Construction of High-Reliability Evaluation Method Concerning Multidisciplinary Optimal Design for Rocket Turbopump

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Rocket turbopumps that are required to have a high degree of reliability are composed of turbines, impellers, bearings, etc. In a multidisciplinary optimal design process of such a complicated rotating system, the shape optimization of each component is addressed to stabilize the dynamic behavior of a rotating system after a design of the component array. In this paper, the shape optimization method based on the response surface incorporating with the magnitude of distribution is proposed. As for estimating the influence of error factors in terms of rotor dynamics, the standard deviation is introduced. As a numerical example, a multidisciplinary optimization of rocket turbopump is presented to verify the utility of our proposed method.

1. Introduction

The stabilization of shaft vibration is an important problem in the basic design of the rotor system of a rotating machine. In particular, in the rocket turbopump with high rotation speed and high pressure, a vibration phenomenon due to the destabilizing action of rotordynamic fluid force (RD fluid force: torque-unbalanced force caused by the circumferential nonuniformity of a turbine rotor tip leakage) caused by the interaction between a rotor system and a fluid system may become problematic(1). However, the current situation is that an analysis technique for such a shaft vibration phenomenon has not been sufficiently established, and in general, the rotor system is far from being optimized.

Meanwhile, there has been proposed a multidisciplinary optimal design method adapted to: regard a rocket turbopump as one big rotor system; as subsystems of it, position ① a turbine, ② an impeller, ③ an inducer, ④ bearings, and ⑤ seals, which are components of the turbopump. In so doing, optimize the layout/arrangement of the subsystems in order to stabilize and suppress the shaft vibration of the turbopump; and then determine the optimal size of each subsystem as design variables(2). The term “layout/arrangement” refers to, for example, bearing layout and turbine impeller arrangement. Differently from a conventional design method adapted to design respective subsystems individually and then combine them, the multidisciplinary optimal design method is characterized by simultaneously treating the respective subsystems. That is, the multidisciplinary optimal design method is a method for exploring optimal design as a rotor system by simultaneously treating the respective subsystems. In the proposed method, a shaft vibration analysis is conducted taking account of predicted RD fluid force, but cannot yet evaluate the reliability of shaft vibration with respect to a variation in RD fluid force.

This study intends to construct a highly reliable rotor system evaluation method taking account of a variation in RD fluid force for the multidisciplinary optimal design method. We also construct a method for the reliability evaluation of shaft vibration characteristics in consideration of, in addition to the RD fluid force, the influence of the deformation ratio and design changes of each subsystem (a change rate of the designated size estimated in the process from concept design to detailed design) on the evaluation indices of the turbopump.

2. Multidisciplinary optimal design method for turbopumps(3)

Figure 1 illustrates the multidisciplinary optimal design method for an upper stage engine liquid hydrogen turbopump(3), which is the subject of this study, and the outline of it is described below.

This design method is roughly divided into the following two steps.

(1) Step 1

The morphology of a turbopump is optimized with the combination order (layout/arrangement) of the respective subsystems of the turbopump as a design variable, and design candidates are narrowed down. In the case of a turbopump having not many morphological elements, the shaft vibration analysis is conducted on all morphologies (84 morphologies) other than physically impossible morphologies, and among them, morphologies superior in shaft vibration characteristics are selected as design candidates in Step 2.

