SOME OBSERVATIONS ON THE THEORETICAL PREDICTION OF STRENGTH AND CLARITY INSIDE HIGHLY DIFFUSING ROOMS

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ABSTRACT

The paper reports the results of an acoustic survey which took into account nine Romanesque churches built in Apulia (Italy), with reference to the measurements of strength and clarity. These values were compared with those predicted by means of theoretical formulas. The results showed that strength is generally underestimated near the source and overestimated at distant points, while clarity is generally overestimated. This behaviour was thought to be due to the highly diffusing architectural elements which were inside the analysed churches. A revised formula is finally discussed in order to obtain better predictions.

INTRODUCTION

In recent years many acoustic parameters have been gaining more and more importance and most of them have been standardized by means of ISO 3382 [1]. Strength (*G*) and clarity (C_t) are two of the most widespread parameters because they provide essential information about the acoustic quality of a room and can be determined quite easily from monaural impulse responses. These acoustic parameters are much more position-sensitive than reverberation time, therefore they provide a more detailed description of the acoustic characteristics of a room.

As a consequence of the growing importance of both strength and clarity many attempts have been made in order to predict their values by means of formulas, or, better, of theoretical models. Many simple relations may be found between room average values of both parameters and mean values of reverberation time. As the strength factor depends on the total acoustic absorption, the room geometry (represented by its volume) plays an important role as well [2]. However, when a parameter is position sensitive, its room average value provides only a partial information, and, in order to predict its local values, a more comprehensive theory is needed.

Barron and Lee [3] proposed a model to predict strength and clarity which proved to be significantly reliable in many auditoria. The model is based on simple assumptions and accounts for the reverberation time (*RT*), for the room volume (*V*), and for the source-receiver distance (*r*). However, Barron and Lee observed that the model did not perform well in rooms with highly diffusing ceiling, where a steeper decrease of the values with the distance was observed. A similar behaviour was found in many churches and other worship places [2,4-6], most of which had a wooden roof with trusses and many other scattering elements such as columns, arches, and niches. Sendra et *al*. [4] proposed a modification to Barron's model in order to predict strength in Mudejar-Gothic churches, but the same model proved not to be reliable in predicting clarity [5].

In this paper, the results of an acoustic survey, carried out in some Romanesque catholic churches built in Apulia (Italy) were used to analyse the problem and to propose some corrections to Barron's theory in order to achieve better performance in predicting strength and clarity inside this kind of places.

THE CHURCHES SURVEYED

The churches analysed in this survey were built in the Romanesque period and share many architectural features such as the basilican plan, with a main nave and side aisles, the wooden roof with trusses, the marble floor with wooden pews, and hard limestone walls and columns. Nevertheless, they have different dimensions, with volumes ranging from 32000 to 1500 m^3 (see Table 1), and specific features briefly described below. St. Nicholas Basilica has a wooden ceiling with painted canvases and two columns which separate the nave from the transept. Bari Cathedral has false women's galleries (i.e. the side aisles are higher and roofed), and on the crossing there is a dome. Bitonto Cathedral has a wooden roof with densely spaced trusses and a pulpit on the right pillar of the triumphal arch. Barletta Cathedral is partly Romanesque and partly Gothic; the first part has wooden roof, the latter has ribbed cross-vaults and a choir with radial chapels. Bisceglie Cathedral has only one big apse on the main nave, on the presbytery area there are carpets and a wooden choir. Ruvo Cathedral has no women's galleries and the aisles are cross vaulted. Bovino Cathedral has no women's galleries but both the nave, and the aisles are roofed; the walls are plastered. Ognissanti church has a domed nave, while the aisles are barrel-vaulted.

Table 1. Geometric details of the 9 churches surveyed.

