Design of a Long-stroke Low-frequency Sound Device

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Abstract: In order to improve the radiation performance of low-frequency sound device, a design method for a long-stroke low-frequency sound device is proposed, which mainly involves the design of the drive structure and radiation structure and the drive structure is designed with an electric long stoke. The flat plate and conical structures of piston plate of radiation structure are compared, and a long-stroke radiation structure with a low-damping guide support motion pair uniformly distributed in the circumferential direction is proposed. The numerical simulation results show that, with six straight-line bearings circumferentially and uniformly distributed, the displacement and stress distribution of piston plate are better than those of piston plate with three straight-line bearings installed in the same manner. The sound device is further tested in the experiment, and it is found that the vibration displacement amplitude at the center of piston plate is 3.9 mm (20 Hz), and the maximum sound pressure level of 40 Hz is found at the location 10 m from the center of sound device along the axial direction, reaching 105.3 dB.

1. Introduction

The low-frequency sound device has been applied to multiple fields such as biological effect, ash cleaning, detection and treatment due to its low frequency, small attenuation and long transmission distance, etc. Low frequency is a significant direction for the development of underwater acoustic transducers. Plenty of work has been carried out in such field by scholars at home and abroad, with reviews made by some scholars. Teng realized low frequency broadband radiation of the transducer through combined utilization of two materials including piezoelectric and magnetostrictive materials at high and low frequencies. Zhang introduced a compliant stack of pipes in the traditional Janus-Helmholtz transducer, with the frequency and bandwidth adjusted based on the duty cycle to render a high sound source level within 300–700 Hz. Liu raised some thoughts on achieving low frequency through attached mass. Bai effectively reduced the working frequency of the transducer through the cutting of spiral grooves on the surface of transducer’s cylindrical tube, lowered the working frequency by a magnitude and increased the vibration amplitude of transducer to 4-5 times that of the un-grooved transducer. Gao proposed a new moving-magnetic type transducer based on the characteristics of cylindrical and flat plate moving-magnetic type transducers, which reduced the resonant frequency of the transducer to 42 Hz and made the maximum sound source level reach 166.58 dB.

The above-mentioned low-frequency transducers and design ideas are derived from underwater acoustic transducers, of which the application to the sound device in the air medium is limited.
Therefore, this paper proposes a design method applicable to the long-stroke low-frequency sound device in the air medium, elaborated mainly from two aspects, namely long-stroke drive structure and radiation structure. A long-stroke radiation structure with a low-damping guide support motion pair uniformly distributed in the circumferential direction is proposed, and the numerical simulations and experimental tests are carried out.

2. Design of Long-stroke Structure
To meet the requirement of low frequency, the long-stroke low-frequency sound device is usually large in size. In order to minimize the difficulty in manufacturing large-size structures, the drive and radiation structures, as two core parts of the sound device, are designed in a split type and subject to adjustable connection through the connection structure. The independent split design eliminates the mutual restriction of radiation and drive structures, maximizes their respective performance indexes and greatly increases the radiation area dominated by the radiation structure and vibration displacement amplitude dominated by the drive structure; Meanwhile, the split design lowers the manufacturing difficulty and process requirement, particularly the centering requirement on the radiation structure, drive structure and various spare parts in the integrated structure, and errors in the assembling process can be adjusted and corrected.

The design of long-stroke structures mainly comprises the design of long-stroke drive structure and long-stroke radiation structure.

2.1. Design of Long-stroke Drive Structure
Generally, drive structures comprise three types, i.e., mechanical, electro-dynamic and electro-hydraulic structures. Among them, the electro-dynamic structure is most widely used in the vibration equipment. Electro-dynamic and electro-hydraulic structures among these three drive structures see a relatively large displacement, while the electro-hydraulic structure shows a larger thrust but has a high manufacturing difficulty and cost. Therefore, the electro-dynamic drive structure is selected upon overall consideration.

First, the driving force is calculated, with the load mass set as \( M_z \) (kg), the mass of movable part of drive structure as \( M_d \) (kg), the maximum vibration amplitude as \( S_m \) (m), the maximum driving force as \( F_m \) (N) and frequency as \( f \) (Hz). The relational expression is as follows:

\[
F_m = M_z + M_d \cdot (2\pi f)^2
\]

Then,

\[
S_m = \frac{F_m}{(M_z + M_d) \cdot (2\pi f)^2}
\]

Substitute the known quantity \( M_z = 3 \) kg, \( S_m = 0.04 \) m, \( f = 10 \) Hz, the following equation is obtained:

\[
F_m = 0.04 \times \left[ (3 + M_d) \cdot (2\pi \times 10)^2 \right] \approx 157.75M_d + 474
\]

According to the above expressions, the size of driving force also depends on the size of \( M_d \), that is the mass of coil, coil skeleton and center axis in the drive structure. It can be seen that, under the premise of meeting all requirements, the smaller the \( M_d \), the better it will be. Hence, \( M_d \) can be reduced to about 3.5 kg through the optimization of coil section dimensions and mass reduction design of the structure. At this time, \( F_m \) is about 1026 N.

When the piston vibrates, considering air resistance, the reactive force from the deformation of return spring and the impact that some installation accessories (such as nuts,) have on mass, the maximum driving force \( F_m \) is not less than 1200 N in the final design.

It can be known from the electromagnetic law that the electromagnetic force is

\[
F = 0.102BIL \times 10^{-3}
\]

In the formula, \( F \) represents electromagnetic force (N); \( B \) represents magnetic induction intensity (Gs); \( I \) represents current in the coil (A); \( L \) represents effective length of conducting wire in the
magnetic field (m). According to the design requirement, the parameters are set as follows: $B = 5000$ Gs, $I = 100$ A, $L = 24$ m, and thus $F = 1224$ N $> 1200$ N.