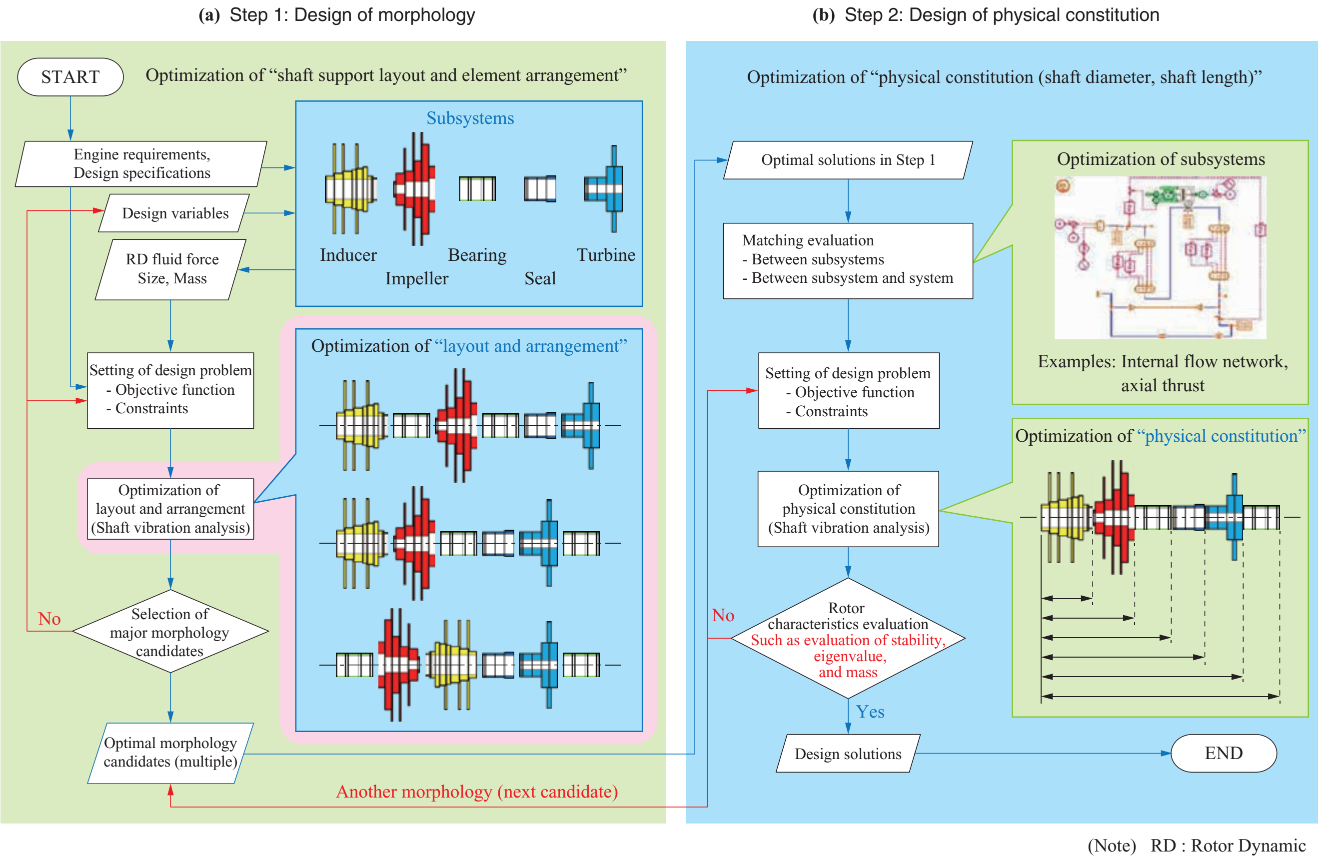

Fig. 1 Multidisciplinary optimal design process of rocket turbopump[3]

(2) Step 2

The shaft vibration analysis is conducted on the design candidates obtained in Step 1 using a Monte Carlo simulation with the length and stiffness of each subsystem as design variables, and thereby a final design solution is obtained.

3. Highly reliable evaluation method

Figure 2 illustrates the outline of a highly reliable design process based on the evaluation method proposed in this study.

The framework of optimization proposed in this study consists of two optimization processes respectively taking and not taking account of error factors. The feature of it is, for each of the evaluation indices obtained as a result of the shaft vibration analysis and listed in **Table 1**, to select a design solution using two response surfaces to be prepared.

From a response surface of the average values of the evaluation indices ① illustrated in **Fig. 2**, entire design solutions approximating the relationship between the shaft vibration characteristics and the design variables are obtained. Also, a response surface ② illustrated in **Fig. 2**, representing the standard deviations of the evaluation indices, is an approximated surface of standard deviations defined as variations in the evaluation indices, from which the reliability of entire design solutions can be evaluated. Using the two response surfaces obtained as described, the final design solution is determined considering the trade-off

