VARIATION OF ENERGY-BASED ROOM ACOUSTIC PARAMETERS WITHIN A MULTIPURPOSE HALL

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1 INTRODUCTION

Energy-based room acoustic parameters based on various integrations of the room impulse response are frequently used to quantify the sound field in concert spaces. However, it has been recognized that impulse responses, and therefore parameters derived from them, vary within a hall both for small displacements of the measurement microphone[1,2] and for different seating areas in a hall[1,3-5]. This variation complicates the characterization of a concert space by single values averaged over several measurement positions, which is the recommended procedure in ISO 3382[6]. While some work has concentrated on smoothing variations on a small scale[1,2] the aim of this paper is to further explore the systematic seat-to-seat variations within a hall.

Several authors[7-9] have in particular identified the early part of the impulse response (up to 80 milliseconds after the arrival of the direct sound) as an important varying quantity within a hall. Barron proposed a theoretical expression for the early sound energy[10] which relies on diffuse sound theory, and has been shown in some cases to incorrectly predict the variation of the early sound energy because of the influence of room geometry[7,9]. Another recent study suggests a complicated relationship between room geometry and room acoustical parameters[11]. This paper seeks to further explore the relationship between room geometry and the early sound field. It is hoped that the results will lead to better characterization of a concert space and that the quantitative results can be better linked both to the architecture of the space and to the experience of listening to music in the space.

2 MEASUREMENT TECHNIQUE

2.1 Hall Surveyed

In situ measurements were taken in Silva Concert Hall, the primary concert venue at the Hult Center for the Performing Arts in Eugene, Oregon, USA. Though a concert hall by name, it is a multipurpose venue seating 2500 people for a wide variety of performances including ballet, opera, symphony orchestra, and amplified popular music. The interior design is distinguished by a "basket-weave" pattern on most of the walls and ceiling. The hall is further distinguished by being the first major performance venue in the United States with an electronic acoustic enhancement system as part of the original design, although that system has fallen out of use. The present measurements have been conducted in conjunction with consulting efforts by Kirkegaard Associates to provide various acoustic upgrades to the hall, including a new orchestra shell and a new enhancement system.

Listening experiences in the hall, along with interviews with Hult Center administration and resident companies have revealed that (with the enhancement system off) seats in the Balcony Level are preferred to seats on the Orchestra Level and that the front of the Orchestra Level is the least desirable seating location. The front portion of the Orchestra Level suffers from a lack of clarity, presence, intimacy, and an inability to clearly hear each section of the orchestra. Listeners comment that envelopment, bass response, and overall orchestral impact are lacking almost everywhere in the hall.

With such a difference of listening experiences from the front to the rear of the hall, a series of measurements along the length of the hall were made in an effort to document and quantify the variation of the sound field. While stage measurements were also conducted to study onstage hearing and ensemble problems, this paper seeks only to explore the acoustics of the audience area.

2.2 Measurement System

Room impulse responses were measured using an omnidirectional, dodecahedral loudspeaker and an omnidirectional microphone. A swept sine signal was sent from a laptop computer to the loudspeaker system, and the microphone signal was simultaneously digitized and recorded on the laptop computer. The recording sampling rate was 48kHz at 16 bits. The signal was swept from 100Hz to 12kHz and averaged over 6 sweeps for each measurement position. The averaged sweep response was transformed to the frequency domain using an FFT algorithm and divided by the FFT of the raw swept sine signal. The result was transformed back to the time domain to yield the room impulse response. The impulse responses were filtered into mid-frequency octave bands centered at 500Hz, 1kHz, and 2kHz for this study.

A calibrated sound source (necessary for measuring Sound Strength, G) was unfortunately not available for the measurements. Instead, a rough calibration scheme to measure relative levels in the hall was devised. A 20 second segment of pink noise was played through the loudspeaker, and after the gain was optimized for the closest microphone position, the pink noise was simultaneously recorded to the laptop and monitored with a sound level meter positioned next to the measurement microphone. This calibration signal, along with the associated sound pressure level, was then used to calibrate the impulse responses. The measurements proceeded without changes to the gain at any point of the signal path, thereby allowing the variation of absolute level in the hall to be measured.

