Experimental methods to measure the acoustical reduction index as a function of the incidence angle

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This paper concerns the measurement of the reduction index \( R(\theta) \) as a function of the incidence angle. Generally the index \( R \) is measured for an incident diffuse field, and does not take into account the angle dependency. However, the variation of \( R \) with the direction of the incoming wave can be significant, specially when the frequency is higher than the critical frequency. That is the reason why experimental set-ups have been implemented to measure the index \( R \) as a function of the incidence angle.

Two experimental methods have been developed. In the first system, the panel is excited by a sound source assimilated to a plane wave corresponding to a given incidence angle. The index \( R \) is measured sequentially, for different positions of the source. In the second system, the panel is excited by a diffuse field, and a wave by wave decomposition of the radiated intensity yields the index \( R \) depending on the angle of incidence.

The decomposition of the radiated intensity is based on a measurement method coming from acoustical holography called NAH-Phonoscopy.

The mathematical formulation of the two methods is detailed. Then, experimental results are presented and compared to theoretical data. Finally, the validity domain of these two methods and their limits are discussed.

1 Introduction

In this paper, two experimental methods to measure the sound reduction index \( R(\theta) \) as a function of the incidence angle are presented. Generally, the reduction index is measured or computed for an incident diffuse field. But it is shown that this index varies a lot according to the direction of the incoming wave [1]. Therefore, it can be necessary to take into account the angular dependency of index \( R \), especially when considering a well directive noise source or a non uniform incident field.

A few solutions have been investigated to evaluate experimentally the reduction index as a function of the incidence angle. In Davis method [2], the studied partition is excited by a directive field, radiated by a simple loudspeaker. The direction of incoming waves is defined by the position of the loudspeaker. The use of impulsive source signals and Fourier transform analysis enables to separate the direct signal from the scattered and reflected parts, in both the emission side and the receiving side. The incident pressure and the transmitted pressure can be isolated, and then the index \( R(\theta) \) is computed. Iwase [3, 4] has been working on a similar method; the partition is also excited by a localized loudspeaker, but an anechoic box is put in the receiving side. It allows to measure directly the transmitted pressure, without any diffracted and reflected signals. Here, the separation between the direct waves and the diffracted or reflecting waves is not a numerical procedure, it is included in the experimental setup. Yoshimura researches [5] lean on the measurement norm ISO-140-5 [6], concerning in situ measurement of the reduction index. A localized loudspeaker is used to excite one wall of a reverberant room. In this method, the incident field is a directive field, as for the other systems, but the radiated field is a diffuse field.

Two other solutions have been tested and are presented in this paper. The first one is close to Yoshimura works. One of the wall of a reverberating room, containing the studied structure, is excited by a directive noise source. In this case, the excitation field is a directive field, corresponding to a given incidence angle. And the field in the transmitted side is a diffuse field. This first type of measurement will be refereed to “directive excitation measurement”.

The second type of measurement carried out is based on an opposite principle. The structure is excited by a diffuse field and an holography technique, called NAH-Phonoscopy is used to decompose wave by wave the radiated field.

For each measurement method, physical principles are developed and experimental results are presented. Then a discussion on the specific interest of each measurement is presented.
2 Directive excitation - Horn measurement

2.1 Principle

In this method, the studied structure is excited by a directive wave, corresponding to a given incidence angle of incoming waves. It requires to generate plane waves in free field. Of course, the generation of plane waves is not easy. A specific system has been implemented in order to obtain a directive incident field. In the transmission side, the wall radiates in a reverberant room (usual receiving room of transmission laboratory).

The reduction index depending on the incidence angle is computed as the ratio of the total transmitted power \( W_t(\theta) \) and the total incident power \( W_i(\theta) \), with

\[
R(\theta) = -10 \log \left( \frac{W_t(\theta)}{W_i(\theta)} \right)
\]

\[
W_t(\theta) = \frac{<p_t>^2}{4\rho c} \times A
\]

and

\[
W_i(\theta) = \frac{<p_i>^2}{\rho c} \times S \times \cos(\theta)
\]

where \( p_i \) and \( p_t \) are the incident and transmitted pressures \( R(\theta) \) can be expressed as a function of the exterior wall pressure level \( L_{p_{ext}} \) and the transmitted pressure level \( L_{p_t} \), [5, 7]

\[
R(\theta) = \frac{L_{p_{ext}}}{\text{incident pressure}} - 6dB - L_{p_t} + 10 \cdot \log \left( \frac{4S \cos(\theta)}{A} \right)
\]

\( L_{p_{ext}} \): averaged wall pressure level, emission side

\( L_{p_t} \): averaged transmitted pressure level, in the receiving room

\( S \): surface area of the structure

\( A \): equivalent absorption area of the receiving room

\( \theta \): incidence angle

Figure 1 represents the corresponding experimental set-up. It can be noted that in this method, one measurement is performed for each incidence angle.

