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## Near field Acoustical Holography Research & Application on Compressor & Refrigerator

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### ABSTRACT

Noise is one important factor for product performance of compressor & refrigerator. Products must satisfy with not only meeting the national standards but also the consumers' gradually increasing requirements for sound quality because of market competition. Near field acoustical holography is a high-resolution imaging technique for reconstructing the vibro-acoustical field that will guide to locate noise source and understand the relationship between structure vibration and sound radiation. Near field acoustical holography method based on the Equivalent Source Method is applied to analyze the vibro-acoustical characteristics of both compressor and refrigerator.

Equivalent Source Method is applicable for arbitrary shaped vibrating surface, presenting calculation faster than the Boundary Element Method, and better than the Helmholtz Equation Least Square Method, especially for elongated and planar sources. In virtue of this approach, velocity & sound pressure distribution over the sample geometry of compressor & refrigerator were gotten at critical frequencies, so main noise sources were located.

### 1. FOREWORDS

For consumer, high-quality refrigerators must be able to meet their most basic functions, but it is also necessary and important to have very competitive low noise and vibration characteristics. Regarding compressor is the main excitation source for refrigerator, how to design or improve vibration and noise for compressor and refrigerator is an important task for engineers in order to gain market and advance customer satisfaction.

Design engineers conduct a preliminary estimate and optimization for product radiated sound field in the initial stage of design by the finite element and boundary element methods, until vibration and noise radiation can be effectively reduced. But relying solely on the numerical calculation to obtain the sound field distribution normally has difference to actual products situation, and during the early stages of design one cannot take all factors into full consideration. Therefore, experimental analysis will contribute to a detailed understanding of sound and vibration field. Near field Acoustic Holography is a visualization technology capable of imaging 3D vibro-acoustical field of source surface, as well as predicting the external sound field. The near field acoustical holography technology has high-resolution characteristics comparing to other approaches. This technology transformz the sound field of only listening into the field we can see. So it can greatly facilitate the designers to improve product, or better support to solve problems.

### 2. NAH BASED EQUIVALENT SOURCE METHOD INTRODUCTION

The near-field acoustical holography is used to analyze the shape of sound sources for separable coordinate system based on two-dimensional Fourier transform on the plane, cylindrical, spherical, and so on. For more details see Maynard and Williams (1985) and Williams and Maynard (1987). In order to meet requirements of vibro-acoustical field analysis for the sound source with arbitrary shape, the researchers introduced the near-field acoustic holography based on the boundary element method, more details see Veronesi and Maynard (1989), namely, Helmholtz equation to be discrete by the boundary element method, formed equation as matrix format, those equations established acoustic volume relationship between source surface and holographic surface, and use regularized inverse method to get physical quantity of source surface. Although the near-field acoustic holography

of the boundary element method can solve the arbitrary shape of the sound field reconstruction, due to inherent process of the boundary integral leads to low computational efficiency, less used in practical applications. Therefore, studying an efficient NAH approach becomes a need. The near field acoustical holography method based on the Equivalent Source Method is an approximate method, but the grade of approximation of this method is sufficient to ensure reliable and rationality in engineering, more details see Wu S F (2004) and Zhang H B *et al.* (2009). Equivalent source method can be divided into wave superposition and Helmholtz equation least square method (HELs) according to the different forms of equivalent source. Statistically optimal near field acoustic holography have an advantage in the analysis of partial sound field, testing and reconstruction focus on some areas of large source surface can be done, but when the test surface is not a covered source surface, its accuracy has decreases. For more details see Cho Y. T. *et al.* (2005) and Jacobsen and Jaud (2007).

According to the different study objects selected, the appropriate near-field acoustic holography can effectively improve the computational efficiency and get high-precision reconstruction results. This article introduces the principle of near-field acoustic holography based on the wave superposition method, and this method was applied to analyze and study compressor and refrigerator vibro-acoustic field. NAH based on the wave superposition method can be used to analyze sources of any shape, of course, for separable coordinate system shape source can be analyzed, such as plane, cylindrical, etc.

