Study on Methodology for Total Design Management

KURE Hirotaka : Manager, Numerical Engineering Department, Research Laboratory, Corporate Research & Development
MORI Hatsuo : Manager, Numerical Engineering Department, Research Laboratory, Corporate Research & Development
WATANABE Osamu : Manager, Numerical Engineering Department, Research Laboratory, Corporate Research & Development

We suggest a new design methodology for a multipurpose trade-off design and a risk management, called Total Design Management (TDM). TDM has two important concepts : "Set Based Design (SBD)" and "Model Based Risk management (MBR)." In SBD, designers firstly calculate the total set of design solutions and then narrow down the solutions complying with the design requirements or constraint conditions by a filtering method. SBD is very simple, transparent and practical process. In MBR, designers manage a design risk based on designers' non-confidence of the mathematical models which they make or calculate. In this paper, we also indicate effectiveness of this methodology with two examples : cantilever problem and impeller design.

1. Introduction

Demand exists for practical design techniques that enable evaluation of several indices, such as performance, cost, and robustness, while ensuring design transparency.

In order to satisfy demands from design worksites and customers, we developed Total Design Management (TDM) for the purpose of integrating various kinds of design techniques, such as multipurpose trade-off design and robust design, as well as risk management techniques, while maintaining practicality and transparency.

2. Design techniques demanded by on-site designers

Designers need to determine various dimensions to create products that satisfy many requirements, while at the same time maintaining a balance among characteristics to be improved from various aspects. Such multi-input and multi-output design has been studied in terms of mathematical programming. However, the fact is that general designers on site tend to avoid using mathematically complicated theories.

In order to consistently develop high-quality products, it is essential to acquire as much knowledge as possible. For this purpose, design worksites demand design methodologies that allow all customers, designers, and professionals to participate in the design process. The demands for design methodologies from design worksites and customers have been classified below (in accordance with reference).[1]

2.1 Demands for system design technologies

(1) Multipurpose trade-off design using a system that has several design variables (design inputs) and achieves a balance between the evaluation indices of performance, cost, and robustness (design outputs).
(2) Robust design with a minimized number of calculations for even large-scale simulation requiring a long period of time for calculation.
(3) Risk management in coordination with design.
(4) Minimization of development tests.

2.2 Demands for base technology in design

(1) Seeking of design solutions from among the entire design space (or a desire to depart from pinpoint design reliant on experience).
(2) Minimization of backward design processes when it is necessary to change requirements and constraint conditions.
(3) Application of design methodologies from the initial design phase in which there is a high degree of freedom in design.
(4) Finding design solutions in a short time.
(5) Easy-to-understand design methodologies.

2.3 Demands for design knowledge

(1) Sharing of ground by designers and customers to select design solutions and calculate their associated risks (assurance of design transparency).
(2) Preservation of knowledge (explicit knowledge).

In order to satisfy the above designer demands, we propose the Total Design Management (TDM) as a simple and practical design methodology.

3. Total Design Management (TDM) [2]

In order to satisfy demands from the design worksites described in **Chapter 2**, we have developed a design methodology in this study to achieve ① multipurpose trade-off design, ② robust design, ③ risk management, ④ design transparency, and ⑤ practicality.

The basic concepts behind this technique are set based design and model based risk management, as shown in **Fig. 1**.

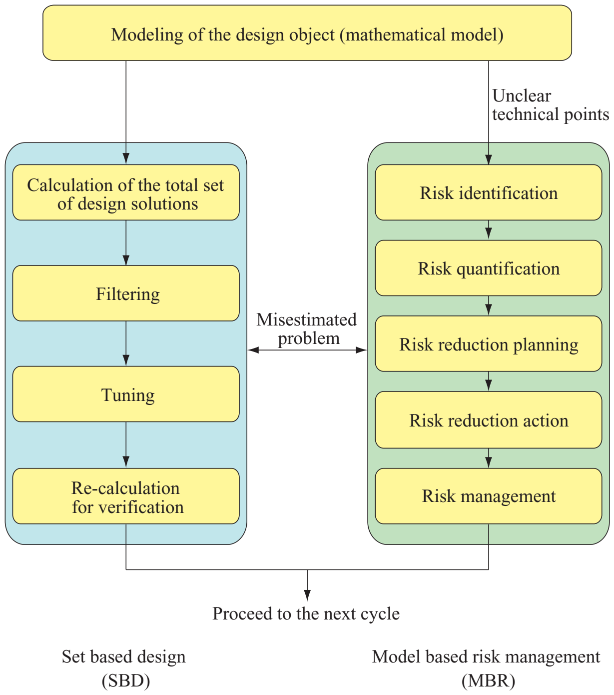


Fig. 1 Flowchart of total design management

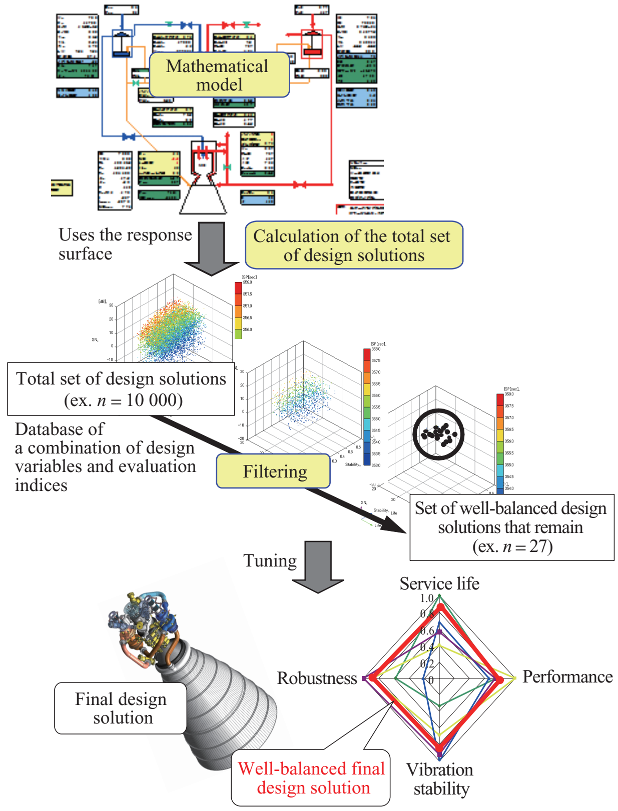


Fig. 2 Case of set based design (System design of rocket engine)

The former achieves a trade-off design from among a total set of design solutions originating in a common mathematical model, while the latter quantitatively expresses the confidence of designers in the applied mathematical model for development management.

