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## The Diagnosis and Optimization of Scroll Compressor Noise Based on the Theory of Near-Field Acoustical Holography

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### ABSTRACT

Based on the theory and characteristics of the near-field acoustical holography (NAH), the scroll compressor acoustic holography measurement is achieved in this paper. The sound field color image is reconstructed by using the measurement data, and then the noise positions of various frequency bands are identified and located. Moreover, the effect of mechanical structure on the noise is analyzed. Then, by optimization and designing of the relevant structural, the noise of the scroll compressor has been effectively reduced. This technology applied successfully to the noise test of the scroll compressor, not only to make up the problem of insufficient information of the traditional measurement method, but also greatly improve work efficiency and shorten the product development cycle.

### 1. INTRODUCTION

Because of its high efficiency, small vibration, simple structure, etc., the scroll compressor techniques has been rapid development in air-conditioned filed, especially in the field of commercial air conditioners. With the social development and progress, the requirement of air-conditioned comfort and environmental protection continues to increase. Therefore, the noise and vibration of the compressor as key performance indicators are getting more and more industry attention.

The scroll Compressor traditional noise measurement data is usually indicated by frequency spectrum, which can accurately reflect the size of compressor noise and noise frequency bands. However, this method does not locate and identify the sound source locations, often leads the designers not to know what to do. This not only extended the R&D cycle, but also it is difficult to achieve design goals.

The acoustic holography technology is a loud reconstruction technique, which reconstruct sound three-dimensional image by using two-dimensional information of the sound pressure field based on the space transform relationship between source surface and the holographic surface and the principles of sound volatility. The technology could achieve sound source position and the other wealth of sound source information by sound field visualization. So, this technology is essential to actual noise vibration analysis, and is great significance to research radiation characteristics of the source and control the noise [1].

In 1980's, E.G. Williams and J.D. Maynard further put forward the near-field acoustic holography (NAH) [2]. The technology can achieve effectively a low-level radiation acoustic composition, especially for evanescent wave (evanescent wave) by controlling distance between holographic surface and measurement surface less than acoustic wavelength range. Thus, a high sound field reconstruction graphics can be achieved by breaking the drawbacks of the traditional sound field reconstruction is subject to wavelengths. Near-field acoustic holography (NAH) not only can identify and locate noise sources more effectively [3], but also reduces the measurement requirements greatly.

At present, this method have been widely used in the aircraft cabin interior, automotive interior sound field, the noise positioning inside the machine [4] [5].

Based on the study of near-field acoustic holography (NAH) theory and characteristics, the holographic sound pressure measurements of the scroll compressor is realized, and then the 3D sound field image is reconstructed.

According to the sound field visualization graphics, the noise positions of various frequency bands are identified and located, so as to the optimization of the related structures is finished. The successful applications of NAH in the noise measurements of scroll compressor, not only quantify the effect of different structural on the noise, but also greatly shorten the development cycle.

## 2. NEAR-FIELD ACOUSTIC HOLOGRAPHY THEORY AND CHARACTERISTICS

According to the small amplitude acoustic wave equation for ideal fluid medium [6] [7], the Helmholtz steady-state sound field equation can be expressed as:

$$\nabla^2 p(x, y, z) + k^2 p(x, y, z) = 0 \quad (1)$$

where,  $p(x, y, z)$  is space complex sound pressure and a function of Cartesian coordinates  $x, y, z$ ,  $k = \omega/c = 2\pi/\lambda$  is acoustic number,  $c$  is the speed of sound,  $\lambda$  is the characterized wavelength.

