Study on Acoustic Radiation Calculation and Far Field Criterion of Oil pan

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Abstract. Diesel engine with low vibration and noise characteristics will be a major trend for the future development. As the shell part on the engine, the vibration and noise control of the oil pan is an urgent problem to be solved. It is of practical significance to predict the oil pan vibration and radiation noise during the design phase. An oil pan of diesel engine was taken as the research object, the finite element model of the oil pan was established and the finite element method (FEM) was used to calculate the oil pan vibration response. Three different numerical calculation methods (Finite element-boundary element hybrid method, finite element-infinite element hybrid method, finite element-automatic matching layer technology) were used to calculate radiated sound power level of the oil pan respectively. The calculation accuracy and efficiency of three different calculation methods were compared and analyzed. The results show that the finite element-boundary element method is more suitable for the calculation of the acoustic radiation of the oil pan. Finally, a method based on the directivity of acoustic radiation to determine the far-field acoustic radiation is proposed and verified.

1. Introduction
With the continuous development of modern industry, the internal combustion engine develops toward high speed, high power and high efficiency, which makes the vibration and noise of the structure more prominent. Vibration and noise have a bad impact on the service life and working efficiency of the internal combustion engine, which requires people to pay more attention to the vibration and noise of the internal combustion engine[1]. Liu S[2] and Xiong F[3] used the sound intensity method to identify the radiation noise source of diesel engine. The results show that the oil pan structure is one of the main components of diesel engine radiation noise. As the shell part on the diesel engine, the vibration and noise control of the oil pan is an urgent problem to be solved. It is of practical significance to predict the oil pan vibration and radiation noise during the design phase. In engineering, numerical methods such as finite element method, infinite element method, boundary element method, and statistical energy method are used to calculate the vibration and acoustic response of the oil pan. [4-9]. Zhang J H[10] and Wang Q W[11] used finite element and boundary element method (FE-BEM) to calculate the radiation noise of oil pan and achieved a good agreement with the measured values. Based on the analysis of the dynamic characteristics of the engine oil pan, Song S S[12] used BEM to predict the noise of the oil pan surface and compared the prediction results with the experimental results. The results show that the BEM has high reliability in predicting the radiation noise of oil pan. Yang Y T[13] used FE-IFEM to calculate the radiation sound field of the oil pan. On this basis, the structure is improved and the changes of the acoustic radiation noise are
compared. Liu R J[14] used the finite element-infinite element method (FE-IFEM) to calculate the radiation noise of an oil pan structure. The results show that the simulated sound pressure values are in good agreement with the test values in 500~3000 Hz.

However, there are still deficiencies in the prediction of oil pan radiation noise. (1) In engineering, most scholars use a single method to calculate the acoustic radiation of the oil pan, and the comparison of different numerical methods rarely involves. (2) For the far-field acoustic radiation, in engineering, the far-field position is usually judged based on experience, and there is a lack of quantifiable judgment methods.

In this study, an oil pan was taken as the research object. Three different numerical calculation methods (Finite element-boundary element hybrid method, finite element-infinite element hybrid method, finite element-automatic matching layer technology) were used to calculate radiated sound power level of the oil pan respectively. The calculation accuracy and efficiency of three different calculation methods were compared and analyzed. Finally, a method based on the directivity of acoustic radiation to determine the far-field acoustic radiation is proposed and verified.

2. Acoustic radiation characteristics of oil pan

The study object is an oil pan as shown in Fig.1. Based on the drawings, the oil pan finite element model was established, as shown in Fig. 2.

![Figure 1. Oil pan model](image1)

![Figure 2. Oil pan finite element model](image2)

The Block Lanczos method was used to calculate the oil pan vibration mode and the frequency range was 0~4000 Hz. The calculated first 6 modes are shown in Fig. 3.

(a) First-order (89.3Hz) (b) Second-order (180.3Hz) (c) Third-order (209.6Hz)
In Fig. 3, the first-mode elastic mode of the oil pan is the torsion of the entire length along the length direction, and the relative displacement near the end of the flywheel is relatively large. The second-order elastic mode of the oil pan is that the left and right side plates simultaneously vibrate inward and outward. The third-order elastic mode of the oil pan is the overall first-order lateral bending. The fourth-order elastic mode of the oil pan is the overall first-order longitudinal bending, and the relative displacement of the middle bottom plate is relatively large. The fifth-order elastic mode of the oil pan is that the left and right side plates vibrate inward and outward respectively. The sixth-order elastic mode of the oil pan is the overall second-order lateral bending and local vibration of the diaphragm, and the maximum relative displacement appears on the diaphragm.

