

PART AXIS MOTIONS

	X	Y	Z
Start	-180.000	-75.000	-29.000
End	-60.000	-15.000	-29.000
Range	120.000	60.000	0.000

	Error	Description	Error Dir	Comments	Ang (AS)	Error (in/ft)	Offset (in)	Full Error (in)	Adj Error (in)	Error %
1	eXx	Lin Acc	x	No positioning in X - no error						
2	erXx	Repeat	x	No positioning in X - no error						
3	eYx	Str Y	y	Y direction - no error						
4	eZx	Str Z	z					0.00210	0.00087	40.9%
5	eAx	Roll	z	Offset Part Width (Y Travel)	8.0	0.00047	60	0.00233	0.00097	50.3%
6	eBx	Pitch	x	Offset Tool Radius	4.8	0.00028	6	0.00014	0.00006	0.2%
7	eCx	Yaw	x	X or Y directions - no error						
8	eoCxy	Sq	x	X direction - no error						
9	eYy	Lin Acc	y	Y direction - no error						
10	erYy	Repeat	y	Y direction - no error						
11	eXy	Str X	x	X direction - no error						
12	eZy	Str Z	z					0.00040	0.00015	1.2%
13	eBy	Roll	z	Offset Tool Radius	12.4	0.00072	6	0.00036	0.00013	1.0%
14	eAy	Pitch	y	X or Y directions - no error						
15	eCy	Yaw	y	Offset Tool Radius	10.6	0.00062	6	0.00031	0.00011	0.7%
16	eoAyz	Sq	y	Offset Tool Radius	-5.5	-0.00032	6	-0.00016	0.00016	1.4%
17	eZz	Lin Acc	z	No change in position - no error						
18	eZz	Repeat	z	No change in position - no error						
19	eYz	Str Y	y	Y direction - no error						
20	eXz	Str X	x	X direction - no error						
21	eCz	Roll	x	X or Y directions - no error						
22	eBz	Pitch	x	Offset Tool Radius	2.5	0.00015	6	0.00007	0.00000	0.0%
23	eAz	Yaw	y	Offset Tool Radius	1.6	0.00009	6	0.00005	0.00000	0.0%
24	eoBxz	Sq	x	Offset Tool Radius	4.6	0.00027	6	0.00014	0.00014	1.0%
25	eXs	Rad Err X	x	X direction - no error						
26	eYs	Rad Err Y	y	Y direction - no error						
27	eZs	Axial Err Z	z					0.00015	0.00015	1.2%
28	eoAxs	Sq SX	x or z	Offset Tool Radius	4.3	0.00025	6	0.00013	0.00013	0.8%
29	eoBys	Sq SY	y or z	Offset Tool Radius	5.3	0.00031	6	0.00016	0.00016	1.3%
							Sum =	0.00616	0.00302	100.0%

Part Flatness Tolerance = 0.006 Part Flatness Est = 0.0014 Part Tolerance Ratio = 4.4

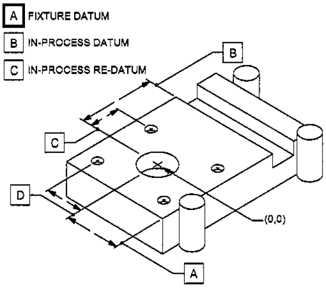

Figure 2: Process datums

4.3.1 Datum reference frame

The use of Coordinate Measuring Machines to inspect parts has improved the principles of identifying datum features. The effect of datums used in processing parts is not as well defined and understood. Fixture datums utilise a combination of planes, pins and balls to fix the part relative to the machine axes. Fixture datums create part errors, which are not a function of machine errors. In-process datums and in-process re-datums (Figure 2) are directly related to the machine's positioning and measuring capability. In-process datums are simply features that are created as part of the material removal process. In-process re-datums involve the machine's ability to measure a feature and re-establish the positioning coordinate system.

4.3.2 Tooling offset effects

The configuration of tooling has effects beyond the metal removal process. The length and diameter of tools create offsets on which the machine's angular and multi-axis errors act. The effect of spindle angular and alignment errors are shown in Figures 3 and 4. The offsets for these effects may be the distances from the gage line or centreline to the tool tip, depth of the feature, or the radius of the tool.

