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Reliability of Scale-Model Researches: a Concert Hall Case

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ABSTRACT

To verify the reliability of acoustical tests on concert halls performed by means of scale models, a quality evaluation has been carried out on a recently constructed concert hall in accordance with the Ando methodology. A scale model has been made of the same concert hall in which the effects of some modifications of the ambient geometry were examined both from the objective standpoint and from the viewpoint of the subjective acoustical quality.

This paper shows the results obtained in the above-mentioned research.

INTRODUCTION

In the last decade psychosubjective techniques for analysis of concert hall acoustic quality have been developed; in the mean time, sophisticated techniques for determining the acoustical features of enclosed spaces have also been developed.

Improvement in measuring techniques has permitted the definition of new descriptive parameters; in particular, progress has been made in the

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determination of the 'impulse response' of an enclosed space, originally defined as the sound pressure signal $p(t)$ received at a point in the hall after a positive pressure impulse has been generated at another point.

The impulse response, also named the 'reflectogram', can be obtained by means of the new techniques, such as the inverse Fourier transform of the transfer function. It is a function in the time domain that represents the response of the physical system connecting two positions (source and receiver) to a signal emitted at the source and composed of a single unitary positive sound pressure impulse of zero duration (Dirac's delta function).

Using digital recording and display techniques, it is possible to integrate the sound energy over arbitrarily selected time intervals of the impulse response and hence provide the opportunity to determine proportions between the energy received a little after the direct wave arrival and the late energy returning from the reverberant field.

The physical parameters achieved by these ratios, based on the acquisition of the impulse response, have been found to be well correlated with each other and with the initial time delay gap (ITDG) criterion, i.e. the time delay between the direct sound and the first strong reflection, as defined initially by Beranek.[1]

Furthermore, the new recording techniques have made it possible to obtain spatial descriptive parameters of the sound field, among which is the inter-aural cross-correlation (IACC) proposed by Schroeder.[2]

The IACC, which is directly measurable from dummy head binaural recordings, is defined as the maximum value of the mutual correlation of the signals obtained through the auricular microphones.

In 1985, Ando,[3] with the publication of his book *Concert Hall Acoustics*, examined the phenomenon of the transmission of sound information from the source to the listener's mind, and concluded that sufficient data are now available to set up a global preference scale; such a scale is obtained by linearly superimposing the preference scales obtained by the single physical parameters, after having reduced their units to the same scale by different weightings according to the pairs comparison technique.

According to Ando, eventually only four independent physical parameters need be considered: the listening level (LpA), the initial time delay gap (ITDG), the reverberation time (RT) and the inter-aural cross-correlation (IACC).

The listening level is measured by the sound pressure level weighted according to the A network; it is expressed in dBA. The initial time delay gap is the delay of the first reflection measured from the time of arrival of the direct wave at a given listening point; it is expressed in milliseconds.

The reverberation time is defined in the classic manner, as the time necessary for a decay of 60 dB of the sound field after the source has been turned off; it is expressed in seconds. For Ando's preference scale, the A-weighted reverberation time, extrapolated from the first 10 dB of the decay, should be considered. The inter-aural cross-correlation is measured by the maximum value of the normalized cross-correlation function of two impulse responses measured by two microphones placed in the dummy head auricular lobes. It is expressed as a dimensionless real number between zero (microphone signals with zero coherence in time) and one (identical microphone signals in time). This parameter is related to the degree of spatiality in the sound field and is a binaural type measure which requires the use of a dummy head.

The normalized inter-aural cross-correlation function $K_{\mathrm{lr}}(t')$ is defined by

$$K_{\mathrm{lr}}(t') = \frac{\displaystyle\int_0^T g_{\mathrm{l}}(t) g_{\mathrm{r}}(t+t')\,\mathrm{d}t}{\left[\displaystyle\int_0^T g_{\mathrm{l}}^2(t)\,\mathrm{d}t \int_{-T}^{+T} g_{\mathrm{r}}^2(t)\,\mathrm{d}t\right]^{1/2}}$$

where $g_{\mathrm{r}}(t)$ and $g_{\mathrm{l}}(t)$ represent the right-ear and left-ear impulse responses and t' represents the time delay between the two signals. The integration time T is 50 ms; the time delay is considered as ranging between -1 and $+1$ ms.

