Efficient Tolerance Design of Topology-Optimized Functional Structures

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Abstract. The topology-optimized functional structure has complex contour described by free curves and its manufacturing for accurate performance implementation is difficult. The boundary of topology-optimized functional structures has different sensitivity to errors. Therefore, it is unreasonable to improve the machining precision blindly to meet performance requirements. The paper presents two different tolerance analysis methods, including uniform tolerance analysis and segment-contour tolerance analysis. In order to achieve performance-oriented tolerance design, the study adopted the improved line profile based on ISO 1101:2017. By building the machining error simulation model and finite element analysis, tolerance design functions for performance are obtained under two tolerance analysis methods. Then, tolerance allocation methods are developed under different performance requirements and machining precision. The segment-contour tolerance design can realize the precision manufacturing of structural performance under the constraint of the large tolerance range, which is more economical than the uniform tolerance analysis method. Finally, a numerical experiment is given to demonstrate the capability of the proposed tolerance design method.

Keywords: Tolerance Design, Topology Optimization, Design for Performance, Functional Structure, Un-uniform line Profile.
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1 INTRODUCTION

The functional structure is a structure with a specific performance, such as the abnormal thermal expansion structure and negative Poisson's ratio structure. Topology optimization is a widely known approach, exhibits a high degree of freedom and has an ability to integrate structure and function in design. In engineering, topology optimization of functional structures has different requirements of the performance. Thus, tolerance design for performance under different requirements is valuable. Manufacturing errors can often directly influence product performance and undermine the design objective [3], [10]. Current tolerance theories are mainly used for solving dimensional chain problems and assembly problems of mechanical products to achieve improved quality [2], [5-6]. A suitable tolerance allocation can enhance quality with reduced costs. Adopting a robust design is an important approach to improving quality at a low cost in tolerance design [3-4]. With a population of concurrent designs, quality and cost should be considered simultaneously, and various quality loss functions are mentioned for tolerance optimization problems [1], [7], [9].

Three main problems in tolerance design of topology-optimized functional structures are identified. First, it should be determined that how manufacturing errors affect the topology-optimized structure performance. The boundary of topology-optimized functional structures is complex and consists of free curves, which is different from traditional products. Therefore, it is a challenge to determine the process of constraining machining boundaries under different performance requirements. Second, the sensitivity of performance to different boundaries varies. Allocating the same tolerance value for different boundaries is not cost-efficient. The pursuit of geometric precision does not imply that the performance can meet the requirements. Therefore, tolerance analysis and allocation are vital processes to ensure the performance precision of manufactured topology-optimized functional structures. Third, the traditional tolerance zone of the line profile is uniform and symmetrical. This type of tolerance zone can cause trouble for performance-oriented tolerance design. The improved line profile based on ISO 1101:2017 should be adopted in the tolerance design of topology-optimized structures [8]. Thus, the development of an approach to tolerance design for topology-optimized structures oriented to high performance would be valuable.

In this study, an integrated approach to tolerance design of topology-optimized structures considering performance precise implementation is proposed. And the paper explains how the improved line profile in the ISO 1101:2017 is applied to the tolerance design of structures with complex topologies. By studying the effect of boundary machining errors on structural performance, both uniform tolerance and segment counter tolerance are analyzed to build tolerance design functions. In tolerance design for a segment, a method is proposed, which involves compensating the different machining contours of the topology-optimized functional structure to improve performance under a low-precision machining environment. The method takes advantage of compensation from different machining boundaries to achieve a low-cost robust tolerance design. At last, a numerical experiment is conducted to verify the feasibility of the tolerance design method of topology-optimized functional structures.

2 UNIFORM TOLERANCE DESIGN FOR PERFORMANCE BASED ON LINE PROFILE

2.1 Simulation of Machining Errors

To clarify how machining errors affect structural performance, machining errors need to be simulated in Computer-aided Engineering (CAE) software. The machining errors and stack-up errors are complicated. Thus, attention should be paid to the machining technique of topology-optimized functional products. The two-dimensional structure with free curves contour designed by topology optimization is often manufactured using non-traditional machining techniques, such as electric spark machining, wire electrical discharge machining, and additive manufacturing. The main error is the profile error, which results from the inconsistency between machining boundaries and theoretical boundaries. Thus, only the finite element simulation model with manufacturing errors need to be built.

