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Acoustical Comparison of Three Theaters

by J.S. Bradley

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RÉSUMÉ

Trois salles de spectacle comprenant une avant-scène et une arche sont évaluées à l'aide de mesures acoustiques encore peu utilisées. Les caractéristiques de chaque salle sont examinées et incluent une fosse d'orchestre partiellement recouverte et un écran réverbérateur. Un modèle informatique permet de déterminer les effets nuisibles d'un trop grand nombre d'ouvertures dans le plafond pour l'éclairage.

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Acoustical comparison of three theaters

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Three theaters, including both thrust stage and proscenium arch designs, are evaluated using acoustical measures not yet in common use. The unique characteristics of each theater are considered and include a partially covered orchestra pit and a music shell. A computer model is used to estimate the detrimental effects of excessive ceiling lighting holes.

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INTRODUCTION

Although the science of auditorium acoustics has made definite progress over the past 20 years, little of this new knowledge is yet used quantitatively by acoustical consultants. Much work is required before the new results can be applied in practical situations. This paper reports evaluations of three theaters using acoustical measures and techniques not yet in common use. It is hoped that such studies will provide the practical information required to advance the application of current knowledge to the design and assessment of theaters.

I. ACOUSTICAL MEASURES

Over the past 80 years the acoustical design of auditoria has been based almost entirely on an optimum reverberation time RT. Only recently has the inadequacy of RT as a single design parameter become apparent. The work of Haas¹ first established the importance of strong early reflections for speech intelligibility when he showed that most early reflections are not perceived separately but as an enhancement of the direct sound. Subsequent work by Lochner and Burger² showed that, in the absence of interfering noise, speech intelligibility is related to the ratio of the sum of the energy in the early reflections to the unwanted late-arriving sound energy. Several such early-to-late-arriving sound energy ratios have been proposed, but they are found to be very highly intercorrelated.³ C_{80} , the ratio of the early sound energy arriving in the first 0.08 s after the direct sound to the later-arriving sound energy, has been found to be a good correlate of subjectively assessed clarity and definition for music.^{4,5} New research suggests that the 0.08-s early sound interval is also suitable for speech intelligibility studies.⁶

Pioneering work by Schroeder⁷ first demonstrated that the subjectively perceived decay time is better related to the initial part of the decay rather than to the conventional estimates of reverberation time obtained from the entire decay curve. Accordingly, EDT (early decay time), the RT calculated from the mean decay rate during the first 10 dB of the decay, has been used to better predict the degree of perceived reverberance in a room. Like C_{80} and subjective impressions, EDT varies from seat to seat in an auditorium.

The principal measured quantities reported in this paper are C_{80} , the 0.08-s early-to-late-arriving sound ratio (or Klarheitsmass), EDT, the early decay time, RT, the conven-

tional reverberation time, and background sound levels. Each quantity was obtained in octave bands for a number of combinations of source and receiver position in each theater. All measures were obtained from digitally recorded pistol shots⁸ and subsequent computer processing. The gun radiated substantial sound levels in an omnidirectional manner in the octave bands from 125 to 8000 Hz. The computer program digitally filtered the pulses into octave bands, and from simple energy summations the early-to-late-arriving sound energy ratios were calculated. The Schroeder integrated-impulse technique was used to calculate EDT and RT values by least-squares fits to the resulting decay curves. Speech intelligibility tests were also performed in each theater using a Fairbanks rhyme test and tape recorded speech.

II. THE THREE THEATERS

The three theaters investigated were the National Arts Centre (NAC) Theater in Ottawa, and the Festival and Avon Theaters in Stratford, Ontario, Canada. The Festival Theater is the largest, with a volume of 9400 m³ and seating for 2262 people. It has a thrust stage, audience seating forming a 220° angle round it. The Avon Theater is an older theater of conventional proscenium arch design having a volume of 4600 m³, excluding the stage house, and seating for 1107 people. In the NAC Theater a thrust stage can be added in front of the conventional proscenium arch stage, reducing the number of seats from the maximum of 967. The NAC Theater has a volume of about 7000 m³, excluding the stage house. All three theaters have a single balcony. The Avon Theater also has a partially covered orchestra pit, and the NAC Theater a movable stage shell that can be added for performances involving small musical groups. Cross sections of the three theaters are shown in Figs. 1–3. The NAC Theater was built in 1967 with N. Papas and Associates as acoustical consultants. The Festival Theater was built in 1957; R. H. Tanner, the acoustical consultant, reported his design considerations in this journal.⁹ The Avon Theater was built in about 1900 and has been modified a number of times since then.

