The new method for focusing properties of the acoustical steady field in room

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ABSTRACT

The phase conjugation method used for the identification and reconstruction of the acoustical steady propagation field in room is studied numerically. The planar array forms of phase conjugation are studied for sound source localization. The numerical results show that: The phase conjugation method can completely achieve the identification and location of the acoustical source in room.

Keywords: Acoustical steady field in room, Phase conjugation, Focusing properties

1. INTRODUCTION

The radiation of the acoustical source is in a bounded space, such as the acoustical measurement in reverberation rooms, presentation in the hall, the noise radiation of the factory machinery, or the cabin of the ship, aircraft, cars and other means of delivery. The standing waves were produced by the sound waves reflection due to the presence of indoor wall, which makes the interior sound field becomes quite complex. Further, the sound field became more complex as the acoustic properties of the wall were not uniform, irregular shape of the room or the scatterers existed. Acoustic propagation had mainly two different phenomena between in room and in the free field: First, when the sound source was stopped there was still the continued acoustic existence in room because the constant reflection of the wall that would form a standing wave; Second, due to the constant reflection of the wall, the acoustic energy was provided by not only the radiation of the sound source but also the reverberation in room. There were mainly two ways to calculate the propagation of sound waves for the sound field in room: wave theory and ray acoustics method. The theoretical solution of normal modes by forced vibration in room was get according to the wave equation by famous acoustician Morse. For decades, the normal mode theory had a profound impact on the steady sound field in room. The rigorous theoretical solution can be obtained for several regular shape bounded space, such as rectangular, spherical, cylindrical shape, but the method was not applicable for complex shape, or the space had certain requirements on the boundary conditions. The ray acoustical theory hypothesis based on the average acoustic energy and only applied to high-frequency, but was not appropriate for large low-frequency space. In order to solve the complex room shapes and complex boundary conditions of sound field distribution in room, many scholars began to introduce the FEM for the acoustics in room [1]. Noise source identification technology was very important for structural noise control and acoustic fault diagnosis. The choice of reasonable noise source identification technology is crucial [2], especially for the steady sound source reconstruction technology in room. Phase-conjugate (time reversal) method [3] is one of the new methods of sound source identification and localization [4] and the previous studies have been applied in optical or acoustic communication, but it doesn't be applied on steady sound field in room for acoustic reconstruction. The time reversal method can be applied because the characteristic that the linear wave equation contains the second derivation of sound

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pressure to time. Time reversal can be used to focus sound and is also called phase conjugation in the frequency domain. The equivalence between phase conjugation in the frequency domain and time reversal in the time domain has been proved. Due to its focusing property, the phase conjugation (PC) arrays could be used to build the image of a noise source and for source identification. The identification and reconstruction can be realized based on the specific time reversal or phase conjugation method through measured the radiation sound field just like the NAH method. Since the reflection sound field of the interior wall, there were acoustical multipath effect arriving at the measuring array which was similar to the acoustic wave propagation channels in the ocean, the phase conjugation method could be used in sound source identification in room. Cai Ye Feng et al [5] studied the feasibility and mechanism of the time-reversal method applied in complex sound field to pick up the acoustical signal by microphone arrays, and put forward the general rules and performance. This paper studied noise source identification for steady sound field in room by the method of phase conjugation.

2. THEORY

2.1 Acoustical FEM in Room

In the volume V, surface S of the closed space, the sound source was assumed to simple harmonic motion and the active acoustic wave equation in room was [6]:

$$\nabla^2 p + k^2 p + i\rho_0 \omega q(r) = 0 \tag{1}$$

The acoustic absorption condition was:

$$ikp + \xi \frac{\partial p}{\partial n} = 0 \tag{2}$$

Where, k was wave numbers, $k = \omega / c$, ω was circular frequency , c was the sound speed, ρ_0 was the air density, ξ was the acoustical impedance ratio, $\xi = z/(c\rho_0)$, Z was the surface impedance, q(r) was the density function of the sound source.

