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The Investigation on Measuring the Reflection Coefficient of Materials in Semi-space by Spatial Fourier Transforms

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Abstract: A new method of measuring the reflection coefficient at arbitrary angles for big samples of absorbent materials has been investigated in semi-space by using SFT(Spatial Fourier Transforms). The paper gives an experimental verification of this method. The experimental frequency is from 3 kHz to 10 kHz. The size of test steel plate is 1.6m×1.5m. The measured results are generally in good agreement with the theoretical values; the mean-square error of data is below 0.06. Because the sound source and the test material are set near the water surface during the experiment, it is very easy to set the measuring system, and this is very useful in practice.

1 Introduction

When the reflection coefficient of material samples is measured by full-space method, the muffling pool is needed. In fact, in order to scan the sound field, water surface can't be covered by sound absorption materials. The sound scattering of that part can produce errors in the measured results. In order to eliminate the effect of water surface boundary, the material samples must be put deeply in the pool. But it can bring difficulties in locating the position of material samples and the placement of hydrophone. In underwater acoustic measurement, when sound wave shoots into the air from the water, water surface can be considered approximately as an absolutely soft boundary. The absolutely soft boundary is equivalent to dissymmetrical boundary condition in mathematic model. If sound source and material samples are placed near water surface where there are no sound absorption materials, the absolutely soft boundary condition can be utilized efficiently. The equivalent free sound field can be obtained if the sound field measured underwater is dissymmetrically mapped about the water surface. Then, the incident wave component and reflected wave component of material samples can be separated by the adoption of Spatial Fourier Transforms. The sound reflection coefficient of material samples can be gotten further. This method has been adopted in this paper to measure the reflection coefficient of big samples in low frequency, and its validity has been verified by experiment.

2 Basic principle

It is supposed that sound source is close to water surface and located at the point (x, y, z) in three-dimensional space. The material samples to be tested is put close to water surface. There are two parallel holograms z_1, z_2 in the radiated sound field, which are shown in figure 1. If the hologram sound pressure in planes $z = z_1, z_2$ is measured, the equivalent holograms above the water surface are obtained by dissymmetrically mapping the measured sound pressure about the water surface. Then, the equivalent field in free space can be obtained. The complex sound pressure distribution in two holograms can be separated into plane wave component $P(k_x, k_y, z_1)$, $P(k_x, k_y, z_2)$ by using two dimensional Fourier Transforms. However, each plane wave component can be expressed by the summation of the corresponding incident plane wave and reflected plane wave. Each plane wave component in $z = z_1, z_2$ can be expressed by incident plane wave and reflected plane wave components in plane $z = 0$ [1].

$$P(k_x, k_y, z_1) = P_i(k_x, k_y, 0)\exp(jk_z z_1) + \mathrm{P_r}(k_x, k_y, 0)\exp(-jk_z z_1) \quad (1)$$

$$P(k_x, k_y, z_2) = P_i(k_x, k_y, 0)\exp(jk_z z_2) + \mathrm{P_r}(k_x, k_y, 0)\exp(-jk_z z_2) \quad (2)$$

The propagation direction of plane wave is given by wave vector (k_x, k_y, k_z) , which is shown in figure 2. The wave number k_0 has the relation with wave number vector, $k_0^2 = k_x^2 + k_y^2 + k_z^2$. k_0 is wave number in the medium. The normal plane wave, namely $k_z > 0$, is considered in the paper.

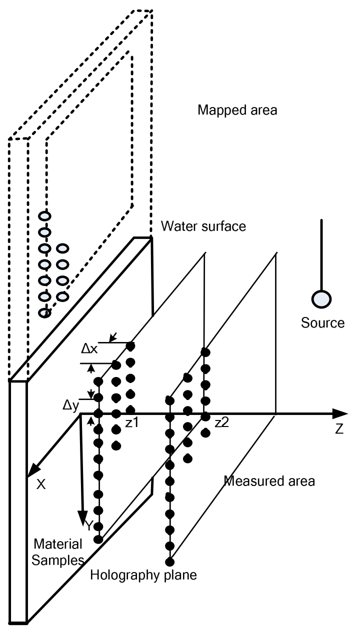


Fig.1 Sound field measurement model of material samples' sound reflection coefficient.

