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The safest point method as an efficient tool for reliability-based design optimization applied to free vibrated composite structures[*]

G. Kharmanda[**]
Lund University, Lund, Sweden

Точечный метод как самый безопасный и эффективный инструмент для оптимизации на основе надежности применительно к свободным вибрированным композитным структурам[***]

Г. Харманда[**]
Лундский университет, г. Лунд, Швеция

Introduction. Reliability-Based Design Optimization (RBDO) model reduces the structural weight in uncritical regions; it provides not only an improved design but also a higher level of confidence in the design.
Materials and Methods. The classical RBDO approach can be carried out in two separate spaces: the physical space and the normalized space. Since lots of repeated researches are needed in the above two spaces, the computational time for such an optimization is a big problem. Fortunately, an efficient method called the Hybrid Method (HM) has been elaborated by which the optimization process is carried out in a Hybrid Design Space (HDS). When designing free vibrated structures, the HM can be used with a big implementation complexity, and that leads to high computing time. An efficient method called Safest Point (SP) method is developed to overcome this drawback.
Research Results. A numerical application on the composite aircraft wing under free vibrations shows the efficiency of the proposed method relative to the HM. The SP method can reduce efficiently the computing time relative to the HM.
Discussion and Conclusions. The simplified implementation framework of the SP strategy consists of decoupling the RBDO problem into a number of simple problems. That provides designers with efficient solutions that should be economically justified for a required reliability level for dynamic cases (modal studies).

Введение. Модель на основе оптимизации надежности (RBDO) снижает структурный вес в некритических регионах, обеспечивает не только улучшенный дизайн, но и более высокий уровень уверенности в конструкции.
Материалы и методы. Классический подход RBDO может быть выполнен в двух отдельных пространствах: физическом и нормализованном. Так как в этих двух пространствах требуется очень много повторных исследований, решающее время для такой оптимизации - большая проблема. К счастью, был разработан эффективный метод, называемый гибридным методом (HM), посредством которого процесс оптимизации завершается в гибридном пространстве проектирования (HDS). При проектировании свободных вибрирующих структур HM может использоваться с большой сложностью реализации и приводит к большому времени вычислений. Для преодоления этого недостатка разработан эффективный метод под названием Safest Point (SP).
Результаты исследования. Численное приложение на крыле самолета при свободных колебаниях показывает эффективность предложенного метода относительно HM. Метод SP может эффективно сократить время вычислений относительно HM.
Обсуждение и заключения. Упрощенная структура реализации стратегии SP состоит в разделении проблемы RBDO на ряд простых проблемах. Это обеспечивает конструкторам эффективные решения, которые должны быть экономически оправдывающими необходимый уровень надежности для динамических случаев (модальные исследования).

Keywords: Reliability-Based Design Optimization, structural reliability, safety factors.

Ключевые слова: оптимизация на основе надежности, структурная надежность, факторы безопасности.

Introduction

The objective of the RBDO model is to design structures which should be both economic and reliable where the solution reduces the structural weight in uncritical regions. It does not only provide an improved design but also a higher level of confidence in the design. The classical approach can be carried out in two separate spaces: the physical space and the normalized space. Since very many repeated researches are needed in the above two spaces, the computational time for such an opti-

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[*] Работа выполнено в рамках инициативной НИР.
[**] E-mail: ghias.kharmanda@bme.lth.se
[***] The research is done within the frame of independent R&D.

mization is a big problem [1,2]. The major difficulty lies in the evaluation of the probabilistic constraints, which is prohibitively expensive and even diverges with many applications. However, an efficient method called the Hybrid Method (HM) has been elaborated [3] where the optimization process is carried out in a Hybrid Design Space (HDS). This method has been shown to verify the optimality conditions relative to the classical RBDO method [3]. The advantage of the hybrid method allows us to satisfy a required reliability level for different cases (static, dynamic, …), but the vector of variables here contains both deterministic and random variables. Next, an OSF (Optimum Safety Factor) methodology has been proposed to simplify the optimization problem (reduction of number of variables) and aims to find at least a local optimum solution because it is based on the optimality conditions [4,5,6]. However, the OSF method cannot be used in some dynamic cases of free vibrated structures. So there is a strong motivation to develop a new technique that can overcome both drawbacks. In this paper, an efficient method, called Safest Point (SP) method is developed to give the reliability-based optimum solutions. A numerical application on a free vibrated composite aircraft wing is presented to show the efficiency of the SP method relative to the HM.