2.3 Source and Receiver Positions

Measurements were conducted with the hall unoccupied. The sound source was located downstage at a concertmaster's position and elevated approximately 3 feet above the stage floor. An orchestra shell, along with musician chairs and stands were in place.

The microphone was moved along a line parallel and near to the centerline of the hall, starting at the second row from the front (seat B204). Measurements were then taken successively at every other seating row. When the rear of the hall was reached, the microphone was moved up through the Mezzanine level and then through the Balcony level, keeping the microphone positions roughly in the same vertical plane as the measurements below. The microphone positions were approximately 3 feet above the floor in each case. Measurement positions are indicated in the plan and section of the hall in Figure 1.

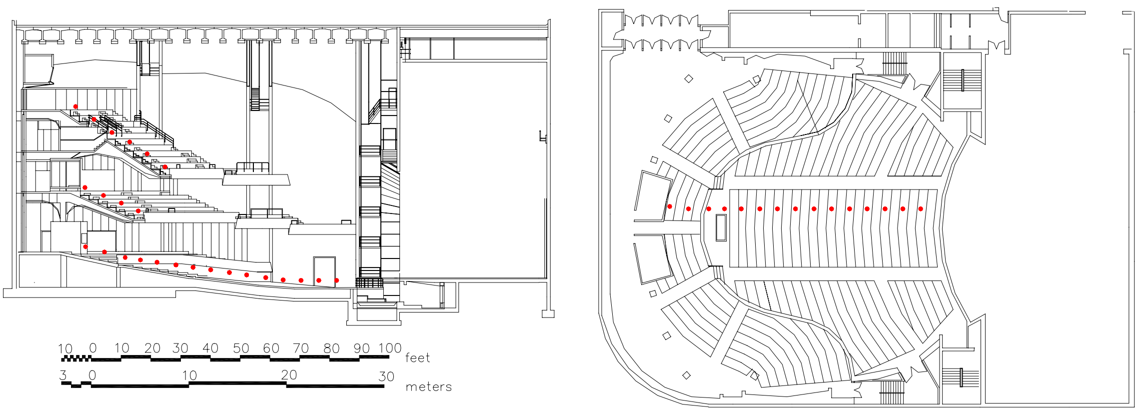

Figure 1. Plan and section of Silva Concert Hall. Measurement positions are indicated by small dots. An orchestra shell in place for the measurements is not shown in the drawings.

3 RESULTS

3.1 Variation of Sound Energy

The sound energy is calculated by integration of the impulse responses:

$$L(t) = 10Log_{10}\left(\int_0^t \frac{p^2(t)}{p_{ref}^2}dt\right) + SPL_{ref} \quad (1)$$

In Equation (1) p_{ref} is the measured calibration signal described in Section 2.2 and SPL_{ref} is the sound pressure level of the calibration signal. The time t is measured from the arrival of the direct sound at each measurement position. Variation of the outer integration limit allows easy comparison of the contribution of the direct, early and late portions of the impulse response to the total sound level. Thus, for the level of direct sound, L_{dir}, t = 5ms, the level of the early sound, L_{80}, t = 80ms, and for the total sound level, L_{tot}, t = 1500ms. Note that L_{tot} would equal Sound Strength (G) if p_{ref} were equal to the source level at 10m and SPL_{ref} = 0, making L_{tot} different from G only by a constant additive value.

Figure 2 shows the variation of the integrated levels through the hall. Note the separation in 500Hz and 2kHz values of the direct sound between positions 4 and 5. The measurement process was interrupted after position 4, and the measurements were continued at position 5 the following day. The sudden change in the source with frequency is therefore likely due to a slight change in orientation of the loudspeaker. Fortunately, the average value of the 3 octave bands is apparently insensitive to the effect. We remark parenthetically here that lower octave band values were not used in this study because of the difficulty in localizing the direct sound below 500Hz in a 5ms time window[6].

