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ACOUSTIC ANALYSIS OF THE ST. MARK'S BASILICA IN VENICE BY MEANS OF QUADRAPHONIC IMPULSE RESPONSE MEASUREMENTS

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ABSTRACT
A measurement campaign inside the Basilica di San Marco in Venice has been conducted with the purpose of characterizing the acoustical properties of some source-receiver configurations which are of interest from the historical point of view. Measurements of quadraphonic impulse responses (including sound pressure and three components of particle velocity vector) have been done with the purpose of studying the relationship between standard room acoustics indices as clarity and reverberation with the behaviour of energetic quantities.

INTRODUCTION
The St. Mark's Basilica in Venice dates back in its present form to the eleventh century and is one of the most important examples of romanesque-bizantine architecture in Italy. The plan of the church is of Greek cross, covered with five hemispherical domes: one over the crossing of the main nave with the transept and the other four, of smaller dimension, on the arms of the cross, connected to each other through barrel vaults which are sustained by massive piers. In the east end of the main nave lies the presbiterial area, which is separated from the church central space by a dividing structure, the *iconostasis*, and terminates with a central apse flanked by other two smaller apses closing the side naves. The main materials used in the interior are marble, mostly at the base of the piers and on some parts of the floors, glass mosaic on the vaults and domes, and several kinds of stones slabs in the floor.

From the sixteen century until the fallen of the Serenissima Republic of Venice, the Basilica was the main site where a particular style of vocal polyphony, the "cori spezzati" (broken choirs), was executed. From a musical history point of view the area of greatest interest is that of the chancel, since there took place all the ceremonies and performances of the Cappella Marciana, the doge's choir in permanent service at the Basilica. In this context different group of singers occupied specific positions, as the medieval pulpit at the right of the iconostasis (the so-called *pulpitum magnum cantorum*, or *bigonzo*), the two later "pergoli" built by the architect Sansovino at each side of the choir area, and the two upper galleries hosting the organs (Fig. 2). As regards the listening points, from several historical documents it is possible to identify those reserved for the various personages attending the ceremonies (see the list reported following section) like the one traditionally reserved for the doge, which in 1535, during the dogeship of Andrea Gritti, was moved from the bigonzo to a seat positioned just behind the iconostasis at the right side of the chancel, changing in significant way the listening conditions [1].

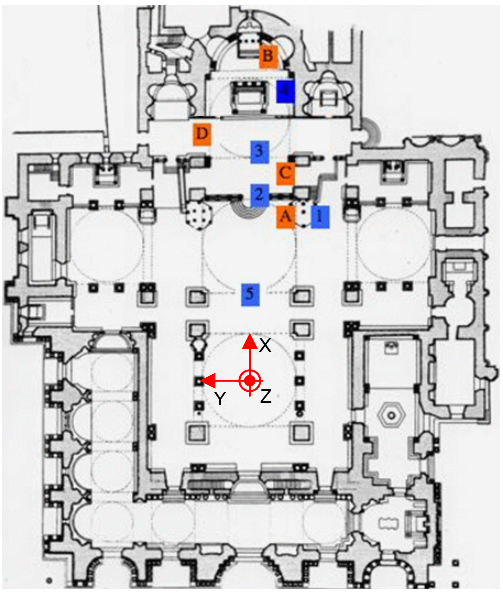
THE MEASUREMENT METHOD
The measurement system, specifically designed for acquiring impulse responses according to the quadraphonic approach (see for example [2]), is based on a 3D Microflown intensimetric probe [3], which is capable of detecting both the sound pressure and the three components of acoustic velocity and a dodecahedron loudspeaker as a sound source. A laptop PC connected to a multichannel firewire digital audio interface is used for generating and playing the test signal generation, calculating the response and its subsequent analysis. The adopted measurement technique is that of logarithmic swept sines. The whole process is implemented on a Matlab routine.
Seventeen measurements have been executed corresponding to the positions of the source and the receiver reported in the list below (see also Fig.1 and Fig.2). The sequence of configurations measured has been the following: A2, A4, A5, B1, B2, B3, B5, C1, C2, C3, C4, C5, D1, D2, D3, D4, D5.