Wave superposition integral equation has been previously presented in the literature, see Koopmann *et al.* (1989), being equivalent to the Helmholtz equation. The sound pressure of a sound source can be evaluated as (1):

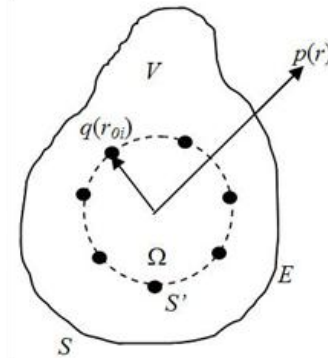


Figure 1: Wave superposition method diagram

$$p(\mathbf{r}) = j\rho\omega \int_V q(\mathbf{r}_0)g(\mathbf{r}, \mathbf{r}_0)dV(\mathbf{r}_0) \quad r \in (S \cup E) \quad (1)$$

where  $p(\mathbf{r})$  denotes the complex pressure;  $q(\mathbf{r}_0)$  is the source strength of equivalent source, which can be set anywhere within the sound source;  $\mathbf{r}$  and  $\mathbf{r}_0$  denote the position vector of the field point and the equivalent source;  $\rho$  and  $\omega$  denote density and angular frequency of the sound propagation medium; as shown in Figure 1,  $V$ ,  $S$  and  $E$  denote the volume of sound source, boundary surface and external space. In this formula, the free-space Green's function is defined as follows:

$$g(\mathbf{r}, \mathbf{r}_0) = \frac{\exp(jk |\mathbf{r} - \mathbf{r}_0|)}{4\pi |\mathbf{r} - \mathbf{r}_0|} \quad (2)$$

being the wave number  $k = \omega/c$  and the unit imaginary number  $j = \sqrt{-1}$ .

Assuming  $N$  equivalent sources distributed within the source, and  $M$  external points (or field points), the relationship between equivalent source and field point can be defined by the following formula (3):

$$\{\mathbf{P}\}_M = [\mathbf{H}]_{MN} \{\mathbf{Q}\}_N \quad (3)$$

Elements of the transfer matrix  $[\mathbf{H}]_{MN}$  can be calculated by equation (4):

$$\mathbf{H}_{ij} = j\rho\omega g(\mathbf{r}_i, \mathbf{r}_{0j}) \quad (4)$$

In formula (3)  $\{\mathbf{P}\}_M$  and  $\{\mathbf{Q}\}_N$  denote field point sound pressure vector and strength vector of equivalent source. The source strength vector  $\{\mathbf{Q}\}_N$  by converse solution can be obtained through formula (5):

$$\{\mathbf{Q}\}_N = [\mathbf{H}]_{MN}^+ \{\mathbf{P}\}_M \quad (5)$$

where superscript "+" represents the inverse operator (regularized inverse).

In formula (5), the inversion process presents an inherent problem in the pathological features, and therefore one needs to adopt a regularization method to reduce the inverse process in order to avoid amplifying noise and error. Two types of regularization are commonly used: Tikhonov and Landweber iterative regularization method, see Hansen (1994). Here is a brief introduction on Tikhonov regularization method, details can be found in the references.

Assuming a transfer matrix  $[\mathbf{H}]_{MN}$  with singular value decomposition as following,

$$[\mathbf{H}]_{MN} = [\mathbf{U}]_{MM} [\mathbf{\Sigma}]_{MN} [\mathbf{V}]_{NN}^H \quad (6)$$

Where  $[\mathbf{U}]$  and  $[\mathbf{V}]$  are unitary matrices,  $[\mathbf{\Sigma}]$  is a diagonal matrix, its diagonal elements being  $\sigma_1 \geq \dots \geq \sigma_{N^*} \geq 0$ ,  $N^* = \text{rank}([\mathbf{H}])$  the superscript in the rank of the matrix  $[\mathbf{\Sigma}]$ , as per formula (6)  $H$  is a Hermitian operator (conjugate transpose operator).

