

Analysis of dynamic contact inside the piezoelectric motor using the RBDO

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ABSTRACT. In this paper, we present a study about the Reliability-Based Design Optimization analysis (RBDO) of the piezoelectric engines with travelling wave taking into account the dynamic contact between the different components (stator and rotor). Generally, the life of these motors is limited by important abrasion of the different components. So, the notion of random variables and the risk of failure must be integrated in the mechanical analysis to ensure the good working of the system. The numerical treatment of the dynamic contact is presented and discussion of two different approaches about RBDO is given. The numerical tests show the efficiency of our proposed approach named dynamic hybrid method.

KEYWORDS: Reliability analysis, Finite element analysis, Reliability-based design Optimization, Dynamic contact.

1. Introduction

The modeling of the piezoelectric motors with travelling waves implies a large variety of physical and mechanical phenomena. This variety leads to approaches and models quite as many and varied, which rest mainly on phenomenological and numerical analyses.

Many sources of energy were explored to ensure the excitation of the vibrations of volume on the stator element of the motor. The most significant results were recorded with devices exploiting of the forces: electromagnetic, electrodynamics, magnetostrictive or piezoelectric. Japan took over this work since the beginning of the years 1980, with significant means which in particular allowed the design and then the first industrial developments of piezoelectric motors (driving SHINSEI, engines of Zoom of the apparatuses auto focus GUN...) are appeared.

The generation of a progressive wave of volume imposes the respect of geometrical and mechanical constraints related to the periodicity of the motors structure. Under normal conditions of operation, the motors are subjected to:

- An axial static loading of pre-stressing producing axial and radial deformations stator and rotor,
- A dynamic excitation of the stator, involving deformations of bending out-plan, which produce by drive a rigid displacement of the rotor's body,
- Efforts of contact and friction, static and dynamic in the interface of contact between the stator and the rotor.

The aim of this study is to propose a numerical modelling by the finite element method of the mechanical behaviour of piezoelectric motor SHINSEI USR 60 pennies dynamic loading taking into account the contact without friction by using the reliability based design optimisation.

Contact problems are treated using an augmented Lagrangian approach to identify the candidate contact surface and contact stresses [1] and the dynamic treatment is solved using a time integration scheme. The time integration parameters are specially selected to ensure that the solution of dynamic contact problem in unconditionally stable and reduce significantly the spurious high-frequency modes, which persist in the traditional Newmark method.

The stochastic role of each parameter of design in the default risk is highlighted. we model the Young's modules of three materials and the external loading by the normal law. For this reliability analysis of the structure, we propose a coupling direct mechanic-reliability between the augmented Lagrangian method to solve the contact, developed on a computer code by finite elements, and the response surface method [2].

Generally, the purpose of the Reliability-Based Design Optimization (RBDO) is to design structures that should be economic and reliable by introducing safety criteria in the optimization procedure. This method is used to perform new design to the studied motor. The results obtained enable us to propose a whole of recommendations to optimize the reliability of the piezoelectric motor SHINSEI USR 60..

2. Brief description of the dynamic contact

2.1 Treatment of the contact

Unilateral contact between solids is generally governed by two constraints which can be written as follows:

$$\begin{aligned} u_N - \delta < 0 &\Rightarrow r_N = 0 \\ u_N - \delta = 0 &\Rightarrow r_N \leq 0 \end{aligned} \tag{1}$$

where δ represents the gap between the contacting bodies, u_N the normal component of the displacement field and r_N the normal reaction [3].

From the Hamilton principle, the system energy and work of external forces can be written in the following form:

$$\begin{aligned} \Pi(u) = & \int_{t_1}^{t_2} \int_V \frac{1}{2} \varepsilon^T D \varepsilon dV dt - \int_{t_1}^{t_2} \int_V \frac{1}{2} \rho \left(\frac{du}{dt} \right)^T \left(\frac{du}{dt} \right) dV dt \\ & - \int_{t_1}^{t_2} \int_{S_1} u^T P dS dt - \int_{t_1}^{t_2} \int_{S_2} u^T R dS dt - \int_{t_1}^{t_2} \int_{S_c} u^T R_C dS dt \end{aligned} \quad (2)$$

Enforcement of the zero-penetration condition on contacting boundaries yields:

$T^T u - \delta \geq 0$, $u \in S_c$. Where, ε is the strain vector; D is the material matrix; ρ is the mass density; u is the displacement vector; P is the external load vector; R is the reaction force vector on prescribed displacement boundary; T is the contact constraint matrix; S_1 is the boundary with prescribed external forces; S_2 is the boundary with prescribed displacements and S_c is the contacting boundary.

