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Observation of absorbing materials by acoustical holography

Haruo Uchiyama* and Kimio Shibayama**

**Department of Energy, Hachinohe Institute of Technology, 88–1, Ohbiraki, Myou, Hachinohe, 031 Japan*
***Department of Information and Communication, Faculty of Engineering, Tamagawa University, 6–1–1, Tamagawagakuen, Machida, Tokyo, 194 Japan*

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A new field measurement method for sound absorbing materials is proposed. The subtractive holographic technique is applied to reject spurious interferences and to extract waves scattered by a sample. The application of holographic techniques for room acoustics promises greatly to observe the effective absorption characteristics of materials.

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1. INTRODUCTION

There have been a number of investigations on the measurements on absorbing materials for room acoustics. The material characteristics are usually measured in anechoic[1] or reverberation chambers[2] using pure[3,4] or pulsed[5] tone wave forms.

In practical field measurements, however, it is not enough only to check how the absorbing materials work, because several objects composed of many kinds of materials are generally situated in rooms with complexity. Several attempts using tone burst[6] or correlation method[7,8] have been made to estimate their whole effects including mounting conditions together with surrounding situations, but have much difficulty to estimate materials' own characteristics and require a frequency analysis to determine an absorbing coefficient of a particular frequency. As the matter of course a pure tone wave has been considered not to fit for such purposes.

In the present paper, we propose a new field measurement method for absorbing materials using the subtractive holographic technique in order to reject spurious interferences, to average unavoidable violent field variations and to extract waves scattered by a sample. In audio frequency range acoustical holography has been likely disregarded for the reason of its poor resolving power except for such special applications as finding out the sound radiation sources.[9,10] However, the resolution will be of secondary importance because we have only to take an interest in only the maximum intensity value of the reconstructed image.

2. THE PRINCIPLE OF MEASUREMENT

Subtractive holography[11] applied to the principle of measurement is based on three sets of holograms as shown in Fig. 1. H_A is the hologram recorded by setting the sample material under test, H_B is one done by replacing it by the rigid wall and H_C is one done by replacing it by the perfectly absorbing material, respectively.

H_A may be regarded as containing two components of scattered waves, namely, H_1 caused by the other area except for the sample and H_R by the sample itself. H_R may be expressed as $H_R=RH_2$, where H_2 is waves reflected from the rigid wall occupied by the same area as the test sample and R is its amplitude reflection coefficient.

$$H_A=H_1+H_R=H_1+RH_2 \qquad (1)$$

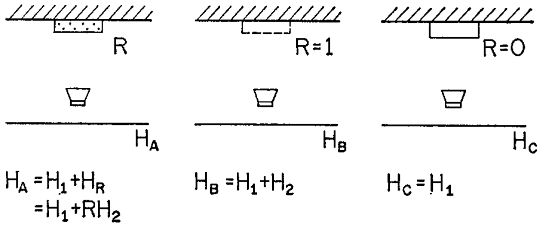


Fig. 1 The principle of measurements.

In the same way, H_B and H_C are expressed as follows.

$$H_B=H_1+H_2 \quad (2)$$

$$H_C=H_1 \quad (3)$$

The holographic absorption coefficient α_h may be defined by the following absorption coefficient of the sample.

$$\alpha_h=1-|R|^2=1-\left|\frac{H_{AB}}{H_{BC}}\right|^2, \quad (4)$$

where

$$H_{AC}=H_A-H_C, \quad (5)$$

and

$$H_{BC}=H_B-H_C. \quad (6)$$

On the other hand the maximum amplitude value of the reconstructed point source image is, as well known, described by $P_{AC}=ROL/\lambda Z_1^2$ for the subtractive hologram H_{AC} and $P_{BC}=ROL/\lambda Z_1^2$ for H_{BC} under one dimensional Fresnel approximation, where O is the amplitude of the point source, L the hologram aperture, λ the sound wave length and Z_1 the distance between the hologram and the point source, respectively. Then Eq. (4) should be reexpressed as

$$\alpha_h=1-\left|\frac{P_{AC}}{P_{BC}}\right|^2. \quad (7)$$

3. MEASUREMENT SYSTEM

Figure 2 shows the block diagram of the experimental set-up for complex amplitude hologram construction.[12] The hologram is recorded by mixing received signals with a pair of temporal reference waves shifted by $\pi/2$ each other.

