Title:
Optimal Design of the Battery Box Considering Uncertain Factors

Authors:
Chunrong Chen, 17crchen1@stu.edu.cn, Shantou University
Jian Zhang, jianzhang@stu.edu.cn, Shantou University
Qingjin peng, qingjin.peng@umanitoba.ca, University of Manitoba
Peihua Gu, peihua.gu@tju.edu.cn, Tianjin University

Keywords:
Optimization, Design, Battery box; Uncertainty; Safety

DOI: 10.14733/cadconfP.2019.132-136

Introduction:

Battery box plays an important role in the safety of electric vehicles compared to the traditional internal combustion engine vehicle [1]. Many accidents are caused by the deformation of the battery box under the vibration and impact that result in fire and even explosion. Therefore, it is necessary to understand the structural response of battery box under the vibration. Safety analysis under the vibration of structures can be considered in the time and frequency domains. As a typical method in the time domain, the rain flow cycle counting method cannot meet engineering applications due to its high computation demand. As a common method in the frequency domain, the spectral analysis has the low efficiency and high cost in computation. The current research on battery packs of electric vehicles is mainly on the energy utilization, thermal management [2], and structural strength design [3]. There is a lack of research on the safety design of battery box considering uncertain factors.

This research improves safety of the battery box in the optimal structure design considering uncertain variables. The goal is to reduce the maximum deformation and increase the minimum natural frequency of the battery box by optimizing structural parameters to ensure the safe operation of the battery box in different environments. Based on the existing research in the frequency domain, this paper combines the finite element method and uncertainty analysis to reduce the maximum deformation and increase the minimum natural frequency of the box structure under uncertain variables. Using the method of the uncertain optimization, an analytic process is conducted in design of a battery box structure with features of the high efficiency and low cost [4].

Main Idea:

Proposed method

A structural failure risk analysis is proposed by quantifying uncertainties for structural safety control and optimization. It considers uncertain factors of safety-related parameters using integrated finite element method and optimization algorithm to find design variables that meet requirements of the structural safety. The structural safety design searches the insensitivity of the system output under uncertain factors, which can reduce the deformation and increase frequency of the battery box. The finite element method is applied in the frequency domain to analyze the dynamic response of the battery box under uncertain conditions. The process steps are explained as follows.

Step 1: Initialization settings

According to the geometric model of the research object, the model discretization is processed for finite element modeling. The mesh quality and quantity of the discretized model are analyzed comprehensively considering the calculation accuracy. According to whether the first six modes are zero in the free model analysis results, the validity of the model is analyzed.

Step 2: Uncertainty constraint setting

Different model specifications and working conditions may lead to changes in parameters within a certain range, following uncertainties caused by changes in specifications and working conditions are considered:

a. Battery box models of different design materials lead to uncertainty of density parameters. Considering the most commonly used aluminum alloy materials, different density parameters are used according to different grades. The density *Di* distribution varies from 2.493 to 3.047 g/cm^3.

b. The working temperature is mostly affected by the working state of the internal battery. For the most commonly used 18650 lithium battery pack, the working temperature of *Ti* changes from - 20 to 50 ℃.

c. Different vibration sources and directions produce different excitation parameters for different vibration states, the battery box must meet the national safety standards. Based on the national standards, excitation values Fi is ranged from 5 to 200 Hz.

Step 3: Optimal design

There are two levels of the uncertainty optimization, namely uncertainty optimization and uncertainty design parameter optimization. The uncertain optimization here is to get the minimum deformation and maximum natural frequency parameter matrix of the analysis by taking the constraint interval as input, and the optimization of uncertain design parameters is to obtain the design variables satisfying the minimum deformation and the maximum frequency through the optimization algorithm as follows.

a. Uncertainty optimization model

$$\begin{gathered} min(f_1(X,U), \ldots, f_K(X,U)) \\ g_i(X,U) \le b_i^I \in [b_i^L, b_i^U],\ i=1,2,\ldots,m \\ X_K^L \le X_{Ki} \le X_K^U,\ j=1,2,3 \end{gathered} \tag{1}$$

Where $f_k(X,U)$ and $g_i(X,U)$ are objective functions and constraints, respectively; X is the optimization variable, U is an uncertain variable; b_i^I is the allowable interval of the ith uncertainty constraint; X_{Ki} is design variables, X_K^L and X_K^U are the range of values of design variables.

b. Design parameter optimization

$$\begin{gathered} min\ f(X)=f(X_i) \\ 1 \le i \le K \end{gathered} \tag{2}$$

Where $f(X_i)$ is the objective function and X_i is the ith design variable satisfying $min\ f(X)$.