2.2 Experimental Set-up

To generate plane waves, an acoustical exponential horn was designed. It plays the role of a wave guide, and provides a directive source, radiating planar wave fronts in a zone defined by the outer section. The efficiency frequency range is determined by the shape and the dimensions of the horn. It was shown that the constructed horn is adapted for the 100-2000Hz frequency range. The outer section is about 1m50 × 1m50, large enough to test materials such as glazings.

The experimental measurement was set-up in the LABE, a french measurement laboratory dedicated to building acoustics, employing huge and modern acoustic measurement facility.

Figure 2 shows the glazings and windows test equipment, where the acoustical horn has been placed.

The averaged transmitted pressure level is measured in the receiving room (standard measurement [8]). The exterior wall pressure level is measured on 16 points, 2cm far from the glazing, to evaluate the averaged incident pressure level.

Mineral wood was placed on the floor and on lateral laboratory walls to avoid disturbing reflection.

2.3 Experimental Results

The case of a simple glazing of 10mm of thickness has been studied. Its critical frequency is around 1100Hz. The glazing is mounted flush on the concrete wall.
Figure 3 represents the reduction index $R(\theta)$ measured for the four incidence angles $0^\circ$, $30^\circ$, $50^\circ$ and $80^\circ$. Data corresponding to the usual diffuse incident field measurement is shown as well (curves referenced as $R_d$).

It is obvious that the incidence angle has a great influence on the sound reduction index. The results show differences of more than 10 dB for some frequencies according to the incidence angle. So it confirms that it can be very important to take into account the direction of incoming waves in sound transmission problems.

Moreover, the coincidence phenomena is clearly seen. Indeed, the sound reduction index presents a dip, which moves in relation with the incidence angle. This dip appears at the coincidence frequencies $f_{co}$, linked to the critical frequency $f_c$ by

$$f_{co} = \frac{f_c}{\sin^2 \theta}$$

Coincidence phenomenon concerns only frequencies above the critical frequency. So, the direction of incoming waves has an important influence at high frequencies. Note that the coincidence frequency measured for grazing waves ($\theta = 80^\circ$) is very close to the critical frequency measured with an incident diffuse field.

Experimental data are compared to theoretical values on Figure 4. The theoretical results have been computed with a model based on a wave by wave approach, where a spatial windowing technique is used to take into account the finite size of the structure [9].

The measured results are in good agreement with what was theoretically expected. Experimental coincidence frequencies are coherent with computed coincidence frequencies, and the global shapes of the different curves are quite satisfying.

Nevertheless, it can be observed that the measured sound reduction index does not match very well the theoretical one for $\theta = 0^\circ$. It seems that $R(\theta = 0^\circ)$ decreases - or does not increase as predicted - for $f \simeq f_c$. It is explained by the fact that the incident field is not directive enough. Indeed, grazing waves are included in the incident field, due to diffraction phenomena on the edge of the glazing. As the index $R$ is really lower for grazing waves than for the other wave directions, a small quantity of grazing waves is sufficient to disturb the global index $R$. This behavior has been confirmed by studying recessed glazings to analyze these singular effects.

3 Diffuse excitation - NAH-Phonoscopy measurement

3.1 Principle

This method is based on the use of NAH-Phonoscopy. In this case, the incident field is not a directive field. On the contrary, the incident field is a diffuse field (standard field in a reverberant room). The wall radiates in a semi infinite duct, composed by a room where absorbing material is put on the opposite side of the studied structure (see Figure 5). NAH-Phonoscopy measurement is used to decompose the radiated field wave by wave, and so incidence direction by incidence direction.

![Figure 5: Experimental Set-up of NAH-Phonoscopy](image)
has been developed in [11]. What is important is that $I_{nt}(\theta, \phi)$, the radiated normal intensity in the direction $(\theta, \phi)$, can be measured with NAH-Phonoscopy. An average over $\phi$ gives the radiated normal intensity $I_{nt}(\theta)$ in the direction $\theta$.

Concerning the emission side, different solutions have been investigated. First, the term $I_{ni}(\theta)$ can be deduced from both an assumption on the angular repartition of the incident field and a measurement of the averaged pressure level in the emission side. The most simple assumption is the case of an incident diffuse field (uniform angular repartition). But other distribution, such as a gaussian or a cosine distribution, have been tested as well.

The second solution consists of measuring the term $I_{ni}(\theta)$. This work has been detailed in [12]. The angular repartition of the incident field is obtained from the study of the NAH-Phonoscopy system, where a membrane wall is set up. This material is chosen for its simple behavior in sound transmission. It is assumed that the reduction index of the membrane $R_m(\theta)$ is known, and follows that of the mass law [13], so the incident intensity is easily obtained from the measured radiated intensity.

