Numerical simulation and experimental analysis of vibration characteristics of heterogeneous sheet structure with adhesive

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Abstract. The use of steel-aluminum heterogeneous sheets and its adhesive-coated hemming process for cover parts helps to realize the lightweight of the car body, and its vibration characteristics greatly affect the NVH characteristics of the vehicle. Traditional cover parts vibration characteristics research ignores the influence of adhesives. Facing the higher performance of lightweight cover parts systems, it is necessary to establish a "sandwich" multi-material structure model consisting of aluminum outer sheet-ductile structural adhesive layer-steel inner sheet. Based on the typical straight edge-flat surface unit structure of cover parts, this paper established a calculation model for the vibration characteristics of steel-aluminum heterogeneous sheet adhesive structure, and the effect of adhesive thickness is quantified through experimental verification. The results show that the natural frequencies of the finite element calculation model and the experimental model are highly consistent in the first two modes, and the first two natural frequencies become larger as the thickness of the adhesive increases. The shell element of finite element calculation model based on the laminated sheet vibration theory can effectively simulate the calculation of the first two modes of the steel-aluminum heterogeneous sheet adhesive structure.

1. Introduction

Cover parts, which are formed by piping the inner and outer sheets, are very important to the appearance of the vehicle, and its vibration characteristics are a considerable factor affecting the NVH characteristics of the whole vehicle. Facing the goal of lightweight, low-density, high-strength lightweight alloys such as aluminum alloys are widely used in the manufacture of outer sheets [1]. Therefore, the connection of steel and aluminum heterogeneous sheets has become a problem to be solved.

Figure 1 shows the three-dimensional model of the hood and four types of hemming. After the adhesive is cured at a high temperature, a bonding force can be formed between the heterogeneous metal sheets, which realizes the connection of the heterogeneous metals and avoids the electrochemical corrosion of the heterogeneous metals [2]. However, the ductile adhesive layer between the outer sheet and the inner sheet not only changes the original metal structure of cover parts, but also changes the contact properties between the inner and outer sheets, which will inevitably affect its vibration characteristics.

However, due to the complex properties of the adhesive and the difficulty of modeling, the past research on the vibration characteristics of cover parts often only considers metal sheets, and the effect of the adhesive is insufficient. Zhou J [3] et al. only used CAE simulation to verify and optimize the structural rigidity performance of the hood without adhesive; B.T. Chandru [4] et al. proved the effectiveness of structural adhesive layer to improve the NVH performance of the hood through finite
element simulation and experiment, but the specific factors that affect the vibration characteristics of cover parts are not quantified.

In order to explore the influence of the adhesive on the vibration characteristics of cover parts, firstly, a shell element grid was used to establish a vibration analysis simulation model of heterogeneous metal sheet adhesive structure containing the geometric characteristics of the adhesive (length, width, and thickness). By setting the contact properties between the steel sheet, the adhesive and the aluminum sheet as tie contact, the connection relationship between the heterogeneous metal sheets is established. Secondly, using steel balls of different diameters (0.5mm, 0.6mm, 0.7mm, 0.8mm, 0.9mm, 1.0mm) and gaskets of different thicknesses (equal to the diameter of the steel balls) to make six groups of heterogeneous metal sheet samples with specific adhesive thickness, and the vibration characteristics of each group of samples were obtained by single point vibration picking hammer strike method. Finally, the comparison of finite element calculation and experimental results reveals and verifies the influence of adhesive thickness on the vibration characteristics of heterogeneous metal sheet adhesive structures.

