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ORIGINAL ARTICLE

Applying a pyramid part in the performance evaluation of multiple types of five axis machine tools

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Abstract When conducting a performance evaluation on five-axis machine tools, it has been impossible to overcome the restrictions of cross-matching across different models over the years; complete evaluation reports have been often limited to certain types of cutting movements, cutting angles, and processing of test pieces of a specific geometry. In order to successfully complete the cross-performance evaluation, we propose a statistical approach to solve this long-standing problem. Pyramid part machining test pieces were used in this study as the source of data analysis to obtain a quantized value for the interactions through analysis with the Taguchi method *S*/*N* ratio and by using the variables separable model. A comprehensive evaluation of the cutting performance was performed on four completely different five-axis machine tool models. We found that PY-TM had the best results, and that PY-A most needed to redefine its quality improvement program, which the mean standard deviation (*σ-Sigma)* of each evaluation type of five-axis machine tools also showed similarity with the above results.

Keywords Five-axis machine tool · Multi-type · Taguchi method · Pyramid · Signal-to-noise ratio · Mean standard deviation

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1 Introduction

The machine tool is an essential part of the machinery industry, and the five-axis machine tool is the most important type of this group. This is because as any company in the Industrial Lifting Equipment industry knows, in order to have stable production quality, they must procure a five-axis machine tool with reliable performance; this is an important issue, especially when performing the "cross-machine" five-axis machine tool evaluations and for "cross-geometric" test piece evaluations. Although it cannot affect the overall impartiality of the assessment, the ability to make "simple" and "intuitive" judgments improves the ease of the evaluation performance, but the most important development to facilitate the industry is evaluation implementation and this evaluation's effective worth. Common analysis approaches use double ball bar (DBB), laser instrument methods, and homogeneous transformation matrices (HTMs) in both calibration and volumetric compensation applications. But as these methods are often limited of by the five-axis tool cross-model restrictions, no comparison can be made between different models. In addition, even the same five-axis machine tool can create different assessments under different environments, and with different appearance and geometric dimensions of test pieces. Because the evaluation equations are often used for the design analysis methods, a large revision of the evaluation procedure is often required to match the actual geometrical appearance and dimensions of the workpieces. If such a substantial revision of the standard operating procedure (SOP) is necessary for implementation, this causes a great burden. Again, these evaluations are derived from a complete cutting action, whether using biaxial, triaxial, four-axis, or five-axis motions, and there is often an "interaction" between linear and rotational motions. The root cause of these "interactions" may be caused by shaking, perhaps due to poor assembly, but the current analysis cannot quantify, or collect data, these “interactions.” Therefore, aside from using expensive peripheral equipment, one difficult point to overcome is defining the differences between different cutting motions. A solution to this problem is absolutely necessary for the machine industry. However, previous research into this topic is rare; we cite several pieces of related literature as follows:

The DBB approach is one of the common assessment methods. In 2015, S. H. H. Zargarbashi and J. Angeles [1] used a method with published tests of the DBB, where the deviations of the rotary axis were measured and then treated to y. Fast Fourier transform (FFT) analysis was applied to the centered readings to obtain the machine frequency spectrum. This method can be used on a regular basis as a predictive maintenance (PM) tool. The novelty of this work falls in the realm of condition monitoring (CM) of rotary-axis components using a commercial instrument, with limited angular velocity and number of turns. However, this type of assessment does not easily apply to the cutting of geometrical test pieces.

In the area of HTM, in 2016, Nuodi Huang, Shaokun Zhang, Qingzhen Bi, and Yuhan Wang [2] used HTM to assessed the accuracy of five-axis machine tools, and he also overcame the installation error with less than 15 points needing to be probed, so that the measurement cycle time decreases for each pattern. However, in the cross-machine model comparison, the evaluation equation often needs to be substantially amended in order to match with the actual geometry and appearance of the test pieces, so there are still considerable spatial considerations that need to be completed.

Another worthy of the assessment method is that of volumetric compensation. In 2015, Mehrdad Givi and J. R. R Mayer [3] expressed using the relationship between differential joint space to Cartesian space, which was also developed and used to calculate minute joint command modifications, so that the effect of inter-axis link errors and intra-axis error motions could be canceled by making small changes directly to the G-code. The following year, Xiangdong Zhou, Zhouxiang Jiang, Bao Song, Xiaoqi Tang, and Shiqi Zheng [4] proposed a new compensation method of geometric errors for five-axis machine tools. First, the principle of time-consuming traditional compensation method based on iteration of forward and inverse kinematic solution was analyzed. According to the analysis, the essential cause of this iteration was considered as the synchronous solving of compensated numerical control (NC) code of each axis. This iteration process can be avoided by the algorithm proposed. Such a complex analysis process can be evaluated with both “simple” and “intuitive” judgments, on which we will focus upon in the following section.