The sound field space V was disserted into a number of units. For any unit, the sound pressure p at any point within the unit could be represented by the sound pressure nodes $\{p_e\}$, bring $\{p_e\}$ into the discrete wave equation:

$$\begin{aligned}&\sum_e \int_{le} ([\nabla N]^T [\nabla N] dV_e \{p\}_e - \sum_e \int_{le} k^2 ([N]^T [N]) dV_e \{p\}_e \\ &- \sum_e \int_{le} (i\rho_0 \omega [N]^T q(r)) dV_e + \sum_e \int_S \frac{ik}{\xi} ([N]^T [N]) dS_e \{p\}_e = 0\end{aligned} \tag{3}$$

Where V_e and S_e was the volume and area of the units.

After finishing the above formula was:

$$([K] + i\omega[D] - \omega^2 [M])\{p\} = \{F\} \tag{4}$$

Where [M], [D], [K] is mass matrix, damping matrix, stiffness matrix respectively, ω is the circular frequency ; {p} is the vector of pressure in room ; {F}is the vector of harmonic force.

2.2 Phase Conjugation Method

The reason that time-reversed sound waves travel backwards is a direct consequence of the lossless linear wave equation for the acoustic pressure $p(r,t)$:

$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = 0 \tag{5}$$

This equation is time-reversal invariant because it contains only second-order derivatives with respect to time. Equation (5) ensures that if $p(r,t)$ is a solution then $p(r,-t)$ is too. Thus, if $p(r,t)$ represents sound waves expanding away from a sound source, then $p(r,-t)$ represents sound waves converging toward the same source. In the frequency domain $p(r,t)$ and $p(r,-t)$ could be replaced by $p(r,\omega)$ and $p^*(r,\omega)$ respectively, where p has a harmonic time dependency of $e^{i\omega t}$ and superscript * designates complex conjugation.

For a perfect PC array, both the original field p and its normal derivative $\partial p / \partial n$ should be recorded to serve as the weighting factors for the arrays of monopole and dipole sources, the phase-conjugated field is given by:

$$p_{PCP}(P) = \int \left[G(Q,P) \frac{\partial p^*(Q)}{\partial n} - p^*(Q) \frac{\partial G(Q,P)}{\partial n} \right] dS'(Q) \tag{6}$$

Where S' denotes the surface of the PC array. The realistic PC arrays are discrete and have N array elements, the output of various discrete PC arrays may be defined as follows:

$$p_{PCP}(P) = \sum_{n=1}^{N} \left[\left(G(Q_n,P) \frac{\partial p^*(Q_n)}{\partial n} - p^*(Q_n) \frac{\partial G(Q_n,P)}{\partial n} \right) \times S_n \right] \tag{7}$$

The phase-conjugated field p_{PCP} is based on both the pressure and pressure gradient measurement and made of both monopole transceivers and dipole transceivers to reverse sound backwards.

The phase-conjugated field by the array made of monopole transceivers based on the pressure measurement is:

$$p_{PCM}(P) = \sum_{n=1}^{N} \left[\left(G(Q_n,P)\, p^*(Q_n) \right) \times S_n \right] \tag{8}$$

The phase-conjugated field by the array made of dipole transceivers based on the pressure gradient measurement is:

$$p_{PCD}(P) = \sum_{n=1}^{N} \left[\left(\frac{\partial G(Q_n,P)}{\partial n} \frac{\partial p^*(Q_n)}{\partial n} \right) \times S_n \right] \tag{9}$$

In the following numerical analysis, the pressure calculated at the array element based on Section 1.2 is used as the measurement pressure in the above equations. A double layer of array elements is used to provide the pressure and the pressure gradient. That is, the pressure $p = (p1 + p2)/2$ and the pressure gradient $\partial p / \partial n = (p2 - p1)/\Delta$, where Δ is the separation distance.

The procedure of numerically calculated the sound source identification by using phase conjugation methods for steady sound field in room:

(1)Firstly, computed the sound pressure p by using the FEM at the location of phase conjugation array;

(2)Secondly, took the conjugate value p^* of the measured sound pressure into the equations as a known sound pressure acoustic boundary conditions, and eventually focused on the sound source.

