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Some effects of orchestra shells

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This paper presents room acoustic measurements of the effects of adding or modifying an orchestra shell in several halls. The average effects, at audience seats, of adding an orchestra shell in three large multipurpose halls were small but within predicted ranges. At mid- and high frequencies, partial shells produced intermediate results. However, at lower frequencies more complex effects were observed, because the addition of an orchestra shell modified the grazing incidence seat dip attenuation. These effects depended on the geometry of the shell and on the receiver position in the hall. On-stage measurements of support were increased by approximately 5 dB with the addition of an orchestra shell. Although orchestra shells had much larger effects on-stage, they were also found to produce significant audible effects at audience seats.

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INTRODUCTION

Modern performing arts facilities in all but the largest cities are usually required to accommodate a variety of types of performances. Typically this requires a large conventional proscenium arch stage for performances of opera, ballet and theatre. An orchestra shell is then often added to adapt the hall to the needs of orchestral music. These shells can take various forms from little more than a reflecting wall at the proscenium, to almost complete enclosures around the orchestra. An orchestra shell is most necessary to provide acceptable acoustical conditions on-stage for the musicians. However, orchestra shells also modify the acoustical conditions experienced by the audience in the hall.

Despite the widespread use of orchestra shells, there is little published information on their acoustical properties. One early paper[1] discussed some practical aspects of orchestra shell design. Rindel's[2] work on reflector arrays could help to explain some aspects of the reflecting properties of shell ceiling components.

This paper reports acoustical measurements of the effects of adding an orchestra shell in a number of halls. Although most of the results describe conditions at audience seats, measures of the effects of orchestra shells on support values, measured on-stage, are also included. The first section of this paper compares the average effects of adding orchestra shells in three large multipurpose halls. The following section examines how some of the effects of adding an orchestra shell vary throughout the audience seating area. Following this the measured effects of modifications to orchestra shells are examined. Finally, the on-stage changes of acoustical conditions due to the addition of an orchestra shell are considered in terms of measured support values.

It is intended that this paper will provide useful quantitative data for estimating the effects of other orchestra shells. It is hoped to encourage others to perform further measurements of the acoustical properties of orchestra shells that could be usefully compared with the present results. This process will hopefully lead to the refining of designs to produce more effective orchestra shells.

I. AVERAGE MEASURED EFFECTS AT AUDIENCE SEATS IN THREE LARGE MULTIPURPOSE HALLS

Detailed room acoustic measurements were made in three large multipurpose halls both with and without an orchestra shell in place. Measurements were made using the combinations of three source positions and between ten and 14 receiver positions. That is, a total of between 30 and 42 measurements were made in each hall for conditions with and without the orchestra shell present.

The three halls were the Alberta Jubilee Auditorium in Edmonton (JUB), the Opera of the National Arts Centre in Ottawa (NACO), and Salle Wilfrid Pelletier in Montreal (SWP). Some details of these halls are given in Table I. The orchestra shells in the three halls were quite different in construction and are illustrated in the sketches of Fig. 1. They are intended to represent the full range of possible shell configurations from little more than a proscenium wall (NACO) to an almost complete enclosure (SWP).

The Alberta Jubilee Auditorium shell was a relatively lightweight general purpose shell. It included both wall and ceiling panels, but there were considerable gaps between the panels. The shell enclosed approximately the rear 2/3 of the orchestra. The shell in the Opera of the National Arts Centre consisted of seven massive towers and a light weight ceiling piece designed specifically for this hall. There were also three side pieces on either side of the stage that could be rotated but were not moved in these studies. The shell was quite effective at separating the hall from the back stage area. It can be described as more of a wall at the proscenium opening than an enclosure around the orchestra. The shell in the Salle Wilfrid Pelletier was an even more substantial construction and formed a quite distinct enclosure in which the orchestra was located. The wall sections were hydraulically raised from below the stage floor and the large ceiling surface was hinged down from the rear wall of the stage. There were no significant gaps in the shell.

Although the structural components of the three shells were quite different, the weight of the surface materials were

TABLE I. Details of the halls. (* RT measured with shell in place, α RT measured for the large reflective condition, LR.)

Hall	Symbol	Volume, m^3 Hall	Volume, m^3 Stage	Number of seats	Mid-frequency RT(500,1000 Hz), s
Salle Wilfrid Pelletier	SWP	32 100	17 300	2982	1.95*
Alberta Jubilee Auditorium	JUB	21 500	12 150	2730	1.63*
National Arts Centre Opera	NACO	20 000	28 500	2300	1.71*
Aird Recital Hall	AIRD	3000	···	352	1.80α
Centre Pointe Theatre	C.Pointe	5100	3600	986	1.19*

quite similar. Neglecting the supporting frame material all three shells had surface materials with surface densities of approximately 8 kg m/m^2.

A. Relative sound levels

The effect, at audience seats, of adding an orchestra shell can most simply be examined in terms of relative sound levels. Typically the volume of the stage house is similar to or a little smaller than the volume of the hall. Adding the orchestra shell usually separates the stage house from the

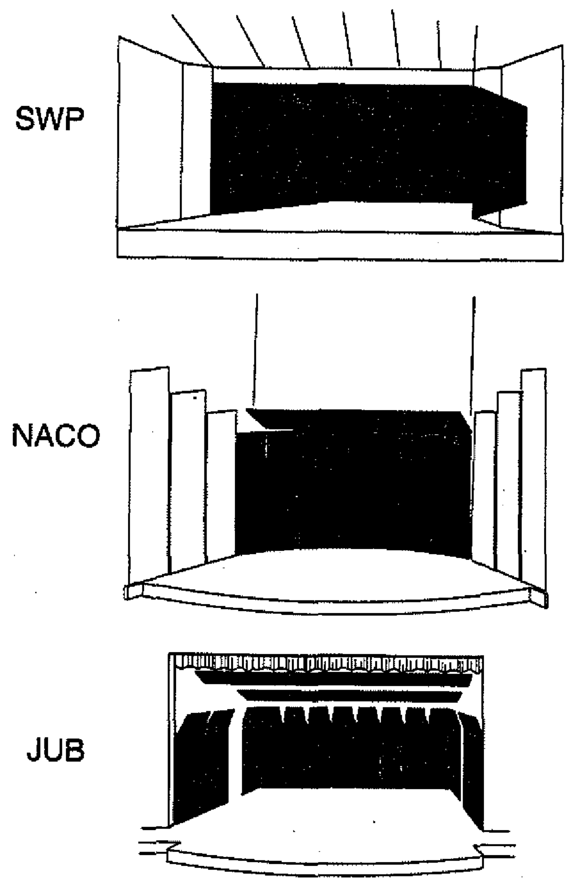

FIG. 1. Sketches of removable orchestra shells in three large multipurpose halls: Salle Wilfrid Pelletier (SWP), the Opera of the National Arts Centre (NACO), and the Alberta Jubilee Auditorium (JUB). The shaded areas are the removable parts of the shells.