To evaluate the preference index of the IDTG and RT another parameter called the 'equivalent reflection amplitude' (A) is necessary; this defines the importance of the reflected field in relation to the direct field and influences the rating scale. This parameter is not an independent descriptor for assessment of quality, but it influences the weighting coefficients, w_i, of the other parameters. It is defined by

$$A = \frac{\left[\displaystyle\int_{5\,\mathrm{ms}}^{\infty} p^2(t)\,\mathrm{d}t\right]^{1/2}}{\left[\displaystyle\int_0^{5\,\mathrm{ms}} p^2(t)\,\mathrm{d}t\right]^{1/2}}$$

and represents the ratio between the reflected energy and the direct wave energy.

The first three parameters are a classical monophonic criterion, whereas the fourth (IACC) is a binaural criterion which evaluates the spatial impression due to the sound field.

For the first three parameters an 'optimum value' exists, which depends on the sound source; the optimum listening level is obviously related to the sound source power, whereas the optimum ITDG and RT are proportional to a time duration, characteristic of the musical piece, called the 'effective duration of the autocorrelation function' (symbol T_{e}). This effective duration is defined as the time after which the envelope of the long-time autocorrelation function of the overall music signals decreases to below 0·1. For the IACC, the optimum value is zero. Each physical parameter is then normalized to its optimum value.

Ando and others determined the preference evaluation scales, which have the same form for all four parameters, as follows:

$$S_i = w_i|x_i|^{3/2}$$

where x_i ($i = 1, 2, 3, 4$) represents the values of the normalized parameters and w_i are the weighting coefficients related to the deviation from the optimum value, defined in such a way that the relative importances of the physical parameters are correctly ranked.

The evaluation scale has been defined so that when the deviation of the parameter from the optimum value is zero then $x_i = 0$; in other words, when the optimum is reached, this scale gives a zero value ($S = 0$), whereas for every other value of the parameter it gives a negative value ($S_i < 0$).

The evaluation indices thus represent a decrease in preference when the parameter deviates from its optimum value. The total preference index is then defined by the sum of the four preference indices.

The fact that for the evaluation of the total preference index the exponent is set at 3/2 for all four parameters is perhaps an approximation of the method, although the experimental data reported by Ando validate the proposed relations for calculation of the total preference index.

THE CASE EXAMINED

Through the joint involvement of architects Castore Inc. and Ass. and acoustician L. Rocco, in 1983 a concert hall was constructed in Avellino, Italy, with 468 seats, as part of the building complex of the new school of music 'D. Cimarosa'.

This hall, inaugurated in 1984 with a concert given by the Teatro S. Carlo di Napoli orchestra, was highly acclaimed by both musical experts and the orchestra. For this reason it was considered a particularly interesting case for an in-depth acoustical study with the most advanced relevant techniques conducted both in the hall and on a model.

Therefore the acoustic quality of the hall has been analyzed by the Ando method and also by the traditional method of measuring the reverberation time at various frequencies.

Afterwards in a laboratory the measurement of the ITDG and of the equivalent reflection amplitude A, have been repeated on a 1:50 scale model of the hall, both in the actual configuration and in other configurations, with

