Multi-spectral acoustical imaging

Kentaro NAKAMURA[1]; Xinhua GUO[2]

[1] Tokyo Institute of Technology, Japan

[2] University of Technology, China

ABSTRACT

Visualization of object through acoustic waves is generally called as acoustical imaging. This concept contain noise source localization, ultrasonic non-destructive testing, medical ultrasound, underwater sonars, etc. In these conventional imaging techniques, frequency information has not yet utilized effectively, though shape, material and even structure behind the surface reflect on the frequency characteristics of their acoustic responses. In this report, we introduce a concept of multi-spectral acoustical imaging, where wide range of frequency responses are investigated with a fine frequency pitch. As typical examples, we demonstrate the responses from a surface with several different holes for the frequency band from 1 to 20 kHz with 30-Hz pitch. The position and depth of the holes are clearly identified by their resonance frequencies. The volume of a small droplet in a well can be precisely measured using the present method. A method for displaying the multi-spectral acoustical data is also discussed.

Keywords: Acoustical imaging, Frequency response, Visualization
I-INCE Classification of Subjects Number(s): 72.7

1. INTRODUCTION

Imaging using acoustic waves have been intensively investigated and practically applied in several areas such as underwater sonar, ultrasonic nondestructive evaluation and medical ultrasound echo technique. Also in air, detection of objects has been carried out by time-of-flight of a 40-kHz pulsed ultrasound. These imaging techniques are so-called ‘active’ methods since the reflected or diffracted waves are detected after illuminating object with pulsed or modulated sound waves, while noise localization is, in most cases, ‘passive’ method since the object itself emit sound waves. Arrayed transducers or a mechanically scanned microphone are used to obtain two-dimensional data in acoustical imaging. In practical medical ultrasound echo machine, for example, a 128- or 256-element one-dimensional array is conventionally used. Depth information is known by the time-of-flight of the reflected waves. Similar technique is used for industrial non-destructive evaluation these days. In these active acoustical imaging, reflected signal strength is recorded and displayed in usual cases. As one of the exceptions, in recent medical ultrasound echo machines, the second harmonic responses are detected and utilized for visualization. We can also find several new studies in non-destructive evaluation utilizing the harmonic and sub-harmonic generation from the object. However, in general, frequency information have not been fully used for characterize objects. In passive acoustical imaging, in contrast, frequency distribution has been of interest, since the feature of noise sources reflect on their frequency characteristics.

In this report, we describe about our trial to establish a new active acoustical imaging in air, ‘multi-spectral acoustical imaging,’ where frequency information is emphasized(1). Surface profiles, structures and materials show their typical frequency responses due to cavity resonances, structure vibrations and attenuation in the materials. To know these characteristics, wide range of frequency is swept with a fine pitch for the illuminating sound, and the reflected/diffracted waves are two-dimensionally measured and recorded. The concept of ‘multi-spectral acoustical imaging’ is followed by several demonstrations in this report.

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[1] knakamur@sonic.pi.titech.ac.jp
[2] xguo@whut.edu.cn

2. MULTI-SPECTRAL ACOUSTICAL IMAGING

2.1 Measurement Setup

For multi-spectral acoustical imaging, two-dimensional measurement of sound field has to be done with a sound illumination of wide frequency range. Figure 1 shows a typical setup to achieve this measurements. Frequency responses are recorded for every measurement point with a fine frequency pitch. Thus, three dimensional data composed of the 2D position and the 1D frequency domains is obtained. In other word, Two-dimensional sound pressure distribution is recoded at each frequency. In our trial experiment shown later, the illuminating sound is swept from 1 kHz to 20 kHz with a 30-Hz step. This means that 635 acoustical pictures are obtained for one measurement.