3.1 Mathematical models

At actual design worksites, designers prepare mathematical models as relational expressions that enable estimation of performance, cost, and robustness indices from existing technologies, although some differences in the accuracy of estimations do exist. TDM begins with these mathematical models. The term "mathematical model" broadly refers to a group of mathematical formulae that convert design variables into evaluation indices, and includes physical equations as well as Computer-Aided Engineering (CAE) codes, experiment formulae, literature formulae, and empirical formulae.

3.2 Set based design

Set based design (hereinafter called SBD) is a design technique that allows designers and customers to voluntarily select desired design solutions from the total set of design solutions incorporating both design variables and evaluation indices.

Figure 2 is an example of SBD applied to a rocket engine. The specific procedure for SBD is described below.

3.2.1 Procedure

(1) Creation of the total set of design solutions

Firstly we calculate the total set of design solutions for the entire possible range of design variables using a mathematical model. If the mathematical model requires a very short calculation time, the Monte Carlo method can be applied directly to the mathematical model. If the mathematical model requires a long calculation time, as in the case of large-scale simulations, the response surface method (approximation method) should also be used.

(2) Filtering

A filtering method is used to identify design solutions that satisfy requirements and constraint conditions from among the total set of design solutions. Filtering is a characteristic technique of SBD. The process of narrowing down design solutions through filtering can easily be visualized using a scatter diagram.

(3) Tuning and re-calculation for verification

Based on a list of the filtered design solutions, designers consider the characteristics common to the design solutions. They then round off the numerical values as necessary and determine the combination of design variable values for the final design solution. If the response surface model has been used, the original mathematical model is used to make calculations to confirm reproducibility of evaluation indices.

3.2.2 Advantages

SBD is a design technique that places the greatest emphasis on the decision-making process between designers and customers by providing both parties with all the necessary information on design solutions, regardless of their positive or negative qualities. The advantages of SBD are described below.

(1) Multipurpose trade-off design

SBD enables simultaneous evaluation and

determination of several design variables and evaluation indices through filtering. Even when the number of evaluation indices increases, the time required for filtering remains almost the same (realization of the demand in **Section 2.1** (1)).

(2) Seeking of design solutions from among the entire design space

The greatest characteristic of SBD is the capacity to make a database of all selectable possible design solutions regardless of whether they satisfy the requirements and constraint conditions. The database can be used to promptly search for design solutions that are the closest to customer requirements while understanding the entire design space. If a customer requirement goes beyond existing technologies, designers are able to decide at an early stage to change the higher-level design policies, for example, by reviewing the requirement or introducing a new technology (realization of the demand in **Section 2.2** (1)).

(3) Minimization of backward processes

The entire design space is entered into a database. If any changes occur in the customer's requirements or constraint conditions, it is unnecessary to make calculations again using a mathematical model. Since it is necessary to redo filtering and subsequent processes only, SBD reduces backward processes (realization of the demands in **Sections 2.2** (2) and (3)).

(4) Design transparency

The search criteria for filtering are the same as the design policies used for selecting the final solution. Thus, design transparency can be assured by sequentially describing the search criteria (realization of the demands in **Sections 2.3** (1) and (2)).

(5) Easy to use and understand

SBD is an intuitive and easy-to-understand procedure congruent with designers' thoughts, and it can be executed to seek design solutions by anyone, without any need to use optimization algorithms that require advanced mathematical calculations. Design solutions can be found in a short time using the auto filter function of EXCEL© (realization of the demands in **Sections 2.2** (4) and (5)).

3.2.3 Comparison with existing design techniques

Figure 3 shows a comparison of SBD and an existing design technique. Compared with a typical conventional optimization design flow, the SBD design flow contains no feedback via a mathematical model when seeking design solutions that satisfy requirements and constraint conditions. This one-way design flow minimizes backward processes in the designing stage even when a change occurs in a requirement or constraint condition. In addition, the parallel implementation of the parametric computation is easily realized, and the computation time is reduced in inverse proportion to the number of computers employed.

SBD allows designers to freely select individual design techniques at each stage, so that their ranges of use and application can be increased according to the designers' ingenuity. To supplement areas that rely on the skills of a designer, SBD emphasizes design reviews, and is thus related to the model based risk management described in **Section 3.3**.

3.3 Model based risk management

The Model Based Risk management (hereinafter called MBR) is a risk management technique for identifying a designer's poor technical understanding of a formula, coefficient or input value of a mathematical model as a risk. The level of the risk is defined as the product of the degree of technological understanding and the degree of influence, and risk mitigating actions are taken to reduce the severity of the risk to a tolerable level or lower.

3.3.1 Procedure

(1) Risk identification

SBD enables acquisition of a total set of design solutions using a mathematical model. It uses the calculated values of the mathematical model rather than values derived from experiments, and differences in values are considered as technical risks. MBR employs the following policy to minimize the possibility of technical risks requiring extraction to be overlooked.

In many cases, when designers create mathematical models especially for new designs and in the initial design phase, they lack sufficient technical grounds for the formulae, coefficients, and input values of the mathematical models. However, if they wait for the mathematical models to be finalized and then carry out SBD, they cannot make project plans. In such cases, TDM requires designers to make only simple formulae, such as $y = ax + b$, as mathematical models. In the process of examining these models, it becomes clear in which of technical items the designers have no confidence. MBR requires designers to identify these items as risks and record them each time. In contrast, SBD allows designers to seek design solutions while being aware of the risks.

(2) Risk quantification

The severity of an identified risk is quantified by using the product of the degree of technological understanding and the degree of influence. It is common to define the severity of a risk as the product of the probability of occurrence and the degree of influence. However, in consideration of the fact that it is unsuitable to discuss the probability of occurrence for items to be developed in the future, MBR has introduced the degree of technological understanding, instead of the probability of occurrence, as an index to quantify designer confidence. Since the degree of technological understanding is to be evaluated subjectively, it should be generalized with the following internal structure.

