COMPARISON OF A MULTI-PURPOSE HALL WITH THREE WELL-KNOWN CONCERT HALLS

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ABSTRACT

The results of detailed measurements are used to compare acoustical conditions in a multi-purpose hall with those in three famous concert halls. The values of five modern acoustical measures are presented for each hall. Significant differences are expected and found between the multi-purpose hall and the dedicated concert halls. The paper is intended to demonstrate the value of using extensive modern measurements to more reliably evaluate acoustical conditions in auditoria.

SOMMAIRE

Les résultats de mesures exhaustives sont utilisés pour comparer les conditions acoustiques d'une salle à usages multiples avec celles de trois salles de concert célèbres. Les valeurs de cinq mesures acoustiques de pointe sont présentées pour chaque salle. L'on prévoyait des écarts importants et on trouvait les différences entre la salle à usages multiples et les salles de concert. La présente communication vise à démontrer que les mesures exhaustives de pointe permettent d'évaluer avec plus d'efficacité les conditions acoustiques des auditoriums.

1. INTRODUCTION

The assessment of acoustical conditions in an auditorium is frequently based on the personal impressions of a single consultant with very limited objective measurement data. The purpose of this paper is to demonstrate the value of comprehensive modern objective measurements to more reliably assess acoustical conditions in large halls. To do this, extensive measurements in the Salle Wilfrid Pelletier, Place des Arts, Montreal, are compared with similar measurements in three famous classical concert halls: Boston Symphony Hall, the Amsterdam Concertgebouw, and the Vienna Musikvereinssaal.

While most would agree that the three classical halls are acoustically excellent concert halls, Salle Wilfrid Pelletier, SWP, is intended to be a multi-purpose hall. Thus, one might wish to compare it with other good multi-purpose halls. However, it is difficult to define or get agreement as to what constitutes a "good" multi-purpose hall, and it was thought to be a more interesting exercise to consider only the performance of SWP as a concert hall. Thus, the paper may be thought of as an exercise to determine why SWP is not a famous concert hall. Of course, it must always be remembered that preferred acoustical conditions in a multi-purpose hall will not be the same as for a concert hall.

The volume and number of seats in each hall are given in Table 1.

Table 1. Hall volumes and numbers of seats.

Hall	Volume, m^3	No. Seats
Salle Wilfrid Pelletier	32,100	2982
Boston Symphony Hall	18,750	2631
Vienna Musikvereinssaal	15,000	1680
Amsterdam Concertgebouw	18,770	2100

2. NEW AUDITORIUM ACOUSTICS MEASURES

The study of concert hall acoustics has made considerable progress over the past 20 years; a small number of newer auditorium acoustics measures are widely accepted as explaining almost all of the variance in subjective assessments of acoustical conditions in halls[1]. There is not complete agreement on which subset of the newer measures should be used, but the quantities that are mentioned in this paper are widely accepted and provide a comprehensive picture of conditions in a concert hall.

Measurements in all four halls were made with our RAMSoft[2] measurement system using a specially modified and calibrated blank pistol as the impulsive sound source. The measurement system consists of a program running on an IBM PC-compatible portable computer interfaced to a Norwegian Electronics type 830 two-channel real-time analyser. The values of 12 different parameters in each of six octave bands are obtained in situ at each position in the hall.

The 0.38 calibre blank pistol was modified so that it was a good approximation to an ideal omni-directional source[3]; black powder blanks are used to ensure that there is adequate energy in all the octave bands from 125 Hz to at least 4000 Hz.

The real-time analyser is used to capture, ensemble average, and filter the pulse responses which are then transferred digitally to the computer. Decay times are calculated from least squares fits to portions of the decay curves obtained by the Schroeder backwards integration technique[4]. Both the classical reverberation time, RT, measured over the decay from -5 dB to -35 dB, and the early decay time, EDT, measured over the first 10 dB of the decay are measured.

Early/late arriving sound energy ratios, C36, C50, and C80 with 36, 50 and 80 ms early time intervals are calculated. C80 values are determined as follows:

$$C80 = 10 \log\{ \int_0^{0.08} p^2(t)\, dt / \int_{0.08}^{\infty} p^2(t)\, dt \}, \text{dB} \qquad (1)$$

where p(t) is the measured pulse response in the auditorium. The other early/late ratios are calculated in a similar manner, but with different early time limits.

