Study on 3D quantization and optimization of the acoustic package of vehicle powertrain by energy boundary element method

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Abstract: Automobile noise has become the first source of environmental noise pollution, and its radiated power reaches 75% of the total environmental noise, while powertrain noise is the main source of automobile noise. With the problem of noise reduction of automobile powertrain, a 3D grid positioning technology, based on energy boundary element method, was proposed to quantify the noise source of automobile powertrain, and the generalized sound holography was applied to obtain the noise cloud map and analyze the noise propagation path, so as to determine the acoustic package material and the optimal location. Through the optimization experiment and simulation of 4 schemes, the acoustic package of automobile powertrain with the best effect was obtained, and the insertion loss of 6.7db could be obtained at 7m of the powertrain. Therefore, the results have important engineering application values for automobile noise reduction.

1. Introduction

Automobile powertrain is one of the main sources of automobile noise. Noise directly affects the stability of the mechanical system and the physical and mental health of the passengers [1]. Therefore, automobile noise reduction has become the focus of automobile design, manufacture and use. However, among many automobile powertrain sources, it is difficult to detect and analyze spectrum width, intensity and direction distribution. In recent studies, there are many advanced methods to reduce the noise of automobiles, but each has its own problems such as insufficient accuracy, complicated calculation or difficult realization in engineering [2, 3].

Under the requirements of additional mass and cost of automobile, this paper uses the generalized acoustic holography technology to establish the acoustic boundary element model of power assembly, deduces its algorithm, equates the energy to three-dimensional noise source, combines the professional simulation software Actran to import the test parameters, which can verify the effectiveness of the sound package and the size of external noise, and the results are intuitive and detailed. By optimizing the acoustic package scheme, the contribution of powertrain through noise is minimized. Finally, a scheme was obtained, in which the insertion loss of 6.7dB could be obtained at 7m of the powertrain, and the noise reduction effect was obvious. The method and results have important engineering significance for the design, manufacture and use of automobile.

2. Mathematical modeling and experiment

2.1 Derivation of energy boundary element method
The energy equation of out-of-plane vibration of two-dimensional thin plate structure is [4]:
\[
-c_s^2 \left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) \langle e \rangle + \eta \omega \langle e \rangle = \pi_m(x, y)
\]  
(2.1)

c_s refers to elastic wave group velocity, \( \eta \) loss factor, \( \omega \) vibration angular frequency, \( \langle e \rangle \) average energy density of elastic wave period, \( \pi_m(x, y) \) input power per unit area.

Based on the above, weight functions \( G(x; \xi) \) are introduced and integrated in the domain, and the energy equation is:

\[
\int_0^L \left( -\frac{c_s^2}{\eta \omega} \frac{d^2 e(x)}{dx^2} + \eta \omega e(x) - \pi_m(x) \right) G(x; \xi) dx = 0
\]  
(2.2)

Then by using the Dirac delta function \( \delta(x - \xi) \), the above formula becomes:

\[
-\frac{c_s^2}{\eta \omega} \frac{d^2 e(x)}{dx^2} + \eta \omega e(x) = \delta(x - \xi)
\]  
(2.3)

\( G(x; \xi) \) is the Green's function of free space and is the basic solution of the above equation. Make the above equation transformed by the Fourier integral, and get:

\[
\tilde{G} = \frac{1}{2\pi} \frac{\eta \omega}{c_s^2 k^2 + \eta^2 \omega^2} e^{-jk\xi}
\]  
(2.4)

The inverse Fourier transform of the above formula can be obtained:

\[
G = \int_{-\infty}^{\infty} \frac{1}{2\pi} \frac{\eta \omega}{c_s^2 k^2 + \eta^2 \omega^2} e^{-jk\xi} e^{j\xi} dx = \frac{1}{2c_s} e^{\frac{\eta \omega}{c_s} |x|}
\]  
(2.5)

With two integration of the energy equation (2.2) by parts according to the boundary element method, we can obtain:

\[
-\frac{c_s^2}{\eta \omega} \left[ \frac{d e(x)}{dx} \frac{dG}{dx} \right]_0^L + \int_0^L e(x) \left( -\frac{c_s^2}{\eta \omega} \frac{d^2 G}{dx^2} + \eta \omega G \right) G(x; \xi) dx = \int_0^L \pi_m(x) G dx
\]  
(2.6)

