IN-SITU MEASUREMENT OF ACOUSTIC IMPEDANCE AT OBLIQUE INCIDENCE BY USING A PARAMETRIC LOUDSPEAKER

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Acoustic measurements of an architectural material in a free field or in-situ are influenced by diffraction from sample edges and reflections from other room boundaries. These undesired waves may cause a measurement error. Especially, a measurement at oblique incidence is quite difficult as the incident angle is larger or the sample size is smaller. In this study, a parametric loudspeaker, which is super-directive by utilizing the nonlinearity of ultrasound, is used to overcome the difficulty. The parametric loudspeaker can reduce the undesired waves by focusing the incident sound onto a small spatial range and will be used as a simple and accurate measurement method. However, the super strong ultrasound used as the source signal causes the nonlinear distortion called "pseudo sound" on the microphone surface and increases the measurement errors. In order to minimize such induced errors, two methods are investigated experimentally: acoustic filtering via phononic crystals and the phase-cancellation excitation of the ultrasound. In our previous work, acoustic impedance of a glass-wool board at oblique incidence is measured using these two methods in an anechoic chamber. The results show that the proposed method is effective at frequencies above 800 Hz in a free field. Based on this, in the presented study, in-situ measurements are conducted in a conference room. This investigation shows that the proposed method can efficiently estimate the acoustic impedance at oblique incidence in-situ at frequencies above 800 Hz.

Keywords: parametric loudspeaker, ultrasound, acoustic impedance, pseudo sound

1. **Introduction**

The acoustic performance of a room is largely affected by the acoustic properties of surfaces, such as walls and ceilings. As the acoustic properties of a material are dependent not only on its inherent characteristics but also the construction conditions, both a free field and in-situ measurements are important. Some different measurement techniques of material characteristics in a free field and in-situ have been developed over the years [11–13]. However, these measurements may be contaminated by the undesired waves,
such as diffractions from the sample edges and reflections from other surfaces. Thus, some restrictions are presented dependent on the relation between the target wavelength and the geometrical set-up in order to reduce the measurement error due to such undesired waves: for example, ISO17497-2 [1] is a standard measurement method to estimate the distributions of the reflected sound from a specimen and it defines the geometrical relation between the sample, the source, and the receiving points. The measurements of the absorption properties at oblique incidence have been investigated for many years [5,7,8], but there is no standard for neither in a free field or in-situ because of its difficulty. When the incident angle is large, the sample size should be large enough while the experimental room has a spatial restriction. It is also quit difficult to measure the target area without being affected by the other area of room surfaces in in-situ situation. Therefore, a new method unaffected by these undesired waves is highly desirable. In this study, a parametric loudspeaker, which has a super-directivity by utilizing the nonlinearity of the ultrasound, is used to measure the acoustic characteristics of materials: it produces a highly directive audible sound beam [11,15]. The parametric loudspeaker was developed by Yoneyama et al. [15] based on the parametric array theory developed by Westervelt [10]. As shown in Fig. 1, when two super-high pressure ultrasound (\(f_1\) and \(f_2\), \(f_1 > f_2\)) are propagating into the same direction, the nonlinear interaction of the primary waves, \(f_1\) and \(f_2\), generates virtual sources along the propagation path, virtually forming an end-fire array. Then, the difference-frequency sound (\(f = f_1 - f_2\)) is self-demodulated along the end-fire array with the super-directivity. The sound pressure of the difference-frequency components, which is the audible sound in this paper, increases with the propagation until the two primary components are attenuated by the air absorption and spherical diffusion. However, a point to be aware of regarding the use of the parametric loudspeaker is the super-high pressure of the ultrasound source signals. The incidence of a super-high pressure sound on a microphone membrane causes a serious problem, i.e., a nonlinear distortion named "pseudo sound", resulting in the detection of higher sound pressure than the existing one [13,14]. This may lead to an inaccurate estimation of the absorption properties of the target material. In order to solve this problem, the following two techniques are applied to measurements in this study; an acoustic filtering via phononic crystals and the phase-cancellation excitation of the ultrasound source signal. The first one is proposed by Ji et al. [16]. They found that this technique is effective to eliminate the pseudo sound when using the parametric loudspeaker by numerical and experimental investigations. The second one is developed by Kamakura et al. [17]. They showed that their technique can reduce the primary waves without deteriorating the difference-frequency components. The basic principles of these two techniques are explained in Section 2. In our previous work, the acoustic impedance of porous materials at oblique incidence is measured by two microphone method proposed by Allard et al. [4,5] in a free field. The results show that these two techniques can provide an accurate estimation of the acoustic impedance of the porous materials at frequencies above 800 Hz [13]. Based on that, the applicability for in-situ measurements are investigated in Section 3. Finally, Section 4 concludes this study.

