Title:
Efficient Tolerance Design of Topology-Optimized Functional Structures

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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 to design, exhibiting high degree of freedom and ability to integrate structure and function in design. In engineering, topology optimization of functional structures has different requirements. Thus, tolerance design for performance under different requirements is valuable. Manufacturing errors can often directly influence product performance and undermine the design objective [3],[9]. 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 population of concurrent design, quality and cost should be considered simultaneously, and various quality loss functions are mentioned for tolerance optimization problems [1],[7-8].

Two main problems in planning topology optimization structures are identified. First, how manufacturing errors affect the topology optimization structural performance has yet to be determined. The boundary of topology optimization parts is complex and consists of free curves, which is different from traditional products. Determining the process of constraining machining boundaries under different performance requirements presents a challenge. Second, the sensitivity of different boundaries to performance vary. 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 requirements. Therefore, tolerance analysis and allocation are vital processes to ensure the precision of manufactured topology optimization structural performance. Thus, the development of an approach to tolerance design for topology optimization structures oriented to high performance would be valuable.

Main Idea:
In this study, an integrated approach to tolerance design of topology optimization structures in consideration of precise implementation performance is proposed. 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. The concept of profile of line tolerance is innovated. In tolerance design for a segment counter, the study proposed a method. This approach involves compensating the different machining contours of the topology optimization 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. Last, a numerical experiment is conducted to verify the feasibility of the tolerance design method of topology optimization results. The process of tolerance design is shown in Figure 1.

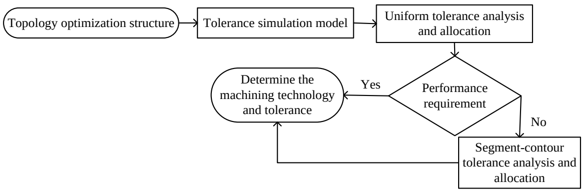

Fig. 1: Tolerance design of the topology optimization structure.

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 optimization structures. 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 boundaries with manufacturing errors need to be built. The topology optimization structure after manufacturing can be simulated by a new model composed of the modified boundary. The simulation model can be imported into the CAE software to analyze the performance. The schematic of the error simulation model is shown in Figure 2(a).

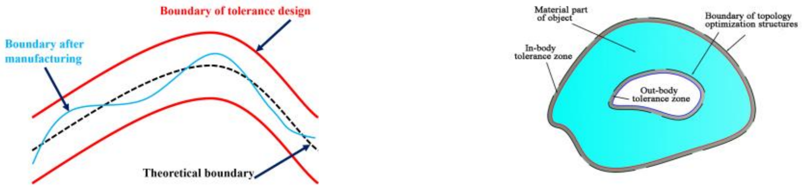

Fig. 2: (a) Boundary of tolerance simulation models, (b) Two types of tolerance zones.

Analysis of Uniform Tolerance:
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, asymmetric tolerance commonly occurs. It appears during assembly or target performance deviation asymmetry. In the iterative process of topology optimization, deleting or adding a material element can considerably affect structural performance. Thus, in manufacturing topology optimization 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 require analysis.

The traditional dimensional tolerance has two types: positive and negative. Similar to that, we define the types of tolerance applied in topology optimization structure 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(b).

By assessing the precision of the machning 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 the topology optimization structure 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 of performance.

By using uniform tolerance analysis, we can easily determine how machining errors affect performance easily. In accordance with the tolerance design function, the proper machining method and tolerance can be chosen reasonably under the specified performance requirement.

Segment-contour Tolerance Analysis:

Allocating the same tolerance to different boundaries in the manufacture of a topology optimization structure 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 performace of the topology optimization 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 bear significance.

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 at the point where the curvature of the contour is obviously abrupt. This segment method may not help obtain a theoretical 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, 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.

Tolerance Allocation Methods under Different Performance Requirements:

Tolerance is determined by the size and location of the tolerance zone. Different tolerance allocation under various performance requirements are identified. The study introduces three allocation methods under various performance requirements.

First, the performance requirements are symmetric, paticularly those for the ±10% type. In accordance with uniform tolerance analysis, the appropriate tolerance value can be selected using the tolerance design function in Section 1. The form of tolerance zone can be referred to as the line profile.