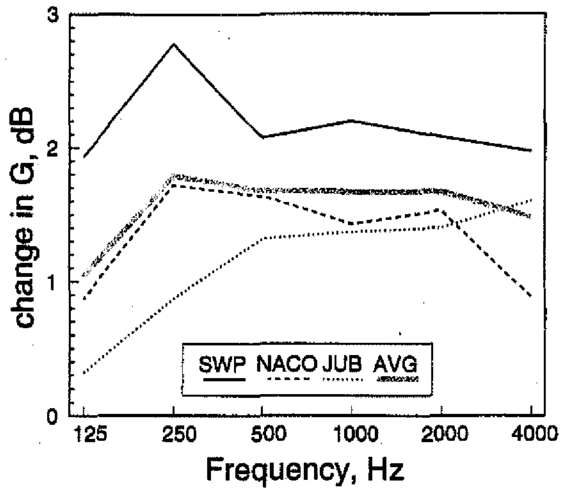

FIG. 2. Hall-average changes in total relative level (G) values with the addition of an orchestra shell for the three large multipurpose halls and the overall average change (AVG).

hall, and greatly changes the effective volume of the room. One can simply explain the expected changes in sound levels in the hall, with the addition of an orchestra shell, in terms of the portion of the sound radiated by the source that directly strikes the orchestra shell. When the shell is present, the sound striking the shell is reflected back into the hall with an amplitude reduced by R_s, the effective reflection coefficient of the shell (i.e., R_s includes the effects of gaps in the shell pieces as well as the reflective properties of the shell material). When the shell is removed, one can assume that almost all of the sound energy that would have struck the shell will pass back stage and be absorbed. Thus the expected change in relative sound levels is given by

$$\delta G = 10 \log\{(F_h + F_s \cdot R_s)/F_h\}, \quad \text{dB}, \tag{1}$$

where F_h and F_s are the fractions of the sound energy radiated by the source that initially strike the hall and shell, respectively.

If the source is close to the proscenium then $F_h \approx F_s$. For this case, and if the shell is perfectly reflective ($R_s = 1$), then Eq. (1) above would indicate a 3-dB increase in sound levels. As the source moves out in front of the proscenium, F_h becomes larger than F_s. Real orchestra shells will not be perfect reflectors and R_s will be less than 1. Where there are large gaps between the pieces of the shell, such as in the Alberta Jubilee Auditorium, then R_s will be much less than 1. These simple arguments suggest that an upper bound to the expected effect of adding an orchestra shell would be a 3-dB increase in sound levels in the hall. Estimates, using Eq. (1), of the effects in the three large multipurpose halls suggest increases of approximately 1 to 2 dB.

Figure 2 plots the average change in overall G values in the three halls due to the addition of an orchestra shell. (G values are measured sound levels relative to the level of the same source at a distance of 10 m in a free field.) Also shown is the average change for all three halls. On average, mid-frequency G values changed by 1.4 to 2.2 dB. Thus the average changes in these halls are less than the suggested 3-dB upper bound for level changes and similar to the expected

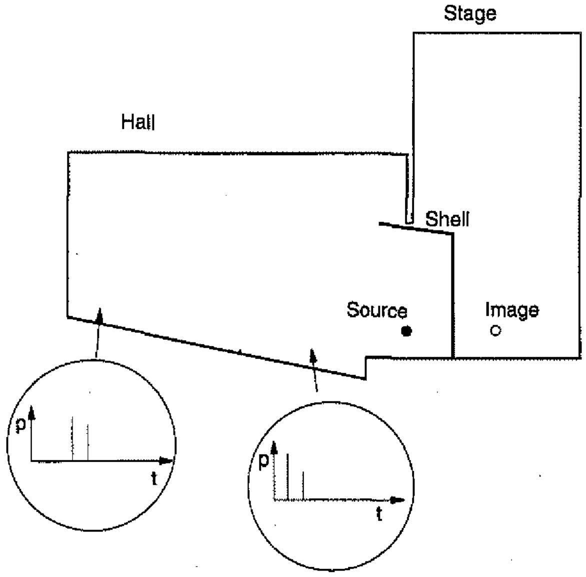

FIG. 3. Simplified section of a hall and orchestra shell to illustrate the effect of a reflection represented by an image source.

changes. The least substantial shell with the most gaps, in the Jubilee Auditorium, produced the smallest increases in G values and particularly so at low frequencies. The most substantial shell, in Salle Wilfrid Pelletier, produced the largest changes in sound levels. On average these results suggest that the addition of an orchestra shell in a large multipurpose hall will increase mid-frequency sound levels by 1.5 to 2 dB.

A 3-dB increase in sound levels is sometimes described as being equivalent to doubling the size of the orchestra. To parallel this analogy, the 1.5- to 2-dB increases are approximately equivalent to a 50% increase in the size of the orchestra. Although the increases of G values vary with frequency, the magnitude of the variations with frequency are quite small and hence the addition of these shells would not be expected to greatly change the timbre of the sound in the hall.

The early and late arriving components of sound in a hall have quite different subjective effects and it is of interest to examine them separately. Here the division between early and late is taken to be 80 ms after the arrival of the direct sound. One can approximately estimate the effect of the shell on the early sound by considering the effect of each surface of the shell to be represented by an image source. As illustrated for the rear wall of a shell in Figure 3, the sound from this image source arrives after the direct sound and is smaller in amplitude than the direct sound. In total we can expect the reflected early sound added by the shell to be lower in level than the sound propagating directly out into the hall. The magnitude of the reflected sound at a particular location will depend on the geometry of the shell and whether the shell directs reflections to that location. Of course the shell will not be perfectly reflecting and the reflected sound will be weaker because of the extra distance travelled by the reflected sound. Thus early sound level increases are expected to be substantially less than 3 dB.