The augmented Lagrangian approach relative to the dynamic contact problem is given by the weak form of the equilibrium state:

$$\Pi^*(u, \delta u) = \Pi(u, \delta u) + \int_{t_1}^{t_2} \int_{S_c} (T^T \delta u - \delta)^T r_N dt \quad (3)$$

where δ is the gap between two contacting bodies.

This nonlinear equation must be solved but it can not be solved directly, so r_N is considered as known via an iterative process using the Newton-Raphson method. The reaction r_N is written in function of a Lagrange multiplier and a penalty coefficient as follows:

$$r_N = \lambda_n + \varepsilon_n u_n \quad (4)$$

2.2 Integration time algorithm

The finite difference method is employed in the time domain to establish a relationship between acceleration, velocity and displacement fields. The Newmark method, the most frequently used implicit time integration scheme, allows us to approximate velocities and displacements at time $t+\Delta t$ as follows:

$$\overset{t+\Delta t}{U} = \overset{t}{U} + [(1-\gamma)^t \overset{t}{\ddot{U}} + \gamma \overset{t+\Delta t}{\ddot{U}}] \Delta t, \quad (5)$$

$$\overset{t+\Delta t}{U} = \overset{t}{U} + \overset{t}{\dot{U}} \Delta t + [(\frac{1}{2} - \beta)^t \overset{t}{\ddot{U}} + \beta \overset{t+\Delta t}{\ddot{U}}] \Delta t^2, \quad (6)$$

It has been shown that the use of the trapezoidal rule ($\gamma=0.5$ and $\beta=0.25$) with a fully implicit treatment of the contact constraints produces oscillations, which can be significant as the time steps and spacial discretization are defined. Recently, the generalized- α method was developed for solving structural dynamics problem with second-order accuracy [4]. In this method, the equation of motion is modified as follows:

$$M^{(t+\Delta t)-\alpha_B} \ddot{U} + C^{(t+\Delta t)-\alpha_H} \dot{U} + K^{(t+\Delta t)-\alpha_H} U = {}^{(t+\Delta t)-\alpha_H} F, \quad (7)$$

where

$${}^{(t+\Delta t)-\alpha_H} U = (1 - \gamma)^{t+\Delta t} U + \alpha_H {}^t U, \quad (8)$$

$${}^{(t+\Delta t)-\alpha_H} \dot{U} = (1 - \alpha_H)^{t+\Delta t} \dot{U} + \alpha_H {}^t \dot{U}, \quad (9)$$

$${}^{(t+\Delta t)-\alpha_B} \ddot{U} = (1 - \alpha_B)^{t+\Delta t} \ddot{U} + \alpha_B {}^t \ddot{U}, \quad (10)$$

$${}^{(t+\Delta t)-\alpha_H} F = (1 - \alpha_H)^{t+\Delta t} F + \alpha_H {}^t F, \quad (11)$$

The time integration scheme (7) is used to solve the above equation of motion. In this study, we choose $\gamma=0.5$ and $\beta=0.25$, with the additional parameters $\alpha_B = 0.5$ and $\alpha_H = 0.5$ for the integration constants. These parameters result in second-order accuracy, unconditional stability, energy and momentum conservation, and do not cause numerical dissipation [5]. For linear problems, both the generalized- α and the Newmark trapezoidal schemes involve the same percentage error elongation and do not cause amplitude decay. Furthermore, the proposed scheme improves convergence in contact problems.

3 Reliability contact analysis

Several parameters are uncertain in this contact problem. In fact, physical tests or measures show that the mechanical properties, the geometrical characteristics of structure elements or applied loads could be random and follow statistical distributions. Thus leads to define a probabilistic model. In general, random variables give a good representation of structural stochastic parameters.

Let $X = (X_1, X_2, \dots, X_m)^T$ be the random vector of the probabilistic analysis. To preserve the integrity of the structure, the failure mode must be defined and the corresponding limit state function $G(X)$ established. In a unilateral contact problem, the real contact surfaces and the contact reactions depend on the values of design parameters which are uncertain. Thus, excessive stresses or strains could appear in an element of the structure. The contact surfaces could not conform to a standard of a geometrical rule and lead to a structural failure. So, problems involving contact are an adequate domain for a reliability analysis.