![Figure 1. Hood and types of hemming](image1)

![Figure 2. Schematic diagram of adhesive structure of heterogeneous sheet](image2)

### 2. Analysis Model of Adhesive Structure of Heterogeneous Sheet

#### 2.1. Theoretical basis

Relevant scholars have conducted theoretical studies on the vibration characteristics of single-material and composite sheet structures. Huang Xiuchang [5] et al. proposed the equivalent mass-spring model for the structure of free curved beams and rigid sheets. A. Zarei [6], P. Vidal [7] and others have conducted numerical studies based on the vibration behavior of composite laminates, and verified the accuracy of the method through numerical vibration experiments. Hong Zhang [8] established a unified analysis model for the vibration characteristics of composite laminates under various elastic boundary conditions, and systematically revealed the vibration characteristics of annular composite laminates. Aiming at the typical adhesive-bonded joints of heterogeneous metals in the car body, Brock Watson [9] used solid element and shell element finite element models to study the mechanical properties of glue-bonded joints, and verified the use of solid in the finite element model. The unit and shell unit simulate the effectiveness of the adhesive. Bartosz Bartczak [10] used shell elements to simulate the glue layer and thin metal sheets, and verified the effectiveness of the model through experiments and finite element calculations. The above scholars' research on the cover parts, sheet vibration and adhesive-bonded joints provides the theoretical basis and modeling basis for the numerical simulation of this article.

For the dynamics of the structure, the discrete element method is used in the finite element method to simulate the continuous change of the structure. Regarding the bonding structure of heterogeneous thin sheets in this study, without considering the influence of damping force, the free state discretized motion equation is as follows.

\[
[M]\ddot{\delta} + [k]\delta = 0
\] (1)
[M] is the mass matrix of the structure; [k] is the stiffness matrix of the structure; \{δ\}, \{δ\} are the nodal displacement and nodal acceleration of the structure.

When the structure does the simple harmonic vibration shown in (2):

\[
\{δ\} = \{ϕ\} \cos ωt
\]  

Putting the above formula into (1), the homogeneous equation can be obtained as (3).

\[
([K] - ω^2[M])\{ϕ\} = 0
\]  

When freely vibrating, the amplitude \{ϕ\} of each node in the structure is not all zero, so the value of the determinant of the matrix in the parentheses in (3) must be equal to zero, so the structure natural frequency equation is obtained as (4).

\[
||[K] - ω^2[M]|| = 0
\]  

The stiffness matrix [K] and the mass matrix [M] of the structure are both square matrices of order n, where n is the number of degrees of freedom of the nodes, so the above formula is the n-th order algebraic equation of \(ω^2\), so the structure can be obtained The n natural frequencies are as follows:

\[ω_1 \leq ω_2 \leq ω_3 \leq \cdots \leq ω_n\]

For each natural frequency, a set of amplitude values \{ϕ\} of each node can be determined by (3), which maintain a fixed ratio to each other, but the absolute value can be changed arbitrarily.

Assume

\[m_{pi} = \{ϕ\}^T_i [M] \{ϕ\}_i\]  

\[k_{pi} = \{ϕ\}^T_i [K] \{ϕ\}_i = \{ϕ\}^T_i ω^2_i [M] \{ϕ\}_i = ω^2_i m_{pi}\]  

\(m_{pi}\) and \(k_{pi}\) are the corresponding generalized mass and generalized stiffness of the i-th mode shape. From (6), \(ω_i\) can be represented by \(k_{pi}\) and \(m_{pi}\) as follows:

\[ω_i = \left(\frac{k_{pi}}{m_{pi}}\right)^{1/2}\]  

It can be seen from (7) that the natural frequency of the structure is proportional to the square root of the generalized stiffness and the generalized mass ratio. The generalized stiffness of the structure is directly proportional to the moment of inertia of its section. Due to the presence of the adhesive, the moment of inertia of the section has changed significantly. The moment of inertia of the section is proportional to the third power of its thickness. Therefore, it is necessary to consider the influence of the thickness of the adhesive on the modalities of the adhesive structure of the heterogeneous sheet.

2.2. Finite element model

The "sandwich" multi-material structure of the heterogeneous metal sheets is shown in figure 2. The upper part is 340*30*1mm A6061 aluminum sheet, the lower part is 340*30*1mm Q235 steel sheet, and the middle part is adhesive layer.

