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Electric Bus Frame Optimization for Side-Impact Safety and Mass Reduction Based on the Surrogate Model Method

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Abstract

The body strength, stiffness and crashworthiness are the key aspects for the mass reduction of the commercial bus body frame. Heavy computation cost is one of the critical problems by the finite element (FE) method to accomplish a high-efficient multi-objective optimizing design. Starting from this point, in this paper, the surrogate model method is adopted to optimize the electric bus frame to reduce the mass as possible while guaranteeing the side-impact strength. The optimizing objective comprises the total mass and side-impact intrusion while the performances of static strength and stiffness in bending and torsion conditions are chosen as the constraints in optimization. First, an FE model is developed to perform the static strength analysis, modal analysis and side-impact strength analysis. Nine groups of candidate variables are determined as the optimizing design variables by sensitivity analysis. Then surrogate models have been formulated based on the methods of least squares regression (LSR) and radial basis function neural network (RBFNN). The precision of the surrogate models are evaluated and validated by comparing with the FE simulation results. Based on the surrogate models the bus body frame is finally optimized by the multi-objective genetic algorithm (MOGA) method. With the optimized parameters, the performance of the body frame is evaluated by comparing with that before optimizing. It is demonstrated that the design objective of lightweight (mass reduction) has been achieved and the side-impact crashworthiness have been improved as well while guaranteeing the basic performance including the static strength and stiffness.

Introduction

With the rapid development of automobile industry, the problems such as energy consumption, exhaust emission, and traffic safety become rather critical. As an alternative solution to these problems, electric vehicles have attracted more and more attention in recent years. Mass reduction is of great significance for an electric vehicle from the viewpoint of energy saving and environment protection. It is one of the great important aspects to guarantee the performance of strength and stiffness of vehicle body in the mass reduction design. Many researchers both in academia and industry realm have made great effort to the issues related to vehicle mass reduction design. Vehicle mass reduction is generally realized by optimizing design of the body structure, using lightweight materials or improving the manufacturing process [1, 2, 3, 4]. The common methods for structural optimization include topology optimization, size optimization and shape optimization. Lan *et al.* [5] investigated the mass reduction design for the automobile steering knuckle by topology optimization, and after optimizing the mass reduction is realized and also the stiffness is increased significantly. In [6] the vehicle body is optimized by combining topology optimization with sensitivity analysis. A multi-objective optimizing design orienting the crashworthiness and mass reduction for the front structure of the vehicle body is presented in [7]. The related studies on automobile collision safety are mainly carried out from the perspectives of vehicle collision, occupant protection, pedestrian protection and so on [8, 9, 10, 11]. For the structural optimization of electric vehicles, the strength and crashworthiness of vehicle body frame should be particularly emphasized for the sake of battery protection [12].

Now finite element (FE) based simulation is widely used in automobile structural design and analysis. Model-based design can provide early feedback before physical components are manufactured and tested to shorten the research and development time of the final product [13]. However, some strong nonlinear problem, *e.g.* FE based crashworthiness analysis and optimization generally costs much computing resource or even leads to failure. As an alternative method to solve such problem, surrogate model based method is often used in automobile structure optimizing. The surrogate model which is a fitted model relating the design variables to the output response is able to replace the complex FE model for optimizing design [14, 15, 16, 17, 18, 19, 20]. In [21], an improved response surface method is proposed to establish a surrogate model for automobile crashworthiness oriented design, and a sequential quadratic programming algorithm is used to optimize multiple groups of structure parameters. In [22], for the uncertainties introduced by meta-models and

5.3. Evaluation and Analysis

The value of optimized design variables is rounded to meet the engineering application and shown in Table 10. With the optimized parameters, a group of FE simulation is carried out to evaluate the optimized scheme comparing with that before optimizing and the result is illustrated in Table 11.