Reliability Analysis

Structural reliability analysis is a tool that assists the design engineer to take into account all possible uncertainties during the design and construction phases and the lifetime of a structure in order to estimate the probabilities of failure. The evaluation of the probability of failure is carried out using numerical integrals. However, Hasofer and Lind [7] proposed to evaluate a reliability index instead of the numerical integral calculation. The reliability index can be found by solving the following constrained optimization:

$$\beta = \min\left(\mathrm{u}^T\mathrm{u} = \min\sqrt{\sum_i^n u_i^2}\right) \quad \text{s.t.} \quad H(\mathrm{u}) \le 0 \tag{1}$$

where $H(\mathrm{u})$ is the limit state function in the normalized space (Figure 1). For more details about reliability index and probability of failure, the interested reader can see [8].

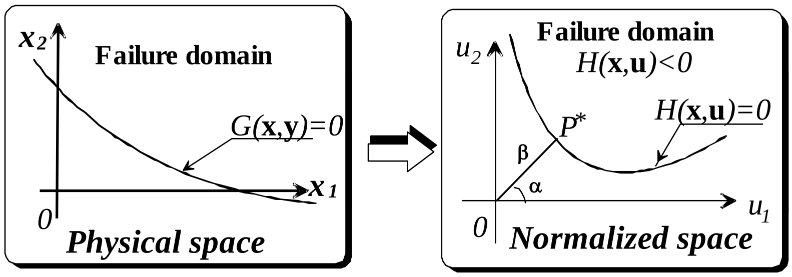


Fig. 1: The transformation between the physical space and normalized one

Рис. 1: Преобразование между физическим и нормированным пространством

Deterministic Design Optimization

In Deterministic Design Optimization (DDO), the system safety may be taken into account by assigning safety factors to certain structural parameters. Using these safety factors, the optimization problem which is carried out in the physical space (Fig. 1a), consists in minimizing an objective function (cost, volume of material,…) subject to geometrical, physical or functional constraints in the form

$$\min : \ f(\mathrm{x}) \quad \text{s.t.} \quad g_k(\mathrm{x}) \le 0 \ , \quad k = 1,\dots,K \tag{2}$$

where **x** designates the vector of deterministic design variables. Over the last 20 years there has been an increasing trend in analyzing structures using probabilistic information on loads, geometry, material properties, and boundary conditions. Using Deterministic Design Optimization (DDO), we can distinguish between two cases:

Case 1: High reliability level: when choosing high values of safety factors for certain parameters, the structural cost (or weight) will be significantly increased because the reliability level becomes much higher than the required level for the structure. So, the design is safe but very expensive.

Case 2: Low reliability level: when choosing small values of safety factors or bad distribution of these factors, the structural reliability level may be too low to be appropriate. For example, Grandhi and Wang [9] found that the resulting reliability index of the optimum deterministic design of a gas turbine blade is $\beta = 0.0053$ under some uncertainties. This result indicated that the reliability at the deterministic optimum is quite low and needs to be improved by reliability-based design optimization.

Reliability-Based Design Optimization

Classical Method (CM)

Traditionally, for the reliability-based optimization procedure we use two spaces: the physical space and the normalized space (Figure 1). Therefore, the reliability- based optimization is performed by nesting the two following problems:

1 *Optimization problem:*

$$\min \quad : f\left(\mathrm{x}\right) \;\; \text{s.t.} : g_k\left(\mathrm{x}\right) \le 0 \text{ and } \beta\left(\mathrm{x},\mathrm{u}\right) \ge \beta_t \tag{3}$$

where $f(\mathbf{x})$ is the objective function, $g_k(\mathrm{x}) \le 0$ are the associated constraints, $\beta(\mathrm{x,u})$ is the reliability index of the structure, and β_t is the target reliability.

2 *Reliability analysis:*

The reliability index $\beta(\mathrm{x,u})$ is determined by solving the minimization problem:

$$\beta = \min d\left(\mathrm{u}\right) = \sqrt{\sum_1^m u_j^2} \;\; \text{s.t.} : H\left(\mathrm{x},\mathrm{u}\right) \le 0 \tag{4}$$

where $d(\mathrm{u})$ is the distance in the normalized random space and $H(\mathrm{x,u})$ is the performance function (or limit state function) in the normalized space. Since a very large number of repeated searches are needed in the above two spaces, the computational time for such an optimization is a big problem. To reduce the effects of this difficulty, a hybrid method (HM) based on simultaneous solution of the reliability and the optimization problem has been elaborated [3].

