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In Situ Measurement of the Absorption Coefficient Based on a Time-Domain Subtraction Technique with a Particle Velocity Transducer

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Summary

Subtraction techniques for *in situ* measurement of the absorption coefficient have been proposed and tested using sound pressure signals. This paper is concerned with the subtraction technique based on the particle velocity measurement. In the method, the acoustic impulse response of the absorbing material surface under test is first measured with a particle velocity transducer, then the direct and reflected waves in the impulse response are separated by the signal subtraction technique in the time domain, and finally the absorption coefficient of the surface under test is obtained with a fast Fourier transform based post-processing algorithm. Three types of material have been tested in both a hemi-anechoic chamber and an office room: a perfectly reflecting plane, a thick polyurethane foam with high absorption property, and a thin polyurethane foam with medium absorption property. The absorption coefficient at normal incidence obtained from the method based on the particle velocity measurement has been compared with the result obtained from the method based on the sound pressure measurement. The investigation shows that the method based on the particle velocity measurement can be used to measure the absorption coefficient *in situ* and has better immunity to the disturbing reflections than the method based on the sound pressure measurement. However, its performance is sensitive to the vibration generated by the loudspeaker, which is not as prominent for the method based on the sound pressure measurement.

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1. Introduction

Absorbing materials are widely used for noise control in many sites, like in a room, a vehicle and urban areas. The absorbing properties of these materials are generally characterized by reflection factor or absorption coefficient. So far, there are many methods having been developed to measure these parameters. Among them, the well-known impedance tube method [1, 2] can give reliable results over a wide frequency range. However, the frequency range is limited by the dimensions of the impedance tubes and a small sample needs to be cut carefully from the original absorbing material and mounted with an artificial fixation, which makes the method not suitable for freely vibrating poroelastic material [3].

The free-field or *in situ* measurement methods [4] have been proposed to overcome the above problems of sample mounting. Allard *et al.* proposed the well-known transfer function method [5, 6] using the sound pressures at two points (PP-method) near the surface of the absorbing material under test. After the new type of probe, *microflown* [7] which can measure the particle velocity directly, was invented, the transfer function methods using the sound pressure and the particle velocity at one point [8, 9, 10, 11, 12, 13] (PU-method) or the particle velocities at two points [14] (UU-method) have been proposed and compared with the PP-method. Hirosawa *et al.* showed that the PU-method is most stable against the effect of specimen area and the UU-method is easily affected by that effect [14]. Besides, Tamura *et al.* proposed a method [15, 16, 17, 18] for measuring the reflection factor at oblique incidence in free-field. The method involves the measurements of sound pressure on two planes parallel to the surface of the material, and the reflection factor is obtained by separating the incident and reflected sounds with the use of two-dimensional spatial Fourier transform. Bi *et al.* [19] further investigated the performance of the method when the input data was changed to the particle velocity. It was shown that the method based on the particle velocity measurement leads to better results than the method based on the sound pressure measurement when the flow resistivity of the material under test is large or the

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frequency is high. The pulse-echo method [20] is another well-known free-field or *in situ* measurement method. The impulse response of the surface of the material is measured using an impulsive sound [21, 22, 23] or a broadband stationary sound with signal processing techniques [24, 25, 26, 27, 28, 29, 30, 31]. The direct and reflected sounds, included in the impulse response of the surface, are separated and the disturbing reflections are removed by the signal subtraction [27] or the temporal separation [28] technique in the time domain. After Fourier transform of both the direct and reflected signals, the reflection factors are obtained by dividing the spectrum of the reflected signal by that of the direct signal. Many studies have been done on this method. However, all of them were based on the sound pressure measurement.

The purpose of this paper is to investigate the performance of the pulse-echo method using the signal subtraction technique (hereinafter referred to as time-domain subtraction technique) based on the particle velocity measurement. Different from the sound pressure, the particle velocity is a vector; and the *microflown*, the sensor used for measuring the particle velocity, is bi-directional. Therefore, it is expected that the method based on the particle velocity measurement is less affected by the disturbing reflections, especially for measuring the absorption coefficient at normal incidence.

This paper is organized as follows. Section 2 describes the principle of the time-domain subtraction technique briefly and the measurement set-up. From Section 3.1 to Section 3.3, the feasibility of the time-domain subtraction technique based on the particle velocity measurement is investigated through experiments carried out in the hemi-anechoic chamber. In Section 3.4, the immunity of the proposed method to the disturbing reflections is analyzed. And, the performance *in situ* is given in Section 3.5. Finally, some conclusions are given in Section 4.

2. The measurement method

2.1. The principle of the measurement method

Figure 1a shows a schematic of the measurement set-up for the time-domain subtraction technique. A loudspeaker is used to acoustically excite the surface of the material under test. A probe (microphone or *microflown*) located between the sound source and the surface measures both the direct sound from the loudspeaker to the material surface and the reflected sound from the material surface. The impulse response of the material surface under test is obtained in the time domain. The overall impulse response h_m as shown in Figure 1b can be written as

$$h_m(t) = h_i(t) + h_r(t) + h_d(t), \tag{1}$$

where $h_i(t)$ is the impulse response of direct sound, $h_r(t)$ is the impulse response of reflected sound, $h_d(t)$ is the response of the disturbing reflections.