Sources

A. *Pulpitum magnum cantorum* (singers of Cappella Marciana during mass and vespers);
B. Presbiterio (clerics singing the plainchant);
C. South pergolo (choir singing during vespers);
D. Upper gallery (organ, instrument players, singers).

Receivers

1. *Pulpitum magnum cantorum* (doge's position before XVI century);
2. Right side of the chancel behind the iconostasis (doge's position from XVI century);
3. Main choir area (government members);
4. Central apse (clerics);
5. Nave (faithfuls).



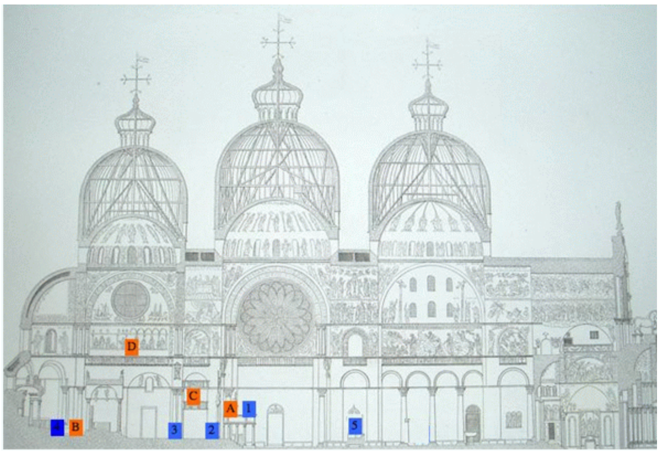


Figure 1.-Ground plan and longitudinal section of St. Mark's Basilica reporting the excitation points (letters) and receiver points (numbers).

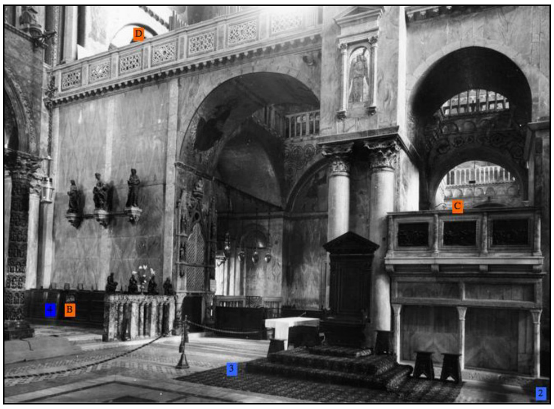


Figure 2.- Left Picture. East side of the interior of St Mark's Basilica: the iconostasis with the *pulpitum* magnum at its right. Right picture. The right side of the choir with the south organ loft at the top left and the *pergola* on the right.

As shown in some previous papers the set of signals formed by impulse responses of sound pressure and air particle velocity represents the maximum of acoustic information which can be determined in a point of a sound field. From a physical point of view this fact is related to the energy and momentum conservation equations that can be expressed in terms of these quantities [4]. In a practical context, a large variety of indices extending the traditional analysis based on sound pressure can be obtained. Among these we here recall:

- the Schroeder plots for potential (i.e. due to pressure) energy density and the three components of the kinetic energy density (due to velocity):

$$W_P(t) = \int_t^\infty \left[g_p(\tau)\right]^2 d\tau \qquad W_{K_i}(t) = \int_t^\infty \left[g_{v_i}(\tau)\right]^2 d\tau \quad i = x, y, z \tag{1}$$

- the distribution vector of instantaneous intensity (impulsive intensity):

$$\mathbf{g_j}(t) = g_p(t)\mathbf{g_v}(t) \tag{2}$$

- calculation of time-averages indices describing the property of field confinement, like the radiation index η:

$$\eta = \frac{\left|\langle \mathbf{j} \rangle\right|}{c\left(\langle W_P \rangle + \langle W_K \rangle\right)} = \frac{\sqrt{\sum_{i=1}^{3}\left[\int_0^\infty g_p(\tau) g_{v_i} d\tau\right]^2}}{c\left(\int_0^\infty \left[g_p(\tau)\right]^2 d\tau + \sum_{i=1}^{3}\int_0^\infty \left[g_{v_i}(\tau)\right]^2 d\tau\right)} \tag{3}$$

Since the main purpose of the present memory is that of understanding as deeply as possible the transmission of sound inside the interior of the St. Mark's Basilica we'll first present an overview of the standard room acoustic parameters and try to compare their behaviour with that emerging from the energetic analysis.

