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1pSPa7. Multi-spectral acoustic imaging on object surface in air
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Conventionally, acoustical imaging has been performed using mono-frequency or a limited number of frequencies. The frequency dependence, however, may provide rich information on surface profiles, structures hidden under surfaces, and material properties of objects. In this study, acoustic imaging on object surfaces was conducted over a wide frequency range with a fine frequency step. A rigid surface with different profiles and a boundary between two objects composed of different materials were illuminated by sound wave swept over the frequency range from 1 to 20 kHz with a 30-Hz step. The scattered sound field was recorded two-dimensionally using a scanning microphone, and the holographic method was used to reconstruct the sound pressure distribution on the surface from the recorded data. From the results, the surfaces with respect to the profile and material properties were experimentally characterized. The depth of the grooves of the characters was identified by its own resonance frequency, and the two different materials were successfully distinguished by multiple images obtained at different frequencies.

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INTRODUCTION

Visualizations in water, human body, and solid objects have often been carried out using the attribute of acoustic waves, because they penetrate into materials in which electromagnetic waves do not propagate. There are a great number of successfully applied examples including underwater sound navigation and ranging (SONAR) [1], medical ultrasonic echogram [2], and nondestructive evaluation [3]. In these visualization techniques, the target object is illuminated by acoustic waves, and their reflected or transmitted waves are obtained, and then the object is visualized after special signal processing.

Acoustically taken images provide different information from optical pictures, and are greatly influenced by elastic properties and surface structures of the object. The elastic properties of different objects have various frequency responses; the surface structures of the object occur with the creation of air cavities, which lead to specific structure properties. Due to the action of a pressure field, every specific structure behaves as acoustic resonators, vibrating at specific frequencies. These reflect on the frequency responses since frequency-dependent phenomena, such as resonance, diffraction, and attenuation, are essentially related to the properties of the object. Consequently, frequency coverage is important in acoustic imaging for taking more highly-functional information. In optical observations, recently, use of multi-spectral camera [4] has been spreading in researches on remote sensing and medical tissue diagnostics. As an analogy to the multi-spectral imaging in optics, a few studies have been reported in acoustics, but only mono-frequency or limited frequencies were used in conventional acoustic imaging [5].

In order to extensively characterize complicated and heterogeneous structures and material properties, such as surface profile and a boundary between two objects composed of different materials, we demonstrate, in this paper, a multi-spectral acoustic imaging (MSAI), which utilizes a wide band of frequency with a fine frequency step. Images are taken for one object at a large number of frequencies, and discussions are carried out on the relationship between the multi-spectral acoustic images and the physical properties of the object.

EXPERIMENTAL SETUP AND DATA PROCESSING

Experimental setup

The experimental setup is shown in Fig.1. It was composed of (i) a commercial loudspeaker (Fostex, T90A) that transmitted frequency-swept sound from 1 to 20 kHz, (ii) a needle microphone (B&K, 4182) that was used to receive the reflected sound wave, which was scanned two-dimensionally over a plane near the object, (iii) an X-Y scanning unit with automatic motion, (iv) and a frequency response analyzer (FRA) (NF5097), which was used to process the received signal. The received data of the amplitude and the phase at each frequency were sent to a personal computer (PC) for further processing. The X-Y scanning area depends on the measured surface dimension. The distance between the sound source and the object was 150 mm, and that between the measurement plane and the object surface was 2 mm. The incident angle was 15 degrees.

![Fig. 1 Experimental setup.](image-url)
Data processing

For visualizing the characteristics of object surfaces, we used the acoustic holography method [6-7] to reconstruct the image on the object surface. From the complex acoustical pressure, that is the amplitude and phase of acoustical field, we reconstruct the pressure distribution on the surface through the Rayleigh integral equation,

\[ p_r(x, y, z) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} p_h(x_h, y_h, z_h) g(x - x_h, y - y_h, z - z_h) dx_h dy_h, \tag{1} \]

where \( p_r(x, y, z) \) is the complex acoustical pressure on the reconstruction plane, and \( p_h(x_h, y_h, z_h) \) is the complex acoustical pressure on the measurement plane, and \( g(x, y, z) \) is the Dirichlet Green’s function.