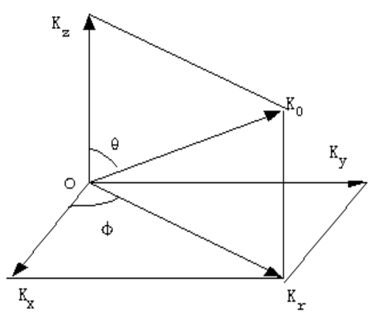


Fig.2 The schematic diagram of wave number vector

From equation (1) and (2), the incident plane wave and reflected plane wave in reflected plane $z = 0$ can be separated. The reflection coefficient is shown

$$C_r\left(k_x,k_y\right)=\frac{P\left(k_x,k_y,z_2\right)\exp\left(jk_z z_1\right)-P\left(k_x,k_y,z_1\right)\exp\left(jk_z z_2\right)}{P\left(k_x,k_y,z_1\right)\exp\left(-jk_z z_2\right)-P\left(k_x,k_y,z_2\right)\exp\left(-jk_z z_1\right)} \quad (3)$$

where, $C_r\left(k_x,k_y\right)$ is the reflection coefficient on a row of the plane wave at vertical angle θ and horizontal angle ϕ.

$$\theta=\arcsin(k_r/k_0)=\arcsin\frac{\sqrt{k_x^{\,2}+k_y^{\,2}}}{k_0},$$

$$\phi=\tan^{-1}(k_y/k_x) \quad (4)$$

Different wave numbers mean the different plane wave incident direction. Therefore, if the sound pressure in two holograms is measured, the plane wave reflection coefficient at arbitrary angles can be calculated in principle.

3 Experimental validations

The geometry parameters in sound field measurement are selected as follows [2]. The size of material samples and measurement plane is greater than 3λ, where λ is wave length. The distance between the neighbouring measured points in one plane is less than $\lambda/4$. The distance between two holograms is less than $\lambda/10$. The distance between material samples and its neighbouring hologram is also less than $\lambda/10$. The distance between sound source and material samples is at the range from $\lambda/2$ to 1λ. The frequencies in the experimental measurement are at the range from 3 kHz to 10 kHz. The tested material samples in the experiment is a rectangle stainless steel plate. The dimension is 1500 cm wide, 1600 cm high, 5 cm thick. 23 points is measured in horizontal direction, 20 points is measured in vertical direction, and the total measuring points are 460. The distance between two adjacent points in horizontal and vertical direction is 6 cm. The transmitting transducer is set 4 cm deep in the water. The experimental place is a muffling pool, of which dimension is 3.6 m wide, 3 m high, 3 m long. The diagram of experimental apparatus connection is shown in figure 3.

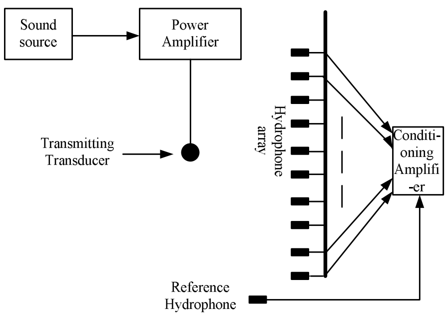
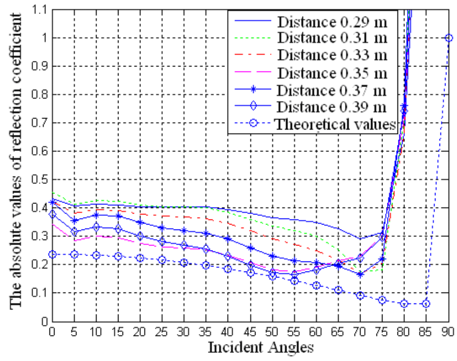


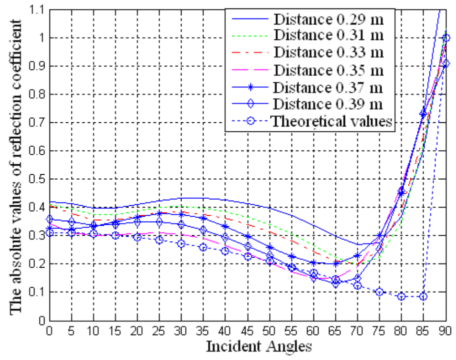
Fig.3 The diagram of experimental apparatus connection