Hybrid Method (HM)

The hybrid approach consists in minimizing a multiplicative form of the objective function $F(\mathbf{x},\mathbf{y})$ subject to a limit state and to deterministic as well as to reliability constraints, as:

$$\begin{aligned} \min &: F\left(\mathrm{x},\mathrm{y}\right) = f\left(\mathrm{x}\right).d_\beta\left(\mathrm{x},\mathrm{y}\right) \\ \text{s.t.} &: G(\mathrm{x},\mathrm{y}) \le 0 \\ &: g_k\left(\mathrm{x}\right) \le 0 \\ \text{and} &: d_\beta\left(\mathrm{x},\mathrm{y}\right) \ge \beta_t \end{aligned} \tag{5}$$

Here, $d_\beta(\mathbf{x},\mathbf{y})$ is the distance in the hybrid space between the optimum and the design point, $d_\beta(\mathrm{x,y}) = d(\mathrm{u})$. The minimization of the function $F(\mathbf{x},\mathbf{y})$ is carried out in the Hybrid Design Space (HDS) of deterministic variables **x** and random variables **y**. An example of this HDS is given in figure 2, containing design and random variables, where the reliability levels d_β can be represented by ellipses in case of normal distribution, the objective function levels are given by solid curves and the limit state function is represented by dashed level lines except for $G(\mathbf{x},\mathbf{y})=0$. We can see two important points: the optimal solution P_x^* and the reliability solution P_y^* (i.e. the design point found on the curves $G(\mathrm{x,y})=0$ and $d_\beta = \beta_t$).

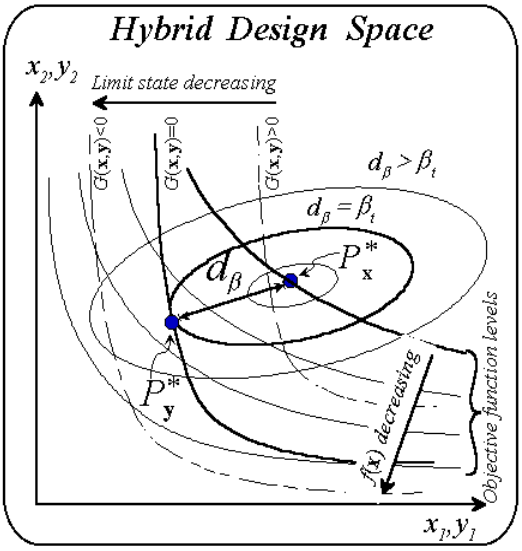


Fig. 2: Hybrid Design Space for normal distribution

Рис. 2: Гибридный дизайн пространства для нормального распределения

The hybrid approach leads to a high computing time especially when considering the dynamic cases. So we develop an efficient technique called Safest Point method (SP).

Safest Point Method (SP)

Let consider a given interval $[f_a, f_b]$. For the first shape mode, to get the reliability-based optimum solution for a given interval, we consider the equality of the reliability indices ($\beta_a = \beta_b$) with

$$\beta_a = \sqrt{\sum_{i=1}^n \left(u_i^a\right)^2} \;\; \text{and} \;\; \beta_b = \sqrt{\sum_{i=1}^n \left(u_i^b\right)^2} \quad i = 1,\ldots,n \tag{6}$$

Here, we distinguish between two cases.

Case 1: Non-symmetric: $u_i^a \neq - u_i^b$ or $\left|u_i^a\right| \neq \left|u_i^b\right|$

The reliability-based optimum structure under free vibrations for a given interval of eign-frequency is found at the safest position of this interval where the safest point has the same reliability index relative to both sides of the interval (Figure 3). A simple method has been proposed here to meet the safest point requirements relative to a given frequency interval. The basic principle is to decompose the RBDO problem into three simple optimization problems.