The simulation model of errors is a model used to describe errors in the finite element analysis software. The model can be imported into the CAE software to analyze the structure performance. The finite element simulation model of the line profile error has the following two methods:

- Generating manufacturing boundaries with actual errors as simulation models. The advantage of this method is that the manufacturing boundary can be approximated to the maximum extent. However, finite element analysis results are affected by the error distribution type of errors.
- Generating the simulation model based on the line profile tolerance zone boundaries. The boundary of the finite element simulation model of the line profile error is the maximum envelope boundary of the tolerance zone, not the actual manufactured boundary of the structure. This model is easy to be built in finite element software. The tolerance design results obtained by this simulation model are highly accurate. This model is versatile and can be used to simulate a variety of applications for line profile.

The random error changes very much for different processing methods and processing environments, which cannot be completely predicted successfully in the tolerance design stage. Therefore, the error simulation model is generated based on the line profile tolerance zone boundaries instead of boundaries with actual errors. With this kind of error simulation model, most of random errors could be considered. In summary, the second method is chosen to establish the finite element simulation model considering the line profile error. The schematic of the error simulation model is shown in Figure 1.

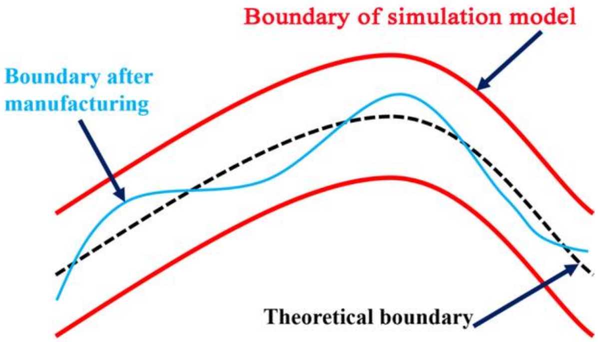

Figure 1: Line profile error simulation model.

2.2 Uniform Tolerance Analysis Method

The machining precision of the free curve contour is often evaluated using the curve profile error with a tolerance zone arranged symmetrically on both sides of the theoretical contour. Symmetrical tolerance such as the profile of lines can often be achieved; however, in some manufacturing processes, the asymmetric tolerance zone commonly occurs. It appears where the assembly or target performance deviation is asymmetry. In the iterative process of topology optimization, deleting or adding a material element can considerably affect structural performance. Thus, in the manufacturing process of topology-optimized functional structures, the in-body or out-body of the tolerance zone exert a different influence on structural performance. The mechanism underlying the effects of in-body and out-body tolerance zone on structural performance requires FEM analysis.

The traditional dimensional tolerance has two types: positive and negative. Similar to that, we define the types of tolerance applied in topology-optimized functional structures as in-body tolerance and out-body tolerance. In-body tolerance represents the reduction in structural volume with a negative value, and out-body tolerance represents the increase in structural volume with a positive value. The in-body and out-body tolerance zone is illustrated in Figure 2.

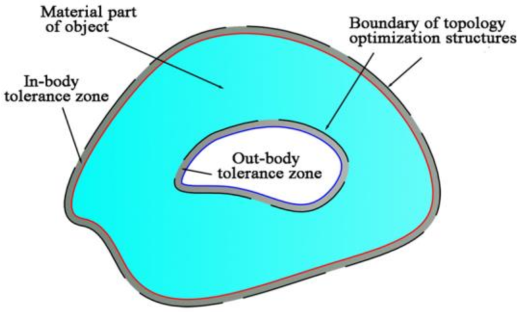

Figure 2: Tolerance zone of topology-optimized functional structures.

By assessing the precision of the machining tool, the range of tolerance simulation is determined to reduce the computing scale. Tolerance changes from negative to positive and the actual machining contour moves from inside to outside. Finite element analysis software is used to analyze the performance of topology-optimized functional structures under different tolerance zones. On the basis of the simulation data, an appropriate mathematical formula can be established to represent the relationship between error and performance. Uniform tolerance analysis is conducted using the following procedures:

- Determining the numerical range of tolerance analysis on the basis of machining conditions.
- Choosing suitable step-size of tolerance analysis.
- Generating equidistant lines to build new simulation models for tolerance analysis.
- Importing the simulation model into ANSYS to calculate the response of the structure.
- Analyzing the simulation data to establish the tolerance design function.

