

Establishment of Analysis Method for Weight Reduction Design of Motorcycle Frame Parts

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ABSTRACT

In the present development of motorcycle frame parts, basic skeleton layouts are designed by repeating some examinations in order to achieve weight reduction considering rigidity and strength targets. Various structural optimization technologies were studied to reduce the man-hours required for the repeated examination. Instead of expanding the design area of the topology optimization technology, an analysis was established by using a method of virtual rigidity enhancement. The analysis obtains ideas easily and rapidly for weight reduction in consideration of rigidity.

1. Introduction

Weight reduction increases both marketability and product appeal, and is constantly demanded in motorcycle development. In addition, demands for weight reduction have also increased in recent years from the viewpoint of enhancing fuel efficiency in relation to environmental issues.

In response to these demands, the use of CAE-based structural optimization technology for parts has become quite common, and is yielding the desired effects⁽¹⁾.

However, advanced CAE operation skills are required, and in many cases this work must be performed by expert analysis engineers. In addition, creating analysis models, calculating them and evaluating the result take much time, therefore it is difficult to conveniently reflect results in development. Motorcycle frames, in particular, must have efficient engine and auxiliary layouts while maintaining the required strength and rigidity, so the investigation of basic skeleton layouts in the initial development stages often

depends on the know-how of experienced designers.

Therefore, analysis technology is needed that can conveniently provide ideas for reducing weight at the basic skeleton layout investigation stage. A new analysis technology for lightweight design that applies topology optimization technology has been developed to meet these demands. This paper describes an outline of this analysis technology for developing motorcycle and all terrain vehicle (ATV) chassis parts, and presents examples of analysis.

2. Development Goals and Target Requirements

Various performance evaluation items such as rigidity, strength and vibration must be investigated when designing motorcycle parts. This study aimed to develop a weight reduction technology that considers rigidity, which contributes significantly to the overall structural balance.

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Conventionally, repeating actual vehicle tests based on past experience, or CAE analysis was performed as shown in Fig. 1. However, iterative process must be reduced to increase developmental efficiency. Therefore, a target process was set as shown in the lower half of Fig. 1. For designers to examine ideas by themselves within this target process, the analysis time must be relatively short, operation must be simple and the results used for evaluation must be easy to understand.

Therefore, the following target requirements were set.

- (1) Ideas for shapes to reduce weight in consideration of rigidity should be obtained.
- (2) The total man-hours spent on analysis should be one working day (10 hours) or less.
- (3) The analysis technology should be easy to use for designers in the future.

3. Theory Establishment

3.1. Comparison of Various Structural Optimization Methods

Conventional analysis technology for lightweight design consists of thickness optimization, shape optimization and topology optimization.

Thickness optimization performs optimization using thickness as the design variable. However, the use of solid meshes for structural analysis is increasing with the recent spread of 3D data product drawings in the industrial world. Solid meshes express thickness using shape, so the concept of thickness does not exist. This means that thickness cannot be set as a design variable, so thickness optimization analysis is not possible. Shape optimization requires numerous calculations when there are ten or more dimensions to be set as design variables, so it is not suitable for analyzing entire models. In addition, the large number of modeling man-hours needed to define the design area is an issue for topology optimization. Therefore, as an alternative, the concept of increasing the Young's modulus hypothetically was introduced in topology optimization, and the feasibility of new structural optimization analysis method was investigated. These details are described below.

3.2. Conventional Topology Optimization

On the basis of the load and constraints set for given space, as shown Fig. 2, topology optimization is a method for obtaining the optimum layout, as shown in Fig. 3. This determines how the materials should be distributed to obtain the strongest (most rigid) structure.

