Machining Quality Evaluation and Optimization of Aircraft Structural Parts Based on Multi-factor Analysis of Variance

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Abstract. Quantitative evaluation of machining quality of aircraft structural parts plays an important role in improving machining quality of parts. The rate of error limit (REL) is proposed as a new evaluation index of the machining quality, which realizes quantitative evaluation of machining quality and is applied to optimization of machining quality. Aiming at the dis ordering of the measurement data and lack of effective analysis in actual production of engineering, a Machining Quality Evaluation and Optimization software (MQEO) is designed and developed with REL as the evaluation index. And the multi-factor analysis of variance is used to find out the main factor influencing the machining quality, and propose optimization suggestions.

Keywords: REL; Quantitative evaluation of machining quality; Multi-factor analysis of variance; MQEO.

1. Introduction
Aircraft structural parts are generally obtained by numerical control machining, and the machining quality is directly related to aircraft performance and flight safety. The manufacturing of aircraft structural parts uses a large amount of new lightweight high-strength difficult-to-cut materials, along with complex thin-walled structures and integrated structures. The machining processes is complex, with high requirements of dimensional accuracy and geometric tolerance, also with long machining cycles and high costs. The evaluation and optimization of the machining quality are very important for the guarantee of product quality. The research can effectively improve the machining quality of aircraft structural parts, used to guide the processing process. A large amount of data is generated during machining, including machine data, process data, and measured data. But the value of these data is not being fully utilized. In the actual production process, a lot of data is not collected, or the collection is only simply checked to render certain if it is qualified, the real value of the data is not deeply mined.

Experts and scholars have done in-depth research on the evaluation and optimization analysis of machining quality. Some scholars analysed the influencing factors and optimization method of machining quality from the perspective of errors sources. Liu Qingjie, Li Hai, et al, achieved the machining accuracy evaluation and optimization, from the degree of machine composition and the impact on the parts machining quality [1, 2]. Wang Wei analysed the influence of position ring and speed ring on the milling accuracy of parts, from the perspective of dynamic and static error sources [3]. Hu Xiaochen studied the influence of machine dynamic factors and process parameters on surface roughness [4]. Wan Xiaojin established the model of "parts - fixture – tool - machine" system, analysed...
the influence of the deviation of machine, fixture and tool on the parts machining error, and predicted the parts error [5].

Some scholars set up mathematical models and put forward optimization strategies from the perspective of error evaluation index. Yao Changfeng, Wang Dong et al studied the influence of milling parameters on surface roughness, and gave the best combination of parameters for high-speed milling by orthogonal test [6, 7]. Wang Xiaoming et al. used multiple linear regression analysis method to study the influence of process parameters on the surface roughness of parts [8]. Some scholars introduced cost and efficiency as evaluation indicators as well to optimize the process planning. Wu Xiaorong, Deng Zhaohui, et al, various methods such as gray level correlation analysis were applied to analyse the selection of machining technology scheme, taking energy consumption and efficiency as the evaluation index [9-12]. Some scholars take machining quality, machining time, machining cost and other objectives as optimization indicators to study the optimization method of machining [13-15].

Scholars have used various methods to study the evaluation and optimization of machining quality. Wu Xiaorong applied fuzzy theory to evaluate and analyse the process parameters to conduct multi-objective optimization analysis for multiple objectives of time, cost and quality, and to find the optimal combination of parameters [12]. Meng zhaoyuxi applied the grey system theory to analyse the machining quality evaluation and prediction of the transmission shaft [16]. Zang Xuebai and Wen Hua applied simulation method to analyse the optimization method of parts machining parameters [17, 18]. Zhao Shuangfeng, Qiao Renjie et al. studied a large amount of data generated in the manufacturing process, and applied data analysis methods such as neural network or R language to realize the quality evaluation and control of the machining [19, 20].

In the previous studies, experts and scholars have analysed the evaluation and optimization methods of machining quality from many perspectives such as error sources and evaluation indexes. They designed experiments, adopted fuzzy mathematics, neural network and other methods to obtain and verify the evaluation and optimization methods of machining quality. However, there is little research about quantitative evaluation of parts machining quality. In this paper, the process planning, machine tool, cutting tool, operator and so on are taken as the error source, and the characteristic quantity of the rate of error limit (REL) is put forward as a new evaluation index of machining quality. So that it can quantitatively evaluate the machining quality of various aspects of parts machining quality more comprehensively. A Machining Quality Evaluation and Optimization software (MQEO) is developed, with the application of REL. The data characteristics of REL are studied, the main error sources of machining quality are analysed with multi-factor analysis of variance, and suggestions for optimization of machining quality were put forward.