If the range of tolerance analysis is $[0 \sim T]$ and the step size of the tolerance analysis is t, the equidistant line distance of topology-optimized functional structures boundaries changes from -T/2 to T/2. By using uniform tolerance analysis, we can easily determine how machining errors affect performance easily. The tolerance design function can be obtained by least squares fitting.

$$k = f(d) \tag{2.1}$$

where k is the percentage change in topology-optimized functional structures performance; *d* is manufacturing error of line profile.

2.3 Uniform Tolerance Allocation Method

Tolerance is determined by the size and location of the tolerance zone. In accordance with the tolerance design function, the proper machining method and tolerance can be chosen reasonably under the specified performance requirement.

Assuming that the performance of the topology-optimized functional structure allows the range of variation to be $[k_{\min},\ k_{\max}]$, the error variation range $[d_{\min},\ d_{\max}]$ can be calculated by the formula 2.1. According to the definition of the line profile, the tolerance value of the line profile is $2 \times Min\ (|d_{\min}|, |d_{\max}|)$.

In fact, if the result of this tolerance allocation method can meet the processing capability, it is a good performance-oriented tolerance design method. The uniform tolerance design method is not suitable if the following two conditions occur.

- First, the performance requirements are unsymmetrical and unconventional, such as the -3%~10% type. According to the tolerance design method above, although the allowable range of error is large, the tolerance value is small due to the definition of the line profile, which is very uneconomical.

- Second, if error allowed variation area is located on one side of the contour, there is no solution to the tolerance design.

So, it is necessary to apply the improved line profile in the ISO 1101:2017 to the tolerance design of topology-optimized. An asymmetric line profile tolerance zone model and non-uniform tolerance analysis method are adapted to different performance indexes and processing capabilities.

3 SEGMENT-CONTOUR TOLERANCE DESIGN BASED ON IMPROVED LINE PROFILE

Allocating the same tolerance to different boundaries in the manufacture of a topology-optimized functional product is unreasonable and uneconomical. The reasons are as follows: First, the sensitivity of different processing boundaries to dimensional change is diverse; thus, machining all boundaries under the same tolerance is costly and non-robust. Second, the aforementioned uniform tolerance analysis indicates that in-body and out-body tolerances exhibit opposite effects on the performance of the topology-optimized functional structure. This type of compensation relationship is preferred to achieve performance-precision manufacturing under low-precision machining conditions. Thus, studying how different segment boundaries with various tolerance values affect the performance of structures is meaningful. Based on the analysis above, an improvement of the line profile and tolerance analysis method is proposed.

3.1 Improvement of the Line Profile Model

The profile of a line describes a tolerance zone around any line in any feature, usually of a curved shape. The tolerance zone of the traditional line profile is symmetrical, which is shown in Figure 3. In order to achieve performance-oriented tolerance design, the form line profile tolerance zone is now improved, mainly including the following two tolerance zone types.

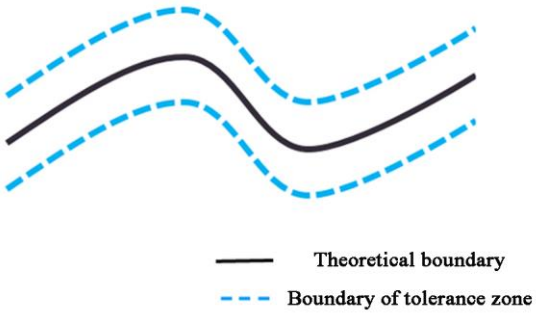

Figure 3: Tolerance zone of traditional line profile.

3.1.1 Asymmetric line profile tolerance zone

The tolerance zone of the asymmetric line profile is asymmetrical to the theoretical boundary of the topology-optimized functional structure, and the inner and outer boundaries of the tolerance zone are generated based on the performance indicators. This type of tolerance zone is mainly used in the case of insufficient processing capacity. The specific application will be described in detail in the following chapters.