Figure 4 shows the average measured changes in the three large halls. Mid-frequency early relative sound level

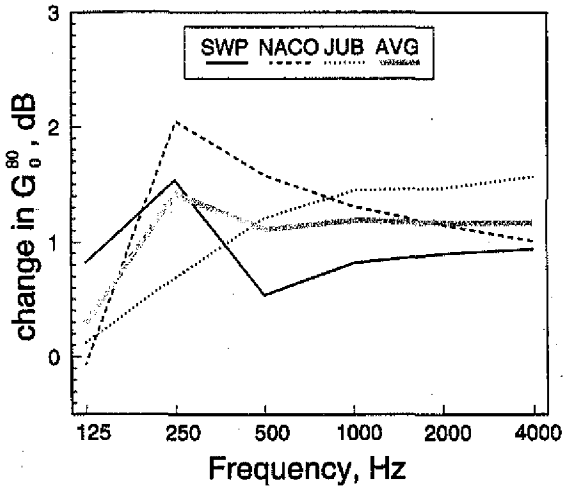

FIG. 4. Hall-average changes in early arriving relative level (G_0^{80}) values with the addition of an orchestra shell for the three large multipurpose halls and the overall average change (AVG).

(G_0^{80}) values are increased by an average of about 1 dB in these halls. The rank ordering of these increases among the three halls is different than for the total G values in Fig. 2. In fact the hall that provided the largest increase in G values (Salle Wilfrid Pelletier) produced the smallest increase in early sound level G_0^{80} values. This is because the increases in (G_0^{80}) values are related to the construction of the shell (as are G values), and also to the geometry of the shell and the audience seating locations. That is, the shell must have surfaces that are positioned to provide useful strong reflections at the measured audience seat locations to significantly increase early sound levels.

The increases in late arriving relative sound level (G_{80}^{∞}) values shown in Fig. 5 are seen to vary more among the three halls. Two of the halls show similar increases of 1 to 1.5 dB while the third hall indicates a mid-frequency increase of about 4 dB. Late sound levels will be influenced by the relative amounts of sound absorption associated with the stage and the hall. We can expect shells that direct strong reflec-

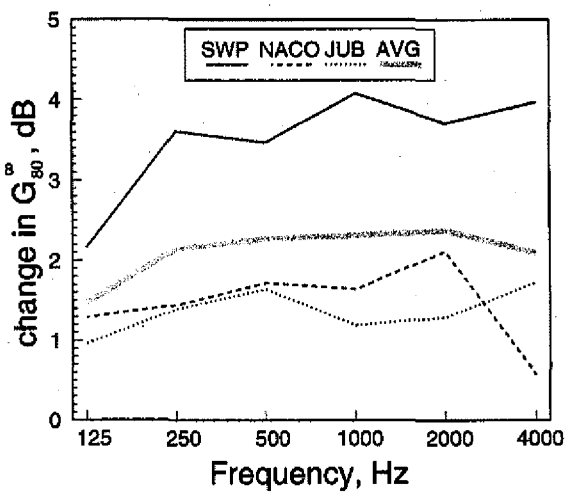

FIG. 5. Hall-average changes in late arriving relative level (G_{80}^{∞}) values with the addition of an orchestra shell for the three large multipurpose halls and the overall average change (AVG).

tions to the audience to provide increases in early sound levels. However, shells that form separate enclosures will lead to multiple reflections within the shell before the sound energy is reflected out to the audience. Such shells will tend to produce greater increases in late arriving sound levels and lesser increases in early sound levels. The shell in SWP is clearly an example of this type of shell, and in this hall late sound levels increased more than in the other two halls.

It is also interesting to note that Barron's revised theory of sound propagation in halls[3] indicates that late sound levels are more sensitive to changes in reverberation time and room volume than early or total relative sound levels. Barron's revised theory suggests that late sound levels vary approximately as 20 times the logarithm of the ratio of reverberation time to room volume. This again indicates that adding an orchestra shell may most effect the late arriving sound levels at audience seat locations.

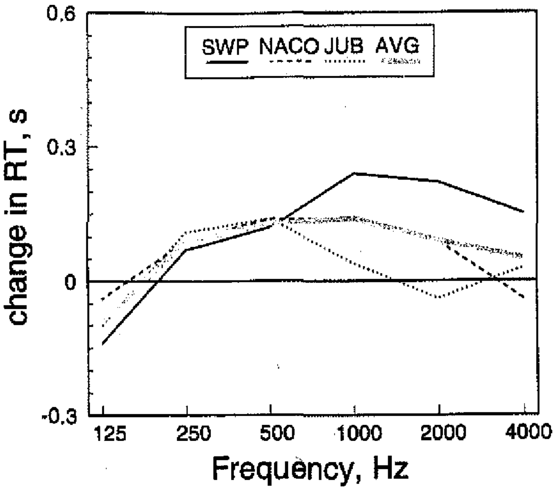

FIG. 6. Hall-average changes in reverberation time (RT) values with the addition of an orchestra shell for the three large multipurpose halls and the overall average change (AVG).

B. Decay times and energy ratios

One can most simply predict the effect of adding an orchestra shell on reverberation times as due to changing the proscenium opening from perfectly absorptive to perfectly reflective. That is, without an orchestra shell one can consider, that to the acoustical properties of the hall, the proscenium opening acts like an absorbing surface and essentially all of the sound energy passing through from the hall to the stage does not return. (This assumes some absorption material such as curtains is present on stage.) Conversely, when the orchestra shell is in place, essentially all of the sound energy in the hall is reflected back from the orchestra shell and cannot travel to the backstage area.

Using this simple explanation one can estimate an expected change in RT values on adding an orchestra shell in these three large multipurpose halls. The average total sound absorption in these halls at mid frequencies is approximately 2200 m^2 and the proscenium opening is about 200 m^2 in area (see data in Table I). Thus one would expect that adding an orchestra shell would decrease the total absorption and hence increase the reverberation time (RT) by about 9%. This corresponds to an approximately 0.15-s change in mid-frequency RT values for these halls. The average measured changes in RT values shown in Fig. 6 confirm that this is a reasonable estimate of what actually occurs. Mid-frequency RT values tended to change by slightly less than 0.15 s when an orchestra shell was added.

At low frequencies the addition of an orchestra shell tended to decrease RT values rather than to increase them. This is assumed to be due to the orchestra shell being an effective sound absorber at low frequencies. At high frequencies the results are more varied because of the different amounts of sound absorption contributed by curtains and other backstage materials in the three halls, as well as the differences in shell constructions. High-frequency RT values were changed least in JUB probably because the large gaps between the shell pieces made it a less effective reflector at these frequencies. High-frequency RT increases were greatest in SWP where the shell formed a more complete enclosure with no gaps. The relative amount of backstage absorption would also influence these changes but unfortunately was not measured.

