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Dynamic analysis and optimization of car's body-in-white based on superelement approach

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Abstract: An approach based on the superelement theory is proposed, and it is applied to model the car's body-in-white as well as to dynamic simulation and optimization. This approach can improve the calculation speed and do the dynamic optimization among substructures respectively in the car's body design. To meet the car's design of harshness, a dynamic optimal design model, based on the mean square of vertical displacement response at two points of the car floor, is also proposed. Satisfactory results are achieved in this paper.

Key words: superelement approach; modeling; optimal design

Today, car design faces challenges of both lighter and more comfortable solutions. The traditional design approach depending on experience cannot keep pace with the development of the automotive industry. Thus, how to deal with the large-scale complex car's body structure and how to design it in an optimal way are put forward. In this paper, superelement analysis is proposed to simulate the behaviors of the car's body-in-white and to optimize the car's floor.

In order to obtain accurate results in the dynamic analysis and optimal design of car's body-in-white, one must build a very detailed and fine meshed finite element model. However, this process requires great computer resources and considerable calculating time. Frequently, in this case, there are no solutions due to the large and complex structure. Until now, the best numeric way to solve this problem is by the superelement method[1-4].

In this paper, the car's body-in-white is divided into four parts, one residual structure and three substructures. Each substructure is calculated in advance to form a corresponding superelement before the model synthesis and Craig-Bampton approach are applied for the final synthesis.

1 Theory of Superelement

In the superelement approach, a large and complex structure is usually divided into several substructures. The main substructure and boundary elements with grids that connect other substructures are defined as the residual structure. And others are defined as superelements. It is shown in Fig. 1.

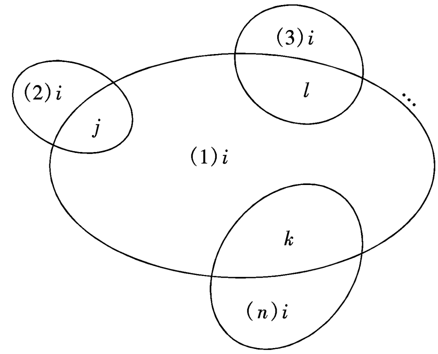

Fig. 1 Sketch of superelement structure

In Fig. 1, the substructure 1 and connecting parts l, j, $\cdots$, k are the residual structure. Substructures 2, 3, $\cdots$, n are defined as superelements. For the response solution loading $f(t) = F\sin\omega t$ should be applied to the residual structure.

The general equation form of the residual structure is

$$\begin{bmatrix} \boldsymbol{m}_{ii}^{(1)} & \boldsymbol{m}_{ij}^{(1)} & \boldsymbol{m}_{il}^{(1)} & \cdots & \boldsymbol{m}_{ik}^{(1)} \\ \boldsymbol{m}_{ji}^{(1)} & \boldsymbol{m}_{jj}^{(1)} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{m}_{li}^{(1)} & \boldsymbol{0} & \boldsymbol{m}_{ll}^{(1)} & \boldsymbol{0} & \boldsymbol{0} \\ \vdots & \vdots & \boldsymbol{0} & \ddots & \boldsymbol{0} \\ \boldsymbol{m}_{ki}^{(1)} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{m}_{kk}^{(1)} \end{bmatrix} \begin{Bmatrix} \ddot{\boldsymbol{x}}_i^{(1)} \\ \ddot{\boldsymbol{x}}_j^{(1)} \\ \ddot{\boldsymbol{x}}_l^{(1)} \\ \vdots \\ \ddot{\boldsymbol{x}}_k^{(1)} \end{Bmatrix} + \begin{bmatrix} \boldsymbol{K}_{ii}^{(1)} & \boldsymbol{K}_{ij}^{(1)} & \boldsymbol{K}_{il}^{(1)} & \cdots & \boldsymbol{K}_{ik}^{(1)} \\ \boldsymbol{K}_{ji}^{(1)} & \boldsymbol{K}_{jj}^{(1)} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{K}_{li}^{(1)} & \boldsymbol{0} & \boldsymbol{K}_{ll}^{(1)} & \boldsymbol{0} & \boldsymbol{0} \\ \vdots & \vdots & \boldsymbol{0} & \ddots & \boldsymbol{0} \\ \boldsymbol{K}_{ki}^{(1)} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{K}_{kk}^{(1)} \end{bmatrix} \begin{Bmatrix} \boldsymbol{x}_i^{(1)} \\ \boldsymbol{x}_j^{(1)} \\ \boldsymbol{x}_l^{(1)} \\ \vdots \\ \boldsymbol{x}_k^{(1)} \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{f}(t) \\ \boldsymbol{f}_j(t) \\ \boldsymbol{f}_l(t) \\ \vdots \\ \boldsymbol{f}_k(t) \end{Bmatrix} \tag{1}$$