The boundary conditions of equation (1),  $p_D(x, y)$  and  $p_N(x, y)$  are Dirichlet boundary conditions and Neumann boundary conditions of flat  $z = 0$  respectively. When the situation  $z > 0$ , the space is the free field, that is to say, all sound sources are located below the flat  $z = 0$ . According to the Green's formula, the solution of equation (1), that is, the sound pressure at any point of space as follows:

$$p(x, y, z) = \int_S p_{D,N}(x', y') g_{D,N}(x - x', y - y', z - z') dx' dy' \quad (2)$$

Where, S indicated that the integral carried out in the infinite boundary plane,  $g_{D,N}$  is Green's function on the infinite plane.

$$g_D(x, y, z) = z(1 - ikr)e^{ikr} / 2\pi r^3 \quad (3)$$

$$g_N(x, y, z) = e^{ikr} / 2\pi r^3 \quad (4)$$

Where,  $r = \sqrt{x^2 + y^2 + z^2}$

If the two-dimensional continuous Fourier transform along the direction  $x, y$  is defined as follows:

$$P(k_x, k_y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) e^{-i(k_x x + k_y y)} dx dy \quad (5)$$

The two-dimensional Fourier transform on both sides of the equation (2) is carried out, and then two-dimensional convolution theorem is used to calculate, then:

$$P(k_x, k_y, z) = P_{D,N}(k_x, k_y) G_{D,N}(k_x, k_y, z) \quad (6)$$

where,  $P(k_x, k_y, z)$ ,  $P_{D,N}(k_x, k_y)$  are the two-dimensional continuous Fourier transform of sound pressure  $p(x, y, z)$  and the boundary conditions  $P_{D,N}(x, y)$  respectively. And  $G_{D,N}(k_x, k_y, z)$  is the two-dimensional Fourier transform of  $g_{D,N}$ . So, the analytical expression as follows:

$$G_D(k_x, k_y, z) = e^{ik_z z} \quad (7)$$

$$G_N(k_x, k_y, z) = e^{ik_z z} / k_x \quad (8)$$

When  $k_x^2 + k_y^2 \leq k^2$ , then

$$k_z = \sqrt{k^2 - (k_x^2 + k_y^2)} \quad (9)$$

When  $k_x^2 + k_y^2 > k^2$ , then

$$k_z = i\sqrt{(k_x^2 + k_y^2) - k^2} \quad (10)$$

The Neumann boundary conditions as follow:

$$P_N(x, y, z) = i\partial p(x, y, z) / \partial z|_{z=0} = 0 \quad (11)$$

The relationship between the two-dimensional Fourier transform  $P_N(k_x, k_y)$  of the boundary conditions and the two-dimensional Fourier transform  $V(k_x, k_y)$  of the normal vibration velocity of the particle on plane  $z = 0$  as follows:

$$P_N(k_x, k_y) = V(k_x, k_y) \rho c k \tag{12}$$

Where,  $\rho$  is the average density of the acoustic medium.

The equation (7), (8) and (12) are taken into equation (6), so equation (6) can be written separately:

$$P(k_x, k_y, z) = P_D(k_x, k_y) e^{ik_z z} \tag{13}$$

$$P(k_x, k_y, z) = \rho c k(k_x, k_y) e^{ik_z z} / k_z \tag{14}$$

At the time  $z = z_H > 0$ , the formula (13) and (14), denote respectively the relationship between the sound pressure of the plane  $z = z_H$  and the sound pressure and the vibration velocity of particle for boundary condition  $z = z_S = 0$ . For any two-plane  $z = z_H$  and  $z = z_S$  ( $z_H > z_S > 0$ ), a more general relationship can established by equation (13) and (14).

$$P(k_x, k_y, z_H) = P(k_x, k_y, k_S) e^{ik_z(z_H - z_S)} \tag{15}$$

$$P(k_x, k_y, z_H) = \rho c k(k_x, k_y, k_S) e^{ik_z(z_H - z_S)} / k_z \tag{16}$$

According to formula (15) and (16), and the sound pressure or the particle vibration velocity of flat  $z = z_S$  are known, the sound pressure situation of a more distant plane  $z = z_H$  can be predicted. Through the Euler formula, the particle vibration velocity of the plane  $z = z_H$  can be easily achieved. Known the sound pressure data of the plane  $z = z_H$  (holographic surface), the sound pressure and the particle vibration velocity of a more near-surface  $z = z_S$  (reconstruction surface) can also be inverted. At this point, the basic reconstruction formula about planar near-field acoustic holography can be setup:

$$P(k_x, k_y, z_S) = P(k_x, k_y, k_H) e^{ik_z(z_H - z_S)} \tag{17}$$

$$V(k_x, k_y, z_S) = k_z P(k_x, k_y, k_H) e^{-ik_z(z_H - z_S)} / \rho c k \tag{18}$$

