Patch near-field acoustical holography based on vector hydrophone array

Bo HU[1]; Desen YANG[2]; Shengguo SHI[3]; Jie SHI[4]; Yu SUN[5]

[1 2 3 4 5]Science and Technology on Underwater Acoustic Laboratory, Harbin Engineering University , China

[1 2 3 4 5]Underwater Acoustic Engineering College, Harbin Engineering University , China

ABSTRACT

Near-field acoustical holography is a powerful tool for identifying noise sources from partially known sound pressure field. Patch near-field acoustical holography (PNAH) is related to the partially measured pressure on the hologram surface in terms of sampling and bandlimiting matrices, which cost more in computation. PNAH procedure based on measuring of vector hydrophone array is described, including the mathematical formulation. The measurement array can been smaller than the source, thus the practicability and efficiency of this technology is greatly enhanced. Then an experiment has been carried out with vector hydrophone array. The experimental results have illustrated the high performance of PNAH and the advantages of a vector hydrophone array in an underwater near-field measurement.

Keywords: Patch, Vector hydrophone, Near-field acoustical holography
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1. INTRODUCTION

Near-field acoustical holography (NAH) was introduced in 1980s. It enables one to see every detail of the sound field of interest (1, 2). However, it is required that the measurement aperture extend over a sufficiently large region to avoid inherent problems related to the use of the DFT.

For the sake of overcoming this problem, two methods have been proposed: patch near-field acoustical holography (PNAH) and statistically optimized near-field acoustical holography (SONAH). Compared with NAH, two methods can relax the usual requirement of a measurement aperture that extends well beyond the source. In a typically iterative patch procedure, the key problem is a numerical tangential extension of the measured sound pressure outside the measured area, followed by the application of the standard DFT based on the extended data window (3). Steiner and Hald (4) optimized the NAH process by realizing a spatial convolution to have a wavenumber spectrum. Meanwhile, in the underwater measurement method, the vector hydrophone is a new acoustic measurement technique (5). It can instantaneously measure the sound pressure and the orthogonal components of particle velocity at the same point. It has also been demonstrated that a vector hydrophone array guarantees more accurate range and velocity estimation than the conventional sound pressure array (6).

However, it is well known that large scale noise sources s are often encountered in practice. Owing to the large number of iteration, the process of PNAH suffers from low computational efficiency. Another problem is that the equipments of underwater near-field measurement used to be sound pressure hydrophone and intensity probe in the past. This limitation has been an obstacle to the extensive application of NAH technology. In the present work, one-step PNAH based on measurement of particle velocity was built by adding regularization theory to the inversions.

[1] kidd1105@sina.com
[2] desenyang@hrbeu.edu.cn
[3] shishengguo@hrbeu.edu.cn
[4] shijie@hrbeu.edu.cn
[5] sunyuyu1222@sina.com

2. OUTLINE OF THE THEORY

In this section, the algorithm of one-step PNAH based on velocity is briefly described. Define the full aperture $H+$ comprised of a finite aperture H and its extension. Let $\mathbf{v}_H(H)$ be the velocity of a point in a finite aperture located at a small distance d in near-field from the source area. Let $\mathbf{v}_H(H+)$ for $(x,y)\in H+$ be the exact velocity field over the complete region. The procedure developed starts with the finite measured velocity zero padded to fill out the full aperture. The velocity $\mathrm{v}_E(H+)$ after zero-padding is

$$\mathrm{v}_E(H+)=\begin{cases}\mathbf{v}_H(H) & (x,y)\in H\\ 0 & (x,y)\notin H\end{cases} \tag{1}$$

where $\mathrm{v}_E(H+)=[\mathrm{v}_{E1},\cdots,\ \mathrm{v}_{EM}]^T$, M is the number of the full aperture. Equation (1) can also be expressed as

$$\mathbf{v}_E(H+)=\mathbf{D}\cdot\mathbf{v}_H(H+) \tag{2}$$

where $\mathbf{D}=diag[D_{11},\cdots,D_{MM}]$ is the sampling operator in the spatial domain. The diagonal terms D_{ii} are

