Discrete structural optimization of a passenger car rear seat frame using aluminium alloy

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Abstract. To reduce the weight and improve the structural performances of a passenger car rear seat frame, this study uses a discrete structural optimization method to design an aluminium alloy seat frame to replace the original steel one. The optimization problem aims to minimize the total mass, manufacturing cost, the maximum displacements and tensile stresses under certain load conditions and maximize the first order natural frequency. The cross-sectional dimensions and material types of members in the seat frame are considered as the design variables. A modified non-dominated sorting genetic algorithm, the third version (mNSGA-III) which is adapted at handling problems with four or more objective functions, is used to solve the optimization problem. To benchmark the performance of the proposed method, a multidisciplinary design optimization (MDO) method is also utilized to solve the optimization problem. The comparison between the solutions obtained by the proposed method and the MDO method shows that the accuracy and the effectiveness of the proposed method are better. A weight saving of 35.1% is achieved by the aluminium alloy seat frame as compared to the original steel seat frame.

1. Introduction
For decades, engineers are challenged to design car and its parts that are reliable and economical. As an important part in cars, the weight of the rear seat frame is relatively large. Thus, it needs a lightweight design. The most popular methods for lightweight design include structural optimization and the use of lightweight materials, e.g. the carbon fiber reinforced plastics, the aluminium alloy and the magnesium alloy [1-3]. Researches have shown that with structural optimization only, the weight reduction is not significant [4-6]. Thus, the usage of lightweight materials is critical to a good lightweight design. Among all of the lightweight materials, the aluminium alloy has the advantages of low density, the corrosion resistance, high recyclability and better energy absorption capability [7-8]. The price of the aluminium alloy is acceptable considering the significant weight reduction by using the aluminium alloy. Therefore, this study proposes to use the aluminium alloy to design the seat frame of a passenger car.

The discrete structural optimization (DSO) refers to a structural optimization method in which the design variables are discrete values. Since the design variables are taken from the available discrete values, the optimal solution can be used directly. Hence, the DSO is a practical design method. In this study, the DSO method proposed by Ma et al. [9] was used to perform sizing optimization and material selection simultaneously. The seat frame to be optimized is modeled by beam finite elements. Thus, the beam finite element (FE) model has a small number of finite elements and high modeling efficiency compared to the detailed shell FE model. Therefore, the efficiency of optimization design can be greatly improved. To demonstrate the validity of the proposed method, a multidisciplinary design optimization (MDO) method is also used to optimize the seat frame.
The remainder of the paper is organized as follows: the structure and load conditions concerned of the seat frame and its FE modeling is introduced in section 2. The validity of the DSO utilized is demonstrated in section 3. Section 4 gives a conclusion.

2. The structure of the seat frame and the FE modelling

2.1. The structure of the seat frame

The rear seat back is generally composed of cover, foam, seat frame, locks, etc.. Among them, the seat frame has two structural forms: one is welded by stamping sheet metals (Figure 1(a)) and the other is welded by shaped pipes (Figure 1(b)).

![Figure 1 The seat frames: (a) the steel seat frame, (b) the aluminium alloy seat frame](image)

The original steel seat frame is shown in Figure 1(a) which is mainly composed of a seat back plate, two axles, bracket for the head restraint and locks. The seat frame can be rotated around the axles and the locks securely connect the seat back with the body. All parts of the seat frame are made of steel sheet metals and their thicknesses range from 0.7-3mm, with a total mass of 9.728kg. In order to reduce its weight, this research aims to use aluminium alloy square tubes instead of steel sheet metals to re-create the seat frame. Firstly, we used the continuum structure topology optimization to obtain the optimal material distribution and then used image processing technique to convert the continuum topology optimization result into the beam FE model shown in Figure 1(b). For clarity, all members to be optimized are indicated by numbers. Considering the manufacturability, the same number will be used for the members with the same attributes (cross-sectional dimensions and material).

2.2. Finite element model development

2.2.1. Mesh generation. The seat frame shown in Figure 1(b) is modelled by beam finite elements. The element size is about 10mm. There are 1,179 beam finite elements. The head restraint is modelled by rods. The diameter of the head restraint is 10mm and the material is Q235. The members in the seat frame are modelled by square tubes. The initial cross-sectional dimensions of the members are denoted as 30mm×30mm×2.5mm. These three dimensions represent the width, height and wall thickness of the cross section of the tube. The initial material of the members is aluminium 7075 alloy (Al 7075). In the DSO process, the aluminium 6061 alloy (Al 6061) is also considered as a candidate material to reduce the manufacturing cost. The material properties and prices per unit of the Al 7075, the Al 6061 and the Q235 are shown in Table 1.