2. Machining Quality Error Sources

There are many factors that affect machining accuracy in machining process. According to the source of error, it can be divided into the following aspects: machining principle error, error caused by process planning, error caused by process system, error caused by thermal deformation, error caused by deformation under force and error caused by residual stress, as shown in figure 1.

![Fig. 1 Source of machining error](image-url)
The error of machining principle refers to the difference between the actual shape and the ideal state caused by the approximate forming and cutting movement. The process planning error refers to the error caused by the applicability of process parameters design, such as spindle speed, feed, cutting depth, etc. The different process parameters design has different influence on the quality of the parts. Process system mainly includes machine tools, fixtures, cutting tools, workpiece, etc., each link of the error will affect the workpiece machining accuracy to varying degrees. The manufacturing of machine tools inevitably exists errors, along with the installation, use, maintenance and other processes, resulting in the parts machining error. Particularly, spindle error, guide error and error caused by the transmission chain of machine tools produce greater impact on the accuracy of the parts. Tool manufacturing accuracy and tool wear will have a certain impact on the machining accuracy. Similarly, the manufacturing accuracy of the fixture, the positioning error, the size of clamping force will also cause the machining error. The deformation under force during the machining process will cause errors in the parts machining. The cutting force, cutting vibration, frequent changes in acceleration and other factors will cause the parts to be deformed under force and affect the machining accuracy. The main heat sources such as cutting heat, machine power source heat and frictional heat of moving parts can cause thermal expansion and contraction of the process system, affecting the relative position between the various links of the process system, resulting in machining errors. The residual stress also causes the error of the parts. Before machining, internal stress is generated due to various reasons such as blank processing and heat treatment. The internal stress is redistributed during the cutting process, and the internal structure changes continuously until the internal stress reaches equilibrium. The redistribution of internal stress causes deformation of the part and affects the machining accuracy of the part.

In the actual machining and production of aircraft parts, the error of machining principle is inevitable and little generally. The deformation caused by stress and heat during the machining process, as well as the machining error caused by residual stress after machining are closely related to the process planning. The fixture error is mainly caused by the difference of operators, and it is more convenient to measure it by operators Therefore, this paper mainly analyses the machining quality from four aspects, the process planning, machine error, tool error and operator error.

The parts are processed according to the process parameters, cutting tools and machining paths designed according to the process procedure, and the required parts shape and surface can be obtained. However, the actual state obtained by machining cannot be completely consistent with the ideal state. The degree of conformity between the actual state and the ideal state is called machining accuracy, and the degree of deviation between the actual state and the ideal state is called machining error. Machining error generally includes dimensional error, geometric error and surface quality error. Each item needs to be tested, as shown in figure 2. The surface quality includes the geometric features of the surface layer and the physical and mechanical properties of the surface layer. Physical and mechanical properties are not commonly used to detect the machining quality of parts, and it is difficult to quantify them, limited to the current situation. Therefore, this paper does not include them in the evaluation index, generally using surface roughness to evaluate the machining surface quality of parts. To quantitatively analyse the machining quality of three kinds of evaluation indexes, REL is proposed as the quantitative evaluation index of the machining quality. The measurement results of the machining quality such as dimension error, geometric error and surface quality error are converted into REL value, and the evaluation results of the machining quality are obtained by analysing the data characteristics of REL.
### Machining Quality Analysis Method

#### 3.1. The Evaluation Index REL

The quality of aircraft structural parts includes dimension error, geometry error and surface roughness. However, the evaluation criteria of the three indicators are not consistent, and the order of magnitude of the test data is also inconsistent. In order to normalize the evaluation indexes, and realize the quantitative evaluation of machining quality, the characteristic quantity REL is put forward as the evaluation indicator of parts machining quality, the computational formula is shown in formula (1).

\[
REL = \frac{X_m - X_p}{X_{max} - X_{min}} \tag{1}
\]

Where, \(X_m\) refers to the measured value of the component test item, \(X_p\) refers to the process design value of this test item, and \(X_{max} - X_{min}\) is the design tolerance limit of this test item. The calculation methods of the three evaluation indicators are shown in table 1.

#### Table 1. Definition of formula symbols under three evaluation indicators

| Evaluation indicators | \(X_m\) | \(X_p\) | \(X_{max} - X_{min}\) |
|-----------------------|---------|---------|-----------------------|
| Dimensional error     | Measured value | Designed value in the NC program | That is the dimension tolerance. The maximum allowable value of the detection item minus the minimum. |
| Geometric tolerance   | The shape tolerance | 0 | That is the maximum allowable error |
|                       | The position tolerance | 0 | That is the maximum allowable error |
| Surface roughness     | 0 | | That is the maximum allowable surface roughness |

REL is proposed as the evaluation index of the machining quality. The difference of the measured value and the process design value is used to measure the actual machining state of the part. The tolerance limit is used as the basis of the requirements of parts processing tolerance. The rate between them take the information into account in the evaluation indicators. When REL is bigger than 1, the test item is in state of out-of-tolerance and unqualified. When REL is between 0.5 and 1, or the test size is not within the tolerance limit, the machining quality of the test item can be optimized. When REL is less than 0.5 and the size is within the tolerance limit, the machining quality is relatively ideal.