3.1 Case A

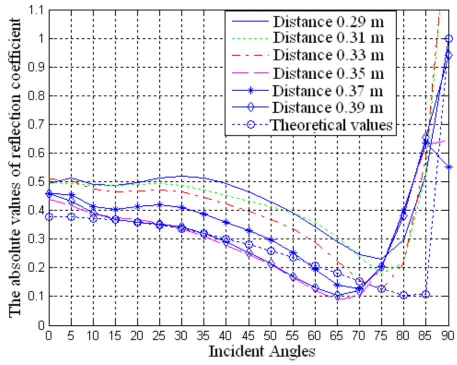
In this case, the relation between the measuring error and the distance between sound source and steel plate is studied. The distance between two holograms is 2 cm, and the distance between material samples and its neighbouring hologram is 3 cm. The measured results are shown in figure 4.



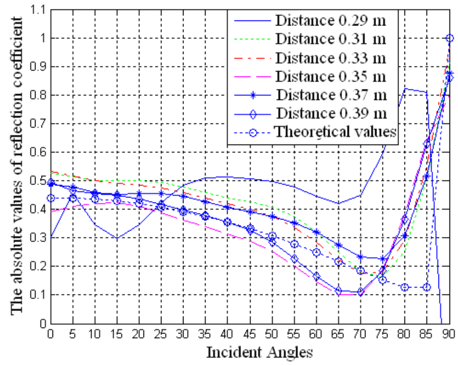
(a) 3 kHz



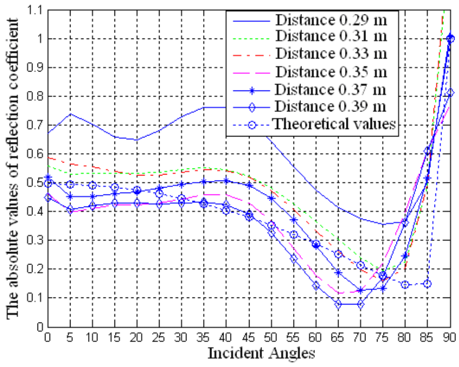
(b) 4 kHz



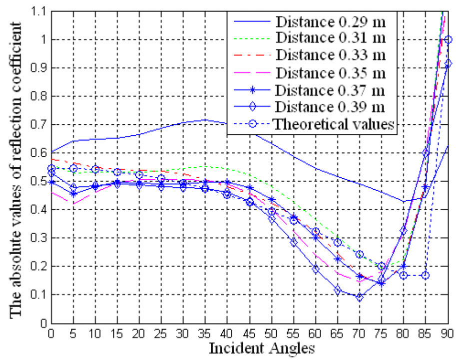
(c) 5 kHz



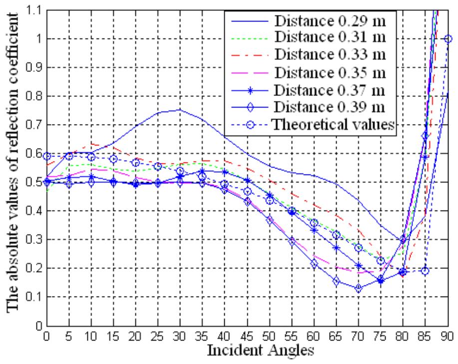
(d) 6 kHz



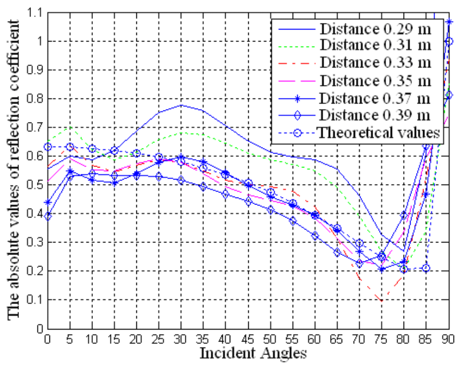
(e) 7 kHz



(f) 8 kHz



(g) 9 kHz



(h) 10 kHz

Fig.4 The comparison between measured results and theoretical values at the frequency range from 3 to 10 kHz

From figure 4, when the distance between sound source and material samples is at the range from 0.6 λ_{max} to 0.75 λ_{max} or from 2 λ_{min} to 2.5 λ_{min}, the measured results agree well with theoretical values, where λ_{max} is the maximum wavelength and λ_{min} is the minimum wave length in the experiment. The curves in Fig. 4 prove that if the distance between sound source and material sample is too near or too far, the error of the measurement is becoming larger. When the distance is quiet near, sound field changes acutely. There is much high wave number component in holograms, which makes the spectra overlaid in Spatial Fast Fourier Transforms and also makes the calculation error bigger.