Figure 7 shows the average changes in early decay time (EDT) values in the three halls when an orchestra shell was added. These results show a similar pattern to the RT values except that the changes are more varied at higher frequencies. These results indicate that the presence of absorbing material on-stage can have a significant effect on higher-frequency EDT values and adding an orchestra shell can increase hall-average EDT times by up to 0.4 s. It is important to determine the effects in terms of the subjectively more important EDT values. They suggest quite large and quite audible changes can occur with the addition of an orchestra shell, while the average changes to RT values are quite small and only just over 0.1 s.

C80 is a measure of perceived clarity and is the ratio of the early-to-late arriving sound energy. One might simplisticly expect that adding an orchestra shell would add early reflected energy and hence increase C80 values. This does

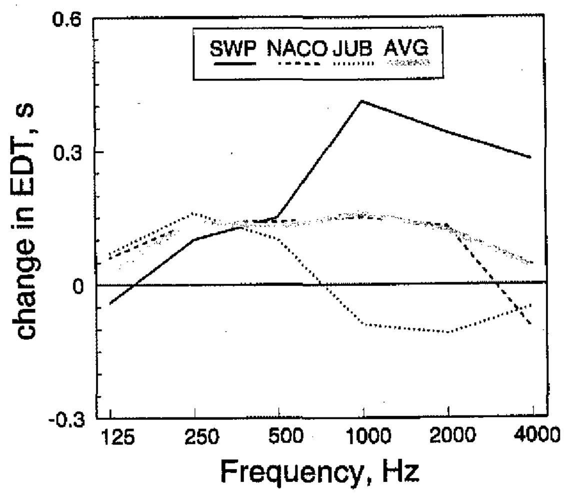

FIG. 7. Hall-average changes in early decay time (EDT) values with the addition of an orchestra shell for the three large multipurpose halls and the overall average change (AVG).

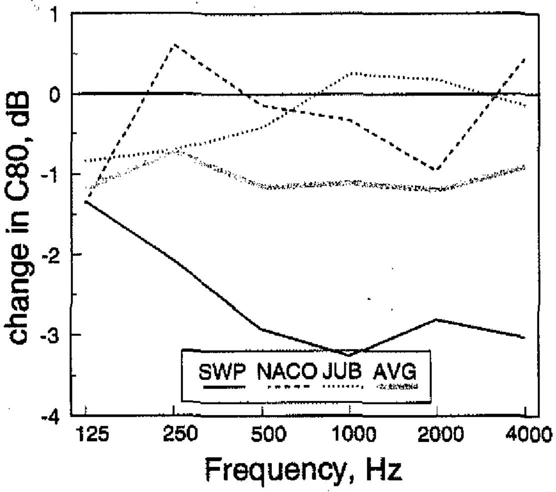

FIG. 8. Hall-average changes in early/late ratio (C80) values with the addition of an orchestra shell for the three large multipurpose halls and the overall average change (AVG).

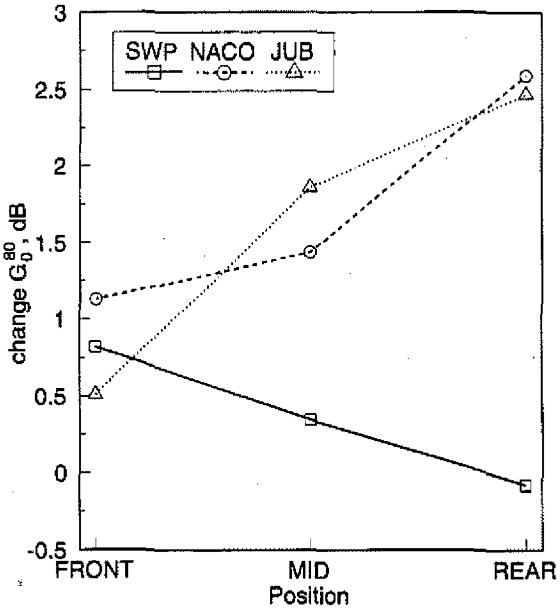

FIG. 9. Average 500 Hz relative early sound levels (G_0^{80}) versus position from the stage for main floor seats in the three large multipurpose halls.

not occur. The effect of adding an orchestra shell on C80 values will depend on how the shell modifies both early and late arriving sound. The results of Fig. 4 showed that adding an orchestra shell increased early sound levels (G_0^{80}) by approximately 1.0±0.5 dB. However, late arriving sound levels (G_{80}^{∞}) were increased by up to 4 dB. In halls where the early and late sound levels are increased by about the same amount, then C80 values will change very little. In halls where the G_{80}^{∞} values are increased much more than G_0^{80} values, then C80 values will decrease when a shell is added.

The average measured changes to C80 values are plotted in Fig. 8. In two of the halls (NACO and JUB) the average changes in C80 values are quite small because both early and late sound levels were increased by similar amounts when the shell was added. In the third hall (SWP) mid-frequency C80 values decreased by approximately 3 dB. This is a result of G_0^{80} values being increased about 1 dB and G_{80}^{∞} values being increased approximately 4 dB. Again this suggests that the audible effects of adding an orchestra shell can be quite negligible in some halls but very significant in others.

The lateral energy fraction (LF) is the fraction of the early sound energy that arrives from lateral directions. It is known to be related to subjective judgments of spatial impression and in particular to the apparent width of the sound source.[4] Measurements of the average change of LF values showed only very small changes due to the addition of an orchestra shell. Almost all octave band changes in LF values were less than ±0.05. Thus on average the orchestra shells did not change this aspect of spatial impression in these halls.

II. SPATIAL VARIATION OF THE EFFECTS OF AN ORCHESTRA SHELL AT AUDIENCE SEATS

Various acoustical measures vary systematically with position in an auditorium. Early, late, and total sound levels usually decrease with increasing distance from the source.[3,5] Although RT values are usually relatively constant throughout a hall, EDT values can vary systematically with source-to-receiver distance.[5] While the various measures may vary systematically with position in a hall, there is little evidence from the present measurements that the changes produced by the addition of an orchestra shell vary systematically with position in the halls.

The simple analysis of Fig. 3 and Sec. I A above would suggest that changes in early sound levels (G_0^{80}) due to the addition of an orchestra shell would tend to increase with increasing distance from the stage. It was reasoned that early sound levels are increased because of the addition of reflections from various surfaces of the orchestra shell. For receiver positions close to the stage, the reflected paths tend to be much longer relative to the direct path. As one moves to the rear of the hall, the relative difference between the direct path and the reflected path lengths become less. This leads to direct and reflected sounds being more similar in amplitude and the addition of the reflection from the shell comes closer to increasing the early sound level by 3 dB. Thus one expects the effect of the shell on the early sound to be greatest at the rear of the hall and to approach a +3-dB change.

