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Sound Field Optimization of Construction Machinery Cab Structure based on Ergonomics and Mathematical Modeling

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Abstract: The continuous progress of science and technology drives the development of domestic construction machinery. Now the emergence of high-power construction machinery, at the same time also brings more and more prominent noise problem, now people pay more and more attention to the noise problem of construction machinery. This paper mainly studies the sound field optimization of construction machinery cab structure based on ergonomics and mathematical modeling. In this paper, firstly, the body structure model and the cab sound chamber model are preprocessed, and the free mode and sound solid coupling mode of the locomotive body structure and cab sound chamber model are calculated and analyzed respectively. According to the analysis results of cab acoustic package, the noise contribution degree is calculated to determine the ceiling and left component with the largest contribution. The acoustic package of the rear coaming and rear coaming is optimized.

1. Introduction

With the development of society and the improvement of people's living standards, people's requirements for low noise are becoming more and more demanding. Therefore, many manufacturers of passenger vehicles, construction machinery and aircraft have invested a lot of manpower, material resources and financial resources to study noise control, among which noise control in closed sound chamber is a hot research topic at home and abroad. For example, the 2000/14 / EC Directive of the European Parliament and the Council of Europe and the GB 16710.1.2010 limit standard of construction machinery noise have clear requirements on the sound pressure level at the driver's ear [1]. In the field of defense industry, the noise in armored vehicles, military transport planes, ships and so on directly affects the comfort of combatants, thus affecting their combat effectiveness. In addition, the amount of outward radiated noise also affects the survivability of the ship, so it is necessary to control the internal and external radiated noise. As is known to all, engineering machinery and equipment products, widely used in plate and shell structure, the rectangular plate is representative of the typical structure, especially the development of lightweight vehicles in recent years, the produced by sound field coupling cab structure of a low roar, has become one of the engineering machinery cab noise of main noise sources, the serious influence the ride comfort [2]. Therefore, in view of the low-frequency noise in the cab, studying the coupling mechanism and coupling characteristics of structural sound field is of great application value to improve the acoustic design level of vehicle cab and reduce the low-frequency coupling noise [3]. In addition, with the continuous progress of science and technology, although most products have no substantial changes in function, people have gradually increased their requirements for quality, especially for the sound quality of vehicle cab [4].

As early as the middle of the 20th century, foreign scientists and technicians have begun to do a lot of researches on vehicle noise control. The theoretical expression of coupling between structural thin plate and sound field is deduced theoretically, and the structural noise is accurately analyzed and predicted by combining the test data with finite element analysis and boundary element analysis, using the acoustic-structure coupling technology and noise transfer path analysis technology [5-6]. In the 21st century, some scholars combine acoustic finite element method with acoustic boundary element method to analyze the vehicle noise. The finite element method and the boundary element method are used to calculate the structural dynamic response and acoustic response of the vehicle, and the vibration velocity results obtained from the calculation of the structural dynamic response are used as boundary conditions for acoustic response analysis to obtain the noise transfer function [7]. Some scholars used noise transmission path analysis technology to obtain noise values at different positions through tests, and used wavelet analysis technology to process and analyze test data to determine the transmission path of noise, so as to improve the impact of tires on vehicle noise [8].

In this paper, the sound and vibration coupling characteristics of the closed sound chamber system in the structural form of construction machinery cab are studied, and the sound quality characteristics and sound quality evaluation model of construction machinery cab are explored, so as to provide a theoretical basis for reducing the low-frequency coupling noise of construction machinery cab and more reasonable evaluation of the noise attribute of construction machinery cab.

2. Bridge Structure Modal Analysis and Acoustic Cavity Modal Analysis

2.1. Structural Modal Analysis of the Cab

(1) Modal analysis theory

The modal of cab structure is one of the inherent properties of cab, which characterizes the vibration of cab structure under external excitation. With the help of modal analysis theory, the frequency and mode shape of each mode of the cab structure are studied, which can be used to avoid the resonance between the cab and the structure excitation [9-10]. In addition, cab structural modes are closely related to cab acoustic analysis.

The dynamic finite element equations of structural vibration are:

$$M_s \ddot{U} + C_s \dot{U} + K_s U = F_s \tag{1}$$

Where, U is the node acceleration, velocity and displacement vectors of the overall structure respectively, and is a function of time. Ms is the global mass matrix, Cs is the damping matrix, Ks is the stiffness matrix, Fs is the excitation vector.