The structure is situated in its safe domain D_s if $\{G(X) > 0\}$ and it is situated in its failure domain D_f if $\{G(X) \leq 0\}$. Then, the failure probability is:

$$P_f = \Pr ob(G(X) \leq 0) \quad (12)$$

Our purpose is a reliability analysis of a structure where a frictionless contact occurs between two solids. In this situation, the analytical expressions of the limit state function G and its derivatives are often not available in function of the physical random variables X_1, X_2, \dots, X_m . Then, it is only possible to obtain the failure probability under an implicit numerical form. So, to solve our reliability contact problem, a combination between

the augmented Lagrangian method coupled with the finite element method and the response surface method is proposed.

The response surface methods have been widely developed in nonlinear reliability analysis. Several authors have proposed solutions to improve the accuracy of results, to decrease the number of necessary numerical calculations on FEM codes and to increase the robustness of the algorithms.

In our nonlinear study, we propose an adaptive surface method coupled with the first order reliability method (FORM) [6]. The sets of design points and the response surfaces are generated in the space of standard Gaussian variables. The scheme of the adaptive process is given as follows:

- $k = 1$, the generated set of points is a central composite design. Its centre coordinates are the mean values of random variables. $d^{(1)}$ is a fixed real number and the distance from the central point to a 'corner' in the design is equal to $\sqrt{md^{(1)}}$. So

$$\begin{cases} \mathbf{u}^{(k,1)} &= (0,0,\dots,0)^T \\ \mathbf{u}^{(k,r)} &= (0,\dots,\pm d^{(k)},\dots,0)^T, \quad r = 2, \dots, 2m+1 \\ \mathbf{u}^{(k,r)} &= (\pm d^{(k)}, \pm d^{(k)}, \dots, \pm d^{(k)})^T, \quad r = 2m+2, \dots, 2^m + 2m+1 \end{cases} \quad (13)$$

- The response surface $\tilde{h}^{(k)}(\mathbf{u})$ is a second order polynomial with crossed terms:

$$\tilde{h}^{(k)}(\mathbf{u}) = a_0 + \sum_{i=1}^n a_i u_i + \sum_{i=1}^n \sum_{j=1}^n a_{ij} u_i u_j \quad (14)$$

- The polynomial coefficients identification is done by the least square method

$$E^{(k)} = \sum_{r=1}^p w_r [\tilde{h}^{(k)}(\mathbf{u}^{(k,r)}) - h(\mathbf{u}^{(k,r)})]^2 \quad (15)$$

$$\frac{\partial E^{(k)}}{\partial a_i} = 0 \quad i = 0, \dots, N_h \quad (16)$$

$p = 2^m + 2m + 1$ and $N_h = (m + 1)(m + 2) / 2$ is the number of coefficients of the function $\tilde{h}^{(k)}(\mathbf{u})$. $w_r = 1$.

- The SQP optimisation algorithm [7] is used to compute the reliability index $\beta_{HL}^{(k)}$ and the design point $\mathbf{u}^{(k,r)}$, solutions of the following minimization problem:

$$\beta_{HL}^{(k)} = \text{Min} \sqrt{\mathbf{u}^t \mathbf{u}} \quad \text{subjected to: } \tilde{h}^{(k)}(\mathbf{u}) = 0 \quad (17)$$

- $k = k + 1$, generation of a new set of points. Its centre is the point $\mathbf{u}^{(k-1,r)}$ and the distance from the central point to a "corner" in the design is equal to $\sqrt{md^{(k)}}$ with

$$d^{(k)} = d^{(k-1)} / q \quad (18)$$

$q > 1$ is a real number which plays the role of a zoom factor,

$$\begin{cases} u^{(k,r)} = u^{(k-1,r)} \\ u^{(k,r)} = (u_1^{(k-1,r)} \pm d^{(k)}, \dots, u_i^{(k-1,r)} \pm d^{(k)}, \dots, u_m^{(k-1,r)} \pm d^{(k)})^T, r = 2, 2m+1 \\ u^{(k,r)} = (u_1^{(k-1,r)} \pm d^{(k)}, u_2^{(k-1,r)} \pm d^{(k)}, \dots, u_m^{(k-1,r)} \pm d^{(k)})^T, r = 2m+2, 2^m+2m \end{cases} \quad (19)$$