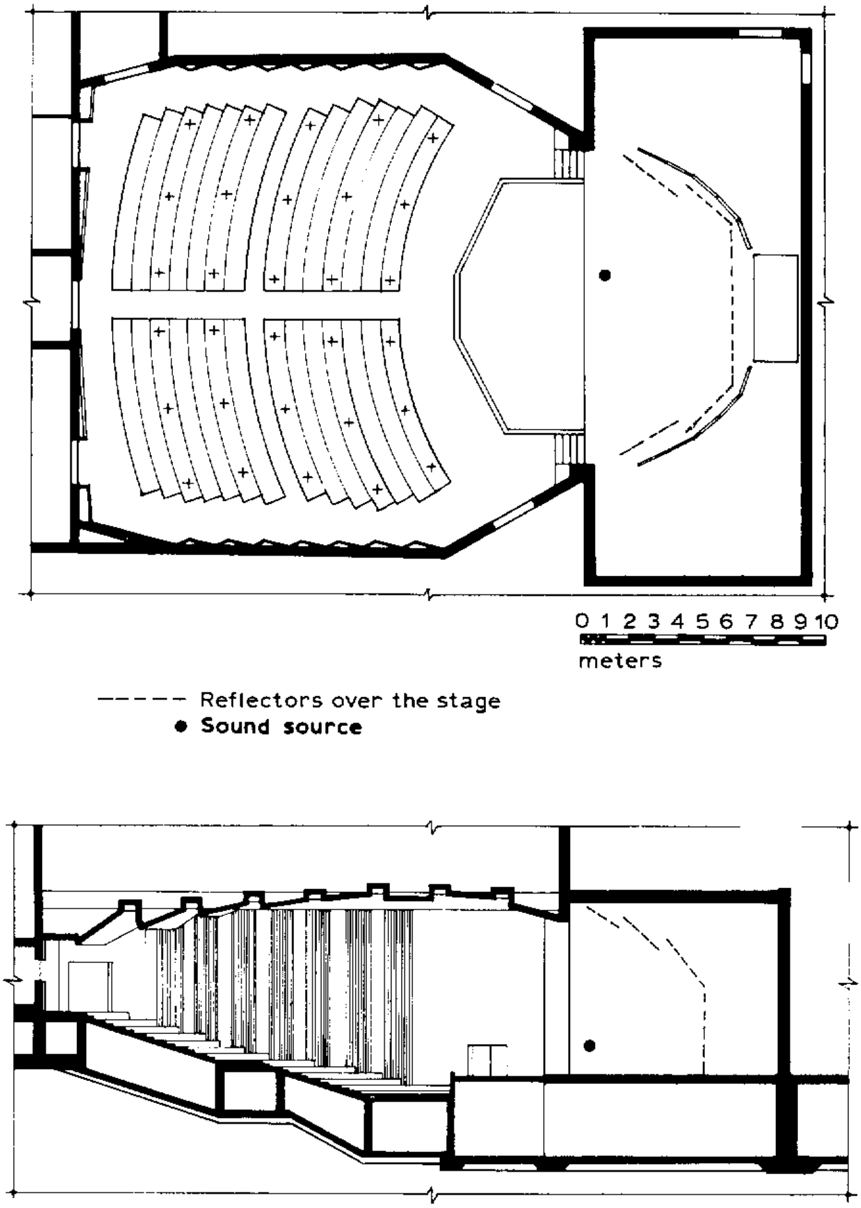


Fig. 1. Plan and section of the hall.

the purpose of examining the effects of the modifications introduced from an objective point of view and from the aspect of acoustic quality of the hall.

The technical characteristics of the hall have been defined in the design as follows:

Seats	468
Volume (m^3)	3 174
Audience floor area (m^2)	411
Stage area (m^2)	66
Audience ceiling area (m^2)	449
Total border area (m^2)	1 398
ITDG (center of auditorium) (ms)	14·5

Designed reverberation times

Hz	125	250	500	1 000	2 000	2 000
RT (s) (with audience)	1·81	1·32	1·23	1·23	1·23	1·32
RT (s) (without audience)	2·18	1·76	1·50	1·49	1·64	1·51

In Fig. 1 are shown the plan and section of the hall and the disposition of the sound-absorbing areas.

EVALUATION OF THE ACOUSTIC QUALITY ACCORDING TO THE ANDO METHOD

The measurements were executed with a Sony type WM-D6 recorder with binaural microphonic headphone. Thirty measuring points were located in the hall, uniformly distributed in the stalls; at each point the impulse response, obtained by a gun shot, and a time segment of 30-s stationary pink noise broadcasted with a loudspeaker was recorded.

From the first recording the ITDG value has been obtained by an Onosokki digital analyzer, type CF 920, shown in Table 1 and the reverberation times have been obtained with a Nortronic analyzer, type RTA 830, and processed according to the Schroeder backward integration method;[2] the values of the reverberation times mediated over all measuring points of the survey of the hall are shown in Fig. 2; for comparison, the results using the traditional measurement system and the design values are shown in the same figure. From the binaural recording of the pink noise the IACC value has been obtained, shown in Table 2; furthermore, the sound level LpA has been measured at the listening point by means of a B & K 2230 integrating sound level meter; the map of the sound level is graphically shown in Fig. 3. Always starting from the impulse response, the equivalent