The impulse response of the direct sound $h_i(t)$ is obtained from a free-field measurement, where the probe is placed far away from any reflective surface. The impulse response of the reflected sound $h_r(t)$ is obtained by subtracting the impulse response of the direct sound $h_i(t)$ from the overall impulse response $h_m(t)$ and gating out the response of the disturbing reflections. In practice, the overall impulse response also contains the influence of background noise, but its effect can be reduced by the proper impulse response measurement technique [32]. After Fourier transformation of the impulse responses of the direct and reflected sounds, the transfer functions of direct path $H_i(f)$ and reflected path $H_r(f)$ are obtained. The reflection factor $R(f)$ in the frequency domain is calculated as follows.

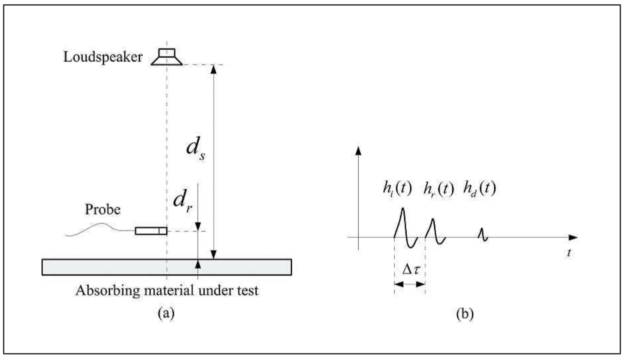

Figure 1. (a) Schematic of the measurement set-up for the time-domain subtraction technique; (b) Schematic of the overall impulse response.

For sound pressure measurement [27],

$$R(f) = \frac{d_s + d_r}{d_s - d_r} \cdot \frac{H_{pr}(f)}{H_{pi}(f)} \cdot \mathrm{e}^{\mathrm{j}2\pi f \Delta\tau}, \tag{2}$$

where d_s is the distance between the loudspeaker and the surface under test, d_r is the distance between the probe and the surface under test, $H_{pi}(f)$ is the sound pressure transfer function of the direct path, $H_{pr}(f)$ is the sound pressure transfer function of the reflected path, j denotes the imaginary unit, $\mathrm{j} = \sqrt{-1}$, and $\Delta\tau$ is the time delay between the direct sound and reflected sound,

$$\Delta\tau = \frac{2d_r}{c}, \tag{3}$$

where c is the sound speed in air.

For particle velocity measurement (see the Appendix),

$$R(f) = -\frac{\mathrm{j}k_0(d_s - d_r) + 1}{\mathrm{j}k_0(d_s + d_r) + 1} \frac{(d_s + d_r)^2}{(d_s - d_r)^2} \frac{H_{vr}(f)}{H_{vi}(f)} \mathrm{e}^{\mathrm{j}2\pi f \Delta\tau}, \tag{4}$$

where $k_0 = 2\pi f/c$ is the wavenumber in air, $H_{vi}(f)$ is the particle velocity transfer function of the direct path, and $H_{vr}(f)$ is the particle velocity transfer function of the reflected path.

The sound absorption coefficient is given by

$$\alpha(f) = 1 - \left|R(f)\right|^2, \tag{5}$$

when it is assumed that there is no transmission through the material (for example if the material is mounted over a rigid surface).

