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Measurement of sound diffusion coefficients of scattering furnishing volumes present in workplaces

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Scattering furniture (desks, chairs, etc.) and people are often present in workplaces or on wall facings. Predictive software tools for mapping the sound pressure field in workplaces employ acoustic characteristics such as the absorption or diffusion of scattering wall facings and furnished volumes. In this work, we developed a measurement system to determine the in-situ sound scattering coefficient of furniture. The measurement technique is based on the Vorländer and Mommertz method originally operating in free-field conditions. In order to overcome problems of parasite echoes coming from the reverberation of other inner-walls of the building and from noisy sources present on the site, we used a dedicated emission/reception system: an acoustic array using multipolar weighting which allows spatial filtering of the parasite echoes and an impulsive sound source which enables the use of a broad temporal window, resulting in adequate time separation of the different signals received by the antenna. Measurements of the sound scattering coefficient of a desk, one or several seated persons, cabinets, panels containing one or several cavities, etc. were carried out for several angles of incidence. These measurements have allowed the construction of an initial database of the sound diffusion coefficient per octave of scattering furniture in workplaces.

1 Introduction

Our work examines the acoustic characterisation of the complex partitions encountered in industrial workplaces. Acoustic prediction software tools [1, 2] require the average acoustic reflection coefficients associated with each partition of the workplace in order to predict the sound levels in workshops.

Industrial workplaces often contain bulky objects / volumes like furniture (cabinets, chairs, desks, etc.), noisy machinery or people. These bulky objects / volumes and uneven surfaces result in sound scattering, and one of the aims of the work undertaken here was to develop an initial sound scattering coefficient database of these partitions and bulky objects.

This database was developed by means of a scattering coefficient measurement system based on the method of M. Vorländer and E. Mommertz [3] which was originally applied in free-field conditions. This method is based on a process of averaging the total reflected sound pressure above the scattering structure, and was adapted, tested and validated to measure the sound scattering coefficient of wall facings on industrial sites, i.e. in reverberating conditions and in the presence of powerful parasitic sources [4]. The use of an acoustic array developed in previous studies [5] allows the spatial filtering of echoes due to reverberation and those stemming from parasitic sources. This system has proved to be of interest for such measurements in semi-anechoic chambers, but more especially in a reverberating workshop [4].

2 Measurement of the sound scattering coefficient

2.1 Definition

Sound scattering can be studied for several incidences of the sound field insonifying an irregular surface. For each incidence, there is a reflection zone termed specular, namely the region of space (or solid angle) where the image source obtained by reflection is visible through the scattering surface. The most common definition of scattering coefficient δ is the ratio of the energy reflected towards the exterior of this specular zone to the total reflected energy:

$$\delta = 1 - \frac{\int_{\Omega_S} E(\Omega)d\Omega}{\int_{\Omega} E(\Omega)d\Omega} \qquad (1)$$

with Ω_S the solid angle corresponding to the area of the reflected specular energy, and Ω the solid angle corresponding to all the reflected energy (Fig. 1).

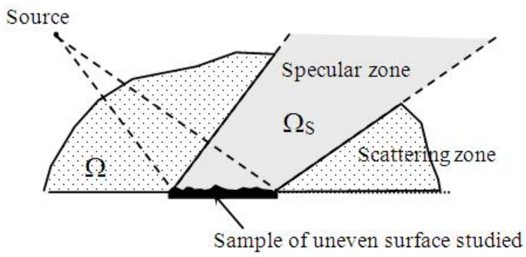

Figure 1: Illustration of the specular and scattering zone

To be able to determine the scattering coefficient of the objects and volumes present in industrial premises, we chose to adapt the measurement method of Vorländer and Mommertz [3] to the case of reverberating and noisy areas. To do this, we used an acoustic antenna with frequency constant directivity [5, 6] as the receiver and an impulsive sound source [4].

2.2 Method to measure the free-field acoustic scattering coefficient

The source (loudspeaker) and the receiver (microphone) are placed in the far field positioned in the specular direction. A rotating plate is employed on which the irregular surface sample studied is placed, allowing measurements for multiple orientations.