Figure 9 demonstrates that this effect was very evident in two of the halls. In NACO and JUB the increase in G_0^{80} values was 1.5 to 2 dB greater at the rear of the main floor than at seats closer to the stage. At the rear seats the increase in G_0^{80} values was approximately 2.5 dB, approaching the estimated upper limit for increases of 3 dB. In the third hall, SWP, there is a small trend for the increases in G_0^{80} values to decrease with increasing distance from the shell. This shell was quite different in that it formed an enclosure around the orchestra which would have acoustical properties almost like a separate room. In this shell, sound could reflect around within the orchestra shell several times before being directed out into the hall. Thus this shell tended to increase late sound levels G_{80}^{∞} more than early sound levels G_0^{80}, and it did not simply reflect sounds immediately out to the audience seating areas.

The increase in late arriving sound levels due to the

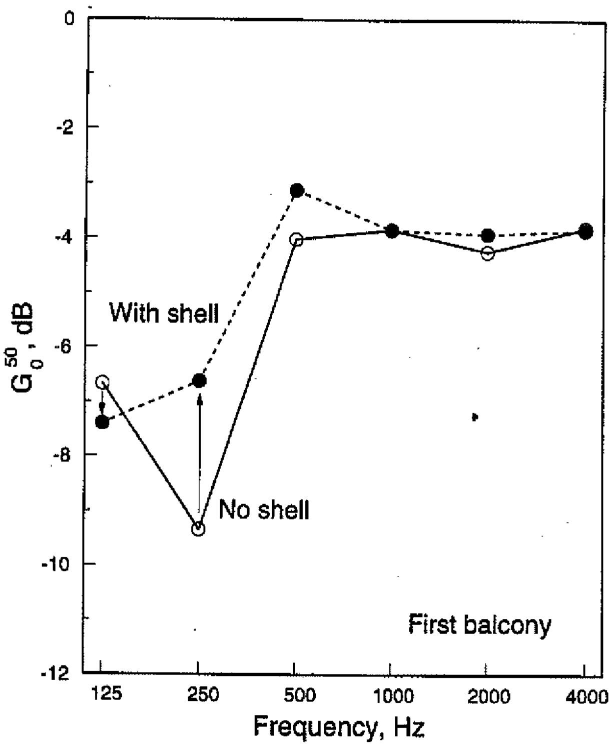

FIG. 10. Average spectra of the relative early arriving sound (G_0^{50}) at seats in the first balcony of the Opera of the National Arts Centre both with and without an orchestra shell present.

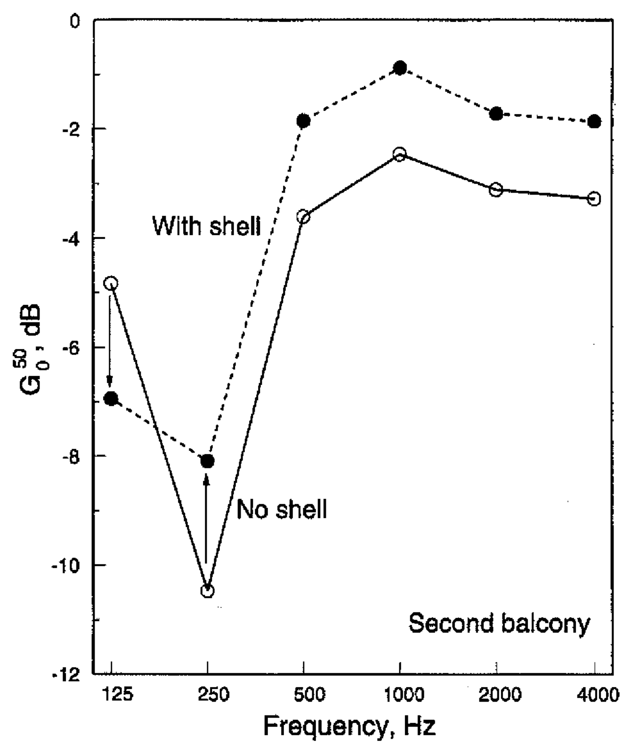

FIG. 11. Average spectra of the relative early arriving sound (G_0^{50}) at seats in the second balcony of the Opera of the National Arts Centre both with and without an orchestra shell present.

addition of an orchestra shell also increased with increasing distance from the stage in the Alberta Jubilee Auditorium. The change in G_{80}^{∞} values was 2 dB greater at the rear seats than at seats closer to the stage. However, this trend was not observed in the other two halls.

Much more complex variations at some receiver locations can be found when measured results are examined in more detail. Figure 4 showed that, on average, at 125 Hz early sound levels (G_0^{80}) changed only very small amounts when an orchestra shell was added. When examined on a seat by seat basis much larger changes in the 125 and 250 Hz G_0^{80} values were observed. Figure 10 shows average measured G_0^{50} values for seats in the first balcony of NACO both with and without an orchestra shell. While there is little change in the mid- and high-frequency G_0^{50} values, the low frequency G_0^{50} values change more significantly. Similar results were found for an average of measurements in the second balcony shown in Fig. 11. Both plots are the average of the six measurements from three source positions to two receiver positions. In both cases early sound levels increased considerably at 250 Hz and decreased at 125 Hz.

These results are thought to be due to a shift in the frequency of the maximum attenuation of the grazing incidence seat dip attenuation. This attenuation is known to be dependent on the angle of incidence of the sound,[6] and the frequency of the maximum attenuation shifts lower in frequency as the angle of incidence departs from grazing incidence. As an example, the results of Fig. 2 of Ref. 4 show the frequency of this maximum attenuation to shift from 180 to 125 Hz when the grazing angle increased from 1 to 10 deg above the surface formed by the chairs. The added reflected sound from the orchestra shell arrives at more elevated angles relative to the audience surface than the direct sound as illustrated in Fig. 12. Thus one might expect the seat dip attenuation maximum to shift to a lower frequency with the addition of an orchestra shell. This is exactly what is observed in the results of Figs. 10 and 11. G_0^{50} values (rather than G_0^{80} values) were shown in these plots to better illustrate the changes in the seat dip attenuations. Of course, to fully explain these low-frequency effects one would have to include the complex interference of the direct sound and the sound reflected from the shell.

