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Design Method for Obtaining Diverse Possible Design Solution Sets to Adapt to Changes in Boundary Conditions

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Abstract

The boundary conditions of a design problem often change as the design process progresses because of the change and addition of required performances and other constrained conditions. Under these conditions, designers need to make a decision about the design problem at an early phase of design to accommodate changes in the boundary conditions. This paper proposes a new design method based on a concept of a set-based design method capable of obtaining diverse possible design solution sets that can rapidly adapt to boundary condition changes by deriving the multiple feasible design domains satisfying the performance requirements. Obtaining diverse possible design solution sets accommodate changing boundary conditions in the early phase by allowing the selection of the optimal design solution from the obtained diverse possible design solution sets in the early phase. This paper discusses the potential of the proposed design method to function as a support to decision-making of the designers in the early phase of design.

Keywords: boundary condition, set-based design method, diverse design solutions, decision-making, particle swarm optimization

1 Introduction

Generally, the early phase of design, which is characterized by the conceptual and embodiment design stages, contains multiple sources of changing circumstances including the change and addition in design constrained conditions as the design process progresses. Quick decision-making at this phase of design has the greatest effect on the lead time of the development process, when the circumstances of a design problem change beyond the designer's expectations. Thus, designers need to select a design solution from suitably diverse design ideas that allow for consideration of possible changing circumstances in the post-design phase. This paper proposes a new design method to obtain diverse possible design solution sets by deriving the multiple feasible design domains satisfying performance requirements.

2 Diverse possible design solution sets

Traditional design practice typically regards engineering design as an iterative process that rapidly develops into a "point solution" that can be evaluated using defined objective criteria in advance and then iteratively moved to other points until the process reaches an optimum point solution under the defined boundary conditions [1]. However, the optimum point solution obtained by such a process does not necessarily correspond to an optimum point solution when the defined boundary conditions are changed. Moreover, even if a slight design modification is undertaken in product development based on, for example, concurrent engineering by multiple departments, the modification can have a profound effect on other departments and possibly necessitate an extended design period. One method of adapting to changing boundary conditions is derived from the concept of set-based concurrent engineering [1]. This concept seeks to obtain a feasible design solution set rather than an optimum unique point design solution, and subsequently narrows the solution set population by removing improper solutions. Therefore, designers can quickly select an optimized design solution from the obtained solution set.

Previously, we proposed a preference set-based design (PSD) method that produced a flexible and robust design under various sources of uncertainties while incorporating the designer's preference structure in the early phase of design [2-4]. This paper proposes a new design method based on the PSD method, which can accommodate design changes by deriving diverse possible design solution sets rather than an optimum point design solution

Designers obtain an optimum point design solution derived from a design solution space under defined boundary conditions by the traditional point-based design method illustrated in **Fig. 1**. On the other hand, the newly proposed set-based design method can derive diverse possible design solution sets by the design method shown in **Fig. 2**. **Figure 3** illustrates a change in boundary conditions as the design process progresses. In this case, the optimum point design solution obtained by the traditional point-based design method might not be included in the adjusted boundary conditions. However, if designers diverse possible design solution sets in advance, the prepared solutions have a greatly improved chance of corresponding to the changing boundary condition. Therefore, designers could quickly adapt their designs to the boundary condition change.

This paper calculates the extent to which the design solution sets satisfy the performance requirements, as shown in **Fig. 3**. For the overlap rate of 1.0, a given design solution set distribution completely satisfies the performance requirements. For an overlap rate of 0.0, the design solution set distribution does not satisfy the performance requirements at all. When an overlap rate is greater than 0.0 and less than 1.0, the design solution set satisfies the performance requirements in part.

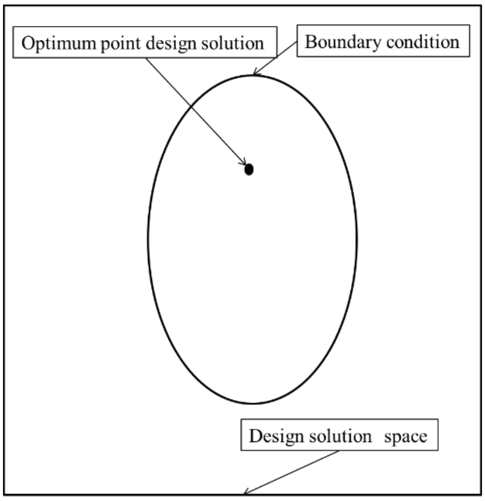

Fig. 1 Schematic of the optimum point design solution developed by the point-based design method under defined boundary conditions