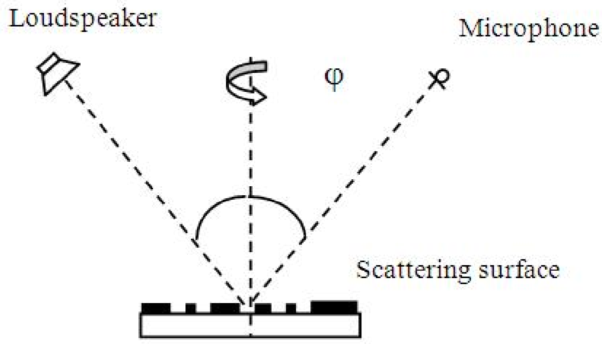

Figure 2: Principle of the method to determine the free-field scattering coefficient [3]

Figure 3 shows an example of the reflected impulses obtained for three scattering surface orientations. The incident signal is a burst centred on the 10 kHz 1/3 octave.

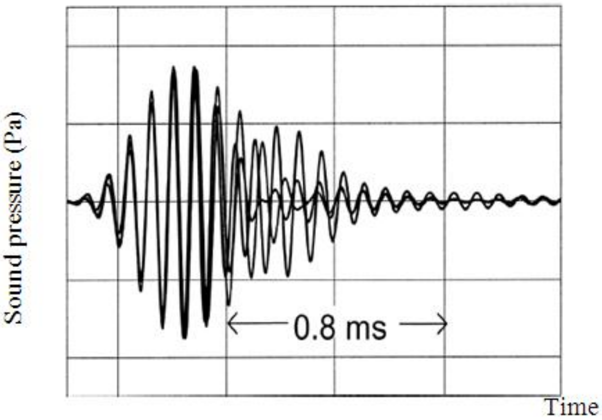

Figure 3: Reflected impulses for three different orientations of an irregular surface [3]

It can be seen in this figure that the initial part of the impulsive responses is coherent (in phase) while the remainder of the temporal pattern shows that these same impulses are no longer in phase. This second part of each impulsive response is therefore attributed to the non-specular component. For an angle of incidence θ_s of source and receiver and an orientation φ_i, the reflected sound pressures $p_{r,\varphi_i}(t,\theta_s)$ can be expressed as the overlapping of a scattering $p_{diff,\varphi_i}(t,\theta_s)$ and specular $p_{spec}(t,\theta_s)$ component:

$$p_{r,\varphi_i}(t,\theta_s) = p_{spec}(t,\theta_s) + p_{diff,\varphi_i}(t,\theta_s) \tag{2}$$

The specular sound pressure is obtained by avera ging a large number of reflected sound pressures according to angle φ: it is considered that the specular component remains coherent as a function of φ, contrary to the scattering component which, once averaged, is attenuated:

$$p_{spec}(t,\theta_s) \cong \frac{1}{n}\sum_{i=1}^{n} p_{r,\varphi_i}(t,\theta_s) \tag{3}$$

In far-field conditions, the total averaged reflected energy in the specular direction θ_s can be expressed as a function of the Fourier transforms $p_{r,i}(f,\theta_s)$ of the temporal sound pressures measured:

$$E_{tot}(f,\theta_s) = K(f,\theta_s).\frac{1}{n}\sum_{i=1}^{n}\left|p_{r,i}(f,\theta_s)\right|^2 \tag{4}$$

$K(f, \theta_s)$ is a constant dependent on the sound power of the source as well as the geometric positions of the source and the receiver. The reflected specular energy is also proportional to the squaring of the Fourier transform of the specular sound pressure:

$$E_{spec}(f,\theta_s) = K(f,\theta_s).\left|p_{spec}(f,\theta_s)\right|^2 \tag{5}$$