These results also help to further explain the average changes in G_0^{80} values in Fig. 4. The larger increases in G_0^{80} values at 250 Hz for NACO are due to the same changes in

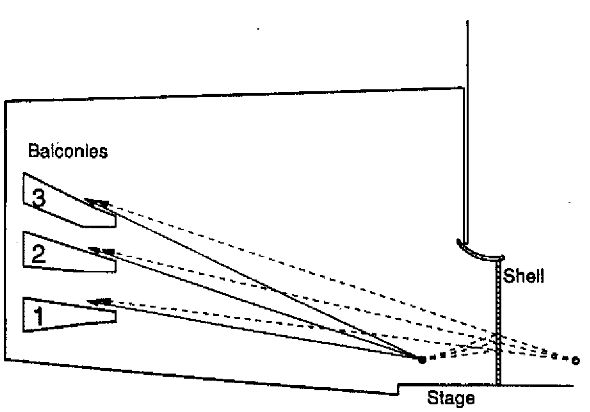

FIG. 12. Simplified section of the Opera of the National Arts Centre, showing the difference in angles of incidence of the direct and reflected sound.

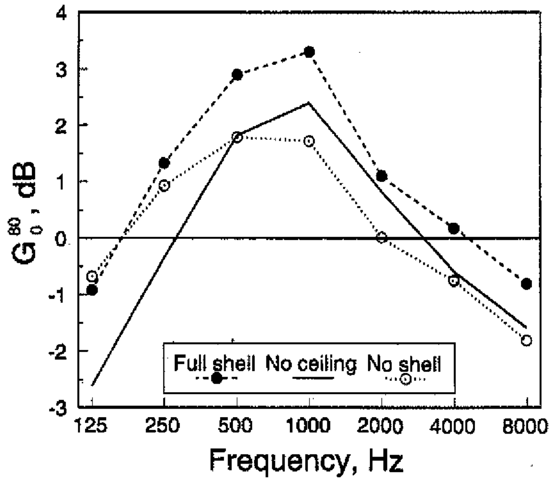

FIG. 13. Average relative early arriving sound levels (G_0^{80}) at main floor seats in the Alberta Jubilee Auditorium for: a full shell, no shell, and a partial shell without ceiling pieces.

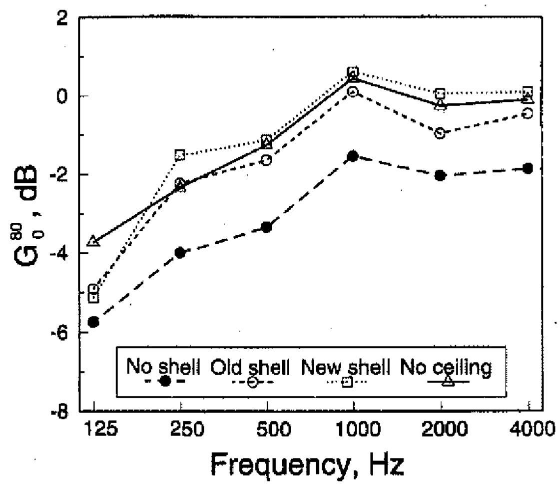

FIG. 14. Average relative early arriving sound levels (G_0^{80}) at main floor seats in the Opera of the National Arts Centre for: no shell, old and new shell configurations, as well as a partial shell without ceiling pieces.

frequency of the maximum seat dip attenuation at some locations.

III. EFFECTS OF MODIFICATIONS TO ORCHESTRA SHELLS

Measurements were also made of various modifications to orchestra shells. These results give an indication of the performance of partial orchestra shells and also help to further increase our understanding of the effects of orchestra shells. Measurements were made for variations of the orchestra shell configuration in two of the large multipurpose halls mentioned above. Tests were also performed to evaluate the effects of variable absorption panels around the stage of a smaller recital hall.

A. Modified orchestra shells in large multipurpose halls

In the Jubilee Auditorium acoustical measurements were made at main floor audience seats for three conditions: no shell, complete shell, and the shell without any ceiling panels. Figure 13 plots hall-average early sound levels versus octave frequency for each configuration. The average G_0^{80} values for the full shell and the no shell cases suggest that the shell is most effective at mid- and high frequencies. At these same frequencies the partial shell case, without the ceiling pieces present, gives results that are intermediate to the other two cases. However, in the lowest two octaves the partial shell case seems to be less effective than the no shell case. The effect of the shell at lower frequencies is more complicated than one might expect.

The more complex effects at lower frequencies are again thought to be related to changes in the grazing incidence seat dip attenuation. Adding only the walls of the shell decreases the early low-frequency sound levels (G_0^{80}). That is, the early reflections from the walls of the shell are significantly attenuated at low frequencies by the grazing incidence seat dip attenuation. However, the reflections from the ceiling pieces of the shell do not arrive at grazing incidence and considerably increase the early arriving low-frequency sound levels. Measurements of the total sound levels showed an almost identical pattern to the G_0^{80} values in Fig. 13, because in this hall the early sound is a significant portion of the overall sound energy.

These results show that even for this relatively light weight shell with significant gaps between the various panels, the ceiling pieces are important for increasing the low-frequency sound levels in the hall. Both the G and G_0^{80} values at 125 Hz were increased by approximately 1.5 dB by the addition of the ceiling pieces of this shell. This corresponds to a 41% increase in the sound energy. It would be very difficult to achieve this magnitude of increase by trying to make the shell more reflective at 125 Hz.

Measurements in the Opera of the National Arts Centre also showed the ceiling component of the shell to have a special effect in the 125-Hz octave band. Measurements were made for two configurations of the shell towers and a third configuration with the ceiling piece raised up. These were compared with measurements for the no shell condition at main floor audience seats. Figure 14 compares average measured G_0^{80} values for these four conditions. In the "old shell" configuration the towers that formed the rear wall of the shell were in a slightly bow-shaped plan. For the "new shell" configuration the rear wall was closer to a straight line. The one ceiling piece formed a relatively minor component of the complete shell. When it was raised up, reflections from it were eliminated.

The results in Fig. 14 show that adding either the old or the new shell configuration increased G_0^{80} values by close to 2 dB except in the 125-Hz octave band. The differences between the effects of the old and new configurations were very small with a trend for slightly larger increases in G_0^{80} values for the new shell configuration. When the ceiling piece for the new shell configuration was removed the increases in G_0^{80} values were very slightly reduced at mid- and high frequencies. However, at 125 Hz removing the ceiling piece led to increased G_0^{80} values. This is the opposite of the effect of removing the more significant ceiling pieces of the shell in the Jubilee Auditorium.

