COUPLING EFFECTS IN CHRISTIAN CHURCHES: PRELIMINARY ANALYSIS BASED ON A SIMPLE THEORETICAL MODEL AND SOME EXPERIMENTAL RESULTS

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ABSTRACT

Ancient worship buildings usually present articulated environments, such as lateral chapels, where the effect of acoustic coupling rooms can influence the sound field. In the acoustically coupled rooms, reverberation times are fairly different from the ones measured without mutual power flow interactions through coupling areas.

A preliminary investigation on the presence of coupling effects has been performed.

Experimental values, measured in the lateral chapels of 3 Italian churches (XI-XVI sec) and in the corresponding coupled volumes of the selected environments, have been considered and compared with computed data given by a simple theoretical SEA (Statistical Energy Analysis) model. Application conditions and limitation of the model are discussed.

INTRODUCTION

Two rooms can be considered 'acoustically coupled' when reverberation times of the two environments with an opening connecting area are fairly different from independently measured ones without any coupling area.

Early studies on the subject [1, 2] explain how the more reverberant room of a simple two coupled rooms (such as in opera houses, between the auditorium and the stage house) can behave as an acoustic power source by means of the aperture connecting the two rooms. More recent studies [3, 4] confirm that the transient asymptotic behaviour of two or more coupled rooms tends to be equalised into a single energy decay slope. In a first approximation the reverberation time can be the result of the sum of the volumes V and of the total absorption A of the coupled rooms, unless the total absorption of the room without sound source is much greater then the coupling aperture area. In this case the aperture behaves like an open window, and the coupling is less effective. The case of quite (acoustically) different rooms, coupled by relatively great apertures or low insulating walls, is much more interesting and has been applied in the present paper to examine the coupling effects between central body and lateral chapels of some churches, that can present coupling effects. The lateral chapels, characterised by a volume smaller than the main church, present an opening area that, in some conditions, can influence the acoustical energy distribution in the main body of the church. Therefore a relevant application of the detection of “coupling phenomena” is represented by the possibility to modify the main acoustic field by closing or making more absorbent these lateral ”coupled” chapels.

The study has been carried out on the basis of experimental results and by applying a SEA model suitable for acoustically coupled rooms, in order to verify the effect of coupling on the variation of acoustic field in the environment. The aim of this work is the application and validation of a SEA model in order to develop a useful tool to theoretically put in evidence the possibility of coupling effects, especially for the energy decay curve predictions (reverberation times).

THE SELECTED CHURCHES

The present investigation is based on the experimental analysis of the main acoustical parameters in the three churches shown in figure 1.