It is advisable to select the appropriate cutting test piece with appropriate follow-up analysis. Regardless of the geometric shape of the test piece, we do not recommend that the evaluation method be limited to any specific geometry (or any model of five-axis tooling machine). Test pieces are necessary for experimental cutting, but the focus should be the processing analysis after the test piece cutting is completed to determine the assessment results reference value for effective evaluation of five-axis machine tools.

In 2015,WeiWang, Zhong Jiang, Wenjian Tao, and Wenhao Zhuang [5–7] described in detail their work on modeling S parts, which presents more characteristics in three-dimensional surface contours. Although the S part presents more machine tool abilities performance than in NAS979. This really is a reasonable evaluation method; however, it can be expensive and tedious to set up the equipment. It also remains to be discussed whether the follow-up will be limited to certain geometric test parts, and whether the evaluation data results can be quantified by a reference value.

The latest assessment method is to use the “direct cutting” approach to evaluate the test piece: by assuming that all third-party measurement data can be trusted and introducing “statistical methods” to test the results data of “cross-machine” five-axis machine tool evaluation; the relevant articles can be penetrated and exposed. In 2009, Pyo Lim [8] proposed to use a statistical method to optimize the rough cutting parameters in impeller machining by using response surface methodology and an efficient strategy to divide cutting regions; the response surface model was estimated by a single surface in order to predict rough cutting time, and the optimum cutting conditions were discovered by the estimated model. Although Pyo Lim does not employ the Taguchi method as the main method of statistical analysis, it can be regarded as a “direct cutting” method to cut test pieces. Most of the traditional literature focuses mostly on the analysis of independent linear axis, or an analysis of the independent of the rotation axis, and less on whole-machine performance evaluation; there is a lack of “cross-machine” five-axis machine analysis and evaluation and attempts to analyze a variety of geometric shape and workpiece designs.

The workpiece design can be in any shape, but the crux of the real problem lies the need for “simple” and “intuitive” solutions. In 2016, Chang HJ, Chen SL and Lee PY [9, 10] attempted to evaluate the cone frustum cut pieces and pyramid cut pieces using a statistical approach with the Taguchi method. They calculated the cutting motion error data from the corresponding direct cutting motion and used mechanical advantage (MA) along with the Taguchi method for *S*/*N* (signal-to-noise) ratio. In addition, in order to solve the interactive effect of multi-axis motion, using the Taguchi’s “variables separable model” to quantify the interaction value of each cutting motion was also proposed, which solves this evaluation question. Chang HJ [11] then went further using the Taguchi method to evaluate different models of five-axis machine tools. The statistical data showed that the results of the “five-axis” machine tool evaluation were both “intuitive” and “simple.” This practical and efficient method can be introduced into the “cross-machine” five-axis co-processing machine analysis and evaluation with variety of geometric shapes of workpieces and is compliant with industrial requirements. Therefore, for the next step, we conducted a multiple shape evaluation experiment and then discuss the details of the experiment.

2 Evaluating the advantages of pyramid workpieces

In this paper, the machining test workpieces used in this study are "pyramid parts," which have analysis advantages, especially in terms of statistical sampling, as multi-axis interaction and processing rotation error are amplified under a variety of evaluable properties. It is recommended that subsequent processing of the test workpiece design can be considered; it is not an absolute and unchangeable reference assessment, and so we hereby compare the following:

- Rotational machining error amplification properties.
- Ability to compare the interactions between a "simple linear axial force" and " linear axis + rotating axial force."
- Ability to compare the interactions between a "rotating axial force" and "rotating axial force."
- Possesses "comparatively more" quality characteristics to calculate the *S*/*N* ratio.