RESULTS

As an example Fig. 3 reports, for all the measurements points, the values of Reverberation Time (T60 calculated between -5 and -45 dB), Early Decay Time (EDT) and Centre Time (Tc), obtained from Schroeder backward integral of the pressure signal only. All the data sets are characterized by a noticeable variation with position which is most evident in Tc and least in T60. In particular, point C2, having the shortest relative distance between the source and the receiver, is the configuration with the smallest values, and suggests a likely optimal listening condition. The points with the largest values are those referred to the receiver placed in the nave (A5, B5, C5, D5), meaning that in that conditions a big amount of reverberation reaches the receiver due to the surrounding space of the church. This simple analysis show how in such a complex environment the different balance between early reflections and the reverberation tail can modify substantially the fundamental parameters characterizing the subjective properties of the sound field. In the common acoustical jargon one may say that sound transmission occurs in a highly non diffuse way because big differences emerge between measurement points and reverberation times calculated taking different sections of the decay curves do not coincide.

This phenomenon can be examined by looking at the radiation index η reported in Fig. 4. According to Eq. (3) it may be interpreted as the ratio of average radiated energy to the total one for a stationary broad band sound field. In practice, a value close to unity is encountered when plane progressive waves are predominant, while values close to zero are related to sound fields formed by standing waves with most of the energy stored around the measurement point. The most remarkable fact is that the variation of the η index with the measurement position appears roughly symmetrical with indices EDT en Tc and, to a smaller extent, to the T60 as can be seen from the plot of cross-correlation function shown in Fig. 5. Low radiation indices, in this specific case of the order of 0.1, are related to larger early decay and centre times meaning that sound energy decreases slowly due to the lack of early contributions and the presence of many interfering terms which create a standing-wave like sound field. The measurement points where the radiation index is large (up to 0.4-0.5) are those where the source and receiver are located along a path where energy is transferred in the average by a progressive-like wave field. This occurs in practice when source and receiver are close to each other and with no big obstacles on their direct path. In this case in fact energy carried by plane progressive waves is not negligible and makes the decay slope occurring soon after the source switching off higher.

A representation of the energy transfer pattern can be achieved by looking in detail the quantities defined in the previous section. As an example Fig. 6 and 7 show the impulsive intensity and the Schroeder decay of the four terms of sound energy in the two measurement points B3 and B5, which represent two extreme cases in the above characterization. Looking at the left plots it may be noticed that the second case differs form the first in having an energy flux vector with delayed contributions which are of the same amplitude of direct one as it is expected in a "diffuse" sound transmission. Even the Schroeder's plots show interesting properties that can be ascribed to the different way the energy is radiated: in the first case the fast decrease of pressure signal (giving an EDT less that 2 seconds), is clearly related to the abrupt decay of kinetic energy along X, which is the direction where the direct sound come from.