Generally, the vibration of the structure is assumed to be linear with small deformation, and the effect of damping on the system mode can be ignored. When the damping term and the external force term are zero, Equation (1) becomes:

$$M_s \ddot{U} + K_s U = 0 \tag{2}$$

This system of linear homogeneous ordinary differential equations with constant coefficients has a solution of the form:

$$U = \overline{U} \sin \omega t \tag{3}$$

Where, U is the column vector of amplitude of displacement U (independent of time); ω is the natural circular frequency. After substituting Equation (3) into Equation (2) and eliminating sin ωt, we get:

$$(K_s - \omega^2 M_s)U = 0 \tag{4}$$

The above equation is the characteristic equation, and the characteristic root ω2 obtained by its solution is the undamped natural frequency ωi of the structure. At this time, Ui(j= L, 2... N is the mode shape at the corresponding frequency.

(2) Establishment of structural model

The first step of using finite element method for numerical analysis is to discretize the structural geometric model into a mesh model [11]. In this paper, the 3D CAD geometric model is imported into Hypermesh software for preliminary geometric simplification, and then divided into mesh models for finite element analysis.

The structure of the loader cab is mainly composed of skeleton, steel plate, glass plate, interior, seat and other main parts and related parts. In order to carry out finite element analysis efficiently and accurately, the CAD geometric model of the cab needs to be simplified to ensure that the drawn meshes are reasonable in quantity and good in quality [12]. In this paper, the simplified treatment of the cab geometric model mainly includes: for some non-bearing structure of the cab, such as lights, interior decoration and wiper and other less influential parts, the geometric treatment is ignored; Part of the joint gap, small curvature surface, geometric defects are straightened; The processing of round corners and small positions such as bolt holes are ignored in the process: structural influences such as flanging, boss and process larvae L are ignored, and the processing is simplified. Ignoring the role of the sealing rubber strip, assume that the connection between the glass and the door is rigid; The influence of the structural mode of the seat in the cab is not considered for the moment [13].

The steel plate, glass and pipe beam of the cab are thin in thickness and are rigorously connected to each other, so they can be regarded as shell units. The material and thickness can be assigned to the property according to the actual situation. When Hyper mesh is used to partition the mesh, the model is processed by taking the middle surface, and then the mesh is divided on the middle surface. When dividing the mesh, it is necessary to consider the factors of model accuracy and computational efficiency. The basic element size of the mesh is 15mm.

In the model, joint coupling is used to define the connection between each plate and pipe beam. It takes less effort to define the mode of node coupling when only structural characteristics are considered without considering the stress of nodes. In the software, rigid RBE2 was used to connect nodes.

2.2. Modal Analysis of Cab Sound

(1) Finite element model establishment

The cab is an enclosed space, forming a separate sound chamber, which is filled with air. Similar to structural modes, cavity modes also have mode shapes and natural frequencies. Cavity mode shapes represent the distribution of sound pressure generated by sound wave transmission, and natural frequencies represent the resonant frequencies of cavity [14]. In the design stage of vehicle cab, the position beside the ears of the driver and occupant should be placed in the node-line position of the acoustic cavity mode as far as possible, so that the occupant can be placed in a good acoustic environment [15].

To establish the finite element model of the sound chamber of the cab, attention should be paid to the parts that have important influence on the sound chamber space, such as instrument panel and seat. The required mesh size should be more than 6 mesh for each wavelength, that is, the following equation should be satisfied:

$$d \leq \frac{6f}{v} \tag{5}$$

Where F is the maximum calculation frequency of 200Hz. V is the speed of sound, usually 340m/s. The mesh size of the cavity finite element model was set as 60mm to meet the calculation accuracy of the model. In Hypermesh, the finite element model of the cab structure was cleaned to remove the redundant structure, the instrument panel and the seat were retained, the plugging holes were filled to form a closed space, and the finite element model of the cab sound cavity was extracted by tetrahedral element. Give the fluid unit properties and set the fluid speed to 340m/s.

(2) Modal analysis

The established finite element model of the cab acoustic cavity was imported into the acoustic finite element analysis module of the analysis software. The mesh was pre-processed to generate the acoustic envelope mesh and the fluid material and attributes were endowed [16]. In order to ensure the calculation accuracy, the frequency range of the acoustic cavity finite element analysis is set to 20~400Hz, which is twice the frequency range of 20~200Hz required for extraction.