Problem 1:

- The first problem consists of minimizing the objective function of the first structure subject to the frequency f_a constraint as follows

$$\min \quad : \quad f^a\left(\mathrm{y}_a\right) \qquad \text{s.t.}: \ freq^a\left(\mathrm{y}_a\right) - f_a \leq 0 \tag{7}$$

Problem 2:

- The second problem consists in minimizing the objective function of the second structure subject to the frequency f_b constraint as follows

$$\min \quad : \quad f^b\left(\mathrm{y}_b\right) \qquad \text{s.t.}: \ freq^b\left(\mathrm{y}_b\right) - f_b \leq 0 \tag{8}$$

Problem 3:

- The third is to minimize the objective function of the third model subject to the equality reliability constraints and the boundary frequency interval as follows:

$$\begin{aligned} &\min: \quad f\left(\mathrm{x}\right) \\ &\text{s.t.} \ \ : \ \beta_a - \beta_b = 0 \\ &\text{and} \ : \ f_a < freq\left(\mathrm{x}\right) < f_b \end{aligned} \tag{9}$$

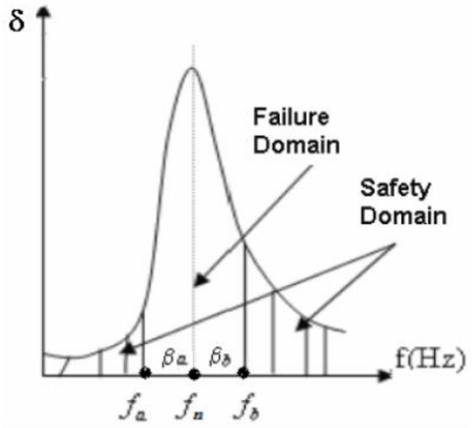


Fig. 3: The safest point at frequency fn

Рис. 3: Самая безопасная точка на частоте fn

Case 2: Symmetric: $u_i^a = - u_i^b$ or $\left|u_i^a\right| = \left|u_i^b\right|$

Problem 1:

- The first problem consists in minimizing the objective function of the first structure subject to the frequency f_a constraint as follows

$$\min \quad : \quad f^a\left(\mathrm{y}_a\right) \qquad \text{s.t.}: \ freq^a\left(\mathrm{y}_a\right) - f_a \leq 0 \tag{10}$$

Problem 2:

- The second problem consists in minimizing the objective function of the second structure subject to the frequency f_b constraint as follows

$$\min \quad : \quad f^b\left(\mathrm{y}_b\right) \quad \text{s.t.}: \ freq^b\left(\mathrm{y}_b\right) - f_b \leq 0 \tag{11}$$

To verify the equality (16), we propose the equality of each term. So we have:

$$u_i^a = - \ u_i^b \quad , \ i = 1, \ldots, n \tag{12}$$

According to the normal distribution law, the normalized variable u_i is given by (12), we get:

$$\frac{y_i^a - m_i}{\sigma_i} = - \frac{y_i^b - m_i}{\sigma_i} \quad , \ \text{or} \ \frac{y_i^a - x_i}{\sigma_i} = - \frac{y_i^b - x_i}{\sigma_i} \ , \quad i = 1, \ldots, n \tag{13}$$

To obtain equality between the reliability indices (see equation 16), the mean value of variable corresponds to the structure at f_n. So the mean values of safest solution are located in the middle of the variable interval [y_i^a, y_i^b] as follows:

$$m_i = x_i = \frac{y_i^a + y_i^b}{2} \quad , \quad i = 1, \ldots, n \tag{14}$$

In the next section, we demonstrate the efficiency of the proposed method on a numerical application of a composite aircraft wing under free vibrations for both cases (equality and inequality).

Numerical application on composite aircraft wing

The wing is uniform along its length with cross sectional area as illustrated in Figure 8a. It is firmly attached to the body of the airplane at one end. The chord of the airfoil has dimensions and orientation as shown in Figure 5. The wing is made of two different low density polyethylenes with the following properties:

Table 1

Таблица 1

Input parameters

Входные параметры

Parameters	Mat 1	Mat 2
Young’s modulus (psi)	18.000	38.000
Poisson’s ratio	0.3	0.3
Density (1bf-sec^2/in^4)	8.3E-5	8.3E-5
Effective thickness (m)	0.025	0.025

Assume the side of the wing connected to the plane is completely fixed in all degrees of freedom. The wing is solid and material properties are constant and isotropic.