3 Cutting motion position of pyramid workpieces

To simplify the coefficient of variation before we designed the cutting path, we separated this pyramid part into 26 cut areas for the purpose of subsequent analysis. The 26 cutting condition settings are as below (Table 1 and Fig. 1):

4 Measure position and error description of pyramid workpieces for multiple types of machine tools

With regard to the evaluation of five-axis cutting motion performance, a very important and difficult issue that occurs is even though different models of five-axis machine tools all have three linear axes and two rotary axes to provide cutting motions, the same geometric workpiece (similar in proportion, but different in size) conditions give entirety different machining error results on different five-axis machine tools. This important threshold problem has been difficult to overcome in traditional performance assessment. As shown in the table below, we have compiled the corresponding relationship data between the various "measured positions" and "cutting error sources" on various five-axis machine tools (Table 2).

5 Pyramid workpiece comparisons on multiple types of five-axis machine tools

This section is a comparison of both the recorded dimensional tolerances and geometric tolerances for five-axis machine tools while processing workpieces. As in 2016, when Chang HJ, Chen SL, and Lee PY [10] used the statistical Taguchi method to evaluate cone frustum test cutting data, the cutting order and measurement order were not necessary the same, and so the evaluation results were also altered due to the design of the workpiece. However, Chang HJ, Chen SL, and Lee PY [10] used the Taguchi method to statistically evaluate the cone frustum cutting test part data to determine the following:

The SN ratio transforms from average quality loss. Assuming n same product index, then the nominal best can be written as (1):

$$\frac{S}{N} = -10log\left[(S_n)^2 + \left(y{-}m\right)^2\right] \tag{1}$$

This process assessment is a comprehensive combined examination, which includes the Taguchi method-based statistical approach, as well as the use of variables separable model comparative interaction method. The results of the evaluation are not necessarily absolute, but they can distinguish between superior and inferior cutting motions in five-axis machine tools. However, the overall performance and unchanging trend analysis should put the focus on the main features or should be able to determine instability within the cutting process. As the *S*/*N* ratio, as calculated by Taguchi method, has already been formulated, it is only necessary to compare the data size (a larger *S*/*N* ratio is better). The smaller the variable separation value comparison to the interaction value is the better; a comparison value of 1 means that the interaction effect is almost the same, which means that it almost does not exist. On the contrary, if during the evaluation of a five-axis machine tool the interactive impact rate is too large, it is recommended that the production process needs to re-develop their quality improvement program.

This comparative table shows that in "*S*/*N* ratio of dimensional tolerances" PY-TM performed the best and PY-A the worst. PY-B is the best and PY-A is the worst in the "cross-comparison" analysis. Thus, it is almost certain that the PY-A manufacturer will need to re-engineer their quality improvement program in accordance with the results of this comprehensive assessment.

6 The tolerance of experimental interval analysis using the position of the mean standard deviation

Until now, although we have successfully compared the data from of a variety of five-axis machine tools, this comparison

Table 1 Test conditions of pyramid workpiece. The following are the basic conditions that must be met by the shape of cutting

Common cutting conditions				
The specimen material	Aluminum alloy 7075_T6 105 × 103 × 80 mm			
Initial workpiece orientation set	+ Z, the top of the pyramid is the Z-axis			
The workholding position origin (yaw)	X4 Y-96 Z0 (mm) (c_x,c_y) = (4196) mm			
Shape cutting conditions				
No.	Machining operation and cut area	Method	Axis	Start position
1(Exp1) 1(Exp2)	1 Level 1 Level	Side mill	+X −X	−Y direction C = 0
1(Exp3)	2 Level		+X	
1(Exp4)	2 Level		C −180, +X	
2(Exp5) 2(Exp6)	1 Level 1 Level	Side mill	+Y −Y	−Y direction C = 0
2(Exp7)	2 Level		+Y	
2(Exp8)	2 Level		C −180, +Y	
3(Exp9) 3(Exp10)	3 Level 3 Level	Side mill	+X −X	+X direction C = −90
3(Exp11)	4 Level		+X	
3(Exp12)	4 Level		C −180, +X	
4(Exp13) 4(Exp14)	3 Level 3 Level	Side mill	+Y −Y	+X direction C = −90
4(Exp15)	4 Level		+Y	
4(Exp16)	4 Level		C −180, +Y	
5(Exp17) 5(Exp18)	5 Level 5 Level	End mill	−X C −180, −X	X direction C = 180 A = −90
6(Exp19) 6(Exp20)	5 Level 5 Level	End mill	−X C −180, −X	X direction C = −90 A = −90
7(Exp21) 7(Exp21)	1 chamfering 1 chamfering	End mill	A −45, −X A+45, +X	−Y direction C = 0 A = −45
8(Exp22) 8(Exp23)	1 chamfering 1 chamfering	End mill	C −90, −Y C + 90, −Y	X direction C = −90 A = −45
9(Exp24) 9(Exp24)	2 chamfering 2 chamfering	Side mill	A −45, −X A + 45, +X	−Y direction C = 0 A = −45
10(Exp 25) 10(Exp 26)	2 chamfering 2 chamfering	Side mill	C −90, −Y C + 90, −Y	X direction C = −90 A = −45

