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Measuring sound reflection coefficient using a directional speaker and two microphones: two applications cases

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Abstract

Using the classical two-microphone approach and a source-image model, this paper investigates the possibility of measuring sound reflection in two specific cases using a directional transducer instead of a classical loudspeaker or a point source (monopole). A first experiment aims at measuring the sound absorption of three materials at normal incidence in a reverberant room. A second experiment is made in a hemi-anechoic room for measuring the sound reflection on a honeycomb panel at oblique incidence. All obtained results depict good agreement with theoretical predictions. The use of a parametric speaker proves to be a solution for limiting influence of both room and sample dimensions, with satisfactory sound absorption measurement results even in highly reverberant environments on small specimen. A directional speaker also allows setting up tests under oblique incidence. Combining these two possibilities provide a basis for the development of *in situ* tests in complex sound environments and for variable incidence angles.

Key words: directional speaker, sound absorption coefficient, reverberant environments

Измерение коэффициента отражения звука с помощью направленного динамика и двух микрофонов: два случая применения

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Аннотация

В данной работе исследуется возможность измерения отражения звука в двух конкретных случаях с помощью направленного преобразователя вместо классического динамика или точечного источника (монополя) с использованием классического подхода с двумя микрофонами и модели мнимого источника. Первый эксперимент направлен на измерение звукопоглощения трех материалов при нормальном падении в реверберационной камере. Второй эксперимент состоит в полу-безэховой камере для измерения отражения звука на многослойную панель при косом падении. Все полученные результаты хорошо согласуются с теоретическими прогнозами. Применение параметрического динамика является решением вопроса об ограничении влияния размеров камеры и образца, с удовлетворительными результатами измерения звукопоглощения даже в среде с высокой реверберацией

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в уменьшенном масштабе. Направленный динамик также позволяет проводить испытания при косом падении. Комбинация двух этих возможностей создает основу для разработки испытаний в месте нахождения в сложных звуковых средах и переменных углах падения.

Ключевые слова: *направленный динамик, коэффициент поглощения звука, реверберационная среда.*

Introduction

Standardized sound absorption measurements consider either a normal incidence plane wave in an impedance tube [1] or a diffuse sound field in a reverberant room [2]. Arrangements or improvements of the impedance tube method so as to include oblique incidence angles were proposed nearly a century ago [3] or more recently with a multi-modal decomposition method [4]. On site (or *in situ)* methods at normal or oblique incidence have also been widely investigated for measuring sound absorption, reflection or impedance in non-laboratory environments. A review published in 2015 points out in its conclusion that '*new methods need to be developed in order to measure the in-situ surface impedance under more realistic conditions (e.g. in small cavities and under reverberant conditions, curved or irregular surfaces, etc.)*' [5].

The concept of directional (or parametric) loudspeaker was invented in the 60s [6], and is based on using an array of ultrasonic transducers for producing a highly directional audio beam using non-linear demodulation effects. Among other possible applications of this technology, several authors have proposed to use directional speakers for measuring sound transmission or absorption of materials. Castagnède et al. [7, 8] were the first to use a parametric loudspeaker for measuring absorption, transmission and dispersion of sound absorbing porous materials in the time domain using a single microphone, with very satisfactory results. Kuang et al. [9] then investigated the possibility of using a parametric loudspeaker to derive the diffuse-field absorption coefficient from a series of measurements made for different incidence angles. Plane wave propagation was assumed and the classical two-microphone method was used [10], with satisfactory results in the 1000-2500 Hz frequency range for a single test sample. A similar idea was used by Sugahara et al. [11] for characterizing materials under normal incidence in a hemi-anechoic room and in a conference quiet room, and it was shown that room and sample size effects could both be reduced. Finally, Romanova et al. [12] recently used a parametric loudspeaker with a sound intensity probe to measure sound absorption of a living green wall with promising results.

Compared with previously cited works, the main contribution of the present paper is to investigate the possibility of measuring sound reflection in a highly reverberant environment or for very specific materials (here a honeycomb structure). Reference measurements are all obtained using a parametric loudspeaker and the classical two microphone method. Three different materials are first characterized under normal incidence in a large reverberant room and a comparison is made with theoretical calculations and with measurements made using a monopole source. The reflection coefficient under oblique incidence of a honeycomb panel, a purely reactive material according to theory, is then measured in a hemi-anechoic room. The obtained measurement results are compared to theoretical ones.