Since Eq. (1) is expressed as a two-dimensional convolution integral of \( p_h(x_h, y_h, z_h) \) and \( g(x - x_h, y - y_h, z - z_h) \), using the convolution theorem [8], (1) yields

\[ p_r(x, y, z) = F^{-1} \left[ P_h(k_x, k_y, z) \right] = F^{-1} \left[ P_h(k_x, k_y, z) \hat{g}_D(k_x, k_y, z) \right], \tag{2} \]

where \( F^{-} \) indicates the inverse Fourier transform. This gives the holographic reconstruction of the pressure in the three-dimensional space \( p_r(x, y, z) \) in terms of the Fourier transformed form \( \hat{P}_h(k_x, k_y, z) \) derived from the hologram data \( p_h(x_h, y_h, z_h) \).

Making discrete operations for Eq. (1), we divided the real space of \( L_x \times L_y \) into \( N \times N \) patches of size \( (L_x/N) \times (L_y/N) \). Eq. (1) for the radiated field becomes

\[ p_r(n_1, n_2, z) = \sum_{l_1=0}^{N-1} \sum_{l_2=0}^{N-1} p_h(l_1, l_2, z_h) g(n_1 - l_1, n_2 - l_2, z - z_h), \tag{3} \]

where \( l_1, l_2, n_1, n_2 = 0, 1, \ldots, N - 1 \). This expression is a finite and discrete form of Eq. (1), the Rayleigh integral. To reduce the leakage in the discrete Fourier transform, the measured data at the edges should be set to zero using a spatial window, such as Tukey (tapered cosine) window. To perform the circular convolution, the sequence \( p_h(l_1, l_2) \) defined only for integers \( (l_1, l_2) \) in \( (0, N - 1) \) is needed to be extended over a \( (2N) \times (2N) \) domain by adding zeros. The finite discrete convolution in (3) is easily evaluated and inverted using the convolution theorem and Fourier transforms. Then, (3) becomes

\[ p_r(n_1, n_2, z) |_{N \times N} = \left\{ F_{2N \times 2N}^{-1} \left[ F_{2N \times 2N} \left[ p_h(l_1, l_2, z_h) \right] \right] \cdot F_{2N \times 2N} \left[ g(n_1 - l_1, n_2 - l_2, z - z_h) \right] \right\} \bigg|_{N \times N}, \tag{4} \]

which is the computational basis for wavefront propagation, in which \( p_r(n_1, n_2, z) \) is determined in any plane \( z > 0 \) if the data \( p_h(l_1, l_2), l_1, l_2 = 0, 1, \ldots, N - 1 \) are provided.

TEST SAMPLES

Example 1: Surface profile

A sample for the first demonstration was a resin block having 5 characters (TUITO, where we define the first T as T1, and the second T as T2) with different depths (6, 9, 13, 18, and 22 mm) on one surface, as shown in Fig. 5(a). The scanning area for the microphone was 100 \times 100 mm near the object surface.

Date acquisition

Frequency responses at every 30 Hz from 1 to 20 kHz were recorded for all the scanning positions. Fig. 2 shows one of the typical recorded data (for the object of the first demonstration) of amplitude and phase just on a point that is located in the center of the character "I" as shown in Fig. 5(a). This frequency swept measurement was repeated at every scanning point. After the measurement was finished, the acquired data were arranged into two-dimensional distributions of the amplitude and phase at each frequency as shown in Fig. 3. It means that we have acoustic holograms at every 30 Hz from 1 to 20 kHz. The total number of the obtained holograms was 635.
Fig. 2 An example of the frequency response. These results were recorded at the center of the character "I" of 9 mm in depth.

Fig. 3 The amplitude and phase distribution. (a) Amplitude, (b) Phase.

Basic frequency responses

Since frequency responses varied by the position in one character, the mean frequency responses of each character were analyzed for simplicity. The mean values of the response for the five characters were processed from all the measured points on the surface. The mean frequency responses for each character are shown in Fig. 4, where the first, second, and third harmonics of the character O were observed, and the first and second harmonics of the U and T2, the first harmonic of the characters I and T1, respectively. Characters with different surface shapes and the different depths 6, 9, 13, 18, and 22 mm exhibited different frequency-dependence since the complex profiles had acoustic resonances characterized by the depths and shapes.

According to the resonant principle of a closed end tube that resonates at the odd harmonics, i.e. $\lambda/4$, $3\lambda/4$, $5\lambda/4$, and $7\lambda/4$ ($\lambda$ represents the sound wavelength), the frequency for the depth resonance of each character (TITUO) can be calculated to be 14167, 9444, 6538, 4722, and 3864 Hz, corresponding to the depths of 6, 9, 13, 18, and 22 mm, respectively. From Fig. 4, the measured resonant frequencies were 15100, 9100, 6310, 4540 and 3490 Hz. Although there existed errors in the results, the depths of the characters were roughly identified by the frequency to some extent. For more precise estimation, two-dimensional or three-dimensional discussion about the acoustic resonance of cavity is required.