Figure 1: Concept of a parametric loudspeaker.
2. **Pseudo sound reduction**

When using a parametric loudspeaker, the pseudo sound on the microphone membrane must be avoided by reducing the ultrasound near the receiving points, while the ultrasound must be strong enough to generate the audible sound along the propagation path.

2.1 **Phase-cancellation excitation**

Kamakura et al. proposed the phase-cancellation excitation of the ultrasound source signals (PCE): the inner and outer transmitters of a circular-shaped parametric loudspeaker emit 180 degrees out-of-phase signals in the ultrasound domain. Hence, the ultrasound waves are cancelled on the propagation axis without deteriorating the audible sound. Based on their work, we fabricated the parametric loudspeaker shown in Fig.2(i), which consists of 896 (14 rows × 64 columns) small piezoelectric ultrasonic transducers (AT40-10PB3, Nippon Ceramic Co., Ltd.) having the resonant frequency of 40 kHz. Each column is individually line-controlled by high-speed 1-bit signal processing with a sampling frequency 11.2896 MHz. The transducers are divided into two rectangular-shaped groups with 32 columns on the left and right halves of the surface: each group generates the source signal 180 out-of-phase. When measuring the acoustic properties at normal or oblique incidence by the method proposed by Allard et al. [4, 5], two receiving points are placed perpendicular to the sample surface: in this situation, they must be inside the null area, where the ultrasound is suppressed by PCE, to prevent the pseudo sound. When the incident angle \( \theta \) is small, two receiving points can be easily placed inside the null area. A problem raises when \( \theta \) is large because the theoretical width of the null area on the propagation axis is zero. It is difficult to place properly inside such a small area. One solution is to enlarge the null area by controlling the propagation angle \( \varphi \) shown in Fig.2(ii); the receiving points are easily placed inside the null area even though \( \theta \) is large. This driving technique refer to Takeoka et al. [19], which proposes a parametric loudspeaker whose radiation direction is changeable by simple delay control synthesizing the surface wave-front. Based on their technique, two groups of the transducers on the right and left halves emit the out-of-phase signals with the propagation angle \( \pm \varphi \), respectively, as shown in Fig.2(ii). In this paper, \( \varphi \) is set to 0 and 2 degrees.
2.2 Acoustic filtering via phononic crystals

This technique, hereinafter called PhCs, is based on the use of the physical band-gap filter that reflects only a specific frequency sound and transmits the rest. PhCs form a periodic structure, as shown in Fig. 3. \(a, \, d, \) and \(\beta\) denote the distance between the scatterers, the diameter of the scatterer, and the incident angle, respectively. The center frequency of the \(n\)-th band-gap is given by

\[
f_c = \frac{nc}{2a \cos \beta}
\]

where \(c\) is the sound speed in air. PhCs built for this study based on Ji et al. is presented in Fig. 3(a). The center frequency of the first bandgap is set as 40 kHz, which is the resonant frequency of the parametric loudspeaker used. The PhCs built for this study consists of \(8 \times 80\) aluminum poles \((W320 \times H320 \times D38mm^2)\). The insertion loss (IL) in the 1/3 octave band is also shown in Fig. 4(b): it is about 13 dB in the 40 kHz band and below 3 dB in the audible frequency range. After transmission through PhCs, we can assume that the ultrasound is suppressed and no audible sound is generated.

\[\text{Figure 3: Schematic of PhCs.}\]

\[\text{Figure 4: PhCs and its frequency characteristics.}\]

3. In-situ measurement of acoustic impedance at oblique incidence

3.1 Experimental set-up

3.1.1 Geometrical relation and examination cases

As mentioned in Section II, our previous paper shows that the proposed method using the parametric loudspeaker and two techniques for reducing the pseudo sound is an effective way to estimate the acoustic
impedance of glass wool boards at frequencies above 800 Hz by reducing the diffraction from the sample edges and the pseudo sound. Since this method can be assumed to have the advantage to avoid the influence of extraneous sound waves due to the surroundings of the target material in-situ, its use is investigated in an seminar room (W7, 000 × D11, 400 × H2, 650mm²). A glass wool board with a density of 96 kg/m³, 15 mm thickness, and a size of 900 × 900mm² is used as the specimen (hereinafter, it is called GW96k). Three cases using the parametric loudspeaker and one case using a common loudspeaker (Mixcube pro, Avantone) are investigated: (1) PCE (\(\varphi = 0\)), (2) PCE (\(\varphi = 2\)), (3) PhCs (in-phase driving), and (4) Loudspeaker. As shown in Fig.5, the source position is placed 4,000 mm from the specimen and the incident angle \(\theta\) are 45 and 75 degrees. In case (3), PhCs is placed at 1,000 mm from the specimen on the propagation axis. The acoustic impedance of GW96k is determined via the two microphone method proposed by Allard et al. [5]. A pair of 1/2 inch microphones (Type 4197, B & K) is set as closely as possible to \(M_1\) and \(M_2\) with their spacing of 13 mm, as shown in Fig.5. The distance between the sample surface and \(M_1\) is 10 mm to ensure the effect of the finite dimensions of the specimen does not noticeably disturb the measurement [4] and the microphone does not touch the material surface not to be damaged.

