Room acoustic properties of concert halls: quantifying the influence of size, shape and absorption area.

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INTRODUCTION

In the 1960's and 70's, great progress was made in the development of objective acoustic parameters capable of describing and quantifying relationships between sound field properties and subjective room acoustic impressions in auditoria. Although there are still good reasons to continue this development, the most widely used objective measures from that period have now been adopted in annexes to the newly revised reverberation time measurement standard, ISO 3382. (Consequently, the title of this standard has also been changed into: “Measurement of reverberation time of rooms with reference to other acoustical parameters”.)

Prediction of values for these newer parameters is more complex than normal reverberation time calculations, since scale or computer modelling techniques are required. However, many aspects of the acoustic properties of a new hall are settled when the architect makes his first sketches i.e. before the acoustician has started any modelling work. Therefore, in order to aid acoustic consultancy in the earliest phases of design, it would be nice to develop some more basic knowledge or simple rules of thumb regarding how - and how much - these newer parameters are affected by the gross shape and dimensions of the hall.

In the 80's, the author 1) and others e.g. John Bradley 2) started making systematic measurement surveys of concert halls in order to get more experience in how these newer objective acoustic parameters behave in different hall designs. Based on acoustic data from the 35 European halls that we had measured by 1990 and measurement of simple geometric parameters and multiple regression analysis, some design/acoustic relationships were found and reported at a ASA meeting in Baltimore five years ago 3). These relationships were given in the form of linear regression models, from which the acoustic effects of changes in certain design variables can be easily quantified. Our data base now contain data from 53 halls including among others nine halls from the US, which are generally larger than the ones we find in Europe. The present paper describe renewed analyses on this extended set of data, but before elaborating on some of these results it is relevant to mention two recent major efforts in the same directions by Chiang 4) and Haan 5) respectively.

Chiang 4) collected acoustical and geometrical data from 22 US concert-, multi purpose-, lecture halls and churches representing a wide range of sizes (volumes between 200 and 20000 cubic metres, and numbers of seats between 50 and 3000). Of these 22 halls eight are also included in our data base. Like in our survey, these data were subjected to multiple regression analysis to reveal relationships between seat averaged acoustic parameters and hall design variables including both geometrical properties and estimated absorption properties of the hall surfaces. Regression models are also found which describe the influence of these variables on the within-hall STD's of the acoustic measures. A very important part of Chiang's work is his many suggestions for precise definitions of variables describing the geometric properties of the halls. Due to his set of geometric parameters being somewhat different from the one used in the Danish survey, Chiang's results are not fully comparable with ours, but in general many tendencies coincide, as described on later.

Haan[5)] collected geometrical and surface material data from a large number of halls all over the world using available literature and drawings and supplemented this by carrying out a questionnaire survey among touring musicians in an attempt to establish relationships between design variables and a subjective acoustic quality index (AQI) without considering the intermediate link of objective acoustic parameters. Based on 53 halls Haan found only rather low correlation coefficients between AQI and the geometrical variables; but a surprisingly high correlation emerged between AQI and the degree to which the room surfaces diffuse the reflected sound as described through his definition of a surface diffusivity index (SDI).

Considering that different geometric variables affect different objective and in turn subjective room acoustic attributes - as illustrated e.g. in the factor analyses by Chiang - and that different people's overall quality judgement will be based on different individual weightings of the different subjective aspects ("reverberance", "timbre", "clarity", "strength" etc.), the lack of correlation between geometry and the uni-dimensional AQI could only be expected. On the other hand, this - and the expected large error variance associated with subjective measurements through questionnaires filled out based on past concert hall experiences excited by different music stimuli - only makes the high correlation with SDI more surprising.

Therefore one is tempted to look for factors that may have given a strong bias to Haan's results e.g. the fact that highly irregular surfaces - especially in older halls - affect the visual impression positively, and visual impressions are generally easier to remember than auditory ditto. Besides, 33 out of the 36 subjects were musicians or conductors, whereby one can not be sure that the results are representative for pure listeners. Since our hall survey cover 18 out of the 53 halls in Haan's database, we have tried to correlate Haan's AQI for these 18 halls with our own objective acoustic data. The result was, that the highest correlation appeared for EDT measured on the stage ($r=0.59$, 1 % significance level), which emphasizes the suspicion of Haan's results being influenced by his choice of subjects or by their location in the halls.