has only been in terms of strengths and weaknesses and so seems inadequate; we do not know where the data results fall on a certain interval in traditional statistics, and so our method seems less persuasive. Therefore, we considered using four models of five-axis machine tools that would provide a larger amount tolerance of experimental interval sample data to analyze, in order to find the standard normal distribution, and then determine the position of the confidence interval. By using this standard normal distribution method to determine the placement position through experimental analysis, we can objectivity determine the strengths and weaknesses of specific five-axis machine tools using traditional statistical theory; our theoretical results are backed by statistical theory in addition to research results. Therefore, in accordance with the work done by Chang HJ, Chen SL, and Lee PY [10], we conducted experimental measurements for the *S/N* ratio and interaction effect for a control group. The basis of analysis was pyramid cutting conditions settings in Exp18/19/25/26, which have four groups of sample data, whereby the design of the standard average mean is different; using the standard normal distribution to analyze the position of confidence interval provides more objective results. We re-emphasize that this is not the only analysis method, but it is a wide-spread acceptable approach.

Standard deviation referring to average deviation, we call *SD* as matrix standard deviation. The formula is showed as below (2):

$$SD = \sqrt{\frac{\sum_{i=1}^{n}\left(y_i - y\right)^2}{n}} \quad (2)$$

However, from the perspective of experimenting on four different models of five-axis machine tools, we will have four different sample mean values. These different sample mean values do not affect how we determine the trend of our