There are two main features to note in Figure 2. First, The difference between L_{80} and L_{tot} is relatively small and constant for all measurement positions beyond 4 or 5. This indicates that the total sound level is already determined in the first 80ms, which is a phenomenon that has been noted by others as well[8,9]. It also suggests that the late part of the impulse response (post – 80ms) is relatively constant through the room. Second, the L_{80} and , L_{dir} curves diverge strongly through the hall, indicating that the early part of the impulse response (the region between 5ms and 80ms) varies depending on the location in the hall.

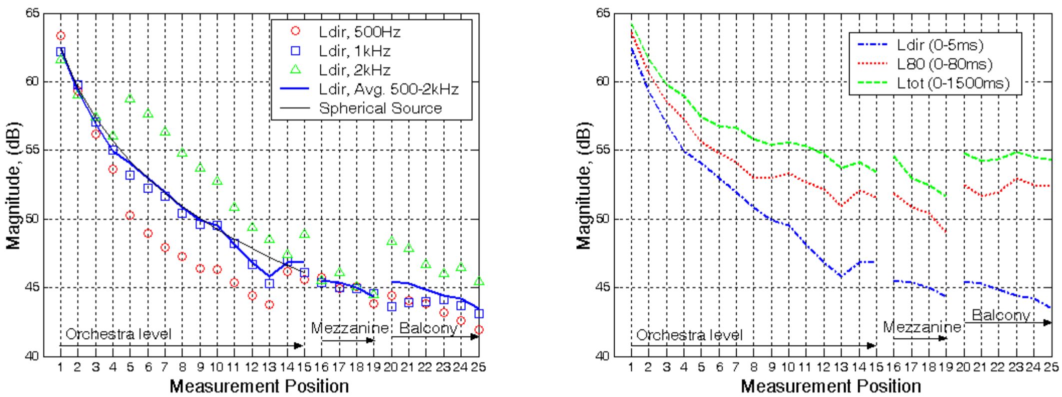

Figure 2. Plot on the left shows variation of direct sound at each measurement position. The measurement positions along the Orchestra level are roughly in a straight line from the source (see Figure 1), and the average values compare favorably to the decay of a theoretical spherical sound source. Plot on the right compares average values of **,** L_{dir}, L_{80}, and L_{tot}.

3.2 Variation of Early Sound

Four of the measured impulse responses are plotted in Figure 3. It is clear from Figure 3 that the profile of the impulse responses in the first 80ms varies greatly in the hall. Note also that the level of the early reflected sound compared to the level of the direct sound changes significantly between the four positions; that is, the ratio of the early reflected energy to the direct energy increases for positions toward the rear and high up in the hall. For example, the response at Position 3 is completely dominated by the direct sound, while reflections between 25ms and 50ms at Position 22 are nearly as strong as the direct sound.

The reflection patterns observed in Figure 3 can be understood by tracing a few simple rays on the plan and section of the hall. From the ray tracing shown in Figure 4, it is evident that the sidewalls and ceiling of the hall cannot direct early sound energy to the front portion of the audience because of their curved shape. This, along with the great width of the hall, accounts for the low ratio of early reflected sound to direct sound at Position 3. The room shape directs the energy to the rear and upper portion of the hall. The clump of strong reflections at Position 22 between 25ms and 50ms can be linked to the time arrival of ceiling reflections indicated in Figure 4.