The reconstructed waves may be computed by applying Fast Fourier Transform techniques to the well known Kirchhoff's equation

$$\dot{O}'=\frac{1}{j\lambda}\iint_{S_1}\dot{O}\frac{e^{-jkr_2}}{r_2}dS_1, \quad (8)$$

where λ and k: wavelength and wave number of sound,

$\dot{O}$: object waves

r_2: distance to reconstruct image

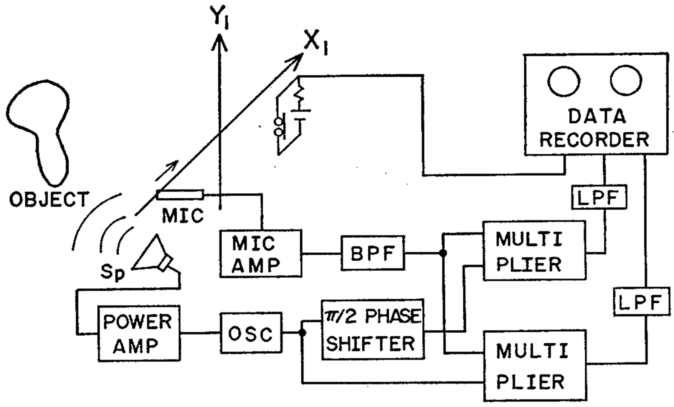


Fig. 2 Block diagram of the experimental set-up.

S_1: aperture of hologram

4. EXPERIMENTAL RESULTS

4.1 Fundamental Experiment

The experiment is carried out in an ordinary room. Figure 3 shows that square of the maximum amplitude values of reconstructed point source images which are marked ○ are coincident with sound intensities marked ×, which are square values of detected voltage at any point of the hologram aperture in variable thickness of glasswool. Then the sound energy through the hologram aperture must be proportional to square of the maximum amplitude value

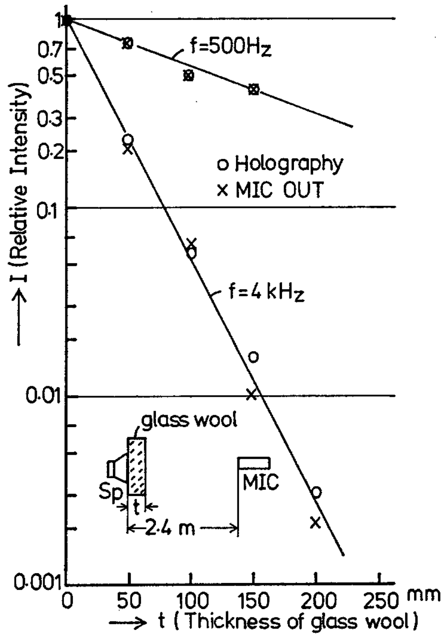


Fig. 3 Square of the maximum amplitude of reconstructed image versus thickness of glasswool.