1. Theoretical background

Let's consider a point source (i.e. omnidirectional or 'monopole' source) placed at a height z_s above a sound absorbing material of thickness h. Such kind of acoustic source can be characterized by its volume velocity q (in m^3/s) or volume acceleration $\dot{q}$ (in m^3/s^2). Two microphones denoted M1 and M2 are placed above the material sample at heights z_1 and z_2, respectively. Figure 1 depicts the general problem under consideration.

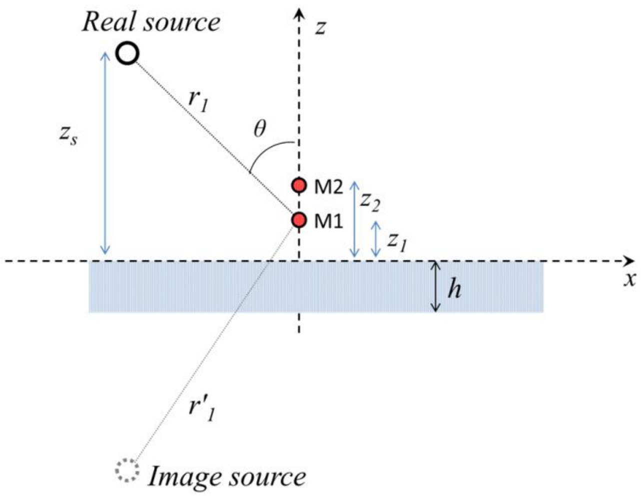

Fig. 1. Typical two-microphone experimental setup based on an image-source model

If the separation of the two microphones is small (so that the incidence angle is approximately equal at each) and for large values of $k_0\, r_j$ (r_j being the distance between the sound source and microphone j), the sound pressure p_j at microphone M_j (j=1,2) at angular frequency ω can be written as a superposition of two spherical fields

$$p_j(\theta,\omega) = \rho_o\, \dot{q} \left(\frac{e^{jk_0 r_j}}{r_j} + R(\theta,\omega) \frac{e^{jk_0 r'_j}}{r'_j} \right) \tag{1}$$

where ρ_0 is the air mass density, k_0 is the acoustic wave number (= ω/c_0, c_0 being the speed of sound), and $R(\theta,\omega)$ is the complex reflection coefficient at the surface of the sound absorbing material. Using the measured transfer function between the two microphones, $H(\theta,\omega) = p_2(\theta,\omega) \,/\, p_1(\theta,\omega)$, and Equation (1) allows calculating the reflection coefficient for a given incidence angle θ and at angular frequency ω [10]

$$R(\theta,\omega) = \frac{\frac{e^{jk_0 r_2}}{r_2} - H(\theta,\omega)\frac{e^{jk_0 r_1}}{r_1}}{H(\theta,\omega)\frac{e^{jk_0 r'_1}}{r'_1} - \frac{e^{jk_0 r'_2}}{r'_2}}. \tag{2}$$

From the result obtained with Equation (2), the sound absorption coefficient can be finally deduced using the relation $\alpha(\theta,\omega) = 1 - |R(\theta,\omega)|^2$.

2. Test case #1: measurements at normal incidence in a reverberant room

A first series of tests was conducted in a reverberant room which has a volume V of approximately 140 m^3 (7.5 m x 6.2 m x 3 m), and a mean reverberation time T of 5.5 s in the 200-1000 Hz frequency range. The reverberation radius r_r [13], for which the amplitude of direct and reflected sound is equal, is approximately 29 cm in this room for an omnidirectional source (using $r_r \approx 0.057\, (V/T)^{0.5}$). The Schroeder frequency f_c, above which the sound pressure field can be considered diffuse [14], is approximately 400 Hz (using $f_c = 2000(T/V)^{0.5}$). A parametric transducer (Soundlazer mini parametric board) and a monopole source (LMS mid-high frequency) were installed side-by-side at a height z_s = 2 m (see

Figure 2). The parametric transducer board is composed of 50 ultrasonic transducers of 10 mm diameter each.