Degree of technological understanding
= Degree of understanding of a phenomenon × Degree of the understanding of environmental conditions × Degree of verification

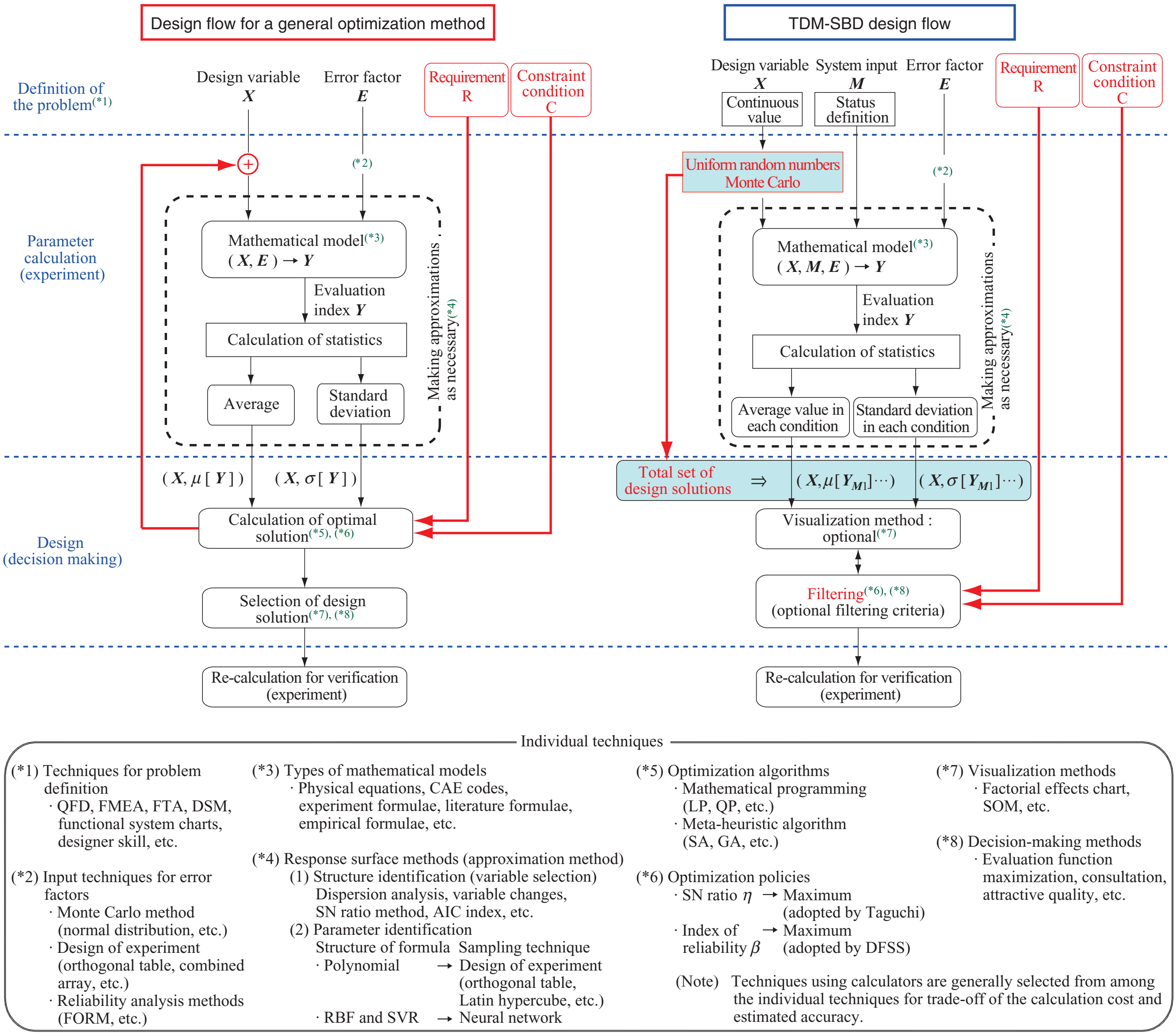


Fig. 3 Comparison of set based design with typical optimization method

In comparison to CAE, a phenomenon corresponds to a physical model, environmental conditions correspond to boundary conditions, and the degree of verification corresponds to the availability of correlation data. If a physical mechanism of a phenomenon is not understood, the risk of the degree of understanding of a phenomenon increases.

(3) Risk reduction plan

Element tests are designed to reduce each identified risk to a tolerable level before delivery. By implementing this step, the necessity for additional tests can be shared by the parties involved in a project, including the customers.

(4) Risk reduction action

Risk reduction actions are carried out according to the risk reduction plan. A case study on misestimated problems is prepared in case a risk cannot be reduced. Unforeseen problems are described in **Section 4.3**.

(5) Risk management

MBR summarizes the risks in a risk matrix table to enable uniform management of the risks. Designers register (1) Risk identification and (2) Risk quantification in the risk matrix table, while the entire project is responsible for making (3) Risk reduction plans. It is very important in system designing to summarize the risks, then distribute them again in the reduction planning stage (**Fig. 4**).

3.3.2 Advantages

MBR is a technique for identifying technical risks based on a mathematical model derived from the technical ambiguities of a designer, as well as for managing risk under the entire project. The advantages of MBR are described below.

(1) Element tests based on a mathematical model

Since it is obvious where a mathematical model is reflected in data derived from element tests conducted

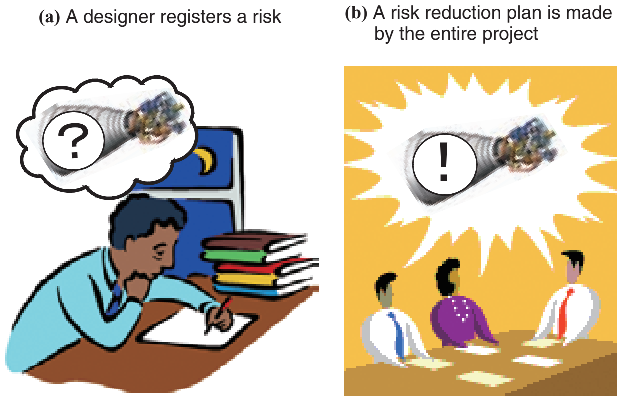
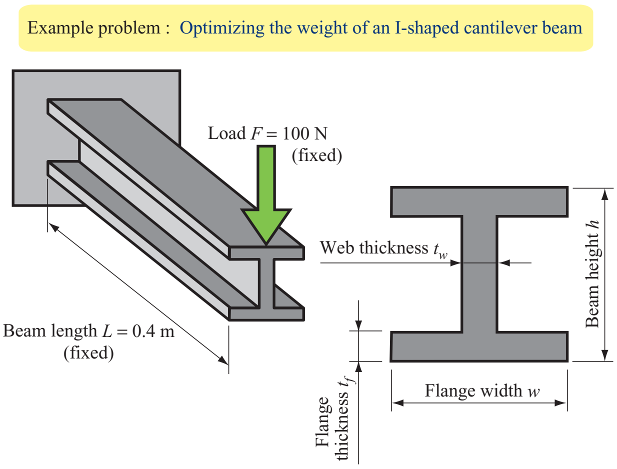


Fig. 4 Risk management in MBR



(Note) Problem : To obtain a solution offering well-balanced weight and robustness when constrained by the amount of bending.

Fig. 5 Cantilever beam problem

according to a risk reduction plan, the degree of importance of element tests can be technically determined based on the mathematical model (realization of the demands in **Sections 2.1** (3) and (4)).

(2) Coordination between designing and risk management

Since risks are identified online with design work, it is unlikely that they will be overlooked, which eliminates the need for other work solely for risk identification (realization of the demand in **Section 2.1** (3)).