#### 3.2. Multi-factor Variance Analysis Method

There are many factors that affect the quality of machining. This paper mainly studies the influence of process planning, machine, tool and operators on the quality of machining. First, the machining quality
is evaluated according to REL, and then the order of the factors that affect the machining quality is analysed by the multi-factors analysis method of variance, the influence on the machining quality is studied, and the optimization suggestions are put forward if it’s needed to be improved.

1) REL characteristics calculation
Analyse the mean and variance of REL under each factor, and observe the fluctuation of REL. And then calculate range of each factor, the greater the difference of the range, the greater the impact on the machining quality.

2) The sum of squares of deviations and significances calculation
By calculating and comparing the variance of each factor, the main and significant effects of each factor on machining quality were judged.

Total deviation sum of squares $S$:

$$S = \sum_{i=1}^{a}(y_i - \bar{y})^2 = \sum_{i=1}^{a}y_i^2 - \frac{1}{a}(\sum_{i=1}^{a}y_i)^2$$

(2)

Where, $y_i$ refers to the rate of error limit of each item, $a$ is the total number of samples, $\bar{y} = \frac{1}{a}\sum_{i=1}^{a}y_i$.

Freedom of the sum of squares of total deviations $f$:

$$f = a - 1$$

(3)

The sum of deviation squares in column $S_j$:

$$S_j = \frac{a}{b}\sum_{k=1}^{b}(\bar{y}_{jk} - \bar{y})^2 = \frac{b}{a}\sum_{k=1}^{b}y^2_{jk} - \frac{1}{a}(\sum_{i=1}^{a}y_i)^2$$

(4)

Where, $b$ is the number of factor levels, $\bar{y}_{jk} = \frac{b}{a}\sum_{i=1}^{a}y_i$, $y_{jk} = \sum_{i=1}^{a}y_i$.

Freedom degree of the square sum of column deviations $f_j$:

$$f_j = b - 1$$

(5)

Freedom of the sum of squares of error deviations $f_e$:

$$f_e = f - \sum f_j$$

(6)

Calculate the significance of each factor and judge whether each factor has a significant impact on the machining quality, that is, judge whether the factor has a fault. If there is a fault, the influence is significant; if there is no fault, the influence is not significant.

$$F_j = \frac{S_j/\sigma_j^2}{S_e/\sigma_e^2} = \frac{S_j/f_j}{S_e/f_e} = \frac{\sigma_j^2}{\sigma_e^2} = F(f_j, f_e)$$

(7)

3) Error source analysis and suggestions
According to the REL and the results of previous analysis, the error source of a certain data is analysed and optimization suggestions are given. There are few quality unqualified contents due to the importance of aircraft parts processing. Therefore, this paper mainly analyses the machining quality evaluation and optimization methods under each qualified test item. As for hole characteristics, if REL is too small, it may be due to tool wear, clamping and positioning problems, etc. If REL is too large, it may be improper tool diameter, improper program allowance, etc. As for shaft features, the reverse turns out to be true.

4. MQEO Development
In order to facilitate the application of engineering production, and easy to operate, to realize the quantitative evaluation of parts machining quality, and the improvement of the machining quality in production, MQEO is developed by using C#.NET and SQL database. The composition of each functional module of the system is shown in figure 3. The software is used to evaluate the machining quality, analyse the influencing factors of machining quality, and put forward optimization suggestions for the parts that need to be optimized. The interface of the software system is shown in figure 4.
5. MQEO Application in Aircraft Structural Parts
A key structural part of a certain aircraft is shown in figure 5. This part is an important bearing part in the aircraft structure, with many processing features, complex structure and complex processing procedures. The quantitative evaluation and optimization of the processing quality of the parts can greatly reduce the waste of productivity and cost and improve the processing efficiency. During the process of machining, 10 sorts data of this part were collected in this processing, including features of test items, measurement value of test items, process design value, machine tool, cutter, operator and other information. They were organized and saved into SQL database.
1) REL characteristics calculation

The machining data includes the measure data, operator, machine, cutting tool and other information of part machining. The REL characteristics of these factors are calculated and shown in table 2-5.

