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Procedia CIRP 26 (2015) 76 – 81

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12th Global Conference on Sustainable Manufacturing

Set-based design method for multi-objective structural design with conflicting performances under topological change

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Abstract

In car manufacturing, sustainable structural design with multiple conflicting objectives like weight reduction for less CO2 emission, strength and rigidity is essential. This research focuses on topological optimization method with which greater weight reduction is expected to be achieved. In view of the application of preference set-based design (PSD) method, topologically satisfied design is considered. We applied PSD method to the design of topological model. This study indicates the efficacy of PSD method to topological design problems including weight reduction aspect.

Peer-review under responsibility of Assembly Technology and Factory Management/Technische Universität Berlin.

Keywords: *structural design; weight saving; optimization; topological design; set based design*

1. Introduction

In the current industrial market, there is a strong emphasis on environmental issues concerning global warming. As an example of industrial development, automobile development is being promoted with the higher priority on body weight reduction, which directly reduces CO2 emissions. At the same time, the other structural design factors, related to strength, rigidity and so on, are considered. These structural factors and the weight reduction are conflicting structural performances each other. It is required to pursue a design solution which satisfies simultaneously multi-objective performances including conflicting requirements.

In general, to seek theoretically optimized structure which satisfies structural performances is called structural optimization. In structural optimization, there are three types of approaches for optimization object such as (1) size optimization, (2) shape optimization and (3) topology optimization [1]. The previous researches on topology optimization mainly cover rigidity, strength, vibration and lightness. Researches to attain multi-objective optimization with the combination of these performances have been also conducted [1].

On the other hand, the authors developed the idea of set-based design method [2,3], and then proposed a practical method, called Preference Set-Based Design (PSD) Method, as a method to find set (interval) solutions of multiple design variables meeting a common space of multi-objective performances [4,5]. The proposed method is different from the previous methods obtaining the minimum point value exactly or approximately in the optimization process. The proposed method has been applied to practical structural problems of static strength, crash strength, rigidity, acoustic absorption and sound insulation, as well as energy consumption, CO2 emission, cost and upgrade possibility in product life cycle. [6, 7, 8, 9,10], but not to topological structural problem.

The purpose of the present research is to present the way of thinking on topological structural design by PSD method and to try to obtain set (interval) solution that satisfies simultaneously multi-objectives, including topological aspect, through solving a structural model problem.

Peer-review under responsibility of Assembly Technology and Factory Management/Technische Universität Berlin.
doi:10.1016/j.procir.2014.07.080

2. Structural optimization and satisfaction

2.1. Studies on structural optimization

Weight reduction of structure is an environmentally concerned issue related to structural design. In category of optimization method for structural design, there are two ways to seek the minimum (or maximum) value of the objective function under constrained conditions.

(a) Way to seek the exact value mathematically (called mathematical programming).

(b) Way to seek numerically or heuristically the engineering value based on FEM calculation, sensitivity analysis and/or others.

In topological optimization method related to category (a), Homogenization Method [11,12], Density Method [13, 14] , Level Set Method [15], Grand Structure Method [16], and so on were proposed.

Examples of application of these methods involve the problems of rigidity, natural frequency, and heat conduction, and a problem with two objectives of rigidity and natural frequency under the constraint of volume. These methods give possibilities of solutions beyond what designers expect by the results of material distribution calculation. One of the methods related to category (b) is Fully Stressed Design [17] that is applied to many practical problems. The optimization method in categories, (a) and (b), tries to give a minimum point value of objective function.

On the other hand, at the early phase of design, engineering uncertainties such as designer's imprecise discretion, changes in environmental design conditions and so on, have great importance. The treatment for the uncertainties is necessary even in the design of structural optimization. In the case of category (b), the process to seek a solution point is iterative, and then there is no theoretical guarantee that the solution converges.

2.2. Multi-objective satisfaction by PSD Method

For the early phase design mentioned above, design solution expressed in terms of point value of design variables cannot easily and effectively handle the design uncertainties. In PSD method, instead of the point value, set (interval) solution of design parameters that satisfies multi-objective performances are introduced for handling the uncertainties.