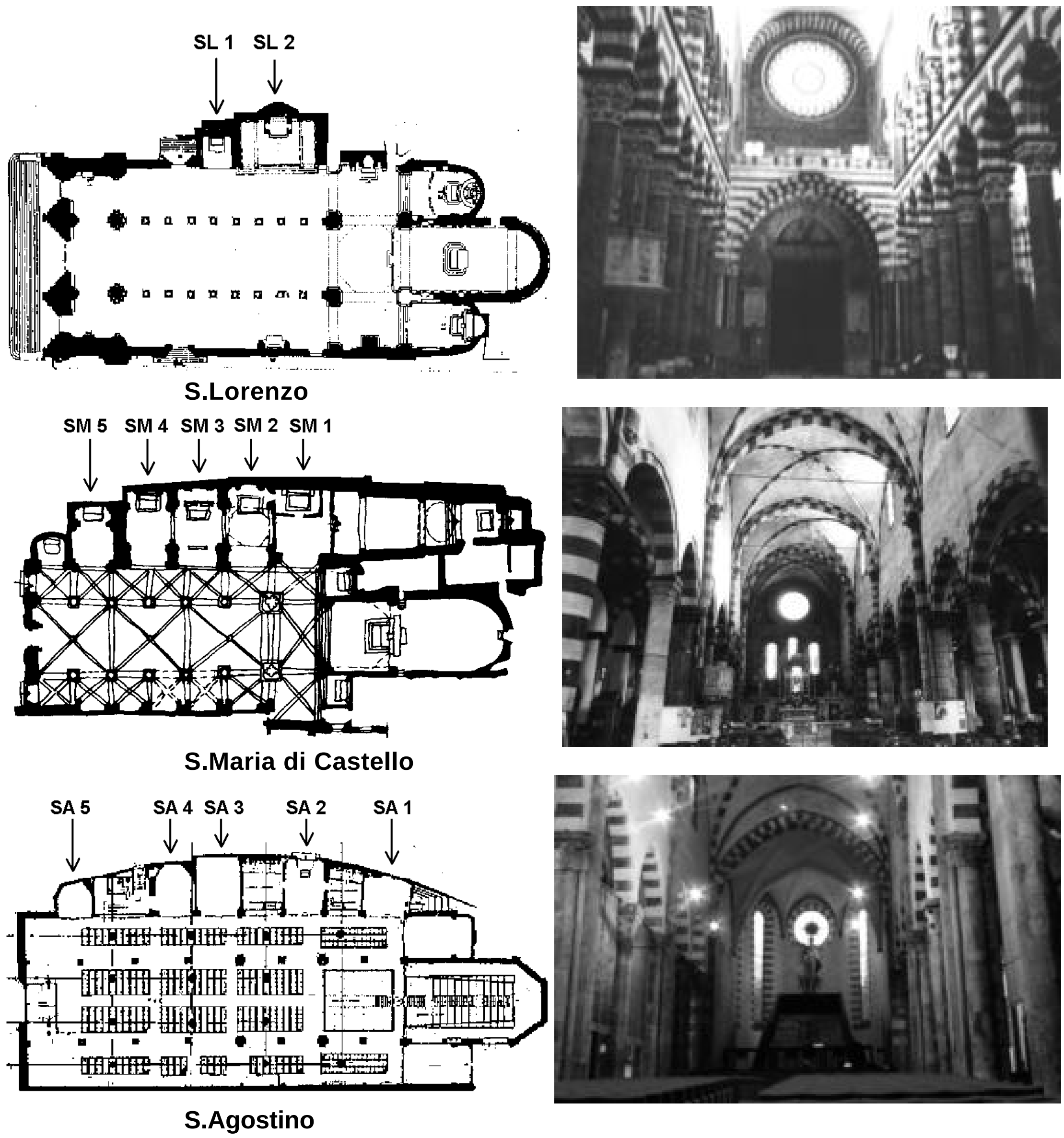

Figure 1 – Plans and interior pictures of the examined churches.
Lateral chapels are indicated on each plan.

The selected churches have all a longitudinal plan with two aisles either and are located in the historic centre of the city of Genova (Italy). Figure 1 shows their plans and interior pictures.

S. Lorenzo is the Cathedral of the city of Genova: the first nucleus was built in 1118, in XIII century the building was transformed from Romanesque to Gothic style.
S.M. di Castello was founded before 1130 and even though it was mutated in various centuries till the XX century, the Romanesque style is prevalent.
S. Agostino is of the XI- XII century in Romanesque-Gothic style and recently converted into auditorium.
As indicated in figure 1, the lateral chapels are differently positioned: S.Lorenzo has only two chapels (SL1, SL2). The other two churches, S.Maria di Castello and S. Agostino, are characterised by lateral chapels, distributed all on the left side: in S.Agostino three of them are closed (respectively, SM1 ÷ SM5, SA1 ÷ SA5).

Dimensional parameters of the churches and the considered chapels are shown in Table 1.

Church	Total Volume of the church [m^3]	Ref. Chapel	Volume of the chapel [m^3]	Connecting area [m^2]	Total area of the church [m^2]	Total area of the chapel [m^2]
S:Lorenzo	43540	SL 1	148.5	40	23500	171.4
		SL 2	677.76	56.4		675
S.M.Castello	21100	SM 1	563	61.2	12368	413.1
		SM 2	509.28	28.6		364.5
		SM 3	401.28	40.04		336.5
		SM 4	364.8	36.4		335.2
		SM 5	222	27.6		225.6
S.Agostino	14500	SA 1	193.5	40	8643	203.5
		SA 2	239.6	37.44		233.6
		SA 3	258.04	40.32		244.5
		SA 4	221.18	34.56		222.8
		SA 5	115.2	28.8		147.2

Table 1 - Geometrical characteristics of the considered environments

MEASUREMENTS

The measurement technique has already been described in former works [5, 6, 7].

In order to detect the presence of coupling effects, reverberation times of the whole selected churches (mean values among the various measurements points) have been compared with the ones of the different chapels. For the lateral chapels, the measurement points are positioned in the centre of each one, indicated in Figure 1. The coupled room effect has been assumed for a minimum difference of 0.4-0.5 s between the experimental values measured in the chapels and the ones that characterise the whole environment. The range of frequencies from 63 to 8000 Hz has been investigated.

The coupling effect seems more significant in the field of the low frequencies, up to 500 Hz, and related to the EDT (Early Decay Time) rather than the TR20 (Reverberation Times calculated on the decay of the first 20 dB). This is a confirmation of scientific works on the topic [3,4] which put in evidence that the main coupling effects especially affect the very first instances of the decay curve (50-100 ms), when the first reflections are important.

In the Table 2 the differences between EDT of the main body of the church and the one measured in the chapels are indicated for the frequencies examined.