Second, the performance requirements are unsymmetrical and unconventional, such as the -3%~10% type. In this case, we can easily choose the appropriate tolerance value, but the location of the tolerance zone is difficult to determine. In the present machining process, the contour manufacturing precision is often defined by the line profile. Therefore, the machining curve should be redefined according to the distribution of the tolerance zone. A deviation value should be introduced to the tolerance allocation. The machining contour may not coincide with the theoretical contour, but it can meet the performance requirements. The relationship between tolerance zone, theoretical contour, and machining contour is shown in Figure 3(a).

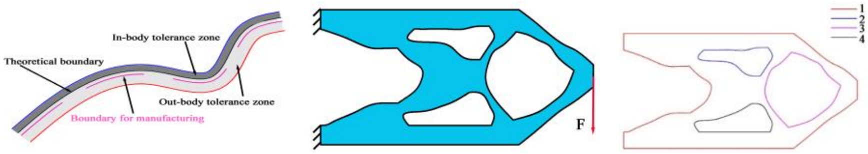

Fig. 3: (a) Asymmetric tolerance zone and machining boundaries, (b) Topology optimization structure, (c) Contour segmentation for tolerance analysis.

Third, limited by machining precision, the topology optimization structure may not meet the performance requirements in some cases. To solve this kind of problem, segment-contour tolerance analysis is important. On the basis of tolerance design functions and sensitivity of different segment contours, we can use a compensation relationship among boundaries to design a innovative type of asymmetry tolerance, which is non-uniform and asymmetric. The tolerance design problem can be converted to an optimization problem. The specific process is described in the following numerical experiment

Numerical Experiment:

To demonstrate the tolerance design of a topology optimization structure with respect to structural performance accuracy, a numerical experiment is conducted in this study. The topology optimization structure is illustrated in Figure 3(b): the loading force is 5,000N; the thickness of the structure made of aluminum alloy is 6 mm; the structural performance is the maximum displacement under loading; the maximum displacement of the theoretical topology optimization structure is 1.03669 mm; and the structural performance requirement of manufacturing is 0%-1%.

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 optimization structure, the error is easily determined to be linearly related to the performance. The tolerance design function can be expressed as a linear function. The effect of in-body tolerance on performance is opposite that of out-body tolerance. The tolerance design function is expressed as $y = -0.2634x$, where x is the tolerance range, and y is the change in structural performance.

The appropriate tolerance can be easily selected in accordance with the performance requirements. The tolerance range is [-0.038, 0].

This topology optimization structure has four closed contours. The segmentation result is presented in Figure 3(c). By segment-contour tolerance analysis of the topology optimization 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.

Boundary number	*Tolerance design function*	*Boundary number*	*Tolerance design function*
1	$y = -0.1531x$	*3*	$y = -0.0664x$
2	$y = -0.0239x$	*4*	$y = -0.0247x$

Tab. 1: Tolerance design function of different boundaries.

Adding up four formulas in Table 1 results in $y=-0.2681x$. Comparison with Formula (1) shows that each boundary bears the same weight. Thus, the tolerance design problem is transformed into an optimization problem. By optimizing calculations, the tolerance range of boundary 1 is [-0.050, 0]; the tolerance range of boundary 2 is [-0.049, 0]; the tolerance range of boundary 3 is [-0.036, 0]; the tolerance range of boundary 4 is [0, 0.050];

$$\begin{aligned} &Find\quad Max\ y(x)=|x_1|+|x_2|+|x_3|+|x_4| \\ &S.t.\quad -0.05\le x_{1,2,3,4}\le 0.05 \\ &\qquad\ -0.1531x_1-0.0239x_2-0.0664x_3-0.0247x_4=1\% \end{aligned} \tag{5.1}$$

Segment-contour tolerance analysis can obtain a combination of non-uniform and non-symmetric tolerance zones. Comparison of results of two tolerance design methods indicates that segment-contour tolerance analysis is more economical under the same performance requirement.

Conclusion:

Two effective tolerance design methods of the topology optimization structure for performance are proposed in this study, which includes the uniform tolerance analysis and segment-contour tolerance analysis. The concept of tolerance of line profile is innovated. 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.

Acknowledgments:

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