The overall strength, G, is calculated as the ratio of the total measured energy in the pulse response to the energy from the same source at a distance of 10 m in a free field as given in the following equation:

$$G = 10 \log\{ \int_0^{\infty} p^2(t)\, dt / \int_0^{\infty} p_A^2(t)\, dt \}, \text{dB} \qquad (2)$$

where $p_A^2(t)$ is the response of the source at a distance of 10 m in a free field.

The program calculates two versions of the lateral energy fraction, LF, which is the ratio of the lateral energy received by a figure-of-eight pattern microphone to the energy measured by an omni-directional microphone over the first 80 ms of the pulse response. The sensitive lobes of the figure-of-eight microphone are pointed at the side walls so that the null in the directional sensitivity is directed towards a centre stage source position. LF values are calculated as follows:

$$LF = \int_0^{0.08} p_L^2(t)\, dt / \int_0^{0.08} p^2(t)\, dt \qquad (3)$$

where $p_L(t)$ is the lateral response from the figure-of-eight microphone. The first integration is sometimes started from 0.005 seconds rather than 0.0 seconds. Both variations of LF are calculated but the differences are very small (typically 0.01 or less in the 500 Hz octave band), because the directionality of the microphone eliminates the direct sound energy arriving in the first 5 ms. Only LF values corresponding to equation (3) are included in this paper.

Values of the background noise levels, the centre time[5], and useful/detrimental sound ratios[6] are also obtained but are not discussed in this paper.

In this paper, octave band values of only five parameters are presented because others are either less commonly used or are usually highly correlated with one of these five parameters. These are: RT, EDT, G, C80, and LF. While RT is related to other physical properties of spaces, EDT values are related to subjective judgments of reverberance. G values relate to how loud a given sound source will be in a particular space and hence to the dynamic range that is possible during musical performances. C80 values relate to perceived clarity or the balance between clarity and reverberance, and LF values are related to the subjective sense of spatial impression or envelopment. In this paper, some further parameters are calculated from these five basic parameters to explore in more detail the strength of the sound arriving in the early and late parts of the impulse responses.

In each hall, measurements were made at all the combinations of three source positions and between 10 and 14 receiver positions distributed over all audience seating areas. Each measurement was calculated from an ensemble average of four pulse responses, and all measurements were for unoccupied conditions.

3. HALL MEAN VALUES

3.1 Reverberation Times, RT

Results are first examined in terms of overall mean values. These means are averages over the results obtained from

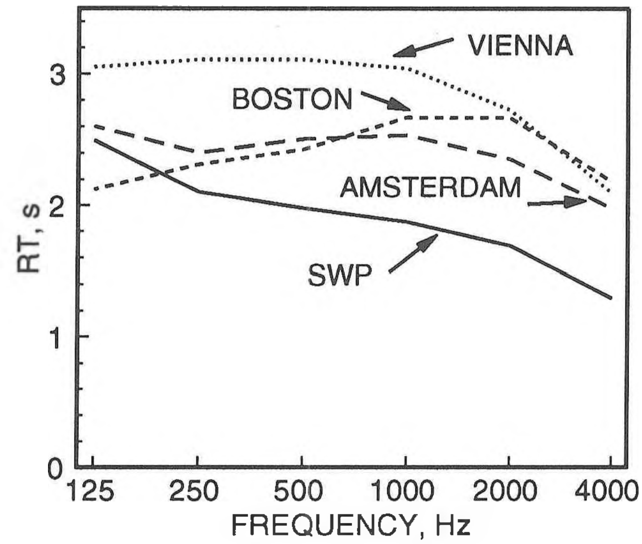

Figure 1. Comparison of hall-average RT values versus octave band frequency.