Valid acoustic reasons for the preference of diffusing surfaces could be, that diffuse reflections might sound "softer", cause less spectral colouration and aid in blending the sound favourably. Besides, it is likely that the sound decay returned from the audience chamber to musicians on stage is more uniform and "soft" in halls with many diffusing surfaces compared to halls with primarily mirror-like, plane surfaces, where sound is not returned until after it has hit the rear wall or a balcony front.

In spite of the doubts mentioned above, the importance of diffusion as found by Haan is a solid statistical fact which needs to be investigated further. (For the subset of 18 halls which we have in common, the correlation between SDI and AQI was as high as 0.89). Also Haan's more detailed analysis made good sense: by weighting diffusivity of walls or ceiling differently he found that in rectangular halls it is of primary importance to apply diffusion to the walls, while in fan shaped halls the ceiling surface is more important.

METHOD

Besides covering halls with a greater variety of geometric properties than previously reported[3)], our new analyses also include a few more geometric variables derived from our drawings of the 53 halls: the number of rear and side balconies, SDI and "Room index" as defined by Haan and the stage ceiling/reflector angle according to Chiang.

The new analyses follow the same lines as described earlier[3)]. Through correlation and factor analysis design variables are spotted which could be promising variables in regression models matching the measured seat and frequency averaged values of the objective acoustic parameters. The measured reverberation time (T) is used to calculate expected values of Strength (G) and Clarity (C): G_{exp} and C_{exp} respectively - assuming the validity of classical diffuse field theory. When used as independent variables in the later regression analyses, it can be assumed that these expected values will account for most of the variance caused by hall volume and total absorption area. Like before, the results of the multiple regression analyses are simple linear models for the acoustic parameters as functions of the expected values and various geometrical variables.

The regression models to be discussed below concentrate on G, C and LEF. Of these G showed a steady and significant decrease with distance in most of the halls. Therefore it has also been attempted to create models for the rate of decrease in G per 10 m source-to-receiver distance $\Delta G(10m)$, as also investigated by Barron[6)].

REGRESSION MODEL RESULTS

The regression models found (so far) have been listed in Table 1 and will be commented on in the following.

The upper four C-models are similar to the ones reported in 1991. Generally, the coefficients to C_{exp} and to the geometrical variables have changed less than 10 %, and the constants have changed less than half a dB. The correlation coefficients have decreased slightly compared to what was found from the 35 halls. This is probably a consequence of the larger variety in size, shape and balcony lay out in the extended data set. The last two C-models are new. The first model illustrate that absorption and volume as reflected in T are responsible for the main part of the variation in C. The other five models all illustrate the positive (but sometimes unwanted) effect of average hall width on Clarity. Besides, it is seen that introducing a moderate 15^{o} slope of the main audience floor (without changing the average width to hight ratio, volume and absorption area) will cause C to increase about 0.5 dB on average. Similarly, changing the basic design from rectangular to a 70^{o} fan shape will make C increase by

