THE INFLUENCE OF BASIC DESIGN VARIABLES ON THE ACOUSTICS OF CONCERT HALLS; NEW RESULTS DERIVED FROM ANALYSING A LARGE NUMBER OF EXISTING HALLS.

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1. INTRODUCTION

In the 1960's and 70's, substantial 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 ISO 3382 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 quite complex, 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 suggested changes in gross shape and main dimensions of the hall.

In the 80's, among others Michael Barron [1], John Bradley [2] and the author [3] 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. From multiple regression analysis of acoustic data and simple geometric parameters from the 35 European halls that the author had measured by 1990, some design/acoustic relationships were reported at the ASA meeting in Baltimore five years ago [4]. These relationships were given in the form of linear regression models, from which the acoustic effects of changes in certain design variables can be quantified easily. Since then, we have extending our data base, and Barron as well as Bradley have published further results e.g. on the effects of balconies [5] and stage shells [6] and design - elements of influence on loudness [7]. However, also two recent major contributions by Chiang [8] and Haan [9] deserve to be mentioned.

Chiang [8] collected acoustical and geometrical data from 22 US concert-, multi purpose-, lecture halls and churches. (Of these, eight are also included in the authors' present data base.) Like in the Danish survey, these data were subjected to multiple regression analysis to reveal relationships between seat averaged acoustic parameters and hall design variables. Many tendencies in Chiang's and our results coincide, as described later. However, compared to the Danish approach, Chiang has very much refined and extended the variables describing the geometric properties of the halls.

Haan [9] 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 important design variables and a subjective acoustic quality index (AQI) without considering the intermediate link of measuring 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 what he called "surface diffusivity index" (SDI). In spite of possible scepticism regarding Haan's approach, the importance of diffusion found in this study is interesting and needs to be investigated further. (For the subset of 18 halls which are included both in Haan´s and in our database, the correlation between SDI and AQI was found as high as 0.89).

2. METHOD

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.

Besides covering halls with a greater variety of geometric properties than previously reported [4], our new analyses also include a few more geometric variables derived from drawings: 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 in [4]. Assuming Sabine diffuse field theory to be valid, the measured reverberation time (T) is used to calculate expected seat average values of Strength (G) and Clarity (C): G_{exp} and C_{exp} respectively . However, in the case of G, also expected values G_{rev} according to Barrons "revised theory" [1)] have been tested. Formulas for these theoretical values have been listed in the Appendix. In formulas including source-receiver distance r, this was set equal to half the distance between the stage front and the furthest row of seating in the hall. 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 absorption in the hall and - in the case of Barrons theory - average source-receiver distance as well. After removing the variance accounted for by the theoretical models, correlation and factor analysis is then applied to identify geometrical variables having a promising relationship with the measured seat and frequency averaged values of the objective acoustic parameters. Finally, the theoretical predictions and the promising geometrical variables are tested in various combinations in a trial and error process of looking for simple, linear regression models accounting for as large a portion of the total variance as possible. Like before, these empirical models express the acoustic parameters as functions of the theoretical expected values and various geometrical variables. Only variables, which improved the fit significantly (at a 5 % level) are included in the models presented.

The regression models to be discussed below concentrate on G and C. Of these G showed the familiar 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: ΔG(10m).

3. REGRESSION MODEL RESULTS

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

3.1 Clarity (C) -models

The upper four C-models in the table are similar to models 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 the theoretical relationship with T are responsible for the main part of the variation in the seat averaged C values. The other five models all illustrate the effect of average hall width on Clarity: the wider the hall, the higher the Clarity. The coefficient indicate, that introducing a moderate 15 degree slope of the main audience floor (without changing the average width to hight ratio, volume or absorption area) will cause C to increase about 0.5 dB on average. Similarly, changing the plan from a rectangle to a 70 degree fan shape will cause C to increase by about 1 dB - even with volume and T maintained as before. The last two models illustrate the effect of the angle of the stage ceiling towards the audience. A 20 degree slope (from horizontal) causes C values to increase about 0.5 dB.

Also in Chiang's results [8] 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.

Room acoustic param.	Regression models: F(theory, geometry)	Cor-rel. coeff.	% of vari-ance	STD residu-als

C [dB]	$-0.1 + 1.0\ C_{exp}$	0.76	58%	1.0dB
	$-1.4 + 0.95\ C_{exp} + 0.47$ W/H + 0.031 Floor slope	0.83	68%	0.9dB
	$-1.7 + 1.1\ C_{exp} + 0.065$ Width	0.84	70%	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
	$-0.56 + 0.84\ G_{rev}$	0.91	83%	1.0dB
	$-3.34 + 0.95\ G_{exp} + 0.14$ 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
	$-7.59 + 1.16\ G_{rev} + 0.14$ V/N + 0.13 Distance	0.95	91%	0.8dB
ΔG (10m) [dB]	$-2.68 + 0.63\ T$	0.31	11%	0.7dB
	$-0.95 + 0.29\ \Delta G_{rev}$	0.26	9%	0.7dB
	$-2.43 + 0.08\ H$	0.42	18%	0.7dB
	-1.85 + 0.42 No.Rearbalc.	0.50	25%	0.7dB
	-1.41 + 0.35 No.Rearbalc. - 3.93 Distance/(HW)	0.55	31%	0.6dB
	$-0.56 + 0.29\ \Delta G_{rev} + 0.21$ No.Rearbalc. - 6.1 Distance/(HW)	0.57	37%	0.6dB

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

3.2 Strength (G) -models

Concerning the strength or total sound level models shown in Table 1, the first two are describing the relationship between the measured data and the two theoretical predictions according to

Sabine (G_{exp}) and Barrons revised theory (G_{rev}) respectively. Contrary to our expectations, use of Barrons theory did not improve the fit to the measured data. This could be related to the choice of "average" source/receiver distance r in the calculation of G_{rev} being unfavourable. (In fact, most of the calculated G_{rev} values are still a little to high compared to G, which could indicate r being too small. Obviously, calculating the Barron predictions for each position before averaging would have been a more correct approach - but also quite a job for fifty-some halls.)