(3) Enabling SBD to begin from the initial design stage

In cases where a technical ambiguity exists in a mathematical model at the initial design stage, designers can begin designing (SBD) by registering the technical ambiguity as a risk in MBR (realization of the demand in **Section 2.2** (3)).

(4) Preserving explicit knowledge derived from risk reduction actions and their results

Risks, reduction plans, and results recorded in a risk matrix have clear technical positioning and can be shared with customers and utilized for broadening knowledge within a company (realization of the demands in **Sections 2.3** (1) and (2)).

4. Example of multipurpose trade-off design using the cantilever problem[3]

This chapter mainly describes the SBD flow using the example of cantilever beam design.

4.1 Trade-off design of strength, weight, and robustness

This section describes a typical robust design problem involving a solving method for trade-off design of the strength and weight of a cantilever beam when error factors, such as production and operation errors, are evident.

Figure 5 shows the cantilever beam problem. To solve this problem, we consider ① evaluation indices, ② a mathematical model, ③ design parameters, and ④ errors, in this order. Evaluation indices are used for determining whether a system is good or bad. The evaluation indices in this case are the weight and the amount of bending. TDM places no restrictions on the number of evaluation indices, and we have added shearing stress in this study.

A mathematical model is a function for deriving the above evaluation indices. In this case, we use a mathematical formula that has been proven in the field of material engineering. However, proven mathematical formulae are not always available on actual design and development sites. When a designer has no confidence in a mathematical formula, precision can be improved through element tests outlined in the MBR procedure and risk reduction actions.

Arguments contained in the mathematical expression are divided into design parameters (which designers can control) and fixed values (which designers cannot control). At the same time, components that vary, regardless of the designer's intention, are summarized as errors. **Figure 6** shows the results of a problem defined in this way. The parameters that designers can voluntarily determine are four dimensions related to cross-section shapes. These parameters are also sources of errors because they involve manufacturing tolerance in production. In this study we define the appropriate errors for material and operational quality.

Next, we determine the range of the design parameters after due consideration of actual manufacturing capacity and application targets. We calculate the total set of design solutions according to the SBD procedure. We also use the response surface method on the assumption that it takes a long time to calculate the mathematical model. In other words, we assign the four design parameters to a L9 orthogonal table, which is the simplest sampling technique, and create nine sample shapes. We then virtually manufacture each model taking into consideration noise, and determine the averages and variations of the evaluation indices (**Fig. 7**).

Once we obtain the averages and variations of the individual evaluation indices for the nine types of cantilever beams with combinations of the four design parameters, we can determine a response surface expression (quadratic polynomial) having the four design parameters as arguments by using a simple scheme of a multi regression analysis (**Fig. 8**).[4] We can derive the following robustness indices from the averages and variations.

(a) Design parameters

(Variables with highly sensitive evaluation indices and variables that can be freely determined by designers)

Name of variable	Unit	Initial value
Flange width : w	m	0.030
Beam height : h	m	0.070
Flange thickness : t_f	m	0.005
Web thickness : t_w	m	0.004

(b) Mathematical model

$$m = \rho L \{2(wt_f) + t_w(h - 2t_f)\}$$

$$I = \frac{wh^3 - (w - t_w)(h - 2t_f)^3}{12}$$

$$v = \frac{FL^3}{3EI}, \quad \sigma = \frac{FL}{I}\left(\frac{h}{2}\right)$$

(c) Errors

(disturbance = noise factor)

Name of variable	Unit	σ	Optimization policy
Flange width : w	m	1.67E–04	General manufacturing tolerance/3
Beam height : h	m	2.33E–04	Same as above
Flange thickness : t_f	m	8.33E–05	Same as above
Web thickness : t_w	m	8.33E–05	Same as above
Young's modulus of beam : E	Pa	5%	Material quality
Load : F	N	5%	Operation quality

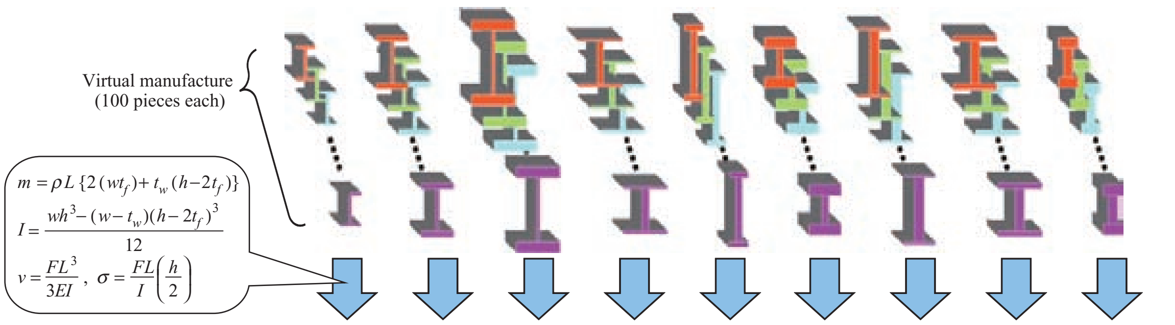
(d) Evaluation indices

(Numerical values that express equirements and failure modes (to be considered first))

Name of variable	Unit	Optimization policy
Weight : m	kg	Minimum positive value
Maximum bending : v	mm	Minimum positive value ($\leqq$ 0.012)
Maximum shearing stress : σ	MPa	5.0

(Notes) ρ : Density (kg/m^3)
L : Beam length (m)
I : Second moment of area (m^4)

Fig. 6 Definition of cantilever beam problem



Evaluation indices with disturbance

	Result of calculation	Unit	1	2	3	4	5	6	7	8	9
S	μ Weight : m	kg	0.319	0.819	1.536	0.726	0.986	1.416	1.056	1.391	1.455
	μ Maximum bending : v	mm	0.446	0.103	0.041	0.165	0.085	0.092	0.107	0.103	0.077
	μ Maximum shearing stress : σ	MPa	17.533	4.800	2.186	7.663	4.543	3.687	5.679	4.082	3.582
N	σ Weight : m	kg	0.017	0.020	0.026	0.025	0.020	0.021	0.025	0.025	0.018
	σ Maximum bending : v	mm	0.046	0.007	0.002	0.013	0.006	0.007	0.009	0.007	0.005
	σ Maximum shearing stress : σ	MPa	1.408	0.260	0.113	0.522	0.215	0.187	0.349	0.213	0.201

(Notes) S : Average
N : Variation (standard deviation)