III. BASIC ACOUSTICAL COMPARISONS

In spite of the importance of the newer acoustical measures, very low background noise levels are still probably the most important factor in achieving high acoustical quality

FIG. 1. Longitudinal section of the Festival Theater: s—stage, b—balcony, h—lighting holes.

for speech. NC-20 (noise criterion curve 20) is the usual optimum limit for theaters and auditoria. In the Avon Theater noise levels reached as high as NC-35, resulting from internal HVAC noise as well as external traffic noise. Measured noise levels in the Festival Theater exceeded NC-25, due to HVAC noise intruding from the ceiling void through the large number of lighting holes in the ceiling. In the NAC Theater noise levels were essentially NC-20 or less, except at one location and in only one octave band. These different background noise levels will be seen to influence measured speech intelligibility scores.

Figure 4 shows the mean RT values versus frequency in each theater. These are averages over receiver positions (between 6 and 15) and source positions (1 to 3). At intermediate frequencies the Festival Theater is slightly more reverberant than the Avon Theater, but both Stratford theaters are a little more reverberant than the NAC Theater. Measurements in the Festival and Avon Theaters indicate that the overall average EDT values are only slightly shorter than the RT values. Figure 5 shows that in the NAC Theater the overall average EDT values are distinctly less than the corresponding RT values. This theater would be perceived to be less acoustically live, or less reverberant, than the measured RT values indicate. Of course, for the EDT values to be shorter than the RT values the decay of sound must be

FIG. 2. Longitudinal section of the Avon Theater: s—stage, b—balcony, p—orchestra pit.

FIG. 3. Longitudinal section of the NAC Theater: s—main stage, t—thrust stage, b—balcony, c—acoustically transparent ceiling, r—removable music shell.

more rapid initially than it is later on in the decay. This corresponds to there being a relatively large chunk of early sound energy, and hence C_{80} values would be expected to be correspondingly larger.

Figures 6, 7, and 8 plot the mean, minimum, and maximum C_{80} values versus octave frequency for each theater. While it may be seen from Figs. 6 and 7 that the mean C_{80} values are quite similar for the two Stratford theaters, Fig. 8 indicates that the NAC Theater has mean C_{80} values several decibels higher than those of the other two. The Festival Theater has the largest range of values between minima and maxima, indicating greater seat-to-seat and source position dependent variations. The NAC Theater has a little less seat-to-seat variation in acoustical quality than the Avon Theater, although the two are of similar size and seating. The differences in the curves of Figs. 6–8 at 125 Hz can be attributed to variations in the seat-dip effect. It is known that sound passing over audience seating at near-grazing incidence is selectively attenuated at lower frequencies.^{10,11} This can show up as a dip in the frequency response of the early-to-late-arriving sound ratios due to the excess attenuation of

FIG. 4. Average reverberation time versus octave frequency for the three theaters.

FIG. 5. Average EDT ---, and RT — versus octave frequency, NAC Theater.

the early-arriving sound. Figure 8 shows that the 125-Hz dip in C_{80} values is most pronounced for the NAC Theater. The other two theaters show much less 125-Hz dip in the mean C_{80} values. The greater seat-to-seat variation at 125 Hz in all the theaters is because this seat-dip interference effect is dependent on the source receiver geometry and the seating configuration.

These results represent conditions in the unoccupied theaters. A procedure to estimate C_{80} values for occupied conditions is available¹² based on the expected change in RT values. As the NAC Theater chairs appeared to be more absorptive than those of the other two theaters, the expected occupied RT values can only be approximately estimated.