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 four G-models also including geometrical variables are all new and all include the ratio between volume and number of seats. That the influence of this ratio (and of distance) is positive was not expected; but this result is also reflected in some of Chiang's models (although N is replaced by total seating area in Chiangs models). The positive effect of introducing balconies (in the fourth model) 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, which is not surprising considering that normally more seats - and measurement positions - are placed on rather than under balconies.)

3.3 Models describing variation in G with distance (ΔG).
Contrary to Sabine's theory, Barron's theory do predict the observed decrease of G with distance. If we disregard the direct sound component, $\Delta G_{rev}(10m)$ should equal - 1.737/T dB per 10 metres. (The more complex expression including the direct sound can be found in the appendix.) Model building was attempted using both. It is seen, that in either case Barrons theory alone explains only about 10 % of the variance, and different geometrical variables turn out to be at least as important, but at present we are only capable of explaining about half of the total variance.

The positive effect of balconies on G mentioned in the previous section is also illustrated by three 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 average ceiling hight is seen to reduce the slope. In the last two models listed in the table, the reduction with distance is seen to increase if the hall is long, narrow and has a low ceiling as reflected in the negative sign of the coefficient to the last variable: the distance from the stage to the rearmost seat divided by the product of average ceiling hight and average hall width. This factor also appear in Chiang's results.

4. CONCLUDING REMARKS

With the larger span in size and shape in our present database, it is no wonder that the correlations are weaker now than they were when only data from 35 halls were included. However, due to the larger amount of data even the smaller correlations represent relationships with at least as high a degree of significance as before. Fortunately, the old models have appeared to be fairly robust, some new relationships have been found, and most of the relationships are intuitively understandable.

Generally, models including theoretical predictions according to Barrons revised theory did not perform better than models using the more simple Sabine predictions. This may be a result of unfavourable choice of mean source receiver distance as discussed above; but another possible reason may be that this information is blurred by other not yet considered design variables. One such variable could be the amount of absorption placed close to the source on stage, which was clearly noticed as being of importance on plots of G - G_{rev} , and which has also been reported before [6] [7]. Still, the STD's in Table 1 indicate the prediction accuracy of the current to be comparable with the subjective difference limens and objective measurement accuracy for the various parameters.

The author has found the information contained in these models useful in consulting and teaching as well as in attempts to adjust electronic reverberation enhancement systems to produce realistic room acoustic conditions [10].

Our analyses are still going on and the possibilities of recording more geometric measures from our drawings have by no means been exhausted yet. Also grouping the halls into subsets with different geometrical characteristics before analysis might lead to interesting results. Finally we will look for models describing acoustic parameters related to musicians' conditions on stage.

In connection with the work presented here, 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 our data base with the data in Beranek's [11] and Barron's books [12] could be tempting.

ACKNOWLEDGEMENTS

Travel expenses in connection with our measurements in nine concert halls in the US were covered by "The Concert Hall Research Group", while the measurements in fourteen European halls was funded by the Rockwool foundation.

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APPENDIX: Definitions of expected values of C and G.

While the objective parameters themselves are defined in the new version of ISO 3382, the expected values of the seat averaged acoustic parameters according to Sabine and Barron theories have been listed below. In all formulas, T is the measured reverberation time value.

Expected value of C according to Sabine diffuse field theory:

$$C_{\mathrm{exp}} = 10 \cdot LOG(e^{\frac{1.104}{T}} - 1)\ dB\ .$$

Expected value of G according to Sabine diffuse field theory:

$$G_{\mathrm{exp}} = 10 \cdot LOG(\frac{T}{V}) + 45\ dB\ ,$$

and according to Barrons revised theory:

$$G_{rev} = 10 \cdot LOG[\frac{100}{r^2} + \frac{31200 \cdot T}{V} \cdot \exp(\frac{-0.04\ r}{T})]\ dB\ .$$

Derivation of G_{rev} with respect to source/receiver distance r yields:

$$\frac{dG_{rev}}{dr} = \frac{-10}{\ln 10} \cdot \frac{\frac{200}{r^3} + \frac{31200 \cdot 0.04}{V} \cdot \exp(\frac{-0.04\ r}{T})}{\frac{100}{r^2} + \frac{31200 \cdot T}{V} \cdot \exp(\frac{-0.04\ r}{T})}\ dB/m\ .$$

The values of G_{rev} and $\Delta g_{\mathrm{rev}}(10\mathrm{m}) = dG_{\mathrm{rev}}/dr \cdot 10\mathrm{m}$ were calculated setting r equal to D/2, i.e. half the distance between stage and the last row of seating in the hall.

In case we can neglect the direct sound component, the above expression reduces to:

$$\frac{dG_{rev}}{dr} = \frac{-0.1737}{T}\ dB/m = \frac{-1.737}{T}\ dB\ per\ 10\ metres\ .$$