A first analysis on the relation between the geometrical characteristics of the coupled volumes and the source position was carried out, in order to find eventually relevant influence of parameters such as the volume of the lateral chapel, the surface of its opening, the distance from the source.

S.Lorenzo	63	125	250	500	1K	2K	4K	8K
SL 1	**3.6**	**-1.6**	0.2	**-0.5**	-0.3	-0.2	-0.1	0.0
SL 2	**3.0**	**-0.8**	0.2	**-0.7**	0.0	-0.3	0.0	0.1

S.M.Castello	63	125	250	500	1K	2K	4K	8K
SM 1	**0.7**	0.3	**0.4**	0.0	0.2	0.2	0.0	0.2
SM 2	0.1	**-1.0**	-0.1	-0.1	**-0.4**	-0.1	-0.2	-0.1
SM 3	**-0.7**	**-1.0**	0.0	0.1	-0.2	-0.1	-0.1	-0.2
SM 4	**-0.6**	**-0.4**	-0.1	-0.3	-0.1	-0.2	-0.2	-0.1
SM 5	**-0.7**	**-0.6**	**-0.5**	**-0.5**	-0.1	-0.2	-0.2	-0.2

S.Agostino	63	125	250	500	1K	2K	4K	8K
SA 1	**0.5**	**-0.3**	**0.4**	-0.2	0.1	0.0	0.1	0.0
SA 2	**-1.4**	**0.4**	-0.2	-0.3	-0.1	-0.3	-0.2	-0.1
SA 3	**-0.6**	**-0.9**	**-0.6**	**-0.4**	**-0.6**	**-0.4**	-0.2	-0.2
SA 4	**-1.3**	**-0.6**	**-0.6**	-0.3	-0.3	-0.1	-0.3	0.0
SA 5	0.0	**-0.6**	-0.1	0.0	0.0	0.1	0.0	0.0

Table 2 – EDT: difference between mean and local values as function of frequencies. Differences higher than 0.3 are highlighted.

THE SEA MODEL

The phenomenon of acoustically coupling rooms has been widely investigated by some authors [3, 4], using the Statistical Energy Analysis (SEA) model. The developed mathematical model is based on approximations and numerical integration of corresponding systems of ordinary first order differential equations; it is based on the assumption of a diffusive field.

S.Lorenzo	63	125	250	500	1K
SL (medium values)	0.039	0.047	0.044	0.045	0.051
SL 1	0.035	0.018	0.021	0.020	0.023
SL 2	0.035	0.023	0.024	0.022	0.027

S.M.Castello	63	125	250	500	1K
SM (medium values)	0.098	0.071	0.059	0.055	0.057
SM 1	0.102	0.062	0.051	0.045	0.047
SM 2	0.084	0.047	0.047	0.044	0.043
SM 3	0.055	0.040	0.041	0.040	0.038
SM 4	0.051	0.042	0.036	0.033	0.036
SM 5	0.045	0.036	0.031	0.029	0.033

S.Agostino	63	125	250	500	1K
SA (medium values)	0.068	0.077	0.086	0.098	0.097
SA 1	0.045	0.040	0.056	0.052	0.057
SA 2	0.031	0.054	0.049	0.054	0.056
SA 3	0.037	0.038	0.046	0.054	0.050
SA 4	0.031	0.039	0.042	0.053	0.052
SA 5	0.031	0.030	0.039	0.046	0.045

Table 3 – The absorption coefficients α_{exp}, calculated from experimental Reverberation Time by using Sabine formula.

The model has been applied to the examined churches, having 12 chapels in total, in order to obtain a first confirmation on the accuracy of the simulation of reverberation times in these particular kind of environments.

The input data needed for this simulation are the following ones: volumes of the two coupled rooms (main body of the church and chapel), connecting surfaces, opening surfaces, transmission coefficients of the connecting and opening surfaces and the absorption coefficients for the considered frequencies. The output is the energy decay curve of both the rooms in each case. In particular, the connecting surface is the area which connects the two rooms and the opening surface is usually an arch; the absorption coefficients α_{exp} have been obtained by the application of the Sabine formula, on the hypotheses of a diffusive sound field, by means of the measured values of reverberation times. Table 3 shows the calculated input data.

COMPARISON BETWEEN MEASURED AND COMPUTED DATA

In order to validate the reliability of the model, the simulation and the experimental results are compared. The results are shown in Table 4 and a good agreement between simulated and measured data can be observed; in some cases, results of the chapels more distant from the source are less reliable.