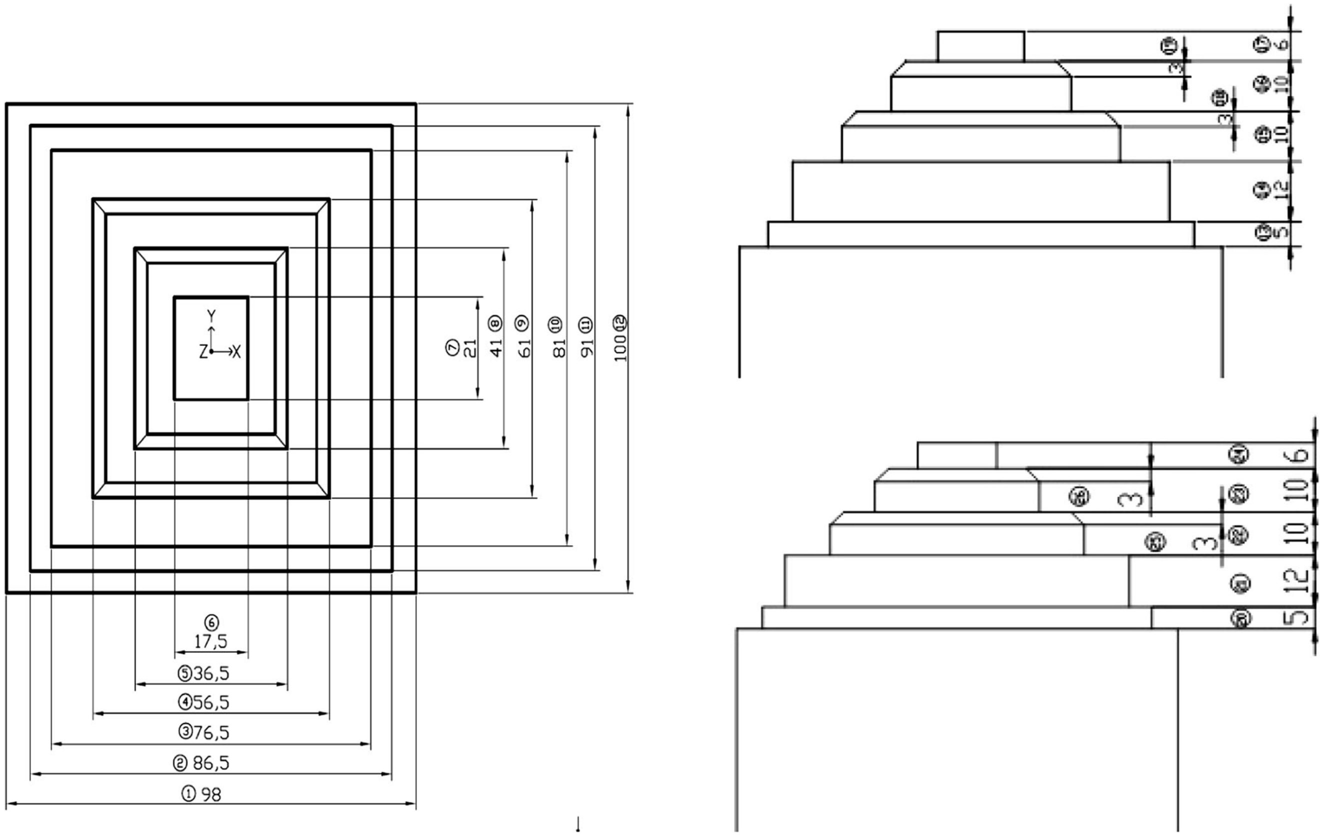

Fig. 1 Pyramid workpiece dimensions

Table 2 Position and error relationship of pyramid workpiece

Position	Error type
Error source of A type five axis machine tools	
2, 3, 4, 5, 6	Y axis liner error, X axis position error
7, 8, 9, 10, 11	X axis liner error, Y axis position error
13, 18, 19, 20, 25, 26	X/Y axis liner error, Z axis position error, B/C axis rotary position error
14, 15, 16, 17, 21, 22, 23, 24	Z axis position error
Error source of B type five axis machine tools	
4, 6	Y axis liner error, X axis position error
7, 9	X axis liner error, Y axis position error
3, 5	Y axis liner error, X axis position error, C axis rotary position error
8, 10	X axis liner error, Y axis position error, C axis rotary position error
2, 11, 13, 18, 19, 20, 25, 26	Y axis liner error, X axis position error, A/C axis rotary position error
14, 15, 16, 17, 21, 22, 23, 24	Z axis position error
Error source of C type five axis machine tools	
3, 4, 5, 6, 7, 8, 9, 10	Y axis liner error, X axis position error, B axis rotary position error
2, 11, 18, 19, 25, 26	X axis liner error, X axis position error, A/B axis rotary position error
13, 14, 15, 16, 17, 20, 21, 22, 23, 24	Y axis position error
Error source of TM type five axis machine tools	
3, 4, 5, 6, 7, 8, 9, 10	Y axis liner error, X axis position error, C axis rotary position error
2, 11	Y axis liner error, X axis position error, B/C axis rotary position error
13, 20	Z axis position error, B/C axis rotary position error
18, 19, 25, 26	Y axis liner error, Z axis position error, B/C axis rotary position error
14, 15, 16, 17, 21, 22, 23, 24	Z axis position error

Table 3 Compare and determine for pyramid test part

No.		Evaluate section	PY-A		PY-B		PY-C		PY-TM	
1	Dimension	*S/N* of Exp2/8+Exp5/11	65.82	X	81.90		88.60		89.00	V
2		*S/N* of Exp3/9+Exp4/10	66.27	X	80.56		86.98		105.21	V
3		Interaction of Exp3/9+Exp4/10 (Pure X to X+C)	3.23T		1.07T		5.50T	X	1.03T	V
4		*S/N* of Exp15/16/22/23	75.57		68.25	X	69.06		82.87	V
5		*S/N* of Exp18/19/25/26	28.32	X	54.55	V	43.35		51.23	
6		Interaction of Exp22/23,Exp25/26 (X+C to X+C)	542.23T	X	3.24T	V	46.21T		45.30T	