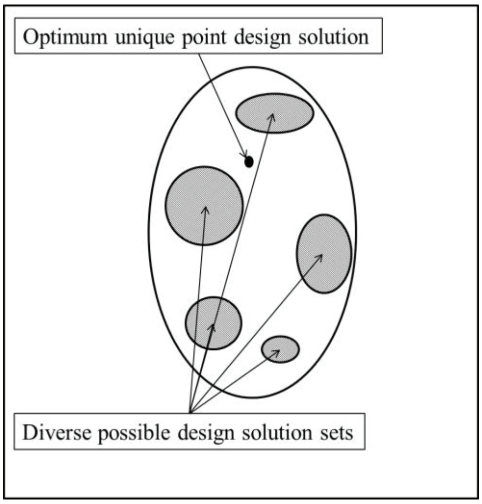

Fig. 2 Schematic of diverse solution sets developed by the proposed set-based design method

Moreover, as shown in **Fig. 4**, when the boundary condition is changed beyond expectations, the all overlap rates of the design solution sets are 0.0. A designer can judge the feasibility of the diverse design solution sets that are obtained more quickly, thus supporting quick decision-making in the early design stages. The next section introduces the method by which the overlap rates are calculated and the method of narrowing the design variables to obtain suitably diverse possible design solution sets.

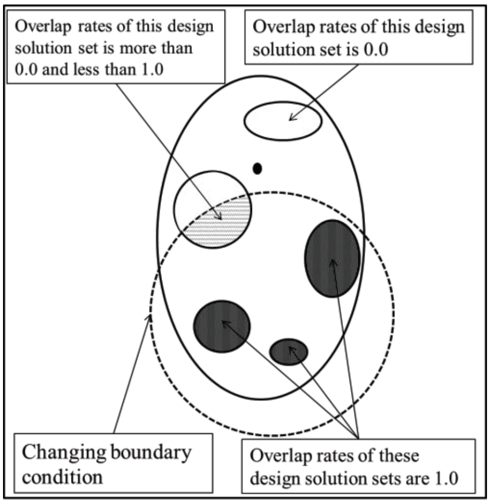

Fig. 3 Schematic of change in boundary conditions

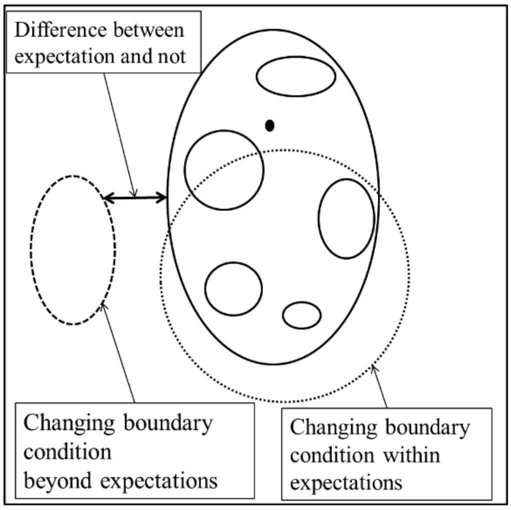

Fig. 4 Schematic of changing boundary conditions beyond expectations

3 Calculation of the overlap rates and the method for narrowing design variables

3.1 Proposed procedure

Figure 5 establishes the details of our proposed design method for obtaining diverse possible design solution sets. To derive and represent the multiple feasible design domains, the proposed method obtains the possible distributions from the defined initial design variables, calculates the overlap rate and establishes the extent to which possible distributions satisfy the performance requirements, and iteratively narrows the interval values of the design variables until all possible distributions exist only within the range of required performances.

3.2 Calculation of the overlap rates

Designers represent design variables and required performances as interval sets. For example, the design variables, x_1 and x_2, are related to the performance Y_i by a mapping function $Y_i = f_i\ (x_1\ x_2,)$, while the associated required performance is defined as Z_i. Then if the function f_i has a non-monotonic relationship, the possible distribution is derived by particle swarm optimization [5]. Afterwards, an overlap rate *ov* is determined by the set of possible distributions and required performance. There are three cases by which the overlap rates are determined.

(1) $ov = 0.0$. As shown in **Figs. 6 (a)** and **(b)**, there are two cases where the interval of required performances does not include the possible distributions, and designers should modify the design variables.

(2) $ov = [0, 1]$. As shown in Figs.6(c), (d), and (e), there are three cases whereby the interval of required performances partially overlap the possible distribution.

(3) $ov = 1.0$. As shown in Fig. 6(f), the interval of required performance is inclusive of the possible distribution. In this case, this set is one of the diverse design solutions that satisfy the performance requirements.