Id	*Church*	*Volume (m^3)*	*Floor area (m^2)*	*Total area (m^2)*	*Length (m)*	*RT_{mid} (s)*
A	St. Nicholas Basilica, Bari	32000	1530	10500	54	4.4
B	Bari Cathedral	30100	1274	9500	46	5.3
C	Bitonto Cathedral	16000	858	6500	42	4.3
D	Barletta Cathedral	15800	912	5500	46	6.8
E	Bisceglie Cathedral	10150	534	4660	29	3.5
F	Ruvo Cathedral	6400	445	3000	29	3.7
G	Bovino Cathedral	3840	452	2420	22	3.8
H	Ognissanti church, Valenzano	1800	258	1300	19	5.4
I	Vallisa church, Bari	1520	162	1130	15	2.1

MEASUREMENT TECHNIQUE

The measurements were carried out using an omni-directional sound source made of twelve 100 mm loudspeakers mounted on a dodecahedron driven by a 300 W amplifier. A GRAS 40-AR omni-directional microphone was used together with a 01 dB Symphonie system installed on a laptop computer. An MLS signal was used to excite the rooms. The order of the signal was adapted to the reverberation characteristics of each room to avoid time-aliasing problems and each MLS sequence was repeated 32 times to improve the S/N ratio.

In each church at least two source positions were used, one on the symmetry axis and one off the axis, both in the presbytery area. The source was placed 1.5 m from the floor. Nine receiver positions were used on average. In very large but symmetrical churches the receivers were only placed in one half of the floor, otherwise they were spread to cover the whole floor area uniformly. The microphone was placed 1.2 m from the floor surface.

All the measurements and the calculations of the indices were carried out according to ISO-3382 standard [18]. In particular the strength index (*G*) was calculated assuming as a reference the sound pressure level measured in a reverberation chamber, employing the same measurement chain and the same settings used during the on site survey.

RESULTS ANALYSIS

The analysis of the results showed that, in each church, the energy-based indices and source-receiver distance were significantly correlated (see Fig. 1). Even if it was impossible to find a general equation through regression analyses, the existence of such correlations supported the idea that more general equations could be found to predict energy-based indices as a function of a simple geometrical parameter as the source-receiver distance.

Predicted and measured values of the strength index and early/late ratio were compared to estimate the reliability of Barron’s theory inside the surveyed churches. As can be seen in Fig. 1, and in Table 2, the following results were observed:

- the mean values of the strength index were predicted with reasonable accuracy, however the theory tended to underestimate the values at points near the source and to overestimate the values at points far from the source;
- the predicted slope of the strength index was always lower than the measured one. The mean difference was –1.1 dB/10 m, with a minimum of –0.3 dB/10 m and a maximum of −1.9 dB/10 m;
- the mean values of the clarity index were systematically overestimated. A similar behaviour was observed in each receiver position, where measured values were often below Barron’s curve;
- the predicted slope of the early/late ratio was always lower than the measured one. The mean difference was high, being –2.4 dB/10 m.

The explanation of this behaviour was found through the observation of the plot of the early (from 0 to 80 ms) and late (from 80 ms to infinity) energy as a function of the source-receiver distance. Fig. 2 and Table 2 show that there was good agreement between predicted and measured late sound levels. On the contrary, the values of the early energy were considerably overestimated by the theory. According to Barron and Lee [3] a high drop-off of the early level can be due to a highly diffusing ceiling which, in reflecting according to Lambert’s Law, sends less energy to the rear of the room (far from the source) than to the front. In a church it is not unusual to find trusses on the roof, columns along the nave, arches, niches and other architectural elements which scatter the incident sound and might lead to the observed behaviour.

Table 2. Relationship between measured and Barron’s values of energy-based indices based on linear regression with source-receiver distance. Mean level differences (dB) and slope differences (dB/10 m) between measured and theoretical values at 1 kHz frequency band.