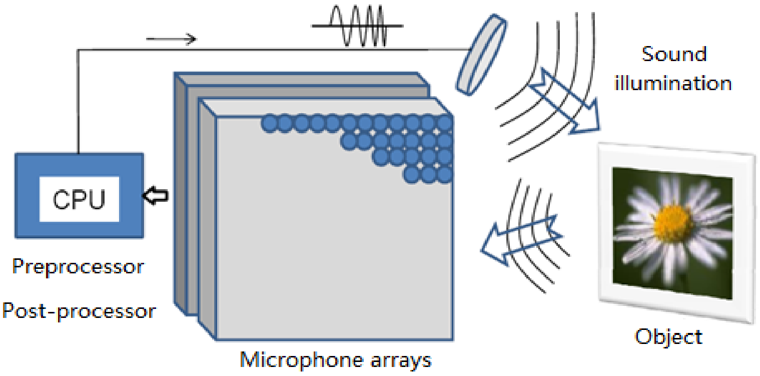

Figure 1 – Conceptual setup for multi-spectral acoustical imaging.

2.2 Concept of Multi-Spectral Acoustical Imaging

Digital camera captures a RGB picture. This means that the optical camera takes three spectral information in usual cases. Recently, multispectral approach is intensively studied in several area of optical imaging to analyze the characteristics of object, and the concept is referred as 'multi-spectral camera.' It might be possible to understand that the multi-spectral acoustical imaging is an analogy to the multi-spectral camera in optics. Here, let us compare the acoustical imaging with the optical one.

1) Highly coherent measurement
2) High signal to noise ratio
3) All electronic spectral analysis
4) Sensitive to surface structure of mm-size
5) Low spatial resolution
6) Ranging capability based on low propagation speed

Acoustic signal source, which is supplied by a function generator with a crystal oscillator time base, is highly coherent, and it is easy to detect both amplitude and phase of the reflected signal through a less expensive electronics. In optical camera, only the intensity of reflected light is recorded. To detect the phase, complicated optical system is required to achieve interferential measurements. Cross-correlation between the received signal and the source signal is also carried out using electronic circuit or digital calculation for acoustic signals. This processing provide very high signal-to-noise ratio. Frequency of the illuminating signal can be controlled very precisely, and the frequency analysis of the received signal is simply conducted. However, spatial resolution is not excellent due to the long wavelength of sound waves. For example, the wavelength at 10 kHz in air is 34 mm, the spatial resolution of the order of only 10 mm is possible in acoustical imaging. We need to use ultrasonic region for higher resolution, but the measurable range is reduced due to increasing attenuation in air. In conclusion, high frequency resolution and low spatial resolution are the nature of acoustical imaging. Consequently, frequency information should be fully utilized in acoustical imaging, and the concept of multi-spectral imaging becomes importance.

2.3 Problems for Display

Two-dimensional sound pressure data are obtained for so many frequencies. This means that we need to consider about a problem how to display the rich information as a picture. As one of the possibilities, high density spectral data are reduced to a RGB picture, where the many spectral images are merged into only three spectra R, G and B according to a certain rule. Practical procedure for the RGB-representation will be explained later.

3. MEASUREMENT OF SURFACE SHAPE

3.1 Experimental Setup

Figure 2 shows the setup to demonstrate the effectiveness of multi-spectral acoustical imaging. A loudspeaker is illuminating the sample with wideband sound swept from 1 kHz to 20 kHz by a step size of 30 Hz. Instead of arrayed microphones, a single microphone is mechanically scanned in x and y directions using a motorized stage to take two-dimensional sound pressure field. The amplitude and phase at every measuring point is recorded for the frequency band. Near field holography is introduced to reconstruct the sound field on the surface of the sample. We prepare a flat rigid surface with nine vertical holes having different diameters and depths.