Although the new acoustical measures reveal much concerning the physics of the sound in the theaters, it is desirable to be able to relate these measures to speech intelligibility test scores obtained in each theater. Figure 9 gives the mean and range-of-speech intelligibility scores in each of the three theaters with a common source level of 50 dB A at 1 m.

FIG. 7. Mean, minimum, and maximum C_{80} versus octave frequency, Avon Theater.

The NAC Theater has the highest mean score and the smallest seat-to-seat variation in these seat-to-seat speech intelligibility scores. The best seats, in terms of speech intelligibility, in the Avon Theater are comparable to the worst seats in the NAC Theater. The seat-to-seat variation is greater in the Avon Theater than in the NAC Theater, and is largest in the Festival Theater. This is the same as the rank ordering of the seat-to-seat variation in the C_{80} values.

The speech intelligibility test results seem to be explained by the differences in background noise levels, C_{80} values, and the basic size and configurations of the theaters. Thus the lower scores and greater variations in the Festival Theater are caused by greater than optimum noise levels and the lower and more varied C_{80} values, which in turn are a result of the larger size of this theater and of the geometry of the thrust stage configuration. Because of its 2/3 circular plan and thrust stage design, there is a lack of strong early reflections and the direct sound is the major component of the early sound. Of course, the strength of the direct sound is strongly influenced by the distance and direction from the person speaking.

The Avon Theater had the lowest mean scores, probably due largely to excessive background noise but also to lower

FIG. 6. Mean, minimum, and maximum C_{80} versus octave frequency, Festival Theater.

FIG. 8. Mean, minimum, and maximum C_{80} versus octave frequency, NAC Theater.

FIG. 9. Mean, minimum, and maximum speech intelligibility scores in each theater.

C_{80} values and its long rectangular shape, which places some of the audience further from the stage where they experience weaker speech levels.

IV. INDIVIDUAL CHARACTERISTICS

A. NAC Theater

The optional thrust stage and stage shell in this theater were evaluated separately (Fig. 3). Reverberation times were a little larger when the source was on the main stage than when the source was on the thrust stage due to the added volume of the stage house. RT values were unaffected by the presence of the stage shell. Figure 10 shows that (compared to the case of a source on the thrust stage) the mean C_{80} values were decreased a little at midfrequencies by the presence of the shell, and were decreased more when the source was moved back to the main stage. As expected, the effect of the stage shell was quite small throughout the audience seating area of the theater.

FIG. 10. C_{80} versus octave frequency, NAC Theater: --- source on thrust stage, — source on thrust stage with shell, - - - sources on main stage (no shell).

FIG. 11. C_{80} versus octave frequency on-stage in NAC Theater: --- no shell, — with shell.

The major purpose of a stage shell is to provide a better on-stage acoustical environment for musicians. Strong early reflections from the stage are necessary to enable the musicians to hear each other and to play together well. Individual pulse responses on stage showed that the shell created a number of new reflections that arrived up to about 0.025 s later than the direct sound. It is also desirable that a shell increase the sense, on stage, that the room is responding. Figure 11 shows that on-stage C_{80} values decreased when the shell was added. One expects an added reflecting surface such as the music shell to add early reflections, but they continue to bounce around the room and become late reflections. Thus the addition of the shell does not simply increase C_{80} values because of increased early reflections. Both early and late reflections are increased, and in this particular case the balance changed so that C_{80} values decreased.

A similar effect was observed for EDT values, which at 1000 Hz increased from 0.05 to 0.15 s on stage when the shell was added. These values are extremely small, but they give some quantitative indication of the function of the shell. The shell cannot create, on stage close to the source, the acoustical conditions that would be experienced by the audience in a live hall, but it can create an increased sense that the hall responds when the musicians play.

FIG. 12. C_{80} versus octave frequency for three on-stage sources (1, 2, and 3) and one source in the orchestra pit (4), Avon Theater.