The authors have applied PSD Method to various actual structures and material designs [5, 6, 7, 8, 18]. For example, in the case of a structural design of car doors [5], the set solutions of five design variables satisfying eight performances (strength, panel rigidity, torsional rigidity, crash energy absorption, cost, weight as well as energy consumption and CO2 emissions in product life cycle) are obtained simultaneously.

From the view of optimization-like point, in the previous studies by PSD method, the design problems of size and shape of product for multi-objective satisfaction design have been treated. Satisfaction design is defined as design to give the set (interval) solutions of design variables that satisfy the set (interval) of requirement performances presented by designers.

In order to perform the topological structural design, the definition of topological design by PSD method is necessary and the way of thinking for the definition is shown by the following two points.

1) The idea of the introduction of structural element, like hole, cross member, stiffener and so on, to design plan, is fixed in advance.

2) Under the introduction, the number of the element is set to be design variables for the topological design by PSD method.

According to the two points, an actual model problem with multi-objective including topological aspect is solved by PSD method. The method and solution of the problem are in Section 4.

3. Preference Set-based Design (PSD) Method

The representation and manipulation of engineering uncertainties, mentioned in Section 2, have great importance at the early phase of design. On the other hand, the idea of set-based approach [2,3] demonstrates the feature in the multiple-objective design problems. The authors have investigated the set-based design method with designer's preference (we call preference set-based design (PSD) method) [4,5,6]. The present Section outlines PSD method.

Concept and procedure of preference set-based design method is shown in Fig. 1. Each region of design space (set) for multi-objectives of design is narrowed by the concept of the preference and robustness of the design solution. PSD method consists of three steps: set representation, set propagation, and set narrowing which are described in the following.

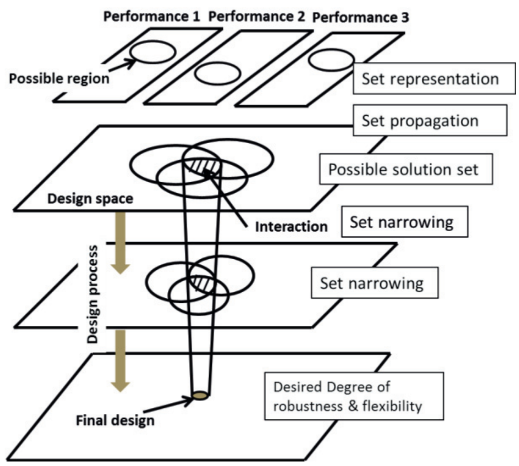

Fig. 1. Concept and procedure of preference set-based design.

Set representation with designer's preference

To capture the designer's preference structure on the set, both an interval set and a preference function defined on this set, which is called the "preference number (PN)", are used. The PN is applied to specify the design parameters and performance requirements, shown in the Fig. 2. The interval set at the preference level of 0 is the allowable interval, while the interval set at the preference level of 1 is the target interval.

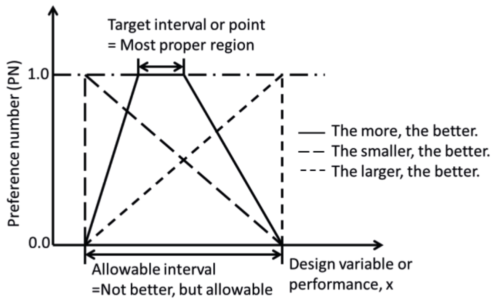

Fig. 2. Representation of designer’s preference.

Set propagation

The set propagation method that uses the extended interval arithmetic (Interval Propagation Theorem [19]) or the optimization method like Particle Swarm Optimization Method [20, 21]) at each level of preference value is proposed to calculate the possible performance spaces which are achievable by the given initial design space. Then, if all the performance parameter spaces have the common spaces (i.e., acceptable performance spaces) between the required performance spaces and the possible performance spaces, there is a feasible subspace within the initial design spaces.

