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RESEARCH PAPER

The Application of Modal Testing for Non-destructive Material Identification of a Car Seat Frame

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Abstract
Material properties of a structure can be estimated using destructive and non-destructive methods. Experimental vibration data of the structure can be used to conduct a non-destructive procedure to identify material properties. In this research, experimental modal parameters obtained from modal testing are utilized to estimate the Young's modulus and the density of different components of a car seat frame. To do so, the finite element model of the structure is constructed and the modal parameters are evaluated by performing modal analysis. The obtained modal parameters are then used in an inverse identification procedure and compared with the experimental counterparts to estimate the material properties of the structure in an optimization framework. The objective function is defined by comparing the numerical and experimental natural frequencies where the material properties are considered as the design parameters of the optimization process. To find the optimum design parameters, the response surface optimization technique is employed to alleviate the computational costs of direct optimization. To this end, the design of experiment method using the Box-Behnken design is conducted to create the design points. The kriging method is then utilized to construct the response surfaces. Finally, the nonlinear programming quadratic Lagrangian method is employed to evaluate the best estimations for the material properties using the response surface optimization method.
Keywords: Car Seat Frame; Material Identification; Mechanical Vibration; Modal Analysis; Response Surface Optimization

Introduction

This research deals with using the experimental modal parameters, obtained from modal testing, to perform a non-destructive material identification procedure. Tam et al. [1] reviewed the non-destructive vibration-based approaches to estimate the Young's modulus of composite plates. These methods usually use inverse approaches to identify material properties [2, 3] where the accuracy of the inverse approaches depends on the accuracy of the experimental data and the accuracy of the numerical modeling and analysis [4].

In this research, the identification process of material properties is considered in an optimization framework. Since the extraction of the natural frequencies is far easier than that of the mode shapes, utilizing only natural frequencies in the construction of the objective function in the vibration-based material identification is prevailed [5]. However, since the natural frequencies show less sensitivity to the changes in the Poisson's ratio, the determination of this material parameter using only the natural frequencies may not be very effective. Among the literatures dealing with vibration-based material identification, Syngellakis and Setiawan [6] studied the inverse problem of finding the mechanical properties of orthotropic plates using experimental natural frequencies, surrogate-based finite element (FE) modeling through an iterative optimization process. Tam et al. [7] developed a meta-

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heuristic optimization approach to enhance the accuracy of material identification in composite panels using vibration data, using the natural frequency error function in the first stage, and frequency response function (FRF) error function in the second stage. Viala et al. [8] also used an inverse approach through FE model updating based on using experimental natural frequencies to find three rigidities and damping ratios of a violin soundboard.

In the current research, the material identification of a car seat frame that consists of different steel grades is performed using the experimental modal parameters. To this end, modal testing is conducted on the frame and the modal parameters including natural frequencies and mode shapes are extracted. Furthermore, the FE model of the frame is constructed with uncertain material properties including the Young's modulus and the density of different parts of the frame. By performing the FE modal analysis, one can find the modal parameters of the structure. By comparing the natural frequencies of the FE model with the experimental counterparts, an objective function is defined to be utilized in an optimization procedure where the material properties are the design parameters of the optimization problems, the mode shapes, however, are only used for experimental and numerical mode-matching.

Since FE simulation usually takes time to be accomplished, to calculate the objective function for different values of the design parameters, the response surface method can be used where a number of design points are used to approximate the outputs of the FE simulation. To perform the material identification using response surface optimization, the modal analysis is conducted for a set of the design points obtained from the Box-Behnken method [9], and the modal parameters are evaluated for each design point. Then, a surrogate model is constructed based on the Kriging-based response surface methodology [10]. After creating the surrogate model, and choosing the optimization methodology, the required simulations for calculating the objective functions are conducted using the surrogate model. To optimize the surrogate model and evaluate the best estimation for the Young's modulus and density of different components of the frame, the nonlinear programming by quadratic Lagrangian (NLPQL) [13], which is a gradient-based algorithm, is utilized.