$$D_{ii}=\begin{cases}1 & (x,y)\in H\\ 0 & (x,y)\notin H\end{cases} \tag{3}$$

The conventional NAH, allows that the normal velocity $\mathbf{v}_S$ and the sound pressure $\mathbf{p}_S$ on the reconstructed surface S can be predicted in a three dimensional space from a hologram velocity $\mathbf{v}_H$. The space Fourier transform of the Helmholtz equation allows one to write

$$\mathbf{v}_H(H+)=\begin{cases}\mathbf{F}^{-1}\mathbf{G}_D\mathbf{F}\mathbf{v}_S\\ \mathbf{F}^{-1}\mathbf{G}_N\mathbf{F}\mathbf{p}_S\end{cases} \tag{4}$$

where $\mathbf{v}_H$, $\mathbf{v}_S$ and $\mathbf{p}_S$ are the column vectors on the mesh of the full surface $(z=z_H)$ and the reconstructed surface $(z=z_S)$. $\mathbf{F}$ represents a two-dimensional Fourier transform operator and $\mathbf{F}^{-1}$ its inverse. The diagonal matrices $\mathbf{G}_D$ and $\mathbf{G}_N$ which can be expressed as $\mathbf{G}_D=e^{jk_zd}$ and $\mathbf{G}_N=k_ze^{jk_zd}/\rho ck$, respectively, are the propagators providing the decay rates of the evanescent waves. The term k is the acoustic wave number defined as $k=\omega/c$, where ω is the angular frequency in radians per second. The k-space vector is $k=(k_x,k_y,k_z)$. ρ is the mass density in medium. c is the acoustic speed in water. This model is provided by the transfer function between the acoustical property in the reconstructed surface and the measured velocity $\mathbf{v}_H$. The boundary in k-space which separates the propagating plane wave region from the evanescent wave region is the radiation circle. In the forward propagation, the exponential decay of the evanescent wave components with distance goes from source outwards to the hologram surface. Thus, the velocity measured on the hologram surface usually satisfies the bandlimitedness signal condition.

The bandlimiting matrix $\mathbf{B}_k$ is defined to deal with the hologram velocity.

$$\mathbf{v}_H(H+)=\mathbf{B}_{k_c}\cdot\mathbf{v}_H(H+) \tag{5}$$

The bandlimiting matrix $\mathbf{B}_{k_c}$ is

$$\mathbf{B}_{k_c}=\mathbf{F}^{-1}\mathbf{L}_{k_c}\mathbf{F} \tag{6}$$

where $\mathbf{L}_k=diag[L_{11},\cdots,L_{MM}]$ is a low-pass filter. $\mathbf{L}_k$ can be defined as

$$L_{ii}=\begin{cases}1 & \sqrt{k_x{}^2+k_y{}^2}<k_c\\ 0 & \sqrt{k_x{}^2+k_y{}^2}>k_c\end{cases} \tag{7}$$

It is well known that the high wave number component is set to be zero if the high wave number is outside k_c space. k_c can be defined as

$$k_c = \begin{cases} k_0 & k_0 \le \min(k_{x\max}, k_{y\max}) \\ \min(k_{x\max}, k_{y\max}) & k_0 > \min(k_{x\max}, k_{y\max}) \end{cases} \tag{8}$$

where $k_{x\max} = \pi / \Delta x$, $k_{y\max} = \pi / \Delta y$, Δx and Δy are the sampling space, respectively.