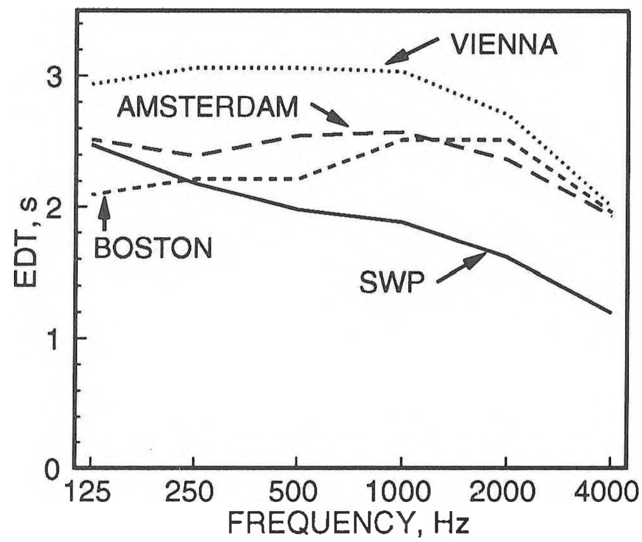

Figure 2. Comparison of hall-average EDT values versus octave band frequency.

between 30 and 42 combinations of source and receiver position in each hall. Figure 1 compares hall-average RT values for SWP and the other three halls. There are differences among the hall-mean RT values; SWP has the lowest RT values in all but the lowest octave band. At 1000 Hz, SWP is almost 1 second less reverberant than the average RT of the other three halls. This is a large difference, and SWP is less reverberant than is normally considered optimum for orchestral music. (A mid-frequency RT of approximately 2 seconds is usually considered optimum for orchestral music).

These measurements were for unoccupied conditions; it would clearly be desirable to have similar results for the occupied halls. Unfortunately, reliable RT values for occupied conditions are not available and the effect of an audience can not be calculated very accurately. Since all of the halls were unoccupied during measurements, one might assume that comparisons are completely valid. This is not strictly true because the three classical concert halls all have seats that are not very absorptive, and SWP has quite absorptive seats typical of most modern halls. Thus, the effect of an audience on RT values would be greater for the classical halls than for SWP, and one would expect that occupied RT values for SWP would be a little closer to those in the other halls. Precise corrections for the effect of an audience would have to consider the different absorptive properties of the seats. Because this information is not available, estimates of acoustical parameters for occupied conditions, which would at best be approximations, are not included in this paper.

3.2 Early Decay Times, EDT

The hall-average EDT values are shown in Figure 2. Comparison of Figures 1 and 2 shows that in these halls, mean EDT values are very similar to mean RT values. Thus, in all of these halls the perceived reverberance, as indicated by EDT values, would be very similar to that indicated by the conventional reverberation time. This is not always true and in some halls decays are markedly non-exponential, leading to differences between RT and EDT values.

The variation with frequency of EDT and centretime values has been related to perceived timbre[7]. The mean EDT values of Figure 2 show relatively lower high-frequency EDT values in SWP. However, the effects of an audience would be expected to decrease EDT values in the other three halls more at higher frequencies because of their less absorptive seats. Thus, timbre differences cannot be precisely determined from this data.

3.3 Overall Strength, G

Figure 3 compares hall average G values. Mean G values in SWP are distinctly lower than in the other halls. Mid- and low-frequency G values in SWP are approximately equal to 0 dB while in the two European halls they are close to 6 dB. Thus, the same sound source would be as much as 6 dB louder in the European halls than in SWP. Barron[7] has found that subjects respond to level differences of only a few decibels. Six decibels corresponds to a fourfold

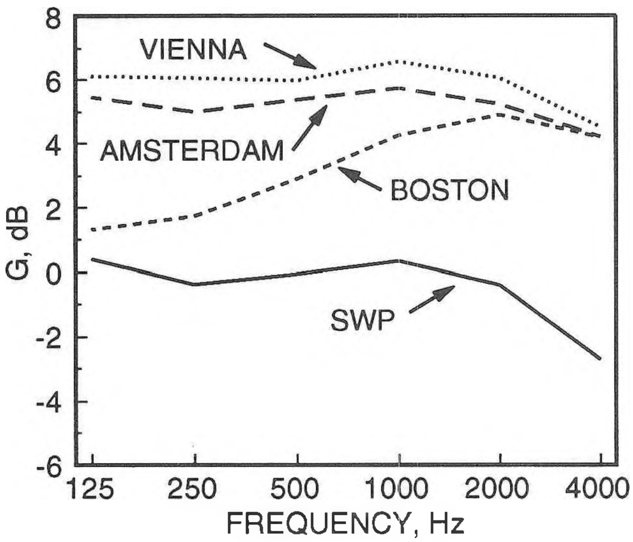

Figure 3. Comparison of hall-average G values versus octave band frequency.