Fig. 7 Calculation of average and variation with virtual manufacturing

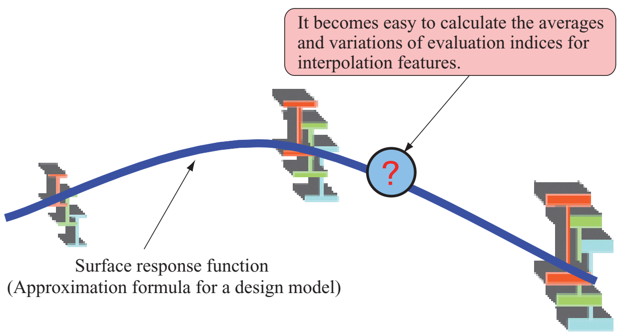


Fig. 8 Response surface model of average and variation

· SN ratio = 20 log (average/variation)
· Index of reliability β = (average – criterion) /variation

By using this response surface expression, we can instantly determine the averages and variations of the evaluation indices for production at a certain design point, or the robustness indices obtained from combinations of the averages and variations. Thus, using the Monte Carlo method, we combine various design parameters and acquire the total set of design solutions. This work can be completed in a short time using a response surface expression, even when a database of 10 000 items is created.

A set of design solutions selected from among the 10 000 design solutions in the database are plotted in the upper right graph of **Fig. 9** with certain requirements assigned to the four axes. The space shown in the graph corresponds to the space of all solutions in this cantilever beam problem. Solutions, such as the one with the lowest weight and the one with smallest bending, are extracted from this set of design solutions and shown on the radar chart. For example, the solution with the lowest weight has a large amount of bending and a high stress, indicating that this design has no allowance. We define the robustness index against the generated stress as β, and filter the design solutions to select ones that demonstrate robustness against disturbance. Since this series of filtering rules becomes the actual design policy, the filtered solutions are reproducible at a level of practical application.

In the beginning we had a total set of 10 000 design solutions, which we narrowed down according to various constraint conditions and requirements. Finally, when we reached an appropriate subset of design solutions, we finished filtering and performed tuning, for example, by rounding fractions in due consideration of subset attributes. A design solution selected in this way has the characteristics shown with the red line in the radar chart in **Fig. 9**. This solution is not the best in terms of the requirement for lightness in weight of this problem, but it improves upon other characteristics by slightly sacrificing performance (weight). This is considered excellent in terms of practical product design.

4.2 Trade-off design between manufacturing tolerances and costs

Manufacturing tolerances should be as small as possible from the perspective of performance design, but people on the manufacturing side generally demand rough tolerances for easy manufacturing. For this reason, there are frequent trade-offs between tolerance requirements and manufacturing costs in actual design worksites. Usually the key to finding a local compromise depends on how much ground the design side will relinquish to the manufacturing side in relation to limits on manufacturing capacity. This section describes the procedure for a trade-off design that achieves a balance between cost and tolerances (magnitude of error factors) while maintaining quality (variation) by utilizing the virtual sensitivities of manufacturing tolerances and costs.

When tolerance requirements become severer, manufacturing slows down and products require screening, which results in increased manufacturing costs. The shape of this tolerance-cost curve varies depending on the know-how of each manufacturer (**Fig. 10**). It is thought that more severe tolerance results in improved product quality. If quality improvement can be connected with indices measured in units of money, such as market profit or loss, achievement of an appropriate tolerance definition that is well-balanced with manufacturing costs can be expected.

Let δx_i be the tolerance of the manufacturing dimension x_i (= beam height, flange thickness, flange width or web thickness).

When the manufacturing cost (C) and the market loss (L) are determined by this tolerance definition, they can be expressed as follows :

$$C = C\,(\delta x_i, \cdots, \delta x_4) \quad \cdots\cdots (1)$$

$$L = L\,(\delta x_i, \cdots, \delta x_4) \quad \cdots\cdots (2)$$

The sensitivity of market loss can be substituted by the

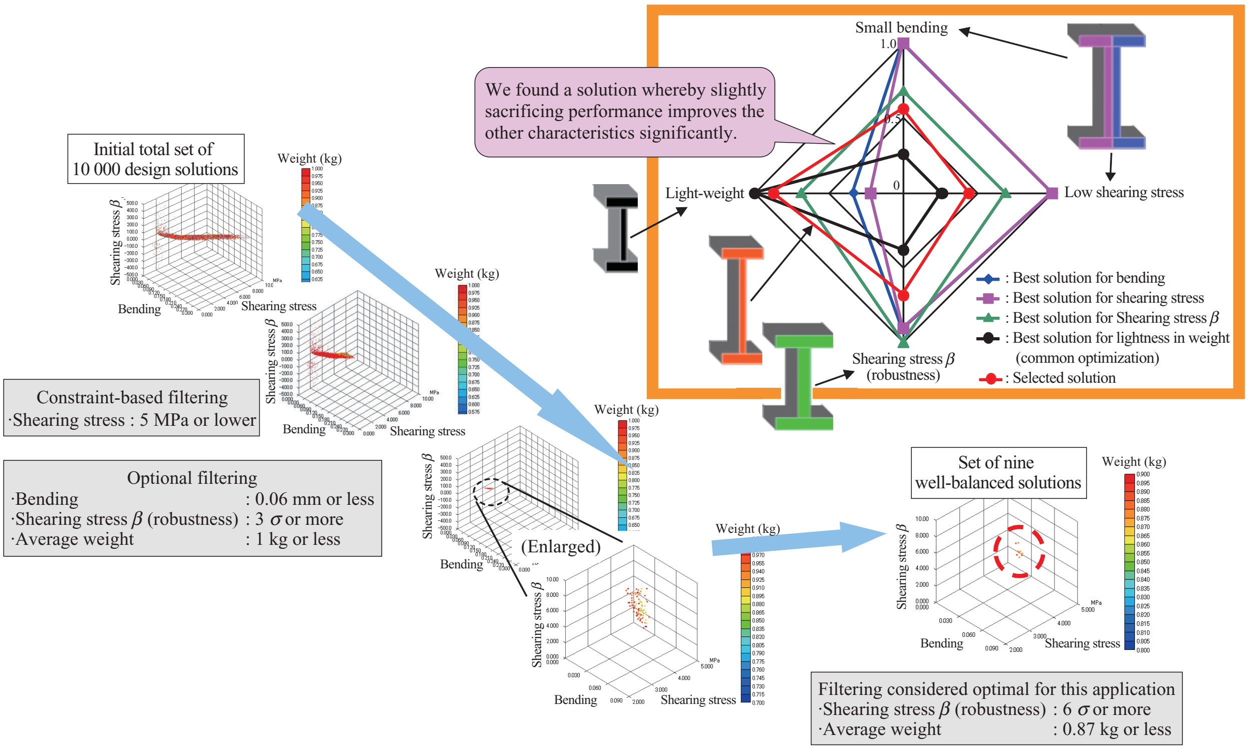


Fig. 9 Filtering

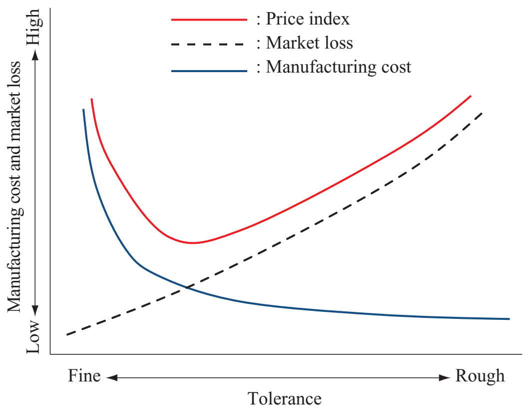


Fig. 10 Relationship between tolerance and design point

index of reliability (β) (product quality) as an evaluation index and expressed as follows :