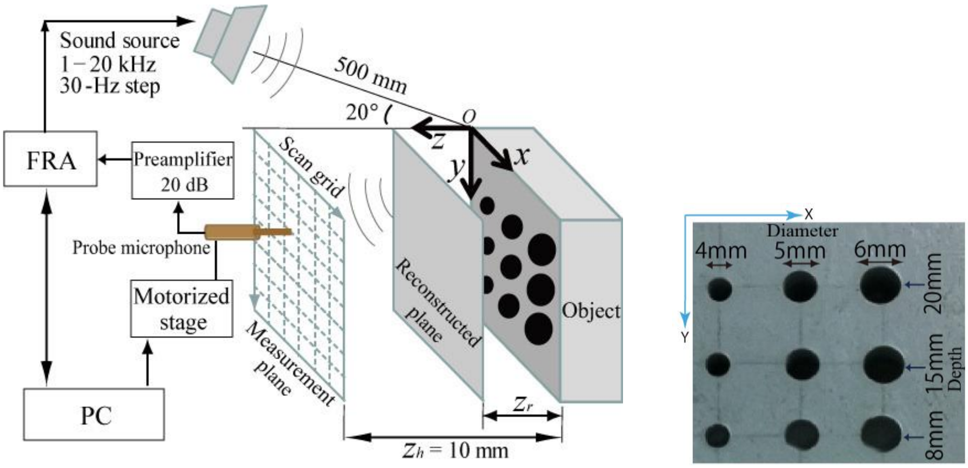

Figure 2 – Experimental setup for the demonstration of multi-spectral acoustical imaging (left) and the sample to be measured (right).

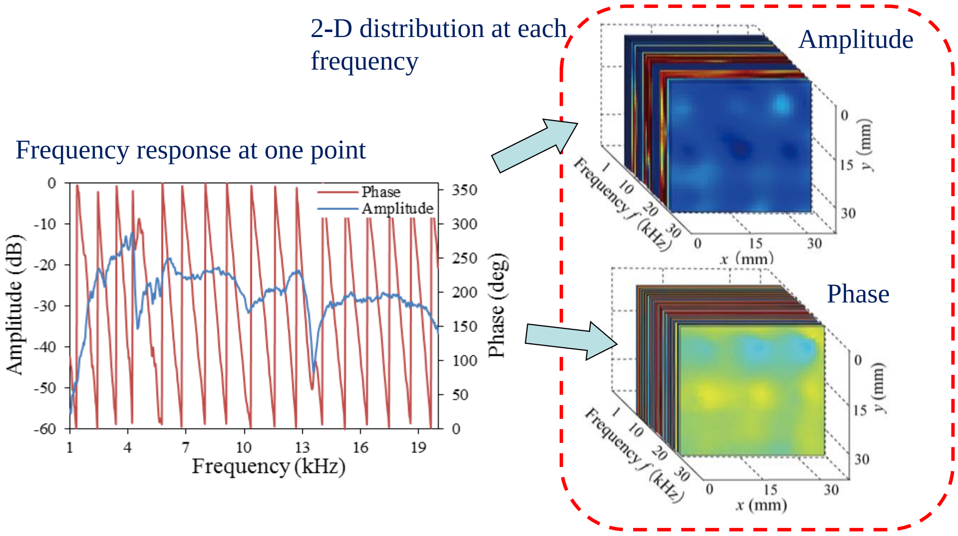

Figure 3 – Originally measured data (left) and the two-dimensional representation at each frequency (right).

3.2 Measured Examples

Amplitude and phase of the sound pressure are measured as shown in the left of Fig. 3. Then, the data are arranged into two-dimensional distribution map for each frequency as illustrated in the right of Fig. 3. Six of 635 pictures are shown in Fig. 4 as examples. The sound pressure is almost uniform over the sample surface at 1990 Hz, while apparent dips are observed at 4780 Hz around the positions of the holes with the depth of 20 mm. Assuming the quarter wavelength resonance of an open-closed hole, the 20-mm deep hole resonates around 4250 Hz. Drops of the sound pressure are also found at 6280 Hz for the holes having the depth of 15 mm. The responses at 13570 Hz and 18340 Hz are third overtone resonances. By observing wide frequency region with the fine pitch in this way, we can encounter the rich information about the surface profile, which are not able to be found by measuring at a single or small number of frequencies.