Fundamentally, the possible values of *ov* described for Case (2) above are represented by a ratio wherein the denominator is the interval of the possible distribution and the numerator is the value of the set of the possible distributions included in the required performance. In the first case, as shown in **Fig. 6 (c),** ($Y_{i\,min} < Z_{i\,min} < Y_{i\,max} < Z_{i\,max}$), and the overlap rate is calculated by eq. (1).

$$ov = \frac{Y_{i\,max} - Z_{imin}}{Y_{i\,max} - Y_{i\,min}} \,. \tag{1}$$

The numerator reflects the difference between the maximum possible distribution and minimum of the required performance.

In the second case, as shown in **Fig. 6 (d),** ($Z_{i\,min} < Y_{i\,min} < Z_{i\,max} < Y_{i\,max}$), the overlap rate is calculated by eq. (2).

$$ov = \frac{Z_{i\,max} - Y_{i\,min}}{Y_{i\,max} - Y_{i\,min}} \,. \tag{2}$$

The numerator reflects the difference between the minimum possible distribution and maximum required performance.

In the third case, as shown in **Fig. 6 (e),** ($Z_{i\,min} < Y_{i\,min} < Y_{i\,max} < Z_{i\,max}$), and the overlap rate is calculated by eq. (3).

$$ov = \frac{Z_{i\,max} - Z_{i\,min}}{Y_{i\,max} - Y_{i\,min}} \,. \tag{3}$$

The numerator is the interval of the required performances.

If the overlap rate is less than 1, the obtained design solution sets exist within the required performances. However, the design solution sets leave some extent of the required performances unaddressed. These unaddressed regions of the required performances represent infeasible space. The next step is to narrow the space to eliminate infeasible space by narrowing design variables.

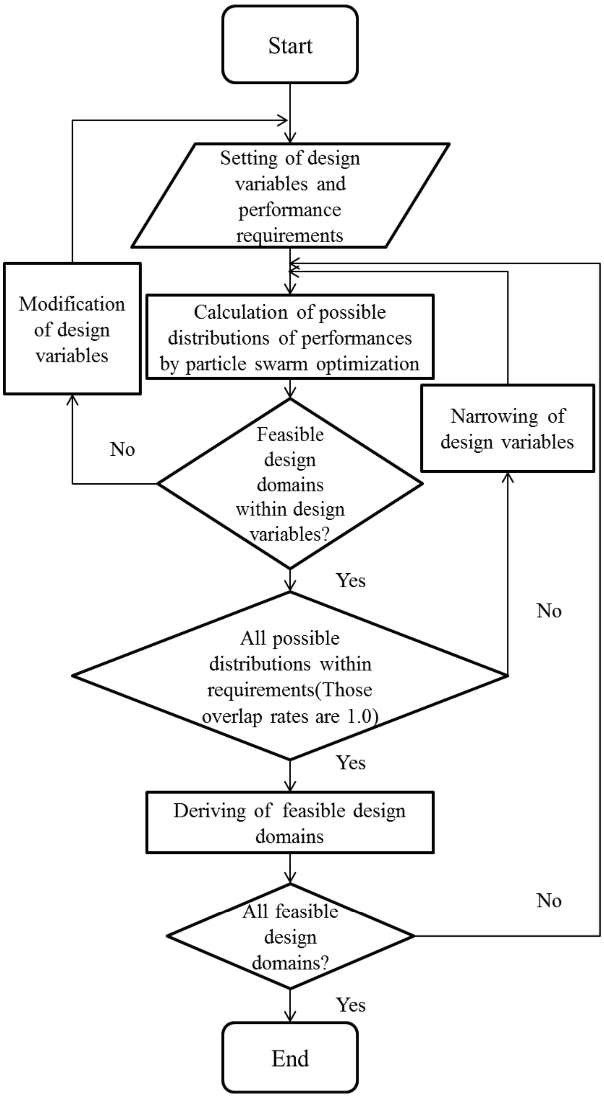

Fig. 5 Procedure of the proposed design method

3.3 Method for narrowing design variables

The narrowing step involves sharpening the initial design variables to eliminate inferior and unacceptable design domains within the initial design variables. Therefore, the initial design variables, x_1 and x_2, are partitioned into two or more levels. For example, **Fig. 7** shows the subsets (i.e., Subspaces I and II) of the design variables partitioned into two levels and the possible distributions y_i that can be obtained by various combinations of the decomposed design spaces. As shown on the left side of **Fig. 7**, the possible distribution by combining design Subspace I of the design variables

x_1 and x_2 exist within the interval of required performances. However, the possible distribution by combining design Subspace I of the design variable x_1 and Subspace II of the design variable x_2 exists partially outside the interval of required performances. The narrowing step must again be applied to this subspace to divide it into two levels. The narrowing step is repeated until the possible distributions exist within the interval of required performances.