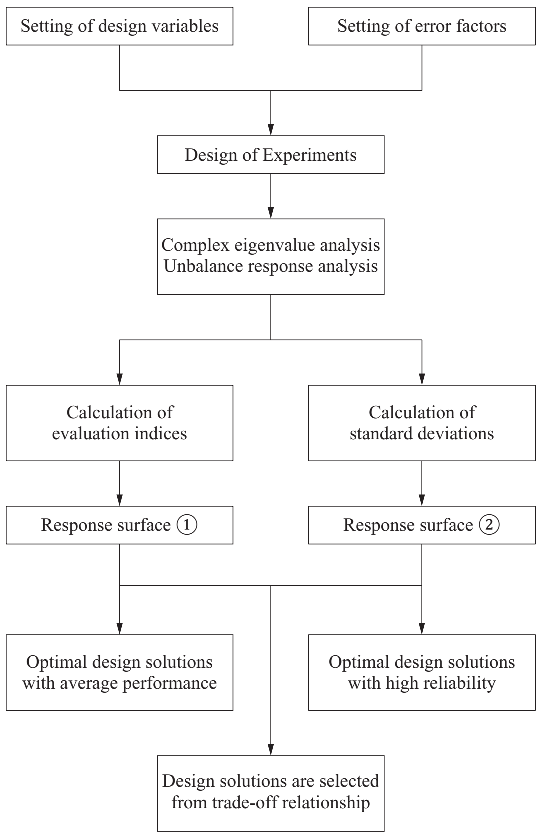

Fig. 2 Flow chart of a highly reliable design process

Table 1 Evaluation indexes

Evaluation index	Unit	Criterion	Characteristic
Rotor weight	kg	—	Smaller the better
Passing number of vibration mode	ea.	—	
Amplitude ratio for unbalance response	—	< 1.0	
Minimum system damping ratio	—	> 0.0	Larger the better
Minimum separation ratio from critical speed	—	≥ 0.05	

relationship between performance and variation.

Note that a standard deviation σ as a reliability evaluation index is defined by Equations (1) and (2) below.

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - m)^2} \qquad \cdots\cdots(1)$$

$$m = \frac{1}{N}\sum_{i=1}^{N} x_i \qquad \cdots\cdots(2)$$

Here, N represents the number of combinations of error factors to be evaluated, x each evaluation index, and m the average value of each evaluation index obtained by Equation (2).

4. Reliability evaluation of rocket turbopump

4.1 Evaluation indices of shaft vibration characteristics and design target

In Steps 1 and 2 of the multidisciplinary optimal design, the shaft vibration characteristics are evaluated on the basis of the shaft vibration analysis[4] including the influence of RD fluid force of each subsystem on the finite element model of a turbopump illustrated in **Fig. 3**. The shaft vibration characteristics are represented by the five indices listed in **Table 1**, and a comprehensive evaluation value F_Σ[5] with a maximum value of 1 and given by Equation (3) as the weighted linear sum of the respective indices is attempted to be maximized as an objective function.

$$F_\Sigma = \sum_{i=1}^{5} w_i F_i \Big/ \sum_{i=1}^{5} w_i \qquad \cdots\cdots(3)$$

Here, F represents each normalized evaluation index, and w represents a corresponding weighting factor set by the Analytic Hierarchy Process (AHP)[6] for specific engineers. Also, since each evaluation index has different dimension, the dimensionless number is calculated by the normalization in accordance with Equation (4).

$$F_\Sigma = \begin{cases} 1 - \left(\dfrac{f_i - f_i^*}{\bar{f}_i - f_i^*}\right)^{\gamma_i}, & \operatorname{sgn}\left(f_i^* - \bar{f}_i\right) \times \left(f_i - f_i^*\right) < 0 \\ 1, & \operatorname{sgn}\left(f_i^* - \bar{f}_i\right) \times \left(f_i - f_i^*\right) \geq 0 \end{cases} \qquad \cdots\cdots(4)$$

Here, $f_i, f_i^*, \bar{f}_i$, and γ_i respectively represent an evaluation index, corresponding ideal value, corresponding aspiration level, and multiplier of corresponding sensitivity. **Table 2** lists an ideal value, aspiration level, multiplier, and weighting factor for each evaluation index.

Figure 4 illustrates a schematic diagram of Type 1 and 2 turbopumps selected in Step 1. In this study, a multidisciplinary optimal design method for physical constitution (the length of each subsystem and bearing stiffness) is constructed in consideration of reliability with the two morphologies[5] of Types 1 (**Fig. 4-(a)**) and 2 (**-(b)**). Note that both of the two morphologies have a shaft diameter of 30 mm and a rotation speed of 70 000 rpm. In addition, the comprehensive evaluation values of Types 1 (**Fig. 4-(a)**) and 2 (**-(b)**) are 0.64 and 0.50, respectively.