where $\boldsymbol{m}_{ii}^{(1)}$, $\boldsymbol{m}_{ij}^{(1)}$, $\cdots$, $\boldsymbol{m}_{kk}^{(1)}$ and $\boldsymbol{K}_{ii}^{(1)}$, $\boldsymbol{K}_{ij}^{(1)}$, $\cdots$, $\boldsymbol{K}_{kk}^{(1)}$ are the mass and stiffness element matrices in the residual structure; $\boldsymbol{x}_i^{(1)}$, $\cdots$, $\boldsymbol{x}_k^{(1)}$ are the boundary coordinates; $\boldsymbol{f}_j(t)$, $\cdots$, $\boldsymbol{f}_k(t)$ are the forces between the residual structure and substructures.

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For superelements $2, 3, \cdots, n$,

$$\begin{bmatrix} \boldsymbol{m}_{ii}^{(2)} & \boldsymbol{m}_{ij}^{(2)} \\ \boldsymbol{m}_{ji}^{(2)} & \boldsymbol{m}_{jj}^{(2)} \end{bmatrix} \begin{Bmatrix} \ddot{\boldsymbol{x}}_i^{(2)} \\ \ddot{\boldsymbol{x}}_j^{(2)} \end{Bmatrix} + \begin{bmatrix} \boldsymbol{K}_{ii}^{(2)} & \boldsymbol{K}_{ij}^{(2)} \\ \boldsymbol{K}_{ji}^{(2)} & \boldsymbol{K}_{jj}^{(2)} \end{bmatrix} \begin{Bmatrix} \boldsymbol{x}_i^{(2)} \\ \boldsymbol{x}_j^{(2)} \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{0} \\ \boldsymbol{f}_j(t) \end{Bmatrix} \tag{2}$$

$$\begin{bmatrix} \boldsymbol{m}_{ii}^{(3)} & \boldsymbol{m}_{il}^{(3)} \\ \boldsymbol{m}_{li}^{(3)} & \boldsymbol{m}_{ll}^{(3)} \end{bmatrix} \begin{Bmatrix} \ddot{\boldsymbol{x}}_i^{(3)} \\ \ddot{\boldsymbol{x}}_l^{(3)} \end{Bmatrix} + \begin{bmatrix} \boldsymbol{K}_{ii}^{(3)} & \boldsymbol{K}_{il}^{(3)} \\ \boldsymbol{K}_{li}^{(3)} & \boldsymbol{K}_{ll}^{(3)} \end{bmatrix} \begin{Bmatrix} \boldsymbol{x}_i^{(3)} \\ \boldsymbol{x}_l^{(3)} \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{0} \\ \boldsymbol{f}_l(t) \end{Bmatrix} \tag{3}$$