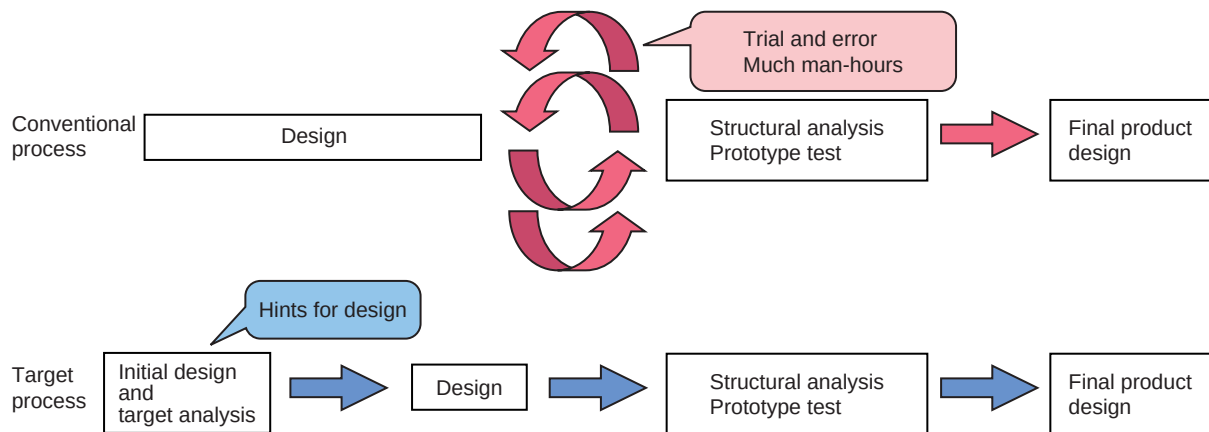


Fig. 1 Target process of design process

Method	Thickness optimization	Shape optimization	Topology optimization
Image			
Design variable	Thickness	Dimension	Density
Merit	Low analysis costs (Shell model) Easy to set design parameters Fast calculation time	Effective for finding ideal shapes	Low analysis costs Easy to set design parameters Fast calculation time
Demerit	Difficulty in analysis by solid mesh models	Large amount of man-hours Difficulty in design parameters setting Difficulty in analysis of complex shapes Long calculation time	Difficulty in design area setting of complex shapes

Table 1 Comparison of various structural optimization methods

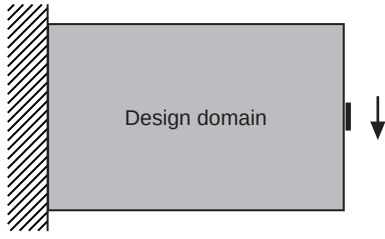


Fig. 2 Design domain for topology optimization analysis

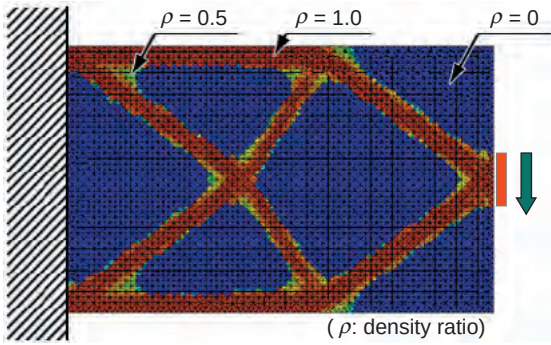


Fig. 3 Topology optimization using density approach

The methods used in topology optimization include the homogenization and density methods. The density method is described here.

In Hooke's law used in structural analysis, if it is hypothesized that the strain is the displacement as shown in Eq. (1), the strain decreases as the Young's modulus increases. Therefore, it can be said that the displacement is small.

$$\varepsilon = \sigma/E \quad (1)$$

ε : Strain

σ : Stress

E : Young's modulus

The density method assumes that the Young's modulus of the material is proportional to the power of the density as shown in Eq. (2), and obtains the optimum topology, using the density ratio of each mesh as design variables^{(2),(3)}.

$$E = \rho^N E_0 \quad (2)$$

E : Young's modulus used in the calculations

ρ : Density

N : Multiplier

E_0 : Set Young's modulus

As shown in Fig. 3, the Young's modulus used in the calculations fluctuates from 0.0 to E_0 by varying the density of each mesh from 0.0 to 1.0. Optimization consists of using each mesh as a design variable and performing iterative calculations to obtain an optimum solution that maximizes or minimizes the objective function while satisfying the constraints.

3.3. Issues with Conventional Design Area Setting Functions

If the density of the initial shape is considered to be 1.0, the rigidity cannot be increased above that of the initial shape.

