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ACOUSTICAL MEASUREMENTS ON CONCERT AND PROSCENIUM ARCH STAGES

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1. INTRODUCTION

The past fifteen years have seen significant advances in the objective assessment of stage acoustics. Prior to this, observations were for the most part anecdotal and conclusions were often of the commonsense variety. In the 1970s studies by Barron [1], Marshall et al. [2] and Meyer [3] introduced a more systematic approach. Then in the 1980s work by Gade [4,5] and Naylor [6,7] established acoustic parameters that correlated with musicians' subjective responses of synthetic [4,6] and real [5] acoustic environments.

Gade's parameters are known as Support ratios and have undergone a number of refinements since first introduced. A Support measurement is a simple logarithmic ratio of reflected to direct sound taken at a distance of either 0.5 or 1.0 m from an omni-directional source. In their original form, objective Support ratios were intended to quantify a musician's need to hear himself, a quality of the room often referred to subjectively as 'Support'. Gade later found that one of the Support ratios corresponded well with subjective Ensemble, also known as Hearing of Other. The different variations of Support result from the different temporal windows for reflected sound. In 1992 Gade defined the following three variations:

$$STx = 10\log\frac{\int_{t1}^{t2} p^2(t)dt}{\int_{0}^{10} p^2(t)dt}$$

Measure	t1 (ms)	t2 (ms)	Effect
ST_{early}	20	100	Ensemble
ST_{late}	20	1000	Support
ST_{total}	100	1000	Reverb

Naylor used the Modulation Transfer Function (MTF) to quantify Hearing of Other. The measurements differ fundamentally from Gade's in that they are taken at the typical distances between musicians on stage, i.e. 2 to 10 m.

2. MEASUREMENT PROCEDURE

The measurements reported here were taken at five locations on each stage, corresponding to Soloist, Violin, Viola, Horn and Bass. Support measurements were measured at both 0.5 and 1.0 m from the closest loudspeaker in the sound source but, unless stated otherwise, only measurements taken at 0.5 m are reported here. The sound source was a small dodecahedron with twelve 75 mm loudspeakers. The source and receiver were located 1.1 m above the stage floor. The receiver was an omni-directional microphone and the excitation signal was a 15th order maximum length sequence generated by a DRA Laboratories' MLSSA system.

In most cases the stages were empty, exceptions to this rule are noted in the text. Initial studies by Gade [4], Naylor [6] and O'Keefe & Bracken [8] used a 50 mm acoustic blanket underneath the source. Except for the data from Vancouver's Orpheum, all measurements reported here were taken with an acoustic blanket. No correction was made for the high frequency directional characteristics of the dodecahedron. Extreme care was taken however to ensure that the microphone location for Support ratios was as consistent as possible each time.

3.. MEASUREMENT SENSITIVITY

The measurement of stage acoustics is a forum that is still in its formative years. Measurement procedures differ in small and sometimes significant ways. One of the most difficult issues to deal with is the high frequency directional characteristics of the loudspeaker source. For example, in the 4 kHz octave band, directional characteristics can result in an overestimation of sound power level by as much as 7 dB [6]. Explosive sources such as balloons and starters' pistols are not a suitable substitute for the loudspeakers because of the near field nature of the measurements - starter's pistols often generate a non-linear acoustic signal sometimes as far away as 10 m. Some researchers have chosen to compensate for this effect by rigorously measuring the free field characteristics of their source then using the information to incorporate a correction factor into their data reduction. Another method is to carefully orientate the receiver microphone to ensure that it is on the same lobe of the loudspeaker response each time.

Gade has studied the effect of source position on stage [9] and found a 1 dB standard deviation for 30 cm displacements. Averaging over four octaves and three locations, the standard deviation for a given stage is 0.3 dB.

The effect of an acoustic blanket was studied in [10]. Measurements were performed in Toronto's Roy Thomson Hall with and without 1 m^2, 50 mm thick glass fibre acoustic blanket underneath the source. The stage was fully equipped with chairs and stands for approximately 50 musicians. The effect of the blanket on Support ratios was less than 0.5 dB when averaged over 5 locations.