Through the study of the structure vibration modes, the basic dynamic characteristics of the oil pan can be more effectively grasped. From the above analysis, it can be seen that the overall rigidity of the oil pan is relatively small, the left and right side plates, and the internal diaphragm have relatively large vibration. The natural frequency of the oil pan is concentrated in the low frequency band, which contributes a lot to the radiation noise of the whole machine. Therefore, for the control of the vibration noise of the oil pan, it is mainly possible to arrange the reinforcement ribs or increase the thickness of the reinforcement ribs and the partition plate, and try not to use a large flat plate structure.

The excitation of the oil pan mainly comes from the connection bolt between the oil pan and the bedplate. In this paper, the vibration acceleration of the bolt is measured, and it is loaded at the center node of the bolt hole of the oil pan. The center node of the bolt hole is connected with the bolt hole surrounding nodes through the rigid elements (RBE2) to ensure the excitation transmission. The measurement site is shown in Fig. 4, and the measured result is shown in Fig. 5.

The BEM, IFEM, and AML are common numerical methods for calculating structure radiation noise in the middle and low frequency. The BEM combines classical integral equations and finite element theory. The integral equation may be regarded as an exact solution of the governing partial differential
equation. The BEM attempts to use the given boundary conditions to fit boundary values into the integral equation. Once this is done, in the post-processing stage, the integral equation can be used again to calculate numerically the solution directly at any desired point in the interior of the solution domain.

The infinite element method is a modification of the finite element method. The method divides the domain concerned into infinitely many sections. The structure of the acoustic IFEM is composed of two parts: the finite inner region of the envelope structure model and the semi-infinite outer region. The limited inner region is dispersed by finite elements, the semi-infinite outer region is dispersed by divergent infinite elements, and the nodes are coupled at the interface to ensure continuity in the process of outward propagation of sound pressure.

The AML is a new type of finite element method. The calculation principle is to artificially set a finite thickness medium layer to absorb sound waves at the acoustic finite element boundary. The absorption layer makes sound waves decay rapidly in exponential form. Therefore, the sound wave at the boundary of the medium layer is substantially zero.

There are many differences between the boundary element method, the infinite element method and the automatic matching layer technology. First, the differences in modeling are as follows: the external flow field of the boundary element method is a surface mesh, and the external flow field of the infinite element and the matching layer is a volume mesh. The acoustic boundary conditions of the three methods are also different. The boundary element method requires the physical quantity of vibration as the boundary condition of the acoustic calculation. The infinite element method and the matching layer technology need to use the physical quantity of the vibration as the boundary condition of the calculation, and the external flow field needs to be specified as infinite attributes or matching layer attributes.

The BEM, AML, and IFEM were used to calculate the radiation noise of the oil pan respectively. The calculated frequency band was 20–1420 Hz with 2 Hz interval. In the BEM, the rigid surface is simulated by setting symmetric boundary condition to close the internal sound field of the oil pan, but in the AML and IFEM, the air impedance is defined at the rigid surface. The acoustic boundary and rigid surface processing of AML and IFEM are shown in Fig. 6. The calculated result of the oil pan radiation sound power is shown in Fig. 7. To study the sound pressure levels of certain specific locations, four different field points are established respectively. The sound pressure levels of these field points were calculated and the results are shown in Fig. 8.
In Fig. 7, within the calculated frequency range, the radiated sound power curves of the oil pan obtained by the three different numerical methods are basically the same. In Fig. 8, the radiation sound pressure spectrums are basically consistent with the oil pan radiation sound power spectrum, the sound pressure peak frequencies are basically the same. In the range of 20–1420 Hz, the radiation sound pressure level curves obtained by the three methods agree well with each other in the trend.

The overall radiation sound power levels of oil pan obtained from FE-BEM, FE-AML, and FE-IFEM are 77.9 dB, 74.8 dB, and 73.8 dB respectively. The sound power value obtained by the boundary element method is higher than that of the other two methods. This is mainly due to the high calculation
result of the boundary element method in the 1200~1420Hz frequency band. The difference in the calculation results of the three different methods is mainly due to the difference in calculation principles and boundary conditions.