By combining equations (3), (4) and (5), we obtain a sound scattering coefficient in a specular direction θ_s:

$$\delta(f,\theta_s) = \frac{\sum_{i=1}^{n}\left|p_{r,\varphi_i}(f,\theta_s)\right|^2 - \frac{1}{n}\left|\sum_{i=1}^{n} p_{r,\varphi_i}(f,\theta_s)\right|^2}{\sum_{i=1}^{n}\left|p_{r,\varphi_i}(f,\theta_s)\right|^2} \tag{6}$$

with n >> 1

where $\sum_{i=1}^{n}\left|p_{r,\varphi_i}(f,\theta_s)\right|^2$ is the total reflected energy and $\frac{1}{n}\left|\sum_{i=1}^{n} p_{r,\varphi_i}(f,\theta_s)\right|^2$ the reflected specular energy

From these different scattering coefficients, it is possible to deduce the random-incidence scattering coefficient:

$$\delta(f) = \int_0^{\pi/2} \delta(f,\theta_s)\sin(2\theta_s)d\theta_s \tag{7}$$

To be able to use this measurement method in unfavourable acoustic conditions like those found in workshops, we replaced the microphone receiver by a directive antenna and the sound source by an impulsive source. The spatial filtering properties of the antenna as well as the very brief emission of the source impulse peaks freed us from parasite echoes coming from other echoes present in the workplace and allowed the temporal windowing of those coming from the scattering reflection of the volumes/objects studied.

2.3 The multipolar antenna and the impulsive sound source

The Vorlander and Mommertz method is unusable in a reverberating environment. The method we developed is based on that used to determine the sound absorption coefficient of the flat surface facings present in industrial workplaces [4]. This method uses a receiving antenna with a frequency-constant directivity and containing 13 sensors. The weighting used is multipolar as it allows directivities with a straight, frequency-constant main lobe to be obtained and attenuation of the secondary lobes of up to 30 dB. The receiving system contains four sub-antennae, each using five of the 13 sensors, the spacing between them being multiples of 2.5 cm [5].

The impulsive source was designed from the reverse impulsive response of an emission system [4]. This reverse filtering technique was used to calculate the signal source necessary to equalise the response of the emission system in order to emit short impulses. The emission system contains an equaliser (Yamaha Graphic Equaliser GQ 1031 BII), a power amplifier (APK 2000) and a loudspeaker 10 cm in diameter (Pioneer TS E1077). The transfer function H(f) of

the emission system was measured in free-field conditions with a MLS signal as the source signal. Filtered by the reverse impulsive response of the emission system and emitted at the input, this signal produces a very short impulse at the output.
The emission and reception systems (source + antenna) were placed on a frame.
This frame can easily be moved around the central axis of the scattering surface studied to conduct acquisitions as a function of φ.

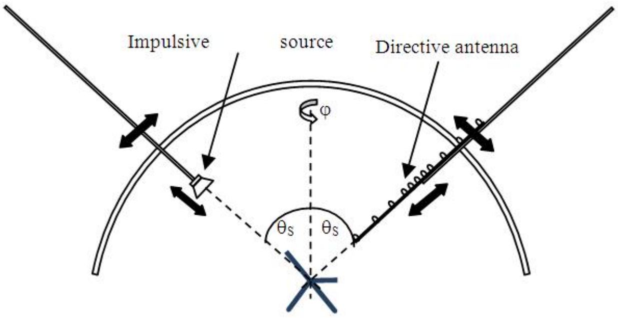

Figure 4: Schematic of the principle of the measurement system

3 Measurement of the scattering coefficient

3.1 The different objects studied

The objects studied were:

- Config 1: a cabinet.
- Config 2: a table.
- Config 3: a chair.
- Config 4: a table + three chairs.
- Config 5: a table + three chairs + a computer.
- Config 6: a seated person.
- Config 7: four chairs.
- Config 8: four seated people.

These volumes have different shapes and the aim was to compare the scattering coefficient of a configuration (e.g. a person) with the scattering coefficient of the same combined configuration (e.g. four people). Other examples were a chair with four chairs, and a table with a table + three chairs + a computer.
Only a few results of the configurations are presented in the following figures.
Figure 5 shows the experimental system for measuring the sound scattering coefficient of a seated person with a volume of $134 \times 72 \times 62$ cm^3. The measurement was taken for θ_S angles lying between 30° and 80°.