$$\vdots$$

$$\begin{bmatrix} \boldsymbol{m}_{ii}^{(n)} & \boldsymbol{m}_{ik}^{(n)} \\ \boldsymbol{m}_{ki}^{(n)} & \boldsymbol{m}_{kk}^{(n)} \end{bmatrix} \begin{Bmatrix} \ddot{\boldsymbol{x}}_i^{(n)} \\ \ddot{\boldsymbol{x}}_k^{(n)} \end{Bmatrix} + \begin{bmatrix} \boldsymbol{K}_{ii}^{(n)} & \boldsymbol{K}_{ik}^{(n)} \\ \boldsymbol{K}_{ki}^{(n)} & \boldsymbol{K}_{kk}^{(n)} \end{bmatrix} \begin{Bmatrix} \boldsymbol{x}_i^{(n)} \\ \boldsymbol{x}_k^{(n)} \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{0} \\ \boldsymbol{f}_k(t) \end{Bmatrix} \tag{4}$$

where $\boldsymbol{m}_{ii}^{(n)}$ and $\boldsymbol{K}_{ii}^{(n)}$ are the inner mass and stiffness element matrices in the substructure n, $\boldsymbol{m}_{kk}^{(n)}$ and $\boldsymbol{K}_{kk}^{(n)}$ are the inner mass and stiffness element matrices on the boundary.

For each superelement, inner coordinates are contracted to boundary coordinates coupling with residual structure by a dynamic coordinate contracting approach[5]. The whole structure is assembled by superelements and residual structure. By reducing inner coordinates of superelements the motion equation of the structure can be represented as

$$\begin{bmatrix} \boldsymbol{K}_{ii}^{(1)} & \boldsymbol{K}_{ij}^{(1)} & \boldsymbol{K}_{il}^{(1)} & \cdots & \boldsymbol{K}_{ik}^{(1)} \\ \boldsymbol{K}_{ji}^{(1)} & \boldsymbol{K}_{jj}^{(1)} + \boldsymbol{\kappa}_{jj}^{(2)}(\omega) & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{K}_{li}^{(1)} & \boldsymbol{0} & \boldsymbol{K}_{ll}^{(1)} + \boldsymbol{\kappa}_{ll}^{(3)}(\omega) & \boldsymbol{0} & \boldsymbol{0} \\ \vdots & \vdots & \boldsymbol{0} & \ddots & \boldsymbol{0} \\ \boldsymbol{K}_{ki}^{(1)} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{K}_{kk}^{(1)} + \boldsymbol{\kappa}_{kk}^{(n)}(\omega) \end{bmatrix} \begin{Bmatrix} \boldsymbol{X}_i^{(1)} \\ \boldsymbol{X}_j^{(1)} \\ \boldsymbol{X}_l^{(1)} \\ \vdots \\ \boldsymbol{X}_k^{(1)} \end{Bmatrix} -$$

$$\omega^2 \begin{bmatrix} \boldsymbol{m}_{ii}^{(1)} & \boldsymbol{m}_{ij}^{(1)} & \boldsymbol{m}_{il}^{(1)} & \cdots & \boldsymbol{m}_{ik}^{(1)} \\ \boldsymbol{m}_{ji}^{(1)} & \boldsymbol{m}_{jj}^{(1)} + \boldsymbol{\mu}_{jj}^{(2)}(\omega) & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{m}_{li}^{(1)1} & \boldsymbol{0} & \boldsymbol{m}_{ll}^{(1)} + \boldsymbol{\mu}_{ll}^{(3)}(\omega) & \boldsymbol{0} & \boldsymbol{0} \\ \vdots & \vdots & \boldsymbol{0} & \ddots & \boldsymbol{0} \\ \boldsymbol{m}_{ki}^{(1)1} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{m}_{kk}^{(1)} + \boldsymbol{\mu}_{kk}^{(n)}(\omega) \end{bmatrix} \begin{Bmatrix} \boldsymbol{X}_i^{(1)} \\ \boldsymbol{X}_j^{(1)} \\ \boldsymbol{X}_l^{(1)} \\ \vdots \\ \boldsymbol{X}_k^{(1)} \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{F} \\ \boldsymbol{0} \\ \boldsymbol{0} \\ \vdots \\ \boldsymbol{0} \end{Bmatrix} \tag{5}$$