Set narrowing

If the common spaces between the possible performance spaces and the required performance spaces exist, there are feasible design subspaces within the initial design space. However, the remaining subspaces are infeasible subspaces. Then, the next step is to narrow the initial design space to eliminate infeasible or unacceptable design subspaces, thus resulting in feasible design subspaces. The design preference and robustness are evaluated to eliminate infeasible design subspaces.

Design metric for design preference and robustness

In engineering design, designer's design preference and the robustness of design solution are greatly important. The high design preference means there are large feasible design subspaces within the designer’s required performance spaces. On the other hand, design robustness includes the accuracy, convergence and stability of design. In the previous study [22] , measuring indices for these are proposed as NDPI, NDAI, NDCI and NDSI for preference, accuracy, convergence, and stability, respectively. To provide the relative effectiveness among design alternatives, these measures need to be normalized with respect to the maximum or minimum value of each index. The present study can measure the preference and robustness, what is called the preference and robustness index (PRI), of possible distributions by combining NDPI, NDAI, NDCI and NDSI. The PRI is defined by

$$PRI = \left((NDPI)^{\omega_P} \times (NDAI)^{\omega_A} \times (NDCI)^{\omega_C} \times (NDSI)^{\omega_S} \right)^{\frac{1}{\omega_P + \omega_A + \omega_C + \omega_S}} \quad (1)$$

where ω_x (x is p, A,C, and S) is weighting factor for each index.

Since more than one performance requirement are commonly considered in the multi-objectives design problem, the PRIs for multiple performances need to be aggregated, what is called aggregated PRI (APRI), to provide the effectiveness of the design alternatives with respect to all performances. A family of parameterized aggregation functions is used for the multi-objective decision making problem, based on the weighted root-mean-power,

$$APRI_S = \left(\frac{\omega_1 (PRI_1)^S + \cdots + \omega_N (PRI_N)^S}{\omega_1 + \cdots + \omega_N} \right)^{\frac{1}{S}} \quad (2)$$

where ω_i (i=1, ・・,N) is the weighting factor of ith PRI (PRI_i). By varying the parameter s, equation (2) produces some well-known averaging operators, minimum, harmonic mean, geometric mean, arithmetic mean, quadratic mean and maximum. The highest APRI measure selects an optimal one from a few feasible design subspaces, which are more preferred by the designer and provide better design robustness.

4. Problem Setting

In the present study, under topological design change of structure, the availability of PSD method for multi-objective structural design with conflicting performances, including weight saving, is considered. The topological design is based on the change of number of structural element. As an example of the change of the number of structural element, a chassis structure of a truck, shown in Fig. 3, is referred. In real truck structures, the number and the positions of the structural member (called “cross member”) which link the frames of both sides varies depending on a truck maker and a specification. A simplified model of chassis structure, shown in Fig. 4, is considered.

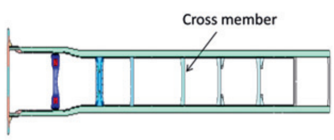

Fig. 3. Chassis frame of a truck.

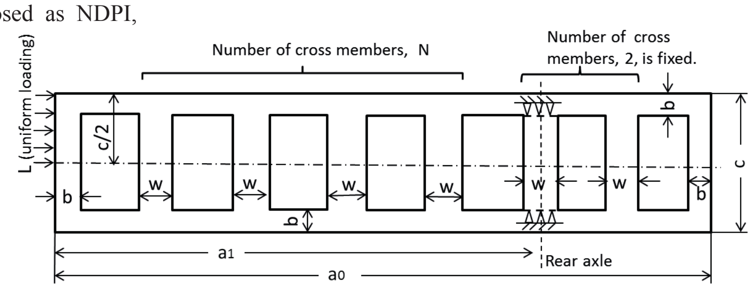

Fig. 4. Topological structural model.