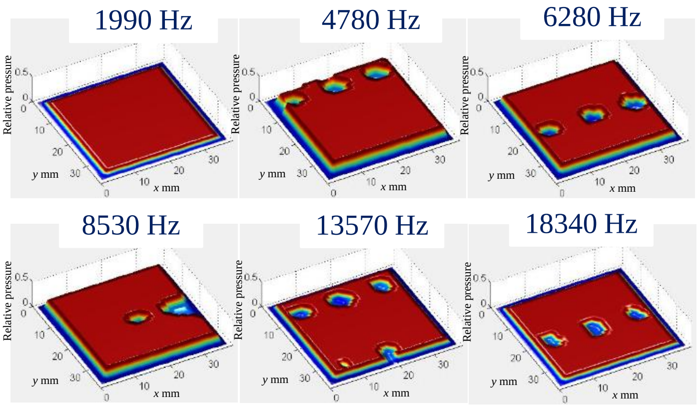

Figure 4 – Examples of sound pressure distributions at the typical frequencies.

3.3 RGB-Representation for Display

Multi-spectral data of acoustical imaging has so large volume that it is difficult to display all information in one picture. One possible method is to attribute the acoustic frequency to color in the image. Applying three band-pass filters on the acoustic signal, lower frequency, middle frequency and higher frequency signals are transformed to red (R), green (G) and blue (B)$^{(2)}$. The power of the signals selected by the filter reflects on the brightness of the corresponding color. Figure 5 shows the RGB representation of the data taken for the sample of Fig. 2. The deepest holes result in red, while the middle and shortest holes are displayed in green and blue, respectively. Selection of the center frequencies and the band width of the filters has great effect on the resultant RGB image. Though the RGB representation is convenient to grasp the overall characteristics of the sample, we should note that a large part of the multi-spectral acoustic data are lost in the display.

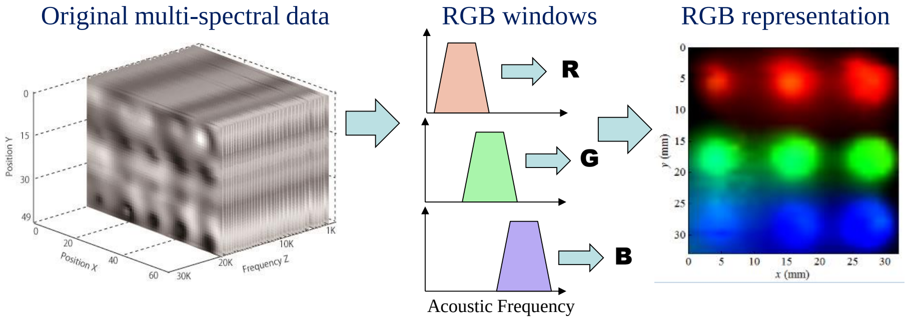

Figure 5 – Processing for the RGB-representation of multi-spectral data.

4. PRECISE EVALUATION

4.1 Sample and Measurement

Here, we are introducing an example of applications of multi-spectral acoustical imaging for more precise measurement. We try to estimate the volume of liquid contained in each well of an 8x12 arrayed well-plate by scanning a one-dimensional microphone array as shown in Fig. 6. The diameter of the well is 9 mm, and the maximum volume is 300 μ*l*. The resonance frequency of the well is increased as the content volume of liquid as demonstrated in Fig. 7.

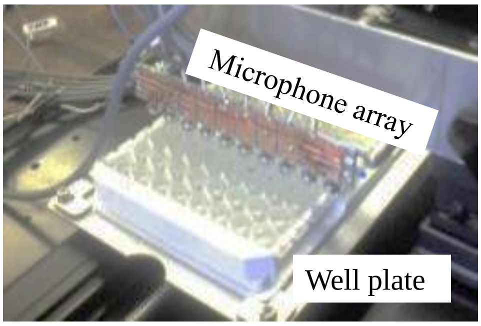

Figure 6 – 96-point well plate and 1-D microphone array.