	G		*C_{80}*		*Early*		*Late*	
Church	*Mean*	*Slope*	*Mean*	*Slope*	*Mean*	*Slope*	*Mean*	*Slope*
St. Nicholas Basilica, Bari	0.1	–0.8	–3.5	–1.5	–2.9	–2.2	0.6	–0.6
Bari Cathedral	–0.4	–0.7	–2.8	–1.3	–3.0	–1.7	–0.1	–0.6
Bitonto Cathedral	–0.1	–1.2	–1.0	–1.3	–1.1	–2.3	–0.1	–1.0
Barletta Cathedral	–0.4	–1.5	–5.0	–2.3	–4.9	–4.5	0.0	–1.5
Bisceglie Cathedral	0.5	–1.9	–2.0	–2.9	–1.8	–4.6	0.8	–0.2
Ruvo Cathedral	–0.9	–1.6	–1.7	–3.6	–2.6	–4.5	–0.7	–0.6
Bovino Cathedral	–0.4	–1.1	–1.4	–3.0	–2.2	–2.6	–0.4	–0.1
Ognissanti church ,Valenzano	–0.3	–0.9	–1.6	–3.7	–2.0	–4.7	–0.1	–0.3
Vallisa church, Bari	–0.6	–0.3	–1.6	–2.5	–1.4	–1.7	0.0	1.0
Mean	*–0.3*	*–1.1*	*–2.3*	*–2.5*	*–2.4*	*–3.2*	*0.0*	*–0.4*
Standard Deviation	*0.39*	*0.48*	*1.26*	*0.94*	*1.13*	*1.33*	*0.48*	*0.68*

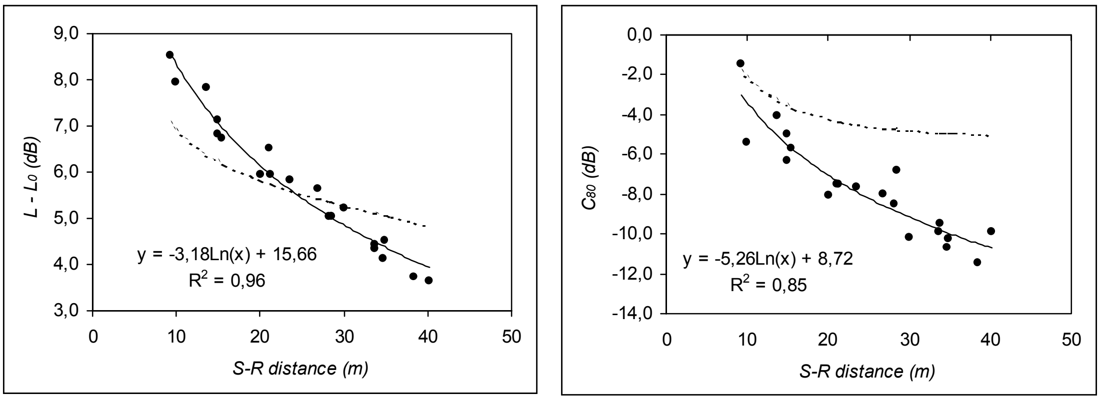

Figure 1 – Plot of measured (●) and predicted (- - -) values of the strength index (left) and early/late ratio (right) at 1 kHz octave inside St. Nicholas Basilica vs. source-receiver distance. (—) regression lines.