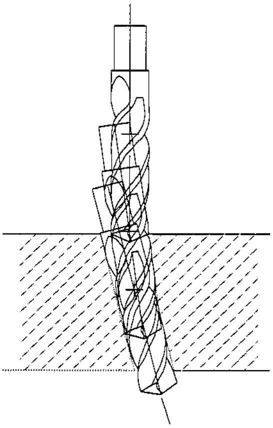

Figure 3: Z axis angular error

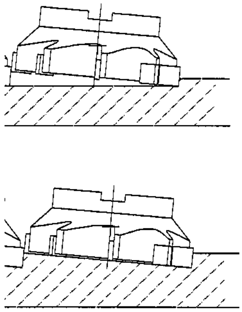

Figure 4: Spindle alignment error

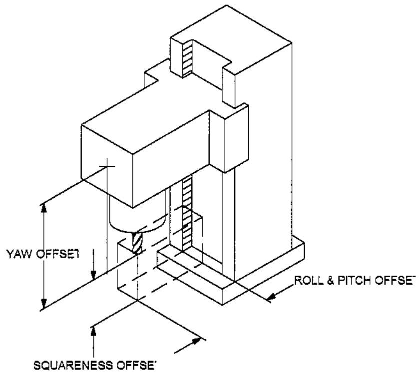

Figure 5: Tooling position

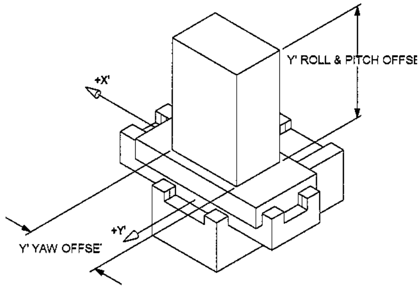

Figure 6: Part positioning

4.3.3 Machine offset effects

The angular and multi-axis errors also act on machine offsets to create part tolerance errors. The offsets are a function of the machine design. Offsets can be categorised into tool positioning, part positioning and tool/part probing effects. These effects are illustrated in Figures 5 and 6.

5 Error control

The Process Error Models can be used to determine the parametric errors limiting machine capability. The Models shown in this paper also determine the percentage of part tolerance consumed by the machine errors in a given process. The errors with the highest percentages should be monitored periodically to maintain control of the process. These errors can be measured and controlled using the methods described in the ASME standards. Adequate documentation of the methods should be maintained to assure reproducibility of the parametric error data.

6 Application experiences

In 1999, a major US manufacturer planned to purchase two large CfWXZS Vertical Lathes. These machines were multi-axis with interchangeable tools and heads. The part features included bearing bores and close tolerance alignment slots. The Performance Specifications were developed in accordance with the ANSI methods using the Process Models.

The machines were performance tested at the supplier's European facility. One of the machines was found to be out of specification, requiring design modifications prior to final acceptance. After completion of the installations in the US, performance tests were repeated, requiring only minor adjustments to meet the original specifications. The machines successfully completed the trial parts within the first two weeks. Both machines have been operating for over one year without a single part discrepancy being assigned to the machines.

7 Conclusion

The methods of matching part feature tolerances with machine performance described in this paper have been used for over 30 years. Acceptance of this approach by the users of machine tools has been extraordinarily slow. The general familiarity with software to process and present data has permitted the development of simpler modeling tools. These simpler tools have been used to develop the performance requirements for millions of dollars of machine tool rebuilds and purchases. The results in all cases were machines that met the expectations of the users with a minimum of start-up delay.

References

[1] The American Society of Mechanical Engineers, *ASME B5.54-1992: Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers*, ASME: New York, 1993.

[2] The American Society of Mechanical Engineers, *ASME B5.57-1998: Methods for Performance Evaluation of Computer Numerically Controlled Lathes and Turning Centers* ASME: New York, 2000.

[3] Donaldson, R. *The Deterministic Approach to Machine Accuracy*, Society of Manufacturing Engineers Symposium, Nov., Golden, 1972.

[4] Bryan, J. & Loewen, E. *The Limit of Accuracy of Machine Tools*, International Conference on Production Engineering, Aug. 26-29, Tokyo, 1974. Lawrence Livermore National Laboratory Report #UCRL 75645.

[5] Schlesinger, G., *Testing Machine Tools*, 7th ed. The Machinery Publishing Co., Ltd: London, 1966.

[6] International Organization for Standardization, Geometric accuracy of machines operating under no-load or finishing conditions (Part 1). *nternational Standard ISO 230/1: Acceptance code for machine tools*, 1st ed. ISO: Geneva, Section 1: Scope and field of application, 1986.

[7] International Organization for Standardization, *International Standard ISO 13041: Machine tools — Test conditions for numerically controlled horizontal turning machines and turning centres with horizontal spindle — Testing of the accuracy*, ISO: Geneva, Introduction, 2000.

[8] Charlton, T. *Metrology and Error Budgeting of Precision Machines,* Second International Precision Engineering Conference (Session 2), May 17-20, Gaithersburg, 1983.

[9] International Organization for Standardization, *International Standard ISO 841: Industrial automation systems and integration — Physical device control — Coordinate system and motion nomenclature*, 2nd ed ISO: Geneva, 1992.

[10] The American Society of Mechanical Engineers, *ASME Y14.5M-1994: Dimensioning and Tolerancing* ASME: New York, 1995.