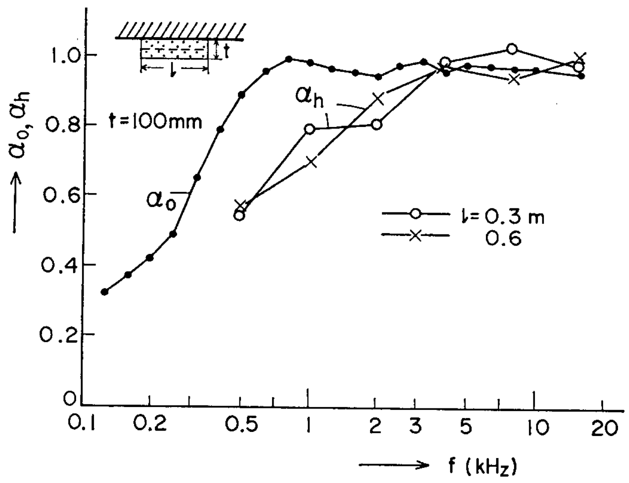
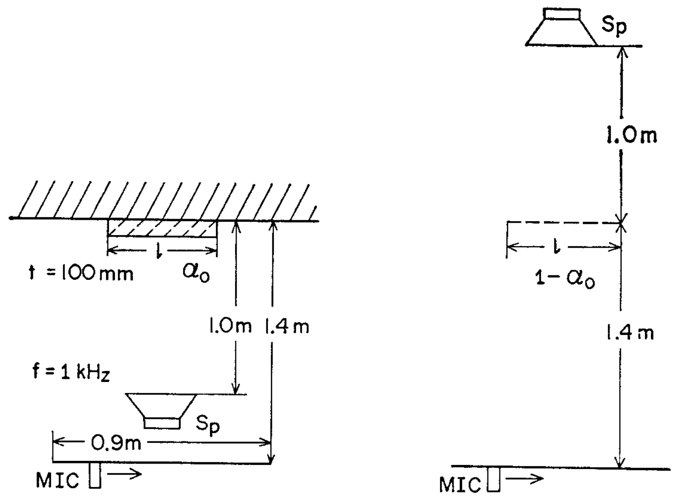
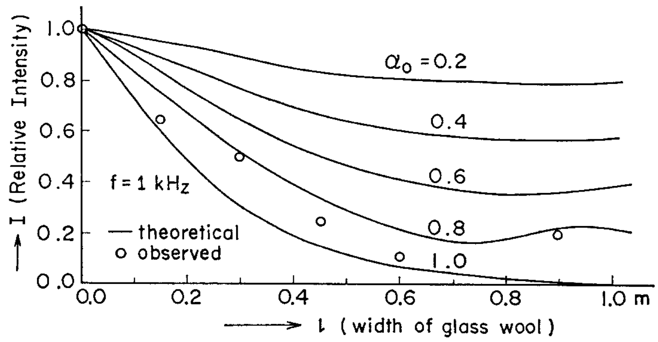


Fig. 4 Behavior of two sheets of the sample.



(a) Experimental set-up. (b) Simple equivalent model.



(c) Sample width effect for the reconstructed image.

Fig. 5 Sample width effect for the holographic method using a simple equivalent model.

of reconstructed point image. This is another meaning that Eq. (4) is describable by Eq. (7).

4.2 Typical Experiment

A glasswool under test is 24 kg/m^3 in density, 2 m in length, 50 mm in thickness and 0.6 m or 0.3 m in width. Three sheets of glasswool are chosen as the hologram H_C condition. Their absorption coefficient is preliminarily measured as almost 1.0 from 0.5 to 10 kHz range by the acoustic tube method. Figure 4 shows the behavior of two sheets of sample. The aperture of the hologram is taken as only one dimension i.e. 0.9 m and sampling points are 5 mm apart. The distance between the former and the receiver is 2.3 m, respectively. The absorption coefficient α_0 measured by the acoustic tube method is also shown in the figure. In higher frequency range both results agree fairly well.

5. DISCUSSIONS

5.1 Observable Area

In Fig. 5 (c), observed relative intensity values are regarded as almost 0.1 which means the absorption coefficient of 0.9, if l is over 0.4 m in width. They correspond fairly well to theoretical results of such a simple model as shown in Fig. 5 (b). Therefore, it may be concluded the observable area should be roughly equal to that of the geometrical imaging method.

5.2 Averaging Process

In spite of subtraction process described as Eqs. (5) and (6), violent fluctuations of the sound field remain as shown in Fig. 6 (a). The source image shown in Fig. 6 (b), however, is smoothly reconstructed. This would be considered that holographic techniques are a sort of signal averaging process detailed as follows.

Considering one dimensional model for simplicity, Eq. (8) should be reexpressed as a conventional integral as follows,