Repeat (13)-(17) until a test of convergence on $\beta_{HL}^{(k)}$ stops the iterative algorithm. Then the failure probability is evaluated by the first order reliability method

$$P_f \approx \Phi(-\beta_{HL}) \quad (20)$$

$u = (u_1, u_2, \dots, u_m)^T$ is a realization of the random vector U . $\tilde{h}^{(k)}(u)$ is the approximated limit state function in the space of standard Gaussian variables. U is the image of X by the probabilistic transformation and Φ is the standard normal distribution function.

This iterative scheme is particularly efficient. The adaptive central composite designs give a very good representation of the random variables domain. The second order polynomial and the least square method assure a good compromise between the computational effort and the approximation accuracy of the real limit state function $h(u)$. The number of necessary calculations is reasonable and depends on the number of variables. The SQP algorithm is robust and efficient for this application in nonlinear finite element reliability analysis.

4 Reliability based design optimization

The ultimate goal of the design under uncertainty is to reach an optimum in terms of total cost. In principle, an optimum balance between structural system reliability and other conflicting societal goals must be obtained. This is a difficult task. Traditionally, the solution of the RBDO model is achieved by alternating reliability and optimization iterations. This approach leads to low numerical efficiency, which is disadvantageous for engineering applications on real structures. In order to avoid this difficulty, the hybrid RBDO methods are proposed [8,9]. In the same direction, we propose the dynamic hybrid method [10]. The efficiency of this method is showed in [11].

4.1 Dynamic hybrid method

The solution of the above nested problems leads to very large computational time, especially for large-scale structures. In order to improve the numerical performance, the hybrid approach consists on the minimization of a new form of the objective function $F(\{x\}, \{y\})$ subject to a limit state and to deterministic as well as to reliability constraints:

$$\begin{aligned}
 \min & : f(\{x\}) \cdot d_\beta(\{x\}, \{y\}) \\
 \text{subject to} & : G(\{x\}, \{y\}, t) \leq 0 \\
 & : d_\beta(\{x\}, \{y\}, t) \leq \beta_c(t) \quad \forall t \in [0, T] \\
 \text{and} & : g_k(x, t) \leq 0
 \end{aligned} \tag{18}$$

In the case $t = 0$ (static problem), $d_\beta(\{x\}, \{y\})$ is the distance in the hybrid space between the optimum and the design point, $d_\beta(\{x\}, \{y\}) = d(\{u\})$. The minimization of the function $F(\{x\}, \{y\})$ 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 1, 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 $G(\{x\}, \{y\}) = 0$. 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 $G(\{x\}, \{y\}) = 0$ and $d_\beta = \beta_t$).

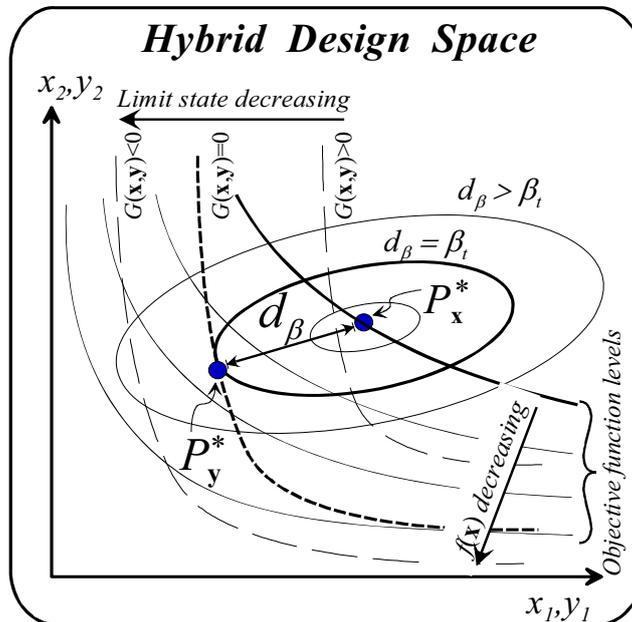


Figure 1. Hybrid Design Space in the case $t = 0$.