The presence of chairs and music stands might be expected to influence measurement results but, again, the effect is weak. Measurements were performed on the stage of the Glenn Gould Studio, a 350 recital hall in Toronto, and Hamilton Place [18] in its concert mode. In both cases there were chairs and stands for approximately 24 musicians and care was taken to remove them from the immediate vicinity of the source and receiver. A 50 mm blanket was placed underneath the source. Support ratios changed by less than 1 dB at high frequencies and less than 0.5 dB at mid frequencies based on an average of five locations. Comparing the MTFs directly, that is without spatial averaging, there was no noticeable difference.

Most surprisingly, the presence of musicians appears to have little effect on the measurements. The experiment to determine this was performed at one end of a small gymnasium and for this and other reasons, the observations should be considered preliminary. Chairs and stands were set up for 25 musicians and this time the acoustic blanket was omitted. MTFs and Support changes were in the order of a 2 or 3 percent. In the case of Support ratios the changes are in the range that Gade reported for simple movement of the source [9]. For MTFs the change is at or below the limit of what is noticeable according to Naylor [11]. Clearly, this requires further investigation, preferably on an actual concert hall stage.

The most significant influence that measurement procedure has on measured values is the choice of Support source receiver distances. Gade originally proposed a 1.0 m distance, which he and others still use. Naylor used a 0.5 m distance [6] using the intuitive argument that the shorter distant was a better representation of the musician holding his or her instrument. He suggested that a 6 dB correction factor be used to allow direct comparison of measurements taken at 0.5 and 1.0 m. O'Keefe & Bracken followed his example [8]. It turns out that the difference between measurements taken at the two locations is less than 6 dB. Comparisons have been performed on seven different stages and show no consistent or reliable conversion factor.

4. PROPAGATION OF SOUND ON A STAGE

The acoustic requirements of a musician are significantly different from a passive listener. Likewise the acoustic environment and the behaviour of reflected sound on a stage are significantly different from conditions experienced in the audience chamber. Acoustic surveys by Barron [12], Gade & Rindel [13] and Bradley [14] as well the revised theory of sound in a room proposed by Barron & Lee [15] have firmly established that reflected sound in the audience chamber attenuates at a rate of approximately 0.1 to 0.2 dB/m. On a stage reflected sound attenuates at more than ten times this rate. On the nine stages measured recently, reflected sound in the 1000 Hz octave band attenuates at a rate between 1.9 and 4.2 dB/m. A typical graph is shown below.

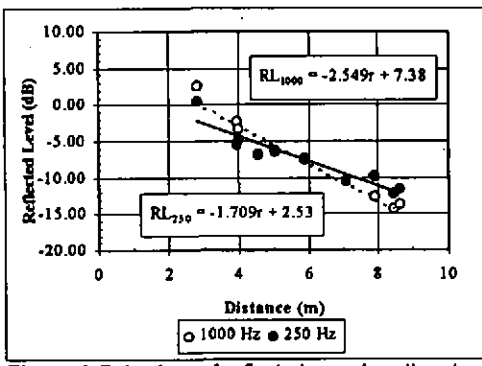

Figure 1 *Behaviour of reflected sound on the stage of The Orpheum, Vancouver Canada.*

In most cases, the fit of the linear regression to the data is very good. The broad range in attenuation rates suggests that the design of the reflecting surfaces around the stage can have important consequences. On the nine stages under investigation, reflected sound levels at a location 5 m from the source ranges from -9 dB to -21 dB with respect to the direct component. In an effort to understand this further, a very simple method of images computer model was prepared. The model room was a simple shoe box, 50 x 20 x 18 m (l-w-h) with a 15 m long, 1m high stage at one end. Fourth order impulse response functions were generated at 1 m intervals across the stage and then from the stage into the audience chamber. The results are shown in Figure 2.

The computer model agrees with measurements on real stages. Note that from 1 to 10 m there is no appreciable difference between reflected level across the width of the stage and down the length of the room into the audience. In the shoe box shaped room, therefore, the effect seems to be due simply to the proximity of the receiver to the source rather than proximity to the end wall.