Therefore, the above equation is further simplified as:

\[
-\frac{c_s^2}{\eta \omega} \left[ \frac{d e(x)}{dx} \frac{dG}{dx} \right]_0^L + e(\xi) = \int_0^L \pi_m(x) G dx
\]  
(2.7)

set \( F(x; \xi) = \frac{c_s^2}{\eta \omega} \left( \frac{dG}{dx} \right) = \frac{1}{2} \frac{(x - \xi)}{|x - \xi|} e^{\frac{\eta \omega}{c_s} |x - \xi|} \), \( q(x) = -\frac{c_s^2}{\eta \omega} \frac{d e(x)}{dx} \)

Substitute into equation (2.7) to obtain:

\[
e(\xi) = \left[ e(x) F(x; \xi) - q(x) G(x; \xi) \right]_0^L + \int_0^L \pi_m(x) G(x; \xi) dx
\]  
(2.8)

\( \xi \): one-dimensional point coordinates, \( x \): excitation point coordinates.

Formula (2.8) shows that energy density and energy intensity can be obtained by the detailed energy
density $e(x)$, energy intensity $q(x)$ and external input of any point in the domain. At the same time, compared with the finite element method of energy, the dimension decreases and the calculation speed increases.

2.2 Measurement method

During the experiment, a microphone array (64 channels) was arranged around a vehicle power system to measure its 3D acoustic radiation. The positioning probe based on the time of flight ensures that the positioning accuracy of the sensor is within 1mm, which facilitates the rapid conversion of the test results of the array coordinate system to the grid coordinate system of the sound source. The measured sound pressure is directly mapped on the acoustic model for simulation and calculation. Signal synchronization between different channels is realized by cross-spectral matrix (CSM) [5].

The cross-spectral matrix ($S_{MM}$) can be obtained by the following formula:

$$S_{MM} = S_{RM}^H S_{RR}^{-1} S_{RM}$$

where $H$ refers to the Hermitian matrix of the interaction spectrum between sensor and microphone array $S_{RR}^{-1}$ refers to the pseudo-inverse matrix of the reference cross-spectral matrix; $SRM$-- one inverse pseudomatrix

The degree of signal synchronization between channels depends on $S_{RR}$ the quality of the inverse of the square matrix. The matrix is decomposed and the virtual matrix of each component matrix is obtained by using equation [2.9]. By measuring the minimum deviation between the cross spectral matrix $S_{MM}$ and the calculated cross spectral matrix, the number of required component matrices is determined. Finally, the global cross spectral matrix is modified by the cross spectral matrix between each channel and the reference channel.

The acoustic transfer function between the nodes on the grid and the microphone is determined by the equivalent source modeling (ESM) method, integrates the algorithm of the estimated transfer function into the test software. After the propagation model is established based on the results of the synchronization test of the transfer function and the harmonic array, the sound pressure amplitude on the power train grid and the location of the main sound source can be obtained. The generalized acoustic holography is constructed by combining the probability statistics method and the above transfer function [6][7]. This method can be used to obtain the distribution results of the minimum residual and the most stable sound source from the energy Angle. Furthermore, the sound power expression can be simplified as:

$$J(q) = |Hq - p|^2 + \lambda \|q\|^2$$

Here: $H$ is the transfer function matrix, which describes the transfer characteristics of sound source from grid node to microphone. The transfer function matrix is obtained by ESM method. $Q$ is the complex amplitude of the point source on the grid node; $P$ is the complex pressure vector calculated by the CSM matrix of resynchronization. Lambda is a regularized parameter calculated using a Bayesian method.

Thus, the Tikhonov equation is obtained:

$$q = H^* \left( HH^* + \lambda^2 I \right)^{-1} p$$

The volume velocity of the point source can map the 3D grid to obtain the sound power on each grid cell.

2.3 Acoustic test modeling

2.3.1. 3D gridding of vehicle body
Figure 1. Vehicle body, ground and far field grid model

The grid of the powertrain is the same as that used in the simulation of sound source characteristics. Therefore, a cube field boundary is established which sized 1 square meter, so as to facilitate the calculation of the directivity and sound power of the sound source. A receiving point is set at 7m to compare the simulation result with the measured sound pressure value of the actual position. The ground is also gridded to account for the effect of the ground on the reflection of sound waves. The influence of this area on the sound pressure at the receiving point is corrected by the sound pressure value at the receiving point. Meanwhile, it is assumed that:

(1) There is no interference between actual sound waves.
(2) The sound power is evenly distributed on the surface of the sound source and propagates freely in all directions. The incident field on each grid node is diffused.
(3) The absorption, reflection and transmission of sound waves by the boundary are diffused and are described by the energy coefficient:

If node $i$ receives the power $W_{\text{incident}} (i)$ transmitted to it by other nodes, the energy absorption coefficient of this node is:

$$w_{\alpha} (i) = \alpha_i w_{i} (i)$$

The node reflection coefficient is $r_i$, then

$$w_{r} (i) = r_i w_{i} (i)$$

The broadcast relationship of power transfer from $k$ to $i$ plane is

$$w_{t} (i) = \tau_{ik} w_{k} (k)$$

Here $\tau_{ik}$ is the transfer coefficient in Diffuses field. It can be known from the energy conservation that, $a_i$, $r_i$, $\tau_{ik}$, suit the relationship:

$$1 = \alpha_i + \tau_{ik} + r_i$$

2.3.2 Perspective factor calculation

The energy exchange at different boundary units depends on the "Angle factor" among the units. The coefficient is only related to geometry and scale, when there is no obstacle between the two elements, the Angle of view factor can be obtained analytically. On the contrary, Hemicube method is needed to calculate the Angle factor [8, 9]. In order to obtain the unsolved system equation to be solved, the energy balance equation of each boundary element is required. For acoustic problems, the sound power radiated by unit $i$ is equal to the sum of reflection, transmission and source power:

$$w_{i} (i) = w_{r} (i) + w_{t} (i) + w_{\text{source}} (i)$$

The relationship between reflection and transmitted or incident power is shown in equations 2.2 and 2.3. The $i$th element of $W_{\text{incident}} (i)$ is equal to the sum of the radiated power of the other elements multiplied by the Angle factor;
According to equations 2.13, 2.14 and 2.16, it can be obtained that:

\[ w(i) = (1 - \alpha_i - \tau_{ik}) \sum_{j=1}^{n} F_{ji} w(j) + \tau_{ik} \sum_{j=1}^{n} F_{kj} w(j) + w_{source}(i) \]  

(2.18)

In this way, n equations (on N boundary element elements), which contains n unknown quantities (radiation power on each element), can be obtained and solved by the Super LU method of sparse matrix. After the grid is set, the corresponding material properties are set for different grid blocks. The full load condition with the largest noise is adopted to calculate the contribution of the power train to the noise. The noise spectrum is loaded into the simulation model in the form of 1/3 octave.

2.3.3 Power balance

The incident power at the location of the sound-absorbing material and the incident power on the panel that may transmit noise to the cabin, the power balance is further calculated, in order to quantify the incident, reflected and transmitted power of the acoustic package.

\[ p^2(j) = \sum_{i} 2 \rho c \frac{W(i)}{S_i} \]  

(2.19)

Here, \( p^2(j) \) is the square value of pressure at the jth point, and W(i) is the radiant power of the ith cell plane, and \( VF_{ij} \) is the solid Angle between the ith plane and the jth point.

2.4. Test

The powertrain is installed in the full anechoic chamber, the support structure covered with acoustic materials in the actual test to avoid sound reflection, and several groups of specific operating conditions selected. The test system simulates the maximum passing noise of the vehicle by the equipment suitable for different engine speeds and different transmission ratio transmission systems. In the experiment, the noise level of the engine was tested under different speed and transmission ratio and idling. Figure 2 shows the array's five test locations (equivalent to 270 microphones), eight of which are selected as reference channels.

Figure 2. Location of engine test bench and engine grid model test array

Figure 3 is an acoustic hologram of the gearbox at 2kHz and 3 gears at the selected engine speed under maximum torque.
2.4.1 Acoustic power analysis

In order to verify the accuracy of array test results, a sound intensity probe was used to test the noise level of the engine at low idle speed and certain torque. According to ISO9614-2 standard, every plane is scanned and tested. Figure 4 shows the comparison between the tested and the calculated results. The maximum deviation between the two groups is 2dB, which belongs to the error range.

FIG. 4. Comparison between the tested and calculated results of the sound intensity probe

Through the above steps, the results of the powertrain noise field can be imported into the simulation software to calculate the noise radiation characteristics of the powertrain installed on the vehicle, which is effective for optimizing the acoustic package.