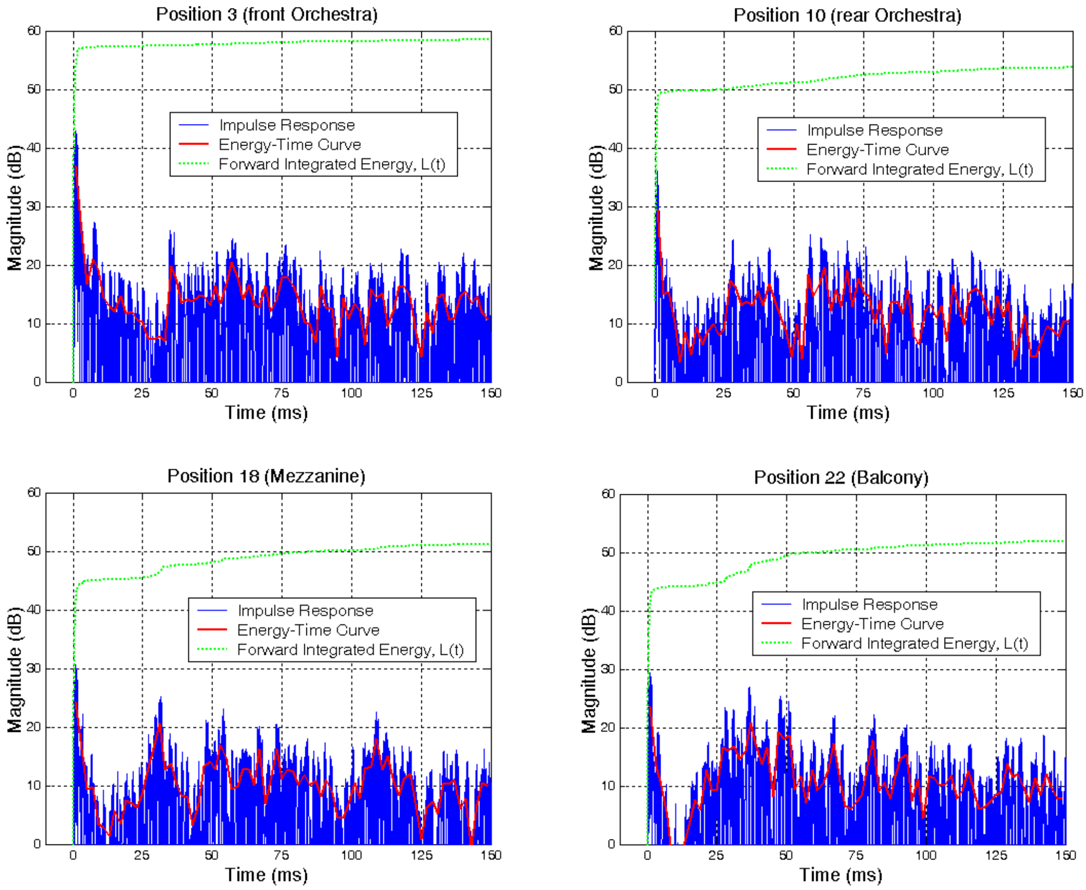

Figure 3. Measured impulse responses at four positions in the hall. All responses are filtered at 1000Hz. Energy-Time curves are plotted by calculating the RMS value of the impulse response in a moving 2ms window. The Forward Integrated Energy is the plot of Equation (1) for each position.

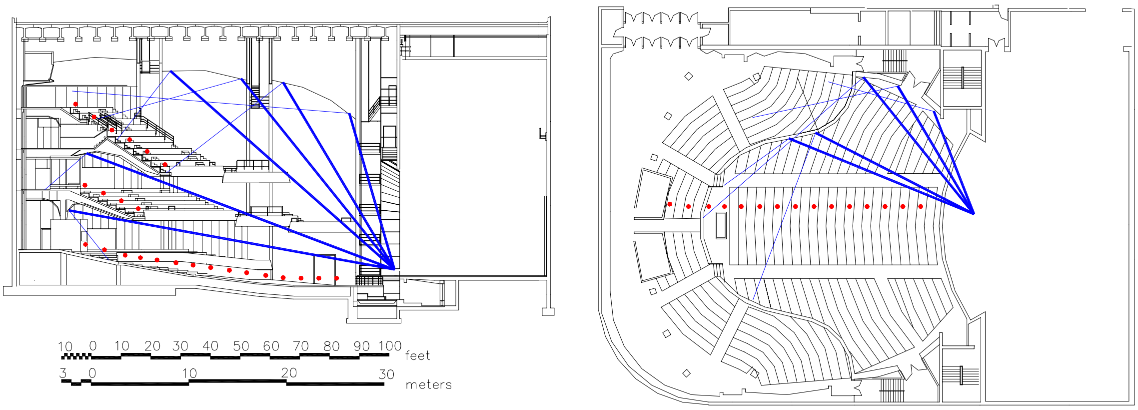

Figure 4. Ray tracing of first order reflections from measurement source position shows the influence of sidewall and ceiling shaping on the early sound reflection pattern. Reflections are directed toward the rear and upper sections of the hall.