5. OVERHEAD REFLECTIONS

Marshall et al. [2] and Meyer [16] have suggested that instrumentalists require reflected sound from above. Marshall et al. have also identified a preferred temporal window for chamber orchestra players, from 17 to 35 ms. Most new concert halls provide overhead reflectors and in many cases the height of reflectors can be adjusted. Measurements have been performed on three fundamentally different stages: The Orpheum in Vancouver [17], Roy Thomson Hall [18], Toronto and the Centre in the Square [18] in Kitchener, Ontario. The first two rooms have reflector arrays although in The Orpheum there are relatively few panels compared to Roy Thomson Hall. Centre in the Square has a single large reflector

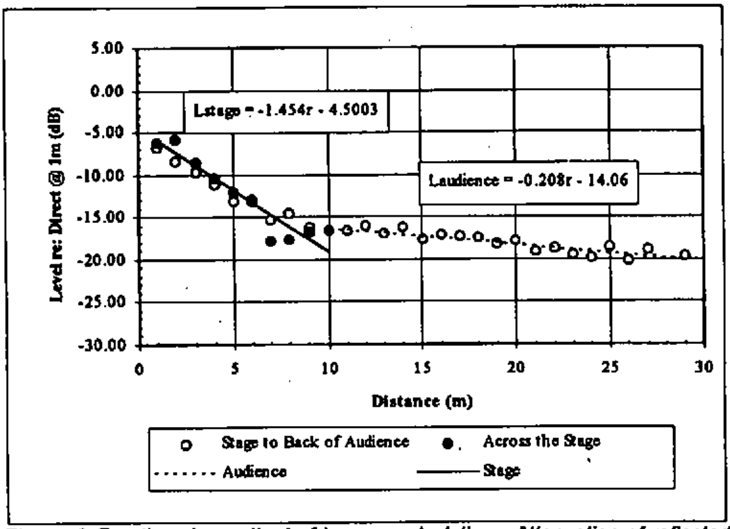

Figure 2 *Fourth order method of images calculation. Attenuation of reflected sound close to the source is much higher than in the middle of the audience chamber.*

covering most of the stage. At The Orpheum, measurements were performed in the normal performance configuration then the reflectors were removed entirely and the measurements repeated. At Roy Thomson Hall measurements were performed with the array set to the normal height used by the orchestra, then at the highest position, which is preferred by the choir. At Centre in the Square, measurements were performed with the reflector at 8.5, 11 and 14.5 m above the stage.

Contrary to initial expectations, 100 and 1000 ms Support ratios (STearly and STtotal) are not that sensitive to the presence or height of overhead reflectors. Differences are in the range of 0.5 to 1.5 dB. The overhead reflectors have a more pronounced effect on the early part of the reflection sequence, most likely the first one or two reflections. Recognising the importance of the temporal window suggested by Marshall et al., the following parameter was studied:

$$\text{Ensemble Reflections} = 10\log\frac{\int_{17}^{35\,ms} p^2(t)dt}{\int_{0}^{10} p^2(t)dt}$$

The results, seen in Figures 3 to 5, show that the reflectors in The Orpheum and Centre in the Square significantly affect Ensemble Reflections but that at Roy Thomson Hall, the change is hardly noticeable.

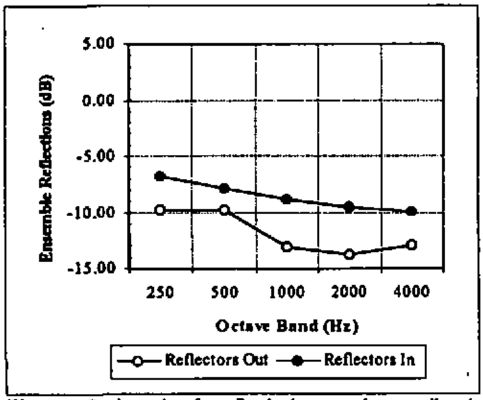

Figure 3 *Level of reflected sound re: direct. Measured at The Orpheum, Vancouver with and without the front reflector panels in place.*

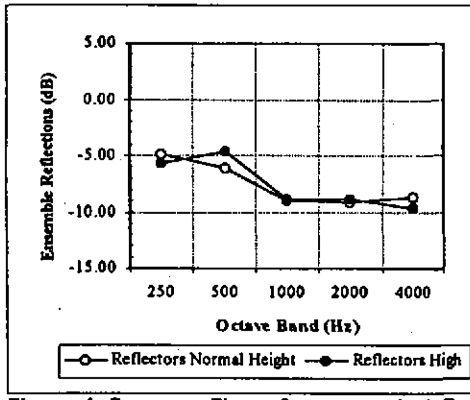

Figure 4 *Same as Figure 3, measured at Roy Thomson Hall, Toronto. Reflector array in its normal and highest positions.*