### 3. EXPERIMENTAL MEASUREMENT

According to the above principle, the acoustic holography measurements are carried out on a scroll compressor. This experiment was finished in semi-anechoic chamber, where the silencer body noise of chamber is below 30dB. Test equipment include in 27kw gas load test-bed, 24-channel data transmission system, 10 microphones, test rack, data

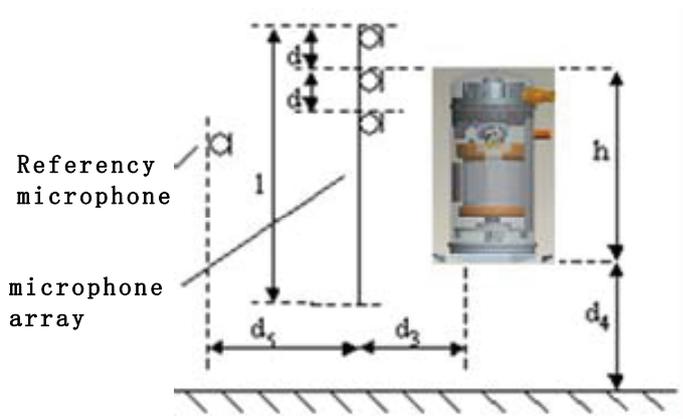


Fig.1 Microphones vertical layout

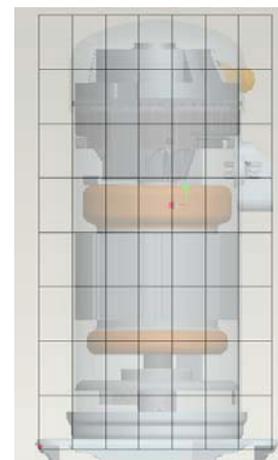


Fig.2 Measurement arrays

acquisition and processing system, as well as a scroll compressor that the capacity is 15kw.

Near-field acoustical holography technology measure generally complex sound pressure or particle vibration vectors of surface through the sensor arrays, and then the sound pressure particle velocity vector and three-dimensional sound intensity vector can be achieved by using some algorithm to reconstruct the sound field to be any point on the object surface tested.

Figure 1 is a microphone vertical layout, in which nine microphones vertically rigid connections in the test rack with the spacing of 60mm, and to ensure that it is vertical to holographic surface, while the tenth microphone as a reference. The minimum distance between measuring tangent plane and measured compressor is less than 100mm. After measurements startup, the array of microphones gradual move from left to right, each moving distance is 30mm. Once the test rack is stable, the test data can be collected, until the completion of all data collection. Figure 2 is the microphones array used in practical test, which is a total of eight rows. By 8 rows 9 arrays tests, the complete coverage of the local oscillator is achieved.

In the testing process, the reference microphone is always immovability. When the data acquisition is completed, the signal processing equipment deal with all array data collected according to the reference microphone information. Moreover, the pressure holographic data is restored. And then, the vertical holographic plane is tested according as aforementioned. This method can reduce effectively the test equipment requirements and reduce cost of test.

## 4. TEST RESULTS AND ANALYSIS

### 4.1 Measurement data analysis

The traditional test approach of the noise indicates usually the size and band of noise occurred by frequency spectrum, seen from Fig.4. However, this method can not reveal the location of noise sources, so that designers have become blind in the noise optimization, and is difficult to achieve first-class design production.

