An intensimetric method to localize secondary sources

M. Gullo, A. La Pica, A. Leto & G. Rodonò

D.R.E.A.M. Dipartimento Ricerche Energetiche e AMbientali
Facoltà di Ingegneria, Università degli Studi di Palermo, Italy

Abstract

Research is presented to find out the amount and direction of the early reflections of a primary sound source in a room. Two rooms, very different in dimensions, were taken into account: the smallest one is about 100 m$^3$ and the largest one 1100 m$^3$. The measurement system consists of a PC equipped with a sound-board connected to the signals coming from the two microphones of an intensity probe at the input and to a loudspeaker at the output. A sweep signal was used for the excitation of the environment.

Signal processing software was developed using LabVIEW by National Instruments. The results of the two measurement sessions are presented as amplitude-direction diagrams and amplitude-direction-time diagrams.

1 Introduction

Early reflections produced in a listening room could have different effects on the perception of direct sound. Typically they emphasize or confuse the voice of a speaker depending on their arrival time. The first reflection after the direct sound is important to define the intimacy of a listening room (Beranek 1962). Also spaciousness is related with this phenomenon. For these reasons it is useful to localize spatially the sources of these early reflections. The measurement technique described in this paper gives an operating method to find out position of early reflection sources in a room using an intensimetric technique.

Typically, the distance of sources from the measuring point could be found by a reflectogram (figure 1) obtained by measuring the impulse response of the room. A peak in the squared envelope of $p(t)$ gives information about the distance of the secondary source, but not about the angular position.
The information about the angle is obtained with an intensimetric measurement, whose result is the time evolution of the intensity vector. The intensimetric measurement is obtained with two or more microphones closely placed.

In this study we want to focus the attention on the origin point and the intensity of the early reflections in a room, more than on the perception of the ones by a listener.

The measurements are presented using diagrams from which reading both the arrival instant and the angle associated to the direction of propagation is possible. These diagrams are called, in the rest of the article, angular reflectograms. From the interpretation of the angular reflectograms finding the geometrical characteristics and acoustic relation of a room is possible.

## 2 Signal processing and block diagram

Sound intensity vector envelope in impulsive condition is traced moving from the impulse responses measured by two microphones of a sound intensity probe in a room. Impulse responses are measured indirectly by using sweep signal. Envelope peaks are presented as amplitude-direction-time diagrams.

### 2.1 Impulse response

The method used to determine the impulse response of the room is based on the cross-correlation between the input signal and the system response, under a particular condition of the input signal itself. With reference to figure 2, if $s(t)$ is the input of the system loudspeaker-transmission path-microphone, $g(t)$ is the system impulse response and $s'(t)$ the system response to $s(t)$, we can form [3] the cross-correlation of $s(t)$ and $s'(t)$:
\[
\phi_{ss'}(\tau) = \int_{-\infty}^{+\infty} s(t)dt \int_{-\infty}^{+\infty} g(t')s(t + \tau - t')dt' = \int_{-\infty}^{+\infty} g(t') \left[ \int_{-\infty}^{+\infty} s(t)dt \right] dt' = \int_{-\infty}^{+\infty} g(t') \phi_{ss}(\tau - t')dt'
\]

(1)

The latter expression leads to the conclusion that by means of a cross-correlation we will obtain the impulse response \( g(t) \) if the auto-correlation function of the exciting sound signal is the function delta or at least approximates it.

![Diagram](attachment:image.png)

**Figure 2**: Cross-correlation method to measure the impulse response

The test signal used to obtain the reflectogram is a sweep signal.

Since sound intensity measurement is obtained in a frequency interval which is related to the length of the spacer placed between the microphones, exciting the room with a wide-band signal is not necessary. A signal which has the capacity to excite the resonance modes of the room in a narrow interval of frequencies is sufficient.