5 Numerical results

We present a study on the Reliability based design optimisation on the stator and the rotor of a piezoelectric motor with annular progressive wave SHINSEI USR 60 (figure 2), which will be subjected to the constraint stress [12].

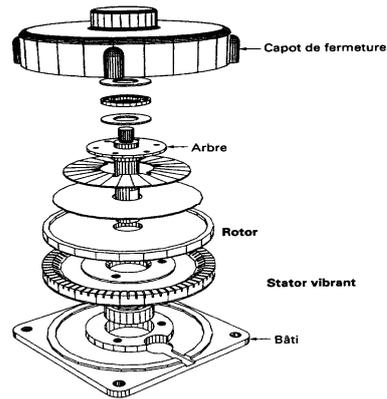


Figure 2. Motor SHINEI USR 60

The objective of this application is to demonstrate the efficiency of the RBDO in the case of the dynamic contact problem. We minimize the cost of structure subject to the stress constraint and the target reliability index constraint.

Figure 3 shows the geometrical dimensions cross section of the stator and the rotor. The body force F_{ext} on the SHINSEI USR 60 motor, is transmitted to the rotor at the ratio $R=21.10^{-3} m$ with the value 140N. The mechanical characteristics of different material and geometry are given in tables 1 and 2 respectively.

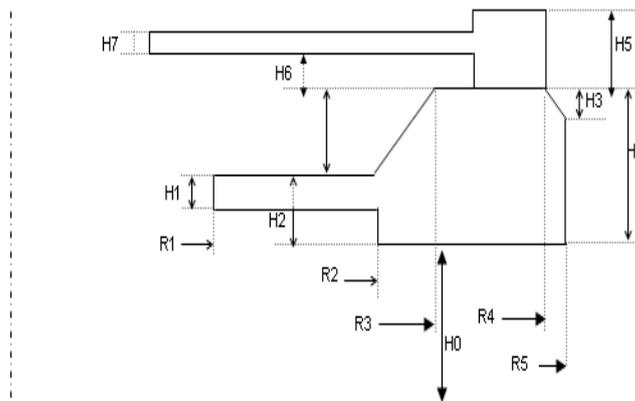


Figure 3. Dimensions cross section of stator and rotor

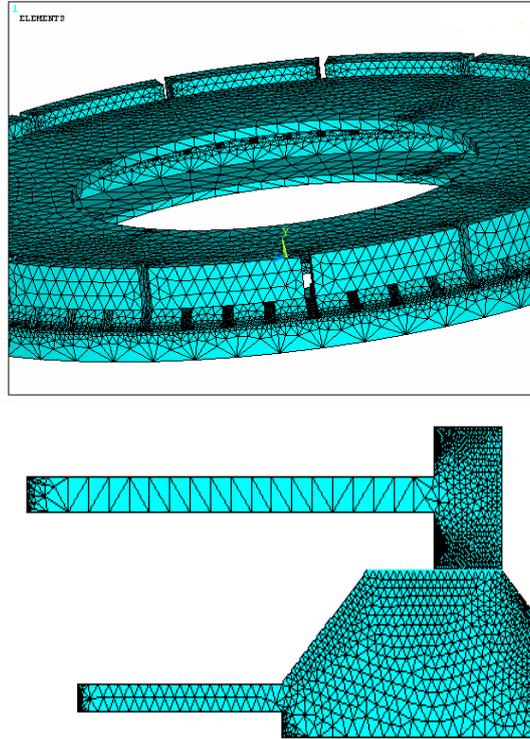


Figure 4. Finite elements of stator and rotor

parameter	H0	H1	H2	H3	H4	H5	H6	H7	R1	R2	R3	R4	R5
(mm)	0.5	0.6	1.2	1	4.2	3.2	1.3	2.1	16.5	22.5	25	29	30

Table 1. Geometry characteristics

Rotor		Stator	
E (MPa)	ρ (Kg/m ³)	E (MPa)	ρ (Kg/m ³)
27000	2700	123000	8250

Table 2. Mechanical characteristics

The treatment of the dynamic contact between the rotor and the stator is discussed in [13]. Firstly, we present here different subjects for RBDO approach: the objective(s), the design variables, the system response, the limit states, and the solution technics and secondly, we give the classical, the hybrid RBDO method and the dynamic hybrid method.