Based on the above analysis and calculations, the drive structure obtained is shown in Figure 1, mainly comprising the coil, magnetic steel, conducting magnet, driving shaft, straight-line bearing, conical spring and bracket.

![Figure 1. Cross section diagram of the drive structure.](image)

2.2. Design of Long-stroke Radiation Structure

Through connection structure, the drive structure transmits the long-stroke motion to the radiation structure that excites the air medium to radiate the sound waves. The radiation performance of the sound device is determined by the flow of air volume excited by the radiation structure. Thus, the design of long-stroke radiation structure is crucial for the effective conversion of long-stroke motion of the drive structure, which determines the ultimate radiation performance of the sound device.

In order to increase the volume flow of the air medium excited by the radiation structure, the structure’s radiation area is relatively large, and can also be called the piston plate. To enhance the rigidity of piston plate and prevent structural damage or segmentation to offset vibration resulted from large-stroke vibration, the flat plate structure of piston plate is updated into a conical structure. A comparative analysis is made in Figure 2 between the maximum and minimum displacements of flat plate and conical structures under different static loads. The result shows that the conical structure is obviously superior to the flat plate structure, which can improve the structural rigidity by a large margin. Meanwhile, the stress of the conical structure is significantly less than that of the flat plate structure.

![Figure 2. Maximum and minimum displacements of the flat plate and conical structures under different static loads.](image)
The traditional rubber edge is adopted for the edge of conical piston plate. The differences are analyzed through dynamic analysis in the presence and absence of acceleration of gravity (500 N loaded), in which the axial displacement distribution of 10 Hz piston surface indicates significant differences, as shown in Figure 3, where the maximum difference of absolute value is 7.7 mm. However, the displacement of the whole piston surface at 20 Hz becomes uniformly distributed. It can be seen from the overall analysis that the displacement distribution of the piston surface at about 10 Hz experiences a greater impact than the average displacement of piston surface after the gravity is considered. The main reason is that the conical piston plate is adopted with a larger structural rigidity, and the mass of piston plate is lowered, with a much larger dynamic load than the gravity, thus mitigating the impact of gravity.

![Nephogram of 10Hz vibration displacement distribution in the presence and absence of gravity.](image)

Figure 3. Nephogram of 10Hz vibration displacement distribution in the presence and absence of gravity.

When frequency is up to about 30Hz, the rubber edge begins to produce local vibration, and obvious segmentation vibration is gradually produced with poorer performance. Moreover, the edge size is relatively large with a high cost in processing and manufacturing. Hence, a connection alternative is proposed, with an overall consideration given to the factors such as displacement distribution of piston surface during the vibration process, edge deformation and cost, etc. Specifically, the straight-line bearing is uniformly and circumferentially installed on the edge of conical piston plate, with the gap sealed by the edge. At this time, the edge of conical piston plate is provided with multiple guide support structures uniformly and circumferentially distributed, which can effectively avoid stress concentration and local deformation, also with a center positioning function. A low-damping rolling design is adopted for the guide support structure, and the piston plate can vibrate freely by a large amplitude in the axial direction, while the edge only plays its part in preventing acoustic short circuit.

The transient analysis module in ANASYS is availed to analyze the impact of different bearing numbers. This module can take into account the nonlinearity of structure, which is the biggest difference from the harmonic response analysis. Between the straight-line bearing and shaft is a linear motion pair inserted to load the cosine load and gravity (see Figure 4). By analysis, the differences can be obtained between three straight-line bearings and six straight-line bearings arranged around as well the displacement curves varying with the time. The displacement of six straight-line bearings circumferentially installed is significantly less than that of three straight-line bearings installed, thus indicating a high stability. As regards the stress of piston radiation surface, with six bearings circumferentially installed, it is obviously less than that of three bearings installed, with the maximum stress less than 8 MPa in a stable state. When started, the stress is large, with the maximum value up to 16 MPa. Thus, six straight-line bearings are proposed with an overall consideration given to the raised vibration mass caused by an increase in the number of straight-line bearings.
3. Experiments and Results

According to the long-stroke sound device manufactured as the above design, the displacement amplitude at the center of piston plate and sound pressure level at 10 m varying with the frequency are tested. It shows that the displacement amplitude at the center of piston plate is remarkably reduced with an increase in frequency, with the amplitude at 20 Hz as 3.9 mm. Sound pressure level at 10 m varies with the fluctuation of frequency, registering the maximum value as 105.3 dB at 40 Hz.

There are big differences between the vibration displacement amplitude obtained from testing and designed values. On the one hand, the difference of testing frequency and transmission efficiency results in an energy loss. On the other hand, the inconsistent phase and diversified mode of piston plate’s vibration leads to an inconsistency of energy dissipation and displacement amplitude. Therefore, it is not enough to test the displacement amplitude at the center of the piston plate, and it is necessary to measure the vibration displacement amplitude of the whole piston plate.

4. Conclusion

This paper proposes a design method for the long-stroke low-frequency sound device and highlights the design of drive structure and radiation structure, with the drive structure designed with an
electro-dynamic long stroke. This paper makes a comparative analysis on the flat plate and conical structures of piston plate of radiation structure and proposes a long-stroke radiation structure, with a low-damping guide support motion pair uniformly distributed in the circumferential direction. The numerical simulation results show that, with six straight-line bearings circumferentially and uniformly distributed, the displacement and stress distribution of piston plate are better than those of piston plate with three straight-line bearings installed in the same manner. For the designed and manufactured long-stroke low-frequency sound device, the measured vibration displacement amplitude at the center of piston plate is 3.9 mm (20 Hz), and the maximum sound pressure level of 40 Hz is observed at the position 10 m from the center axis of sound device, reaching 105.3 dB.

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