When taking an overview at the above four different models of five-axis machine tool, item numbers 1/2/4/5 are related to the *S/N* ratio analysis range, where the greater the value, the better the *S/N* ratio. Item 3/6 is the comparison of the interaction, where it is suggested that the evaluation should increase proportionally with the actual demand. For example, in the evaluation of "rotary axis motion" and "rotary axis simultaneous motion," the proportional analysis should be adjusted. "V" mark means the best item and "X" mark means the worst item

complete range of five-axis machine tools, as the σ (Sigma) can be determined from the mean standard deviation (MSD). We view the analysis results as being in the same matrix and use the matrix approach to gain the MSD value. This MSD can be determined using the pyramid cutting conditions settings in Exp18/19/25/26 as an experimental basis for the σ (Sigma) analysis. Thus, we will be able to obtain the MSD as (3):

$$\mathrm{MSD} = \frac{1}{N} \sum_{i=1}^{n} (SD) \tag{3}$$

The MSD value is calculated as 0.0645. Using this value as a base parameter, the four σ (Sigma) values for the four models of five-axis machine tools are PY-A = 0.30/PY-B = 6.63/PY-C = 3.18/PY-TM = 5.25. In this analysis trend, we discover that PY-B and PY-TM have the highest σ (Sigma) values, with nearly 5–6 σ (Sigma) (i.e., 99.977–99.99966%), and PY-A has the lowest σ (Sigma) value, less than 1 σ (Sigma) (i.e., 68.29%). If we compare with the Tables 3 and 4, we find that although the PY-TM model does not have the best evaluation assessment, it is among the highest ranked. The worst evaluation results still belong to the PY-A model, which is consistent with the overall trend of assessment in Table 3. Thus, we can objectively define traditional statistical values of σ (Sigma) for each of the four models:

PY-A, 0.3σ(Sigma)
PY-B, 6.63σ(Sigma)
PY-C, 3.18σ(Sigma)
PY-TM, 5.25σ(Sigma)

This is an alternative evaluation method, with an emphasis on direct cutting experiments with machine tools of different sizes, and so the issue of "different sample mean values" will inevitably occur. However, through this evaluation method, this difficulty can be overcome. We could also collect more (an inexhaustible amount) of complete parameters, and so the target value would be closer to the real matrix of the MSD (1 σ Sigma), but here our purpose was to show an example of how "different sample mean values" can be used to find a reliable MSD, and that the trend is mostly consistent with the traditional statistical comparison. This is sufficient to demonstrate the reliability of the statistical approach in the evaluation of the five-axis machine tools.

In order to perform a variety of five-axis machine tool evaluation, we successfully overcame cross-machine limitations. As the geometry of the test workpieces are subject to different interpretations, with the successful completion of the performance evaluation, we confirmed that our solution is feasible and satisfactory through a statistical approach.

The results presented in the overall comparison showed PY-TM to be the best and PY-A the worst, but we would like to reiterate that this process assessment is like a comprehensive combined examination; if there is only one side of the

Table 4 Calculating for MSD and Sigma number

Exp.	Base	P1	P2	P3	P4	SD	*S/N*	Sigma (σ)
PY-A / 18,19,25,26	6.0000	5.5539	5.5884	5.5153	5.4610	0.2156	28.3273	0.30
PY-B / 18,19,25,26	5.2000	5.1939	5.2125	5.2002	5.1860	0.0097	54.5570	6.63
PY-C / 18,19,25,26	3.0000	2.9950	2.9603	2.9951	2.9595	0.0203	43.3576	3.18
PY-TM / 18,19,25,26	4.5000	4.4718	4.4747	4.4697	4.4764	0.0123	51.2370	5.25
		MSD, mean standard deviation				0.0645		

data presented for the same machine tool, we can easily determine the results. However, it is understandable if the outcome is mixed, and we can conduct a more detailed analysis based on these quantitative assessment data to find the impact on quality improvement or work the development of a quality improvement program for the planning and design of a new model.

7 Conclusions

Through the use of the direct cutting method combined with the Taguchi method, the cutting piece is not limited to a specific geometric shape, which subsequent users must acknowledge; more statistical sampling data helps in the further assessment of real machine tools, so long as after third-party certification of sufficient cutting piece statistical data can be collected. The concept of simplicity and intuition is in line with our original evaluation concept. This paper successfully implements a "cross-machine" five-axis tool machine performance evaluation, and with sufficient data, which can analyze the best five-axis cutting machine tools. Although the best item machine tool is a direct separation of between superior and inferior, the machine tools' single axis can be graded differently. From another perceptive, each five-axis machine tool is like a comprehensive combined examination of a candidate, whereby the total score can be analyzed to determine strengths and weaknesses; continuous improvement is the essence of cross-matching across different models through both the direct cutting method and the Taguchi Method.

Base, setting dimension (unit: mm); *P1/P2/P3/P4*, real dimension (unit: mm); *SD*, standard deviation; *S/N*, signal-to-noise ratio; *MSD*, mean standard deviation ; *Sigma (σ)*, MSD

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