The Parterre wall provides early lateral reflections to the rear Orchestra, visible in Figure 3 at Position 10 beginning at 25ms.

The observation that the shape of the room directs early sound energy to the rear and upper portions of the hall coincides with the variation of listening experience described in Section 2.1. In order to quantify this effect, and to attempt to isolate the portion of the reflected sound that varies in the hall, Figure 5 shows the direct sound, L_{dir}, subtracted from the early sound, L_{80}, for each measurement position. The result is L_{early}, the integrated sound energy between 5ms and 80ms.

It is interesting to compare L_{early} to C_{80}, the traditional measure of clarity which calculates the ratio of the early sound to the late sound:

$$(2) \qquad C_{80} = 10Log_{10}\left(\int_{0}^{80} p^2(dt) \Big/ \int_{80}^{\infty} p^2(dt) \right).$$

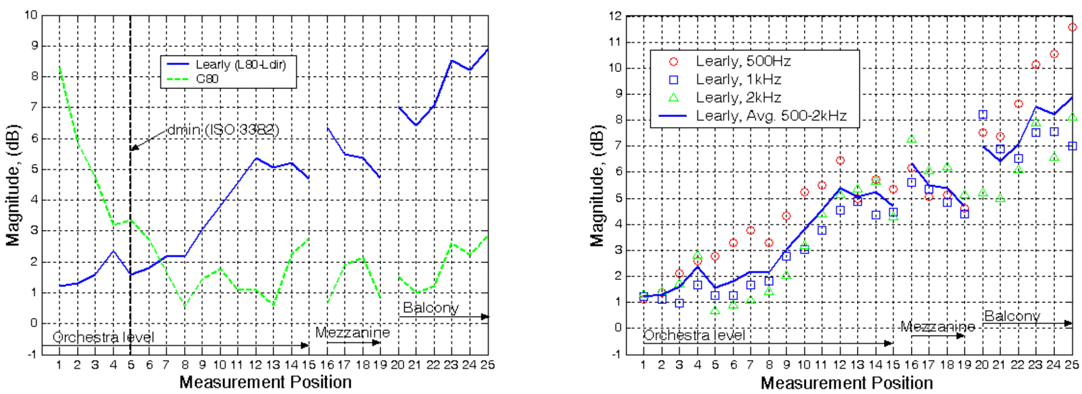

Figure 5. The left plot compares L_{early} (averaged across the 500 – 2kHz octave bands) to C_{80} for each measurement position. The right plot shows the contribution of each octave band to the average of L_{early} at each measurement position.

Because the impulse responses have a finite length, the upper limit of integration in the denominator of (2) is set to t = 1500ms.

A similar expression for L_{early} can be derived from Equation (1):

(3) $$L_{early} = L_{80} - L_{dir}$$

$$= \left[10Log_{10}\left(\int_0^{80} \frac{p^2(t)}{p_{ref}^2}dt\right) + SPL_{ref}\right] - \left[10Log_{10}\left(\int_0^{5} \frac{p^2(t)}{p_{ref}^2}dt\right) + SPL_{ref}\right]$$

$$= 10Log_{10}\left(\int_0^{80} p^2(dt) \bigg/ \int_0^{5} p^2(dt)\right)$$

so that L_{early} can be thought of as the ratio of the early sound to the direct sound. Thus L_{early} is similar to the measure of stage support, *ST1*, proposed by Gade[12]. Note also that p_{ref} and SPL_{ref} cancel out of Equation (3), indicating that a calibrated source is not required to make the measurement.

Because the direct sound energy is included in the numerator of (2), the value of C_{80} becomes very large for positions close to the source. For this reason ISO 3382 recommends a minimum distance between source and receiver to exclude positions dominated by the direct sound[6]. This minimum distance is indicated by the dashed vertical line on the left side of Figure 5. Following the standard rigorously, however, would exclude a portion of the front Orchestra level considered to be important for this study. Moreover, the C_{80} plot in Figure 5 does not suggest a clear trend of the parameter that can be understood in terms of the early sound reflection pattern shown in Figure 4. The insensitivity of C_{80} to the variation of the early sound field is apparently due to the inclusion of the direct sound in the numerator (which tends to mask the energy in the 5ms to 80ms region) and to the inclusion of the late sound energy in the denominator, which in this case is relatively constant throughout the hall.