			Frequency [Hz]				
		EDT [s]	**63**	**125**	**250**	**500**	**1K**
S.LORENZO	SL1	exp	4.0	7.9	6.6	7.1	6.1
		SEA	8.1	7.2	7.5	8.3	6.2
	SL2	exp	4.6	7.1	6.6	7.3	5.9
		SEA	8.0	7.2	6.8	7.4	6.1
	SL (medium values)	exp	7.6	6.3	6.8	6.6	5.8
		SEA	7.5	6.1	6.6	6.4	6.2
S. MARIA di CASTELLO	SM1	exp	2.1	3.5	4.2	4.9	4.6
		SEA	2.7	3.5	4.4	4.9	4.5
	SM2	exp	2.7	4.8	4.8	5.0	5.2
		SEA	3.3	4.1	5	5.1	5.1
	SM3	exp	3.4	4.8	4.6	4.8	5.0
		SEA	3.5	4.3	4.7	4.7	5.1
	SM4	exp	3.4	4.2	4.8	5.2	4.9
		SEA	3.5	4.4	4.8	5	4.7
	SM5	exp	3.5	4.4	5.1	5.4	4.8
		SEA	2.8	4.3	5	4.8	4.8
	SM (medium values)	exp	2.8	3.8	4.6	4.9	4.8
		SEA	2.8	3.6	4.2	4.8	4.6
S. AGOSTINO	SA1	exp	3.4	3.8	2.7	2.9	2.7
		SEA	4.5	3.1	3.4	3.4	2.4
	SA2	exp	5.3	3.0	3.3	3.0	2.9
		SEA	5.5	3.4	3.2	3.1	3
	SA3	exp	4.6	4.4	3.7	3.1	3.4
		SEA	5.2	4.1	3.5	3.1	3
	SA4	exp	5.2	4.1	3.7	3.0	3.1
		SEA	5.4	4.2	4	3.2	3
	SA5	exp	4.0	4.1	3.2	2.7	2.8
		SEA	4.9	4.1	3.3	3	3
	SA (medium values)	exp	3.9	3.5	3.1	2.7	2.8
		SEA	3.9	3.5	3	2.6	2.8

Table 4 – SEA model applied for the prediction of the Reverberation Time: obtained values in comparison with the measured ones

In addition, a further development has been carried out in order to estimate the applicability of the SEA model when the α_{exp} is not available: in such a case a theoretical α is considered as input data.

The estimation of the error (E_a) has been evaluated taking into account the experimental (R_e) and assumed (R_a) ratio between the absorption coefficients of the two coupled rooms: $E_a = (R_e-R_a)/R_e$. In Figure 2 the relationship between the estimated error on the absorption ratio (E_a) and the one referred to the corresponding EDT values ($E_v = (EDT_e-EDT_a)/EDT_e$) is shown. For an error $-10\%<E_a<+15\%$ the matching EDT error is $-25\%<E_v<+25\%$.

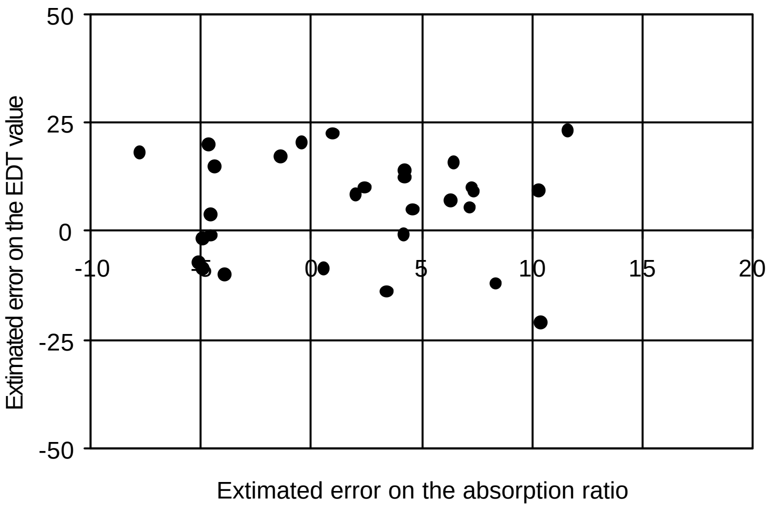

Figure 2 - Relationship between the estimated error on the absorption ratio (E_a in %) and the one referred to the corresponding EDT values (E_v in %)

CONCLUSIONS

The SEA model used in this analysis can be useful tool for a preliminary investigation on the presence of coupling effects in lateral chapels of a church. In such a case, during a design phase or for the acoustical restoration of the environment, it could be useful to consider the more convenient means to reduce or to amplify the sound in these areas. Introducing more or less absorbent materials in a lateral chapel the whole acoustic response of the whole church can vary. Therefore this type of solution can be verified by means of the SEA model here applied. A deeper research is currently under development to reach useful information that can correlate the style of construction and the more appropriate absorbing coefficients.

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