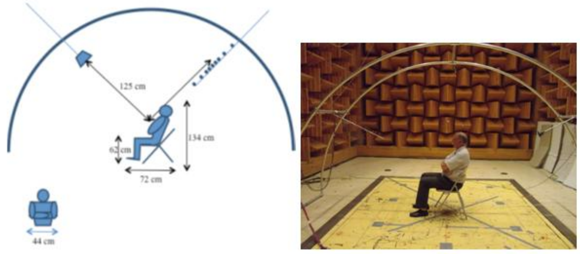

Figure 5: Experimental system to measure the scattering coefficient of a person

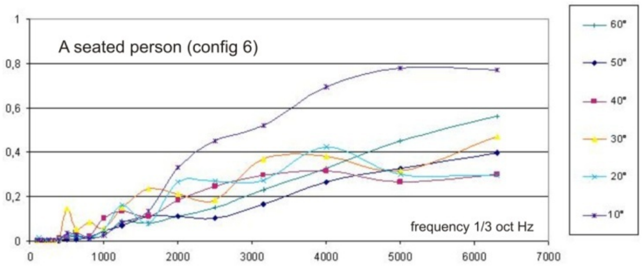

Figure 6: Sound scattering coefficient of a seated person with a volume of $134 \times 72 \times 62$ cm^3

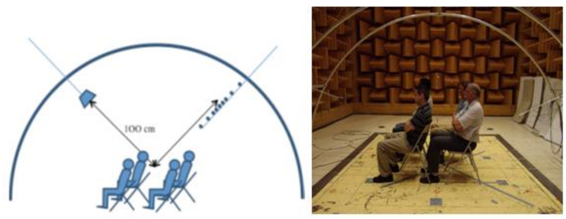

Figure 7: Experimental system for measuring the scattering coefficient of four people

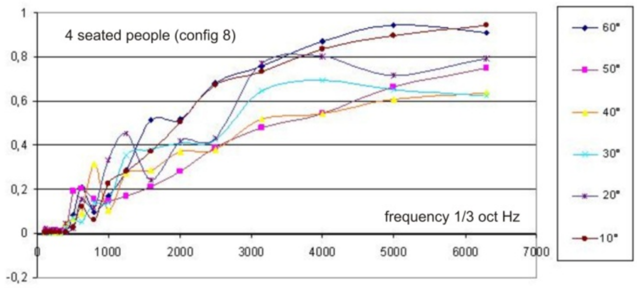

Figure 8: Sound scattering coefficient of four people

In the one-person configuration, the scattering is high from the 3 kHz octave upwards, its maximum being reached for the angle θ_s =10° at f = 5 kHz. For the configuration containing four people (Figure 8), the scattering coefficient is high from the 500 Hz octave upwards, and its maximum (~ 0.9) is also reached for the angle 10°.

Figure 9 presents the comparison between the sound scattering coefficient for one person and for four people. We observed that the larger the number of people, the higher the scattering coefficient. This can be explained by a more complex and convoluted surface, which results in more scattering. The scattering coefficient virtually doubles when the number of people becomes large. We observed the same results when measuring the scattering coefficient above a chair, which we compared to that of four chairs (Figure 10) or with three chairs + a table + a computer (Figure 11).

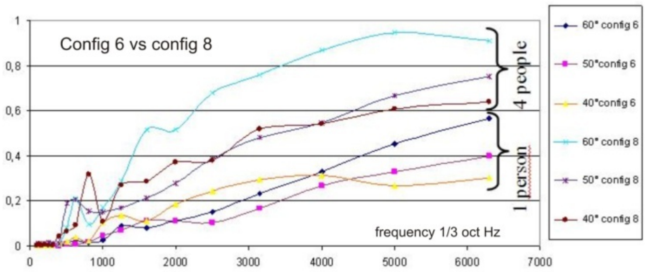

Figure 9: Comparison of the sound scattering coefficient of a person and that of four people