DDO problem:

1- Optimization problem:

We minimize the cross-section area subject to eigen-frequency constraint as the following:

$$\begin{aligned} \min : & \text{Surface}(H0, H2, H3, H5, H6, H7) \\ \text{subject to } & \sigma(H0, H2, H3, H5, H6, H7) - \sigma_c = 0 \quad (22) \end{aligned}$$

2- Reliability analysis of the optimal solution:

For a normal distribution, the normalized variable u has the following form:

$$u_i = \frac{x_i - m_{x_i}}{\sigma_{x_i}} \quad (23)$$

with $\{x_i\} = \{H0, H2, H3, H5, H6, H7\}$.

In order to compute the reliability index introduced by Hasofer and Lind [6], we have to formulate two sub-problems

$$\beta_1 = \min d_1(\{u\}) = \sqrt{\sum_1^m u_j^2} \quad (24)$$

subject to : $\sigma(H0, H2, H3, H5, H6, H7) - \sigma_c = 0$

RBDO problem:

The classical RBDO approach leads to a weak stability of convergence but the hybrid method allows the coupling between the reliability analysis and the optimization problem. The hybrid RBDO problem can be expressed as:

$$\begin{aligned} \min & : f((H0, H2, H3, H5, H6, H7)) \cdot d_\beta(\{x\}, \{y\}) \\ \text{subject to} & : \sigma(H0, H2, H3, H5, H6, H7) - \sigma_{ad} = 0 \\ & : d_\beta(\{x\}, \{y\}, t) \leq \beta_c(t) \quad \forall t \in [0, T] \end{aligned} \quad (25)$$

where $H0, H2, H3, H5, H6$ and $H7$ are grouped in the random vector $\{Y\}$ but to optimize the design, the means m_{D1}, m_{D2}, m_{D3} and m_{H3} are grouped in the deterministic vector $\{x\}$, and their standard-deviation equals to $0.1 m_x$.

Variable	DDO		RBDO	
	Design Point	Optimum Solution (safety factor 1.5)	Design Point	Optimum Solution
H0	0.52195×10^{-3}	0.53998×10^{-3}	0.57767×10^{-3}	0.71853×10^{-3}
H2	0.11563×10^{-2}	0.12749×10^{-2}	0.11494×10^{-2}	0.13036×10^{-2}
H3	0.66719×10^{-3}	0.99276×10^{-3}	0.87807×10^{-3}	0.11079×10^{-3}
H5	0.32564×10^{-2}	0.24628×10^{-2}	0.25716×10^{-2}	0.23572×10^{-2}
H6	0.12530×10^{-2}	0.13973×10^{-2}	0.80493×10^{-3}	0.87639×10^{-3}
H7	0.20121×10^{-2}	0.20821×10^{-2}	0.14356×10^{-2}	0.13696×10^{-2}
Stress	0.23564×10^9	0.23530×10^9	0.2358×10^9	0.1560×10^9
Reliability index	3.6	-----	3.8	----

Table 3. Results of RBDO in stator and rotor

Variable	Design Point (a)	Optimum Solution	Design Point (b)
R2	22.211×10^{-3}	21.214×10^{-3}	20.76×10^{-3}
R3	25.59×10^{-3}	23.959×10^{-3}	25.4×10^{-3}
R4	29.66×10^{-3}	27.925×10^{-3}	28.33×10^{-3}
H1	0.428×10^{-3}	0.562×10^{-3}	0.678×10^{-3}
H2	1.345×10^{-3}	1.483×10^{-3}	1.549×10^{-3}
H3	1.5×10^{-3}	1.318×10^{-3}	1.66×10^{-3}
H4	3.66×10^{-3}	3.435×10^{-3}	3.489×10^{-3}
β	3.65×10^{-3}	-----	3.6
Frequency [KHz]	37.2	39.5	41

Table 4. Results of RBDO in stator

Tables 3 and 4 show the RBDO results when using the different distribution laws. Here, we improve the optimum value of the structural volume and satisfy the required reliability level for the same initial design but we need more computing time relative to the lognormal distribution case.

6 CONCLUSION

The solution of DDO problem can be improved by the use of RBDO model in order to satisfy the safety requirements. When solving the reliability-based optimization problem in a hybrid space containing random and deterministic variables, we obtain all numerical information about the optimization process that leads to a good efficiency for practical cases.

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