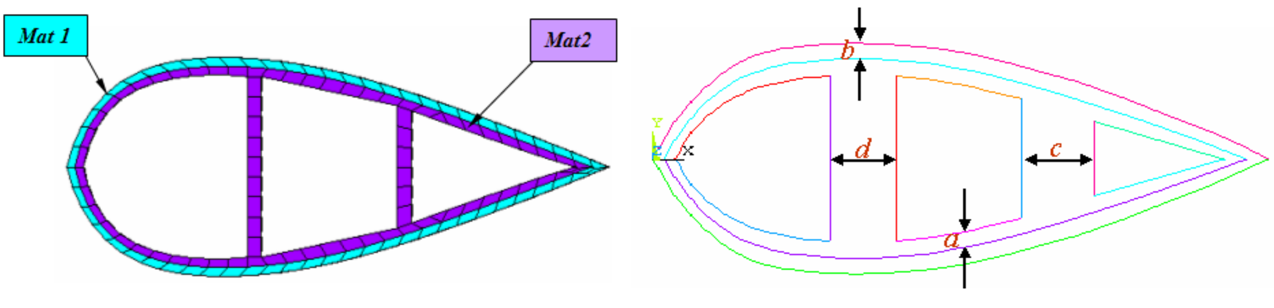


Fig. 4: Aircraft wing section and materials

Рис. 4: Сечение крыла самолета и материалы

The objective is to find the Eigen-frequency for a given interval [16,18] Hz, that is located on the safest position of this interval. So the first structure corresponds to the first frequency value of the given interval f_a=16 Hz, and the third structure corresponds to the last frequency value of the given interval f_b=18 Hz. However, the second structure corresponds to the unknown frequency value f_n=? Hz, which must verify the equality of reliability indices: $\beta_a = \beta_b$ (see Figure 5).

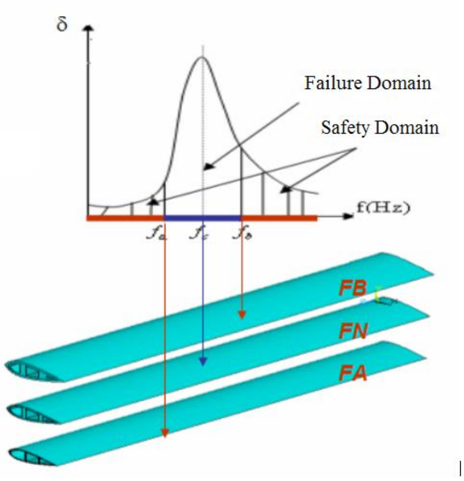
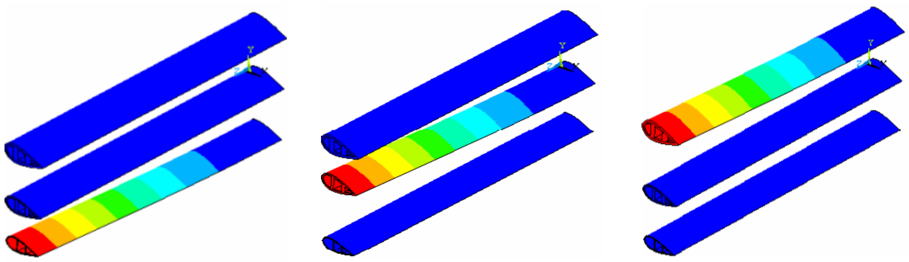


Fig. 5: Aircraft wing optimization models

Рис. 5: Модели оптимизации крыла самолета

Figure 6 shows the first shape mode of each structure, where the maximum values of displacements are located on the free wing side and the minimum values (zeros) of displacement is located at the fixed side.



Structure f_a Structure f_n Structure f_b

Fig. 6: Shape modes

Рис. 6: Режимы формы

Here, we can deal with two reliability-based design optimization methods: hybrid and safest point methods. The hybrid method (HM) simultaneously optimizes the three structures but the safest point method consists in optimizing three simple problems. So we distinguish two cases: $u_i^a \neq -\ u_i^b$ and $u_i^a = -\ u_i^b$: as follows:

Case 1: Non-symmetric: $u_i^a \neq -\ u_i^b$ or $|u_i^a| \neq |u_i^b|$

1- HM procedure: We minimize the multiplicative form of the objective function subject to the different frequencies constraint and the reliability one as follows:

$$\begin{aligned} &\min \ :Vol_n\left(m_A,...,m_D\right).d_{\beta_a}(A_a,...,D_a,m_A,...,m_D).d_{\beta_b}(A_b,...,D_b,m_A,...,m_D) \\ &\text{s.t.} \quad :\beta_a\left(A_a,...,D_a,m_A,...,m_D\right)-\beta_b\left(A_b,...,D_b,m_A,...,m_D\right)=0 \\ &\text{and} \ :f_a < freq^n(m_A,m_B,m_C,m_D) < f_b \end{aligned} \tag{15}$$