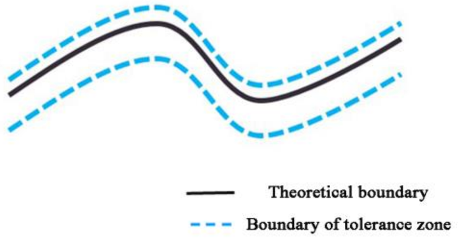

Figure 4: Asymmetric line profile tolerance zone.

3.1.2 One-sided line profile tolerance zone

The one-sided line profile tolerance zone is based on the traditional tolerance zone, whose tolerance zone in one direction is deleted, leaving only the line contour tolerance domain of the single side. This type of tolerance is mainly introduced into the tolerance design in the form of a compensation loop, and the specific application will be described in detail in subsequent chapters.

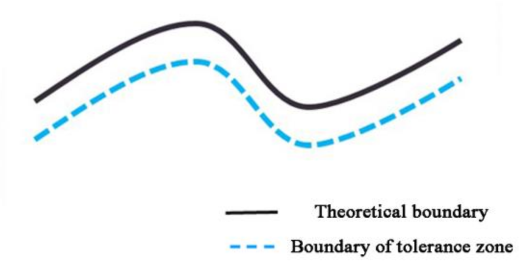

Figure 5: One-sided line profile tolerance zone.

3.2 Supplement to the Mathematical Representation of Line Profile

The mathematical description of the traditional line profile is a positive number, which cannot distinguish between the in-body error and the out-body error, nor can it fully represent the above-mentioned improved line profile tolerance zone. So it is necessary to supplement the mathematical description of the line profile.

The tolerance zone of the line profile is divided into two parts: the in-body tolerance zone and the out-body tolerance zone. The in-body tolerance zone is biased towards the inside of the part body, which means that the volume of the structure after machining compared with the ideal structure is reduced; the out-body tolerance zone is biased toward the outside of the body, which means that the volume of the structure after machining compared with the ideal structure increases.

For improved line profile, the mathematical description is a combination of two parameters: t_1 and t_2. The value of the out-body tolerance zone is defined as a positive number, which is the distance between the limit boundary of the out-body tolerance zone and the theoretical boundary. The value of the in-body is defined as a negative number, which is the distance between the limit boundary of the in-body tolerance zone and the theoretical boundary. According to the above definition, the improved line profile is marked as $^{t_1}_{t_2}$.

The line profile of the part shown in the Figure 6 has a value of 0.04. According to the above mathematical expression method, the mathematical expression of the line profile is $^{0.02}_{0.02}$. The mathematical expression of the one-sideline profile is $^{t_1}_{0}$ or $^{0}_{t_2}$.

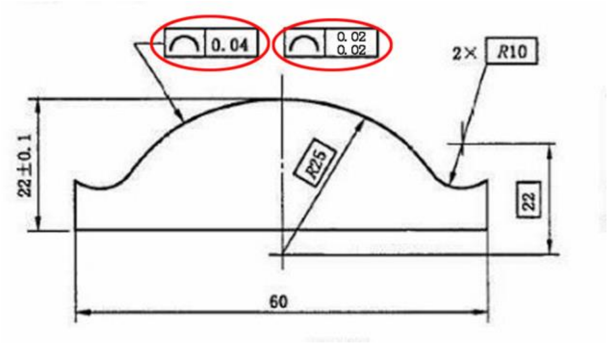

Figure 6: Mathematical description of the improved line profile.

3.3 Segment-contour Tolerance Analysis Method

Segmentation of machining contour largely affects tolerance analysis and allocation. The contour in one section indicates that the same machining technique and tolerance are used for manufacturing. Considering the continuity of processing and machining path planning, we can consider a closed contour as a segment if numerous closed machining profiles are present.

Otherwise, we can segment boundaries at the point where the curvature of the contour is obviously abrupt. This segment method may not help obtain a theoretically optimal solution to a tolerance design problem, but it is the most reasonable and convenient technique in manufacturing.

Following the tolerance analysis method mentioned in Section 2.2, tolerance for each segment boundary to be machined changes from negative to positive. The tolerance design function and the sensitivity of each contour can be obtained by tolerance analysis. Subsequently, the relationship between the uniform tolerance design function mentioned in Section 2 and the segment tolerance design functions are comprehensively analyzed to determine the weight of different boundaries.