Room acoustic param.	Regression models: F($PAR_{expected}$, geometry)	Cor-rel. coeff.	% of vari-ance	STD resid-uals
C [dB]	-0.1 + 1.0 C_{exp}	0.76	58%	1.0dB
	-1.7 + 1.1 C_{exp} + 0.065 Width	0.84	70%	0.9dB
	-1.4 + 0.95 C_{exp} + 0.47 W/H + 0.031 Floor slope	0.83	68%	0.9dB
	-1.2 + + 1.03 C_{exp} + 0.43 W/H + 0.013 Wall angle	0.84	70%	0.9dB
	-1.56 + 1.02 C_{exp} + 0.47 W/H + 0.04 Stageceil.angle	0.86	74%	0.8dB
	-1.77 + 1.10 C_{exp} + 0.055 W + 0.027 Stageceil.angle	0.86	74%	0.8dB
G [dB]	-0.2 + 0.94 G_{exp}	0.91	83%	0.9dB
	-3.34 + 0.95 G_{exp} + 0.14 V/N	0.94	88%	0.9dB
	-4.56 + 1.03 G_{exp} + 0.17 V/N + 0.38 No.Rearbalc.	0.94	89%	0.9dB
	-5.61 + 1.06 G_{exp} + 0.17 V/N + 0.04 Distance	0.94	89%	0.9dB
ΔG(10m) [dB]	-1.85 + 0.42 No.Rearbalc.	0.50	25%	0.7dB
	-2.43 + 0.08 H	0.42	18%	0.7dB
	-1.41 + 0.35 No.Rearbalc. - 3.93 Distance/(HW)	0.55	31%	0.6dB
LEF [-]	0.39 - 0.061 Width	0.70	49%	0.05
	0.24 - 0.0017 Wall angle	0.53	28%	0.06
	0.37 - 0.0051 Width - 0.00069 Wall angle	0.72	53%	0.05
	*0.42 - 0.059 Width - 0.067 SurfaceDiffusionIndex	0.73	53%	0.05

Table 1: *Revised regression models from extended data base. *Only rectangular halls. See text for further explanations.*

about 1 dB. The last two models illustrate the effect of the new geometric variable: the angle of stage ceiling towards the audience. A slope of 20 ° (from horizontal) result in C values becoming about 0.5 dB higher.

Also in Chiang's results the factors inherent in C_{exp} (but there represented by Log(T) and volume) appear as important variables, and also the influence of stage ceiling angle appear in his models with a similar coefficient.

The G model only considering G_{exp} is almost as in 1991, i.e. it has changed no more than what was mentioned above for the C models. The constants in all the models illustrate the fact that G is always a couple of dB lower than G_{exp}, as also predicted by Barron's "revised theory [6].

The three G-models including geometrical variables are all new and all include the ratio between volume and number of seats. That the influence of this ratio is positive was not expected; but this result is also reflected in some of Chiang's models (in which N is replaced by total seating area). The positive effect of introducing balconies may be related to the fact that the level of sound at the more distant seats is increased when these are elevated on balconies and thereby placed closer to the reflecting ceiling. (Apparently, the well known reduction in level under balconies has not neutralized this effect, since normally more seats - and measurement positions - are placed on rather than under balconies.)

The positive effect of balconies on G is also illustrated in two of the $\Delta G(10m)$ models where the number of rear balconies is seen to reduce the negative slope of G with distance. Also increasing the hight is seen to reduce the slope. Finally, the reduction with distance is seen to increase if the hall is long, narrow and has a low ceiling as reflected in the coefficient related to the distance from the stage to the rearmost seat divided by the product of average room hight and average hall width. This dependancy also appear in Chiang's models for the within hall standard deviation of G.

At the bottom of Table 1 are listed some models for LEF as functions of hall geometry. The effects of width and angle between side walls are again very close to what was found in the previous analyses, but new is the effect of SDI. However, also Chiang has found sound diffusing properties to affect the inter-aural cross correlation function, which is intended to describe the same room acoustic aspect as LEF.

CONCLUDING REMARKS

Our analyses are still going on and the possibilities of recording more geometric measures from our drawings or of grouping the halls into subsets with different geometrical characteristics before analysis have by no means been exhausted yet. Also models for the acoustic parameters describing stage conditions will soon be looked at.

With the larger span in size and shape, it is no wonder that the correlations are weaker now than they were when only the (35) more homogeneous halls were included in the database. However, due to the larger amount of data even the smaller correlations represent relationships with higher degree of significance than before, some new relationships have been found, and the old models are seen to be fairly robust.

In connection with this work, it would be nice if one could rely on different measurement procedures and systems giving comparable results, since that would allow a pooling of data into larger data bases with even better possibilities of isolating important geometrical factors in different types of halls. For example pooling of all the data in Beranek's magnificent new book $^{7)}$ could be tempting.

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Application of the models in connection with design of realistic settings in reverberation enhancement systems will be mentioned in the oral presentation.

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