Using the regularization method as per formula (5), the source strength vector solution results:

$$\{\mathbf{Q}\}_N = [\mathbf{V}][\mathbf{F}^\alpha] \text{diag}\left(\frac{1}{\sigma_1}, \dots, \frac{1}{\sigma_{N^*}}\right) [\mathbf{U}]^H \{\mathbf{P}\}_M \quad (7)$$

Diagonal matrix  $[\mathbf{F}^\alpha]$  is called the filter factor, the superscript " $\alpha$ " stands for the regularization parameter. The filter factor of Tikhonov regularization method is shown below:

$$[\mathbf{F}^\alpha] = \text{diag}\left(\frac{\sigma_1^2}{\sigma_1^2 + \alpha}, \dots, \frac{\sigma_{N^*}^2}{\sigma_{N^*}^2 + \alpha}\right) \quad (8)$$

For regularization method, selecting the appropriate regularization parameter will seriously affect the results. An appropriate regularization parameter can effectively inhibit the evanescent wave on behalf of high wave number component and retained on behalf of the passing wave components of low wave number, to find a balance between reservations to passing wave and suppression of evanescent wave. This will not only inhibit the amplification error by high wave number components, but also ensure there is enough wave components to form the external acoustic field. In search of the best methods for regularization parameter, the L-curve method and GCV is widely used, see Hansen (1994).

After getting equivalent source strength by regularized inverse method, the entire external sound field can be calculated by formula (5).