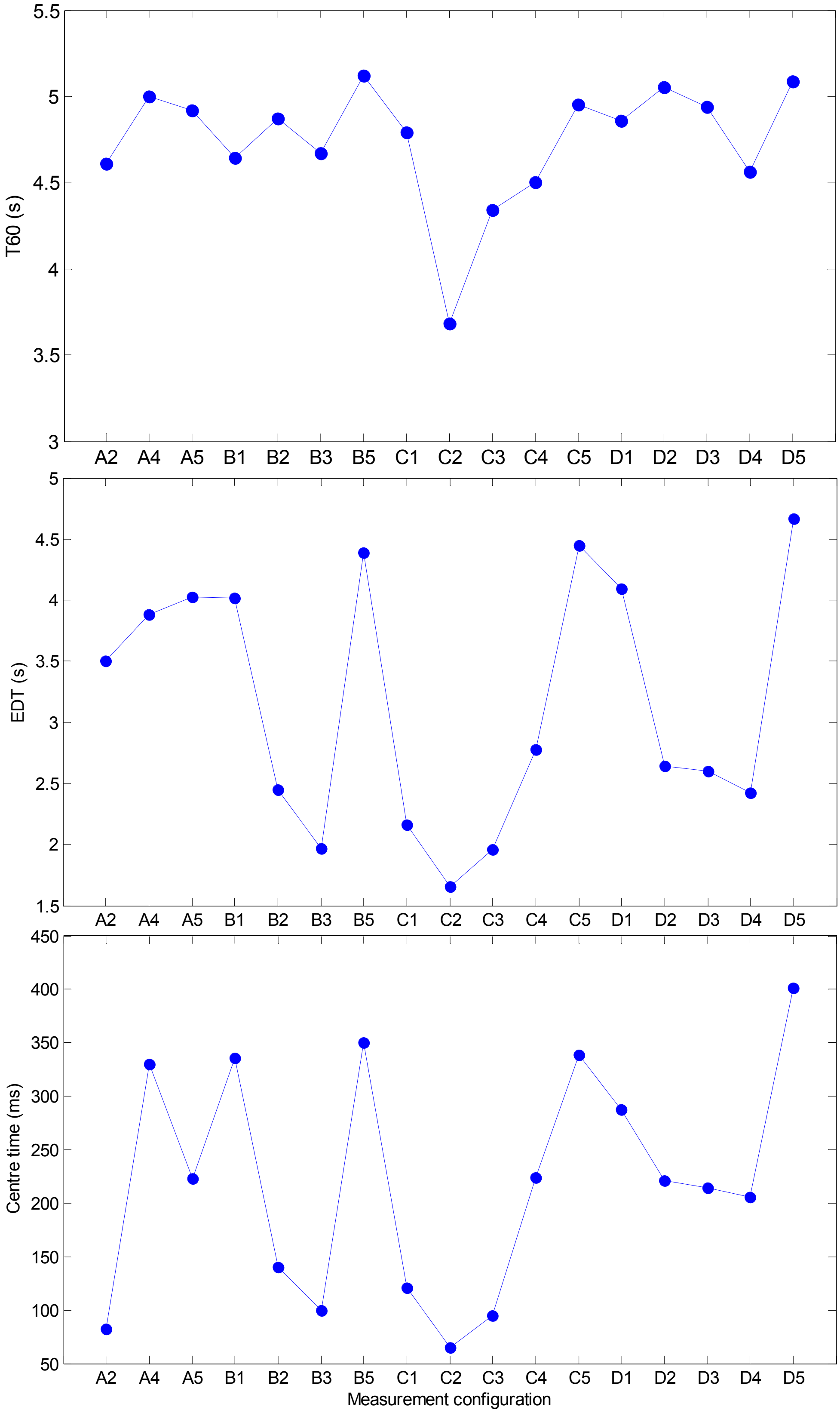


Figure 3.-From top to bottom: Reverberation time, Early Decay Time and Centre Time of the 17 measurement points.