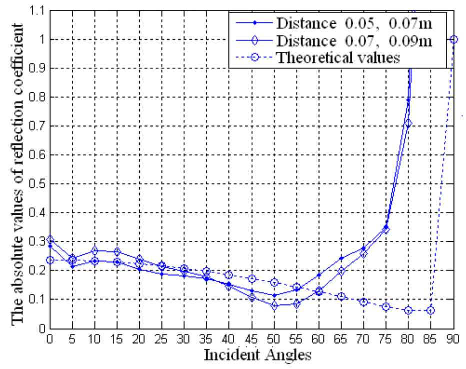
The table 1 lists the root mean square error of each frequency at the angle range from 0 to 60 degrees. From table 1, the root mean square error value of the measured results at high frequencies is bigger than at low frequencies. The sound field at high frequencies is more complicated, because the scattering effect of hydrophone array rack is much bigger, meanwhile. The root mean square error of measured results at 3 kHz is also bigger, because low limit frequency of the muffling pool in the experiment is 3.15 kHz, which has some effect on sound elimination at 3 kHz.

f \ D	0-10	0-20	0-30	0-40	0-50	0-60
3	0.06	0.06	0.06	0.06	0.05	0.05
4	0.01	0.01	0.02	0.02	0.02	0.02
5	0.04	0.03	0.03	0.02	0.03	0.04
6	0.03	0.02	0.02	0.03	0.03	0.04
7	0.09	0.08	0.06	0.06	0.06	0.07
8	0.11	0.09	0.07	0.06	0.06	0.06
9	0.07	0.06	0.06	0.05	0.05	0.06
10	0.06	0.07	0.06	0.05	0.05	0.04

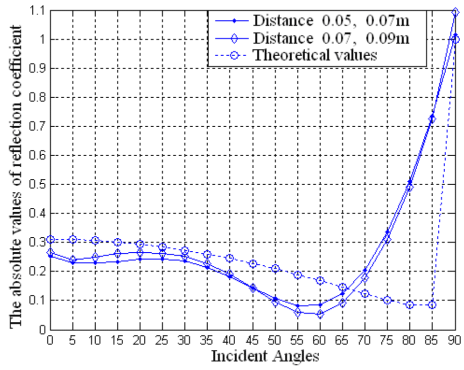
Table 1 The root mean square error of measured results at the angle range from 0 to 60 degrees. Character 'f' represents the frequencies and its unit is kHz, while character 'D' represents the degrees.

3.2 Case B

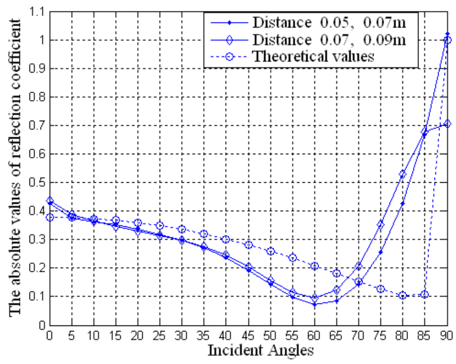
In this case, the relation between the measuring error and the distance between hologram planes and steel board is studied. The measured results and theoretical values are shown in figure 5.