3. NUMERICAL SIMULATIONS

The feasibility of identification and location the sound source by using phase conjugation method was realized in the size of 5.0m * 4.0m * 3.0m room as the example. The coordinate origin was taken as the geometric center of the room. Sound source located at the point (-1.9, 0, 0) and sound pressure amplitude was unit. All walls in room were taken as rigid wall. The sketch of the room was shown in Figure 1:

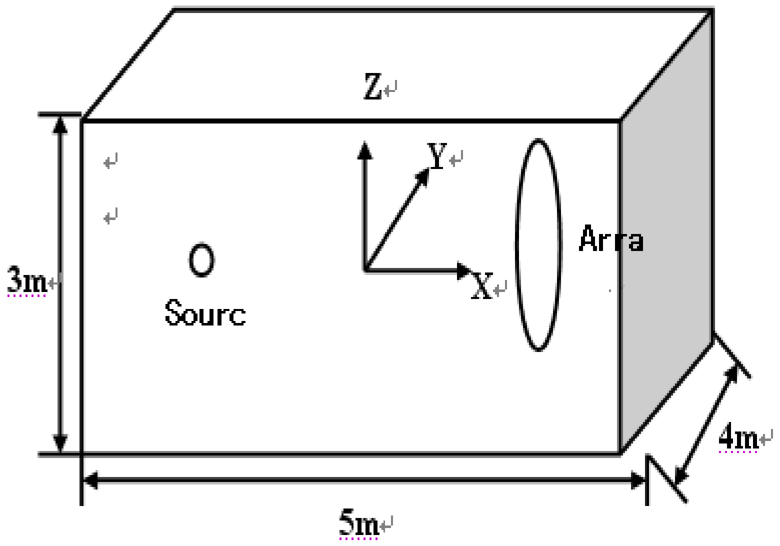

Fig.1 the diagram of the acoustical field in room and the measurement array

The natural frequency of the room acoustical cavity was calculated with FEM and the result was shown in Table 1:

Table.1 The natural frequency of the room acoustic cavity

Numbers of mode	Natural frequency（Hz）
2	34.3
14	99.1
40	149.0
79	200.7
227	300.1

The speed of sound in air is 340m/s. The calculated frequency is f=300Hz corresponding to the 227th modes, then the corresponding acoustic wavelength λ = 1.13m. Modal shape was shown in Figure 2:

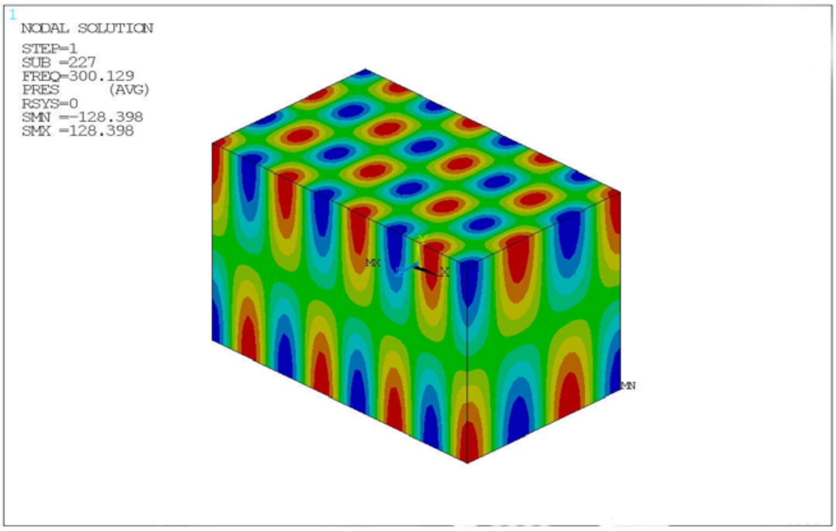

Fig.2 The mode shape corresponding f=300Hz

The phase conjugation methods were used to identify and locate sound source in room. First, the sound pressure level of the array calculated by FEM and took the conjugate value then re-emitted into the sound field and focus at the position of the focus source.

Consider the planar array form. The distance between the planar array and sound source was 0.5λ, λ, 2λ, 3λ in X direction. The normal direction of the array was the X-axis positive direction. The length along the Y-axis and Z-axis direction was 3.6m, 2.6m. Array element number 266, the array element spacing: $\triangle$ = 0.2m = 0.18λ, meet the requirements of phase conjugation method element spacing must be less than 0.5λ.

Consider the source location, i.e., the intersection line of X =-1.9m and plane Z = 0 plane. Figure 3 shows the sound amplitude field distribution of the source (dB) and Figure 4 shows the reconstructed sound field amplitude distribution by the planar array based on the phase conjugation method.