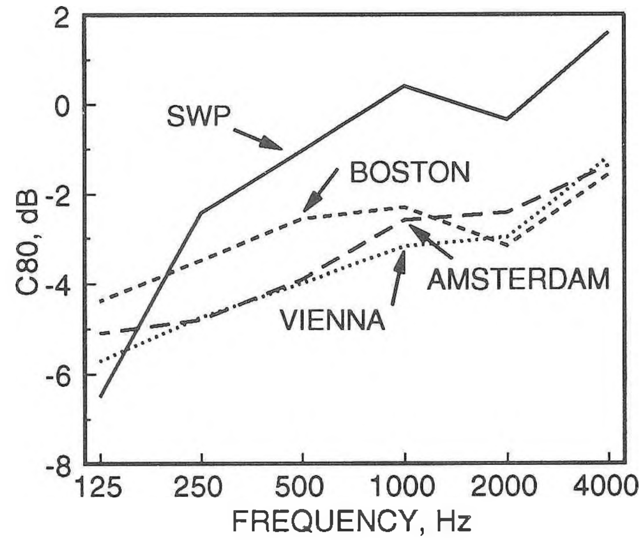

Figure 4. Comparison of hall-average C80 values versus octave band frequency.

increase in sound energy and so it can be thought of as the same as having an orchestra four times as large. Such a difference is very significant and would enable a much greater dynamic range in the music performed in the two European halls.

The Boston hall-mean G values are intermediate to those of the other halls and they vary more with frequency. Since the Boston Symphony Hall is considered one of the world's best concert halls, this may indicate that this range of G values represents what is acceptable in a good concert hall. It is also possible that G values in the Boston hall are less than optimum but other factors compensate to make this hall famous for its fine acoustics.

3.4 Early/Late Ratios, C80

The hall average C80 values in Figure 4 also show interesting differences between SWP and the other halls. In all but the lowest octave band, C80 values are largest in SWP. Thus, the sound in SWP will have more clarity than the famous concert halls. This higher clarity in SWP is probably more than is optimum for orchestral music, but perhaps is more appropriate for a multi-purpose hall.

Mean C80 values also vary with frequency more in SWP than in the other halls. The SWP mean C80 values are characterized by a prominent minimum in the 125 Hz octave band. This is due to the grazing incidence attenuation of low-frequency sound by audience seating. Although this phenomenon was discovered some time ago[8,9], its dependence on the details of an auditorium are not well understood. New results[10] suggest that the seat dip attenuation is less in halls with strong ceiling reflections. SWP has a very high reflective ceiling that is behind an acoustically transparent ceiling and various duct work. Thus, strong ceiling reflections do not occur at most seats in SWP and the low frequency seat dip attenuation is particularly pronounced.

3.5 Lateral Energy Fractions, LF

The hall-average LF values in Figure 5 show that these values are lowest in SWP. The values of this ratio in the other halls are approximately double the SWP values. Thus, the fraction of the early energy that arrives at listeners from the side is much less in SWP. Consequently, spatial impression or the sense of being immersed or surrounded by the music will be much less in this hall. Spatial impression is known to be a very important attribute of a good concert hall. The narrow rectangular shapes of the classical concert halls naturally produce relatively strong early side wall reflections. The wide fan-shaped plan of SWP makes it almost impossible to provide strong early reflections to all members of the audience. However, this plan does make it possible to seat more audience members closer to the stage, which again may be more important in a multi-purpose hall.