Fig. 4 Frequency responses for five characters.
Results of reconstructed images

All of the 635 holograms from 1 to 20 kHz with a 30-Hz step were reconstructed by the discrete form of the Rayleigh integral in Eq. (4). Seven reconstructed images in three-dimensional form of the object picked up from the whole frequencies are shown in Figs. 5(b)-(h). With increasing frequency, five characters "TITUO" engraved in the plate showed different responses. The deepest character "O" had the responses at lower frequencies as shown in Fig. 5(b). The characters "U", "T_2", and "I" are observed in Figs. 5(c), (e) and (f). The shape of the character had some effects on the frequency responses. The profile of the character "I" was not uniformly distributed although the character had the uniform depth, as shown in Fig. 5(f). Though it is difficult to identify the two "T"s from the optical images, they were easily recognized by the multi-spectral acoustic imaging technique. The characters "T_1" and "T_2" were not observed at the same frequency, but at 12910 and 14680 Hz in Figs. 5(f) and (g). However, both of "T_1" and "T_2" were observed at the same frequency of 12910 Hz as shown in Fig. 5(h). In addition, the responses of the four characters were observed at the frequency of 12910 Hz, but the character "T_2" could not be seen.

As the structures of the object surface are complicated, it cannot be simply regarded as a one-dimensional closed end tube. It may resonate also in other directions. Throughout the obtained images, the characters were observed at their particular resonant frequency band. The measured resonant frequency bands of each character were from 12940 to 15430, 8680 to 11950, 5140 to 6970, 4480 to 4930, and 3040 to 4270 Hz, respectively, corresponding to the characters "TITUO". From these results, the detailed structures of the object seem related to their characteristic acoustic spectral bands.

Fig. 5 (a) Optical image of the object, and (b)-(h) reconstructed images of the object.
Example 2: Material properties of the surfaces

The second experiment was carried out to investigate the effects of the material properties on the result of MSAI. A sample with a boundary between two regions with different reflectivities is shown in Fig. 6(a). The upper part of the sample was a rubber plate, and the lower part was a wood plate. The original dimensions of the object surface were 100 by 100 mm, and the measurement area was 50 by 50 mm. The spatial interval between the two scanning points was 2 mm. The same procedure as the first experiment was carried out for this sample. Five images of the 635 reconstructed sound pressure distributions were picked up as shown in Figs. 6(b)-(f).

Figs. 6(b) and (e) show the reconstructed sound pressure on the surfaces at 3640 and 15340 Hz. The sound pressure on the two plates was different. Note that the sound pressure on the wooden plate was larger than that on the rubber plate at the frequency of 3640 Hz, and that on the rubber plate was larger than that on the wooden plate at the frequency of 15340 Hz. In Figs. 6(c), (d), and (f), no obvious boundary was observed between the two surfaces, and thus at some frequencies, it was difficult to identify the two surfaces composed of different materials. At the frequency of 5140 Hz, the sound pressure of the two surfaces was distributed almost uniformly as shown in Fig. 6(c). There were circular regions on the surfaces that reflected sound pressure strongly and weakly at the frequencies of 11140 and 19960 Hz. The sound pressure on the two surfaces was not distributed uniformly, which might be influenced by the illuminating sound source. The material properties of the object surfaces are distinguished by observing at wide frequency range, although it cannot be found by using only one or a few numbers of frequencies.

![Figure 6](image_url)

Fig. 6 (a) Optical image, and (b)-(f) distributions of sound pressure on two surfaces composed of different materials.
CONCLUSIONS

We demonstrated the effectiveness of the multi-spectral acoustic imaging through the demonstrations for two examples in which 635 acoustic images were obtained from 1 to 20 kHz at every 30 Hz. The different structures of the surface and the material properties of the objects were distinguished or recognized by the characteristics of their acoustic frequency responses. The present approach might be an analogy to multi-spectral camera in optics, which is recently used for characterization in various applications instead of the conventional RGB-based camera. The multi-spectral imaging is easily accomplished in acoustics, and powerful processing methods such as acoustical holography or other imaging techniques can be used.

For more precise characterization, the evaluation of the illuminating sound source such as the uniformity of the strength in space and frequency should be discussed. A long measurement time will be shortened by employing a large-scale microphone array and a smart data acquisition system.

REFERENCES