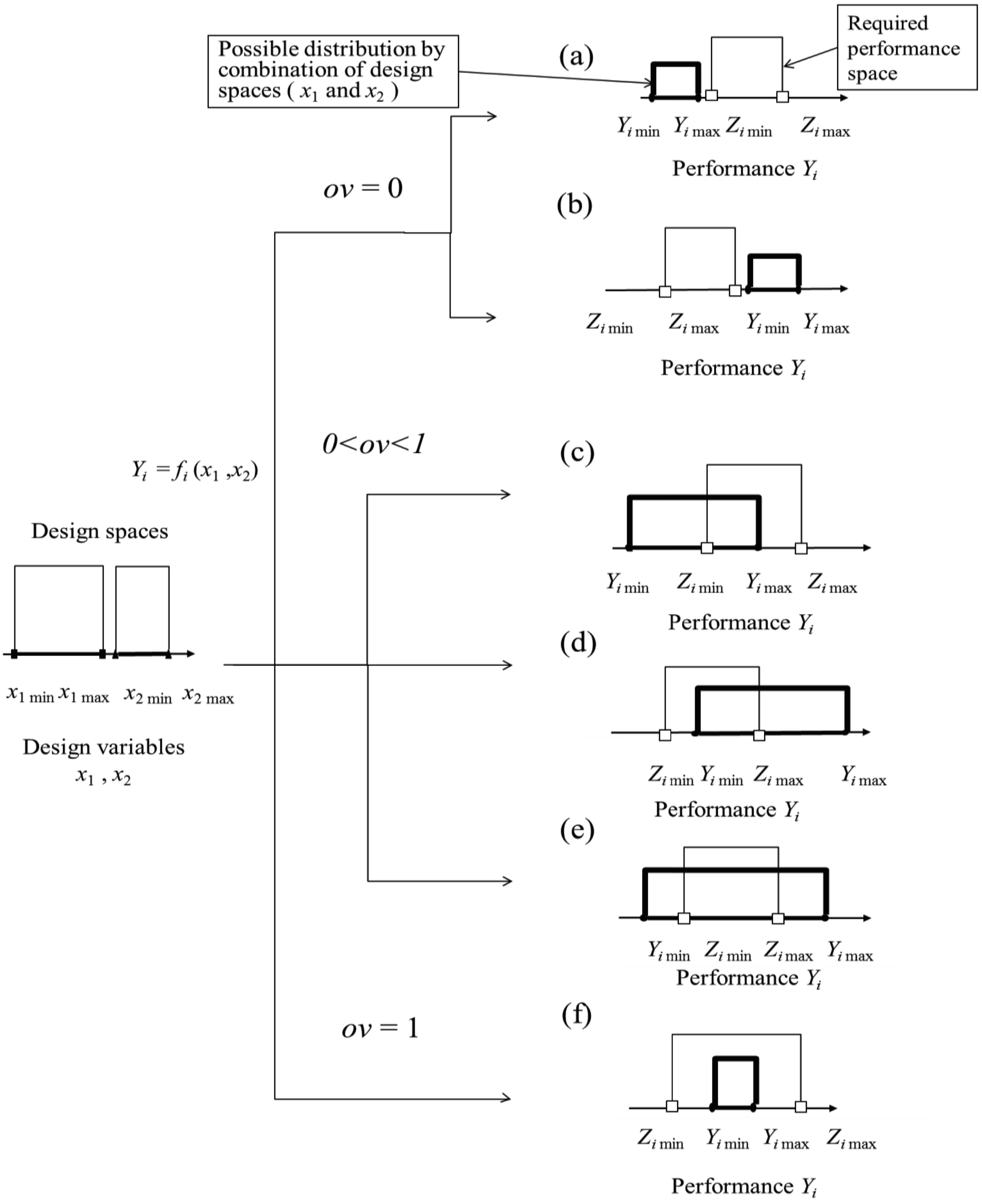

Fig. 6 Calculation of overlap rates based upon cases (1)-(3)

