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Lightweight Design of Automotive Front Side Rail Based on Robust Optimisation

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Abstract

Nowadays, both conventional automobiles and new energy cars require urgently the lightweight design to realise energy economy and environmental protection in a long run. The weight reduction of body structure plays a rather important role in decreasing the weight of full vehicle. In the real engineering problems, the variation in sheet gauge, geometrical size and material parameters, caused by environmental factors and other uncertainties, may affect the structural performances of body parts. Therefore, the lightweight design without considering this kind of tolerance may result in the loss of feasibility and reliability in engineering application. In this work, based on robust optimisation method, the study on the front side rail lightweight design is performed. The response surface method (RSM), coupled with design of experiment (DOE) technique, is employed to create the approximate functions of structural performances. The robust optimisation and deterministic optimisation formulations are constructed, respectively, for comparison. The solutions are obtained by using the sequential quadratic programming (SQP) algorithm. The lightweight design, considering the impact of the tolerance of sheet gauge, mechanical parameters of material and structural performances, is still guaranteed to be reliable when structural random varieties are present. The weight reduction achieved by using robust optimisation reached 29.96%.

Keywords: Front side rail; Lightweight design; RSM; Robust optimisation; DOE; Structural crashworthiness

1. Introduction

Energy economy and environmental protection are the crucial problems needed to be solved urgently facing the automotive industry all over the world in the 21st century. It is stated that oil consumption may decrease 6–8% once the lightweight effect of full vehicle reaches 10% [1]. Vehicle weight reduction is a primary and necessary way to realise energy savings and oil economy, which promotes the lightweight technology to be a hot research area. The weight reduction in body structure plays a rather important role in decreasing the weight of full vehicle, which results from the fact that body structure possesses about 30% weight of full vehicle.

A perusal of available related literature, some of which are outlined here, revealed that a quantity of study in lightweight design and application in body structures have been developed. The ultralight steel material was used in the lightweight design of automotive closures [2]. Structural foam material was applied in bumper and B pillar structures, reaching the lightweight effect of 37% with the guarantee of original structural performances [3]. Topology optimisation technique was utilised in the lightweight design of the air suspension and frame cross member [4]. The design of car doors was performed with the application of lightweight material and structures [5]. The lightweight design of body structure was developed, from the point of view of crashworthiness performance of full vehicle, with the application of the high strength steel and aluminium alloy materials, respectively [6]. The utility of aluminium alloy material and the improvement of structural design were integrated to achieve a satisfactory lightweight effect of the bonnet [7]. The response surface method (RSM) was applied to develop an optimisation formulation for the lightweight design of a front side rail structure [8].

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It is required that the structural performances should be guaranteed in the lightweight design of body structures. But in the open literature about autobody lightweight designs, the uncertainty in the gauge thickness, geometrical size and mechanical parameters of material is not considered during the design optimisation process, which may rise to the variation of the structural performance and make the optimum fail to meet the requirements of structural performances. The robust design, considering the variation of design variables, noise factors and structural performances, can avoid the above problem and make the lightweight solution still feasible even when the environmental random factors are considered. Based on the robust optimisation method, this paper addresses the lightweight design of the front side rail structure, by considering the tolerance of factors such as gauge thickness, yield limit of material and variation of structural performance.

2. Worst-case robust design methodology

Parkinson et al. [9,10] pointed out that robust design is an optimisation problem in essence. A key concept in robust design is that the variation of design variables and random parameters will be transferred to performance functions, leading to the variation of objective and constraint functions. The robustness of engineering problems can be identified in two categories: sensitivity robustness and feasibility robustness. It means that when the sensitivity of the objective function to the variables is reduced, the constraint conditions should also be satisfied when considering the variation caused by the fluctuation of variables. The conventional deterministic optimisation formulation is as follows:

$$\begin{aligned}
&Min && f(x,z) \\
&Set. && g_j(x,z)\leqslant 0, \\
& && x^L\leqslant x\leqslant x^{\mathrm{U}}, \qquad i=1,2,\cdots,m. \\
& && X=(x_1,x_2,\cdots,x_n)^T, \\
& && Z=(z_1,z_2,\cdots,z_k)^T,
\end{aligned} \tag{1}$$