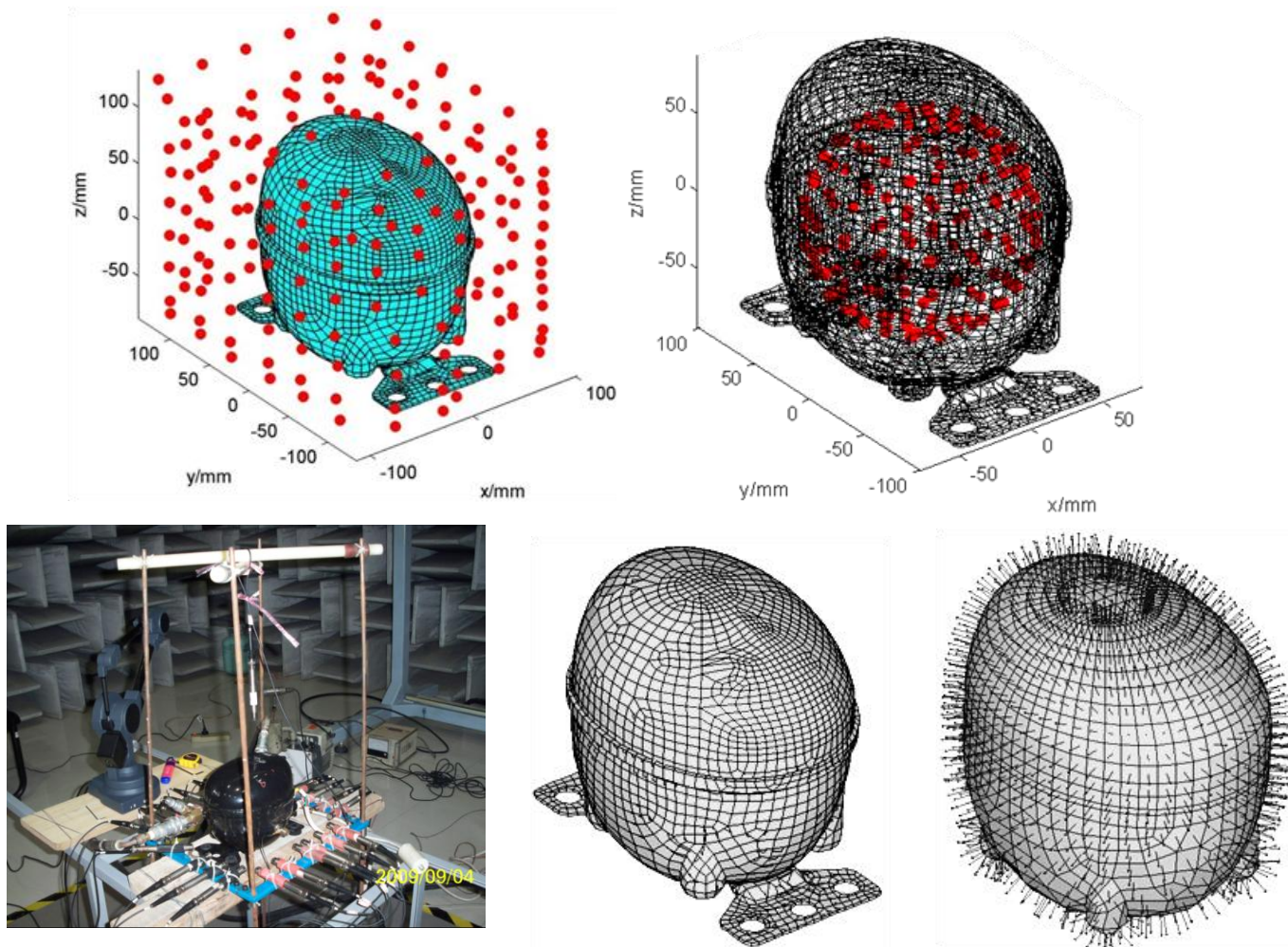
### 3. NAH RESEARCH AND APPLICATION

The near field acoustic holography method is very helpful to identify the locations of root cause of noise through visualization. In this section two cases this method is applied in two cases of vibra-acoustic field analysis, on both compressor and refrigerator, aiming to optimize their noise characteristics.

#### 3.1 Compressor NAH

Relative NAH experiment and analysis was performed and are depicted in Figure 2. Scanning test form was applied to collect signals, one fixed microphone at compressor top regarded as reference source and used for calibration phase of the scanning step. According to principle of NAH parameter definition, 201 measuring points were analyzed. During test process, the location of each microphone was determined by three-dimensional coordinate meter.

Distance of adjacent points in vertical direction is 4cm; adjacent microphone space in microphone array is about 4cm. Distance between microphone to compressor surface is about 5cm. 152 equivalent source are evenly distributed in a sphere of radius of 6.5cm, the sphere being 0.7 times of compressor size (see Figure 2).



**Figure 2:** Compressor near-field acoustic holography experiments, equivalent points, compressor schematic, and simplified schematic

Reconstruction result for critical frequency 784Hz shown in Figure 3, it showed whole compressor had evident & strong SPL distribution. After comparing these figures with the design, it was evident the mains source for this frequency was the suction system, which has been lately optimized aiming to optimize this critical frequency, results shown in Figure 4.

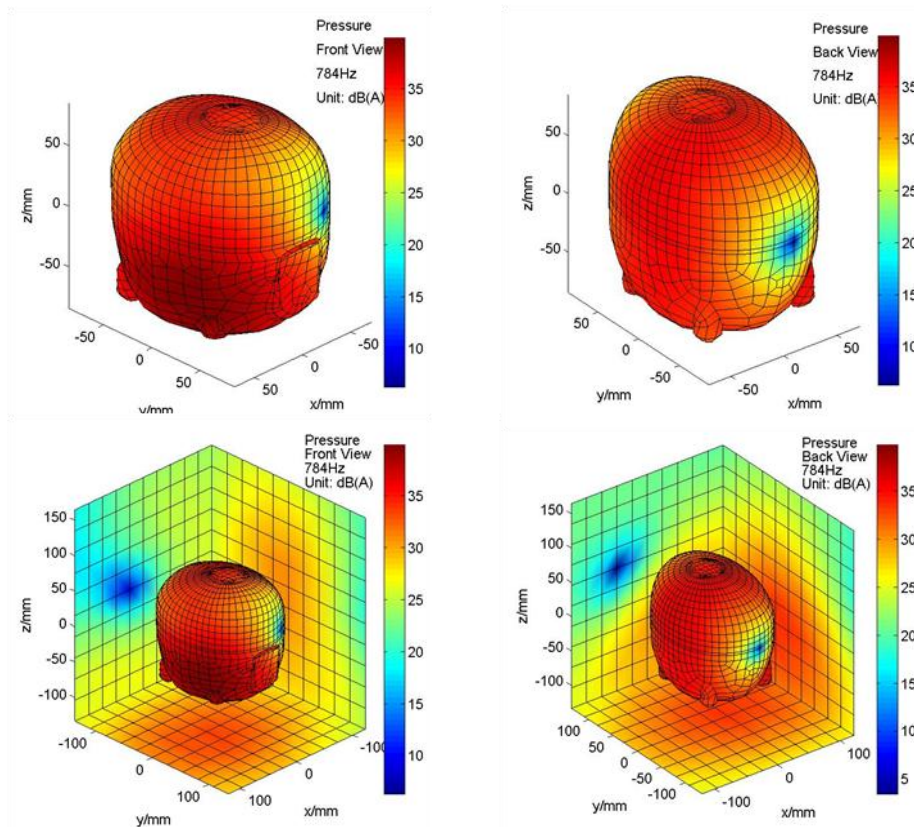


Figure 3: Surface Result of sound pressure, external radiation sound pressure maps, before improvement, 784Hz