Both sources were driven with a swept sine signal from 200 Hz to 3000 Hz, the 200 Hz cut-off frequency being linked to low frequency limitations of the sources. Two quarter inch microphones were placed above the material surface, at heights z_1 = 3.5 mm and z_2 = 33.5 mm (see Figure 1). The data were acquired using a LMS Testlab system, and the transfer function between the two microphones was post-processed so as to calculate the sound reflection according to Eq. (2). Small samples of three different sound absorbing materials were directly laid on the room's floor, with no specific mounting conditions (a thick glass wool, a thin compressed glass wool board and melamine foam with two thicknesses; the materials non-acoustic parameters were measured at GAUS labs; see details in Table 1). For the melamine foam of 1 in. thickness, two measurement positions were considered (see Figures 2 c) and 2d), respectively)

Table 1
Characteristic of the tested materials in the reverberant room under normal incidence

	Glass wool	**Compressed glass wool panel**	**Melamine foam**
Tortuosity (-)	1	1	1
Porosity (-)	0.99	0.96	0.98
Flow resistivity (Nsm^{-4})	4860	22200	7920
Viscous length (μm)	225	57	132
Thermal length (μm)	388	115	149
Foam mass density (kg/m^3)	10	66	6.1
Sample dimensions (length x width x thickness, in m)	1.24 x 0.35 x 0.095	1.24 x 0.61 x 0.025	1.3 x 0.7 x 0.025 0.8 x 0.5 x 0.013

In order to obtain a reference value for sound absorption under a normally incident acoustic plane wave, numerical simulations were done using the Transfer Matrix Method (TMM) [15]. Both materials are considered as laterally infinite layers of finite thickness on a hard backing, and modeled as rigid porous materials. The equivalent fluid model thus assumes that the skeleton of the material is rigid (the solid phase of the material remains motionless). The Johnson-Champoux-Allard material model was used in all cases [15].