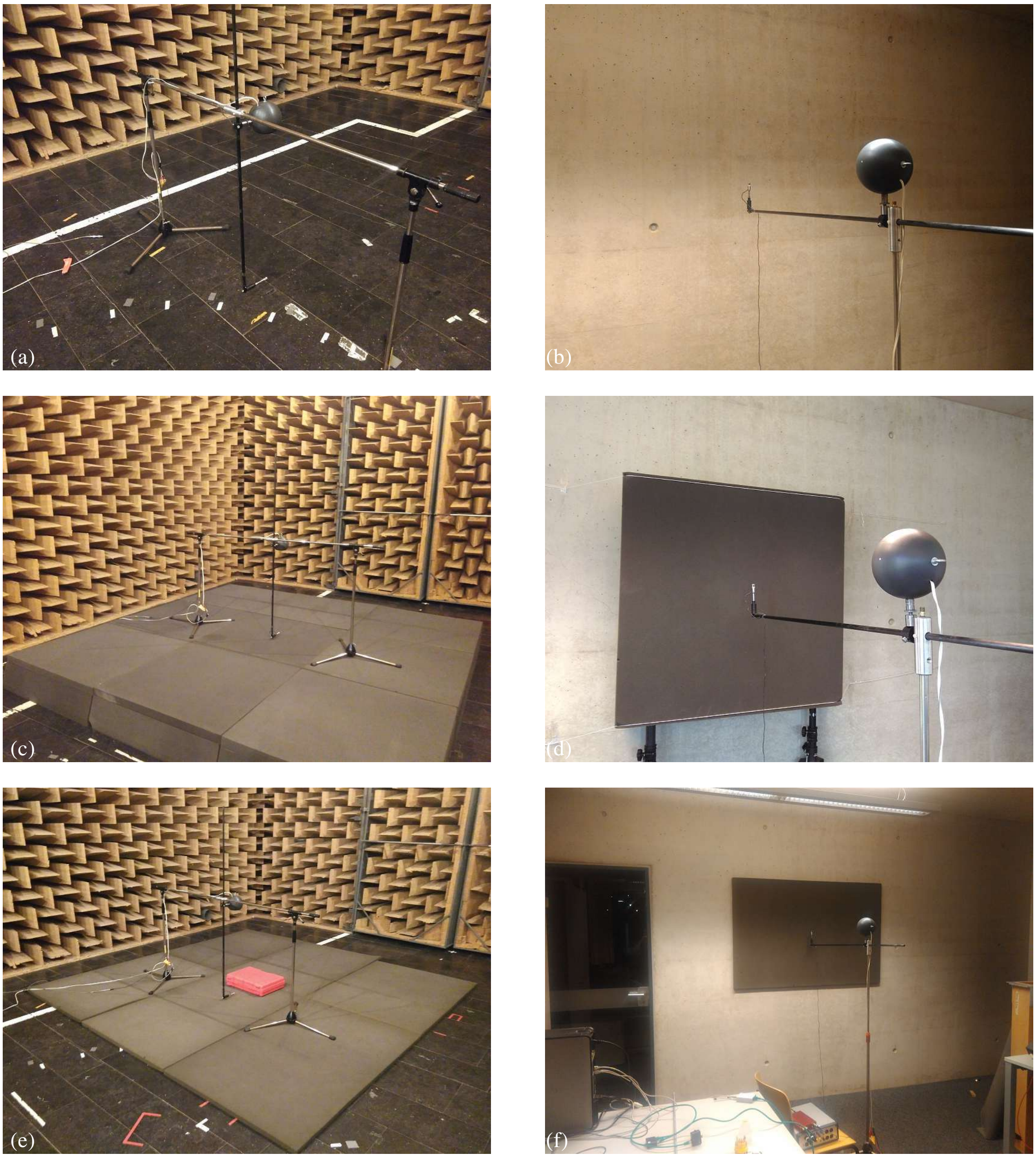

Figure 2. (Colour online) Measurement structures: In the hemi-anechoic chamber,(a) Rigid surface; (c) Thick foam (e) Thin foam; In the office room, (b) Rigid surface; (d) Thick foam (f) Thin foam.

2.2. The measurement set-up

The measurement system used in this paper basically consists of a Personal Computer, a 24-bit sound card, a loudspeaker mounted on a spherical baffle with a diameter of 12 cm, and a *PU-mini* (usually called *pu-probe*) by Microflown, which consists of a *microflown* particle velocity sensor and a Knowles FG pressure sensor. Two structures were built for the measurement in a hemi-anechoic chamber and an office room, respectively, as shown in Figure 2.

The impulse responses of the sound pressure and particle velocity were measured by exponential sweep technique for improving the signal to noise ratio at low frequency and reducing the harmonic distortions due to the small nonlinearity of the measurement system. The length of the exponential sweep signal was 5.461 s. Besides, the signal to noise ratio was further improved by averaging over 5 measurements for both the sound pressure and particle velocity impulse responses.

The loudspeaker and probe were both fixed on a carbon fiber tube with a diameter of 1cm as shown in Figure 2 in order to keep the distance between the loudspeaker and probe strictly constant during the two measurements (free-field and material measurements), for realizing a better elimination of direct impulse response. The distance from the *pu-probe* to the loudspeaker and the surface un-

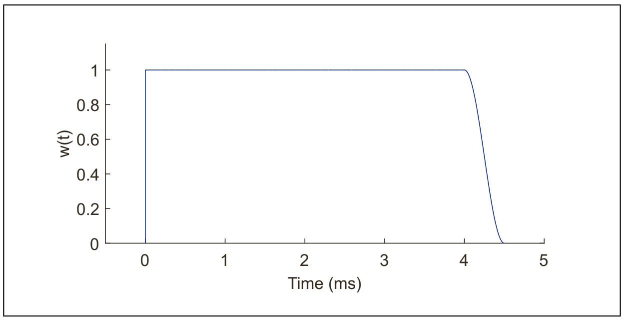

Figure 3. (Colour online) Plot of the time window used.

der test was 75.0 cm and 2.0 cm, respectively. In addition, the half-hanning window as seen in Figure 3, was used for gating out the disturbing reflections from objects nearby, like stands and loudspeaker. The length of the time window was chosen as 4.5 ms. Thus, the low-frequency limit was 222 Hz. The sampling frequency was 96 kHz, which was high enough to capture the shape of the impulse response properly.

The measurements have been carried out in both the hemi-anechoic chamber and office room. Three types of material have been tested: a perfectly reflecting plane, a 253-mm-thick polyurethane foam with high absorption property, and a 30-mm-thick polyurethane foam with medium absorption property. In the hemi-anechoic chamber, the perfectly reflecting plane was the rigid floor of the hemi-anechoic chamber as shown in Figure 2a. The foams were directly placed on the floor. The total surface area of the 253-mm-thick and 30-mm-thick polyurethane foams were both 9 m^2, formed by 9 small samples with 1 m by 1 m and 6 small samples with 1.5 m by 1 m, respectively, as shown in Figures 2c and 2e. The area was large enough to eliminate the influence of the edge effect, in order to start the investigation with a nominally infinite sample size. In the office room, the perfectly reflecting plane was a concrete wall of the room as shown in Figure 2b. The foam was directly placed on the concrete wall. However, only one sample was used in this case as shown in Figures 2d and 2f.