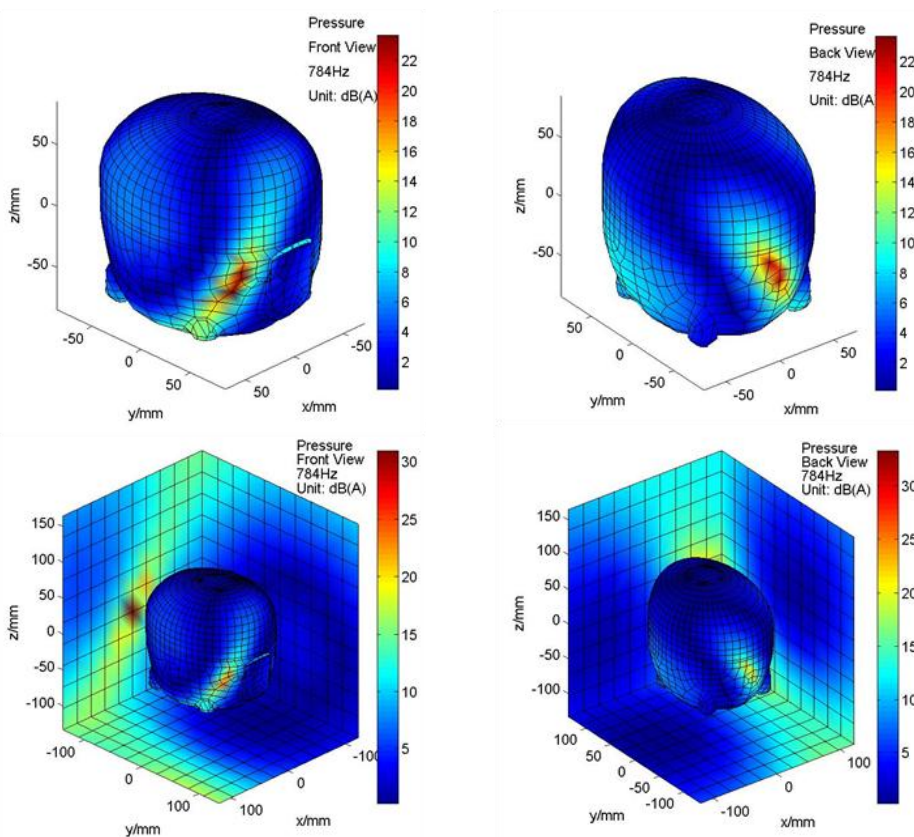


Figure 4: Surface Result of sound pressure, external radiation sound pressure maps, after improvement, 784Hz

### 3.2 Refrigerator NAH

SWL in an specific appliance resulted out of specification; after analysis on 1/3 octave and narrow frequency for four surfaces of front & back & left & right, it has been identified that main SPL noise contribution came from back surface, and faulty frequencies were defined for NAH analysis.

For refrigerator NAH analysis, scanning measurement form was also applied to test signals, 36 microphone line arrays with 6cm interval, with 17 scanning step, resulting 612 measurement points. Refrigerator size and scan measurements shown in Figure 5.

Reconstruction results of back surface for analyzed frequencies are depicted in Figure 6. It showed whole back surface of refrigerator had evident & strong SPL distribution, main noise radiation had been located at compressor compartment and freezer area. After combined with known design, it has been concluded the main cause was matching problem due to resonance; generated by discharge pulsation effect and specific discharge configuration of cabinet, also led to generate evaporator gas flow noise.

After optimizing compressor discharge system, it was also necessary improvements on cabinet discharge tube configuration. Noise result after solution was greatly improved, exceeding the initial requirement.