3.6 Early and Late Energy Levels, G80, GEL, and G(late)

The mean overall G values in Figure 3 indicated substantial differences between SWP and the other halls. It is therefore of interest to consider these differences further by

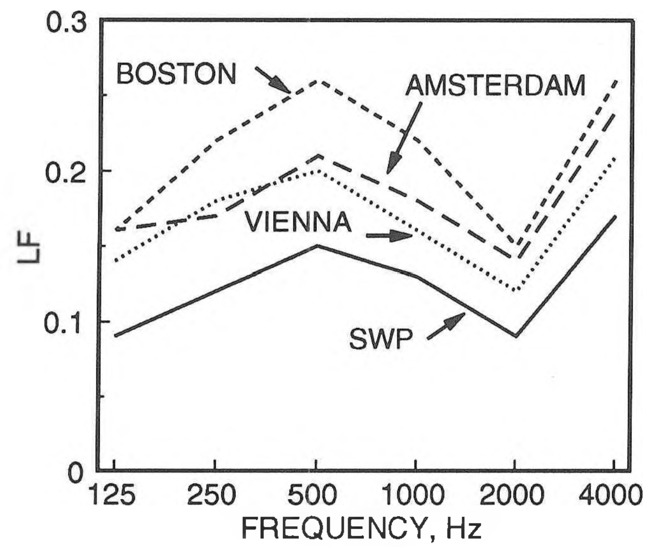

Figure 5. Comparison of hall-average LF values versus octave band frequency.

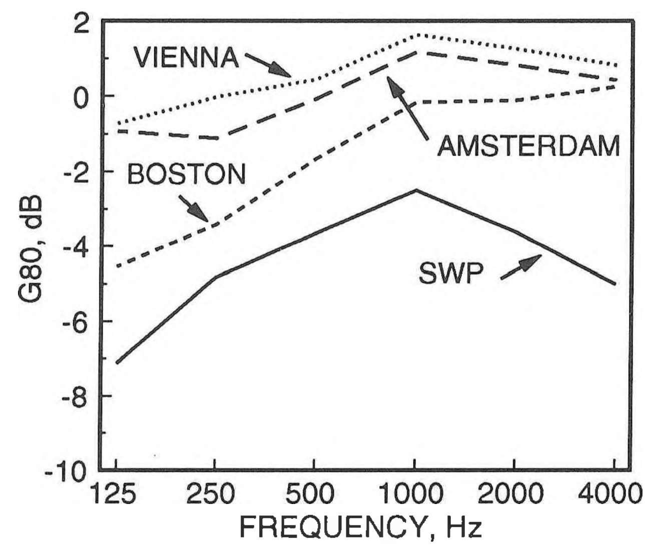

Figure 6. Comparison of hall-average G80 values versus octave band frequency.

examining the separate temporal components of the sound energy in each hall. Thus, the early, the late, or the early lateral energy are considered separately in terms of G values. G80 is the G value of the sound energy arriving within the first 80 ms after the direct sound. G(late) is the G value of the sound energy arriving more than 80 ms after the direct sound, and GEL is the G value of the early lateral energy arriving within the first 80 ms after the direct sound.

Figure 6 compares hall-average G80 values for all four halls. These early sound levels are lowest for SWP and approximately 4 dB lower than in the two European halls at mid-frequencies and even more different at lower frequencies.

Hall average GEL values in Figure 7 show that the early lateral energy is considerably smaller in SWP than in the other halls. At mid-frequencies, the mean GEL values for SWP are approximately 5 dB lower than those in the other halls. This lack of early lateral energy is a major cause of the lower LF values in this hall. GEL values were particularly low at 125 Hz where they are more than 8 dB less than in the two European halls.

Spatial impression depends on having an adequate portion of the early energy arriving from the side and also on having relatively high sound levels. Low-frequency lateral energy is particularly important for a good sense of spatial impression. Having low GEL values is evidence of a lower portion of early lateral energy, as well as having lower levels of this sound. Given that this is particularly true at lower frequencies, it is clear that the sense of spatial impression will be much less in SWP than in the other halls.