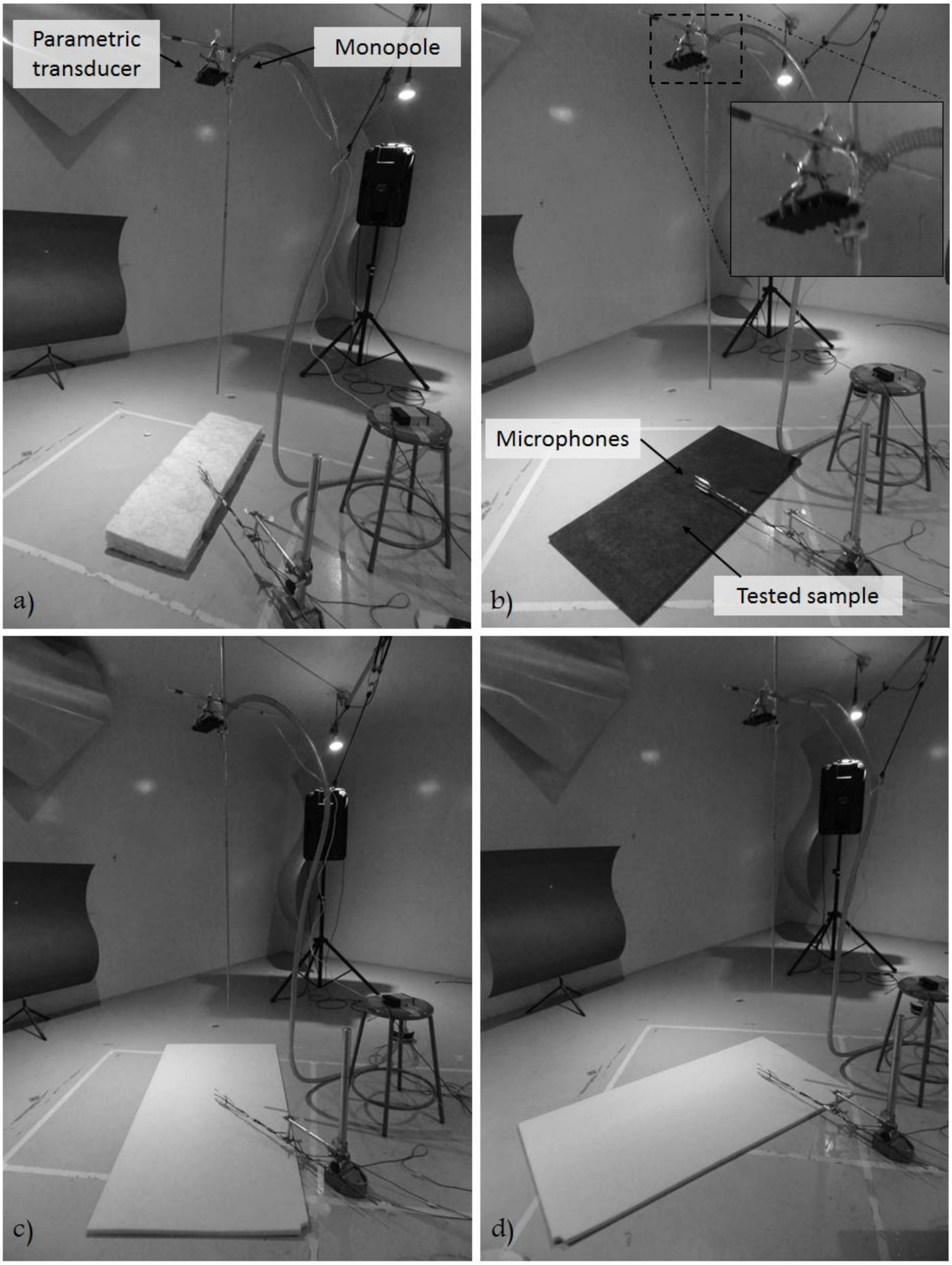

Fig. 2. Pictures of measurements in the reverberant room – a) Glass wool – b) Compressed glass wool panel – c) Melamine foam, 1-inch thick (position 1) – d) Melamine foam, 1-inch thick (position 2)

Measurement and simulation results are presented in Figs. 3-6 in terms of sound absorption coefficient for the glass wool, the compressed glass wool panel and the melamine foam with two thicknesses, respectively (values given in 1/12th octave frequency bands). For each tested material, the obtained results with the monopole source present an erratic behavior. Anomalous sound absorption values are obtained in a large part of the considered frequency band. These are values that are non-consistent with the simulation target or even negative, especially for a low sound absorption sample like the 0.5 in thick melamine foam, see Fig. 6. This can be attributed first to spurious sound reflections in the room and also to finite size effects of the sample (especially edge's effect).

When the parametric speaker is used, its directional properties allow focusing the sound energy on the material surface (and not on edges) and limiting the adverse effect of sound reflections. The sound absorption values obtained with the parametric speaker are in good agreement with the simulation results from 500 to 3000 Hz. The discrepancy seen below a frequency of approximately 500 Hz is attributed to the low-frequency limitations of sound sources. A larger microphone spacing would be also desirable so as to limit phase mismatch in low-frequency [10] that might have non-negligible influence below 1000 Hz. Finally, it is also known [10] that discrepancies are expected for low values of $k_0\, r$, since Eq. (2) rely on a spherical decoupling hypothesis which implies an approximation of the actual sound pressure field above the material surface.

The method also shows to be robust to the microphone positioning, as illustrated by the result given in Figure 5, with two measurement positions on the same sample, see Figure 2 c) and d). The results obtained at two positions using the parametric speaker are nearly superimposed above a frequency of 500 Hz. Using the monopole source, the results obtained are not coherent with the theoretical result, and not even coherent between the two measurement points.