![Figure 5: Geometrical relationship between the source, the receiving points, PhCs, and the specimen](image)

3.1.2 Measurement signal

The analysis is based on the impulse response obtained from swept-sine signal. The audible sound pressure generated by the parametric loudspeaker is proportional to \(f^2\), theoretically [15]. Thus, a logarithmic swept-sine signal, for which the sound pressure at low frequencies is superior, is used to assure audible sound pressure high enough in the low frequency range for the parametric loudspeaker. For the loudspeaker, linear swept-sine signal is used.

3.2 Results and discussion

3.2.1 Impulse response

Fig.6 shows impulse responses measured at \(M_1\) at \(\theta = 45\) degrees. The red arrow indicates the direct sound and that reflected from the specimen, which are the main response needed for the analysis. Since the parametric loudspeaker emit super-high pressure ultrasound, the impulse responses have pre-distortion due to the harmonic distortion [20], as shown in Fig.6(1) 0-10 ms. However, this can be removed in the time domain and kept from influencing the main response. When extracting the main
response from the overall impulse response, its length must be long enough to include both the direct sound and that reflected from the specimen [2]. In case (4) Loudspeaker, the undesired reflections from the surroundings overlap with the main response, as shown in Fig. 6(4). On the other hand, in cases (2) to (3), such undesired reflections do not appear and the main response is easily identified in the time domain, as shown in Fig. 6(1) to (3). In spite of some reflections, for example, Fig. 6(2), they can be easily removed because they do not overlap with the main response. Thus, the super-directivity of the parametric loudspeaker enables us to avoid the undesired reflections from the surroundings. This is also a great advantage in practical use as it simplifies the analysis.

![Figure 6: Impulse responses measured in-situ (θ = 45).](image)

### 3.2.2 Acoustic impedance

Fig 7 shows the acoustic impedance in cases (1) to (3) at frequencies 0.8 to 4.5 kHz. The red bold line and black thin line denote real and imaginary parts of the acoustic impedance, respectively. The measured results of a sufficiently large specimen are used as the references (broken lines): it is the results for a 2,100 × 2,300mm² sample, measured with the loudspeaker at 1,000 mm from its center point. The distance between two microphones and that between the sample surface and \( M_1 \) are 13 mm and 10 mm, following [5, 11]. Given the short distance between the source and specimen, the spherical-wave approximation proposed by Allard et al. [9] is applied to the data.

All results do not have fluctuations due to the reflections from other surfaces because of the super-directivity of the source. When the incident angle \( \theta \) is 45 degrees, in cases (1) to (3) applying the techniques for reducing the pseudo sound, such spuriously high values is decreased and both results show a good agreement with the reference data, as shown in Fig. 7(1-a), (2-a), and (3-a). Case (3) PhCs (in-phase driving) also agree well with the reference data when \( \theta \) is 75 degrees. However, in case (1) PCE (\( \phi = 0 \)), the result is affected by the pseudo sound due to the difficulty to place both receiving points inside the null area, where the ultrasound is suppressed, as shown in Fig. 7(1-b). This problem is solved in case (2) PCE (\( \phi = 2 \)) by widening the null area, even though the incident angle is large, as shown in Fig. 7(2-b). Thus, the proposed methods using two techniques can accurately estimate the acoustic impedance at frequencies 0.8 to 4.5 kHz without being deteriorated by the undesired waves and the pseudo sound.

### 4. Conclusion

A measurement method of acoustic impedance of a porous material by using a parametric loudspeaker is investigated in in-situ condition. It is confirmed that its super directivity can avoid undesired
reflection from the surroundings of the target material. A typical problem when using the parametric loudspeaker is the error induced by the pseudo sound, which is a nonlinear distortion on the microphone membrane. Two techniques, acoustic filtering via phononic crystals and phase-cancellation excitation of the ultrasound source signal, are investigated to reduce this influence. The proposed methods using the parametric loudspeaker with these two techniques enable us to accurately estimate the acoustic impedance of the target material by reducing the pseudo sound at frequencies above 0.8 kHz. However, further investigation is needed to evaluate the measurement accuracy at frequencies below 0.8 kHz. In addition, the applicability of the proposed methods will be investigated regarding the geometrical relation, types of materials, and so on.

REFERENCES