3.4 Tolerance Allocation Method

Limited by machining precision, the topology-optimized functional structure may not meet the performance requirements in some cases. When the performance index is harsh, the allowable error range of each segment is very small, which undoubtedly increases the difficulty of manufacturing. No matter what tolerance optimization method is adopted, the ideal tolerance design result cannot be obtained. To solve this kind of problem, on the basis of tolerance design functions and sensitivity of different segment contours, we can use a compensation relationship among boundaries to design an innovative type of asymmetry tolerance, which is non-uniform and asymmetric. We choose the appropriate contour as the compensation loop and assign different values of one-side line profile tolerance according to the segment-contour tolerance design function. By utilizing the offset effect of the structure, manufacturing errors of the compensation profile don’t affect the structural performance macroscopically, so that the remaining contour segments can be given bigger tolerance values.

It should be noted that the compensation contour segment should not be chosen too much. In the tolerance analysis process, the finite element model of manufacturing errors is the boundary of the tolerance zone rather than the boundary containing the manufacturing error. Only when the error distributions of two compensation segments are the same, the performance variation caused by the manufacturing error can be completely offset. Therefore, when the processing capability and processing cost can meet the requirements, it is wise to avoid the application of the compensation contour segment.

Based on improved line profile and tolerance analysis methods, tolerance allocation can take into account manufacturing costs, processing capabilities and performance metrics. The tolerance design problem can be converted to an optimization problem.

$$\begin{aligned} &Find \quad \min \ C(t) = c(t_{i\max} - t_{i\min}) \\ &S.t. \quad T_1 \le \left| t_{i\max} - t_{i\min} \right| \le T_2 \\ &\qquad k_{\max} = f_i(t_{i\max}) \\ &\qquad k_{\min} = f_i(t_{i\min}) \end{aligned} \tag{3.1}$$

where T1 and T2 are constraints of the processing capability; C(t) is manufacturing cost function, $k_{\max}$ and $k_{\min}$ are performance requirements; $f_i(t)$ is the tolerance design function of segment contour. $t_{i\max}$ and $t_{i\max}$ are the mathematical expression of the improved line profile.

3.5 Improvements in Processing Path Planning

The machining tools and detection methods of the line profile are based on the traditional line profile model. The above-mentioned asymmetric and non-uniform line profile tolerance model will cause inconvenience to the manufacturing and inspection. In order to enable the current processing technology to support the non-uniform and asymmetric tolerance zones proposed in this paper, machining curves should be redefined according to the distribution of the tolerance zone. This section proposes a theory of the offset between the theoretical boundary and the machining boundary to increase the manufacturability of the topology-optimized functional structure.

The Figure 7 shows an example. The values of in-body tolerance zone and out-body tolerance zone are different. If it is manufactured according to the design boundary, it may be out of tolerance. It is necessary to bias the theoretical boundary and process it according to the offset boundary. Although the machining boundary is inconsistent with the theoretical boundary, the topology-optimized functional structure manufactured by this method can meet the performance requirements. The relationship between the tolerance zone, theoretical contour, and machining contour is shown in Figure 7.

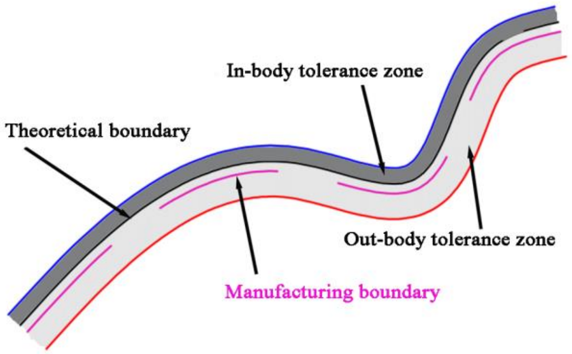

Figure 7: Offset of the processing path.

4 NUMERICAL EXPERIMENT

To demonstrate the tolerance design of a topology-optimized functional structure with respect to structural performance accuracy, a numerical experiment is conducted in this study. The topology-optimized structure is illustrated in Figure 8: the loading force is 5,000N; the thickness of the structure made of aluminum alloy is 6 mm; the structural performance is its stiffness, which is the ratio of the concentrated force (F) to the displacement (x) of the load position.