(3) Acoustic - solid coupling modal analysis

In the process of modal analysis of the sound cavity, the boundary of the sound cavity (the plate of the cab, the door, the roof and other parts) is set as a rigid boundary, which will not have any influence on the sound cavity. However, in the actual situation, the structural plate sealing the sound chamber of the cab is not the assumed rigid wall, but the elastic material, so the vibration between the structure and the sound chamber will affect each other. When the sound wave is transmitted to the cab structure, the vibration of the structure will be resonated by the fluctuation of the sound cavity in the same phase, which will enhance the vibration of the structure and generate resonance. When the vibration of the structure is subjected to the sound wave with opposite phase, the vibration of the structure will be inhibited each other, and the fluctuation between the structure and the sound cavity will be reduced. After the acoustic wave is reflected by the plate, the incident wave and reflected wave will also interact with each other, so that the sound wave will be superimposed or cancelled. It can be seen that there is an important relationship between the vibration characteristics of the cab structure and the sound cavity, and the two influence each other [17-18].

The coupling effect of the cab structure and air makes the structure and the sound cavity interact with each other, which leads to the relative change of the structural and acoustic cavity modes. The analysis of the acoustic-solid coupling mode can not only reflect the vibration of the structure and the distribution of the sound cavity, but also find out the reasons for the structural resonance and the resonance of the sound cavity. The structural vibration of the coupled model can be used as boundary conditions to accurately obtain the acoustic frequency response curve of the driver's ear.

In LMS Virtual lab. The acoustic simulation module to import the above structure finite element model is established and acoustic finite element model, respectively is a structure set grid properties, fluid mesh and the definition of the two coupling surface and grid data mapping relationship, because the spoke finite element mesh is composed of structural finite element mesh extraction, although different grid size, As a result, the mesh density is different, but the mesh shape is the same. The acoustic cavity mesh nodes are corresponding to the structural mesh nodes. The Maximum Distance mapping algorithm is used to establish the acoustic-solid coupling relationship.

The acoustic-solid coupling model of the cab is large, and the linear superposition method of structural modes and acoustic cavity modes can effectively improve the calculation efficiency and accuracy. The results of the previous structural mode calculation are imported to perform coupled mode calculation, which greatly improves the computational efficiency.

Due to the effect of acoustic structure coupling, compared with the results of structural modal analysis and acoustic cavity modal analysis, it can be found that the natural frequency of the coupled model is reduced compared with that of the structural model, and the mode shape and position of the structural mode do not change greatly, but the modes become more dense.

3. Contribution Analysis of Cab Noise

Each plate in the cab vibrates under the action of vibration excitation and acoustic radiation excitation, thus radiating noise to the car. Based on the hybrid FE-SEA model of the cab, noise sources can be identified in VAone software. Based on the noise contribution analysis, subsystems that contribute more to the noise in the cab can be obtained, so as to optimize the acoustic package of the cab and reduce the IF noise in the cab. This paper will analyze the noise contribution degree under the engine speed of 1510R /min, and focus on the sound cavity of the cab head.

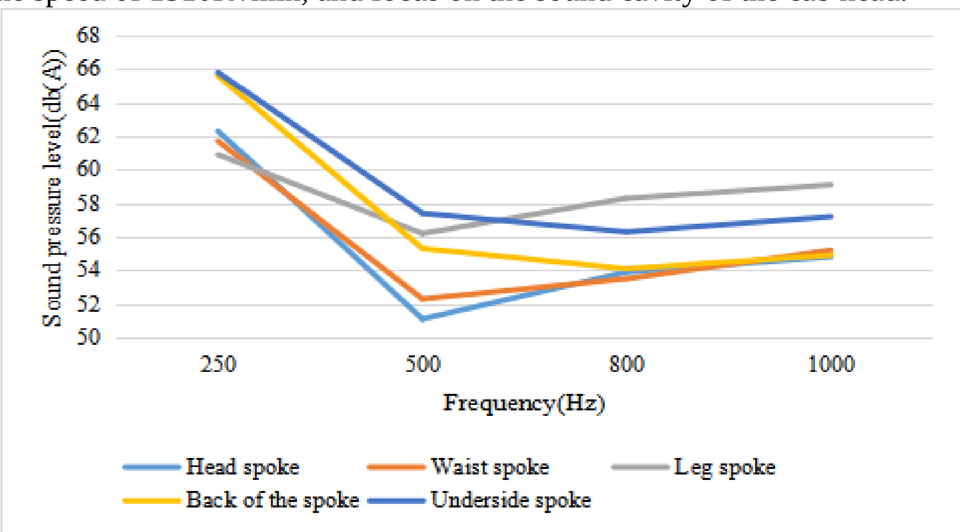

Figure 1. Sound pressure level response of sound chamber in cab

The sound pressure level responses of the seven sound cavities in the cab are shown in Figure 1. As can be seen from the figure, in the whole analysis frequency band, the SPL response of the driver's head cavity is generally the smallest, which indicates that the noise in the cockpit is transmitted from other sound cavities to the head cavity.

