Measurements of the sound energy polarization at some locations inside an Italian opera house

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Abstract: The measurement of a new discovered property of sound energy i.e. the polarization, has been carried out for the first time inside an opera house. This quantity, whose effective value in dB rel. to 10^{-12} Watt/m^2 accounts for the amount of energy which just oscillates through the measurement point, has also a more complete representation as an intensity ellipsoid oriented in space by means of a reference frame associated with the 3D sound intensity probe. The highly symmetric architectural structure of the historical “Teatro Comunale” in Ferrara, Italy, has been investigated at three locations comparing the sound energy polarization with the sightline from each measurement point to the stage. Furthermore the transient behavior of oscillating energy has been monitored during the sound decay. The obtained results are here condensed.

INTRODUCTION

The term polarization used in the acoustical context is not referred to as a characteristic of the sound propagation (which of course cannot be "polarized" due to the longitudinal nature of the sound wave) but is a property of the time-averaged sound intensity as introduced in [1]. For what we are here concerned it’s enough to recall the definition of oscillating intensity whose physical interpretation is given in [2]: \( r(t) = j(t) - a(t) = \langle j^{2} \rangle (p^2 - \langle p^2 \rangle) \), where \( j \) is the usual instantaneous sound intensity and \( a(t) = \langle p^2 \rangle \) is the radiating intensity, \( p \) and \( v \) are sound pressure and particle velocity respectively, while \( \langle \cdot \rangle \) stands for the stationary time-average process. It is easily shown that the usual active intensity coincides with the time average radiating intensity \( A = \langle a \rangle \); on the other hand, since \( \langle r \rangle = 0 \) by definition, the second order statistical moment \( R = \sqrt{2 \langle r \otimes r \rangle} \) must be evaluated to get a suitable measure of oscillations of energy. Roughly speaking both the magnitudes of \( A \) and \( R \) can be evaluated using a dB rel. to 10^{-12} Watt/m^2 scale (as in Table 1), moreover \( R \) can also be represented as an ellipsoid in the intensity space. Precisely this last kind of representation of \( R \) is visualized in the next section for three locations inside the “Teatro Comunale” in Ferrara. The next figure sketches the three measurement points and the experimental setup prepared in the theater.

The measurement of sound energy polarization has been accomplished by using a new kind of sound intensity-meter entirely developed at CIARM-CNR Cemoter Laboratories in Italy.

MEASUREMENT OF THE STEADY SOUND FIELD ENERGY POLARIZATION

Table (1) reports the overall (50 + 1200 Hz) levels of the radiating and oscillating intensities and of the sound pressure. At every point the inequality \( ||R|| > |P_{rms}| > |A| \) holds. Thus the flow of energy is mostly localized, due to the high value of \( ||R|| \), rather than transmitted to outer regions by \( A \).

| Measurement Point          | \(|A|\)    | \(|P_{rms}|\) | \(||R||\)     |
|----------------------------|-----------|--------------|--------------|
| 1° Order, Box 7            | 78.6 ± 0.2| 84.8 ± 0.2   | 89.2 ± 0.5   |
| Stalls, Row 13             | 79.4 ± 0.2| 86.9 ± 0.2   | 92.4 ± 0.5   |
| 1° Order, Box 17           | 81.8 ± 0.2| 84.8 ± 0.2   | 90.2 ± 0.5   |

(Table 1)

Moreover, in the next figure the measured polarizations are compared (left to right: 1° Order, Box 7; Stalls, Row 13; 1° Order, Box 17). Units are 10^{-3} Watt/m^2. All the ellipsoids are stretched along the source-measuring line, but two major differences can be revealed: between the central ellipsoid and the lateral ones. Firstly, the former has
longer hemiaxes indicating that there is more energy trapped here, than at the boxes mouth. Secondly, though the lateral ellipsoids have not equally long hemiaxes, they are both squashed along $z$. It can then be said that the energy polarizations at the mouths of the two symmetric boxes are similar but they differ from that measured at the stall.

![Image of ellipsoids]

**TRANSIENT BEHAVIOR**

Oscillating intensity has been also studied during the transient condition which establishes after having turned off the source (reverberation process). At the three points of Table (1) both the pressure $g_p(t)$ and velocity $g_v(t)$ impulse responses have been evaluated by means of a B&K 4433 analyzer connected to the 3D probe and sending its instantaneous analog outputs (in turn pressure and velocity) to the MLSSA board on a PC. Multiplying the impulse responses, sample by sample, we obtained the quantity: $g_i(t) = g_p(t)g_v(t)$ which represents the total instantaneous intensity caused by a broad band impulse having the same spectral density of the signal employed for the previous steady measurements. It is possible to split even the transient intensity $g_i(t)$ into an oscillating and radiating part, simply by defining the two stationary-like averages: $\langle g_i \rangle_N = \frac{1}{N} \sum_{i=1}^{N} g_i$, and $\langle g_p^2 \rangle_N = \frac{1}{N} \sum_{i=1}^{N} g_{p,i}^2$, where $N$ is the number of points in the sampled time history; in this way the two radiating-like and oscillating-like components can be defined as: $g_a(t) := \frac{\langle g_p^2 \rangle_N}{\langle g_i \rangle_N}$ and $g_r(t) := g_i(t) - g_a(t)$. It can be seen that these quantities are independent of $N$, furthermore $\langle g_a \rangle_N = \langle g_i \rangle_N$ and $\langle g_r \rangle_N = 0$ according to the usual stationary definition of $a$ and $r$. The plot of $g_r$ for the stall measurement point, corresponding to the central ellipsoid in the above figure, is reported below.

![Plot of oscillations]

**CONCLUSIONS**

Sound energy polarization has been measured in an Italian opera house, both in steady state and transient field conditions. Three locations were investigated: the mouths of two first order opposite boxes and the central stall between them. While the measured polarization confirm the predominant contribution of direct sound for energy oscillations at all the three locations, the similar values obtained at the boxes seem to be related to the architectural symmetry. Furthermore the transient behavior of this quantity at the central stall show a more uniform distribution in time of the energy oscillations along the $y$ axis (orthogonal to the sightline) while synchronous oscillations happen along the sightline and the $z$ direction. Work is in progress at CIARM to establish the psychoacoustic relevance of the sound energy polarization.

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**REFERENCES**