Finally, with either a theoretical assumption or an experimental measurement of the angular repartition of the incident field, the reduction index $R(\theta)$ is computed as the ratio of the normal incident intensity $I_{ni}(\theta)$ and the normal transmitted intensity $I_{nt}(\theta)$, i.e.,

$$R(\theta) = -10 \log \left( \frac{W_i(\theta)}{W_t(\theta)} \right) = -10 \log \left( \frac{I_{nt}(\theta)}{I_{ni}(\theta)} \right)$$  \ \ \ \ \ \ (6)$$

Note that with this process, only one NAH-Phonoscopy measurement is sufficient to compute the reduction index for all directions $\theta$.

### 3.2 Results

The case of a simple homogeneous wall made of plaster blocks, 5cm of thickness, has been studied. Its critical frequency is about 800Hz.

#### 3.2.1 Assumption of diffuse incident field

Figure 6 represents the reduction index $R(\theta)$ as a function of the frequency for the four incidence angles 10°, 30°, 50° and 80°. This results are obtained assuming an uniform angular repartition for the incident field.

The results are presented for the 500-5000Hz frequency range. Indeed, NAH-Phonoscopy measurements are not exploitable for frequency below 500Hz [11].

The experimental data are quite coherent, the global shapes of the different curves agree with what was expected, and coincidence effects are well observed. So it shows that this method of evaluating $R(\theta)$ based on NAH-Phonoscopy measurement is a valid method.

Nevertheless the results corresponding to the angle $\theta = 10^\circ$ are surprising. Indeed, the curve for $\theta = 10^\circ$ should be above all the others (the normal waves are the most attenuated). It is explained in the next section that the use of a measured angular repartition of the incident field corrects this problem.

#### 3.2.2 Measurement of the angular distribution of the incident field

As mentioned before, the angular distribution of the incident field was obtained with NAH-Phonoscopy measurement on a membrane system [13].

Figure 7 represents the reduction index $R(\theta)$ as a function of the frequency, computed for the four incidence angles 10°, 30°, 50° and 80°, using a measured angular repartition of the incident field.

The results seem to be a little better than what is obtained
3.2.3 Comparison with theoretical results

A comparison between experimental data and computed values of $R(\theta)$ is given Figure 8. The experimental data have been computed with the measured angular distribution of the incident field.

![Figure 8: Comparison between measured and computed $R(\theta)$ - Wall of plaster blocks](image)

If the measured curves do not quite match the theoretical curves, it is important to remark that the global shapes of the experimental curves agree with the theoretical curves shapes. Moreover, the positions of experimental dips are coherent with computed data, and the minimum $R$ values (obtained at coincidence frequencies) are coherent too. So, the results seems quite good for low $R$ values, corresponding to high radiated energy. Nevertheless, the results obtained when the radiated energy is low are less satisfying.

The understanding of this behavior is still under investigation. The sensibility of the NAH-Phonoscopy measurement set-up may not be adapted for low radiated energy. An other explanation may be linked to the measurement noise, widely increased by the retro propagation, who can disturb the measured data when the transmitted level is too low.

Finally, it seems that NAH-Phonoscopy measurements can be used to evaluate the global behavior of the acoustical transmission through systems, and to detect singular effects (such as large decrease of $R$ index at coincidence frequencies). Nevertheless, the current process is not yet adapted to obtain quantitative results.

4 Discussion and Conclusion

Two experimental set-ups have been implemented in order to evaluate the reduction index of materials as a function of the incidence angle of incoming waves.

The two systems are based on very different processes. In the first case, the studied structure is excited by a directive field (corresponding to a well define incidence angle), and it radiates in a reverberant room. The reduction index is then computed from a measurement of both the averaged transmitted pressure and the averaged incident pressure. In the second case, the incident field is nearly a diffuse field, and the structure radiates in a semi-infinite duct. The use of the NAH-Phonoscopy technique gives a wave by wave decomposition of the radiated field. Then a theoretical assumption or an experimental measurement of the angular distribution of the incident field gives the reduction index for each wave direction.

Note that the two systems are not adapted for the same types of materials. The first method can be used to analyze small elements, area less than 1m50 × 1m50. So it is quite good for studying glazings or windows.

In both cases, the experimental results are very encouraging. Indeed, specific effects depending on the incidence angle are well observed (it concerns mainly coincidence effects). It means that singular behaviors can be detected, in particular, the large decrease of the reduction index observed for a given incidence angle at the coincidence frequency can be evaluated.

Finally, the experimental results show that differencies superior to 10dB can be measured on $R(\theta)$ curves, according to the incidence angle. So it confirms that, in some situations, this common reduction index measured for an incident diffuse field is not good enough to characterize accurately the sound transmission of systems.

References