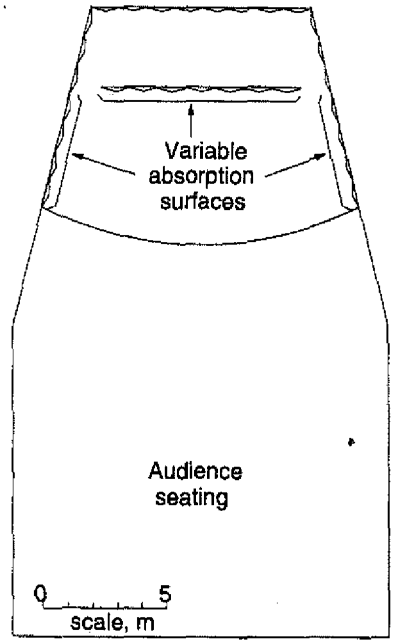

FIG. 15. Simplified sketch plan of the Aird recital hall showing the location of variable absorption panels.

Again the effect of the shell on early arriving low-frequency sound levels is more complex than might be expected. The grazing incidence seat dip attenuation phenomenon is the result of the destructive interference of various sound waves. The addition of the orchestra shell adds new sound waves that arrive from different directions and may either increase or decrease this destructive interference depending on the details of arrival times, phase, and directions.

The effect of the different shell configurations on G_{80}^{∞} values were very similar. The addition of a either shell configuration increased G_{80}^{∞} values by 1.5 to 2 dB in all but the 4-kHz octave band where increases of about 1 dB were measured. The difference in the effects of the old and new shells on G_{80}^{∞} values was no more than about 0.2 dB. Removing the ceiling piece produced G_{80}^{∞} values intermediate to the old and new shell results.

The effects of orchestra shells on early and late sound levels can be quite different, and the effect of adding a shell on the total sound levels will depend on the relative importance of the early and late sound levels.

B. Modifications to the stage surfaces in a small recital hall

The Aird Recital Hall in Waterloo, Ontario, Canada has a volume of 3000 m^3 and seats 352 people. It has a relatively large stage with variable absorption panels on the side and rear walls. Figure 15 is a sketch of the plan of this hall. As illustrated in this figure parts of the side walls of the stage can be rotated to reveal either reflective or absorbing surfaces. A rear wall can also be added that reduces the depth of the stage and this surface can be either reflective or absorptive. Measurements were made at audience seats in this hall for a range of different configurations of the stage surfaces.

Figure 16 summarizes the measured changes in mid-frequency early, late, and total sound levels (G_0^{80}, G_{80}^{∞}, and G values) for two different changes of the stage surfaces. The lower half of this graph shows the measured average differences between the small reflective (SR) and small absorptive (SA) conditions. The upper half of the graph shows the differences between small reflective (SR) and all absorptive (AA) conditions. The small reflective (SR) case is for all surfaces reflective. The small absorptive (SA) case is with the side walls absorptive, and the all absorptive case (AA) is for both the side and rear walls absorptive. For all cases shown in Fig. 16 the moveable rear wall was installed to create the small stage configuration.

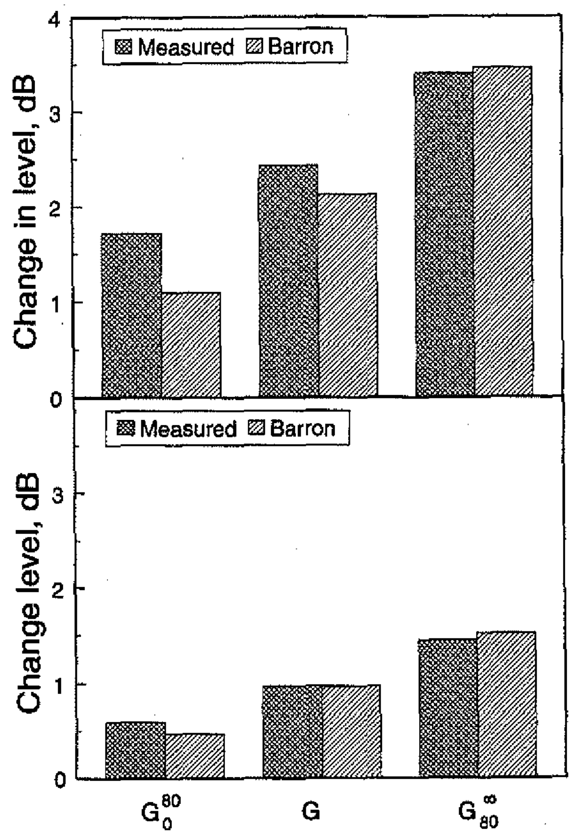

FIG. 16. Comparison of measured average changes in early, late, and total mid-frequency relative level (G_0^{80}, G, and G_{80}^{∞}) values due to changing the absorbtivity of stage surfaces with predictions using Barron's revised theory.[3]

These changes did not involve any change to the shape or volume of the hall, they only changed the absorption of the surfaces of the orchestra enclosure formed by the stage area of this recital hall. The expected changes were calculated using Barron's revised theory[3] for each condition. The differences between the theoretical calculations for each pair of conditions are generally in very good agreement with the measured changes. The exception is the change in G_0^{80} values between the small reflective (SR) and the all absorptive (AA) conditions. The measured G_0^{80} values show a larger change than predicted, presumably because the theory does not correctly account for the addition of significant amounts of absorbing material close to the source. With this small exception, it is seen that Barron's revised theory can be quite useful in predicting the effects of such changes to the surfaces of an orchestra shell.

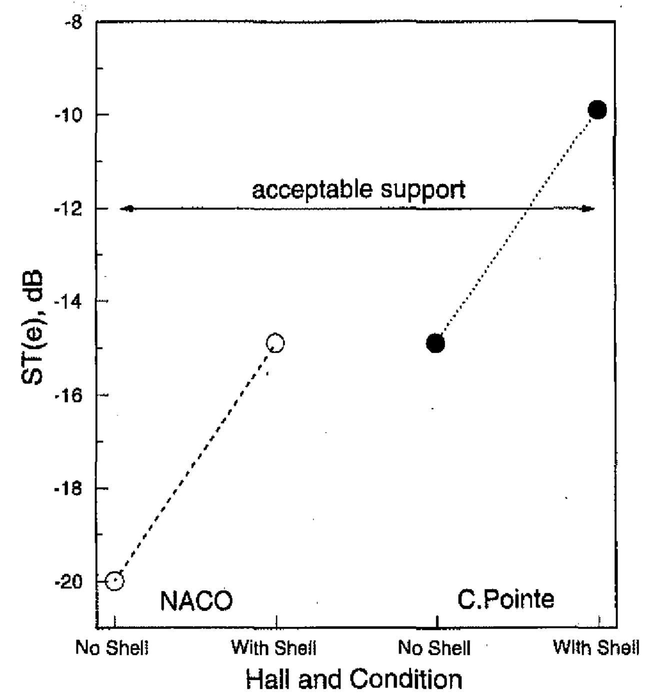

FIG. 17. Average measured changes in early support [$ST(e)$] values with the addition of an orchestra shell in two different halls.