Where x and z are vectors for design variables and uncontrollable variables, and $f(x, z)$ and $g_j(x, z)$ are objective functions and the jth constraint function of m constraints, respectively. x^L and x^U are lower and upper bounds. In a general engineering problem the performance indicator is frequently a nonlinear function of both design and uncontrollable variables. The nonlinear function can be approximated with linearisation approach when the variation of design variables and noise factors is very small and it changes continuously[11]. It is reasonable to use the first-order Taylor series and the function can be formulated as follows:

$$f\approx f(\bar{x},\bar{z})+\sum_{i=1}^{n}\left(\frac{\partial f}{\partial x_i}\right)\Delta x_i+\sum_{i=1}^{k}\left(\frac{\partial f}{\partial z_i}\right)\Delta z_i. \tag{2}$$

To guarantee the feasibility of design optimum, the variation of constraint functions must be considered. The worst-case approach is much more convenient and also suitable in the situation where the probability distribution attributes of design and uncontrollable variables are unknown. The variation of constraint function is obtained as follows:

$$\Delta g=\sum_{i=1}^{n}\left|\left(\left.\frac{\partial g}{\partial x_i}\right|_{\bar{x},\bar{z}}\right)\Delta x_i\right|+\sum_{i=1}^{k}\left|\left(\left.\frac{\partial g}{\partial z_i}\right|_{\bar{x},\bar{z}}\right)\Delta z_i\right|. \tag{3}$$

In the situation where the constraint function is highly nonlinear and the fluctuation of variables is large, the second-order terms should be added to the approximate function. It can be formulated as follows:

$$\Delta g=\sum_{i=1}^{n+k}\left|\left(\left.\frac{\partial g}{\partial b_i}\right|_{\bar{x},\bar{z}}\right)\Delta b_i\right|+\frac{1}{2}\sum_{i=1}^{n+k}\sum_{j=1}^{n+k}\left|\left(\left.\frac{\partial g}{\partial b_i\partial b_j}\right|_{\bar{x},\bar{z}}\right)\Delta b_i\Delta b_j\right|. \tag{4}$$

Generally the robust optimisation problem can be formulated as follows [11]:

$$\begin{array}{llllll}
Min & \Phi(x)=E(f(x,z)) & & Min & \Phi(x)=Var(f(x,z)) \\
S.t. & g_j(\bar{x},\bar{z})+\Delta g_j\leqslant 0, & & S.t. & g_j(\bar{x},\bar{z})+\Delta g_j\leqslant 0, \\
or & g_j(\bar{x},\bar{z})+\Delta g_j\leqslant 0, & & or & g_j(\bar{x},\bar{z})+k\sigma_{gj}\leqslant 0, \\
 & Var(f(x,z))-\varepsilon\leqslant 0, & & & (E(f(x,z))-y_0)^2-\varepsilon\leqslant 0, \\
 & x^L\leqslant\bar{x}\pm\Delta x\leqslant x^{\mathrm{U}}, & or & & x^L\leqslant\bar{x}\pm\Delta x\leqslant x^{\mathrm{U}},
\end{array} \tag{5}$$

where x^L and x^U are lower and upper bounds and $g_j(\bar{x},\bar{z})$ and σ_{gi} are the mean and standard deviation of the jth constraint function, respectively.

3. Lightweight design of front side rail based on robust optimisation

Front side rail is a key part of energy absorption in the frontal crash and its structural crashworthiness performance is commonly represented by the deformation mode and the absorbed energy. This can affect greatly the crash performance of full vehicle. Therefore the structural crashworthiness performance of the front side rail should be guaranteed primarily in the lightweight design process. The lightweight design has been treated as an optimisation problem in the previous study[8,12–14], where structure weight is the objective function subject to the structural performance constraints. But to ignore the impact of the tolerance of design variables, the random noise factor may result in the designed lightweight structure unable to meet the requirements of structural crashworthiness performances, which makes the design suffer from reliability and feasibility.

In this study, the high strength steel material is used in the lightweight design of the front side rail, instead of the original mild steel. The material parameters are shown in Table 1. Based on the above determined lightweight structure with the high strength steel material, we will