According to the structural schematic diagram of the heterogeneous thin sheet shown in figure 2, a three-dimensional assembly geometric model of aluminum sheet, adhesive layer and steel sheet was established. Screw joints and gaskets are mainly used to ensure the thickness of the initial adhesive layer when making samples. In order to eliminate irrelevant factors, after the adhesive layer is cured, the screw joints and gaskets will be removed before natural frequency measurement experiments. Therefore, the finite element model actually established omits the screw joints and gaskets. According to the finite element sheet structural unit theory, by extracting the middle surface of steel sheet, aluminum sheet, adhesive and other parts, the grid unit type is set to shell unit, and at the same time, the grid of the circular hole is optimized to ensure the calculation Accuracy. The material properties of aluminum sheet, steel sheet and adhesive are shown in table 1. The boundary condition of the model is fixed at both ends, and
the contact between the aluminum sheet and the adhesive layer, and the contact between the steel sheet and the adhesive layer is set as tie contact.

| Properties         | Materials |
|--------------------|-----------|
|                    | Aluminum  | Steel    | Adhesive |
| Elastic modulus(Pa)| 7.0E10    | 2.1E11   | 2.3E9    |
| Density(kg/m³)     | 2.69E3    | 7.85E3   | 1.5E3    |
| Poisson's ratio    | 0.32      | 0.3      | 0.34     |

The thickness of the vehicle adhesive is usually about 0.1-0.5mm, and the preferred value is 0.3mm. However, in the actual experiment process, it is difficult to guarantee the thickness accuracy of the adhesive layer of 0.1-0.4mm (the error of manual assembly of samples is large), and this article only focuses on the influence of adhesive thickness on the vibration characteristics of the adhesive structure of heterogeneous sheets. Simulation and experimental verification within a larger thickness range (0.5-1.0mm) are selected. There are six sets of comparative models with adhesive thicknesses of 0.5mm, 0.6mm, 0.7mm, 0.8mm, 0.9mm, and 1.0mm. According to the finite element model, the thickness of the adhesive is set, and six sets of finite element comparison calculation models are obtained.

2.3. Experimental model

The production of heterogeneous sheet adhesive structure samples mainly includes three steps: sheet surface cleaning, adhesive coating, and high temperature curing of the adhesive.

In the adhesive coating process, in order to control the thickness of the adhesive, two methods are used: one is to evenly spread the steel balls corresponding to the thickness of the adhesive in the adhesive to ensure that the thickness of the adhesive between the aluminum sheet and the steel sheet is the specific value; The second is to add gaskets of the required thickness to both ends of the sample (between the two sheets) and fix them with screw joints, which is installed to avoid the movement of the sheet from the application of the adhesive to the curing process. The gasket can ensure that the distance between the steel sheet and the aluminum sheet is equal to the required adhesive thickness.

After coating the adhesive on the surface of the sheet and putting the samples in the oven, the curing temperature is set to 180°C, the curing time is set to 30min. The cured samples are shown in figure 3. The numbers from 1 to 6 respectively represents the adhesive thickness of 0.5~1.0mm.

The schematic of single point vibration picking hammer strike method is shown in figure 4. Divide the sample into 10 equal parts. Because the two ends of the sample are fixed, there are 8 striking points in total, except for point 3 which is the vibration picking point.

The experimental equipment is shown in figure 5, including fixtures, acceleration sensor, hammer, computer display terminals, and dynamic signal acquisition and analysis system.

Figure 3. Cured samples
3. Results and Discussion

Because the car body is subjected to low-order frequency loads and vibrates more, in order to avoid resonance in low-order modes, according to the finite element simulation calculation results, a model with an adhesive thickness of 1.0mm is selected, and the first three modes are drawn as shown in figure 6.

According to the frequency response curve of each group of experiments, the first three natural frequencies of each group of samples are calculated by the dynamic signal acquisition and analysis system, and compared with the results of the finite element simulation calculation, the curve shown in figure 7 is obtained. (fre_at5-10 respectively represents adhesive thickness of 0.5-1.0mm).