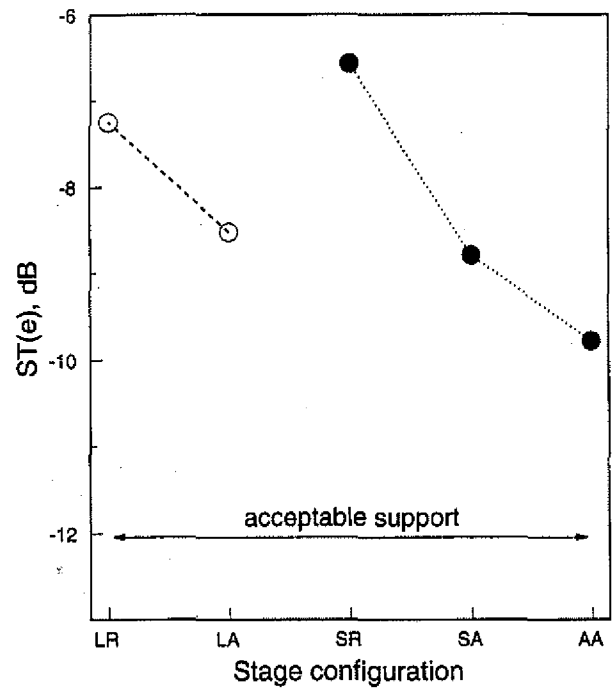

FIG. 18. Average measured changes in early support [$ST(e)$] values for varied configurations of absorbing stage wall panels.

IV. ON-STAGE EFFECTS OF ORCHESTRA SHELLS

Although this paper has concentrated on the effects of orchestra shells at audience seats, orchestra shells were also evaluated at on-stage locations. Measurements of Gade's support measure were made to evaluate the effects of orchestra shells for performers. Gade has defined early support as follows:[7]

$$ST(e)=10\log\left\{\int_{0.02}^{0.10}p^2(t)\,dt\Big/\int_{0}^{0.01}p^2(t)\,dt\right\},\quad \text{dB},\quad (2)$$

where $ST(e)$ is related to the support or response of the hall to the performers efforts. It is measured in octave bands and an average of the four octave values from 250 to 2000 Hz is calculated. In these measurements, results were an average of the data obtained at four positions on stage that were representative of where orchestral musicians would sit.

Measurements were made in two halls both with and without an orchestra shell present. One hall was the Opera of the National Arts Centre and the other, the Centre Pointe Theatre, is a medium sized hall described further in Table I. The shell in the Centre Pointe Theatre was a general purpose light weight shell with both wall and ceiling pieces. It was quite similar to the shell in the Alberta Jubilee Auditorium. The effects of adding an orchestra shell in these two halls are illustrated in Fig. 17. In both halls adding an orchestra shell increased $ST(e)$ values by approximately 5 dB. Gade suggests that an $ST(e)$ value of about -12 ± 1 dB is a desirable optimum.[7] Adding the shell in the Centre Pointe Theatre increased average $ST(e)$ values above this level. In the larger Opera of the National Arts Centre, adding the shell did not increase $ST(e)$ values to this desired value. Of course, $ST(e)$ values are below -12 dB in several halls well known for their good acoustics and a 5-dB increase is certainly a substantial improvement.

Support values were also measured for a range of configurations of the stage surfaces in the Aird Recital Hall (see Fig. 15 and Table I). The configurations included the small reflective (SR), small absorptive (SA), and the all absorptive (AA) described in the previous section. Measurements were also made for the large reflective (LR) and large absorptive (LA) conditions. For these large conditions the removable rear wall shown in Fig. 15 was not present, and only the absorptive side panels were in place for the large absorptive case. The resulting average $ST(e)$ values are shown in Fig. 18. The largest measured change was about 3.5 dB. This was smaller than completely removing the orchestra shells in the other two halls.

These measurements show that even small changes to the absorbing properties of the orchestra shell surfaces can significantly modify acoustical conditions on-stage. As would be expected, the addition of a complete orchestra shell has a larger effect on-stage than at audience seat locations.

V. CONCLUSIONS

The results presented in this paper give an overview of typical effects of orchestra shells both at audience seats and on-stage. The average changes in measured acoustical quantities when an orchestra shell was added were usually similar to simple predictions. In general, the average effects at audience seats were small but are expected to be audible. Larger effects were measured on-stage.

The addition of an orchestra shell increased overall sound levels, but by less than 3 dB. Early arriving sound levels were increased less but later arriving sound levels were increased by as much as 4 dB.

Low and mid frequency (125 to 500 Hz) RT and EDT values were increased by as much as 0.1 to 0.15 s when an orchestra shell was added. Mid- and high-frequency (1000 to 4000 Hz) RT and EDT values could be more varied and high-frequency EDT values increased by up to 0.4 s. Average C80 measures of clarity showed little change or decreased by up to 3 dB. Thus orchestra shells do not usually increase clarity as is often assumed. LF values were on average not changed significantly by the addition of an orchestra shell.

Where the shell is shaped to reflect sound directly out to the audience, there was a trend for mid-frequency G_0^{80} values to be more increased toward the rear of the hall.

Low-frequency RT values were decreased by the addition of a shell but on average low-frequency EDT values showed small increases when a shell was added. The effect of an orchestra shell on early low-frequency sound levels was more complex, and sometimes resulted in octave band changes of ± 2 dB in G_0^{80} values. Adding an orchestra shell could increase or decrease low-frequency early-arriving sound levels. These effects are due to the complex interference of direct and reflected sounds from the orchestra shell modifying the grazing incidence seat dip attenuation.

It is seen that designing an orchestra shell to provide adequate increases in low-frequency sound levels is not just a question of having an adequately massive construction that will better reflect low-frequency sound. The geometry of the shell is also important. It must provide reflections with significant low-frequency sound energy. Thus it is important that these reflections arrive at audience locations from nongrazing angles of incidence.

Tests of partial shells also confirmed the importance of low-frequency reflections arriving from suitable directions and with appropriate time delays. In a recital hall with variable absorption surfaces on the orchestra shell, the effect of the varied absorption could be accurately predicted using Barron's revised theory of sound propagation in halls.

As is usually assumed to be true, the effects of the orchestra shells were much greater at on-stage measurement locations. Although the addition of an orchestra shell can have significant audible effects at audience seats, orchestra shells are most important to provide adequate acoustical conditions on-stage for musicians.

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