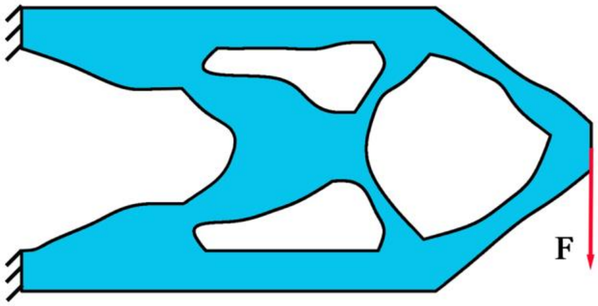

Figure 8: Topology-optimized structure.

4.1 Numerical Experiment of Uniform Tolerance design

The numerical range of tolerance analysis varies from -0.05 mm to 0.05 mm, and the step size of tolerance analysis is 0.001 mm. By uniform tolerance analysis of the topology-optimized functional structure, the relationship between error and performance can be expressed in Figure 9. the error is easily determined to be linearly related to the performance. The primary function and the quadratic function are used to fit data separately, and we find that the fitting errors of two functions are close. For simplicity of calculation, the primary function is chosen to describe the relationship between manufacturing error and performance deviation. The tolerance design function can be expressed as a linear function. The effect of in-body tolerance on performance is opposite with that of out-body tolerance. The tolerance design function is expressed as $k = -0.2634d + 1.9241e^{-5}$, where x is the tolerance range, and y is the change in structural performance. The results of the tolerance analysis are shown in the figure below.

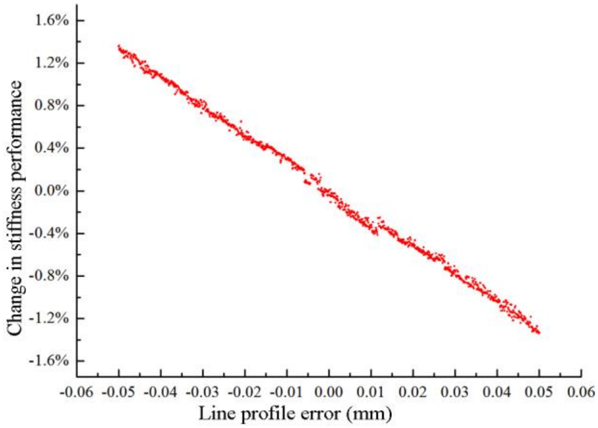

Figure 9: Simulation results for different line profile errors.

For different performance indicators, the corresponding line profile tolerance value is calculated by the uniform tolerance design.

- The stiffness performance of the cantilever beam is allowed to vary from -1% to 1%.

$d_{min} = -0.0379, d_{max} = 0.0380, T = 0.0758$.

- The stiffness performance of the cantilever beam is allowed to vary from -0.7% to 1.3%.

$d_{min} = -0.0493, d_{max} = 0.0266, T = 0.0532$.

- The stiffness performance of the cantilever beam is allowed to vary from 0% to 1%.

$d_{min} = -0.0379$, $d_{max} = 0$. In this case, tolerance design has no solution.

Analysis of test results shows that the same range of performance variation will result in different tolerance values. Limited by the definition of line profile and the method of uniform tolerance analysis, tolerance design reduces the range of allowable error variations. In extreme cases, there will be no solution to the tolerance design.

4.2 Numerical Experiment of Segment-contour Tolerance Design

This topology-optimized functional structure has four closed contours. The segmentation result is presented in Figure 10. By segment-contour tolerance analysis of the topology-optimized functional structure, tolerance design functions of four boundaries can be obtained. Similarly, the relationship between tolerance and performance of different boundaries can be expressed as a linear function with its slope representing sensitivity. Tolerance design functions of four boundaries are presented in Table 1.

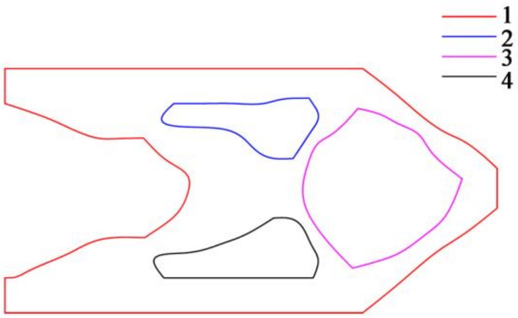

Figure 10: Segmentation of topology- optimized structure for tolerance design.