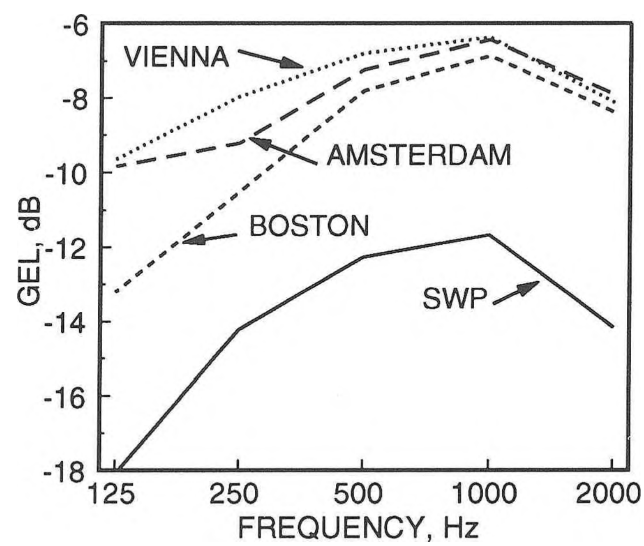

Figure 7. Comparison of hall-average GEL values versus octave band frequency.

The mean G(late) values are compared in Figure 8. These values are quite similar to the overall G values in Figure 3, indicating that the late arriving energy makes up most of the overall G values. The mean mid-frequency late energy is approximately 7 dB lower in SWP than in the two European halls. One might therefore expect a much smaller sense of reverberance in SWP than in the two European halls. It is unlikely that the added effect of audience absorption would greatly diminish this difference. Again, the Boston hall results are intermediate to the others, suggesting that lower

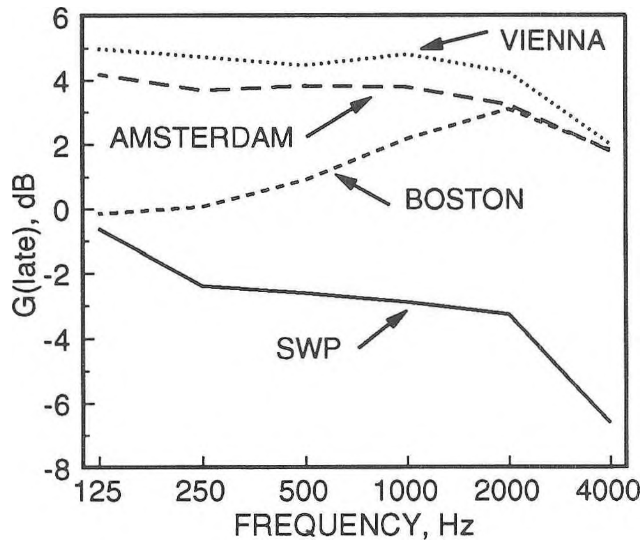

Figure 8. Comparison of hall-average G(late) values versus octave band frequency.

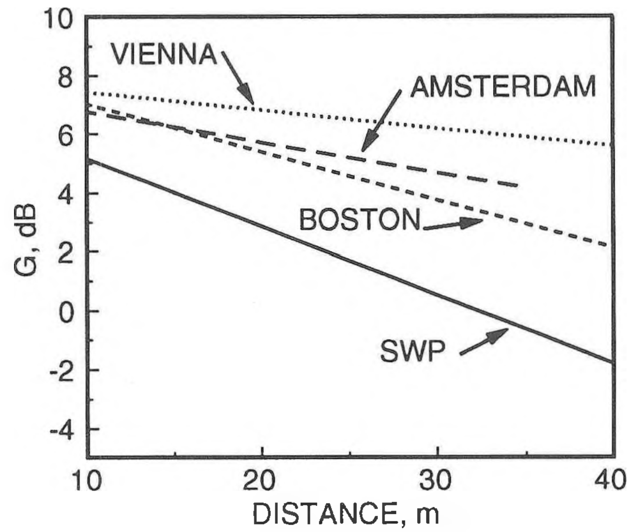

Figure 9. Linear regression lines for 1 kHz G values versus source-receiver distance.

late energy levels are, at least in some combinations of conditions, acceptable.

4. VARIATION OF LEVELS WITH DISTANCE

It is of interest to examine the variation of measured values from position to position within each hall. Some halls have larger seat-to-seat variation which is assumed to be less desirable than uniformly good conditions. In all of these halls, the within-hall variation of RT, EDT, and C80 values were all quite small. LF values tend to vary more from seat-to-seat than the other parameters and these four halls were no exception. The within hall variation of the overall sound levels was examined further by plotting G values versus source-receiver distance.