B. Avon Theater

The Avon Theater was unique among the three theaters in having an orchestra pit. The stage floor had been extended over the pit so that approximately half of it was covered. This arrangement is most undesirable acoustically because the radiation of sound from the pit is severely impeded and it is very difficult to obtain a balance throughout the theater between on-stage sources, such as singers, and the musicians in the pit, as well as making it more difficult for singers to properly hear the orchestra. Of course the control of the overall balance between singer and orchestra is the conductor's prerogative, but if one component of this balance, the orchestral sound, varies throughout the theater it is impossible to obtain the desired balance at all seats. In addition, partially enclosing the pit tends to increase sound levels there, so that it is excessively loud for the musicians. Consequently, they tend to play a little less loudly, and as sound-absorbing material is often added in partially covered pits, the result is that the orchestral sound becomes even weaker throughout the theater.

Figure 12 shows measured C_{80} values averaged over all audience seats for three on-stage source positions as well as one in the orchestra pit. When the source is in the orchestra pit, C_{80} values throughout the theater are distinctly lower, especially at medium and high frequencies. From Figs. 13 and 14, which show results averaged over two or three receivers in particular seat rows, it may be seen that seat-to-seat variability is considerably greater when the source is in the pit rather than on stage. The solution to these problems is to remove any sound absorbing material from the orchestra pit and to make it much more open to the theater proper.

C. Festival Theater

The thrust stage design of the Festival Theater, with the audience seated around the stage, presents unique and difficult acoustical problems. For most of the audience the ceiling and the stage rear wall are the only surfaces that can provide essential early reflections. There are really no signifi-

FIG. 14. C_{80} versus octave frequency for various seat rows, source in orchestra pit, Avon Theater.

cant side wall reflections in this theater, where the floor plan is approximately $\frac{2}{3}$ of a circle and the stage is at the center of the circle. The important early reflections from the ceiling have been rendered much less effective by the inclusion of very large areas of lighting holes in the ceiling.

To study the possible effects of these holes and the improvements that could be obtained with the addition of a new over-stage reflector, a simple two-dimensional computer ray tracing model was developed. This was thought to be adequate for this case where side wall reflections played no significant part. Figure 15 shows an example of the rays traced from one source to one receiver for a cross section along the centerline of the theater. The lower part of the figure shows the calculated impulse response for the same configuration. Energy sums of the calculated energy arriving

FIG. 13. C_{80} versus octave frequency for various seat rows, source on stage, Avon Theater.

FIG. 15. Example of computer ray trace for on-stage source (lower right) to balcony seat (upper left).

FIG. 16. Calculated relative early energy level versus seat row through the center section of the theater.

in the first 0.08 s were calculated for many combinations of source and receiver and various configurations of the theater. Figure 16 gives an example of the results, showing how the relative early energy sums could be increased by closing the lighting holes and adding a new over-stage reflector. The integration of these features into the theater would require further practical considerations that would be influenced by the relative priorities of good acoustics versus good lighting.

To assess the acoustical quality of a thrust stage theater in more detail, the test methods require some further refinement. The early-to-late sound ratios obtained using an omnidirectional source can be considered to represent an average of all possible directions of the actor speaking. To assess particular worst cases, it is necessary to use a source with directional characteristics similar to those of a human speaker. Early-to-late-arriving sound ratios were obtained using a loudspeaker source that approximated human directional characteristics, but this was not entirely successful because of the difficulty of producing high-amplitude pulses to provide the necessary signal-to-noise ratios for calculation of early-to-late ratios and decay times. Larger speakers could radiate more power, but would not have the desired directional characteristics. A better approach would be to use cross-correlation techniques and pseudorandom noise to produce the required pulse responses. This method will be attempted in future studies.

V. CONCLUSION

The theaters studied represent a wide range of designs, as well as being three of Canada's most successful. The comparisons demonstrate the value of the newer acoustical measures for examining particular problems associated with each of the three theaters. The accumulated experience of many more such studies is now needed for interpreting, using, and refining these measures in designing new theaters and assessing existing ones. The simple computer models used here once more affirm the need to develop sophisticated computer models for the precise and efficient design of theaters and auditoria.

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