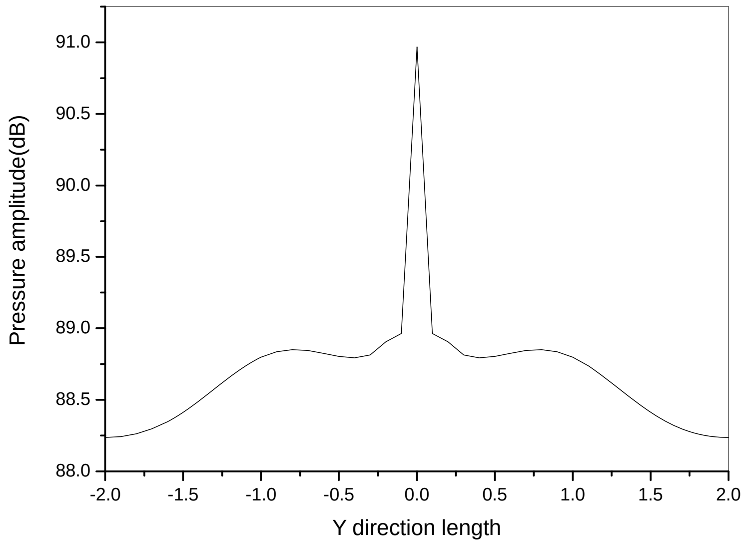

Fig.3 The source pressure amplitude distribution at the cross line between the plane X=-1.9 and Z=0

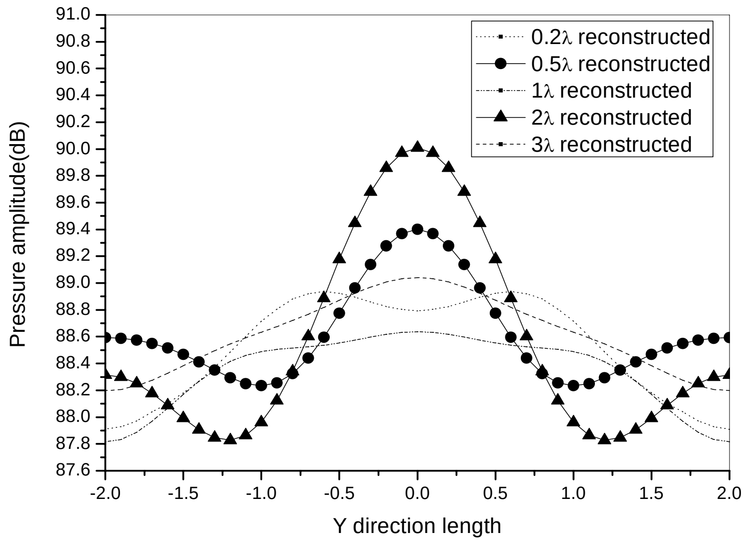

Fig.4 The reconstructed pressure amplitude distribution with the planar array

The sound source location and identification could be obtained by using phase conjugation method as seen from the results in Figure 4 and the perfect reconstruction results were obtained at the distance between the array and source of 0.5λ and 2λ. The sound field reconstruction was complete failure when the distance between the sound source and array was0.2λ as the phase conjugate sound field existed two extreme points. This is very different with the phenomenon [7] to break the diffraction limit based on phase conjugation method in near field measurement and the spherical wave propagation attenuation inversely proportional to the distance in free field or semi-free field. This was due to that the normal mode wave was produced as the acoustic wave emitted by the sound source immediately reflected between the walls when the acoustic wavelength was the same order or less than the space dimensions roughly in room not as the strength was inversely proportional to the square of the distance and the higher strength at the long distance point than the recent point. According to the interaction of the normal modes, so that the sound intensity at the source side was the strongest and leaving the sound source gradually reduced, but not far away increased with increasing distance from the endless undulating movements [8].

4. CONCLUSIONS

The phase conjugation method used for the identification and reconstruction of the acoustical steady propagation field in room is studied numerically. The planar array forms of phase conjugation are studied for sound source localization. The numerical results show that: The perfect reconstruction results were obtained at the distance between the array and source of 0.5 wavelengths and 2 wavelengths. The phase conjugation method can completely achieve the identification and location of the acoustical source in room.

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