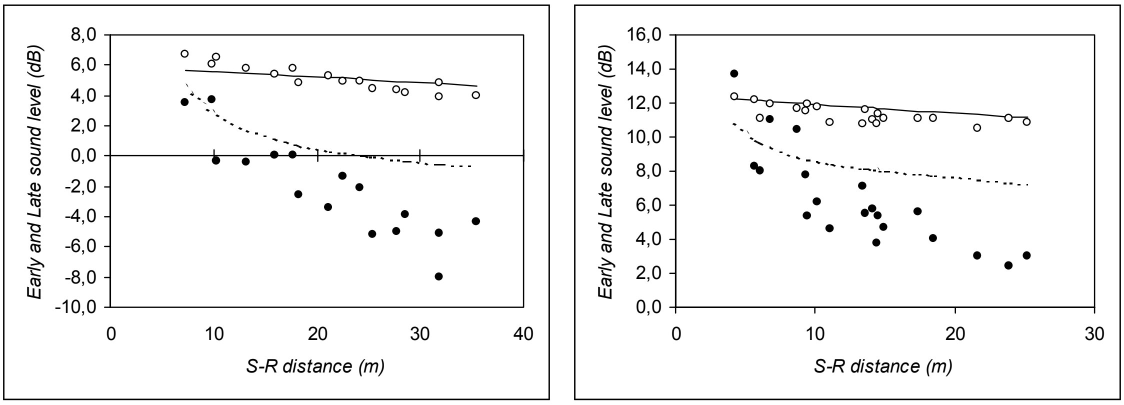

Figure 2 – Plot of predicted (using Barron's model) and measured early and late sound level at 1 kHz octave as a function of the source-receiver distance relative to Bari Cathedral (left) and Bovino Cathedral (right). (●) measured early level, (- - -) predicted early sound level, (○) measured late sound level, (—) predicted late sound level.

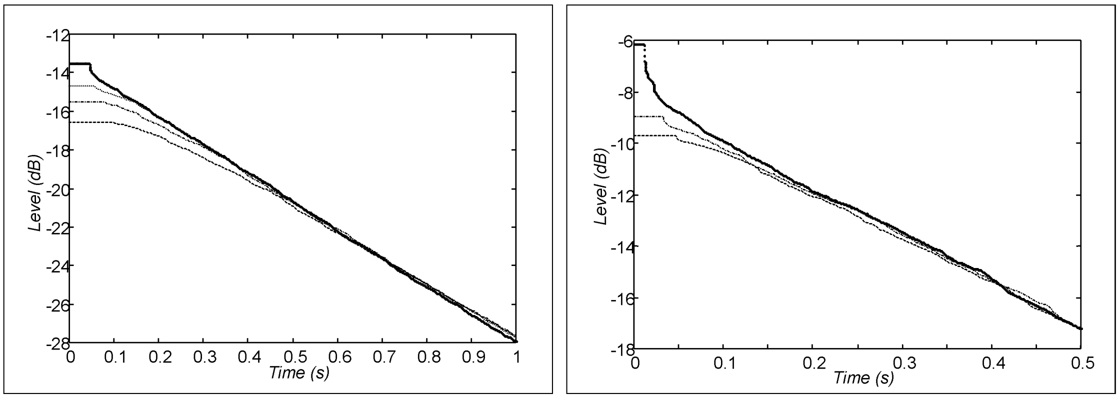

Figure 3 – Early decay traces at 1 kHz octave, measured in different points of the nave of St. Nicholas Basilica (left) and of Ruvo Cathedral (right). Lower curves correspond to farthest points.

The behaviour of the early sound was further investigated by plotting the early decay traces of points at different distance from the source. Fig. 3 shows two examples of such curves. First of all it was observed that the reverberant sound field was sufficiently uniform at different points of the room, in fact, the linear parts of each decay curve were nearly coinciding. It appeared, however, that the time at which the decay began to be linear grew with the distance from the source. Then, the early energy and the "ideal" reverberant field, extrapolated by extending the linear part common to all the decay traces, were compared. At points near the source the early reflections brought more energy than the ideal reverberant field, in fact the decay curves were above the line. On the contrary, as the distance from the source grew the early reflections became weaker and the decay curves moved below the ideal line. This behaviour influenced the early decay time that in most cases showed a tendency to grow with the source-receiver distance.

IMPROVING THE MODEL

The results discussed above show that the early energy part of Barron's model need to be revised to improve its prediction accuracy. In fact, the early energy decreases significantly as the source-receiver distance grows. This part of the sound decay is characterised by discrete reflections which are more or less spaced in time according to the geometry of the room. The magnitude of these reflections is proportional to that of the direct sound according to the characteristics of the room surfaces.

In order to simplify the model, the energy of the discrete reflections was schematised by means of a continuous linear function varying from an initial value (at the arrival time of the direct sound, $t = r / c$), proportional through a factor γ to the energy of the direct sound (d), and a final value (at time t + 0.08 s), equal to the energy of the reverberant field (g_{80}) at the same time. The factor γ was introduced to account for two different aspects of the early reflections: their magnitude and their spacing in time.