2.2.2. The load conditions. The performances of the seat frame are subjected to strict requirements set by authorities. There are three important tests for the rear seat frame: (i) Test of the strength of the seat back and its adjustment systems. (ii) Test of performance of the head restraint. (iii) Test of devices intended to protect the occupants against displacement luggage. For simplicity, these three tests are denoted as Step-1, Step-2 and Step-3, respectively.

| Material property | Al 7075 | Al 6061 | Q235 |
|-------------------|---------|---------|------|
| density/(kg/m³)   | 2700    | 2700    | 7900 |
Young’s modulus/(GPa) | 71.4 | 70 | 210
Poisson’s ratio | 0.33 | 0.33 | 0.3
Yield stress/(MPa) | 462 | 280 | 235
Price per unit/($/kg) | 6.15 | 2.36 | 0.71

2.2.2.1 Test setup of the Step-1. GB15083-2006 [10] stipulates that through the center of mass of the seat frame, a longitudinal load equal to 20 times its own weight is applied forwards or rearwards along the x direction, as shown in Figure 2. No permanent deformation that increases the degree of damage of occupants shall be produced during the test. Since the rearward load is not the worst case, thus, the horizontal forwards load ($F_g$ in Figure 2, 4725N) is applied to the seat frame during FE analysis and the DSO. To avoid localized penetration, the load is evenly distributed to five equidistant points (black dots in Figure 2).

2.2.2.2 Test setup of the Step-2. According to GB15083-2006, the specifications of Step-2 are as follows: Two test blocks are placed on the floor of the luggage compartment which weigh 18kg and their dimensions are 300mm×300mm×300mm. The blocks are placed symmetrically about the longitudinal median plane of the car, the one is 50mm away from the other and both of them are 200mm from the seat frame.

The test procedure can be described as: Firstly, all of them (the car, the seat frame and the blocks) are moved at a speed of 50km/h. Secondly, the car is decelerated at a specified deceleration. Finally, the blocks hit the seat frame owing to the inertia. Deformation that beyond the yz plane (across the point that is 100mm away from the seat reference point) or fracture is not allowed.

Because the dynamic simulation is time-consuming, to save the computational cost during the DSO process, this research replaces dynamic simulation with equivalent static simulation. Firstly, a detailed shell FE model of the original seat frame for dynamic simulation was established. Based on the principle of conservation of momentum, the impact force in the dynamic simulation is converted into a quasi-static load $F_c$. The calculated $F_c$ is 15.397kN along the x-axis and 6.683kN along the z-axis. The load application point is the position where the luggage touches the seat frame during the collision (Figure 2).

2.2.2.3 Test setup of the Step-3. GB11550-2009 [11] stipulates that a load $F$ perpendicular to the reference line of the manikin is applied to the head restraint, and a load $F_1$ is applied to the seat frame. During the test, it is necessary to ensure that the head restraint and its fixing device are not damaged. According to the regulation, the $F_1$ and $F$ for the seat back are 1243N and 890N, respectively. The rear seat can accommodate three passengers. Thus, three $F_1$ and three $F$ act on the seat frame and three head restraints, as shown in Figure 2. The axles and locks are modelled by rigid finite elements as are shown in Figure 2 in which 1-3 and 4-6 denote the translational degrees and rotational degrees of freedom that are restrained.
3. The proposed discrete structural optimization method

3.1. Optimization problem
In this study, aims of the optimization problem are to minimize the maximum tensile stress $\sigma_{I,\text{max}}$ in the Step-1, the maximum deformation along $x$-axis $d_{II,\text{max}}$ in the Step-2, the maximum tensile stress $\sigma_{III,\text{max}}$ and deformation along $x$-axis $d_{III,\text{max}}$ in the Step-3, the total mass and the cost while maximize the first order natural frequency $f_1$. The material types and cross-sectional dimensions of members in the seat frame are considered as the design variables. Two types of aluminium alloy will be considered in this study, i.e. the Al 7075 and the Al 6061. Thus, the optimization problem can be formulated as:

$$\begin{align*}
\text{find:} & \quad x(i) = [p_1, p_2, \ldots, p_9]^T \\
\text{min:} & \quad m, \sigma_{I,\text{max}}, \sigma_{III,\text{max}}, d_{II,\text{max}}, d_{III,\text{max}}, \text{Cost}, -f_1 \\
\text{s.t.} & \quad \text{mat} = [\text{Al 7075, Al 6061}]^T \\
& \quad \text{dimen} = [10 \times 10 \times 1.5, \ldots]^T \\
& \quad p_j \in \text{Prop}_j \quad j = 1, 2, \ldots, 19
\end{align*}$$

(1)

where $\text{Prop}$ denotes the property set. $\text{Prop}_j$ denotes the property set for $j$th member. $x(i)$ denotes a candidate solution in which each component $p_j$ is the property assigned to $j$th member. $m$ is the total mass and the Cost denotes the manufacturing cost. $\text{mat}$ denotes the material set and $\text{dimen}$ denotes the cross-sectional dimension set which are available from the original equipment manufacturer.