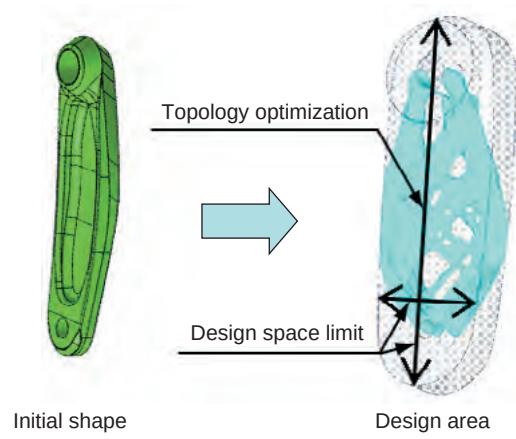


Fig. 4 Set design area

Therefore, the design area is expanded before performing topology optimization, as shown in Fig. 4. However, the number of modeling man-hours is quite high, except for simple shapes, so work to expand the design area does not satisfy the target requirement for no more than 10 man-hours for analysis. In addition, because the engine and auxiliary units are mounted on a motorcycle frame, expanding design area is difficult, and the effect of optimization cannot be obtained easily.

3.4. Topology Optimization Method with an Expanded Concept

To resolve these design area setting issues, the method of setting a high Young's modulus hypothetically, as shown in Eq. (3), was devised as an alternate method to expanding the design area. Here, the Young's modulus is multiplied by k .

$$E_{01} = kE_0 \quad (3)$$

Next, the Young's modulus multiplied by k is substituted into Eq. (2), and Eq. (4) is obtained.

$$kE = \rho^N kE_0 \quad (4)$$

By varying the density from 0.0 to 0.1, the Young's modulus used in the calculation becomes 0.0 to kE_0 , and the rigidity also becomes a multiple of k . For example, doubling the Young's modulus reduces the displacement by 1/2 and makes it possible to increase the initial rigidity hypothetically, as shown in Fig. 5. This creates some margin in the rigidity, allowing use of the topology optimization method. This is the result of increasing the rigidity hypothetically, so it has no meaning as an absolute value. However, the results are output with shading of density, so areas with high density can be judged as locations that require strengthening, and

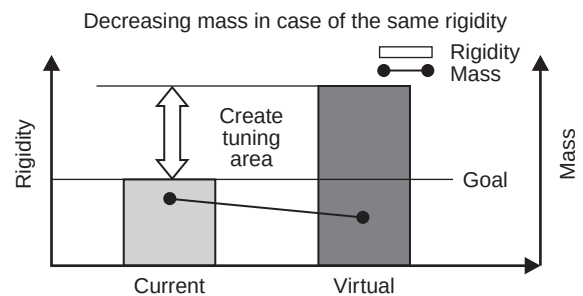


Fig. 5 Increasing virtual rigidity

areas with low density as locations that require weakening. In other words, the results can be understood as the sensitivity relative to the target rigidity. The calculations performed are for topology optimization, but the results are viewed as sensitivity, so this method was named topology sensitivity analysis. Weight reduction can be achieved by strengthening locations with high sensitivity and weakening locations with low sensitivity. Of course, analysis can be also performed using different conditions to efficiently increase the rigidity with a minimum increase in mass, and this is often necessary in intermediate development stages. That is, the mass and rigidity can be optionally set as constraints and objective functions for optimization. Previously, comprehensive countermeasures were considered while judging from stress diagrams, deformation diagrams and other structural analysis results, so it was challenging and took a long time to make judgments. However, the newly developed analysis method enables judgment directly from the density distribution, so judgment errors are reduced and the time is also shortened.

3.5. Comparison of Stress Countermeasure Method and Topology Sensitivity Analysis Method

When investigating an increase in rigidity, the usual method is to reinforce areas with high stress when a load is applied. While this method is not wrong, it is not an appropriate method when considering both rigidity and mass. On the other hand, topology sensitivity analysis is a topology optimization method, that is, an optimization issue, so this method sets an objective function, constraints and design variables as shown below, and then performs optimization by iterative calculations⁽⁴⁾.

Objective function: Min. $\{f(x)\}$

Constraints: $g_i(x) \leq 0; i = 1, 2, \dots, k$

Design variables: $x = (x_1, x_2, \dots, x_n)$

Therefore, this method obtains a more optimum shape than the stress countermeasure method. This means that the topology sensitivity analysis method is more effective than the stress countermeasure method from the viewpoint of both rigidity and mass.

4. Verification

Two examples of verification results for the analysis method explained in section 3.4. are described below.