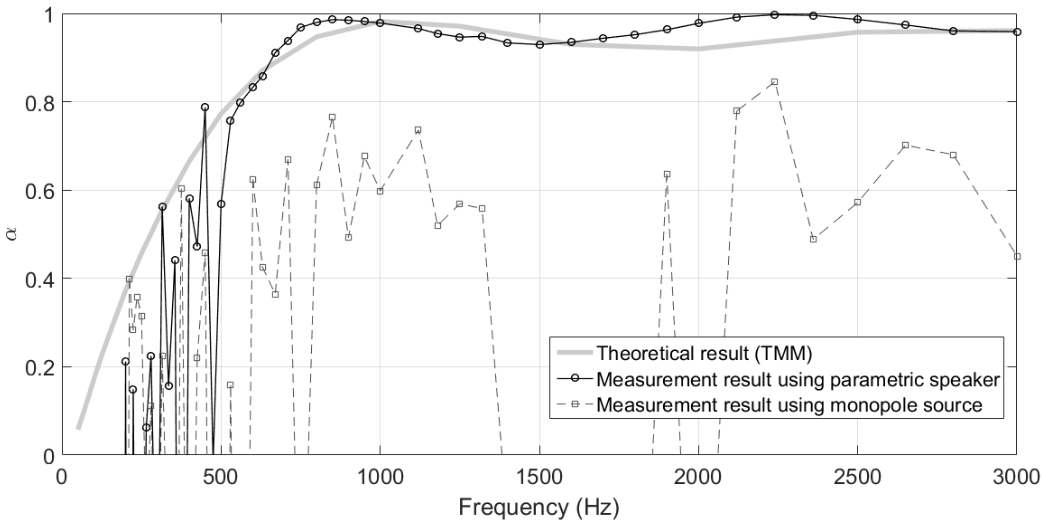

Fig. 3. Measurement and simulation results for the glass wool

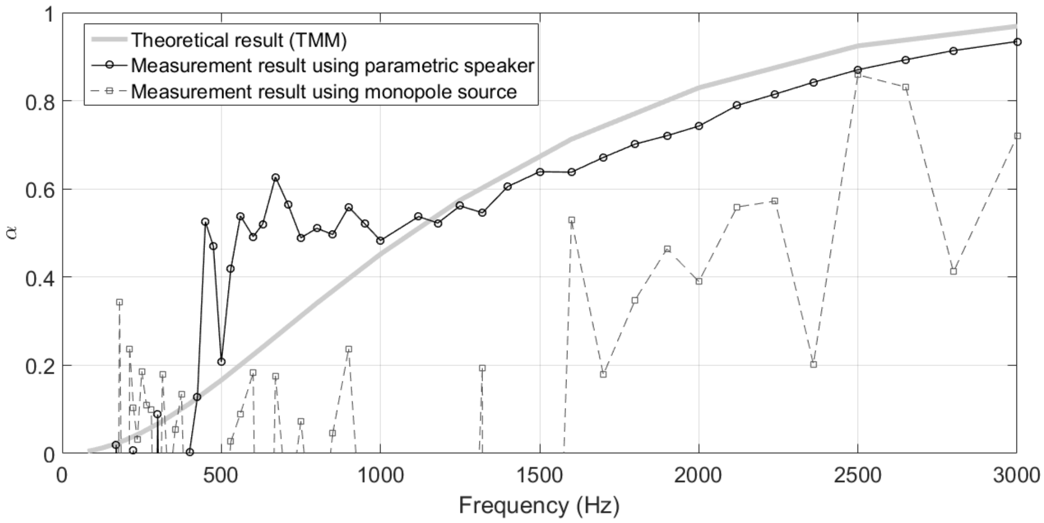

Fig. 4. Measurement and simulation results for the compressed glass wool panel

The discrepancy between measurement and simulation results in the 500 – 1000 Hz range for the compressed glass wool panel and for the 1-inch thick melamine foam (25.4 mm) is attributed to possible movement of the material's frame, since it was directly laid on the floor of the reverberant room with no back-adhesive (the rigid backing condition using in simulation might thus be not fully verified in practice). As pointed out by Sugahara et al. [11], this could also be linked to the so-called 'pseudo-sound' (a spurious signal generated by nonlinearity effects), but this effect contaminated their measurements up to a frequency of 1.5 kHz. Nevertheless, the obtained results in this harsh acoustic environment and for such small samples are very promising.