Finite Element Modeling and Modal Analysis of the Car Seat Frame

To construct the finite element model of the car seat frame, first, a geometric model is required. As shown in Figure (1), based on the dimensions received from the manufacturer of the car seat, the geometric model has been constructed in SolidWorks [11]. To implement the FE model of the frame, ANSYS Workbench [12] environment is utilized. To perform the response surface optimization, the ANSYS Exploration module is used. The meshed FE model of the frame is shown in Figure (2). Based on the shape and geometry of the frame's components, different 1D, 2D and 3D elements are used to discretize the structure.

The modal parameters including the natural frequencies and mode shapes are extracted by solving an eigenvalue problem given in Eq. (1).

$$([K]-\omega^2[M])\{\phi\}=0 \tag{1}$$

$[K]$, $[M]$, ω and $\{\phi\}$ are the stiffness matrix, the mass matrix, the natural frequency and the mode shape vector of the FE model of the frame, respectively. The first five natural frequencies and the corresponding mode shapes of the FE model of the car seat frame are evaluated by conducting the modal analysis. Since there are some uncertainties regarding the material properties of the different parts of the frame, as tabulated in Table 1, an identification process is performed by the response surface optimization method. To better interpret the descriptions provided in Table (1), the exploded view of the car seat model is also shown in Figure (3).

1. Material Identification Using the Response Surface Optimization Method

The material identification is conducted as an inverse optimization approach in which the objective function is defined as the summation of the normalized differences between the natural frequencies of the surrogate model and the corresponding experimental ones as shown in Eq. (2).

$$\pi = \sum_{i=1}^{N}\left(\frac{\omega_i^S - \omega_i^X}{\omega_i^X}\right)^2 \tag{2}$$

The superscripts S and X refer to the surrogate and the experimental models, respectively. N is also the number of vibration modes utilized in the optimization process. The best values for the design parameters (i.e. the material properties) are obtained by minimizing the objective function. To solve this minimization problem, NLPQL approach is used. Note that, to construct the surrogate model, the Box-Behnken design and the Kriging-based response surface optimization method [14] are utilized. Moreover, the roving hammer modal testing, as shown in Figure (4), is conducted on the frame to extract the frequency response functions (FRFs), as illustrated in Figure (5). The FRF data are then used to extract the modal parameters using the complex mode indicator function method [15].