According to Equations (2) and (5), the relationship between the zero-padded velocity $\mathbf{v}_E(H+)$ and the full velocity $\mathbf{v}_H(H+)$ in the enlarged aperture is expressed as

$$\mathbf{v}_E(H+) = \mathbf{D} \cdot \mathbf{B}_{k_c} \cdot \mathbf{v}_H(H+) = \mathbf{DF}^{-1}\mathbf{L}_{k_c}\mathbf{F}\mathbf{v}_H(H+) = \mathbf{G}_r\mathbf{v}_H(H+) \tag{9}$$

where $\mathbf{G}_r = \mathbf{DF}^{-1}\mathbf{L}_k\,\mathbf{F}$. By substituting Equation (4) into Equation (9), after zero-padding and filtering, the acoustical property in the reconstructed surface, which is obtained from Equation (4), can be expressed as

$$\mathbf{v}_E(H+) = \mathbf{D} \cdot \mathbf{B}_{k_c} \cdot \mathbf{v}_H(H+) = \begin{cases} \mathbf{DB}_{k_c}\mathbf{F}^{-1}\mathbf{G}_D\mathbf{F}\mathbf{v}_S \\ \mathbf{DB}_{k_c}\mathbf{F}^{-1}\mathbf{G}_N\mathbf{F}\mathbf{p}_S \end{cases} = \begin{cases} \mathbf{W}_D\mathbf{v}_S \\ \mathbf{W}_N\mathbf{p}_S \end{cases} \tag{10}$$

Finally, the particle velocity and the sound pressure on the surface of the source can be reconstructed from the particle velocity and its continuation into the region $H+$ after the generalized projection process. The inversion of Equation (9) is ill-posed, the evanescent waves amplified by the inverse propagator are filtered by a low-pass regularization filter. The inversions of Equations (9) and (10) are

$$\mathbf{v}_H(H+) = \mathbf{G}_r^+\mathbf{v}_E(H+) = (\alpha I + \mathbf{G}_r^H\mathbf{G}_r)^{-1}\mathbf{G}_r^H\mathbf{v}_E(H+) \tag{11}$$

$$\mathbf{v}_S = \mathbf{W}_D^+\mathbf{v}_E(H+) = (\alpha I + \mathbf{W}_D^H\mathbf{W}_D)^{-1}\mathbf{W}_D^H\mathbf{v}_E(H+) \tag{12}$$

$$\mathbf{p}_S = \mathbf{W}_N^+\mathbf{v}_E(H+) = (\alpha I + \mathbf{W}_N^H\mathbf{W}_N)^{-1}\mathbf{W}_N^H\mathbf{v}_E(H+) \tag{13}$$

where + denotes the regularized inverse, I is the identity matrix, the symbol H representing Hermitian transpose. The terms $\mathbf{G}_r^+$, $\mathbf{W}_D^+$ and $\mathbf{W}_N^+$ refer to the “data restoration” and “projection” matrices, respectively. The regularization parameter α can be determined by the Tikhonov regularization method from the extrapolated velocity. The signal relation between the normal velocity and the acoustical property to be reconstructed is established in terms of sampling and bandlimiting matrices.

3. EXPERIMENTAL RESULTS

An experiment based on measurement of vector hydrophone array has been carried out in an anechoic pool. The sound pressure and the normal velocity on the hologram surface were measured using a vector hydrophone array, which consists of 8 vector hydrophones spaced by 0.25m in Figure 1. During the experiment, a robot moved the vector hydrophone array over the measurement plane, which was put vertically in the water.

To examine the method discussed above the aperture of hologram surface is the same as the reconstructed surface. Because it is difficult to complete the measurement of the whole acoustic field, we adjust the depth of the array by 0.08 m twice. One extracted a small patch of data from this measured pressure and velocity consisting of 24×40 points. A B&K analyzer system (type PULSE 3560) was used for measuring the experimental data and the signal generated by the HP33120 signal generator for driving the source. The signal from signal generator was passed through a B&K 2713 power amplifier and used as a reference signal.