4.1. Topological structure model and finite element analysis

This research does not focus on the actual structure of a chassis frame of a truck, but rather focuses on the basic structure with number change of cross member as one of design parameters for considering the availability of PSD method. To do so, we discuss simplified 2-dimensional model, shown in Fig.4, in structure analysis. The structure is elastic body (the material is steel). In Fig.4, design parameters are number (N) and width (W) of cross members in the left side of a constrained member and thickness (T) of whole structure. The width of the all cross members located uniformly are the same within each model. The width (b) of the outer frame of the model are fixed (b=50mm). The multiple performances are total mass weight (P), maximum von Mises stress (σ_{max}), and rigidity (G). The maximum von Mises stress and rigidity are obtained by the result of elastic FEM analysis. The finite calculation is carried out under the uniform loading (L) in the x-direction in the section of length (c/2) and constraint conditions, imaging off-set frontal collision of a truck, shown in Fig.4. Rigidity is defined as average displacement against the uniform loading. Weight is defined as total mass volume, because the material of model structure is one kind, namely, steel. Weight reduction and maximum stress (or rigidity) performances conflict with each other. Finite element type used is triangular element. An example of number of finite elements of the structure including cross member is 6572.

4.2 Application result of PSD method

To use PSD method, approximation equations (response curved surface) which show the relations between required performances and design parameters (variables) are needed to be obtained. Von Mises stress and rigidity are obtained from the results of 2-dimensional FEM calculation, and Mass (volume) is calculated arithmetically. To express each calculation result of performances, three levels for the value of design parameters (shown in Fig. 5,6 and 7) are adopted. There are three design parameters, then the analysis of 3^3=27 were performed. For the design variables of width and thickness, to express the relationship between performance and design variables, approximated continuous quadratic equation is used.

However, the design parameter of number of cross members is discrete number. In the present study, the following equation to handle discrete number is proposed. The discrete variable, x_{di} is defined as follows.

$$x_{di} = x_{i\min} + round\left(\frac{x_i - x_{i\min}}{\Delta x_i}\right)\Delta x_i \qquad (3)$$

where x_{imin} is the minimum value of discrete design variable, Δx_i is the increment of discrete number, round function is to take the integer mostly closed to the value. We use x_{di} instead of x_i. By the equation, the minimum and maximum integer values of the interval of discrete number, like the number of cross member are given.

The initial intervals and preference functions (PN) of design parameters (N, W, T) are shown in dotted line with symbol (□) in Fig.5, 6, and 7, respectively.

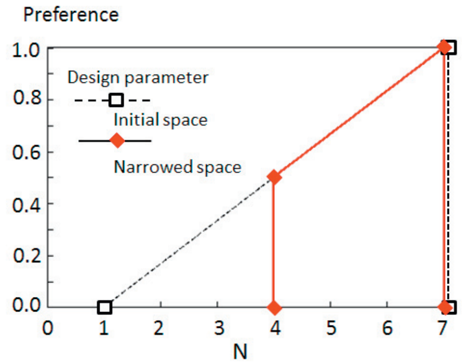

Fig.5. Preference number (PN) of design parameter, number of cross member (N).

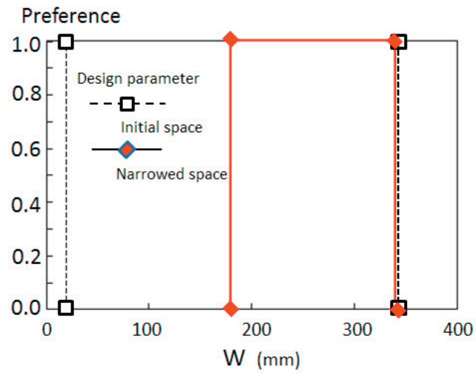

Fig.6. Preference number (PN) of design parameter, width of cross member (W).