TABLE 1
Values of the ITDG (ms)

Stage front

Row number	*Column number*					
	1	*2*	*3*	*4*	*5*	*6*
1	10·62[a] 11·33[b] (11·13)	17·26[a] 16·02[b] (26·17)	17·73[a] 16·21[b] (23·24)	17·14[a] 16·02[b] (22·85)	14·84[a] 16·21[b] (22·46)	8·94[a] 8·98[b] (14·46)
2	12·11[a] 8·40[b] (8·40)	13·16[a] 14·26[b] (19·53)	14·18[a] 14·26[b] (18·55)	14·10[a] 14·46[b] (18·95)	13·48[a] 14·26[b] (18·75)	10·66[a] 8·21[b] (8·01)
3	10·86[a] 8·98[b] (9·38)	12·34[a] 11·91[b] (15·43)	12·26[a] 11·91[b] (15·82)	12·22[a] 12·11[b] (15·82)	12·03[a] 11·91[b] (15·63)	9·73[a] 11·13[b] (10·92)
4	10·66[a] 10·35[b] (11·33)	10·46[a] 10·96[b] (11·91)	9·72[a] 10·56[b] (11·91)	9·88[a] 10·74[b] (11·91)	10·58[a] 9·76[b] (11·72)	10·19[a] 11·72[b] (12·11)
5	7·77[a] 7·03[b] (11·72)	7·50[a] 7·26[b] (9·18)	8·67[a] 7·05[b] (9·96)	8·63[a] 7·26[b] (9·76)	7·57[a] 7·26[b] (9·57)	7·18[a] 7·03[b] (12·50)

End wall front

[a] Values measured in the hall.

[b] Values measured in the scale model with and without reflecting panels over the stage.

Values in parentheses are measured in the scale model with a horizontal plane surface ceiling instead of the realised varions inclined surface ceiling.

TABLE 2
Values of IACC Measured in the Hall

Stage front

Row number	*Column number*					
	1	*2*	*3*	*4*	*5*	*6*
1	0·349	0·586	0·681	0·488	0·390	0·176
2	0·280	0·466	0·629	0·540	0·542	0·309
3	0·409	0·403	0·496	0·630	0·514	0·313
4	0·200	0·407	0·528	0·497	0·484	0·200
5	0·217	0·324	0·334	0·414	0·323	0·348

End wall front

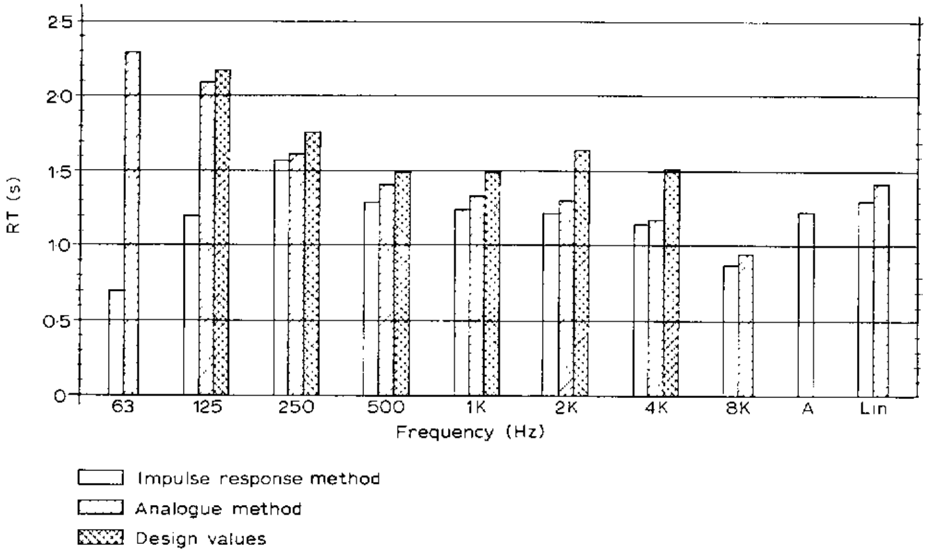


Fig. 2. Reverberation times (RT) without audience.

reflection amplitude *A* has been calculated, values of which are shown in Table 3. Starting from the measured objective data the indices of preferences according to the Ando procedure have been calculated. To do this it was necessary to suppose a typical sound source and a musical or spoken piece; in this case, the quality evaluation has been made referring to the spoken piece and to two pieces of music, characterized by an effective duration time T_e of the autocorrelation function equal to 12 ms for the spoken piece and to 43 and 127 ms for the musical piece. We supposed that the sound source would be able to give an optimum listening level of 80 dBA in the center of the audience and at a distance of 20 m from the source.