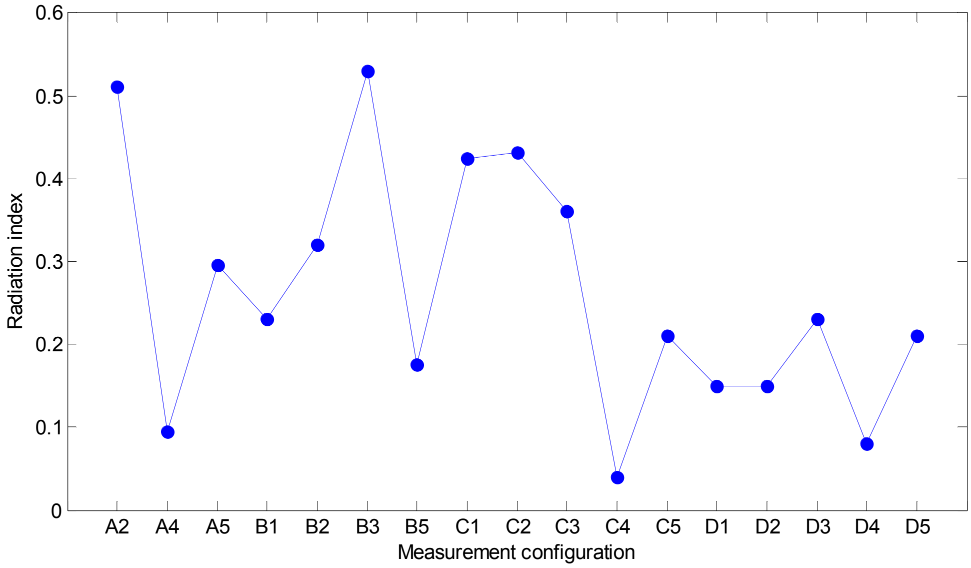


Figure 4.- η index.

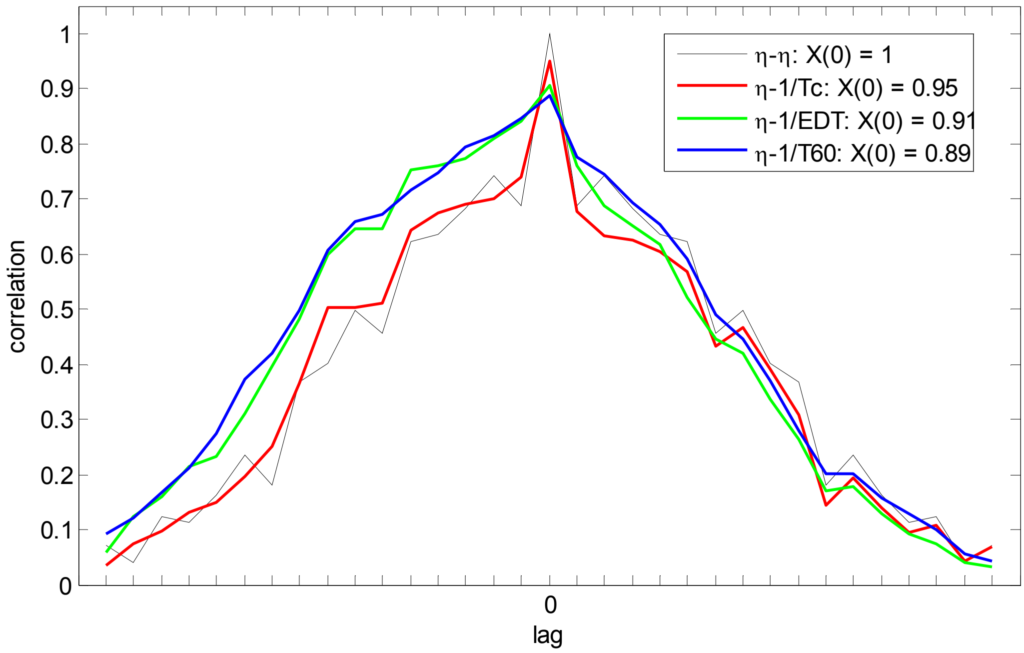
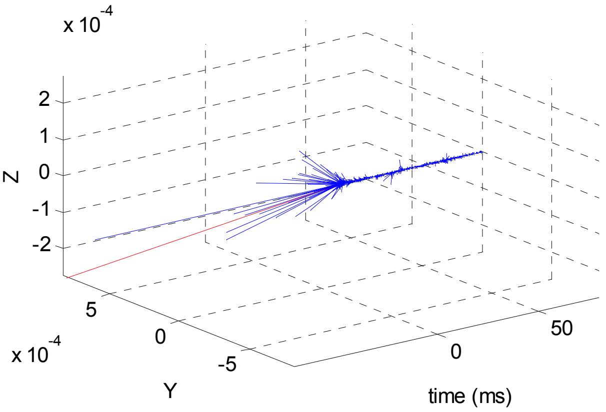


Figure 5.- Correlation function between η index and parameters 1/Tc (red line), 1/EDT (green line) and 1/T60 (blue line). Autocorrelation of η (black line) is reported for comparison. The value at zero lag (X(0)) show the degree of correlation between the indices.