Boundary number	*Tolerance design function*	*Boundary number*	*Tolerance design function*
1	$k_1 = -0.1531d_1$	*3*	$k_3 = -0.0664d_3$
2	$k_2 = -0.0239d_2$	*4*	$k_4 = -0.0247d_4$

Tab. 1: Tolerance design function of different boundaries.

Adding four formulas in Table 1 results in $k = -0.2681d$. Comparison with uniform tolerance design function shows that each boundary has the same weight. Thus, the tolerance design problem is transformed into an optimization problem.

Researchers have proposed many mathematical models of manufacturing costs, and the parameters of each model need to be obtained by analyzing production data. In this study, in order to simplify the calculation process, the area of the tolerance zone is used to represent the manufacturing cost. The larger the area of the tolerance zone, the smaller the manufacturing cost.

In addition, the manufacturing capability constraints in tolerance optimization are expressed in terms of the range of optimal economic accuracy. If the structural performance allows a maximum change of -1%, the optimization equation is as follows.

$$\begin{aligned}
&Find \quad Min\ \ C(t) = -(321\left|t_{1\max}\right| + 73\left|t_{2\max}\right| + 96\left|t_{3\max}\right| + 77\left|t_{4\min}\right|) \\
&s.t.\ 0.030 \le t_{1,2,3\max} \le 0.1 \quad \text{(a)} \\
&\quad -0.1 \le t_{4\min} \le -0.030 \quad (b) \\
&\quad -0.0239 t_{2\max} - 0.0247 t_{4\min} = 0 \quad \text{(c)} \\
&\quad -0.1531 t_{1\max} - 0.0664 t_{3\max} = -1\% \quad \text{(d)}
\end{aligned}$$

In the above formula, the optimization goal is to minimize manufacturing costs. The equation (a) and (b) represent the processing ability and can also be understood as the economic processing precision range. The equation (c) is the constraint of the compensation contour segment. Boundary 2 and 4 are selected as compensation contour segments and assigned different values of one-side line profile tolerance according to the segment-contour tolerance design function. By utilizing the offset effect of the structure, manufacturing errors of the compensation profile don’t affect the structural performance macroscopically, so that the remaining contour segments can be given bigger tolerance values. The equation (d) is a constraint on the structural performance response indicator.

For different performance indicators, the calculation results are as follows.

- The stiffness performance of the cantilever beam is allowed to vary from -1% to 1%.

$$T_1 = {}^{0.052}_{-0.052},\ T_2 = {}^{0.060}_{0},\ T_3 = {}^{0.030}_{-0.030},\ T_4 = {}^{0}_{-0.058}.$$

- The stiffness performance of the cantilever beam is allowed to vary from -0.7% to 1.3%.

$$T_1 = {}^{0.033}_{-0.072},\ T_2 = {}^{0.060}_{0},\ T_3 = {}^{0.030}_{-0.030},\ T_4 = {}^{0}_{-0.058}.$$

- The stiffness performance of the cantilever beam is allowed to vary from 0% to 1%.

$$T_1 = {}^{0}_{-0.052},\ T_2 = {}^{0.060}_{0},\ T_3 = {}^{0}_{-0.030},\ T_4 = {}^{0}_{-0.058}.$$

Segment-contour tolerance analysis can obtain a combination of non-uniform and non-symmetric tolerance zones. Comparison of results of two tolerance design methods, the tolerance zone width calculated by segment-contour tolerance design method is smaller than that calculated by uniform tolerance design method, which indicates that segment-contour tolerance analysis is more economical under the same performance requirement.

5 CONCLUSIONS

Two tolerance design methods of the topology-optimized functional structure are proposed in this study for guaranteeing performance. The two methods include the uniform tolerance analysis and segment-contour tolerance analysis. The paper describes the application of the improved line profile based on ISO 1101:2017 in the tolerance design. In segment-contour tolerance analysis, the tolerance design problem can be transformed into an optimization problem. Segment-contour tolerance design can achieve precision manufacturing of structural performance under the constraint of a large tolerance range. The tolerance design method mentioned in this study can be extended to the manufacturing of products with free curve contour.

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