It is noted from Table 11 that the first-order natural frequency in extreme bending and torsion condition is respectively 5.13Hz and 2.93Hz, and respectively increases by 8.48% and 6.48% comparing with that before optimization. The maximum stress and deformation is respectively 243.5MPa and 11.67mm, and respectively increases by 45.28% and 21.60% comparing with that before optimization. Though the peak stress has increased remarkably, there is still a large gap to the stress limit (355MPa) that is the safety coefficient is 1.45 which meets the engineering design requirement. Figure 16 presents the comparison of peak intrusion of the side-battery protective beam before and after optimization. We can find from the figure that the peak of the upper part intrusion (I_{up}) and the peak of the lower part intrusion (I_{down}) is respectively 92.4mm and 121.2mm and decreases by 13.41% and 19.41% respectively comparing with that before optimization. This obviously means the side-impact crashworthiness has been improved. The mass of the body frame decreases from 1032.3kg to 913kg that is 119kg (11.56%) is reduced after optimization and thus the mass reduction is obvious.

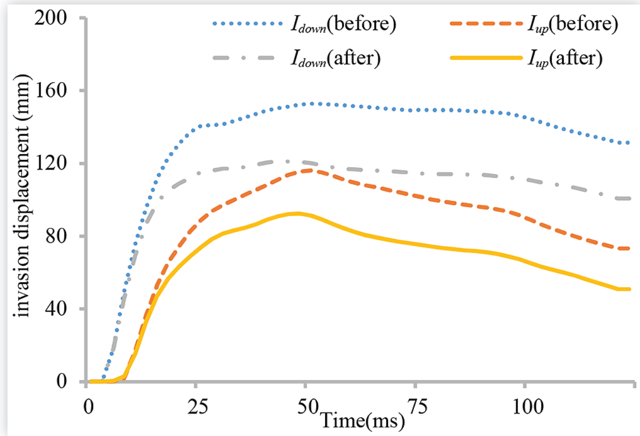
TABLE 10 Optimized results of the design variables.

Variables	Base value (mm)	Optimized (mm)	Rounded (mm)
S2	1.5	1.1196523	1.1
S3	1.5	1.0055196	1.0
S4	2.0	2.985268	3.0
S7	1.5	1.1712993	1.2
S9	1.5	0.7521095	0.8
S10	2.0	1.0136226	1.0
S11	1.5	0.770136	0.8
S13	1.5	1.0078593	1.0
S14	1.5	1.1048076	1.1

TABLE 11 Comparison of the performance indicator before and after optimization.

Performance indicator	Before optimization (mm)	After optimization	Variation
M(t)	1.0323202	0.912976	–11.56%
d_{sw}(mm)	7.3434431	10.18	38.63%
s_{sw}(MPa)	140.90271	219.4	55.71%
d_{sn}(mm)	9.5969368	11.67	21.60%
s_{sn}(MPa)	167.6103	243.5	45.28%
f_{1_sw}(Hz)	4.7295572	5.130743	8.48%
f_{1_sn}(Hz)	2.7588162	2.937655	6.48%
I_{up}(mm)	106.71087	92.4053	–13.41%
I_{down}(mm)	150.39317	121.208	–19.41%

FIGURE 16 Comparison of the peak intrusion before and after optimization.



6. Conclusions

This work investigates the optimizing design of the body frame of an electric bus orienting the mass reduction and side-impact safety based on the surrogate model method.

The surrogate models corresponding to the relevant performance of body frame have been formulated based on the methods of LSR and RBFNN. In real application, according to the certain concerned performance, the appropriate surrogate models are adopted since the characteristics and advantage of the surrogate models formulated by various methods may be much different. Hence, in this work we employ the surrogate model fitted by the LSR method for mass, static performance and side-impact intrusion, while for the natural performance we use the surrogate model fitted by the RBFNN method to obtain a high fitting precision. The bus body frame is optimized based on the surrogate models by the MOGA method and the objective of mass reduction and side-impact crashworthiness have been achieved, while the basic performance such as the static strength and stiffness can be guaranteed as well. Furthermore, the mass of the body frame is reduced by 11.56% and the peak intrusion of the upper and lower part of the side-battery protective beam is respectively reduced by 13.41% and 19.41% that is the crashworthiness is improved. It is reasonably to believe that the surrogate model method can be well used for vehicle optimizing design and the optimizing of the body frame of the electric bus in this work is feasible.

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