2.4.2 Cloud image analysis

The main propagation path of sound pressure can be seen directly from the radiation cloud map of the power and radiation intensity on each grid cell at the receiving point. Figure 5 shows that most of the radiation source is in the right side of the engine compartment, passing through the hole next to the acoustic package under the powertrain and the ground reflection to the receiver on the right side. The radiated power is mainly caused by the reflection of sound waves rather than by transmission. The results show that the transmission coefficient of the acoustic package is high enough so that the reverberation between the acoustic package and the ground can be reduced by the sound absorption coefficient at the bottom of the acoustic package.
The contribution of different surfaces of the powertrain to the noise can be obtained by turning on the source term of the response in a specific condition, which provides effective guidance for determining the main vibration source of the powertrain and installing the acoustic package on the noise propagation path.

2.5. Optimization and analysis of acoustic package
The sound absorption material is made of micro perforated aluminum plates. The relationship between sound absorption coefficient and material thickness is not obvious, so we use the universal 0.1mm. The aperture, hole spacing and the size of the cavity behind the plate are important factors affecting the sound absorption effect [10, 11]. Therefore, we adopted four experimental schemes respectively, as shown in table 1:
Table 1. Parameter table of acoustic package optimization scheme unit: mm

| Plan | Plate thick | Aperture | Hole spacing | Plate behind the |
|------|-------------|----------|--------------|------------------|
| 1    | 0.1         | 0.8      | 1.0          | 0.4              |
| 2    | 0.1         | 0.6      | 1.5          | 0.6              |
| 3    | 0.1         | 0.4      | 2.0          | 0.8              |
| 4    | 0.1         | 0.2      | 2.5          | 1.0              |

Under the guidance of the previous theories and experiments, we arranged the sound absorption materials on the right inner side of the engine compartment and on the sensitive parts of the engine. According to the above measurement methods, the noise parameters were detected at a distance of 7m from the noise source and compared with the simulation results. The schematic model of the optimized acoustic package effect is shown in figure 7:

![Figure 7. Effect diagram of optimized acoustic package](image)

3. Results

3.1 Radiated acoustic power

Figure 8 shows the noise power of the vehicle at low idle speed. Acoustic power results of the blue curve standard acoustic package model. The red curve is the result of measuring the sound power according to ISO standard. The measured result is 1.2db lower than the standard value. The main reasons include: the method of sound source characterization, the measurement of sound power, the uncertainty of the calculation model, the difference between the experiment and the real assembly, the interference of aerodynamic noise and other factors.

![Figure 8. Comparison between the measured acoustic power value and the standard value at idle speed](image)
3.2 Insertion loss
Based on the standard acoustic package, an optimal scheme can be obtained by comparing several optimization schemes. Corresponding to plan 4 in the curve in figure 9, 6.7db insertion loss can be obtained at 7m of the powertrain. The noise reduction effect is obvious.

![Figure 9. Optimized acoustic packet insertion loss value](image)

3.3 Sound pressure level
During the test, the noise of the same order is minimized to increase the uncertainty of the test. The speed and gear ratio of the engine meet the requirements of PBN (pass-by Noise) test for total acceleration, and the engine noise is at the maximum level. The mean values of the sound pressures obtained from the four microphones were compared with the theoretical values obtained. See figure 10. The calculated value is on the high side in the low frequency range and on the low side in the 1600-2500Hz range, but the total calculated result is only 0.9dB away from the actual test value. The experiment has reached the accuracy requirement completely.

![FIG. 10 comparison between the measured sound pressure level of the Powertrain under PNB test conditions and the simulation results](image)

4. Conclusion
We propose a method to calculate the noise level of powertrain based on the energy boundary element 3D grid method by using generalized acoustic technology, in order to improve the noise level of vehicles. With the results into the vehicle body acoustic model, we can predict vehicle passing noise, optimize the acoustic package design, and meet the engineering requirements. Also, two conclusions are obtained:

1. This 3D generalized acoustic holography technology uses the same set of grids for transfer function simulation, calculation and post-processing of array test data. It avoids the disadvantages of other methods such as large bandwidth, many nodes, large amount of data and tedious processing.
process.
(2) The experiment shows that the generalized acoustic holography is used to optimize the scheme on the basis of the standard acoustic package, and the reasonable arrangement of acoustic materials in the corresponding position can achieve 6.7db insertion loss at 7m of the automobile powertrain. The optimization of the acoustic package has achieved obvious results, which can greatly improve the engineering quality of automobile manufacturing, design and use.

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