4.1. Verification of Plate Shape Analysis

This verification example compares the countermeasure method that focuses on high stress areas with the countermeasure method based on topology sensitivity. The calculation conditions for topology sensitivity are as follows.

- (1) Design variables: Entire model
- (2) Constraints: Equivalent rigidity
- (3) Objective function: Minimization of mass

Figure 6 shows the analysis conditions and analysis results for each method. The upper right shows the stress distribution obtained from static analysis, and the lower right shows the topology sensitivity analysis results. Red areas indicate high sensitivity, and blue areas indicate low sensitivity. When adding a patch as a countermeasure, the greatest effect is achieved by applying the patch to the red area for both analysis methods. Figure 7 shows the patch shapes derived from each analysis result. The patch mass is equivalent for comparison purposes. Figure 8 shows the results, and indicates that the newly developed analysis method effectively

increases the rigidity by approximately 20% for the same mass compared to the stress countermeasure method. Although the mass is the same in this example, targeting the same rigidity would allow the mass to be reduced by the amount of increase in rigidity.

4.2. Verification of Frame Part Shape Analysis

This verification example shows the results of confirming the effects of applying reinforcing patches to areas with high, low and medium sensitivity in the analysis results. The calculation conditions are as follows. In this example two constraints are set.

- (1) Design variables: Entire model
- (2) Constraints: Increased torsional rigidity, equivalent lateral rigidity
- (3) Objective function: Minimization of mass

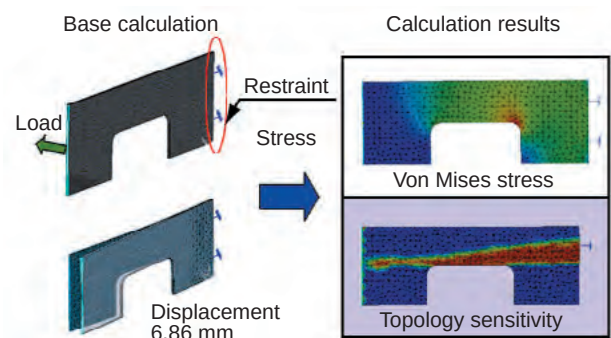


Fig. 6 Verification plate model

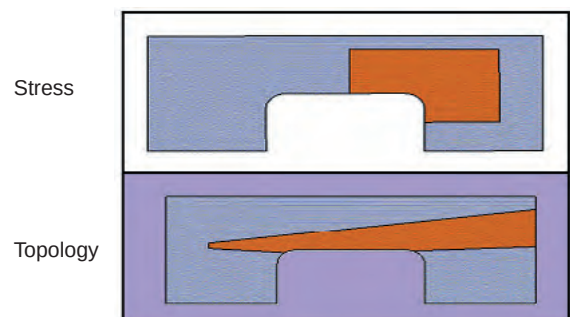


Fig. 7 Comparison of additional patch shapes

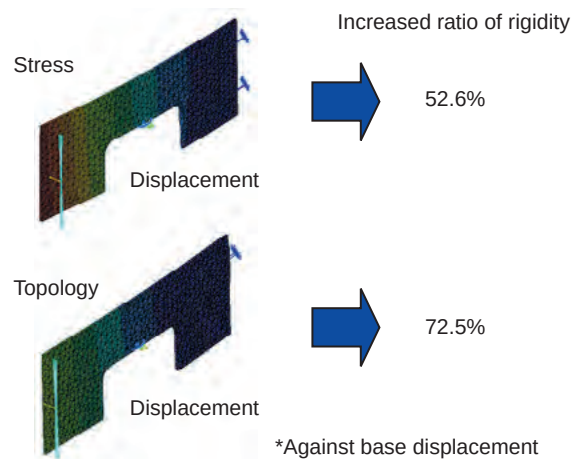


Fig. 8 Comparison of displacement

Figure 9 shows the analysis results, and Fig. 10 shows the patches for the high, medium and low sensitivity areas derived from Fig. 9. The patch mass was set to the same mass for comparison purposes. Table 2 summarizes the results for each patch, and shows that the countermeasure efficiency is greatest in areas with high sensitivity. In addition, applying patches to high sensitivity areas caused the lateral rigidity to decrease slightly. Generally, when one rigidity is increased, the remaining rigidity also increases, but these results showed a drop in lateral rigidity. In terms of sensitivity, however, this is the same as the direction set by the constraints. This example indicates that the newly developed analysis method is also effective for tuning the various rigidities in terms of direction.