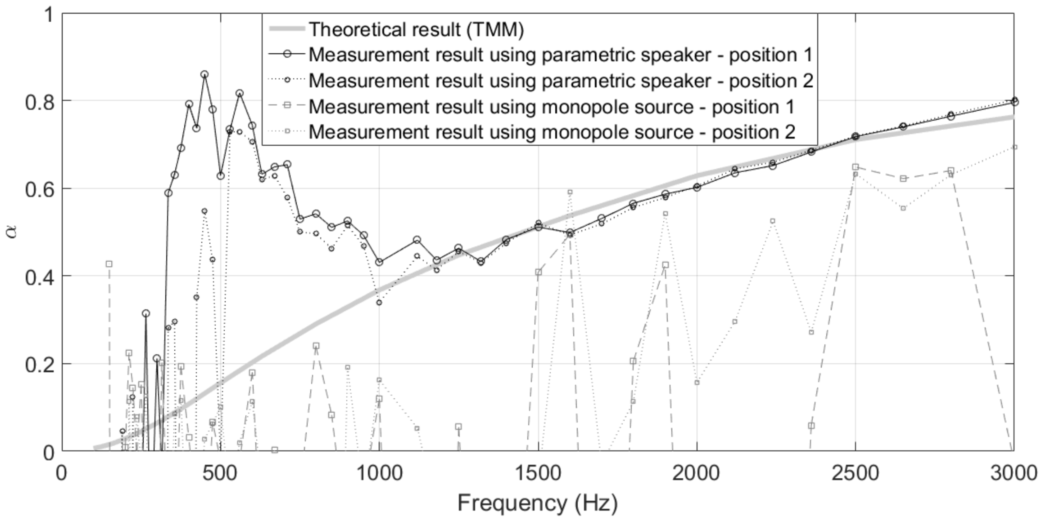

Fig. 5. Measurement and simulation results for the 1 in. thick melamine foam

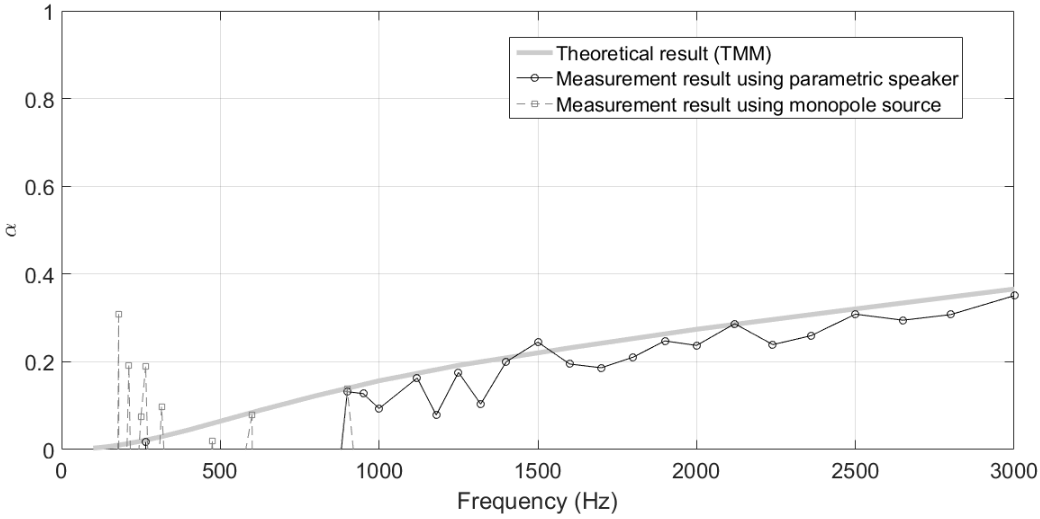

Fig. 6. Measurement and simulation results for the 0.5 in. thick melamine foam

3. Test case #2: measurements at oblique incidence on a honeycomb panel in controlled acoustic conditions

In this section, a honeycomb panel is considered. Such structures are widely used in the aeronautical industry, and typically combined with micro-perforated panels for designing engine liners. It is known that the sound absorption of liners is highly dependent on both the incidence angle and the sound pressure level [15], but measurements on these highly reactive and possibly non-linear materials are usually challenging. A measurement technique that would be robust to noise and environmental conditions and that could be applied for oblique incidence characterization of such materials is highly desirable. A first proof of concept towards this goal is briefly presented in this section, with a measurement of the sound reflection coefficient under an oblique incidence angle (see Figure 7). The only difference with the experimental setup described in section 2 is the source height z_s that now equals 1.2 m. Microphone type and separation, excitation signal and acquisition system are identical. The honeycomb sample has a 1.3 m^2 area and a thickness D = 31.75 mm.