2- SP procedure: We have three simple optimization problems:

- The *first* is to minimize the objective function of the first model subject to the frequency f_a constraint as follows:

$$\min \ :Vol_a\left(A_a,B_a,C_a,D_a\right) \ \text{s.t.} \ : freq^a(A_a,B_a,C_a,D_a) - f_a \leq 0 \tag{16}$$

- The *second* is to minimize the objective function of the second model subject to the frequency f_b constraint as follows:

$$\min \ :Vol_b\left(A_b,B_b,C_b,D_b\right) \ \text{s.t.} \ : freq^b(A_b,B_b,C_b,D_b) - f_b \leq 0 \tag{17}$$

- The *third* is to minimize the objective function of the third model subject to the equality reliability constraints and the boundary frequency interval as follows:

$$\begin{aligned} &\min \ :Vol_n\left(m_A,m_B,m_C,m_D\right) \\ &\text{s.t.} \quad :\beta_a\left(A_a,...,D_a,m_A,...,m_D\right)-\beta_b\left(A_b,...,D_b,m_A,...,m_D\right)=0 \\ &\text{and} \ :f_a < freq^n(m_A,m_B,m_C,m_D) < f_b \end{aligned} \tag{18}$$

Table 2

Таблица 2

Results of the aircraft wing for the first case

Результаты применения методов для первого случая

	Variables	Initial design	Optimum design with SP	Optimum design with HM
FN	A	0.04	0.03948	0.03960
	B	0.05	0.04138	0.04758
	C	1.00	0.98826	0.98815
	D	0.425	0.47733	0.41764
FA	A1	0.02	0.02730	0.02944
	B1	0.02	0.02004	0.02531
	C1	0.9	0.90021	0.91867
	D1	0.5	0.49983	0.48806
FB	A2	0.06	0.05346	0.05688
	B2	0.08	0.06088	0.06386
	C2	1.1	1.0002	1.0581
	D2	0.35	0.42485	0.37862
	FA	15.60	16.001	16.100
	FB	18.55	17.999	17.903
	FN	16.91	16.814	16.796
	DIF = β1-β2	0	-0.00578	-0.09884
	volume	0.334	0.280	0.310
	Time(S)	-	280	1920

Table 2 shows the results of the hybrid and SP methods for the first case when considering a given interval [16,18] Hz. The value of f_n presents the equality of reliability indices. The SP method reduces the computing time by 85% relative to the hybrid method. The advantage of the SP method is simple to be implemented on the machine and to define the eigen-frequency of a given interval and provides the designer with reliability-based optimum solution with a small tolerance relative to the hybrid method. So this method can be also a conjoint of the OSF method.

Case 2: Symmetric: $u_i^a = - u_i^b$ or $\left|u_i^a\right| = \left|u_i^b\right|$

1- HM procedure: We minimize the multiplicative form of the objective function subject to the different frequencies constraint and the reliability one as follows:

$$\begin{aligned}
\min\ &: Vol_n\left(m_A,...,m_D\right).\ d_{\beta a}\left(A_a,...,D_a,m_A,...,m_D\right).\ d_{\beta b}\left(A_b,...,D_b,m_A,...,m_D\right)\\
\text{s.t}\ &: d_{\beta a}\left(A_a,...,D_a,m_A,...,m_D\right) - d_{\beta b}\left(A_b,...,D_b,m_A,...,m_D\right) = 0\\
&: u_A^a(A_a,m_A) + u_A^b(A_b,m_A) = 0\\
&: u_B^a(B_a,m_B) + u_B^b(B_b,m_B) = 0\\
&: u_C^a(C_a,m_C) + u_C^b(C_b,m_C) = 0\\
&: u_D^a(D_a,m_D) + u_D^b(D_b,m_D) = 0\\
&: freq^a(A_a,B_a,C_a,D_a) - f_a \le 0\\
&: freq^b(A_b,B_b,C_b,D_b) - f_a \le 0
\end{aligned} \tag{19}$$