5. Examples of Application

5.1. Example of Frame Parts Analysis

This example describes the results of analysis performed to

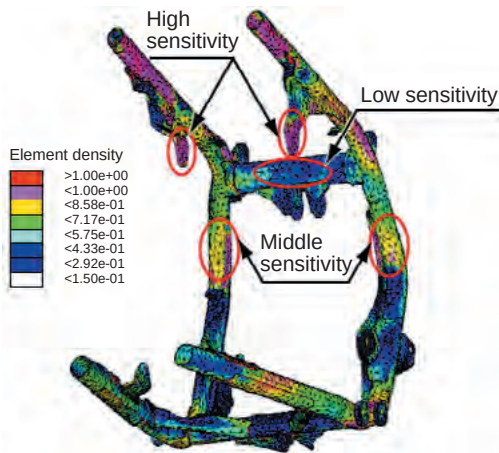


Fig. 9 Result of topology optimization sensitivity for conventional pipe frame

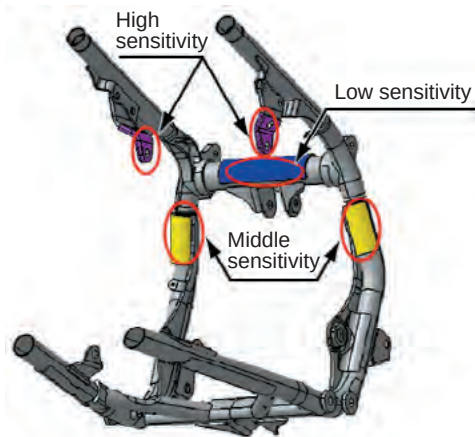


Fig. 10 Example of additional patches

Table 2 Verification effect of each patch

Sensitivity	Low	Middle	High
Torsional rigidity	0.03%	1.21%	4.31%
Lateral rigidity	0.32%	0.84%	-2.01%
Effect	Non	Small	Large

obtain frame rigidity with the aim of minimizing the increase in mass. This analysis used a sports type motorcycle frame, and the calculation conditions are as follows.

- (1) Design variables: Entire model
- (2) Constraints: Increased torsional rigidity, equivalent lateral rigidity
- (3) Objective function: Minimization of mass

Figure 11 shows the analysis results. In these results, red and purple areas indicate locations that require strengthening, and blue areas indicate locations that require weakening. Concretely, measures include tuning the thickness and diameters, adding and deleting ribs, patches, and others. In some cases a change of the skeleton layout is also considered. However, manufacturing technique requirements, strength, cost and other factors are also examined. Previously, parts that required strengthening or weakening were not able to be found out, and there were cases in which misjudgment was made, however, this analysis method is effective for understanding the key locations. Finally, static analysis is performed with the proposed countermeasures input, and the effects are confirmed. Figure 12 shows the example proposed countermeasures. The results confirmed a 10.7% increase in efficiency of the ratio of torsional rigidity to mass.

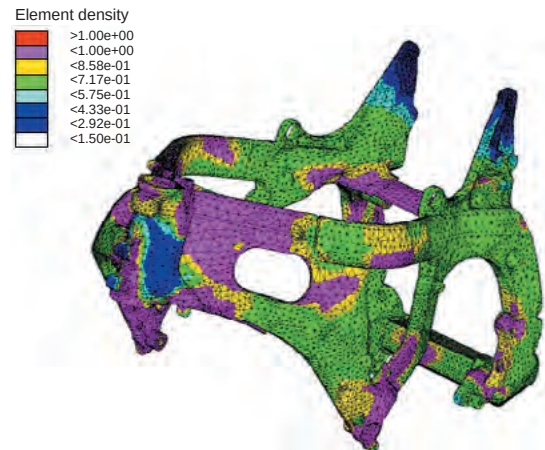
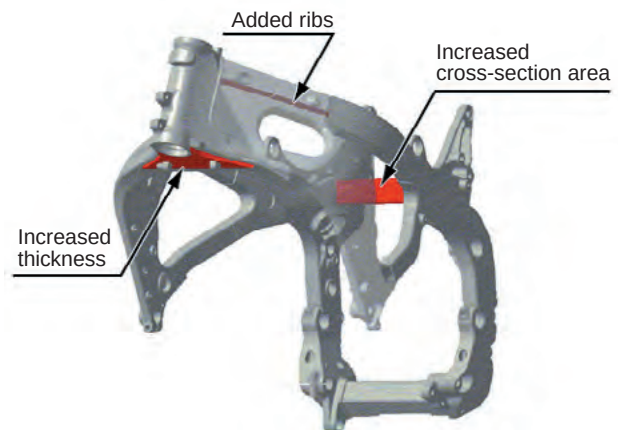