$$\frac{\Delta L}{\Delta \delta x} = \frac{\partial L}{\partial \beta}\frac{\partial \beta}{\partial \delta x} \quad \cdots\cdots (3)$$

Equation (4) indicates the sensitivity of product quality (quality control information) and Equation (5) indicates the sensitivity of quality tolerance (design information).

$$\frac{\partial L}{\partial \beta} \quad \cdots\cdots (4)$$

$$\frac{\partial \beta}{\partial \delta x} \quad \cdots\cdots (5)$$

When the manufacturing cost (C) is added, the sensitivity of manufacturing cost (manufacturing information) is expressed as follows :

$$\frac{\partial C}{\partial \delta x} \quad \cdots\cdots (6)$$

The number of units sold (N) for mass-produced products affected by product quality and market sensitivities (sales information) is expressed as follows :

$$\frac{\partial N}{\partial \beta} \quad \cdots\cdots (7)$$

In this way, where cost is considered in the tolerance design, the design points should be determined through coordination between the design and manufacture, as well as by introducing information from a quality control or sales department. Definition of the problem shown in **Fig. 6** can be rewritten to **Fig. 11**. It is evident that if the information on manufacturing costs and market loss can be formulated, the tolerance can be reflected in the dimension design in the same procedure as described in **Section 4.1**.

4.3 Design with adjustable factors (misestimated problems)

It is common in short-time development for design calculations (or manufacturing drawings) to be made alongside element tests. In such cases, when the results of element tests conducted afterwards significantly deviate from the initial predicted values of the mathematical model used for designing, the deviations become a development risk (project risk). These are known as misestimated problems in TDM. If components that allow for adjustment

(a) Design parameters

Name of variable	Unit	Minimum value	Median value	Maximum value
Flange width : w	m	0.03	0.04	0.05
Beam height : h	m	0.06	0.07	0.08
Flange thickness : t_f	m	0.001	0.003	0.005
Web thickness : t_w	m	0.001	0.002 5	0.004
Flange width tolerance : δ_w	m	0.000 5	0.002 75	0.005
Beam height tolerance : δ_h	m	0.000 5	0.002 75	0.005
Flange thickness tolerance : δt_f	m	0.000 5	0.002 75	0.005
Web thickness tolerance : δt_w	m	0.000 5	0.002 75	0.005

(b) Calculation formulae

$$m = \rho L\{2(wt_f) + t_w(h - 2t_f)\}$$

$$I = \frac{wh^3 - (w - t_w)(h - 2t_f)^3}{12}$$

$$v = \frac{FL^3}{3EI}\ , \quad \sigma = \frac{FL}{I}\left(\frac{h}{2}\right)$$

$$C + L = C(\delta_w, \delta_h, \delta t_f, \delta t_w) + L(\delta_w, \delta_h, \delta t_f, \delta t_w)$$

(c) Errors

Name of variable	Unit	σ	Optimization policy
Flange width : w	m	δ_w	General manufacturing tolerance/3
Beam height : h	m	δ_h	Same as above
Flange thickness : t_f	m	δt_f	Same as above
Web thickness : t_w	m	δt_w	Same as above
Young's modulus of beam : E	Pa	5%	Material quality
Load : F	N	5%	Operation quality

(d) Evaluation indices

Name of variable	Unit	Optimization policy
Weight : m	kg	Minimum positive value
Maximum bending : v	mm	Minimum positive value ($\leqq$ 0.012)
Maximum shearing stress : σ	MPa	5.0
Total loss : $C + L$	Yen	Minimum positive value

(Notes) ρ : Density (kg/m^3)
L : Beam length (m)
I : Second moment of area (m^4)

Fig. 11 Definition of cantilever beam problem in consideration of tolerance of deviations can be integrated into a product in advance, especially during long-term development of large-scale equipment such as airplanes and spacecrafts, it becomes possible to achieve robust design against development risks.

As a familiar example, this type of design applies to the small balancers attached to automobile tires. It is generally more logical to define a certain tolerance and make adjustments to the balancers, rather than applying severe tolerances to the shafts, wheels, and rubber to make well-balanced tires that require no adjustment, or by increasing the shaft diameter to make vibration-proof tires. This approach achieves a balance between the magnitude of the adjustable factor and other evaluation indices (such as strength, weight, variation, and cost).

In the case study on the I-shaped beam in **Section 4.1**, the primary requirements are its weight and bending. Let us assume a case where beams that are heavier than expected are produced for some reason. The following measures can be implemented to enable use of the heavy beams rather than disposing of them.

① Provision of a high-level system (a system assembled using this type of beam) incorporating a procedure for combining heavy and light beams
② Provision of design components with adjustable weights

Deviations in weight should be absorbed in the system in the former measure, but we will adopt adjustment on a component level in this case.

Except in cases where the components have already been optimized and there is no room left for adjustment, the components are unlikely to have optimized shapes due to manufacturability or costs. The beam is initially assumed to have an I-shaped cross section and thus there is room for adjustment. The beam should be tapered with respect to load distribution, but a tapered shape should not be a prerequisite from the beginning in terms of the manufacturing cost. For this reason, we define an adjustable factor (cutting stock in this case) in advance as an individual measure against a component where a problem occurs (**Fig. 12**). Needless to say, this increases the cost.

TDM incorporates dimension A into design parameters as an adjustable factor. The evaluation indices are the weight difference and the bending difference according to the value of A. It is not yet possible to define a unique condition by which dimension A is selected as the adjustable factor. We need to select the most appropriate method by performing Failure Mode and Effect Analysis (FMEA) and examining failure scenarios, in response to the problem in question. As shown in **Fig. 13**, we can initially determine the dimension as an adjustable factor by incorporating weight saving measures, increase in bending, and raising the cost due to additional work.