2.3. The impulse response of velocity

For the time-domain subtraction technique based on the sound pressure measurement, the length of the impulse response of the loudspeaker under the free-field condition is recommended not to be larger than 2 ms [20]. This is easily achieved by using a loudspeaker with a smooth frequency response or using the pre-filtering technique [33]. Figure 4a shows the normalized (divided by the maximum absolute value) direct (free field) pressure impulse response of the loudspeaker shown in Figure 2. This response is actually the convolution of the radiating transducer (loudspeaker) with the receiver transducer (electret microphone). It can be seen that its length is around 1.5 ms, which means that the loudspeaker used has a quite smooth frequency response and an almost zero phase, and the combination with the microphone frequency response introduces no additional drawback. However, the length of the direct velocity impulse response of the same loudspeakers is longer around 7 ms as shown in Figure 4b, which can be interpreted as an effect of the frequency response of the particle velocity probe and the connected analogue hardware. The velocity impulse response can be shortened by using the filter in the signal conditioner of the *pu-probe* (using the mode "correction on" which makes the frequency response of the particle velocity probe flat, see the manual of the signal conditioner MFSC-2 [34]) as shown in Figure 4c. Nevertheless, using the filter exaggerates the small harmonic distortion at the beginning of the velocity impulse response. It should be noted that all direct impulse responses above were measured in the hemi-anechoic chamber in the case where there is no mechanical connection between the loudspeaker and *pu-probe*, in order to eliminate the potential influence of the vibration generated by the loudspeaker.

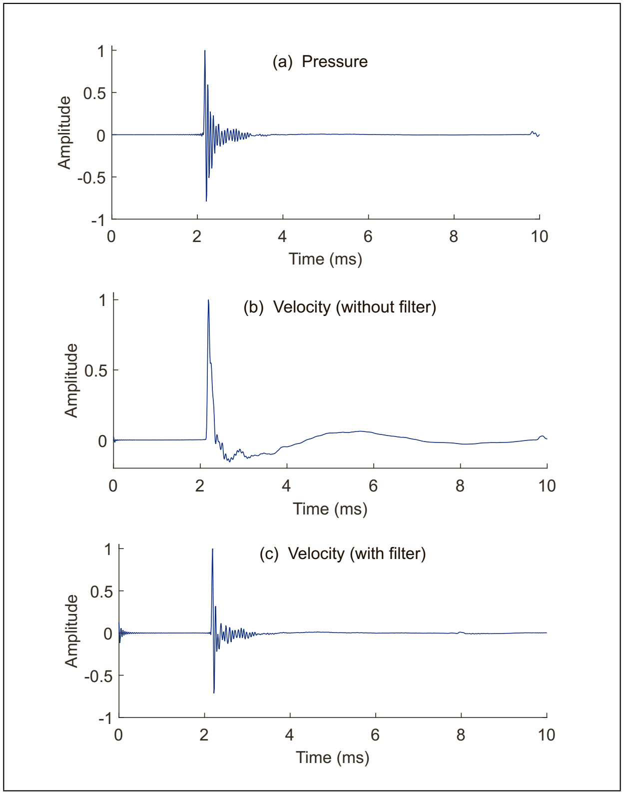

Figure 4. (Colour online) The normalized direct impulse of the loudspeaker under free-field condition: (a) pressure; (b) velocity without filter (c) velocity with filter.

3. Measurement results

3.1. The rigid floor

Figure 5 shows the normalized pressure and velocity impulse responses (cropped by the time window) of the rigid floor of the hemi-anechoic chamber (11 m × 5.97 m × 4.5 m). It can be seen that both direct impulse responses have been eliminated well by subtraction. Then the re-

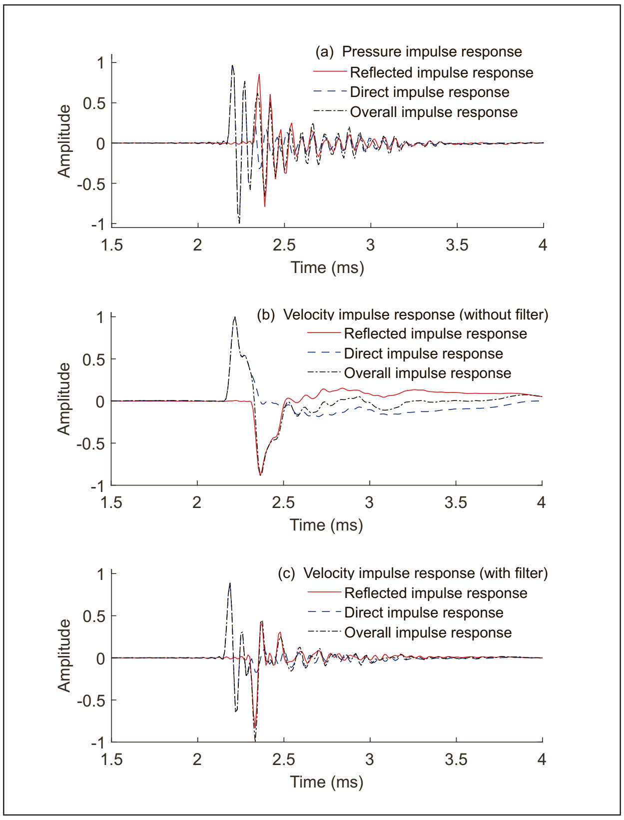

Figure 5. (Colour online) The normalized impulse responses of rigid floor: (a) pressure (b) velocity without filter (c) velocity with filter.

flected impulse responses obtained can be further used to calculate the absorption coefficient in the post-processing.