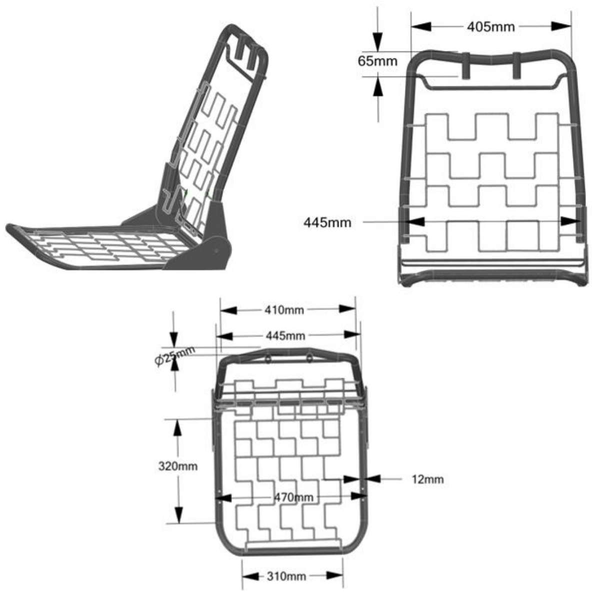

Figure 1. The geometric model of the car seat frame with dimensions

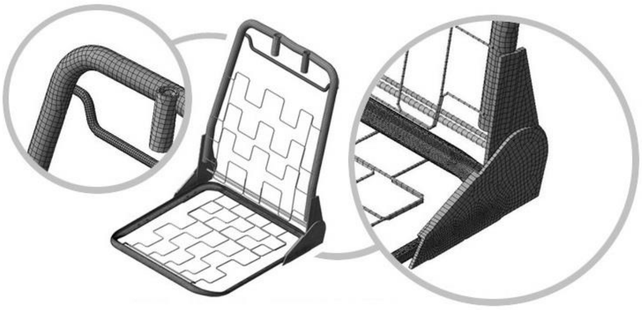

Figure 2. The discretized FE model of the car seat frame

Table 1. The designed parameters of the FE model of the car seat frame

Parameter	Description
E_1 (GPa)	Young's modulus of the base and back frame (Steel ST44-2)
E_2 (GPa)	Young's modulus of the recliners and their connecting mechanism (Steel ST-37)
E_3 (GPa)	Young's modulus of the base and back suspension springs (Steel CK 67)
E_4 (GPa)	Young's modulus of the headrest bushings, the recliner actuation mechanism, and the backrest reinforcement rod (Steel ST12)
ρ_1 (kg/m^3)	Density of the base and back frame (Steel ST44-2)
ρ_2 (kg/m^3)	Density of the recliners and their connecting mechanism (Steel ST-37)
ρ_3 (kg/m^3)	Density of the base and back suspension springs (Steel CK 67)
ρ_4 (kg/m^3)	Density of headrest bushings, the recliner actuation mechanism, and the backrest reinforcement rod (Steel ST12)

Figure 3. The exploded view of the car seat model: 1. Back Frame, 2. Base Frame, 3. Recliners 4. Recliner Mechanism's Rods, 5. Base Suspension Springs, 6. Back Suspension Springs, 7. Headrest Rods 8. Base Cushion, 9. Back Cushion, 10. Headrest Cushion

Figure 4. Performing the modal testing on the car seat frame

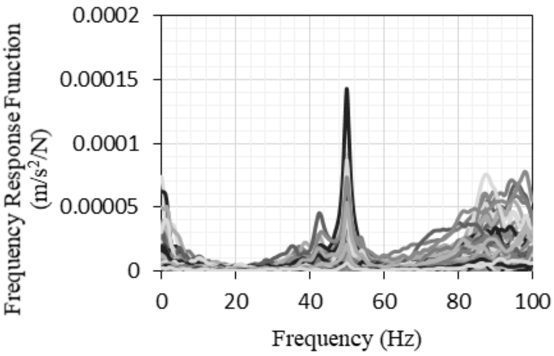

Figure 5. The frequency response function of the car sear frame obtained from modal testing

Results and Discussion

The Box-Behnken design method creates 65 design sets as shown in Figure (6). Note that, based on the methodology of this approach, three values are considered for each design parameter including the lower, the upper, and the average values on the parameter search space. For each design point, the objective function is also evaluated as depicted in Figure (6). The Kriging method is then utilized for the response surface construction. The accuracy of the Kriging method for approximating the response is evaluated by the goodness of fit provided in Figure (7) where the predicted natural frequencies from the Kriging method match well with the observed natural frequencies from the FE model. After 276 iterations, the best values obtained for the material properties by the NLPQL approach are given in Table (2). The initial values of these parameters are also mentioned in this table. Using these two sets, one can compare the natural frequencies obtained from the initial and updated FE model with the experimental ones to evaluate the frequency errors. As tabulated in Table (3), except for the fifth mode, the frequency error of other modes significantly decreased in the updated FE model and the accuracy of this model, and the estimated values for the material properties in the updated FE model, is reasonable.