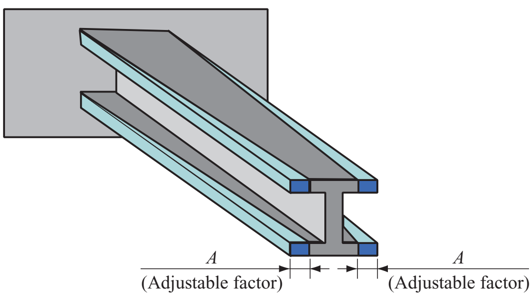


Fig. 12 Cantilever beam problem in consideration of adjusted factor

Even in cases where an adjustable factor is taken into consideration, the problem remains the same as that in the original dimension design, and the same procedure can be used to determine a solution.

5. Example of application to an actual product (Impeller design for avoiding resonance)(5)

When designing compressor impeller vibration, the impeller shapes are tuned so that their natural frequency does not match the frequency caused by rotation, while fluid performance is maintained. Impellers are available in different sizes for different purposes. Each impeller is conventionally examined by a designer to determine the tuning shape.

This chapter describes how we utilized the SBD technique to obtain a desirable shape without redoing the design at each tuning.

5.1 Definition of the problem

This impeller has two design parameters : the diameter and the blade height, and each type of impeller is required to avoid resonance. To achieve this, we defined the following three new design parameters (tuning parameters) : the impeller blade length, the fillet roundness, and the disc thickness, as shown in **Fig. 14**, in order to determine a shape that does not cause resonance. We selected the detuning ratio given by the following formula as the evaluation index and adjusted it to exceed the threshold where no resonance was caused.

$$\text{Detuning ratio} = \frac{\text{natural frequency}}{\text{rotation frequency}} - 1 \quad \cdots\cdots\cdots\cdots\cdots (8)$$

We made Finite Element Method (FEM) calculations using an experimental design and created a mathematical model using the response surface method, in order to determine the natural frequency of the impeller in the entire range of design parameters. **Figure 15** shows a flowchart of the considerations described in **Section 5.2**.

5.2 Creation of the mathematical model

In order to determine the calculation points for creating a response surface, we assigned a total of five parameters : two design parameters and three tuning parameters for avoiding resonance, to a L27 orthogonal table. Next we determined the natural frequencies of the 10th to 80th order according to assignment in this orthogonal table using commercially available FEM analysis software.

We created a response surface for each order, which is given by the following second-order polynomial :

$$f = \beta_0 + \sum \beta_i x_i + \sum \beta_{ii} x_i^2 + \sum \beta_{ij} x_i x_j \quad \cdots\cdots\cdots\cdots (9)$$

(a) Design parameters

Name of variable	Unit	Minimum value	Median value	Maximum value
Flange width : w	m	0.03	0.04	0.05
Beam height : h	m	0.06	0.07	0.08
Flange thickness : t_f	m	0.001	0.003	0.005
Web thickness : t_w	m	0.001	0.002 5	0.004
Flange width tolerance : δ_w	m	0.000 5	0.002 75	0.005
Beam height tolerance : δ_h	m	0.000 5	0.002 75	0.005
Flange thickness tolerance : δt_f	m	0.000 5	0.002 75	0.005
Web thickness tolerance : δt_w	m	0.000 5	0.002 75	0.005
Cutting stock : A	m	0	1.5	3

(b) Calculation formulae

$$m = \rho L\{2(wt_f) + t_w(h - 2t_f)\}$$

$$I = \frac{wh^3 - (w - t_w)(h - 2t_f)^3}{12}$$

$$v = \frac{FL^3}{3EI}, \quad \sigma = \frac{FL}{I}\left(\frac{h}{2}\right)$$

$$C + L = C(\delta_w, \delta_h, \delta t_f, \delta t_w) + L(\delta_w, \delta_h, \delta t_f, \delta t_w) + Ca(A)$$

$$\Delta m = 0.8\, t_f A \rho$$

$$\Delta v = func(v, A)$$

(c) Errors

Name of variable	Unit	σ	Optimization policy
Flange width : w	m	δ_w	General manufacturing tolerance/3
Beam height : h	m	δ_h	Same as above
Flange thickness : t_f	m	δt_f	Same as above
Web thickness : t_w	m	δt_w	Same as above
Young's modulus of beam : E	Pa	5%	Material quality
Load : F	N	5%	Operation quality

(d) Evaluation indices

Name of variable	Unit	Optimization policy
Weight : m	kg	Minimum positive value
Maximum bending : v	mm	Minimum positive value (≦ 0.012)
Maximum shearing stress : σ	MPa	5.0
Total loss : $C + L$	Yen	Minimum positive value
Weight saving : Δm	kg	Maximum positive value
Increase in bending : Δv	m	Minimum positive value

(Notes) ρ : Density (kg/m^3)
L : Beam length (m)
I : Second moment of area (m^4)
Ca : Cost caused by adjustment

Fig. 13 Definition of cantilever beam problem in consideration of adjusted factor

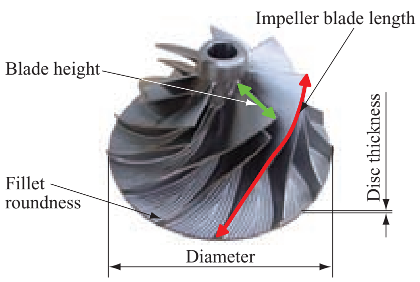


Fig. 14 Design parameters

Where f is the natural frequency, x is the design parameter, and β is the coefficient of the response surface. We adopted the interaction term for the final term only when necessary.

5.3 Creating the total set of design solutions

We obtained a total set of detuning ratios in the entire range of each design parameter by using the response surface. To determine the set of design solutions, we divided the range of each design parameter into approximately 100 parts and made exhaustive calculations across the entire range.

The five design parameters adopted in this case study are shape-related dimensions and involve manufacturing errors. Therefore, we evaluated the detuning ratios as the worst values allowing for fluctuations caused by drawing tolerances.