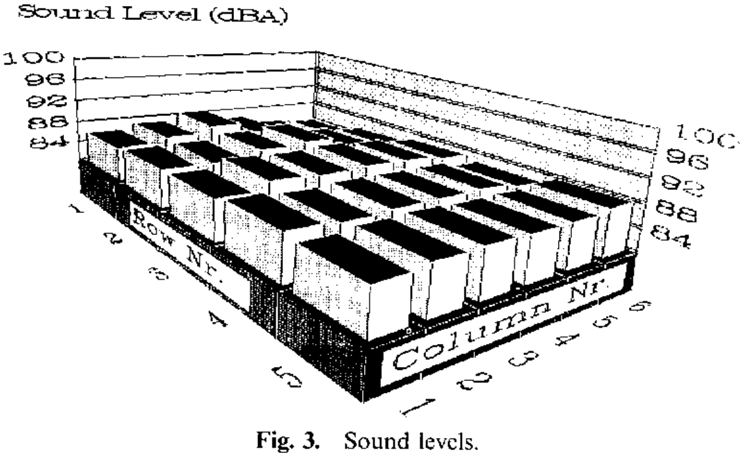


Fig. 3. Sound levels.

TABLE 3
Values of Reflection Equivalent Amplitude (A)

Stage front

Row number	*Column number*					
	1	*2*	*3*	*4*	*5*	*6*
1	1·94[a] 1·25[b]	1·46[a] 1·58[b]	1·73[a] 1·97[b]	1·9[a] 1·85[b]	1·61[a] 1·31[b]	2·77[a] 1·94[b]
2	2·41[a] 2·69[b]	2·39[a] 1·66[b]	1·72[a] 1·20[b]	2·06[a] 1·20[b]	2·67[a] 0·98[b]	3·21[a] 1·97[b]
3	2·83[a] 1·87[b]	2·75[a] 1·26[b]	2·03[a] 1·47[b]	1·96[a] 1·17[b]	2·54[a] 1·03[b]	3·62[a] 1·70[b]
4	3·2[a] 1·81[b]	3·17[a] 1·33[b]	2·23[a] 1·77[b]	1·9[a] 1·44[b]	1·62[a] 1·92[b]	3·55[a] 1·26[b]
5	3·84[a] 1·59[b]	2·78[a] 1·85[b]	2·58[a] 3·24[b]	2·83[a] 2·26[b]	3·03[a] 1·76[b]	3·58[a] 1·45[b]