According to the finite element simulation and experimental results, the maximum increments of the first-mode natural frequency for both are:

\[
K_{\text{Simulation}} = \frac{126.35 - 100.34}{100.34} \times 100\% = 25.9\%
\]

\[
K_{\text{Experiment}} = \frac{125.73 - 98.46}{98.46} \times 100\% = 27.7\%
\]

According to the comparison between the finite element simulation results and the experimental results, it can be seen that the variation rules of the first two natural frequencies are similar and have good consistency. From the comparison curve of each group, the simulation value and the experimental value have a high degree of coincidence on the first two natural frequencies, but there is a deviation on the third frequency. This phenomenon is caused because the shell element is used when the finite element model
is established. When the contact properties of the aluminum sheet and the steel sheet and the adhesive are established separately, in order to avoid the displacement conflict of the nodes of the same layer, it is impossible to set the corresponding contact pairs for all nodes. The variation rule of natural frequency of heterogeneous sheet adhesive structure with adhesive thickness is shown in figure 8, which is the first three natural frequency histogram of six models in simulation (figure 8(a)) and experiment (figure 8(b)).

According to the result of the histogram in above analysis, for the first two natural frequency, the simulation and experimental results showed good consistency, and with the increase of thickness of adhesive, natural frequency of the heterogeneous thin adhesive structure increases, the study on the structure of heterogeneous adhesive sheet vibration characteristics must be considered when the thickness of the adhesive on the influence of the modal structure itself to explore quantitative adhesive thickness on the influence law of structure vibration characteristics, the data to make use of polynomial function fitting, get heterogeneous adhesive sheet structure in the first two natural frequency changes with the thickness of the adhesive function equation is as follows:

\[
\begin{align*}
    f_1 & = -82.13h^2 + 248.68h + 167.25 \\
    f_2 & = -22.39h^2 + 84.52h + 64.01
\end{align*}
\]  

\(f_1, f_2\) respectively represent the first and second natural frequencies of the adhesive structure of the heterogeneous sheet; \(h\) is the adhesive thickness.
The fitting curve of the function is shown in figure 9. Within the range of adhesive thickness studied in this paper, the fitting function shown in (10) can effectively represent the relationship between the adhesive thickness and the first two natural frequencies of the adhesive structure of the heterogeneous sheet. In the design of the vibration characteristics of the cover parts considering the thickness of the adhesive, the value of the adhesive thickness can be deduced inversely according to the required natural frequency requirements.

4. Conclusions
Based on the lightweight body and higher NVH characteristics, it is necessary to establish a numerical simulation model of the vibration characteristics of the heterogeneous sheet adhesive structure, and further study and quantify the influence of the adhesive thickness on the dynamic characteristics of the typical adhesive structure of the heterogeneous cover parts. Based on the straight edge-flat surface structure, this paper establishes a finite element model of the heterogeneous metal sheet adhesive structure of the cover parts. Through modal experiment analysis, it reveals the influence of the adhesive thickness on its vibration characteristics. The conclusions are as follows:

1) From the comparison of the finite element calculation and the experimental results, the comparison of the first two natural frequencies of the heterogeneous sheet adhesive structure shows that the finite element calculation model established in this study has a high consistency with the experimental model, so the shell element based on the laminated sheet vibration theory is adopted. The finite element calculation model can effectively simulate the calculation of the first two modes of the heterogeneous sheet adhesive structure.

2) Aiming at the heterogeneous sheet adhesive structure with the thickness of the aluminum sheet and the steel sheet of 1mm and the thickness of the adhesive in the range of 0.5~1.0mm, the first two natural frequencies increase as the thickness of the adhesive increases. In the simulation results, the maximum increase of the first natural frequency is 25.9%. In the experimental results, the maximum increase of the...
first natural frequency is 27.7%. Therefore, when studying the vibration characteristics of a heterogeneous sheet adhesive structure, the influence of the adhesive thickness must be considered.

3) Based on the finite element simulation and experimental data, the functional relationship between the adhesive thickness and the first two natural frequencies of the heterogeneous sheet adhesive structure is obtained by polynomial fitting, which is beneficial to the design and development of the cover parts taking into account the influence of the adhesive.

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