where ω is the angle frequency,

$$\boldsymbol{\mu}_{jj}^{(2)}(\omega) = \boldsymbol{m}_{ji}^{(2)} \boldsymbol{H}_{ij}^{(2)} + \boldsymbol{m}_{jj}^{(2)}$$
$$\boldsymbol{\mu}_{ll}^{(3)}(\omega) = \boldsymbol{m}_{ll}^{(3)} \boldsymbol{H}_{il}^{(3)} + \boldsymbol{m}_{ll}^{(3)}$$
$$\vdots$$
$$\boldsymbol{\mu}_{kk}^{(n)}(\omega) = \boldsymbol{m}_{ki}^{(n)} \boldsymbol{H}_{ik}^{(n)} + \boldsymbol{m}_{kk}^{(n)}$$
$$\boldsymbol{\kappa}_{jj}^{(2)}(\omega) = \boldsymbol{k}_{ji}^{(2)} \boldsymbol{H}_{ij}^{(2)} + \boldsymbol{k}_{jj}^{(2)}$$
$$\boldsymbol{\kappa}_{ll}^{(3)}(\omega) = \boldsymbol{k}_{ll}^{(3)} \boldsymbol{H}_{il}^{(3)} + \boldsymbol{k}_{ll}^{(3)}$$
$$\vdots$$
$$\boldsymbol{\kappa}_{kk}^{(n)}(\omega) = \boldsymbol{k}_{ki}^{(n)} \boldsymbol{H}_{ik}^{(n)} + \boldsymbol{k}_{kk}^{(n)}$$
$$\boldsymbol{H}_{ij}^{2}(\omega) = (\boldsymbol{k}_{ii}^{2} + \omega^2 \boldsymbol{m}_{ii}^{2})^{-1} (\omega^2 \boldsymbol{m}_{ij}^{2} - \boldsymbol{k}_{ij}^{2})$$
$$\boldsymbol{H}_{ij}^{3}(\omega) = (\boldsymbol{k}_{ii}^{3} + \omega^3 \boldsymbol{m}_{ii}^{3})^{-1} (\omega^3 \boldsymbol{m}_{ij}^{3} - \boldsymbol{k}_{ij}^{3})$$
$$\vdots$$
$$\boldsymbol{H}_{ij}^{n}(\omega) = (\boldsymbol{k}_{ii}^{n} + \omega^n \boldsymbol{m}_{ii}^{n})^{-1} (\omega^n \boldsymbol{m}_{ij}^{n} - \boldsymbol{k}_{ij}^{n})$$

in which $\boldsymbol{\kappa}_{jj}^{2}(\omega)$, $\boldsymbol{\kappa}_{ll}^{3}(\omega)$, $\cdots$, $\boldsymbol{\kappa}_{kk}^{n}(\omega)$ are called affixing stiffness matrices; $\boldsymbol{m}_{jj}^{2}(\omega)$, $\boldsymbol{m}_{ll}^{3}(\omega)$, $\cdots$, $\boldsymbol{m}_{kk}^{n}(\omega)$ are called affixing mass matrices.

2 Superelement Models and Superelement Analyses

The entire finite element model of car's body-in-white is shown in Fig.2.

The floor is one of main parts in the car's body design. Most of car's body design works such as modeling, analysis, optimization and redesign works focus on it. Herein a direct component modal synthesis of boundary displacement method is proposed.

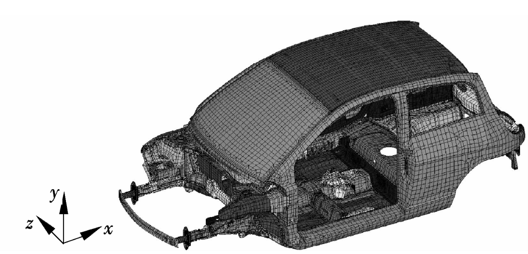


Fig.2 Finite element model of car's body-in-white

The procedure of superelement modeling can be described in the following steps:

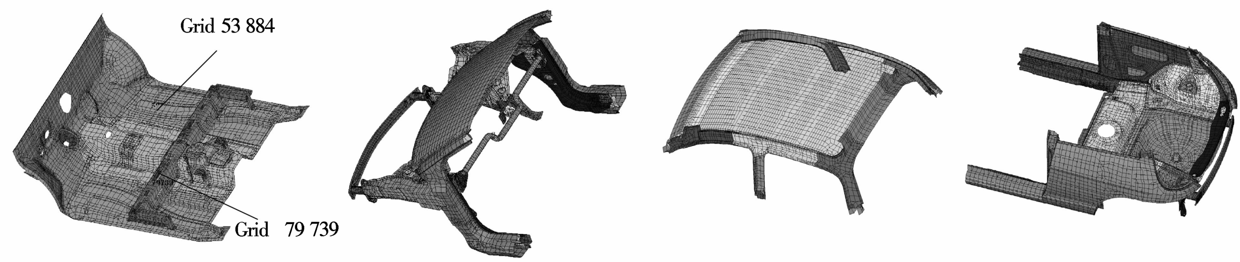
① Dividing entire model into several parts and defining one as a residual structure, and others as substructures.

② Calculating substructure stiffness matrices $\boldsymbol{K}_1$, $\boldsymbol{K}_2$, $\cdots$, $\boldsymbol{K}_n$ and mass matrices $\boldsymbol{M}_1$, $\boldsymbol{M}_2$, $\cdots$, $\boldsymbol{M}_n$.

③ Assembling calculated stiffness matrices and mass matrices to form total stiffness matrix $\boldsymbol{K}_{2G}$ and mass matrix $\boldsymbol{M}_{2G}$.

When these processes are finished, the entire model can be calculated by using total stiffness matrix $\boldsymbol{K}_{2G}$, mass matrix $\boldsymbol{M}_{2G}$ and the residual structure.

Fig.3 shows the car's residual structure and substructures.



(a) (b) (c) (d)

Fig.3 Car's superelement model. (a) Residual structure; (b) Substructure front; (c) Substructure roof; (d) Substructure rear

Here, the car's floor (due to its importance in car design) and rigid bar elements along the floor as well as newly created rigid bar elements between substructures are defined as the residual structure. It is shown in Fig.3(a).

Fig.3 (b) shows the substructure front. On the frame sections, some rigid bar elements with zero length are created to connect with other substructures (roof and rear) instead of the original grid points on cross section.

Fig.3 (c) shows the substructure roof. In this substructure, some rigid bar elements with zero length along the window edge are created to connect with the substructures front and rear.

Fig.3 (d) shows the substructure rear. In this substructure, rigid bar elements are created to connect with the substructures front and roof.

3 Criteria of Valuation for Dynamic Optimization

In a car's body, seats are installed and vibrations from the engine and road would transmit to them. Hence, the body reflects the car's dynamic problems. For this reason, two grid points, 79 739 (driver seat attachment point) and 53 884 (midpoint on the right floor) are chosen as valuation points (see Fig.3(a)).

Since the method of choosing the response as an objective function to optimize the car's body-in-white is more direct and efficient, the criteria evaluating the dynamic property of the car's body-in-white are dynamic responses at grid points 79 739 and 53 884 on the floor. Our final objective is to reduce responses to a minimum. In this paper, mean square displacement response is used as an objective function to optimize car's body-in-white[6].

The objective is to minimize the mean square of vertical acceleration or displacement response at grid points 79 739 and 53 884. Thus it can be expressed as

$$\min F = \sum_{i=0}^{200} (u_{z,\,79\,739}^{2i})^2 + \sum_{i=0}^{200} (u_{z,\,53\,884}^{2i})^2 \tag{6}$$

The above notation indicates the square of response at two grid points summed over 2.0 Hz intervals from 0 to 200 Hz. In the calculation, the constraint is the weight of the floor; the variables are the thickness of eight parts on the floor (see Fig.4).