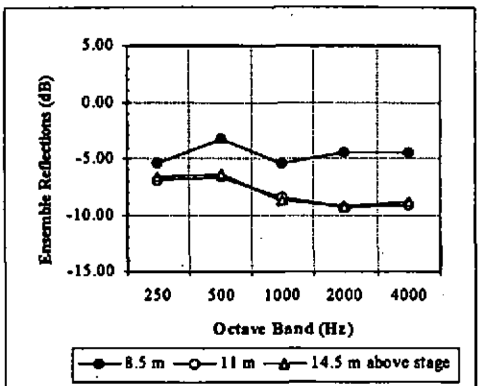

Figure 5 *Same as Figure 3, measured at Centre in the Square, Kitchener. Single component reflector in its lowest (8.5 m), concert (11 m) and highest (14.5 m) positions.*

An interesting comparison may be made between The Orpheum and The Centre in the Square. The overhead reflectors for these two stages are profoundly different. At The Orpheum, only five of the small reflectors actually function for the stage. Conversely, the reflector at the Centre in the Square covers almost the entire orchestra platform. Figures 3 and 5 however suggest that the important 17 to 35 ms ensemble reflections are equally affected. It appears that the acoustician in charge of the Orpheum's conversion from a vaudeville house, Ted Schultz, located the reflectors with a very sensitive touch.

One should be careful in interpreting the results shown in Figures 3 to 5. They do not necessarily suggest that the Support ratios or, for that matter, the reflectors at Roy Thomson Hall have been found wanting. What these results point to is the need for stage acoustic measurements that address the directional properties of the reflected sound. Most all measurements to date, including those presented here, have been performed with omni-directional microphones. This despite the clear evidence that reflections arriving at the performer from above are important. The impediment seems to be the practicality and expense associated with accurate directional microphone systems, at least for the time being.

6. ANECDOTAL OBSERVATIONS

The dilemma faced in stage acoustics design has typically been to provide the delicate balance between the musician's need to hear himself and his associates. At the Centre in the Square however it appears that the needs of the listener have superseded both these concerns. Stage acoustics measurements suggest that the optimum position for this reflector is 8.5 m yet its concert setting is 11 m. Further investigation of the measurements revealed that the Early Decay Time heard by the conductor on stage was significantly longer at the 11 m height. In terms of stage acoustics, the conductor's concerns are more like those of a listener; he does not play an instrument so is not concerned with keeping in tune or on tempo. It's perhaps not surprising that he might be more concerned with reverberance than Support or Ensemble. At the Centre in the Square it was the conductor who chose the reflector height and it appears that he did so with the listeners' requirements in mind rather than the performers'.

At Massey Hall in Toronto, the ceiling is approximately 20 m above the stage. The optimum range for performers is half this, about 8 to 10 m. In the 1970s plastic reflectors similar to those in The Orpheum were installed in an effort to improve acoustic conditions on stage. One of the design objectives for the new Roy Thomson Hall, in fact, was to improve conditions for the performers on stage. Prior to the completion of Roy Thomson Hall, the reflectors in Massey Hall were removed. The reasoning was that they created a harsh sound in some seats of the audience chamber.

In Marshall and Meyer [19] it was found that singers project the important formant frequencies down towards the stage floor rather straight out towards the audience. The consequence for stage design is that the choral risers should be built with a rake of 45°. At the Centre in the Square the resident choir is said to prefer the 400 mm risers to the shallower 200 mm risers.

Marshall and Meyer also studied singers' assessments of synthetic sound fields of reverberance with and without a few discrete reflections. They found a clear preference to sound fields with reverberance than to those without. The only exceptions were the sound fields with reflections corresponding to a 40 ms delay. The choir at Centre in the Square prefers the 14.5 m reflector height to the 11 m used by the orchestra. Apparently, they would never use it at the lowest height, 8.5 m. When the choir is standing on their risers, the 8.5 m reflector height, coincidentally, corresponds to the deleterious 40 ms delay found by Marshall and Meyer.

7. ACKNOWLEDGEMENTS

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