When a sound hits a wall, part of its energy is absorbed and part is scattered, the first is lost, while the second is "distributed" in time and space. Therefore, the early reflections are expected to contain only a fraction of the direct sound energy corresponding to the specularly reflected energy. So, the factor γ was assumed to be proportional to $(1 - \alpha)(1 - \delta)$, where α and δ are, respectively, the mean absorption coefficient and the mean scattering coefficient of the room surfaces. The estimation of the mean scattering coefficient can be somewhat difficult owing to the relative lack of data in the literature. However a rough, but realistic, estimation may be tolerated because the model proved to be quite immune to small variations of the parameter. Finally, in order to transform a discrete process into a continuous one, the factor γ had to account for the early reflection density $\varepsilon = 1/\Delta\tau$, where $\Delta\tau$ is the average time interval (in seconds) between two consecutive early reflections. A reasonable estimation of the early reflection density ε is given by the mean reflection frequency, calculated according to the classical diffuse-field theory as the ratio between the sound velocity in air *c*, and the mean free path (*MFP*) equal to 4*V*/*S*, where *V* is the room volume and *S* is the room surface area. In conclusion, the factor γ is given by:

$$\gamma = \varepsilon(1-\alpha)(1-\delta)\,. \tag{1}$$

According to Barron's theory the direct (*d*), early (e_r), and late (*l*) components of the sound field are given by:

$$d = 100/r^2\,, \tag{2}$$

$$e_r = (31200RT/V)\exp(-0.04r/RT)[1-\exp(-1.11/RT)]\,, \tag{3}$$

$$l = (31200RT/V)\exp(-0.04r/RT)\exp(-1.11/RT)\,. \tag{4}$$

The instantaneous value, at time $t + 0.08$, of the reverberant field energy is given by:

$$g_{80} = (31200\cdot 13.8/V)\exp[-(0.04r+1.11)/RT]\,, \tag{5}$$

so the "revised" integrated early energy e_r may be written as a trapezium area having γd and g_{80} as bases and 0.08 as height:

$$e_r = 0.08(\gamma d + g_{80})/2\,. \tag{6}$$

As an example of the effects of the new model on both early and late energy, Fig. 4 (left) shows the early, late and total energy levels calculated by means of Barron's theory compared with those obtained using the proposed model. It can be seen that the "new" values show a steeper decay as the distance from the source grows, in agreement with the results shown in Fig. 1. Fig. 4 (right) shows the early decay trace of points at increasing distances from the source, calculated using the modified model.

Figure 5 shows the better agreement between measured and theoretical values calculated using the proposed "revision". Table 3 reports the differences between measured and predicted data, showing that the mean errors are considerably reduced.

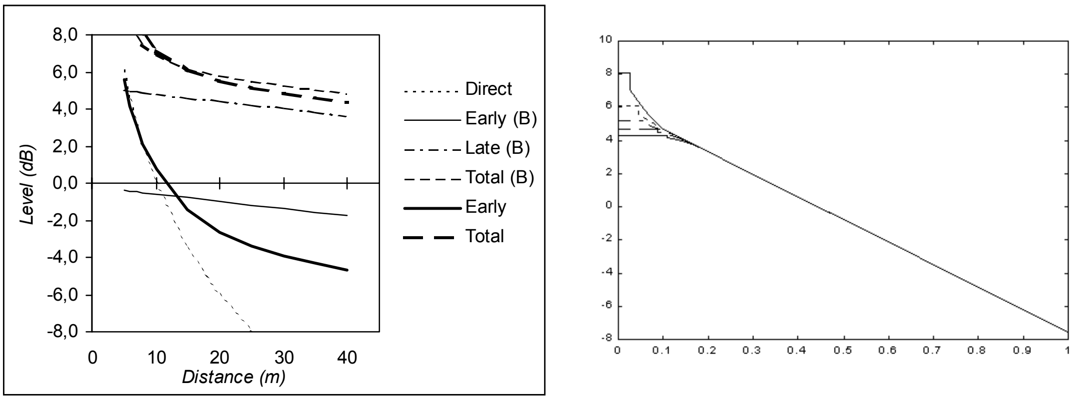

Figure 4 – Left: theoretical behaviour of the various temporal components of sound energy as a function of source-receiver distance according to Barron's model (B) and to the proposed model (thicker lines). *Right*: theoretical early decay trace calculated at 1 kHz using the proposed model. Different curves correspond to points at different distances from the source. (V = 33000 m^3, RT = 4.4 s, γ = 20).