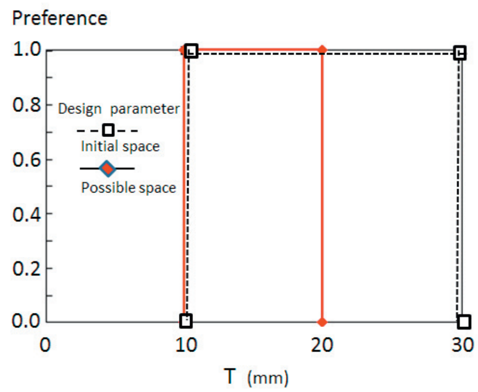

Fig.7. Preference number (PN) of design parameter, thickness of cross member (T).

Namely, the more the number of cross member, the better the design, and the width and thickness are most proper anywhere in the initial intervals.

The initial intervals and preference functions (PN) for required performances are set as follows. Von Mises stress

(M) should be smaller than the about 60% (annealing treatment) of yield stress (345N/mm^2) of Carbon Steel for

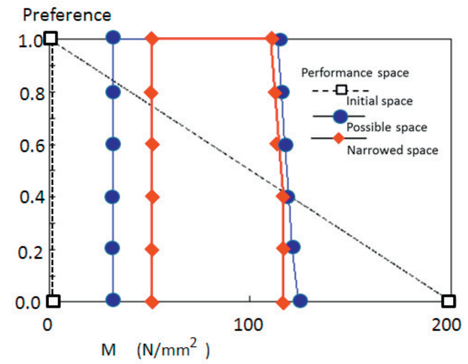

Fig.8. Preference number (PN) of required performance, von Mises stress (M).

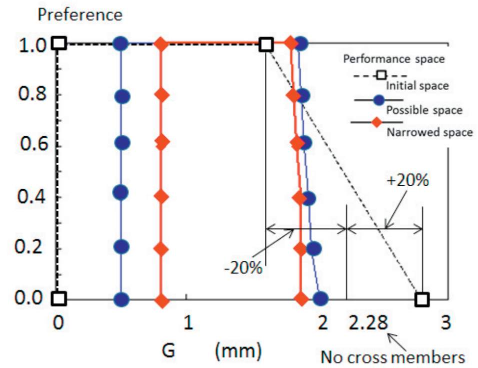

Fig.9. Preference number (PN) of required performance, rigidity (G).

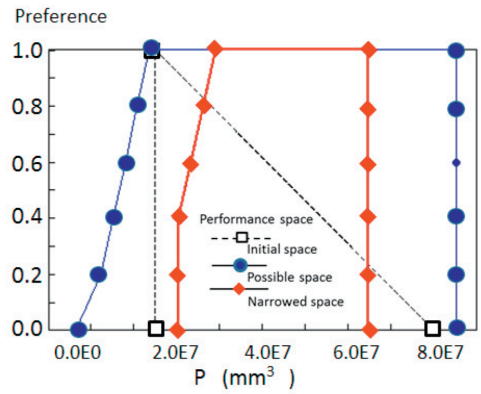

Fig.10. Preference number (PN) of required performance, volume (P).

Machine Structural Use (JIS: S45C), shown in Fig.8. The smaller von Mises stress is, the better the design is. Rigidity of the structure should be less than the value in the range of approximately +-20% of rigidity of the frame structure without cross members, shown in Fig.9. In the range of rigidity less than -20% of the frame rigidity is equally most proper anywhere. Volume (P) of the structure should be in the range between without cross members and with maximum size of cross members, and the smaller the volume, the better the design. The initially designed PNs for required performances are shown in dotted line with symbol (□) in Fig. 8, 9 and 10, respectively. The given initial design spaces are propagated to calculate the possible performance spaces which are achievable by the initial design space. These possible performance spaces of von Mises stress, rigidity and volume are shown in solid line with symbol (●) in Fig.8, 9 and 10, respectively. All the performance spaces have the overlapping spaces (i.e., acceptable performance spaces) between the required performance space and the possible performance space. This means there is a feasible subspace within the initial design space. Then, the next step is to narrow the initial design spaces to eliminate inferior or unacceptable design subspaces, thus resulting in feasible design subspaces. The intervals of design parameters (N, W, T) satisfying simultaneously the narrowed intervals of performance spaces are shown in solid line (◆) in Fig. 5, 6 and 7. As a result, the narrowed intervals of performance spaces (M, G and P) are also shown in solid line (◆) in Fig.8, 9 and 10, respectively.