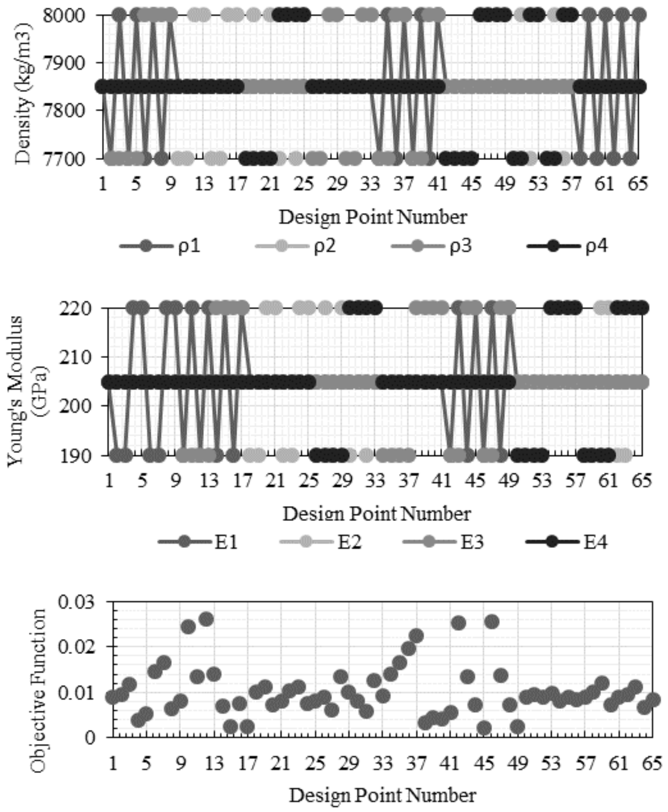

Figure 6. The material properties and the objective function value of the design points chosen by the Box-Behnken method

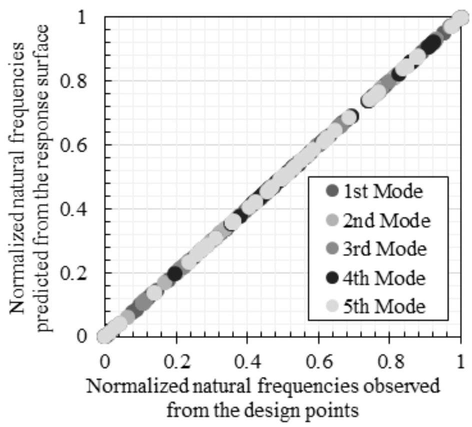

Figure 7. The goodness of fit of the Kriging method

Table 2. The initial and updated values for the material properties of the FE model of the frame

Material Properties	Initial Value	Updated Value
E_1 (GPa)	205.0	219.9
E_2 (GPa)	205.0	219.9

E_3 (GPa)	205.0	217.0
E_4 (GPa)	205.0	219.8
ρ_1 (kg/m^3)	7850	7700
ρ_2 (kg/m^3)	7850	7873
ρ_3 (kg/m^3)	7850	7849
ρ_4 (kg/m^3)	7850	7784

Table 3. Comparing the natural frequencies obtained from the initial and updated FE models of the frame with the experimental ones

Mode No.	Natural Frequency (Hz)			Absolute Relative Error (%)	
	Experimental	FE Model			
		Initial	Updated	Initial	Updated
1	42.5	40.482	42.156	4.75	0.81
2	50.0	48.569	50.113	2.86	0.22
3	86.5	81.972	84.361	5.23	2.47
4	89.0	84.056	87.194	5.56	2.03
5	99.0	98.893	102.55	0.11	3.58

Conclusions

In this research, material properties of different components of the finite element model of a car seat frame were estimated using the experimental modal parameters in an optimization framework. To reduce the computational costs, surrogate modeling using the Box-Behnken method for selection of the design points and the Kriging method for the response surface construction were utilized to imitate the behavior of the FE model of the frame as closely as possible. The objective function was defined by comparing the natural frequencies of the surrogate model with the experimental ones. The mode shapes were also utilized to ensure mode-matching between the finite element and experimental models. Using the response surface optimization based on the NLPQL method and utilizing the first five experimental modes of the frame, the material properties were identified.

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