3.2. Introduction to the discrete structural optimization method
The DSO method proposed by Ma et al. [9] was utilized in this study and the flowchart of the method can be seen in Figure 3. A candidate solution can be encoded and be represented by a chromosome which is composed of $n$ genes. $n$ is the number of members to be optimized. Each gene is an integer which corresponds to a property. Many new chromosomes can be generated by initialization or genetic operations. These new chromosomes can be decoded into new structures and corresponding FE models can be outputted in formatted fem files which can be solved by Altair Optistruct®, a popular FE solver.

In Figure 3, the deep grey members represent their material are changed into the Al 6061.

Figure 3. Flowchart of the discrete structural optimization method

The optimization problem was solved by the mNSGA-III and the details of the algorithm can be referred to [9,12]. The control parameters are crossover ratio, the mutation ratio, the population size and the maximum generation number. In this study, they are 0.7, 0.2, 100 and 100, respectively. The optimization was performed in a computer with a 3.1GHz processor and 8GB of RAM memory. To demonstrate the validity of the proposed method, a separate study using a MDO method was also performed. The MDO process started by performing five hundred of high fidelity FE simulations on five hundred of sample points selected from the whole design space following a design of experiment (DoE) strategy, the Latin Hypercube Sampling. The surrogate modelling technique is the quartic
response surface model. To ensure whether the optimal solution has been reached or not, the multiple
correlation coefficient $R^2$ was used to inspect the accuracy of the surrogate model. The expressions of
the coefficient can be written as:

$$ R^2 = 1 - \frac{\sum_{i=1}^{N} (y_i - \bar{y})^2}{\sum_{i=1}^{N} (y_i - \bar{y'})^2} $$

where $y_i$ denotes the true response value of $i$th sample point while $\bar{y'}$ denotes the approximated value
of the $i$th sample point. $\bar{y}$ is the average of all of $y_i$. $N$ is the number of sample points, $N=500$ in this
study. The closer the coefficient is to one, the higher the accuracy of the model is.

The coefficients for each structural performance are shown in Table 2. It is clear that the accuracy of
the surrogate model is higher enough to perform the DSO. The surrogate model was solved by the
NSGA-II. The control parameters are the same with the mNSGA-III.

| Structural response | $R^2$ | By the proposed method | By the MDO |
|---------------------|------|-----------------------|-----------|
| mass (kg)           | 0.996| 6.32                  | 7.01      |
| $f_1$ (Hz)          | 0.997| 126.30                | 114.40    |
| $\sigma_{\text{I},\text{max}}$ (MPa) | 0.996| 10.16                 | 13.90     |
| $\sigma_{\text{III},\text{max}}$ (MPa) | 0.968| 137.70                | 245.00    |
| $d_{\text{II},\text{max}}$ (mm)   | 0.992| 12.12                 | 12.28     |
| $d_{\text{III},\text{max}}$ (mm)  | 0.983| 11.49                 | 13.09     |
| Cost ($)            | 0.935| 34.20                 | 35.50     |

The comparison in terms of structural performan ces of the optimal solutions obtained by the
proposed method and the MDO method is shown in Table 2. It is clear that the proposed method is better
than the MDO method. Based on the proposed method, a weight saving of 35.1% is achieved by the
proposed method compared to the steel seat frame, i.e. the weight of the seat frame is decreased from
9.728kg to 6.32kg. The other responses of solution obtained by the proposed method are all better than
those of solution obtained by the MDO method. Therefore, the optimal solution by the proposed method
realizes a desirable lightweight design. The optimal solution is shown in Table 3.

4. Conclusion

This study used a DSO method to design a passenger car rear seat frame. The discrete sizing optimization
and material selection are performed simultaneously. Thus, the design space is expanded and a global
optimum can be achieved. The comparison between results obtained by the proposed method and the
MDO method demonstrate that the proposed method obtains a better solution. By using the aluminium
alloy, a weight saving of 35.1% is achieved as compared to the original steel seat frame. Two types of
aluminium enable a low cost design since the Al 6061 is cheaper than the Al 7075. The proposed method
can be considered competitive in finding innovative and lightweight design.
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