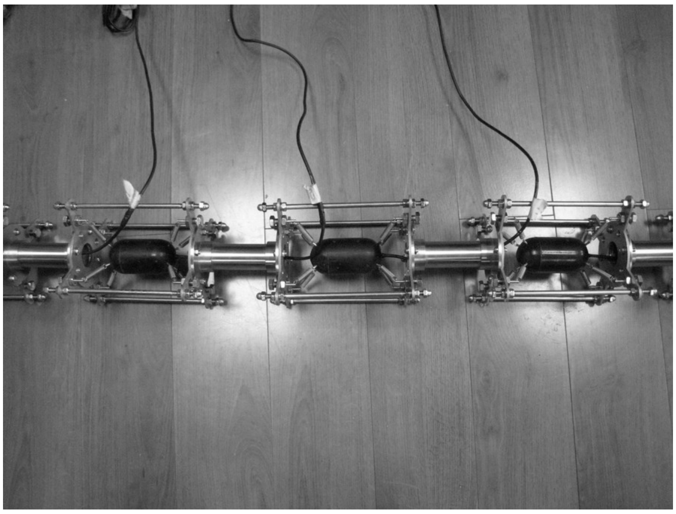

Figure 1 – Vector hydrophone array

Owing to the complex structure of vector hydrophone array, the possibility that signals can be refracted and scattered should be taken into account when vector hydrophone array was used to near-field measurement. Therefore, one needs to examine the effect of the structure of array before experiments. The procedures are as follows. First, the received signals of each vector hydrophone theoretically satisfy the rule that the amplitude of signals is in inverse proportion to the distance between sound source and measurement position in spherical wave sound field. In the other words, the pressure level of signals decreases 6 dB with distance increasing one times. Given that the structure of array directly influences measurement results, the amplitude of signals would not satisfy this rule. Consequently, the difference between received quantities and the true help us to estimate the scattered result of vector hydrophone array. Figure 2 shows the attenuation curves of when the signal frequency is 2 kHz. It demonstrates that the attenuation of each vector hydrophone almost meet the rule of spherical wave sound field. Thus, this vector hydrophone array can be used to underwater near-field measurement.

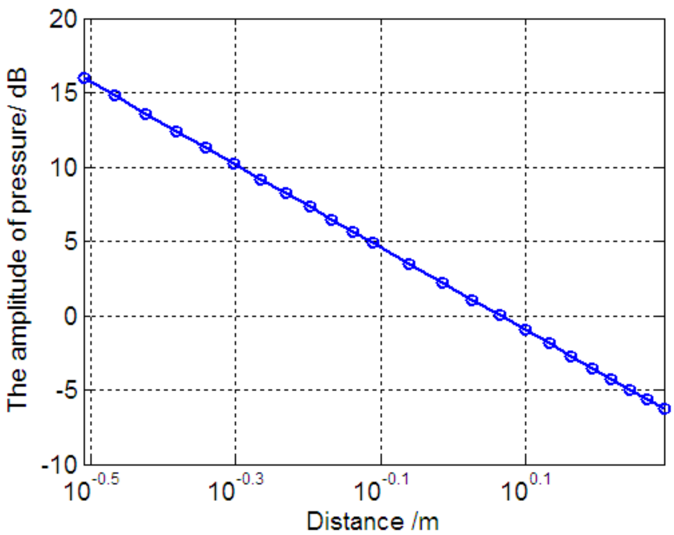

Figure 2 – Radiated attenuation when the signal frequency is 2kHz

A small patch was selected for the extrapolation and reconstruction, which covered an area of $1.6\ \mathrm{m} \times 1.75\ \mathrm{m}$ in this experiment. If the measurement quantity in plane, where the shortest distance between the line array and the monopole source is 0.05m, is chosen as the “true” pressure in prediction plane. The comparison of the results reconstructed from 0.1 m to 0.05 m based on pressure and particle velocity and the “true” pressure in 0.05 m prediction plane is shown in Figure 3. In Figure 3, the frequency is 2 kHz. The results demonstrate that the quantities based on pressure are not very accurate, whereas the pressure based on velocity is almost consistent with the theoretical values and the velocity based on the velocity is by far the best. The errors of pressure and velocity predicted from pressure are 24.9% and 23.3%. The errors of pressure and velocity predicted from velocity are 23.6% and 15.8%.