4.2 Design variables and error factors

Tables 3 and **4** list the design variables and the error factors in this study, respectively. Note that in the tables, the upper and lower limit values of the design variables and the respective level values of the error factors are given as ratios with respect to corresponding reference values. In addition as the upper and lower limit values of the error factors, values are employed on the assumption of variation ranges caused by various design ideas for each subsystem and by various designers.

Table 2 Ideal value, aspiration level, multiplier and weighting factor for each evaluation index

Evaluation index	Ideal value	Aspiration level	Multiplier	Weighting factor
Rotor weight	15	25	1	0.016
Passing number of vibration mode	0	1	1	0.108
Amplitude ratio for unbalance response	0.2	0.6	2	0.362
Minimum system damping ratio	0.1	0.0	1	0.352
Minimum separation ratio from critical speed	0.20	0.05	3	0.161

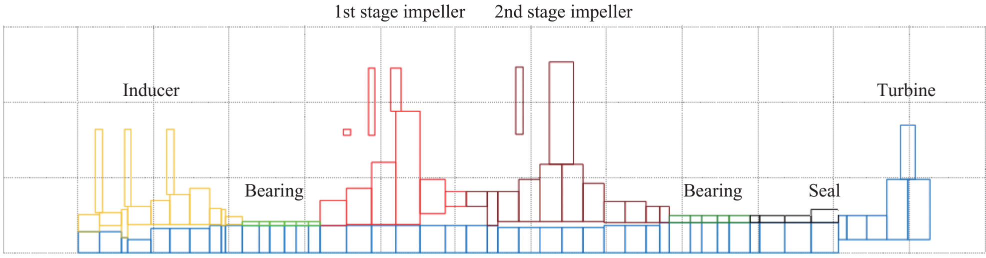

Fig. 3 Finite element model of the turbopump

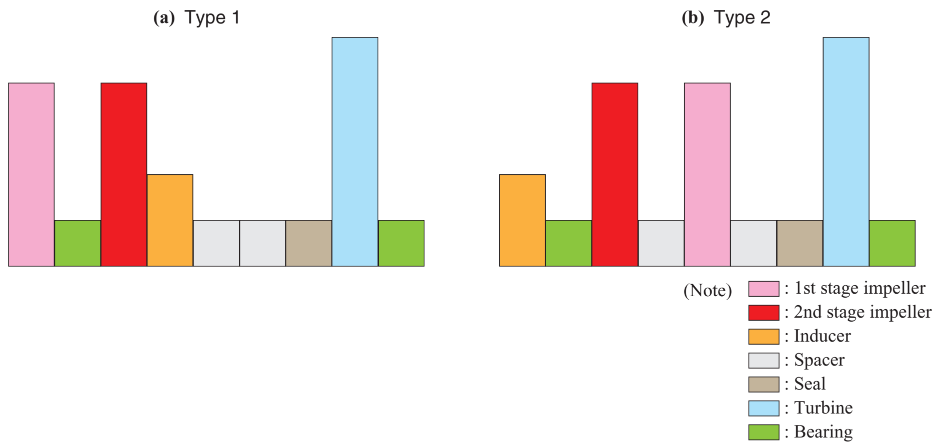

Fig. 4 Schematic diagrams of Type 1 and 2 turbopump designs

Table 3 Design variables of turbopump

Design variable	Symbol	Lower limit value	Upper limit value
Inducer axial length	InL	1.0	2.0
Impeller axial length	ImL	1.0	1.2
Turbine inlet length	TuL	0.5	1.5
Bearing axial length	BeL	0.5	1.5
Bearing stiffness	BeS	0.5	1.5

4.3 Design of experiments

In this study, 50 initial cases are prepared for the five design variables based on a Latin Hypercube Sampling method, and for each of the cases, the shaft vibration analysis is conducted on 18 combinations of the error factors allocated in an orthogonal table (L18) (total number of calculations: $50 \times 18 = 900$).