A frequency swept signal (sweep signal) is a signal modulated in frequency according to the law:

\[
y(t) = A \sin \left( \frac{2\pi(f_2 - f_1) t}{T} \right) + b
\]

\[
a = \frac{2\pi(f_2 - f_1)}{T}, \quad b = 2\pi f_1
\]

(2)

The duration \( T \) of the signal and the initial and final frequencies of the sweep are chosen in function of the kind of measurement.

In figure 3 the sweep signal pattern, its auto-correlation function and its "flat" energy density spectrum are presented. It is possible to notice how such a signal presents a flat energy density spectrum in a large portion of its center-band: in such an interval of frequencies a rectangle is sufficiently approximated, which is equivalent, in the domain of time, to a very narrow function of the type sinc(t), almost equal to the function delta band-pass filtered.
2.2 Sound intensity envelope

The cross-correlation of the two output signals with the sweep gives two sound pressure impulse response \( p_1(t) \) and \( p_2(t) \) used to calculate \( I(t) \) components. Instantaneous sound intensity is

\[
I_n(t) = p_n(t) u_n(t) \quad (W/m^2)
\]

By mean of the intensimetric probe we take two signals of sound pressure in two points: M1 and M2. The approximation of sound pressure in the medium point between microphones is

\[
p_n(t) \approx \frac{1}{2} [p_1(t) + p_2(t)] \quad (Pa)
\]

while the particle velocity component in the direction \( \hat{n} \), from M1 to M2, is calculated by a finite difference approximation of pressure gradient

\[
u_n(t) \approx \frac{1}{\rho_0 d} \int_{-\infty}^{\infty} [p_1(\tau) - p_2(\tau)] d\tau \quad (m/s)
\]

where \( d \) is the distance between microphones in meters and \( \rho_0 \) is medium density in Kg/m\(^3\) (air density is \( \rho_0 = 1.21 \) Kg/m\(^3\)).

Then intensity can be written as

\[
I_n(t) \approx \frac{1}{2\rho_0 d} [p_1(t) + p_2(t)] \int_{-\infty}^{\infty} [p_1(\tau) - p_2(\tau)] d\tau \quad (W/m^2)
\]

The intensity envelope is useful to emphasize reflection peaks in the sound intensity components. Sound intensity envelope (Suzuki 1991) is:

\[
I_e(t) = \frac{1}{2} \text{Re}[p_a^*(t) \cdot u_a(t)] \quad (W/m^2)
\]

where

\[
p_a(t) = p(t) - j \rho_h(t) \quad (Pa)
\]

and

\[
u_a(t) = u(t) - j \omega_h(t) \quad (m/s)
\]

are the analytical parts of, respectively, the pressure and the particle velocity,
while the functions $p_h(t)$ and $u_h(t)$ are theirs Hilbert transforms and the asterisk denotes the conjugate.

The representation of the intensity vector envelope allows to show in a clear way the peaks of the sound intensity absolute value associated to the reflections. Bi-dimensional cartesian co-ordinates ($x,y$) are used:

$$\tilde{I}(t) = I_x(t)\tilde{x} + I_y(t)\tilde{y} \quad (W/ m^2) \tag{8}$$

2.3 Software architecture

To measure $I_x(t)$ and $I_y(t)$ a VI (Virtual Instrument) called "Sound Intensity" is used, designed and customized in laboratory, which allows to store on PC the intermediate and final data of the elaboration.

The following block diagram (figure 4) shows this VI's architecture. The impulse response, calculated starting from the signal taken at the output of every microphone, is first stored on hard disk and subsequently, using the relative data to the previous calibration step, filtered from a third of octave filters bank and elaborated to obtain the sound intensity envelope. The result is finally stored on hard disk in order to be subsequently elaborated by another VI: "Elab Dati".