Figure 9 compares 1 kHz G values versus distance in all four halls. Only the best fit linear regression lines to the measured data have been included to simplify the comparison. In all cases, the data were well represented by the regression lines with associated standard errors of between 0.6 and 0.8 dB. As observed earlier, G values were lowest for SWP. They also decrease more rapidly with distance in SWP. The regression lines indicate that, on average, 1 kHz G values decrease at 2.3 dB/10 m in SWP, while in the Vienna hall, 1 kHz G values decrease at only 0.6 dB/10 m. These two values are close to the two extremes of decay rates that we have measured in halls. Closer seats in SWP may have G values that are 2 to 3 dB lower than the other halls, but the farthest seats have G values that are 5 to 6 dB lower. Thus, the weaker sound in SWP would be most noticeable at rear seats.

The observed decreases of overall G values with distance are in contradiction with simple diffuse field theory. In an ideal diffuse field, sound levels are essentially constant with distance in the reverberant field where the contribution of the direct sound is not significant. Although such diffuse conditions rarely occur in real rooms, diffuse field G values can be predicted by the following equation:

$$G = 10 \log\{ Q/(4\pi r^2) + 4RT/(0.161V) \} + 31, \text{dB} \quad (9)$$

where:

V is the room volume, m^3;

Q is the directivity factor of the source and is 1 for an omni-directional source;

r is the source-receiver distance, m.

Barron and Lee[11] have developed an improved technique for predicting sound levels in concert halls that better correlates with measurements. Their procedure sums separate estimates of the contributions of the direct, early, and late arriving sound energy. All three components vary with source-receiver distance, causing predicted G values to decrease with increasing source-receiver distance. Figure 10 plots measured 1 kHz G values versus source-receiver distance in the Vienna hall. For comparison, the predictions of simple diffuse field theory and Barron and Lee's revised theory are also included. While the diffuse field theory does not agree well with measurements, Barron

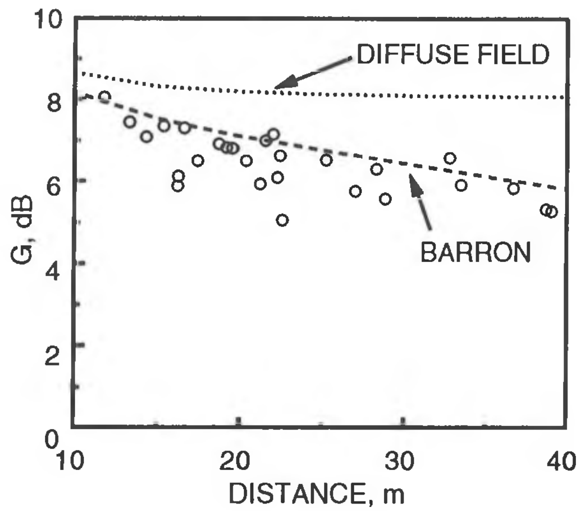

Figure 10. Comparison of measured 1 kHz G values with predictions of diffuse field theory and Barron's revised theory for the Vienna Hall.

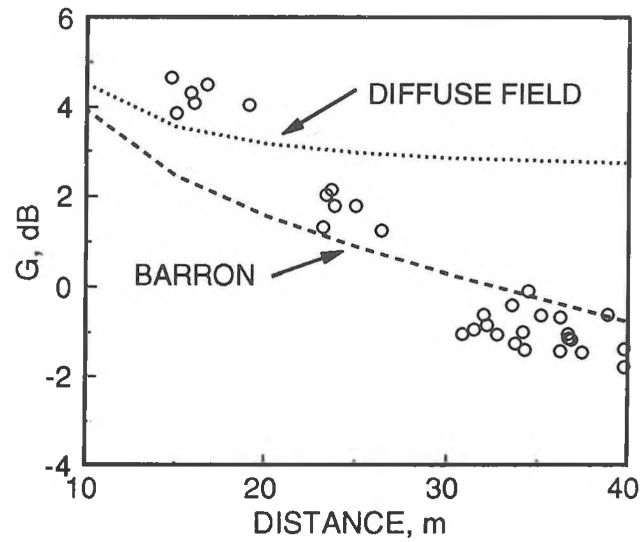

Figure 11. Comparison of measured 1 kHz G values with predictions of diffuse field theory and Barron's revised theory for SWP.

and Lee's predictions do agree well with these measurements. Similar improved agreement has been obtained with measurements in other halls.