Compared with the infinite element method, the matching layer technology has no requirements on the shape of the volume mesh, and at the same time, it can adapt to the grid properties. Therefore, the matching layer technology is superior to the infinite element method in the calculation of the acoustic radiation of the oil pan. Compared with the matching layer technology, the boundary element method does not require volume meshing, the modeling scale is small, and the acoustic radiation calculation speed is also better than the matching layer technology. Therefore, in engineering, the FEM-BEM method is recommended for oil pan radiation noise calculation.

The differences in the modeling scale, computational accuracy and computational time-consuming of the three methods are shown in Table 1.

The coefficient matrix of the linear equations formed by the traditional BEM is an asymmetric dense matrix, which leads to its shortcomings of high computation and high memory consumption. According to engineering experience, when the boundary element model degree of freedom N exceeds 15000, the traditional BEM will consume a lot of computer resources and a long solution time.

Fast multipole BEM replaces the direct connection between the source point and the field point with the indirect connection by introducing the multipole expansion of the kernel function. The interaction between particles is replaced with the interaction between set elements. The fast multipole algorithm speeds up the multiplication of matrix and vector, and reduces the computation and memory consumption from O(N^3) to O(N), which increases the solution speed.

Table 1. The differences between the three methods.

| Methods | Modelling scale | Computational accuracy | Time-consuming/h |
|---------|-----------------|------------------------|------------------|
| FE-BEM  | small           | good                   | 8.0              |
| FE-AML  | medium          | good                   | 24.5             |
| FE-IFEM | large           | medium                 | 45.5             |

3. Far field criterion of oil pan
In engineering, the sound radiation field is divided into the far field and the near field. The sound pressure in the near field is disordered and the sound pressure fluctuates greatly. The far field is selected for general sound radiation calculation and testing, the far-field sound pressure satisfies formula (1):

\[ P(r, \theta, \varphi) = \frac{P_{\text{eq}}(\theta, \varphi)}{r} \quad \text{(1)} \]

where, \( r \) is the distance from the field point to the equivalent sound source, and \( P_{\text{eq}} \) is the equivalent sound pressure amplitude, \( \theta \) is the azimuth angle, \( \varphi \) is the elevation angle.

The acoustic radiation directivity function is shown in formula (2):

\[ \Theta(r, \theta, \varphi) = \frac{P_{\text{eq}}(\theta, \varphi)}{\max[P_{\text{eq}}(\theta, \varphi)/r]} = \frac{P_{\text{eq}}(\theta, \varphi)}{\max[P_{\text{eq}}(\theta, \varphi)]} \quad \text{(2)} \]

It can be seen from formula (2) that the directivity of far-field acoustic radiation no longer changes with the distance, so the far-field distance can be determined by the directivity of acoustic radiation.
The boundary element method is used to calculate the acoustic directivity under different acoustic radiation radius, and the calculation results are shown in Figure 9.

In Fig. 9, at 200 Hz, the acoustic radiation directivity of oil pan under different radiation radius is similar, which is mainly due to the long wavelength of sound waves at 200 Hz. The oil pan acoustic radiation exhibits overall radiation characteristic, and the directivity of acoustic radiation is not obvious.

At other given frequencies, When the sound radiation radius is 0.3m, the directivity of the sound radiation of the oil pan no longer changes with the increase of the radius, so 0.3m is the far-field distance of the sound radiation of the oil pan.

4. Conclusion
In this study, an oil pan of diesel engine was taken as the research object, three different numerical calculation methods (Finite element-boundary element hybrid method, finite element-infinite element hybrid method, finite element-automatic matching layer technology) were used to calculate radiated sound power level of the oil pan respectively. The calculation accuracy and efficiency of three different calculation methods were compared and analyzed. Finally, a method based on the directivity of acoustic radiation to determine the far-field acoustic radiation is proposed and verified. The main conclusions are summarized as follows:

(1) Compared with the IFEM and AML, the BEM does not require volume meshing, the modeling scale is small, and the acoustic radiation calculation speed is also better than the IFEM and AML. Therefore, in engineering, the FEM-BEM method is recommended for oil pan radiation noise calculation.

(2) It is effective and reliable to judge the far-field acoustic radiation of the oil pan by the directionality of acoustic radiation.

5. References
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