**Figure 4: "Sound Intensity.vi" block diagram**
VI "Elab Dati" (see figure 5) is responsible for producing the angular reflectogram, for the selected band, starting from the measurement data saved before. First $|I(t)|$ is calculated from $I_x(t)$ and $I_y(t)$, from which peak events are revealed. $I_x(t)$ and $I_y(t)$ are normalized with respect to $|I(t)_{max}|$ the maximum peak value which is, generally, in relation with the direct wave coming from the source. Subsequently $I_x(t)$ and $I_y(t)$ are "filtered in time" so that it's possible to preserve just the value corresponding to the instants when the peaks occur. A ramp generator allow to produce the information concerning the time in order to obtain the angular reflectogram.

![Figure 5: "Elab Dati.vi" block diagram](image)

3 Measurements

3.1 Description of the rooms under test

Measurements were carried out in two different environments: the "A room" is a small one, which volume is about 100 m$^3$ and allowed for the simple rectangular geometry to quickly verify the indications deriving from the measurement results during software design and tuning; the "B room" is a large classroom, which volume is about 1100 m$^3$, and was object of a more careful spatial sampling. The planimetry of the two rooms together with the measurement points are represented in figures 6 and 7.
Figure 6: A room planimetry and measurement points

Figure 7: Room B planimetry and measurement points
3.2 Measurement description and instrumentation

The measurement system consists of: a sound source B&K type 4224, a pressure gradient sound intensity probe B&K type 3519 with $\frac{1}{2}''$ microphones and a standard spacer of 12 mm. The signals registered by the microphones, after being pre-amplified, are acquired using a 16 bit sound board with a 44,1 kHz sampling frequency. In case of evaluation of the room response with swept signal, the card is used in full-duplex mode to send the test signal and acquire the system response.

The measurement frequency range is 100-1000 Hz due to the intensimetric probe limitations.

The intensity vector components in every measurement point were measured according to the reference directions x and y (see figures 6 and 7). Two measurements are performed in each point, two times, one along the x direction and the other along the y direction and the intensimetric probe, mounted on a tripod, is free to rotate round the middle point between the two microphones.

3.3 Results and diagrams

For both measurements three diagrams normalized with respect to the highest $I(t)$ peak are presented only in the first 100 ms. The frequency interval taken into consideration is the third octave band with a center frequency of 1000 Hz.

The first diagram (figure 8) contains $I(t)$, $I_x(t)$ and $I_y(t)$ patterns; the second diagram (figure 9), the envelope of $I(t)$ vector; the third diagram (figure 10) the peaks distribution of the $I(t)$ vector envelope vs time, keeping the information about the angle.

![Small room](image1)

![Large room](image2)

Figure 8: $I(t)$, $I_x(t)$ and $I_y(t)$ envelopes
The small room (figure 10, small room) is characterized by a direct sound more powerful then early reflection. Main early reflections arrive before 20 ms. There are other relevant peaks at 40 ms (5) and at 70 ms (6).

In the angular reflectogram can be noticed that third peak arrives from a different direction respect 1, 2 and 4, but it’s not perceived as a different peak by the human hear. Peaks 5 and 6 can be perceived as separate echoes, so they can confuse the voice of the speaker. Comparing direction and arrival time of these two peaks with the shape of the room it can be said that they arrive after multiple reflections. The last emitting surface can be easily located and corrected.

Many reflections of comparable intensity with that of the direct sound characterize the classroom (figure 10, large room). The measurements point is very far from the source, in correspondence of the last row of chairs. The chairs of this row are not provided with back so the reflections arrive by all the directions with high intensity.
146 Modelling and Experimental Measurements in Acoustics III

It is possible to distinguish two peaks with a large angle (2,3) in the angular reflectogram. These, for instance, are associated to the reflections on the side walls. Many undesirable reflections come from the wall back to the listener (4,5). A back panel around the seat can reduce the undesirable effects due to these echoes.

4 Conclusions

Thanks to the invariance of the test signal and of the environments it was possible to obtain this kind of measurement with a monodimensional intensimetric probe. This is a low cost operating method that permits to obtain information on reflections magnitude and direction, together with their delay time, in a room.

References