According to results of Step 2, parameters of the wall thickness of the battery box are defined as input and the deformation and frequency of the box are defined as output. The parameter optimization module in ANSYS is used. In order to obtain the optimal solution set in the interval to ensure the efficiency of the optimization process, a mathematical iteration method of the local approximation is used in the analysis process.

According to the original model design parameters group, the control group is set up to decide whether the optimization design meets requirements according to the robustness index after optimization. In order to minimize the maximum deformation and maximize the minimum frequency of the battery box model under different conditions, it is necessary to search the robustness of the battery box model. The robustness index R is defined as follows.

$$R=f(X)_{max}\ (m<m_0) \tag{3}$$

Where the mass of optimized battery box m should be less than that of original battery box m_0, and $f(X)_{max}$ is the maximum deformation of the battery box. The smaller the maximum deformation of the battery box, the higher the strength of the box structure. While the larger the minimum natural frequency, the lower the probability of resonance with the car body is. The quality is improved after the optimization to indicate that the lightweight degree of the battery box is improved. Therefore, the parameter optimization problem of the whole box structure can be described as follows.

Optimization objective: *minimizing* $f(X)_{max}$; Optimized area: *battery box body;*

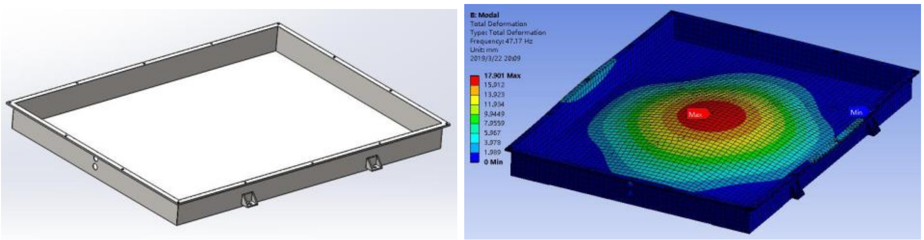
Finally, the robustness index list of the battery box structure before and after optimization is obtained. The structural robustness verification can be concluded.

Case Study:

Taking the battery box of an electric vehicle as an example, the study considers uncertainties of manufacturing and working environments in the material property, working temperature and vibration of the battery box as follows.

Step 1: Initialization settings

The schematic diagram of an actual battery box model is shown in Fig. 2. The model consists of 13412 cells, 49564 nodes. The minimum cell size is 1 mm, and the average Jacob ratio is 0.8. The box body is made of Aluminum alloy, material density D_i=2.77g/cm^3, modulus elasticity E=71Gpa, Poisson ratio V=0.33, initial parameters of the battery box structure are shown in Tab. 1.



(a) 3-D model (b) Finite element model

Fig. 2: Battery box model.

Parameters	*Expression*	*Amount*	*Units*
Length of box	L	1323	mm
Width of box	W	1000	mm
Height of box	H	108	mm
Mass of box	M	29.778	Kg
Thickness of box wall	X_{K1}	[2 7]	mm
	X_{K2}		
	X_{K3}		

Tab. 1: Initial parameters of battery box.

Step 2: Uncertainty constraint setting

Constraints caused by uncertainty in this case are shown in Tab. 2. Because the bottom of the battery box is fixed, the excitation perpendicular to the bottom of the battery box has a great influence on the deformation and frequency of the battery box. This direction is defined as Z direction. The vibration excitation in this case mainly considers the deformation and frequency caused by Z direction excitation. Optimizing parameters X_{K1}, X_{K2}, X_{K3} and regions are shown in Fig. 3.

Uncertainty parameters			
Parameter type	*Material density*	*Operating temperature*	*Vibration excitation*
Parameter expression	D_i	T_i	F_i
Allowed band	$D_i \in$ [2.493 3.047] g/cm^3	$T_i \in$ [-20 50] ℃	$F_i \in$ [5 200] Hz

Tab. 2: Uncertainty parameters.