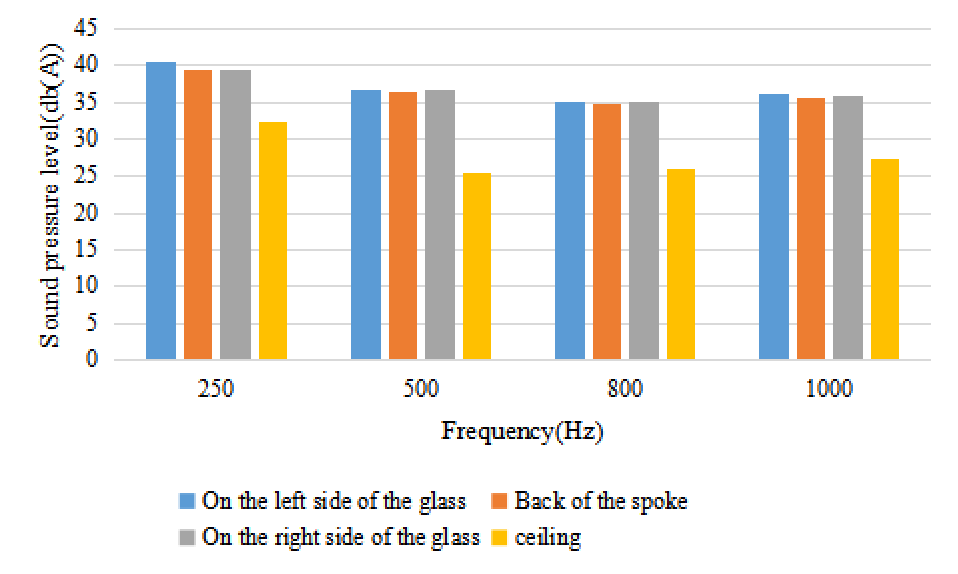

Figure 2. Head acoustic contribution

As shown in Figure 2, for the head cavity, the energy mainly comes from the left rear glass, followed by the back cavity, and the right glass and ceiling. Among them, the left rear glass, right glass and ceiling have high contribution to the head cavity in the whole frequency band. Although THE dorsal cavity ONLY CONTRIBUTES IN PART OF the frequency band, its total contribution is the second, so it should be further analyzed to find the structural subsystem that contributes more to it.

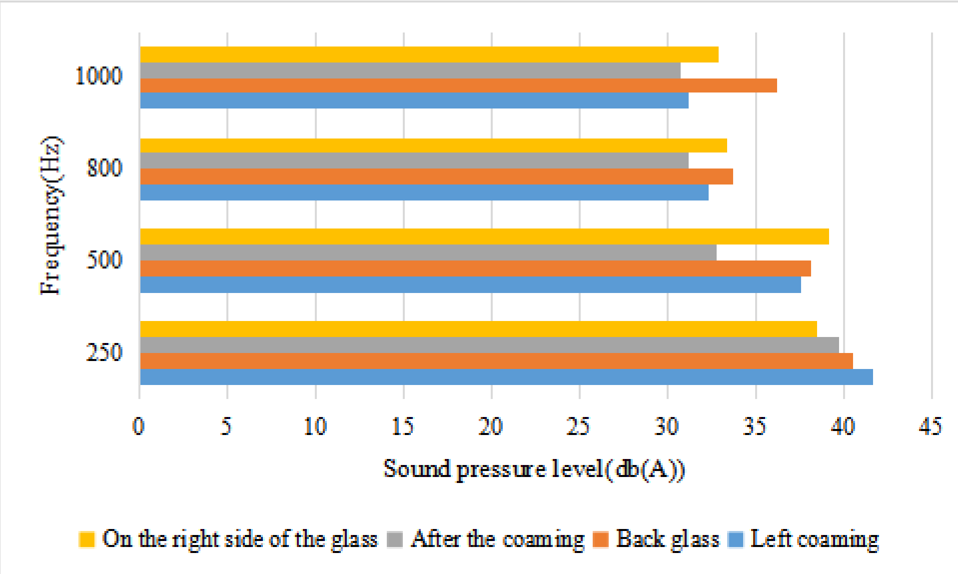

Figure 3. Back acoustic contribution

As shown in FIG. 3, for the back acoustic cavity, the energy mainly comes from the left rear coaming plate, rear glass, rear coaming plate and right glass, and these four subsystems all have high contributions in the whole frequency band.