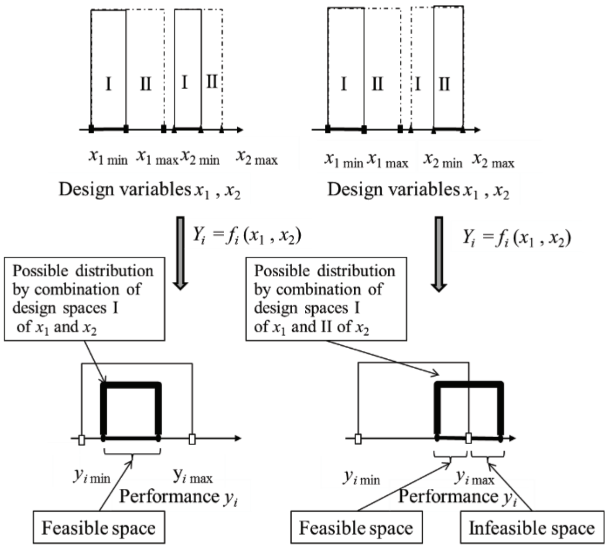

Fig. 7 Steps involved with narrowing the initial design variables

4 Application to claw clutch

4.1 Setting of design problem

This paper applies the proposed method to design of a claw clutch. This study assumes that a designer prefers a light and enough strength claw clutch. This paper defines the two design variables and two required performances of claw clutch. Design variables are inside diameter D_1 and outside diameter D_2 of the claw. D_1 has a range of [40, 75] (mm). D_2 has a range of [80, 150] (mm). Required performances are Shearing stress τ and Mass M. τ has a range of [0, 0.3] (kgf/mm^2). M has a range of [0, 3] (kg).

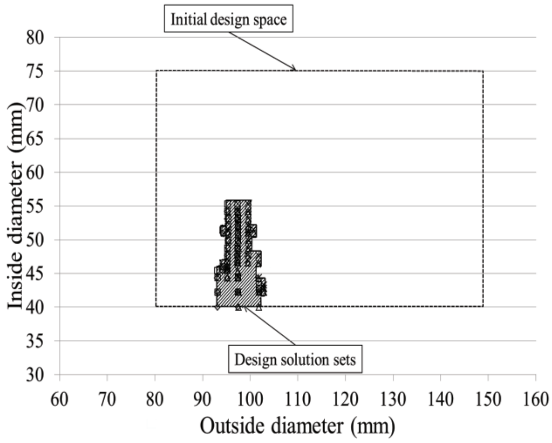

Fig. 8 Diverse possible design solution sets of inside diameter and outside diameter

4.2 Diverse design solution sets

First, the possible distributions are obtained by combining the design variables. Next, the overlap rates are calculated and the ranges of the design variables are narrowed. This narrowing step is repeated until the possible distributions exist within the interval of required performances. As a result, diverse possible design solution sets are obtained. As shown in **Fig. 8**, a dotted line is the initial design space and a solid line is the design solution sets. **Figure 8** shows that it is possible to obtain the design solution sets from the initial design space. As shown in **Fig. 9**, a dotted line is the required performances and solid line is the possible distributions which is obtained by combining the design solution sets. **Figure 9** shows the all possible distributions satisfy the required performances.

These results show the availability of the diverse possible design solution sets for changes in boundary conditions which is within the possible distributions.

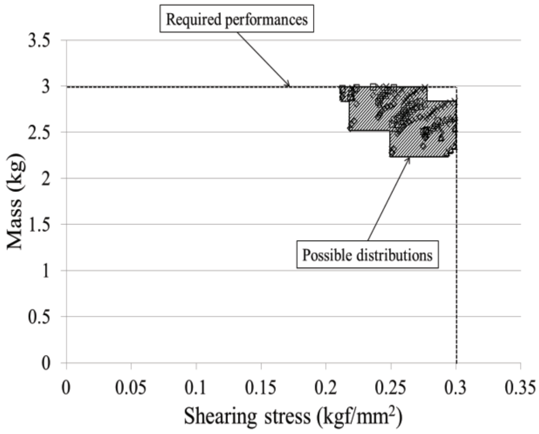

Fig. 9 Possible design distributions of shearing stress and mass

4.3 Discussions

The proposed method can adapt to changes in boundary conditions. In this paper the method apply to the design problem which has two design variables and two required performances. In the future, the method applies to complex design problems which have many design variables and many required performances and show the availability of the method.

5 Conclusions

This paper proposed a new design method for obtaining diverse possible design solution sets based on the PSD method. Designers can quickly respond to a change in the boundary condition early on in the design process by selecting a design solution from the diverse design solution sets obtained.

The proposed method can be applied to design problems whenever the relationship between design variables and required performances is defined. Future research regarding the availability of the proposed design method as a decision-making support method must be verified by application of the method to a design example which a designer need change the boundary conditions of a design problem.

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