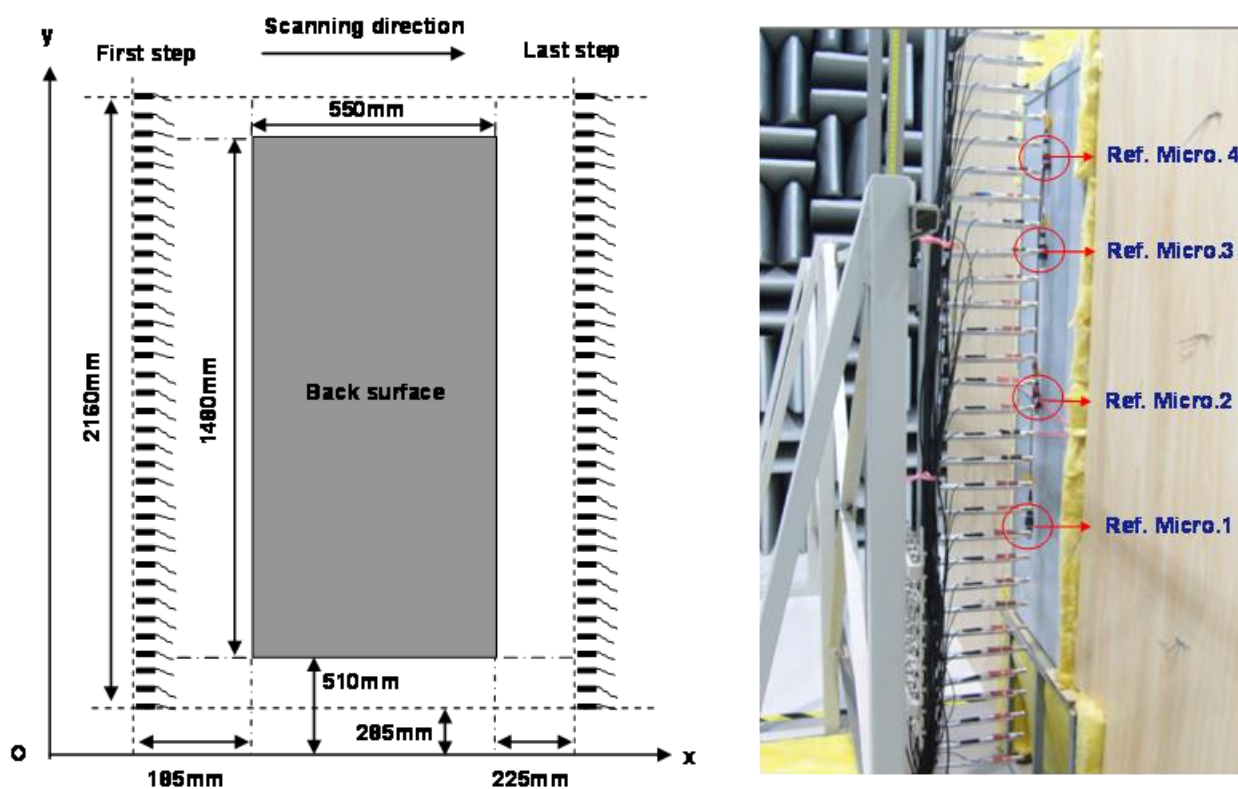
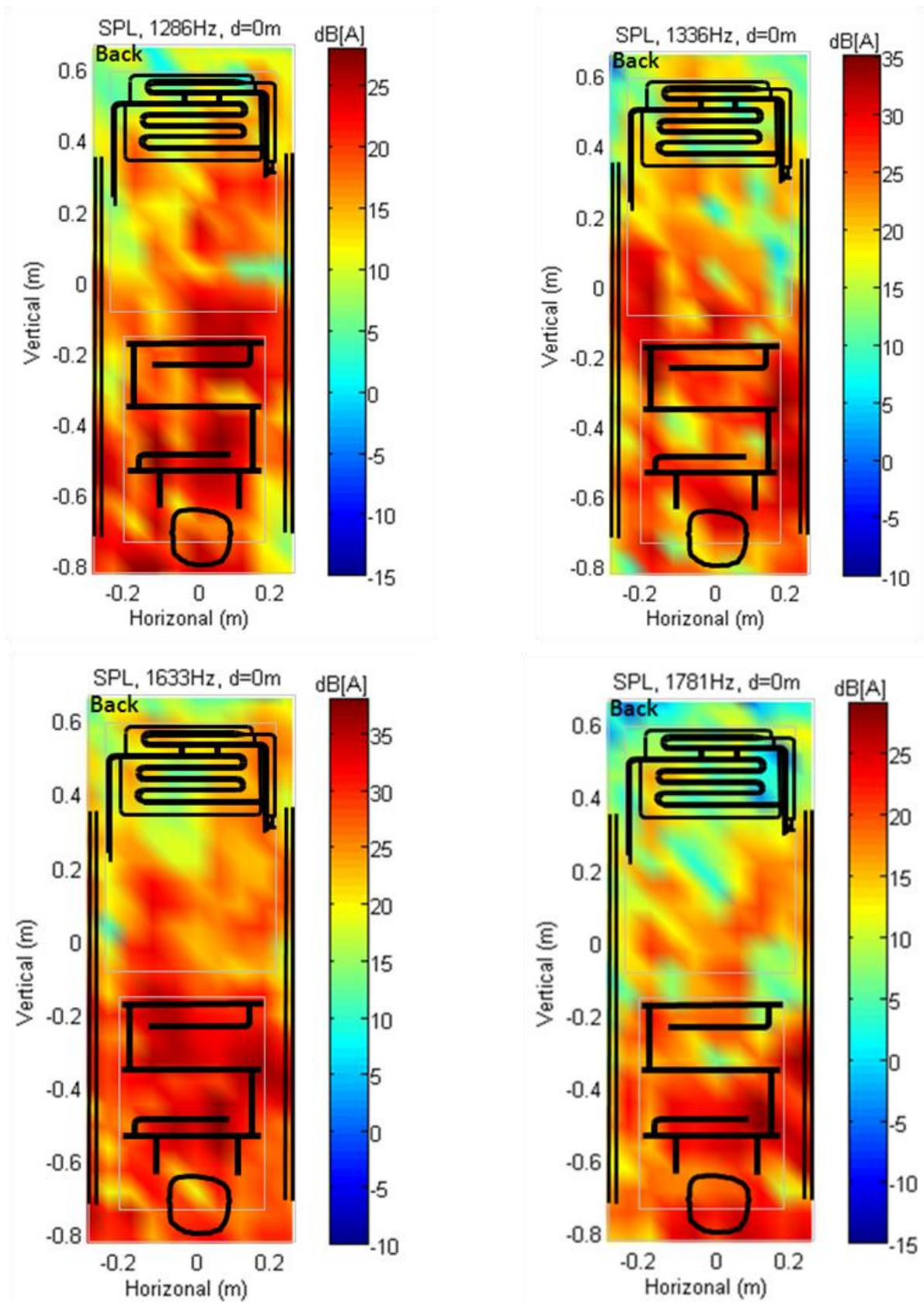