4. Multi-objective Optimization of Cab Noise

The purpose of predicting the IF noise in the cab by the hybrid FE-SEA method is to optimize the design of the acoustic package based on the prediction results of the hybrid model, and then control the IF noise. Considering that the acoustic package processing of the glass subsystem cannot be carried out, in order to reduce the noise response of the sound cavity of the driver's head, the acoustic package optimization of the ceiling, left rear coaming and rear coaming with high contribution will be focused. Among them, the ceiling is treated with three layers of acoustic materials: felt, knitted fabrics and hard fibreboard. There is only one layer of sound insulation material PP glass fiber board on the left rear coaming and rear coaming. In order to enhance its sound absorption and insulation performance, a certain thickness of sound absorbing cotton material should be added on the basis of the existing acoustic materials. In general, the larger the thickness of the acoustic material, the smaller the SPL response of the head cavity, but considering the weight and installation space limitations, the thickness is limited.

Based on the above multi-objective optimization of acoustic package, the optimal values of the acoustic package material thickness of the ceiling, left rear coaming and rear coaming components are obtained as shown in Table 1. Then, the optimized acoustic package material thickness parameters were input into the cab hybrid FE-SEA model. Based on the vibration excitation transmitted by the optimized rotating platform, the noise response of the head cavity was simulated and predicted again, and the results were compared with those before optimization.

Table 1. Optimized acoustic package material thickness

Name	Material	Thickness/mm
Ceiling first floor	Felt	3.0
Ceiling second floor	Fiber board	2.0
Ceiling third floor	Knitting fabric	1.8
First layer of coaming	Sound-absorbing cotton	19.5
Coaming second layer	PP glass fiber board	3.0

As can be seen from FIG. 4, the SPL response of the optimized head cavity of the acoustic package is reduced on the whole, with the maximum at 800Hz frequency.

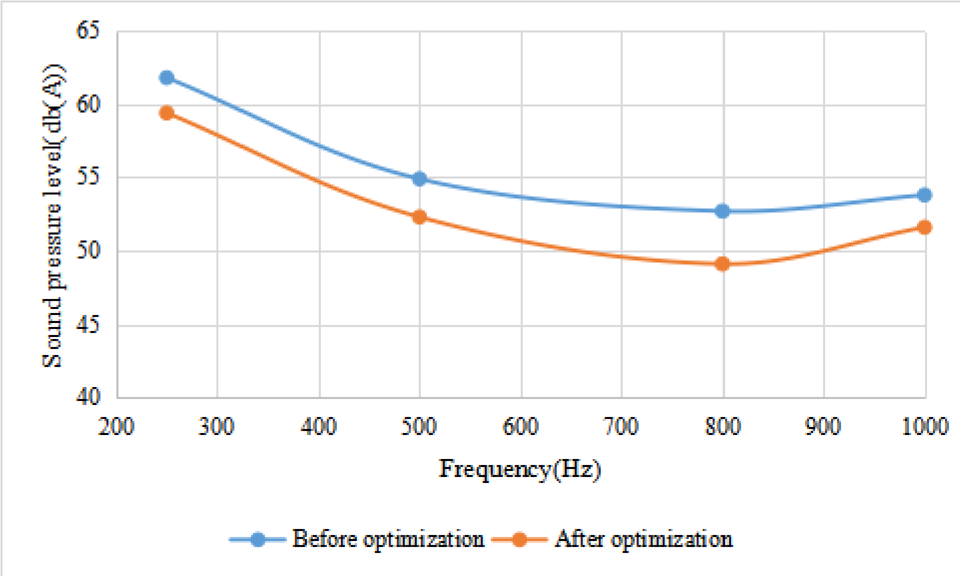

Figure 4. Comparison of sound pressure level response before and after acoustic package optimization

5. Conclusion

In this paper, the sound pressure of the loader cab is taken as the target object, and the sound field inside and outside the cab is analyzed when the excavator is running normally. Through the method of simulation and theoretical analysis, the acoustic characteristics of the cab are analyzed respectively, and the sound absorption and sound insulation measures are applied to the excavator cab. Finally, the final excavator combined noise reduction scheme is designed. As a hot research topic in recent years, vibration and noise control of construction vehicles is a very complex problem. Due to the limited resources at the disposal and my research level, there are still many shortcomings in this study, and many problems need further verification and discussion, mainly reflected in the following aspects: Considering the economic efficiency of the actual production of the project, the type of sound absorption and insulation of the cab selected in this paper is limited. In future research, the forms of excellent vibration reduction performance and active noise reduction can be considered to further improve the vibration and noise performance of construction vehicles.

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Data Availability

Data sharing is not applicable to this article as no new data were created or analysed in this study.

Conflict of Interest

The author states that this article has no conflict of interest.

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