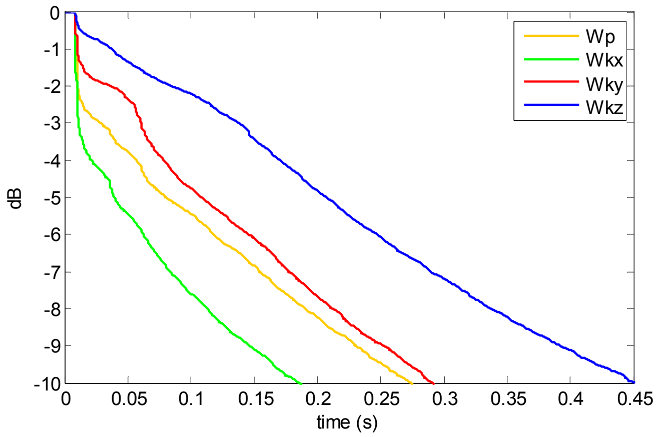


Figure 6.- Left: 3D representation of the first 80 ms of impulsive intensity in B3 (Notes: X axis coincides with time axis, the red line indicates the direct sound). Right: early decay of single energy components.

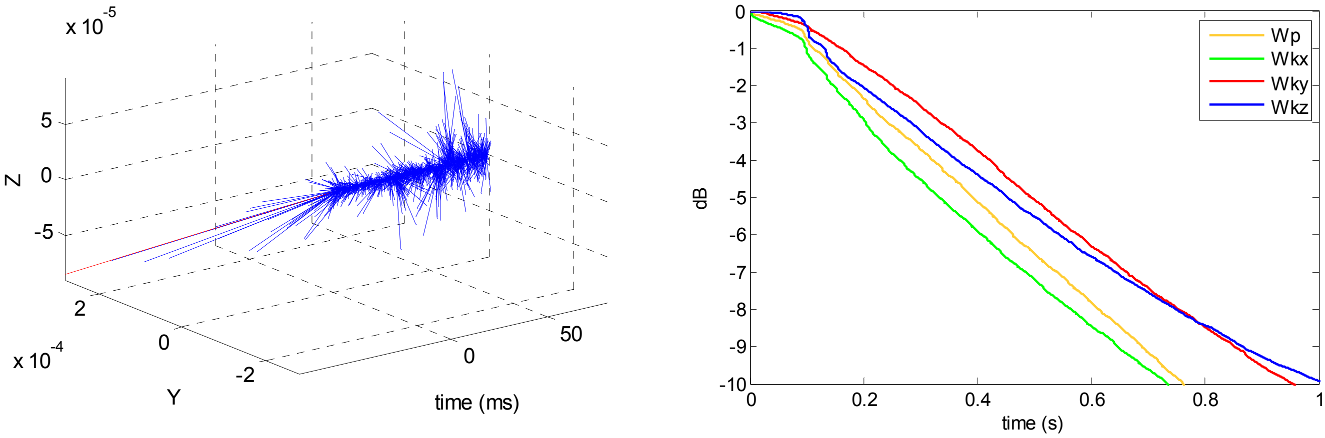


Figure 7.- Impulsive intensity and decay of energy components in B5.

CONCLUSIONS

The above reported results confirms the great complexity of acoustic fields which can be generated inside the St. Mark's Basilica in Venice. The well-constructed spatial layout ascribable to different architectural volumes affect the behaviour of energy decay curves which are found to be strongly dependent on the source-receiver configuration. This clearly proves that the acoustic field inside the Basilica is not at all a diffuse field. In spite of this, a remarkable correlation is found between the radiation indicator η and differently calculated time-averaged parameters related to energy decays, thus strengthening the robustness of quadraphonic measures. A deeper insight of transient behaviour of the sound energy transfer is achieved by analyzing the impulsive intensity distribution in the first part of energy decays. This explain the already observed fact that different decays rates can coexist for potential and kinetic parts of sound energy depending on spatial properties of energy transfer. In conclusion quadraphonic room acoustic indicators not only allow a more complete physical analysis of complex sound fields than traditional ones based only on pressure measurements, but thanks to their high reliability and robustness, they can be also employed for studying perceptual aspects of communication acoustics.

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