Table 3. Relationship between measured and theoretical values of the energy-based indices predicted using the improved model. Mean level differences (dB), r.m.s. error (dB) and slope differences (dB/10 m) between measured and theoretical values at 1 kHz frequency band.

	G			*C_{80}*		
Church	*Mean*	*RMS*	*Slope*	*Mean*	*RMS*	*Slope*
St. Nicholas Basilica, Bari	0.3	0.7	–0.6	–2.1	2.4	–0.5
Bari Cathedral	–0.2	0.5	–0.4	–1.5	1.9	–0.1
Bitonto Cathedral	0.1	0.7	–0.8	0.1	1.2	0.3
Barletta Cathedral	–0.1	1.2	–1.4	–2.9	3.2	–1.3
Bisceglie Cathedral	0.8	1.2	–1.2	–0.7	2.0	–0.7
Ruvo Cathedral	–0.5	0.8	–1.0	–0.1	1.4	–1.4
Bovino Cathedral	–0.1	0.4	–0.3	0.0	1.1	0.1
Ognissanti church ,Valenzano	0.0	0.2	–0.3	–0.1	0.8	–0.4
Vallisa church, Bari	0.2	0.5	0.7	0.6	1.0	0.7
Mean	*0.06*	*0.7*	*–0.60*	*–0.75*	*1.67*	*–0.38*
Standard Deviation	*0.36*	*0.3*	*0.61*	*1.18*	*0.78*	*0.71*

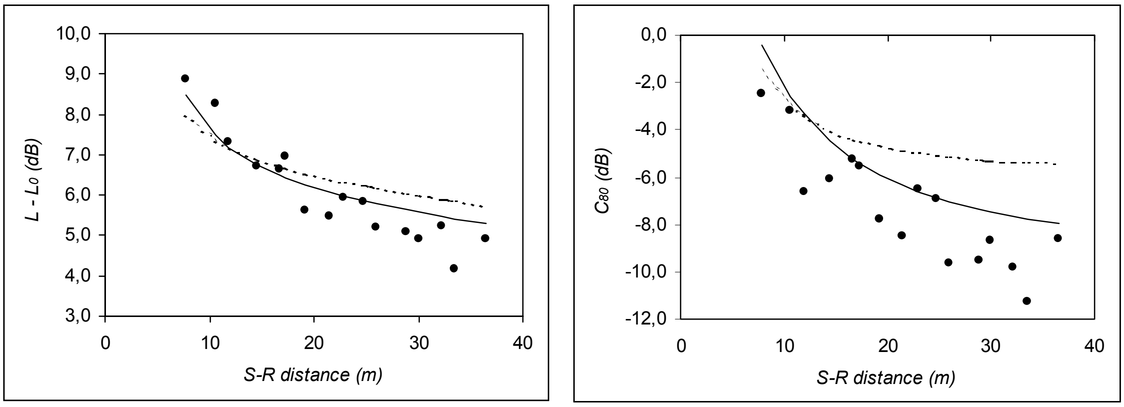

Figure 5 – Plot of measured (●) and predicted values of the strength (left) and clarity (right) index at 1 kHz vs. source-receiver distance according to Barron's model (- - -) and to the proposed model (—).

CONCLUSIONS

The results of the acoustic measurements of strength and clarity made in nine churches were used to investigate the prediction accuracy of Barron's model in this kind of places. The theory proved to be unsatisfactory, and it was observed that the early sound decrease with distance was steeper than predicted. A revised model for the early reflected energy was proposed and its better performance was shown. A more comprehensive model, more complex, but more accurate has been discussed in another paper [7].

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