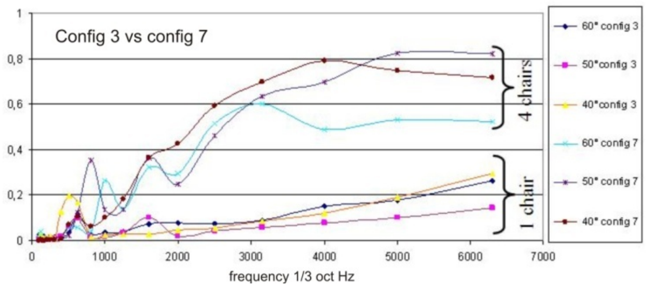

Figure10: Comparison of the sound scattering coefficient of a chair and that of four chairs

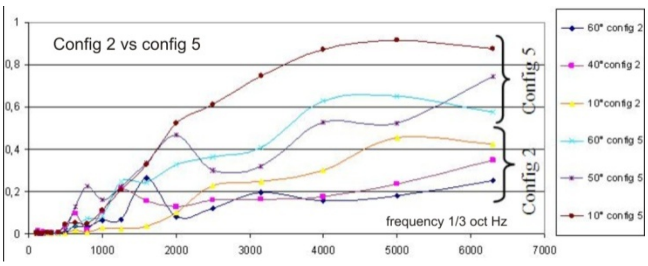

Figure 11: Comparison of the sound scattering coefficient of a table and that of table + three chairs + computer

4 Sound scattering coefficient database

This set of measurements allowed the construction of an initial comprehensive database of objects and people present in industrial workplaces by octave band (Table 1).

Table 1: Sound scattering coefficient of the scattering structures studied

Configuration	125Hz	250Hz	500Hz	1KHz	2KHz	4KHz
A cabinet	0.019	0.012	0.056	0.066	0.101	0.151
1 chair	0.021	0.017	0.085	**0.015**	**0.031**	**0.097**
4 chairs	0.007	0.002	0.040	**0.075**	**0.200**	**0.441**
1table	0.013	0.009	0.053	**0.060**	**0.081**	**0.147**
1table+3chairs	0.014	0.008	0.035	**0.076**	**0.149**	**0.311**
1table+3chairs +PC	0.003	0.004	0.045	**0.077**	**0.210**	**0.431**
1 Person	0.003	0.002	0.031	**0.043**	**0.131**	**0.251**
4 People	0.008	0.006	0.064	**0.122**	**0.275**	**0.473**

We have deliberately left the values to three decimal points in this table to show the low diffusion caused by certain scattering structures at certain octaves. We are aware and in full agreement that these values cannot be as accurate as that, given that the measurement uncertainty is clearly higher than the accuracies shown in Table 1. Scattering coefficients to two decimal points will subsequently be retained for use in acoustic prediction software tools.

Below 500 Hz, this coefficient is low for the category of structures studied (people, chairs, tables, cabinets). The scattering produced is indeed low because of the unevenness of the surface responsible for the scattering not being very great (compared to the wavelength) or most of the acoustic reflection being specular, as stated earlier in the case of the table or cabinet. On the other hand, above 1 kHz, this coefficient becomes higher. This overall coefficient confirms that scattering increases with frequency and when the structure has a more complex uneven surface producing more convolutions, as is the case for example with the configuration containing a table + three chairs.

5 Conclusion

This work presents the initial outline of a database of the sound scattering coefficient of the uneven structures present in industrial workplaces (furnishings, presence of people).

This series of measurements was conducted using a portable device allowing the in-situ measurement of the sound scattering coefficient of uneven partitions in industrial premises. This portable device, based on the method developed by Vorländer and Mommertz, was adapted to the reverberating conditions of industrial workplaces by using a directive antenna and impulsive source already employed to measure acoustic absorption.

These measurements were carried out in a semi-anechoic chamber and allowed the logical observation of:

-a high scattering produced by an increasingly complex uneven surface,

-a low scattering on furniture including a large flat surface such as a cabinet,

-an increasingly high scattering with frequency whatever the uneven structure studied,

- higher scattering in normal incidence, lower in grazing incidence.

The global sound scattering coefficient, then more accurately as a function of the angle of incidence, will, in the longer term, be integrated into sound field prediction software tools.

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