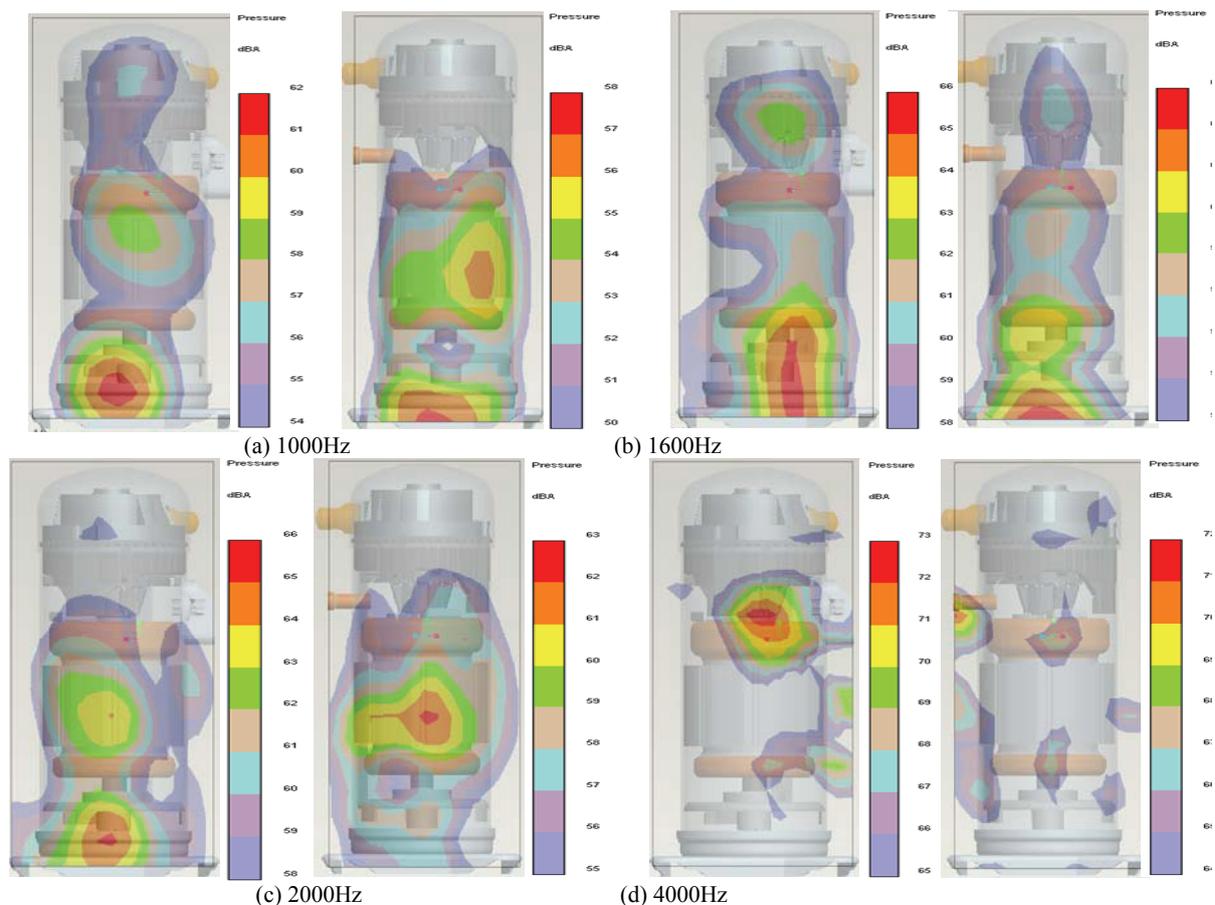


Fig.3 The holographic color image

In this paper, the focus of the frequency bands are determined based on frequency spectrum data, seen from Fig.4 and table 1, is 1600Hz, 2000Hz and 4000Hz respectively. In order to ensure information integrity and extends the measuring range, the holographic test data of 500Hz, 1000Hz and 8000Hz is added. According to above-mentioned measurement principle and method, the holographic image can be gotten. Figure 3 (a) ~ (d) is the holographic color image corresponding to frequency of 1000Hz, 1600Hz, 2000Hz and 8000Hz. Then, the location of the noise source can be determined based on the holographic test data of the two planes, the results are written in Table 1.