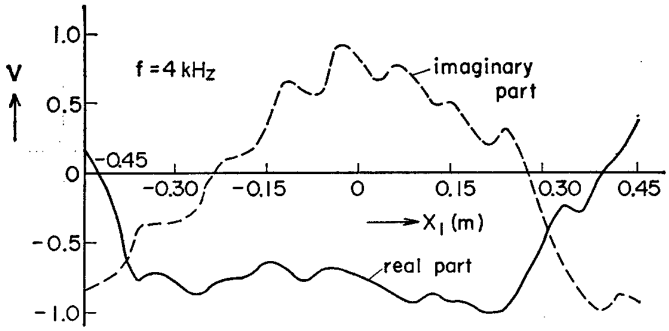
$$\dot{O}'(x_2)=\frac{1}{j\lambda}\int_{-\infty}^{\infty} g(x_1)h(x_2-x_1)dx_1 \qquad (9)$$

where

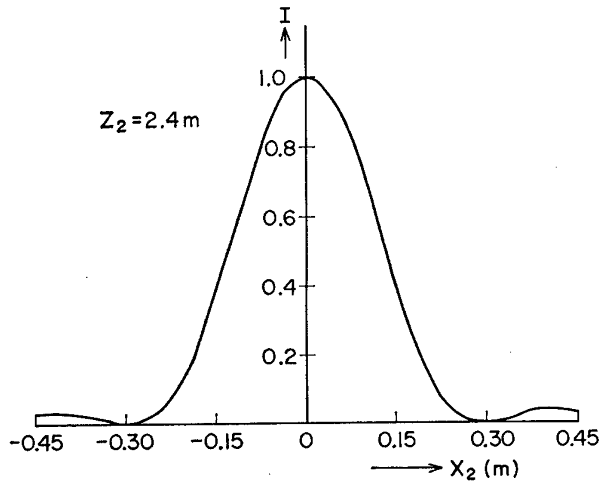
$$g(x_1)=\dot{O}(x_1) \quad \text{for } |x_1|\leq h_1$$
$$=0 \quad \text{for } |x_1|>h_1$$
$$h(x_2-x_1)=e^{-jkr_2}/r_2$$

x_1: coordinate of the hologram
x_2: coordinate of the image
$2h_1$: the aperture of the hologram.

where function $h(x)$ is so called the point spread



(a) The complex amplitude hologram.



(b) The reconstructed image.

Fig. 6 The record of hologram and the reconstructed image.

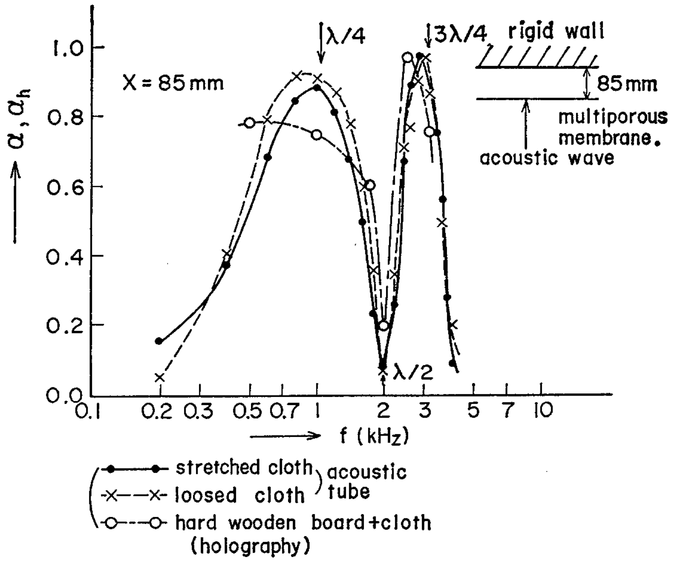


Fig. 7 Absorption characteristics of the membrane system backed with the hard wooden board.

function or the impulse response. So the reconstructed image is regarded as the wave front traveling reversely from the hologram weighted by $h(x_2-x_1)$ toward the original point. In accordance with this definition the average value $\bar{x}$ over N sampling points is expressed as follows

$$\bar{x}=\frac{1}{N}\sum_{i=1}^{N}\dot{O}(x_{1i})h(x_2-x_{1i}) \tag{10}$$

where

$$N=2h_1/\Delta x\,.$$

As N approaches infinity,

$$\bar{x}=\frac{1}{2h_1}\int_{-\infty}^{\infty}g(x_1)h(x_2-x_1)dx_1\,. \tag{11}$$

Both of Eqs. (8) and (11) are the same form except for constant factors.