Figure 6 shows the reflection factors (modulus) of the rigid floor calculated by the time-domain subtraction techniques based on the measurement of sound pressure and particle velocity (hereinafter referred to as P-method and V-method). It should be noted that, for the rigid floor, the modulus of the reflection factors instead of absorption coefficients were given for the convenience of showing the results more clearly. The rigid floor can be considered as the perfectly reflecting plane. Thus, the theoretical modulus value of reflection factor for the rigid floor should be one. It can be seen that the results for the V-method are quite close to the theoretical value at frequencies from 1 kHz to 5 kHz. However, there are relatively large oscillations at frequencies below 1 kHz. When using the filter, the results are similar to the former ones, still having relatively large oscillations at frequencies below 1 kHz. Thus, the oscillation should not be due to the long length of direct velocity impulse response. The reason could be the vibration generated by the loudspeaker which would affect the direct impulse response. It is assumed that the reflected impulse response was not influenced by this because both direct and overall impulse responses contained the same distortion by the vibration and would be cancelled through subtraction. Since the results for the V-method with and without the filter are in a good agreement, especially at frequencies larger than 1 kHz, only the results for the V-method without the filter are given in the following.

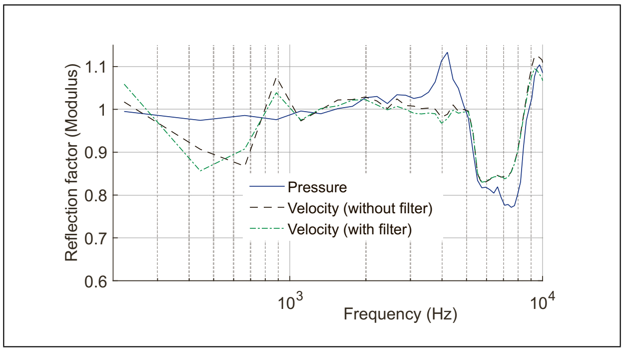

Figure 6. (Colour online) Reflection factors (modulus) of the rigid floor calculated by the P- and V-methods in the hemi-anechoic chamber.

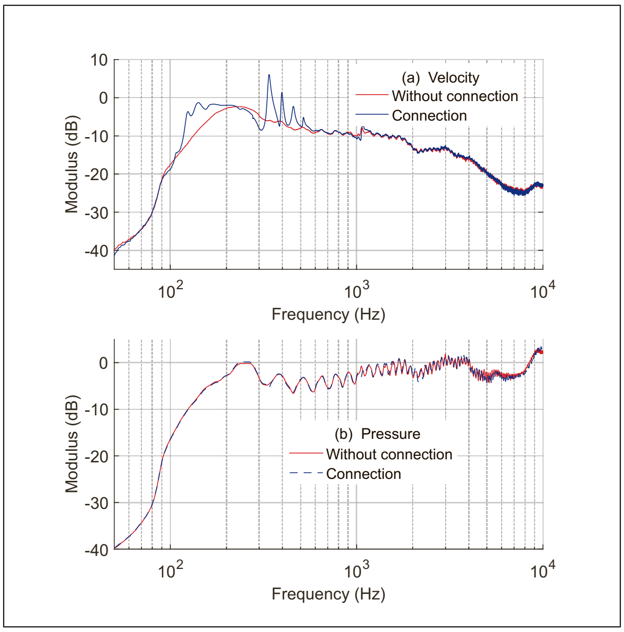

Figure 7. (Colour online) Comparison of the direct frequency responses between the cases with and without the mechanical connection between the loudspeaker and *pu-probe* : (a) velocity (b) pressure.

In order to validate the explanation above, the comparison of the direct velocity and pressure frequency responses between the cases with and without the connection between the loudspeaker and *pu-probe* have been made as illustrated in Figure 7. The obvious resonances could be seen in the velocity frequency response at frequencies below 600 Hz when the loudspeaker and *pu-probe* were connected through a carbon fibre tube. For pressure frequency responses, there is no obvious deviation found. The difference between the performances of velocity and pressure on avoiding the influence of structure-borne vibration should be ascribed to the different measuring principles of velocity and pressure sensors. It should be noted that better results of the V-method at low frequencies could be obtained if a suspension system [35] that decouples the loudspeaker from the probe is used.

Due to suffering rare effect from the vibration generated by the loudspeaker, the P-method leads to a relatively flat curve at frequencies below 1 kHz as seen in Figure 6. However, there appears a peak around 4.2 kHz and large deviation from the theoretical value at frequencies larger than 5 kHz. The large deviation can be also found in the results of the V-method at frequencies larger than 5 kHz. The reason should be the relatively large back-scattering effect of the *PU-mini* probe. The similar phenomena have also been found by Müller-Trapet *et al.* [13]. The scattering effect described above would be reduced for materials with higher absorption which can be seen in the following.

3.2. Thick polyurethane foam

Figure 8 shows the absorption coefficients of the thick polyurethane foam calculated by the P- and V-methods, together with the results predicted by the theoretical Delany-Bazley model [36].The flow resistivity of the thick polyurethane foam is 5.4 kPa·m^{-2} [18]. It can be seen that the results for the V-method agree with the values predicted by the theoretical model. The oscillations at frequencies below 1 kHz become small. As mentioned above, the reflected impulse response is not influenced by the vibration. Thus, only the denominator of Equation (4) suffers from the distortion by the vibration. For materials with high absorption, the numerator of Equation (4) is small and the distortion of denominator has a less quantitative effect on the final value in comparison with the case with large numerator, which corresponds to the highly reflective surface. The results for the P-method also agree with the values predicted by the theoretical model.