Figure 5: Refrigerator near-field acoustic holography experiments according to the scan schematic



**Figure 6:** Sound pressure distribution diagram of refrigerator back surface, 1286/1336/1633/1781H



## 4. CONCLUSIONS

The near-field acoustic holography is a high resolution imaging technology to the visualization, aiming better support to find the noise radiation area, and solve vibration or noise issues. Here near-field acoustic holography based on wave superposition method was applied, in virtue of reconstruction of vibro-acoustical field in combination with known design, two engineering problems for compressor and refrigerator were analyzed and solved.

The near-field acoustic holography can not only get the sound field distribution of surface, moreover, it can also predict the sound field distribution on external space. This also helps engineer to take reasonable actions outside of compressor. For example, it is available to set the sound absorbing structure in the path of acoustic radiation focusing on major noise source.

## NOMENCLATURE

$p(r)$	complex pressure	(Pa)
$q(r_0)$	source strength of equivalent source	(W/m <sup>2</sup> )
$r_0$	position vector equivalent source	(m)
$\rho$	density	(g/m <sup>3</sup> )
$\omega$	angular frequency of sound propagation medium	(rad/s)
V	volume of sound source	(-)
S	volume of boundary surface	(-)
E	volume of external space	(-)
k	wave number	(m <sup>-1</sup> )
N	equivalent sources distributed within the source	(-)
M	external points (or field point)	(-)
$[H]_{MN}$	transfer matrix	(-)
$\{P\}_M$	field point sound pressure vector	(-)
$\{Q\}_N$	strength vector of equivalent source	(-)
[U]	unitary matrix	(-)
[V]	unitary matrix	(-)
$[\Sigma]$	diagonal matrix,	(-)
H	Hermitian operator (conjugate transpose operator)	(-)
$[F^\alpha]$	filter factor	(-)
$\alpha$	regularization parameter	(-)

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