2- SP procedure: We have two simple optimization problems and a model evaluation:

- The *first* is to minimize the objective function of the first model subject to the frequency f_a constraint as follows:

$$\min\ : Vol_a\left(A_a,B_a,C_a,D_a\right) \text{ s.t. } : freq^a(A_a,B_a,C_a,D_a) - f_a \le 0 \quad (20)$$

- The *second* is to minimize the objective function of the second model subject to the frequency f_b constraint as follows:

$$\min\ : Vol_b\left(A_b,B_b,C_b,D_b\right) \text{ s.t. } : freq^b(A_b,B_b,C_b,D_b) - f_b \le 0 \quad (21)$$

- The model evaluation leads to analytically compute the mean values corresponding to the frequency f_n

$$m_A = \frac{A_a + A_b}{2} \tag{22}$$

$$m_B = \frac{B_a + B_b}{2} \tag{23}$$

$$m_C = \frac{C_a + C_b}{2} \tag{24}$$

$$m_D = \frac{D_a + D_b}{2} \tag{25}$$

That leads to $Vol_n(m_A, m_B, m_C, m_D)$ and $f_a < freq^n(m_A, m_B, m_C, m_D) < f_b$.

Table 3 shows the results of the hybrid and SP methods for the second case when considering a given interval [16,18] Hz. The value of f_n presents the equality of reliability indices and the equality case $u_i^a = - u_i^b$. The SP method reduces the computing time by 91% relative to the hybrid method. In the hybrid problem (19), we need a high computing time because of the big number of optimization variables and of constraints relative to hybrid problem (15). The advantage of the SP method is simple to be implemented on the machine and to define the eigen-frequency of a given interval and provides the designer with reliability-based optimum solution with a small tolerance relative to the hybrid method. So this method can be also a conjoint of the OSF method.

Table 3

Таблица 3

Results of the aircraft wing for the second case

Результаты применения методов для второго случая

	Variables	Initial design	Optimum design with SP	Optimum design with HM
FN	A	0.04	0.04028	0.04204
	B	0.05	0.04046	0.04664
	C	1	0.95020	0.9979
	D	0.425	0.46234	0.42683
FA	A1	0.02	0.02730	0.02639
	B1	0.02	0.02004	0.02615
	C1	0.9	0.90021	0.90971
	D1	0.5	0.49983	0.49124
FB	A2	0.06	0.05346	0.05739
	B2	0.08	0.06088	0.06669
	C2	1.1	1.0002	1.0921
	D2	0.35	0.42485	0.36206
	FA	15.60	16.001	16.100
	FB	18.55	17.999	17.908
	FN	16.91	16.920	16.874
	DIF = β1-β2	0	-0.00578	0.10125
	surface	0.334	0.279	0.320
	Time(S)	-	230	2700

Conclusion

A RBDO solution that reduces the structural weight in uncritical regions both provides an improved design and a higher level of confidence in the design. The classical RBDO approach can be carried out in two separate spaces: the physical space and the normalized space. Since very many repeated searches are needed in the above two spaces, the computational time for such an optimization is a big problem. The structural engineers do not consider the RBDO as a practical tool for design optimization. Fortunately, an efficient method called the Hybrid Method (HM) has been elaborated where the optimization process is carried out in a Hybrid Design Space (HDS). However, the vector of variables here contains both deterministic and random variables. The RBDO problem by HM is thus more complex than that of deterministic design. The major difficulty lies in the evaluation of the structural reliability, which is carried out by a special optimization procedure. The use of HM necessitates a high computing time and a complex implementation. The SP method is proposed to overcome this drawback. As it is shown in the numerical application on a composite aircraft wing under free vibrations, the SP method can reduce efficiently the computing time relative to the HM.

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Об авторе:
Гиас Харманда,
приглашенный научный сотрудник кафедры биомедицинской инженерии Лундского университета (Ole Römersväg 1, Box 118, 221 00 Lund, Sweden),
ORCID: http://orcid.org/0000-0002-8344-9270
ghias.kharmanda@bme.lth.se

Author:
Ghias Kharmanda,
guest researcher of the Department of Biomedical Engineering, Lund University (Ole Römersväg 1, Box 118, 221 00 Lund, Sweden),
ORCID: http://orcid.org/0000-0002-8344-9270
ghias.kharmanda@bme.lth.se