The normalized surface impedance at oblique incidence for a layer of finite thickness backed by an impervious rigid wall (an air cavity in this case) is theoretically given by [15]

$$Z_s = -\frac{j}{\cos\theta}\cot\left(\frac{\omega D}{c_0}\cos\theta\right). \tag{3}$$

From the surface impedance and under a plane wave hypothesis, the reflection coefficient can be obtained using the relation $R = (Z_s \cos\theta - Z_0) / (Z_s \cos\theta + Z_0)$, with Z_0 the air impedance (the product of the air mass density with the speed of sound).

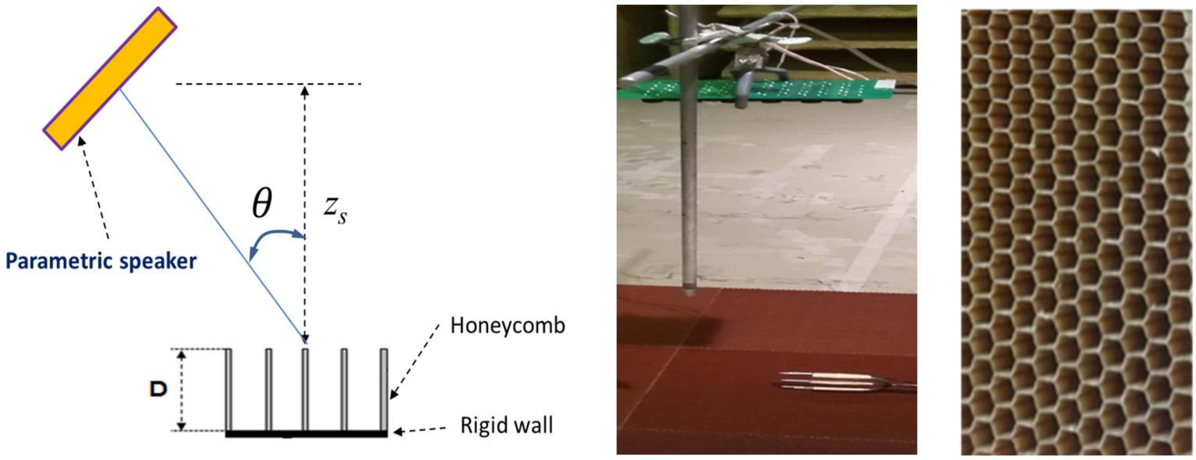

Fig. 7. (left) Sketch of the measurement setup – (middle) picture of the parametric speaker and measurement microphones installed above the honeycomb structure – (right) close-up view of the honeycomb

The real and imaginary parts of the measured and theoretical reflection coefficient are presented in figures 8 a) and 8 b), respectively. The considered incidence angle is 10 degrees, and a good agreement between results is seen on the whole considered frequency range (limited to 1500-4000 Hz for this material). The results obtained for a 30^o incidence angle in terms of real part (resistance) and imaginary part (reactance) of the surface impedance are provided in Figures 9 a) and b), respectively. It is confirmed by measurements that the surface impedance is nearly always purely imaginary on the tested frequency range. Tests conducted for other incidence angles (0^o and 20^o) also showed satisfactory agreement between measurements and theory [16]. When the monopole was used in this controlled acoustic environment, similar results were obtained between the two acoustics sources. A point of interest when using the parametric speaker is that larger sound pressure levels can be easily reached (above 100 dB), when a level of 80 dB is hardly attained for the monopole. This could be an asset for testing such materials in complex environment and under high sound pressure levels.