5.3 Proposal on Standard Absorbing Materials

In previous discussion, we have assumed H_C is given by the complete absorbing material. Such a condition, however, is not easy to realize. Using the standard material with a known amplitude reflection coefficient $R'(\neq 0)$, Eq. (7) is easily exchanged by

$$\alpha_h=1-\left|\frac{P_{AC}}{P_{BC}}(1-R')+R'\right|^2. \tag{12}$$

If a thin membrane causing flow resistance is stretched a quarter wavelength away from the rigid wall, high absorbing effect is experienced.[13] Figure 7 shows the frequency characteristics of a membrane resistance backed a hard wooden board. The values marked ○ indicate the holographic absorption coefficients measured by the present method, and ones marked × and ● do the normal incidence absorption coefficients measured by the acoustic tube method under the stretched or the loosed condition, respectively. About a quarter wavelength interval results in the maximum absorption effect in each case, because of the highest velocity of air particle at the membrane position.

Table 1 shows the calibrated absorption coefficients of the individual quarter wavelength membrane systems measured in the anechoic chamber of which walls should be assumed as the perfectly absorbing material in H_C. In Fig. 8, the values marked ○ which indicate the holographic absorption coefficients of a sheet of sample backed by a hard wooden board are observed by means of the proposed membrane system and Eq. (12), and ones marked × are done by means of the anechoic chamber wall and Eq. (7),

Table 1 Absorption coefficients α' calibrated in the anechoic chamber and standard amplitude reflection coefficients calculated by $R'=\sqrt{1-\alpha'}$.

f (kHz)	0.5	1.0	2.0	4.2	8.3*
α'	0.86	0.76	0.96	0.77	0.27
R'	0.37	0.49	0.20	0.48	0.85

* The membrane is $3/4\lambda$ apart from the hard wooden board.

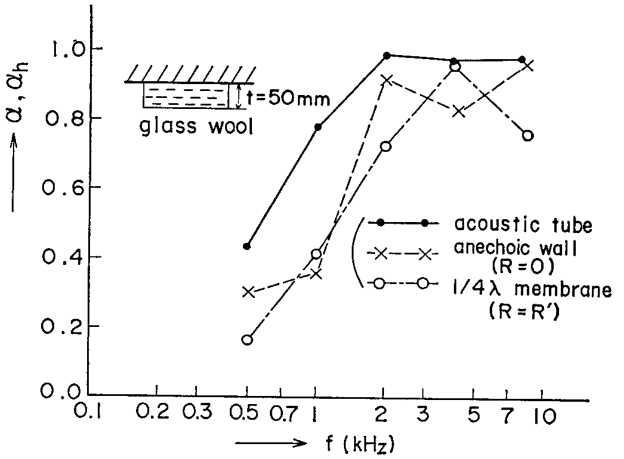


Fig. 8 Experimental results referenced by the 1/4 wavelength membrane system as the standard material, by the anechoic wall as the perfectly absorbing material and by the acoustic tube method as a well known means.

respectively. Both results agree fairly well. The results which are obtained by the well-known acoustic tube method as a typical condition of the normal plane wave incidence are shown by ● marks.

6. CONCLUSION

We have proposed and successfully proved a new method for the measurement of absorption coefficient of materials. This method has following four features: 1) It is possible to measure in an ordinary room, without preparing an anechoic or a reverberation room, by the subtractive holographic technique rejecting spurious field. 2) It is not necessary to remove constructed absorbing materials by attaching a hard board in front of them for hologram H_B and a known absorbing index material for hologram H_C. 3) Violent field variations are automatically smoothed out by the holographic data processing. 4) The obtained values can be regarded as evaluating the absorbing effects in some limited area including the effects of mounting and surrounding conditions as well as the materials' own features.

The application of holographic techniques for room acoustics will show great promise in the observation of the effective absorption characteristics of materials, if resolved following problems: 1) How to construct standard absorbing materials, as proposed in Fig. 7? 2) A finite material indicates a different effect from the materials' own feature by reason of so called the edge effect through diffraction, especially at higher frequency range. Is it possible to separate edge effects from whole? 3) The tube method shows the one limited estimation characterizing materials' own feature and the reverberation room method does the other limited estimation including influences of modes and edge effects. Generally our results would not be coincident with both. Is it possible to relate this method with either or both for easy measurement on real materials in an ordinary room? 4) Is it possible to estimate an equivalent absorption coefficient of a room corner or a absorbing complex rib construction?

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