3.3. Thin polyurethane foam

Figure 9 shows the absorption coefficients of the thin polyurethane foam calculated by the P- and V-methods. It can be seen that the results for the V-method are in accord with those for the P-method at frequencies larger than 1 kHz, and the oscillations at frequencies below 1 kHz are larger than those of the thick foam but smaller than those of the rigid floor, because, as explained above, the absorption property of the thin foam is lower than that of the thick foam, but higher than the rigid surface.

From the analysis above, it could be concluded that the time-domain subtraction technique based on the particle velocity measurement could be used to measure the absorption coefficient. However, its performance is sensitive to the vibration generated by the loudspeaker at low frequencies, which could be solved by using a suspension system [35].

3.4. The immunity to the disturbing reflections

The particle velocity sensor is bi-directional. When the sensor is oriented to the normal of the surface under test and positioned near to the surface, less sound information would be detected at oblique direction. Therefore, it is expected that the method based on the particle velocity measurement has better immunity to the disturbing reflections. In order to investigate this matter, a plastic box (44.9 cm × 36.1 cm × 10.7 cm) acting as a scattering object was placed close to the *pu-probe* as shown in Figure 2d. The nearest distance between the *probe* and the point on the box is around d_o = 30 cm as shown in Figure 10. Figure 11 shows the reflection factors (modulus) of the rigid floor calculated by the P- and V-methods with the scattering object put nearby in the hemi-anechoic chamber. It can be seen that the results for the V-method have not changed much. In contrast, large deviations can be found on the re-

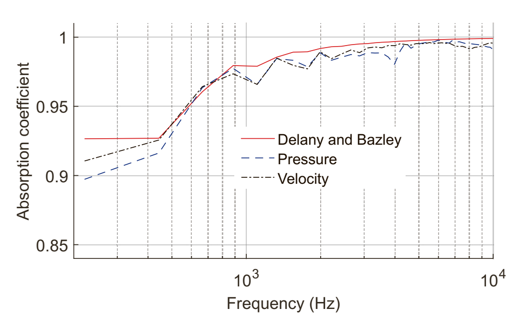

Figure 8. (Colour online) Absorption coefficients of the thick polyurethane foam calculated by the P- and V-methods in the hemi-anechoic chamber.

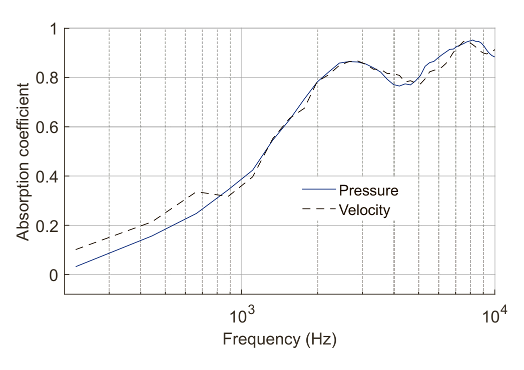

Figure 9. (Colour online) Absorption coefficients of the thin polyurethane foam calculated by the P- and V-methods in the hemi-anechoic chamber.

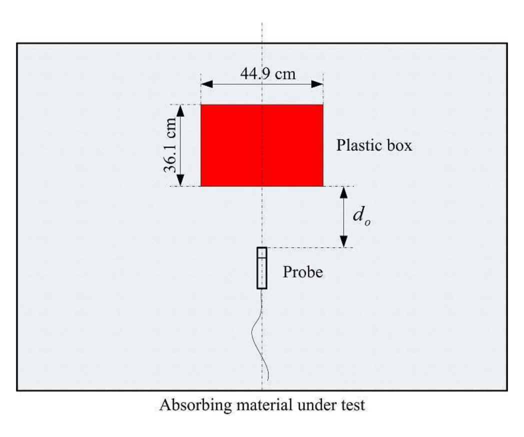

Figure 10. (Colour online) Schematic of the arrangement of the scattering box (vertical view).

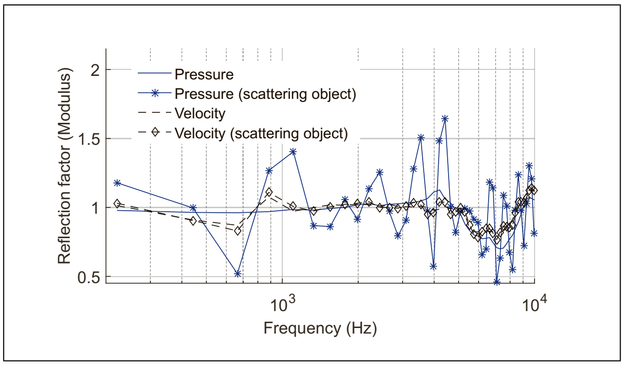

Figure 11. (Colour online) Reflection factors (modulus) of the rigid floor calculated by the P- and V-methods with the scattering object put nearby in the hemi-anechoic chamber.