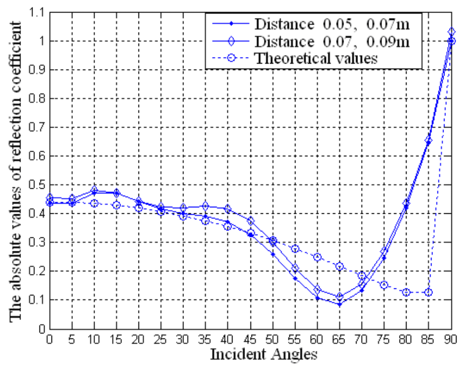
(a) 3 kHz



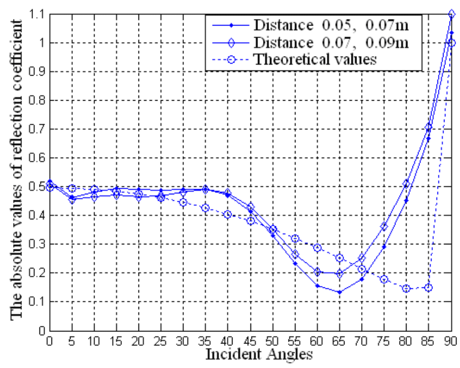
(b) 4 kHz



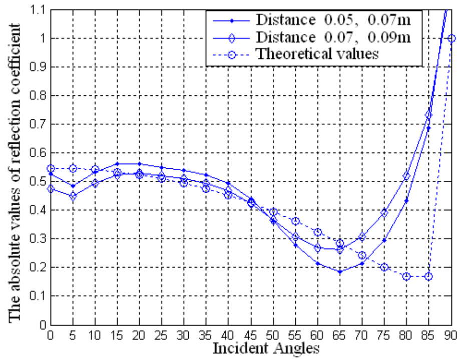
(c) 5 kHz



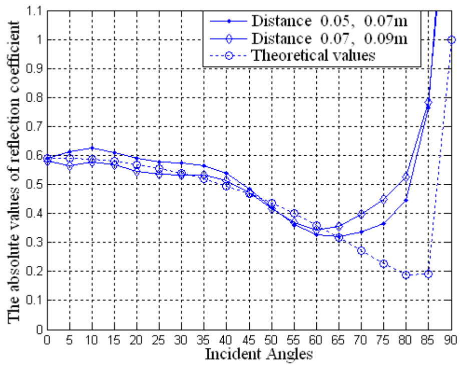
(d) 6 kHz



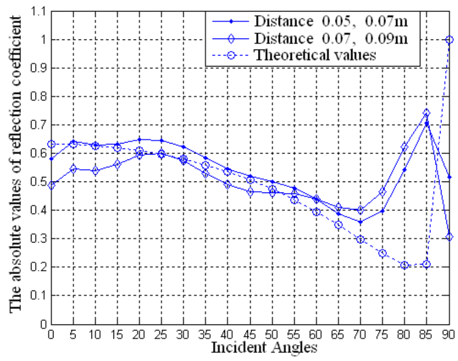
(e) 7 kHz



(f) 8 kHz



(g) 9 kHz



(h) 10 kHz

Fig.5 The comparison between measured results and theoretical values at the frequency range from 3 to 10 kHz, when the distance between hologram and steel board is different. The distance between sound source and steel board is 0.35 m.

The curves in figure 5 show that with the increase of the distance between the hologram and steel plate, the measured results don't have been much affected for the incident angles less than 60 degrees. On that measurement parameters condition, the steel plate edge's diffraction disturbance and limited sound field truncation error have less effect on the measured results than the distance between sound source and material samples does.

4 Conclusions

The reflection coefficient measuring method for big samples at low frequency is validated by experiment in semi-space in the paper. The merits of the measurement method are as follows. First, the area of material samples is enlarged equivalently by dissymmetrically mapping the measuring sound field above the water surface; it is easy to meet the demand of material samples in the experiment.

Second, the space resolution ratio of vertical direction is enhanced; the reflection coefficient of more angles can be obtained in principle. Third, sound source can be placed close to water surface, which improves the accuracy of locating material samples and the experiment is carried out easily. Fourth, the incomplete sound elimination effect of measurement method in full space due to water surface can be eliminated. In order to eliminate the measured error, some factors are also required to pay attention to. The distance between sound source and material samples should be in the range from 0.6 λ_{max} to 0.75 λ_{max} or from 2 λ_{min} to 2.5 λ_{min} when broadband measurement is carried out. The distance between two holograms should be less than $\lambda_{min}/10$.

Acknowledgments

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References

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[2] Shang Dejiang, Liu Yang, "The method investigation on measuring the reflection coefficient of materials at arbitrary angles by near field hologram sound pressure", *The Tenth Shipping Underwater Noise Science Proceedings*, 66-73(2005)