On the other hand, in the narrowed intervals of deign parameters, a point value of each design parameter, N=6 for the number of cross member and almost median values, W=280 for width and T=15 for thickness, shown in Table 1, are selected and substituted to the approximated equations mentioned above. As a result of the substitution, each value of performance parameters is obtained in Table 2. It is found that these values are in the performance intervals narrowed by PSD method. It is concluded that PSD method is applicable to some kind of topological problems of structural design with multi-objectives, including weight reduction of structure that is an important factor for environmental issues.

Table 1. Point values for the confirmation of PSD interval calculation.

	Number of cross member	Width of cross member	Thickness
A value in solution set	6	280(mm)	15(mm)

Table 2. Performance requirement values obtained from the point values in Table 1.

	von Mises stress	Rigidity	Volume
Performance value	72.4(N/mm^2)	1.15(mm)	4.5E7(mm^3)

PSD method introduces preference function to evaluate the preference and robustness of interval solution in the narrowing process. The consideration about the effect of the preference function on the narrowing results in PSD method in view of topological aspect is important. Then, using the topological structural model that is the same as the previous one, the effect of preference function of design parameter of cross member is considered. Fig. 11 shows the different preference function (the dotted line in the figure), meaning that the smaller the number of cross member, the better the design (case 2), from the one in Fig. 5 (case 1). The other initial conditions of the model for PSD calculation are the same as ones for the previous calculation (case 1). Under these conditions, PSD calculation is performed. The representative results of the calculation are shown in Fig.11 and Fig.12. In Fig.11, it is found the smaller number of cross member is selected, following the prescribed preference function. Fg.12 shows the solution interval of performance of von Mises stress is obtained in the region of possible solution space.

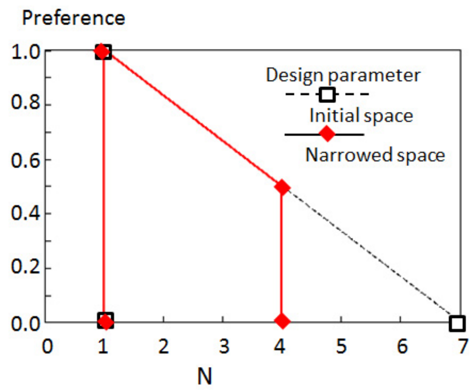

Fig.11. Preference number (PN) of design parameter, number of cross member (N) (case 2).

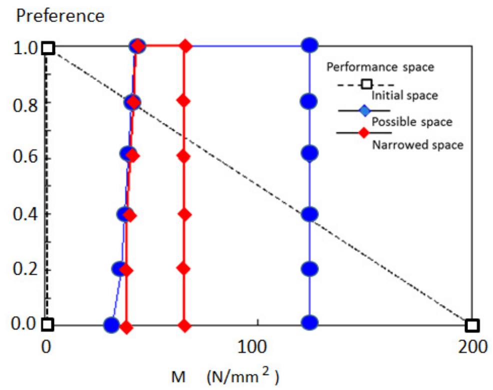

Fig.12. Preference number (PN) of required performance, von Mises stress (M) (case 2).

5. Concluding remarks

From the viewpoint of weight saving of product that is one of the important environmental issues, topological aspect of product structure is considered, using structural design problem with change of the number of cross members of ladder type structure, such as chassis frame of truck. Requirement performances are strength, rigidity and weight. Design parameters are the number, width and thickness of cross members. By the application of PSD method, narrowed intervals of the design parameters, including the number of cross member, that satisfy the prescribed interval of requirement parameters are obtained. PSD method is applicable to some kind of topological problems of structural design with multi-objectives, including environmental issues.

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