| Table 2. REL under operator factor |
|-----------------------------------|
| Operator | A    | B    | C    | D    | E    |
| Number   | 32   | 33   | 32   | 15   | 20   |
| Average  | 0.1634 | 0.1143 | 0.1333 | 0.0590 | 0.0377 |
| The Variance | 0.126 | 0.65 | 0.73 | 0.007 | 0.004 |
| Range    | $l_o = 0.1634 - 0.0377 = 0.1257$ |

| Table 3. REL under machine tool factor |
|--------------------------------------|
| Machine | I | II | III |
| Number  | 36 | 48 | 32 |
| Average | 0.1146 | 0.0992 | 0.1129 |
| The Variance | 0.071 | 0.067 | 0.064 |
| Range    | $l_m = 0.1146 - 0.0992 = 0.0154$ |

| Table 4. REL under cutting tool factor |
|---------------------------------------|
| Cutting Tools Number | D0601 | D0602 | D0603 | D0604 | D1001 |
| Number                | 10    | 12    | 14    | 19    | 17    |
| Average               | 0.0312 | 0.1582 | 0.1089 | 0.1101 | 0.1272 |
| The Variance          | 0.024 | 0.141 | 0.008 | 0.044 | 0.096 |
| Cutting Tools Number  | D1002 | D1003 | D2001 | D2002 | D2003 |
| Number                | 17    | 15    | 14    | 8     | 6     |
| Average               | 0.0941 | 0.1502 | 0.0945 | 0.2153 | 0.0031 |
| The Variance          | 0.066 | 0.119 | 0.057 | 0.093 | 0.012 |
| Range                 | $l_t = 0.2153 - 0.0031 = 0.2122$ |

| Table 5. REL under feature factors |
|------------------------------------|
| The Features | Bore Diameter | Linear dimension | Axle Diameter |
| Number       | 22            | 44               | 11            |
| Average      | 0.1017        | 0.0576           | 0.0198        |
| The Variance | 0.027         | 0.005            | 0.002         |
| The Features | Surface Profile | Vertical Accuracy | Cylindricity Accuracy |
| Number       | 22            | 11               | 22            |
| Average      | -0.1439       | 0.7440           | 0.2425        |
| The Variance | 0.018         | 0.079            | 0.007         |
| Range        | $l_r = 0.2425 - (-0.1439) = 0.3864$ |

2) Machining quality evaluation

The calculation results of deviation sum of squares and degrees of freedom under each factor are shown in table 6. With the calculations in these tables, the analysis shows that the feature factor has the biggest range around the factors. And from Table 6, only the feature factor’s significance test smaller than the limit. They prove that feature factor, as well as the process planning, is the main factor affecting the machining quality. When the parts are processed in different positions, the machining quality will be significantly different, and the machining quality of some parts that are difficult to be processed is worse. But the machine, the cutter, the operator has little influence on the machining quality, namely these several kinds of factors do not have the obvious breakdown questions.
| Check Item     | Deviation Square | Degrees of Freedom | Mean Square Error | F       | Significant |
|---------------|------------------|--------------------|-------------------|---------|-------------|
| The Operator  | 0.011            | 20                 | 0.003             | 0.163   | 0.957       |
| Machine       | 0.016            | 1                  | 0.008             | 0.466   | 0.629       |
| Cutting Tool  | 0.139            | 4                  | 0.015             | 0.874   | 0.551       |
| Feature       | 6.16             | 2                  | 1.232             | 69.872  | 0           |
| Error         | 1.957            | 111                | 0.18              | -       | -           |
| Total         | 10.344           | 132                | -                 | -       | -           |

3) Quality optimization suggestions
From the analysis data above, it can be found that under the factors of operator, machine and cutter, the difference of REL is small. That is, these factors have little influence on the machining quality. There is no obvious fault problem in these factors and no need for optimization. But under the feature factor, the difference of REL is obvious. It means that the process planning is the important influence factor of the part machining quality. Optimization suggestions should be given at this time: optimize the parameters in the process planning, especially in the machining parts with poor machining quality.

6. Summary
In this paper, REL is proposed as the quantitative evaluation index of processing quality, MQEO software is designed and developed for quantitative evaluation and optimization of processing quality, and processing quality data obtained from the production and processing of key structural parts are collected to analysis and verification. Through analysing REL’s data characteristics, the processing quality of parts was quantitatively evaluated, and the main factors affecting the processing quality of parts were analysed with the multi-factor analysis method. It was verified that REL could be used as the evaluation index of the processing quality, and the processing quality could be optimized according to the analysis results of this index.

With the increasingly in-depth research and more and more applications of digital manufacturing and intelligent manufacturing, the machining and production of aircraft parts is increasingly pursuing high efficiency, high quality and high convenience machining methods. Quantitative analysis and scientific analysis of machining quality can provide a theoretical basis for machining and production, and will play an increasingly important role in machining and production, providing a basis for the subsequent prediction and optimization of machining quality.

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