4.4 Optimization results

Figure 5 illustrates a design solution set for the turbopump, in which a scatter diagram between the comprehensive evaluation value and standard deviation of a design solution obtained by the virtual exploration depending on Multi-Objective Genetic Algorithm (MOGA) on a response surface based on a Radial Basis Function (RBF) is illustrated. Note that in this study, in order to make it possible to deal with multi-peak responses and to explore local optimal values, the RBF and the MOGA were used, respectively. The comprehensive evaluation value and the standard deviation respectively correspond to the larger-the-better characteristic and the smaller-the-better characteristic, so in **Fig. 5**, better design solutions are plotted toward the lower right of the diagram.

It turns out from **Fig. 5** that even for Type 2 whose comprehensive evaluation values are inferior to those of Type 1, design solutions having standard deviations comparable to those of Type 1 can be selected. It also turns out that, as indicated by the evaluation in Step 1, the comprehensive evaluation values of Type 1 are better than those of Type 2, and even considering reliability, Type 1 is better in layout/arrangement.

Figure 6 illustrates the trends of the design variables (parallel coordinate chart) constituting a Pareto solution for Type 1. In the parallel coordinate chart, the horizontal axis gives the respective design variables, a comprehensive evaluation value, and a standard deviation, and the vertical axis gives the upper and lower limit values of them, and one polygonal line corresponds to one design solution. It turns out from the results illustrated in **Fig. 6** that although selected Pareto solutions have a variation in standard deviation, the Pareto design solution set with high comprehensive evaluation values is extracted. The trends of the design variables of the design solutions corresponding to the Pareto solutions are almost the same, and it is suggested that by appropriately selecting values of the design variables, a reliable design solution superior in shaft vibration characteristics can be selected.

Next, a design solution was selected from among Pareto solutions for Type 1 illustrated in **Fig. 6**, and shaft vibration analysis was conducted to confirm the actual evaluation indices. The design variables, comprehensive evaluation value, and standard deviation of the design solution are listed

Table 4 Error factors of turbopump

Error factor	Symbol	First level value	Second level value	Third level value
Inducer deformation ratio	InRAR	0.89	1.00	
Impeller deformation ratio	ImRR	0.93	1.00	1.15
Inducer RD fluid force *C*	InRDC	0.80	1.00	1.20
Inducer RD fluid force *k*	InRDk	0.80	1.00	1.20
Impeller RD fluid force *M*	ImRDM	0.80	1.00	1.20
Turbine disk diameter ratio	TDiskR	0.90	1.00	1.10
Seal axial direction length ratio	AR	0.90	1.00	1.10
Bearing support damping ratio	BDR	0.80	1.00	1.20