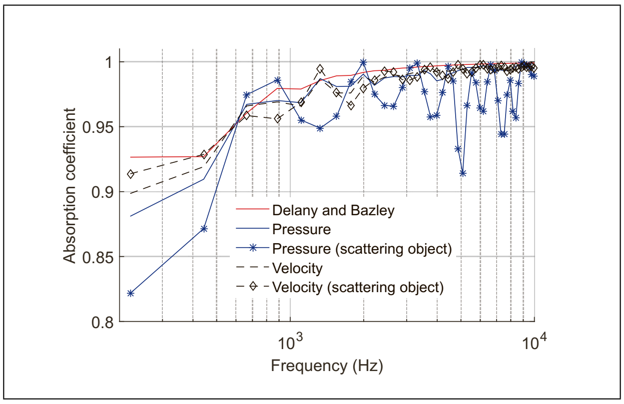

Figure 12. (Colour online) Absorption coefficients of the thick polyurethane foam calculated by the P- and V-methods with the scattering object put nearby in the hemi-anechoic chamber.

sults for the P-method. The similar phenomenon can be seen in Figures 12 and 13, which show the results for the P- and V-methods in the cases where the surface under test are thick and thin polyurethane foams, respectively. The results above show that the time-domain subtraction technique based on the particle velocity measurement does have better immunity to the disturbing reflections, which is in agreement with expectation. Figure 14 further shows reflection factors (modulus) of the rigid floor calculated by the V-method with the plastic box put on different positions. It can be seen that the acceptable results could still be obtained even though the box was just placed 20 cm away from the *pu-probe*.

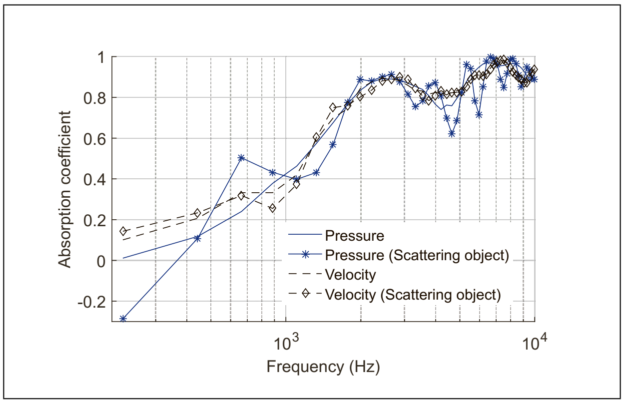

Figure 13. (Colour online) Absorption coefficients of the thin polyurethane foam calculated by the P- and V-methods with the scattering object put nearby in the hemi-anechoic chamber.

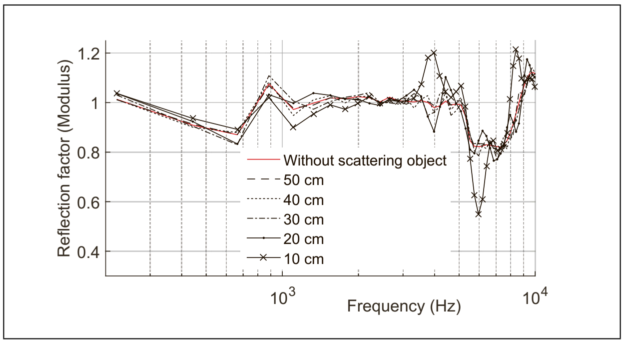

Figure 14. (Colour online) Reflection factors (modulus) of the rigid floor calculated by the V-method with the scattering object put on different positions in the hemi-anechoic chamber.

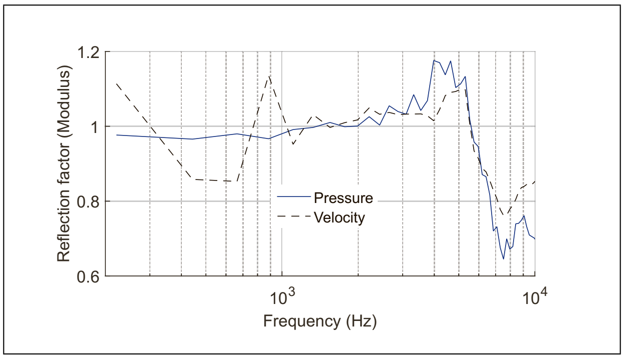

Figure 15. (Colour online) Reflection factors (modulus) of the concrete wall calculated by the P- and V-methods in the office room.

3.5. The performance in situ

Measurements have also been carried out in an office room as shown in Figure 2 to check the performance of the method based on the particle velocity measurement *in situ*. It should be noted that the structure used here is different from that used in the hemi-anechoic chamber. One stand instead of two was used to support the part of loudspeaker-to-probe as can be seen in Figure 2, because the latter one is not suitable for the measurement in the office room due to the different arrangement of material under test. Figures 15 to 17 show the results for the concrete wall, the thick polyurethane foam, and the thin polyurethane foam, respectively. It can be seen that the results are similar to those obtained in the hemi-anechoic chamber except for the larger deviation of the V-method at frequencies below 1 kHz. The background noise could be one minor reason for this, but it is believed that the major reason should be the greater influence of the vibration by the loudspeaker. It is reasonable that the one-stand structure would suffer more from the vibration generated by the loudspeaker. In spite of the larger deviation at lower frequencies, the

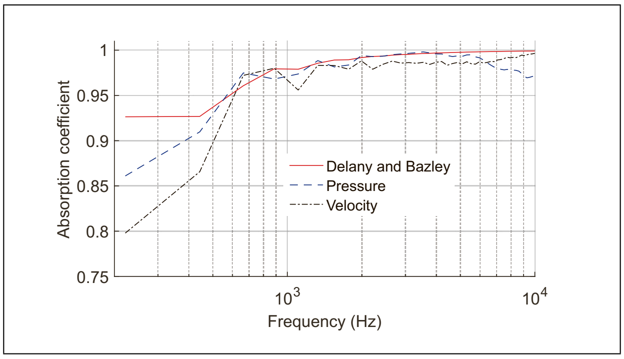

Figure 16. (Colour online) Absorption coefficients of the thick polyurethane foam calculated by the P- and V-methods in the office room.