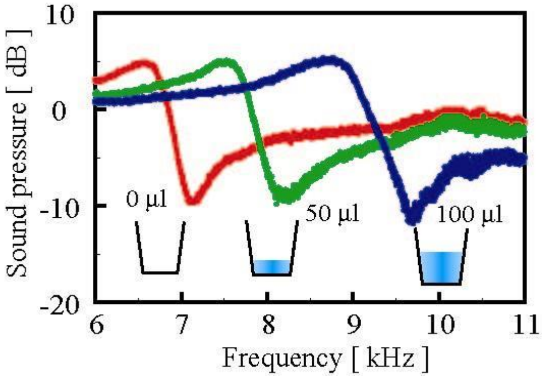

Figure 7 – Frequency responses of the well with different liquid volume.

4.2 Results

Measurements were repeated 10 times for water with varied volume, and the results are summarized in Fig. 8. The theoretical resonance frequency of quarter wavelength with open-end correction is also drawn in the figure. The actual resonance frequency was slightly higher than the theory. Variation in the volume of 1µ*l* caused a change in the frequency by 20 Hz. Error in the estimation of 100 µ*l* was approximately 0.2%. Evaporation of water cannot be ignored in this measurements.

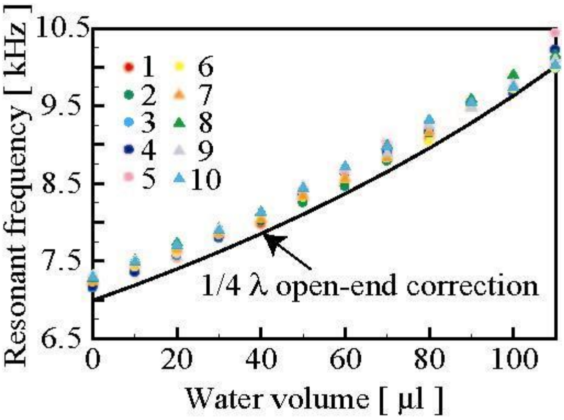

Figure 7 – Frequency responses of the well with different liquid volume.

Next, the volumes of all the wells in the plate were estimated, where a 33.5-µ*l* metal ball is located in the well of 3-3 and a 4.2-µ*l* metal ball is located in the well of 4-5. The results are summarized in Fig. 8. The resonance frequency for each well was measured 10 times and the average was recorded. The volume was estimated according to the results of water. As can be seen from Fig. 8, the positions and the volume were successfully found from the results. However, the empty wells showed not zero but several µ*l* maximum. The adjacent wells of the well containing the 4.2-µ*l* metal ball had higher errors. This is mainly due to acoustic coupling between the wells.

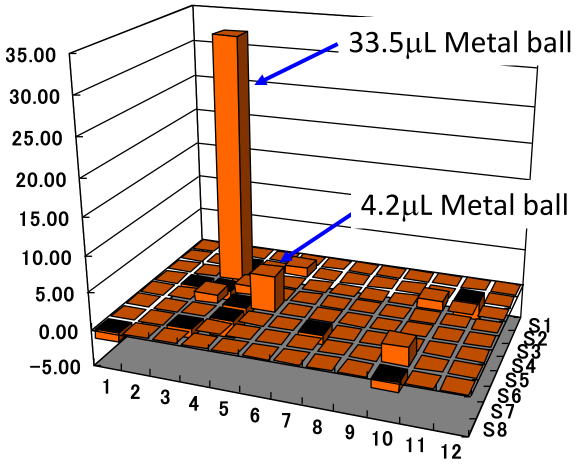

Figure 8 – An example for measuring the contents of a well-plate.

5. FINAL REMARKS

Here, we have introduced a concept of 'multi-spectral' acoustical imaging, where imaging is carried out over wide frequency range with fine frequency pitch. If the frequency information is deeply considered, acoustically taken picture gives us quite different knowledge about the specimen from optical picture such as surface shape and structure. If frequency dependence of surface impedance is taken into account, there is a possibility to identify materials. We also demonstrated a method to display the multi-spectral data in a RGB picture. Two dimensional microphone array shall be essential for practical measurements.

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