Figure 11 shows similar comparisons for the SWP. Again, the diffuse field predictions are not acceptable, but the measured values do not agree as well with Barron and Lee's predictions for this hall. For seats closer to the stage, measured values exceed predictions by approximately 2 dB. At the farthest seats from the stage measured, values are less than predicted by about 1 dB. Conditions in SWP are less diffuse than found in many auditoria and show more variation with distance than predicted by Barron and Lee's revised theory.

5. CONCLUSIONS

In comparison with the three famous concert halls, SWP is seen to be lacking as a concert hall. The sound in SWP is first of all weaker; G values are lower by up to 6 dB. Thus, the same sound source in SWP would be weaker than in the other halls, and the dynamic range available to musicians would be less. Secondly, the sound in SWP is lacking in spatial impression compared to the other three halls. The sense of being immersed in, or surrounded by the music, which is essential to a fine concert hall, is much diminished in SWP. This was identified by lower LF and GEL values. The clarity of the sound in SWP is higher than in the other halls and there is stronger evidence of the attenuation of low-frequency early energy due to grazing incidence propagation over audience seating. Conversely, the sense of reverberance is less in SWP. EDT and RT values are generally lower, and late arriving sound levels are as much as 7 dB lower than in some of the other halls.

The geometry and materials of SWP are largely the cause of these differences. The much larger volume would relate to lower G values. The wide fan-shaped plan naturally leads to weaker early lateral reflections. The lack of strong ceiling reflections would lead to the greater decrease of sound levels with distance and to the stronger attenuation of early low frequency sounds in SWP.

These differences probably explain the major acoustical reasons why SWP is not generally considered to be a famous concert hall. However, while the other three halls are single purpose concert halls, SWP is a multi-purpose hall. The acoustical requirements for a multi-purpose hall must be a compromise between the needs of the various types of performances. Thus, at least some of these differences make the hall more suitable for other types of performances. For example, less reverberant conditions would be preferred for amplified performances and strong side wall reflections would not be needed. Seating the audience closer to the stage, for visual reasons, would then be more of a priority than lateral reflections. Although higher G values might be preferred for almost all types of performances, the smaller hall volume that this would require would again conflict with the needs of other types of performances.

A multi-purpose hall must be a balance between the needs of the various intended uses. It can be more or less acceptable as a concert hall depending on how important this particular type of use is seen to be. An optimum compromise (which is perhaps a contradiction) can only be decided in terms of the priorities of the owners and users.

The results in this paper consider only the major differences between SWP and the three classical halls. It is possible to go into much more detail in examining the within-hall variation of these properties. This can lead to a better understanding of acoustical conditions in each hall but is beyond the scope of this paper. It is also possible to evaluate the influence of particular aspects of the hall such as the removable orchestra shell. Measurements for this purpose were made and will be reported in a future paper.

Of course, the results of this paper relate only to unoccupied conditions. The addition of an audience would change conditions in these halls and the changes would be larger in the three classical concert halls because of their less absorptive seats.

The quite obvious differences that were found very clearly demonstrate the value of using thorough modern measurements to evaluate acoustical conditions in auditoria. The differences are unambiguously described in terms of objective quantities. This systematic objective assessment leads to a better overall understanding of acoustical conditions in each hall. The alternative, of largely unsubstantiated individual opinions, is simply not reliable and not acceptable.

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The association has recently received several requests to purchase CAA proceedings and publications. These, it seems, are scattered all over the country, mainly in the hands of past conference organizers. We would now like to locate all of these documants in order to offer them for sale. We would therefore appreciate if anyone in possession of CAA proceedings and publications would get in touch with Murray Hodgson. Tel: 613-993-0102 Fax: 613-954-5984.