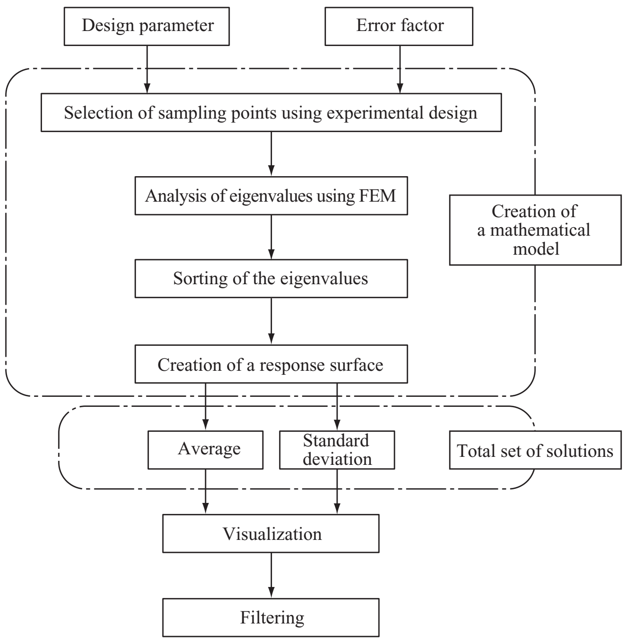


Fig. 15 Flowchart of impeller design

5.4 Filtering

Figure 16 shows the detuning ratios in the nominal state (the basic shape before tuning) and the detuning ratios after tuning. We determined the detuning ratios in the nominal

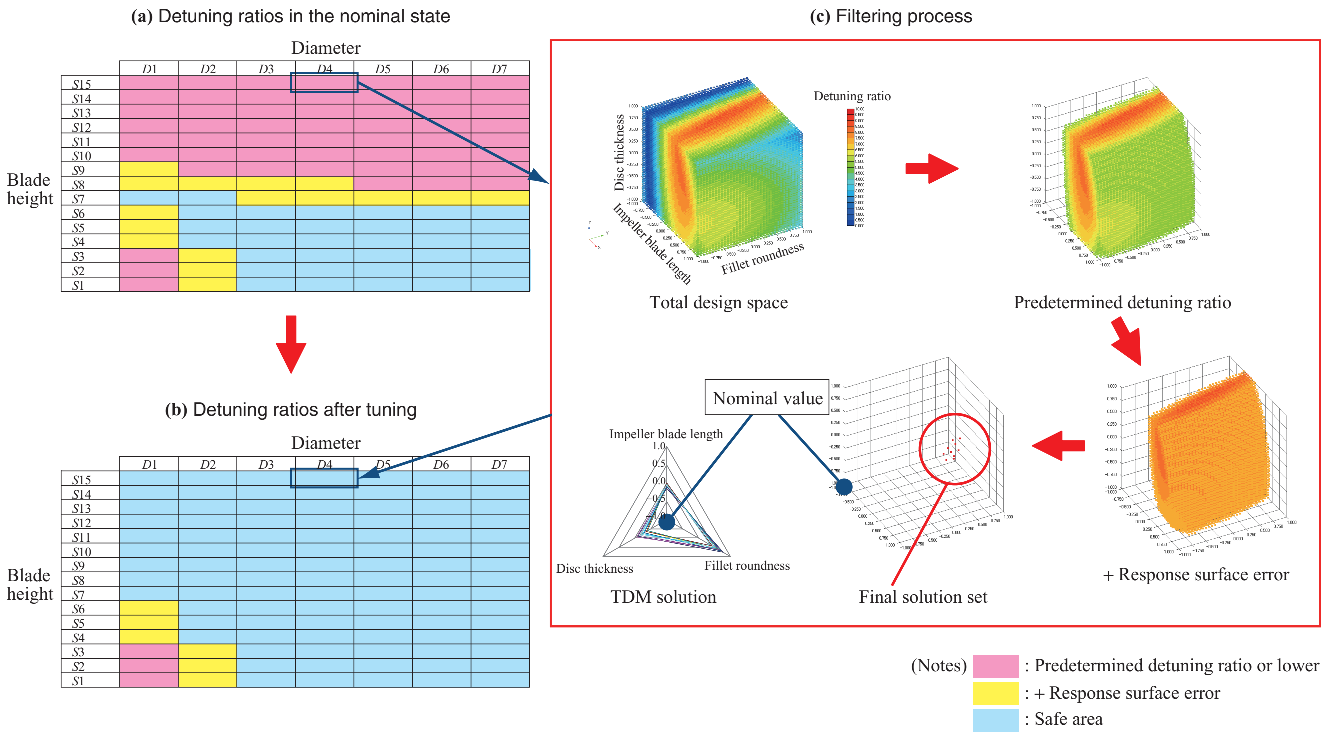


Fig. 16 Example of results of impeller design

state by incorporating the diameter and blade height of each type of impeller while fixing the three tuning parameters in the nominal state. In regards to the detuning ratios after tuning, we filtered the total set of design solutions that have the shape of each impeller type, and identified the design solutions with the desired detuning ratios.

5.5 Design results

Figure 16-(a) shows the detuning ratios in the nominal state, **Fig. 16-(b)** shows the detuning ratios after tuning, and **Fig. 16-(c)** shows the filtering process for the impeller shape combining the diameter (*D*4) and the blade height (*S*15). The red areas in the tables indicate insufficient detuning ratios, the blue areas indicate sufficient detuning ratios, and the yellow areas indicate margins for the precision of the response surface. Filtering was applied to individual cells in the tables (for example, a filtering process was carried out for impellers that belong to the cell with diameter *D*4 and blade height *S*15). In this case, filtering was applied to 105 types of impellers, and instant simple macro filtering was possible.

As a result of filtering, we obtained solutions having the shape of the selected tuning parameters as shown in the radar chart in **Fig. 16-(c)**. The final solution set indicates that the fillet roundness factor should be high in this case.

Figure 16-(b) indicates that tuning increases the areas that exceed the standard detuning ratio. The red and yellow cells in the lower left-hand corner of **Fig. 16-(b)** indicate that it is not effective to adjust the tuning parameters in the current range. It clearly indicates the need to implement other measures for impellers in this area, such as increasing the range of a parameter.

As mentioned above, designers conventionally examine each type of product through trial and error by making individual FEM calculations. However, we used the SBD technique to improve the design process in this case study, and obtained the shape for avoiding resonance for all types of impellers simply by systematically making 27 FEM calculations.

6. Conclusion

This study demonstrates a systematic design methodology that is both simple and suitable for practical application in design worksites, and which aims to achieve a multipurpose trade-off design, robust design, risk management, design transparency, and practicality.

This design methodology consists of Set Based Design (SBD) and Model Based Risk management (MBR).

This methodology is not intended as an automatic design tool that allows a designer to design a product by just pushing one button, but rather, it is intended as a system to aid in design or similar processes, and functions like a common language to support smooth decision making throughout the entire project.

As described in the two application examples, a design process using set based design differs greatly from conventional design processes. That is to say, the SBD process significantly reduces the design time by searching for design solutions that satisfy the design requirements, rather than determining solutions each time. This methodology is expected to work more effectively when used in combination with the recently accelerating IT automation technologies for design tools.

In order to improve design quality, it is important to gather the wisdom of many in the initial design phase, during which there is a high degree of freedom in design. Model based risk management is designed to enable front loading of the design and development process by positively dealing with the technical ambiguities of each designer.

We will expand this study into the area of product planning and morphological design as an upstream design concept, in order to improve design methodology for product value creation.

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