End wall front

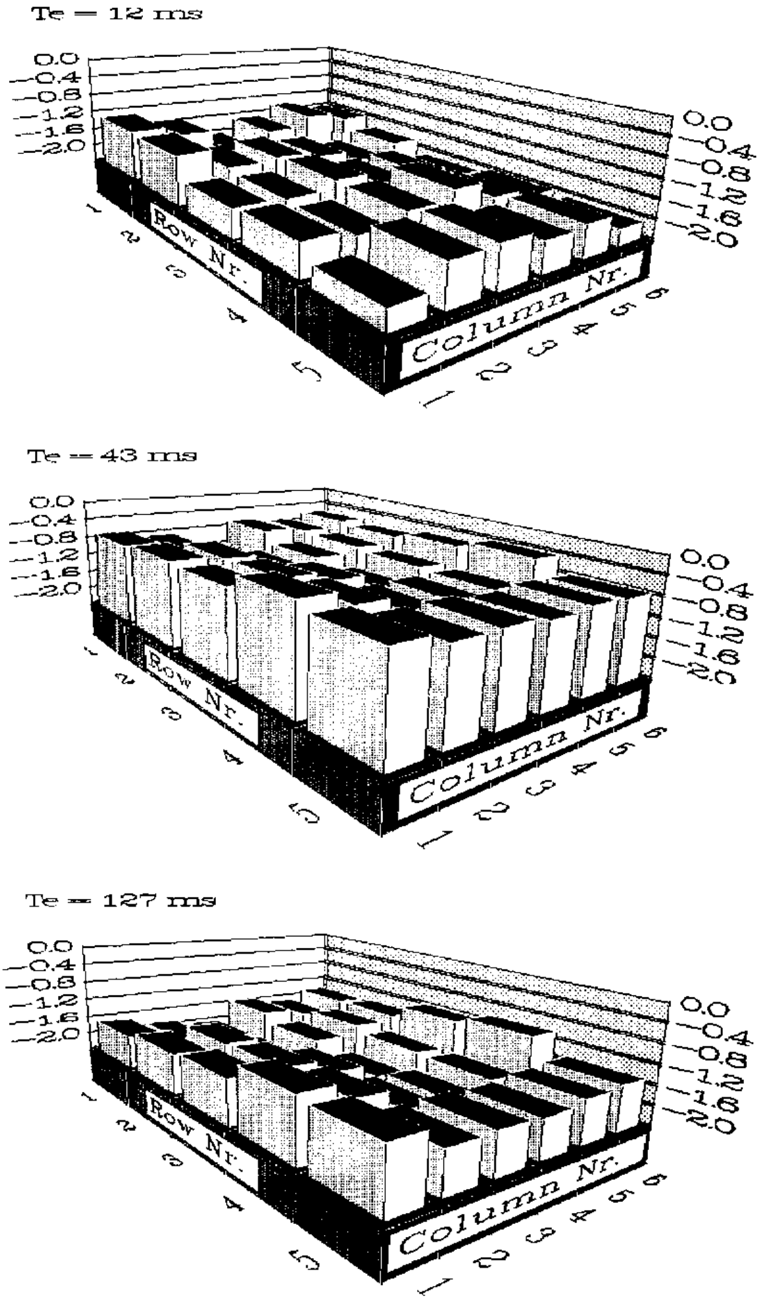
[a] Values measured in the hall.
[b] Values measured in the scale model.

Based on the values of the four independent parameters and on the values of the equivalent reflection amplitude, the total preference indices S_T have been calculated, and are reported in map form in Fig. 4.

Even if it is not yet possible to give an absolute evaluation of numerical results obtained, we can observe that the values of the preference indices are very high for the situation of listening to the musical piece with $T_e = 43$ ms, but even in the other two cases, the value remains rather high, which confirms the subjective ratings given by experts on the quality of the hall.

These subjective judgements were collected from personnel of the school of music 'D. Cimarosa' at the end of various concerts by questioning the more expert listeners and attending orchestral groups. Great weight was placed on the opinion expressed by the orchestra of the Teatro S. Carlo of Naples which gave the concert, as previously mentioned, in the hall on the occasion of its inauguration. Both conductor and musicians appreciated the acoustical environment in which they performed. Even the auxiliary personnel of the orchestra, present in the hall during the concert, agreed with this judgement.

Since this occasion, the orchestras which have played in the hall have expressed similar judgements, both from the performers' and the audience's standpoint.


Te = 12 ms

Te = 43 ms

Te = 127 ms

Fig. 4. Preference indices (PI).

With the same method of Ando other Italian concert halls have been tested in the past,[4,5] and they gave much lower values of the S_T; nevertheless, because of insufficient collected data, it is not yet possible to make an absolute evaluation of the acoustical quality of the Avellino hall.

TESTS ON THE SCALE MODEL

A 1:50 scale model was built, using 3 and 5 mm polyurethane foam sandwich boards between two layers of cardboard. The wall at the back of the hall has not been reproduced in the model, because in reality this wall has very high absorption; even the wall at the back of the stage has not been reproduced in the model, as it was demonstrated that it had no effect on the acoustic field of the first reflection and in any case would create problems in the positioning of the source.

The sound source was made from an internal combustion engine sparkplug. A $\frac{1}{4}$in Electret microphone was used as receiver. The model was shown to agree with the experimental results in the hall. At 30 points in the model located at positions corresponding to the measurement points in the real hall, recordings were made of the impulse response with a digital analyzer.