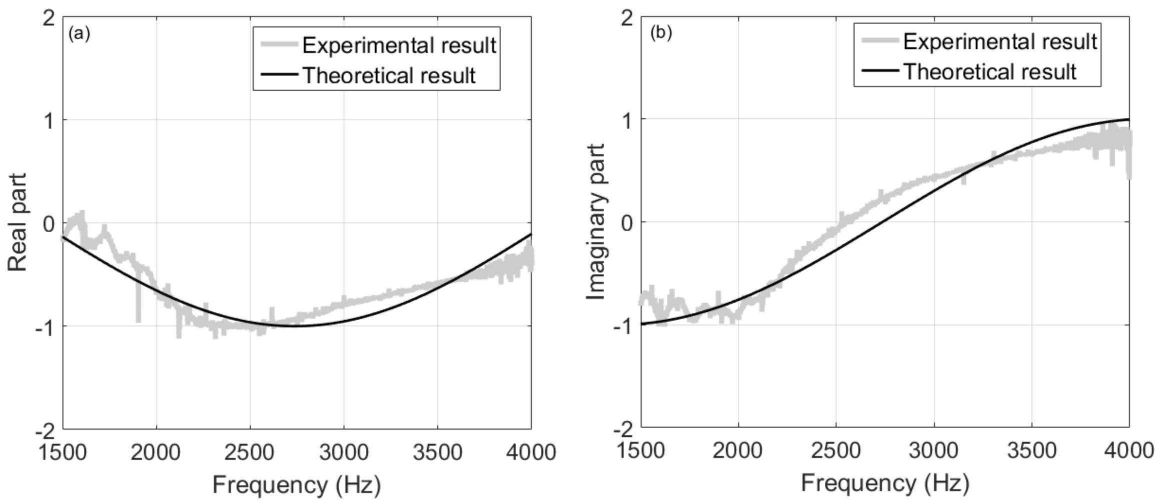

Fig. 8. Measurement and simulation results for the honeycomb panel – Reflection coefficient for a 10^o incidence angle

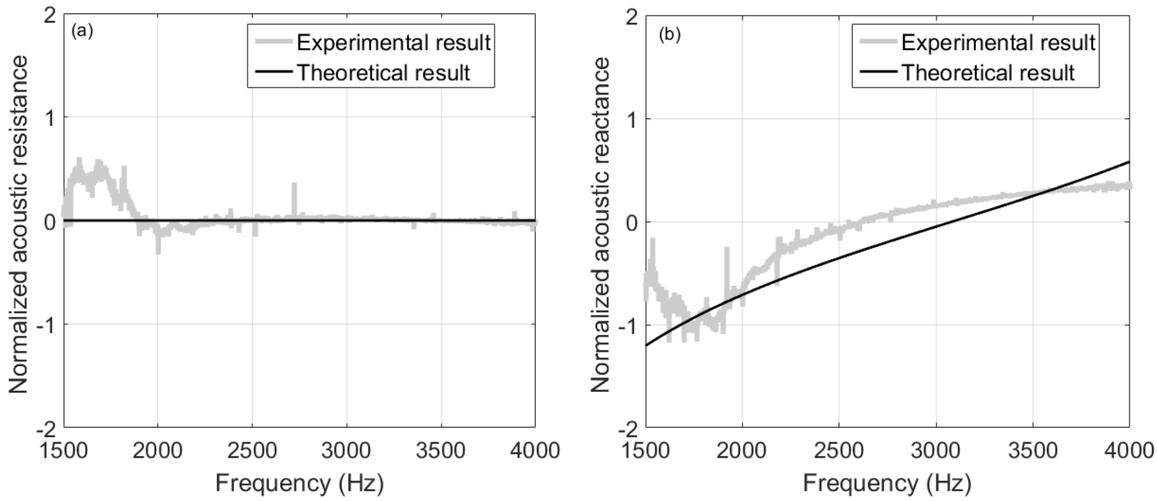

Fig. 9. Measurement and simulation results for the honeycomb panel – Normalized surface impedance for a 30^{o} incidence angle

Conclusion

This paper presented two application cases for sound reflection measurement on materials that were first conducted in a complex environment, a reverberant room. The use of a directional speaker proves to be a solution for performing measurements in such rooms. For a normal incidence case, the obtained results are in overall good agreement with theoretical predictions on the 500 – 3000 Hz frequency range when measurement made using a monopole source provided largely erroneous results in the considered frequency band. Sound reflection measurements were also conducted at oblique incidence in controlled acoustic conditions (i.e. a hemi-anechoic room) on a honeycomb structure. Comparisons made with theoretical predictions are satisfactory.

The technology of the parametric speaker that was still prohibitive in terms of price ten years ago has now become affordable, and allows designing interesting measurement apparatus. The high sound directivity provides large immunity to room effects and easiness to reach high localized sound pressure levels and to perform measurements under oblique incidence. These features are especially adequate for the development of an *in situ* measurement system. Further work includes possible improvements below a frequency of approximately 500 Hz (using either other sensors, or specific post-processing), and testing the proposed approach with other commercially available transducers that might offer improved performance.

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