Table.1 The relationship between sound source and noise size

Frequency (Hz)	Sound source	Maxmum Pressure Noise (dB)
500	Between main frame and motor	53
1000	Bottom case	60
1600	Bottom frame	63
2000	Between bottom case and motor	64
4000	Discharge pipe	72
8000	Above the non-orbit scroll plate	65

**4.2 Noise optimization**

From Figure 3 and Table 1, the maximum noise occurred in 1600Hz, 2000Hz and 4000Hz, and the noise sources are located nearby the discharge pipe and bottom case. The problem caused by balance weight is excluded according to

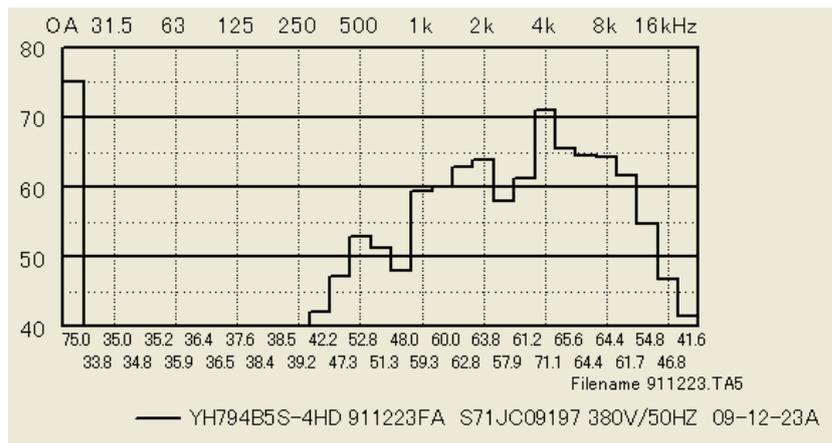


Fig.4 Noise frequency spectrum before optimization

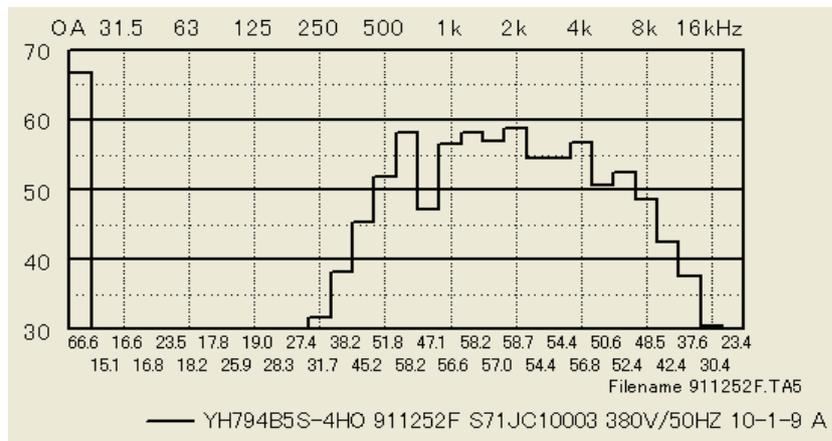


Fig.5 Noise frequency spectrum after optimization

balance principle and the vibration size of main frame. Moreover, it is preliminary judged the cause is induced by

high speed gas flow.

Figure 5 is the noise frequency spectrum by adopting traditional measurements method after structural optimization. It can be seen from this picture, the noise sizes lower than Fig.4 about 8–9dB, and the maximum effective pressure noise is 66.6dB. This performance improves significantly and basically meets design requirement.

## 5. CONCLUSIONS

In this paper, a scroll compressor acoustic holography test is achieved based on theoretical research of near-field acoustic holographic technology. Through the visualization technology, the sound source location of the different frequency bands are identified and located. Furthermore, the cause of problem is analyzed depending on the location of sound source, as well as scroll compressors structural features. The value of the compressor noise is reduced successfully through structural optimization design.

The application of Near-field full-noiselessly holography technology successful in the development of scroll compressor, not only provides the quantitative and significant experimental data for designers to improve the speed and effectiveness of the development, but also is significance for further understanding of different structure effect on the noise.

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