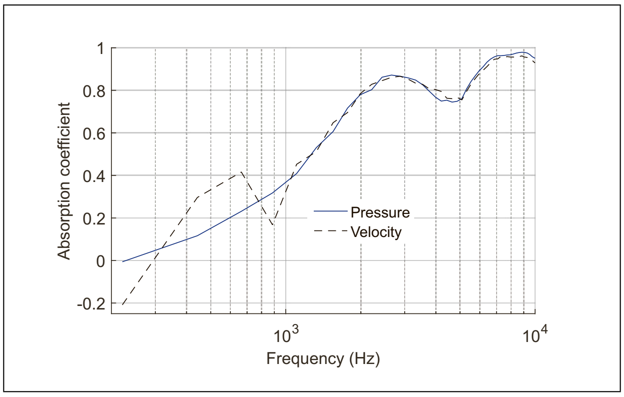

Figure 17. (Colour online) Absorption coefficients of the thin polyurethane foam calculated by the P- and V-methods in the office room.

satisfactory performance of the V-method at frequencies larger than 1 kHz could also be obtained in a common office room.

4. Conclusions

The present paper focuses on the time-domain subtraction technique for measuring the absorption coefficient when the input data is the particle velocity. In order to investigate its applicability, three types of material have been tested in the hemi-anechoic chamber: the perfectly reflecting plane, the thick polyurethane foam with high absorption property, and the thin polyurethane foam with medium absorption property. The results show that the time-domain subtraction technique based on the particle velocity measurement could be used to measure the absorption coefficient. However, its performance is sensitive to the vibration generated by the loudspeaker at low frequencies. Besides, it has been shown that the time-domain subtraction technique based on the particle velocity measurement has better immunity to disturbing reflections in comparison with the method based on the sound pressure measurement. The measurements have also been conducted in an office room to check its performance *in situ*. Similar conclusions could be obtained as those in the hemi-anechoic chamber. In future, a structure incorporating a suspension system that decouples the loudspeaker from the probe will be designed and manufactured. This structure will then be used to investigate the possibility of decreasing the low-frequency limit. And, the investigation of the method for measuring the absorption coefficient at oblique incidence will be done.

Appendix

For a point source, the time-domain Green's function of sound pressure $h_p(t)$ (also called pressure impulse response) in free field can be represented as

$$h_p(t) = \frac{\delta(t - d/c)}{d}, \tag{A1}$$

where δ denotes the Dirac delta function, and d is the distance between the sound source and the receiver. Thus the derivative of the radial particle velocity impulse response with respect to the time, $\partial h_v(t)/\partial t$, at the receiver point can be represented as

$$\begin{aligned} \frac{\partial h_v(t)}{\partial t} &= \frac{-1}{\rho_0}\frac{\partial h_p(t)}{\partial d} \\ &= \frac{1}{\rho_0}\frac{\delta'(t - d/c)d/c + \delta(t - d/c)}{d^2}, \end{aligned} \tag{A2}$$

where ρ_0 is the air density and δ' denotes the derivative of the Dirac delta function. Using Equation (A2), one obtains

$$\frac{\partial h_{vi}(t)}{\partial t} = \frac{-1}{\rho_0}\frac{\delta'(t - \frac{d_s - d_r}{c})\frac{d_s - d_r}{c} + \delta(t - \frac{d_s - d_r}{c})}{(d_s - d_r)^2}, \tag{A3}$$

$$\frac{\partial h_{vr}(t)}{\partial t} = \frac{1}{\rho_0}\frac{\delta'(t - \frac{d_s + d_r}{c})\frac{d_s + d_r}{c} + \delta(t - \frac{d_s + d_r}{c})}{(d_s - d_r)^2} * r(t), \tag{A4}$$

where $*$ denotes the convolution operator, and $r(t)$ is the reflection factor of the surface under test in the time domain. After Fourier transformation of both sides of Equations (A3) and (A4), the following equations are obtained:

$$\mathrm{j}w\rho_0 H_{vi}(f) = \frac{-1}{(d_s - d_r)^2}\left[\mathrm{j}k_0(d_s - d_r) + 1)\right] \cdot \mathrm{e}^{-\mathrm{j}k_0(d_s - d_r)}, \tag{A5}$$

$$\mathrm{j}w\rho_0 H_{vr}(f) = \frac{1}{(d_s + d_r)^2}\left[\mathrm{j}k_0(d_s + d_r) + 1\right] \cdot \mathrm{e}^{-\mathrm{j}k_0(d_s + d_r)} R(f). \tag{A6}$$

Dividing Equation (A6) by Equation (A5), the reflection factor $R(f)$ can be calculated by

$$R(f) = -\frac{\mathrm{j}k_0(d_s - d_r) + 1}{\mathrm{j}k_0(d_s + d_r) + 1}\frac{(d_s + d_r)^2}{(d_s - d_r)^2}\frac{H_{vr}(f)}{H_{vi}(f)}\mathrm{e}^{\mathrm{j}2\pi f\Delta\tau}. \tag{A7}$$

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