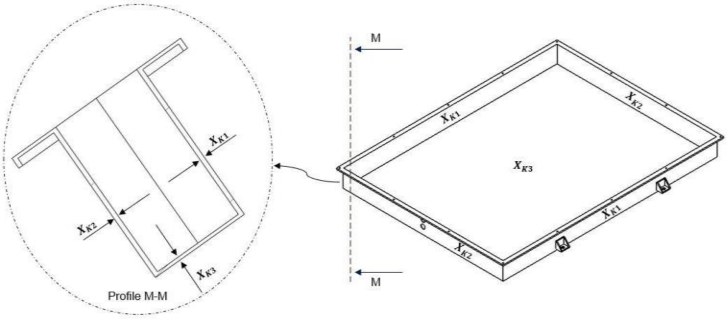


Fig. 3: Optimization object.

Step 3: Optimal design

Optimization for safety of the battery box structure includes the uncertain optimization and uncertain design parameters optimization as follows:

a. Uncertainty optimization model
   Objective function: Maximal Deformation and Frequency;
   Design variables: Material density *D*, Operating temperature *T*, Vibration excitation *F*;
   Constraint conditions: $D_i \in$ [2.493 3.047] g/cm^3
   $T_i \in$ [-20 50] ℃
   $F_i \in$ [5 200] Hz

b. Design parameter optimization
   Objective function: Minimal Deformation and Frequency of box;
   Design variables: Length, Width, and Height of box X_1, X_2, X_3;
   Constraint conditions: $m<m_0$
   X_1, X_2, $X_3 \in$ [2 7] mm

The input, output and constraints are set in the optimization module of ANSYS. A Neural network algorithm (ANN) is used to solve the optimization problem. The objective of the optimization design is to reduce the maximum deformation and increase the minimum frequency of the battery box. The deformation, frequency and geometry mass of the battery box under test conditions can be obtained. The uncertain optimization results of battery case are presented in Tab 4.

Design		*Initial*	*Optimal*	*Units*
Results	X_{K1}	6	2.0805	*mm*
	X_{K2}	6	2.2322	mm
	X_{K3}	6	6.9961	mm
Minimum Mass		29.778	27.992	Kg
Maximum Deformation		1.269	0.42409	mm
Minimum Frequency		47.17	51.025	Hz

Tab. 4: Comparison of optimization results.

In order to determine the maximum deformation and minimum frequency of the battery box, uncertainties related to the structural deformation or frequency are comprehensively considered. Tab. 5 shows the improvement of the battery box structure before and after the optimization. Through parameter optimization design, the maximum deformation is reduced and the minimum frequency is increased while the weight of the box is also reduced. The optimized box has the characteristics of the high strength and light weight, low sensitivity to uncertainties, which greatly improves the safety and robustness of the box structure.

Design	*Maximum Deformation (mm)*	*Improvement (%)*	*Minimum Frequency (Hz)*	*Improvement (%)*
Initial design	1.269	+66.58	47.17	+8.17
Optimal design	0.42409		51.025	

Tab. 5: Comparison of design schemes.

Conclusion:

A method is proposed for the structural safety under vibration of the battery box considering uncertain conditions to reduce the failure risk of the box structure. At the same time, the box weight is also reduced. The method uses the multi-objective robust optimization theory [5] and finite element method in the frequency domain to improve the efficiency of analysis and reduce the cost of process.

Acknowledgements:

The authors wish to thank the National Natural Science Foundation of China (No: 51505269), and the Sailing Talent Program, Pearl River Scholar Program, and the Science and Technologies Program (No: 2017B090922008) of Guangdong Province, China for providing financial supports to this research.

References:

[1] Yao, L.; Wang, Z.; Ma, J.: Fault detection of the connection of lithium-ion power batteries based on entropy for electric vehicles. Journal of Power sources, 2015, 293: 548-561. https://doi.org/10.1016/j.jpowsour.2015.05.090

[2] Tie, S. L.; Tan, C.W.: A review of energy sources and energy management system in electric vehicles. Renewable and Sustainable Energy Reviews, 2013, 20: 82-102. https://doi.org/10.1016/j.rser.2012.11.077

[3] Arora, S.; Hen, W.; Kapoor, A.; et al.: Review of mechanical design and strategic placement technique of a robust battery pack for electric vehicles. Renewable & Sustainable Energy Reviews, 2016, 60: 1319-1331. https://doi.org/10.1016/j.rser.2016.03.013

[4] Wang, W.; Cheng, Y.; Jiang, W.; et al.: Random Vibration Fatigue Analysis of Electric Vehicle Battery Box. Journal of Automotive Engineering, 2016, 6(1): 10-14.

[5] Ma, Y.; Xu, T.; Qian, F.: Machine tool support multi-objective robustness design under uncertainties. Computer Integrated Manufacturing System, 2017(3).