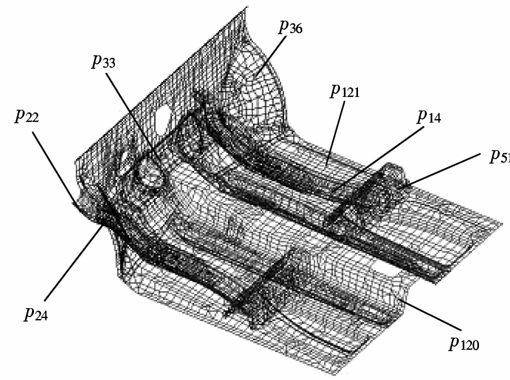


Fig.4 Eight parts of the floor

The constraint weight's upper bound is set to 45. 6 kg. Variables of eight parts' thickness are: p_{36}(1.0 to 2.5 mm), p_{120} (0.7 to 2.0 mm), p_{121}(0.5 to 2.0 mm), p_{14}(1.4 to 1.7 mm), p_{22}(2.0 to 2.5 mm), p_{24}(1.8 to 2.2 mm), p_{33}(1.0 to 1.4 mm), p_{51}(0.7 to 1.0 mm).

Optimal results are $p_{36}=1.351$ mm, $p_{120}=0.837$ mm, $p_{121}=0.953$ mm, $p_{14}=1.1$ mm, $p_{22}=1.21$ mm, $p_{24}=1.$

106 mm, $p_{33}=1.13$ mm,$p_{51}=0.927$ mm. In this case, weight reaches 44.3 kg.

Fig.5 shows responses by using results of acceleration response optimization with eight variables. In Fig.5 the vertical coordinate is the acceleration response in logarithm. From this figure we can see the response of an optimized car's floor is much lower than the original one.

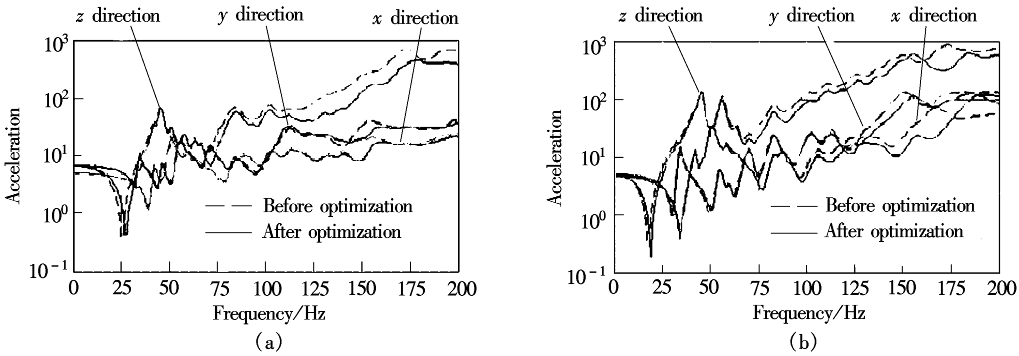


Fig.5 Response comparisons at two grid points. (a) Grid point 53 884; (b) Grid point 79 739

4 Conclusions

1) Using dynamic response (acceleration or displacement) as an objective function, one can always achieve better results. During the low frequency range, the solution using displacement response as an objective is better than that using acceleration response.

2) The more variables we choose, the better results we obtain.

3) There are some differences between one point optimization and two-point optimization. It shows multi-point optimization would become more complex, but may be better.

4) The optimization result of the weight of the floor often reaches the upper-bound weight of constraint.

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基于超单元法的轿车白车身动态分析和优化

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摘要: 采用基于超单元的方法对轿车的白车身进行了建模和动态仿真设计. 该方法不仅可以提高计算速度, 同时可以对轿车车身中的各个子结构进行独立的动态优化设计. 针对轿车设计中平顺性问题, 还提出了车底板上2点垂直方向位移响应的均方值为最小的车身优化方法, 对车身结构进行动态优化设计, 获得了令人满意的优化结果.

关键词: 超单元法; 建模; 优化设计

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