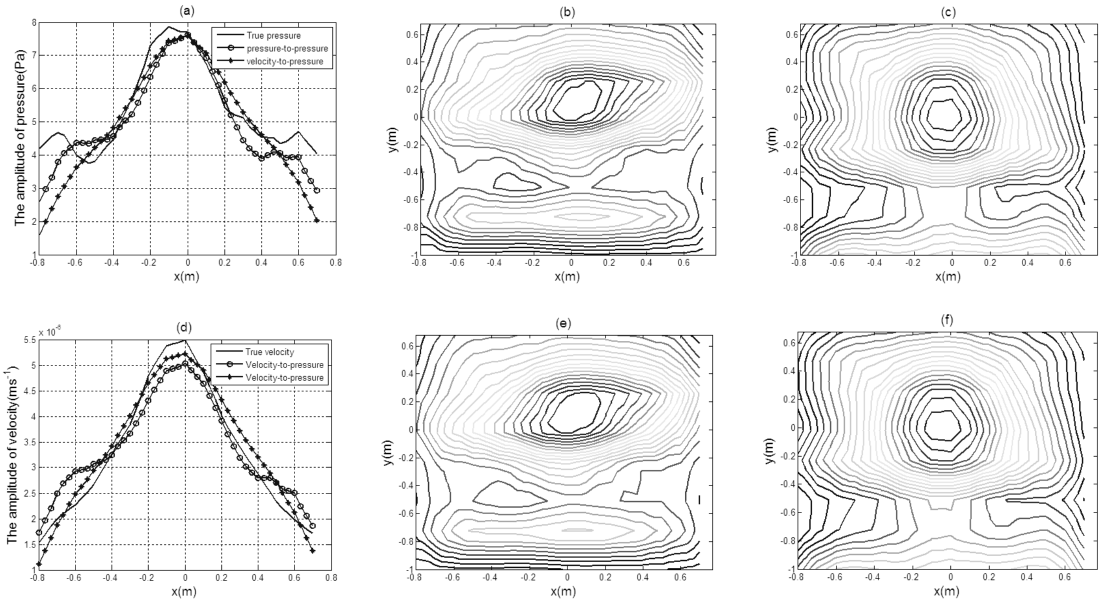

Figure 3 – Reconstructed results based on the measurement of pressure and velocity when the signal frequency is 2 kHz. (a) Comparison of the amplitude of reconstructed pressure on y=0; (b) The magnitude of reconstructed pressure predicted from pressure; (c) The magnitude of reconstructed pressure predicted from velocity; (d) Comparison of the amplitude of reconstructed velocity on y=0; (e) The magnitude of reconstructed velocity predicted from pressure; (f) The magnitude of reconstructed velocity predicted from velocity.

Besides the above results, it also can be seen that the vector hydrophone array can obtain not only the sound pressure but also orthogonal all three components of particle velocity at the same point. Compared with three hours needed when the conventional pressure hydrophone array and the velocity probe array were all used, the vector hydrophone array only needs forty minutes to accomplish the whole process, saving the time of underwater acoustical measurement and simplifying the measurement procedure.

4. CONCLUSIONS

In the present study, extrapolating particle velocity data beyond the measurement aperture has been applied to a one-step patch near-field acoustical holography. The various acoustical properties can be reconstructed directly from partially measured hologram velocity, instead of iterative procedure. An experiment was conducted to confirm the superiority of the proposed method and the feasibility of using vector hydrophone array in underwater NAH measurement. The results demonstrated that the velocity-based prediction was somewhat more accurate than the pressure-based prediction. Some drawbacks resulting from the conventional method can be overcome, such as the cost of complexity and computational demands, the less accurate results predicted from pressure. The use of vector hydrophone array made it possible to obtain more sound information in underwater near-field measurement. Therefore, the technique is applicable to large scale industrial-type sources emitting stationary noises, and is not limited to laboratory cases where source excitation is controlled.

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