From the impulse response of the model the values of the ITDG and of the equivalent reflection amplitude A have been calculated. The ITDG values of the model in relation to the values taken in the hall are shown in Table 1.

The tests on the model have been conducted both in the configuration of the added reflecting surfaces in the stage area as foreseen in the project and without these reflecting surfaces (which do not exist in the real hall). Significant differences in the ITDG were not observed. The measured values in the model agree on average to within 1 ms with the values in the real hall. It has been observed, however, that an error of a few millimeters in the positioning of the panels or of the microphone, or of a few degrees in the inclination of the reflecting mirrors easily leads to errors of 1 ms or more in the values of the ITDG. Therefore great precision in the construction of the model is important, within tolerances of ±1 mm for the dimensions and ±2° for the angles of the reflecting planes.

In the model an investigation was carried out to replace the original tilted mirror ceiling with a horizontal flat surface, placed 7·90 m above the stage; substantial differences appeared only in the front central zone where the flat ceiling produced high values of the ITDG, the difference ranging between 4 and 6 ms (see Table 1).

The values of the equivalent reflection amplitude A of the model are compared with the real values in Table 3. The shift is systematic and is caused by the different absorption of the boundary surfaces.

TABLE 4
Values of Reflection Equivalent Amplitude A. Effects of Geometrical Variations Tested on the Scale Model

Stage front

Row number	*Column number*					
	1	*2*	*3*	*4*	*5*	*6*
1	1·25[a] 1·65[b] (1·79)	1·58[a] 1·48[b] (2·04)	1·97[a] 1·18[b] (1·46)	1·85[a] 1·12[b] (1·69)	1·31[a] 1·68[b] (2·57)	1·94[a] 1·84[b] (2·51)
2	2·69[a] 1·86[b] (1·47)	1·66[a] 1·56[b] (1·65)	1·20[a] 1·32[b] (2·01)	1·20[a] 1·22[b] (2·15)	0·98[a] 1·69[b] (1·09)	1·97[a] 1·98[b] (1·58)
3	1·87[a] 2·18[b] (2·53)	1·26[a] 1·49[b] (1·99)	1·47[a] 1·33[b] (1·66)	1·17[a] 1·49[b] (1·84)	1·03[a] 1·59[b] (1·28)	1·70[a] 2·12[b] (1·82)
4	1·81[a] 1·79[b] (1·84)	1·33[a] 1·58[b] (1·88)	1·77[a] 1·87[b] (2·01)	1·44[a] 2·35[b] (1·60)	1·92[a] 2·31[b] (1·90)	1·26[a] 1·66[b] (1·95)
5	1·59[a] 1·58[b] (2·54)	1·85[a] 1·57[b] (2·04)	3·24[a] 1·49[b] (2·30)	2·26[a] 1·40[b] (1·73)	1·76[a] 1·70[b] (2·06)	1·45[a] 1·67[b] (1·75)

End wall front

[a] Values measured in the scale model with varions inclined surface ceiling.
[b] Values measured in the scale model with a horizontal plane surface ceiling placed at a height of 7·90 m over the stage.
Values in parentheses are measured in the scale model with varions inclined surface ceiling plus reflecting panels over the stage as planned in the original design.

In Table 4 the values of A measured on the model with the two configurations of the tilted mirror ceiling and horizontal flat ceiling are compared; it can be seen that the flat ceiling reduces strongly the equivalent reflection amplitude A, making worse the acoustics of the hall. In the same table, the values of A in the model obtained with and without reflector over the stage are compared; it can be seen that the value of A increases by about 50% with the addition of the reflectors.

The use of a model of this type, capable of simulating the early reflection field only, was demonstrated as totally reliable for the determination of ITDG and, even if it does not permit the determination of the actual value of A in real space, it allows the effect of geometrical modification on the parameter to be tested. Furthermore, an estimated value of the actual A can be obtained, as the early reflection surface absorption coefficient can be assumed by the designer at the planning stage.

CONCLUSIONS

The experimental results show that Ando's preference index corresponds well with the subjective rating of the acoustic quality of the Avellino concert hall, and therefore its validity as a method of rating a hall is confirmed.

In the scale model, the accuracy of construction was the important factor; the model can supply, however, valid indications both about the proper geometric shapes of the reflecting surfaces and about a partial judgement of the acoustic quality of the hall.

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