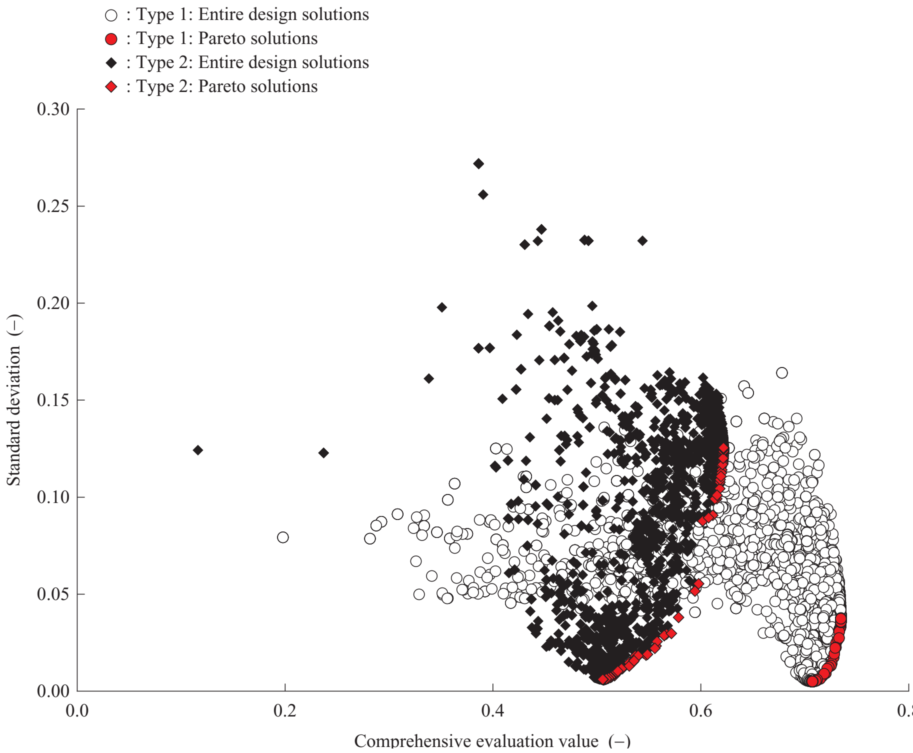

Fig. 5 Design set for turbopump

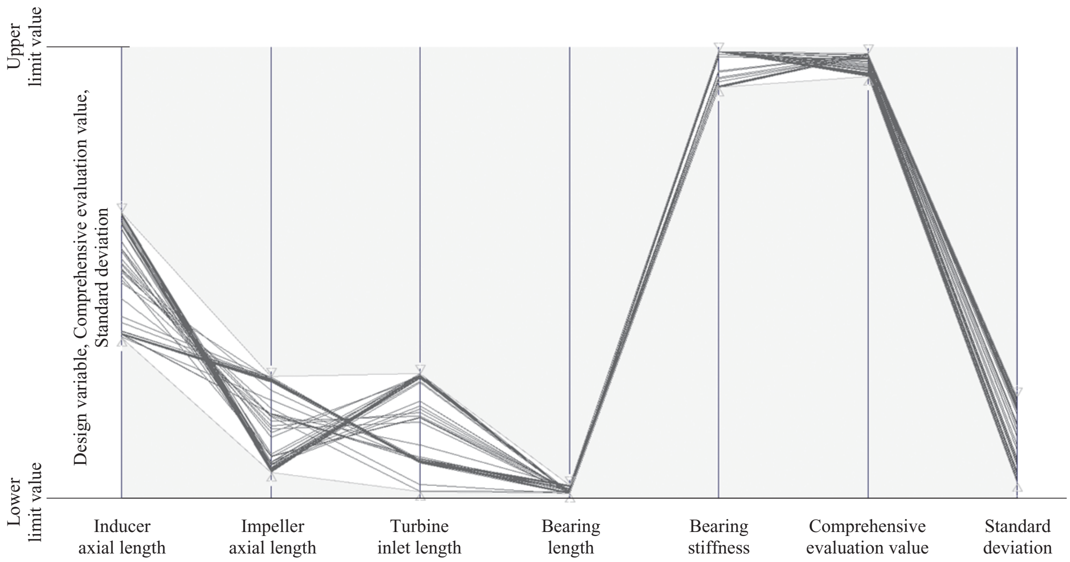

Fig. 6 Parallel coordinate chart for Pareto-optimal set

in **Table 5**, compared with the values of the initial design solution. Note that the initial design solution refers to a solution whose design variables all have reference values. It turns out from **Table 5** that it was revealed that we can select the design solution whose comprehensive evaluation value and standard deviation were both better than those of the initial design solution. In particular, it turns out that the standard deviation of the selected solution was considerably improved as compared with that of the initial design solution, and the selected solution was highly reliable.

5. Conclusion

In this study, we have proposed a reliability evaluation method appropriate for the multidisciplinary optimal design method for a rocket turbopump. The proposed method is one adapted to prepare two types of response surfaces respectively taking and not taking account of error factors, and select a Pareto solution satisfying both performance and reliability from among all design solutions.

As a result of using the proposed method to evaluate reliability against RD fluid force with some aspects of the physical constitution of a turbopump as design variables, we

Table 5 Design variables, evaluation index and standard deviation of design solution

Design solution	Design variable					Approximate value from response surface		Calculation result	
	InL	ImL	TuL	BeL	BeS	F_{Σ}	σ	F_{Σ}	σ
Selected solution	1.63	1.03	0.85	0.55	1.32	0.70	0.039	0.66	0.030
Initial design solution	1.00	1.00	1.00	1.00	1.00	—	—	0.64	0.094

have shown that there are design solutions satisfying both performance and reliability, and that there are the specific trends of the design variables constituting the design solution set. In addition, from the actual shaft vibration analysis, it is shown that the selected design solution has superior axial vibration characteristics particularly in reliability, compared with an initial design.

In the future, we will also extend this method to the optimization of layout/arrangement in the multidisciplinary optimal design method.

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