Fig. 11 Result of topology optimization sensitivity for box section frame



	Base	Modified
Torsional stiffness/Mass	100	110.7
Lateral stiffness/Mass	100	102.6

Fig. 12 Modification by using topology optimization sensitivity results

5.2. Other Analysis Examples

The devised topology sensitivity analysis can be applied not just to frames, but to any part that requires rigidity. Figure 13 shows an example of analysis results for a seat bottom plate. Normally, when investigating ribs, the ideal method is to increase the design area and then perform topology optimization using the conventional method. However, depending on the development stage, there are many cases in which the design cannot be changed due to the relation between the layout and the proposed countermeasure support time. The newly developed analysis method is effective in these cases. The design changes shown in Fig. 13 are concretely investigated based on the analysis results within the range over which design changes are possible. For example, ribs are added and thickness is increased in locations that require strengthening, and ribs are taken out and thickness is reduced in locations that require weakening, and others.

Figure 14 shows the analysis man-hours for the results shown in Fig. 11 and Fig. 13. Analysis can be performed within one day (10 hours) in both cases, although this assumes the existence of a static analysis model. There are cases in which the analysis results show little effect for parts that were designed to the optimum shape. However, an approximate 10-20% reduction in weight can normally be achieved by maintaining the same rigidity, or the rigidity can be tuned to suppress the increase in mass.

In addition, the newly developed analysis method is based on existing static analysis models, and analysis can be performed without changing the model, simply by making the settings for topology sensitivity analysis. Therefore, simplification allows designers to use the new method by themselves without requiring the assistance of expert analysis engineers.

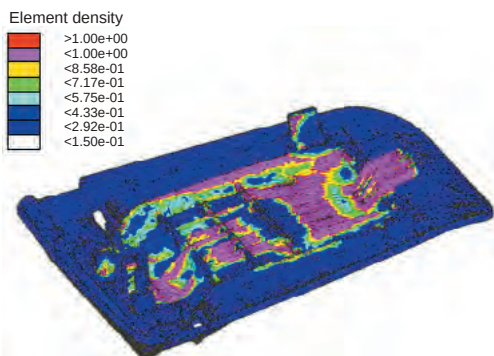


Fig. 13 Result of topology optimization sensitivity for seat bottom

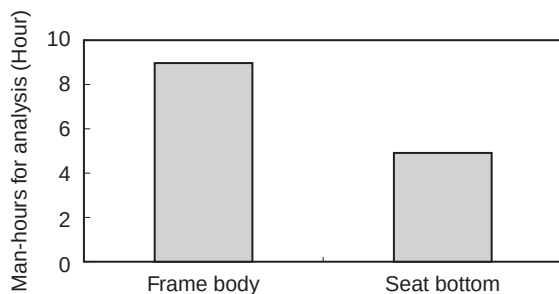


Fig. 14 Total man-hours for analysis

6. Conclusion

It was found that the sensitivity relative to the rigidity of each location of an existing shape can be obtained by increasing the Young's modulus hypothetically instead of expanding the design area in topology optimization.

Construction of this analysis technology yielded the following results.

- (1) Ideas for shapes to reduce mass in consideration of rigidity could be obtained.
- (2) The total man-hours required for analysis were within one day (10 hours), and investigations could be carried out in real time in accordance with the development flow.
- (3) An approximately 10-20% weight reduction was made possible assuming the same rigidity for the applied parts.

The newly developed analysis method allowed target development requirements to be met, and it is thought that this new technology can be applied to the design of not only motorcycle parts but also various mechanical parts. In the future, the authors intend to enhance the functions, simplify operations, and promote faster speed to allow designers to use the newly developed method by themselves.

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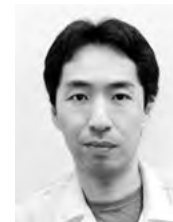
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