The quantity L_{early} contains essentially sound energy in the 5ms to 80ms time region, and it therefore provides a better “map” of the room reflections (which must arrive after the direct sound) shown in Figure 4. The variation of L_{early} also indicates that the Balcony receives a much more generous supply of early energy than the front Orchestra level, which supports the description of listening experience in the hall in Section 2.1. It is clear from Figure 5 that reporting an average value for L_{early} would not be appropriate since it varies in a systematic way due to the shape of the room. A distribution of L_{early} values across a seating plane appears to be more appropriate.

The right side of Figure 5 shows the frequency content of L_{early} in the 500Hz, 1kHz, and 2kHz octave bands. The separation of the 500Hz values from the 1kHz and 2kHz values is likely due to the repositioning of the source described in Section 3.1. Likewise, it is difficult to determine if the larger 500Hz values in the Balcony are due to the room or the loudspeaker used. The overall trend of the values, however, suggests that frequency averaging is appropriate.

3.3 Variation of Energy Decay

Figure 6 shows the variation of the Reverberation Time (RT) through the hall. There is no significant spatial variation of the measured RT, nor is there significant variation of the late sound energy level (the difference between the L_{tot} and L_{80} curves in Figure 2). This indicates that both these parameters are statistical in nature, making spatial averages appropriate. This agrees with results found by Pelorson et. al.[4]

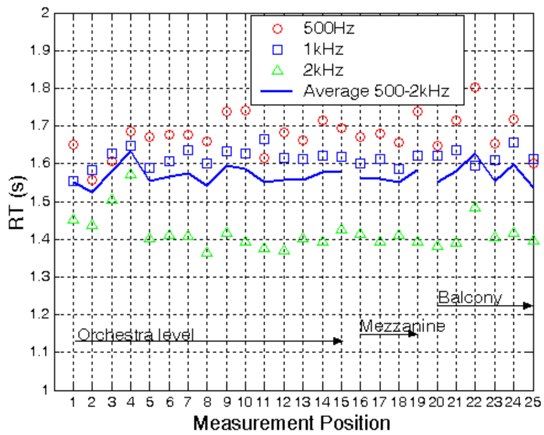

Figure 6. Variation of Reverberation Time in the hall.

4 CONCLUSIONS

It was found that the strength of the early sound, L_{early}, is a useful energy parameter to characterize the early sound field in a hall. The spatial distribution of this parameter can be linked both to the geometry of the room and to listening experience, making it especially useful to a designer of concert spaces.

Other commonly used room acoustic parameters, L_{tot} (related to G), C_{80}, and RT were not found to vary in a systematic or predictable way through the hall. While the values themselves fall within expected ranges, and spatial averaging of them usually seems appropriate, they fail to distinguish the fine structure of the early sound in the hall studied.

Further work should include a more careful characterization of the sound source. This seems especially important in order to compare L_{early} values between different halls. Averaging measurements over different rotations of the loudspeaker might smooth out directivity irregularities, particularly above 1kHz. A calibrated source would allow better repeatability of absolute levels, although calibration of absolute level does not appear to be important for measurement of L_{early} itself. Increasing the number of measurement positions further, perhaps to a two-dimensional grid, would provide better resolution of the structure of the early sound field.

5 REFERENCES

1. D. de Vries, et. al., 'Spatial fluctuations in measures for spaciousness', J. Acoust. Soc. Of America, 110(2), 947-954. (Aug 2001).
2. K. Sekiguchi & T. Hanyu., 'Study on acoustic index variations due to small changes in the observation point' , Proc. of the 15th ICA, Seattle, 2141-2142, (1998).
3. J.L. Nielsen, et. al., 'On spatial variability of room acoustics measures' , Proc. of the 15th ICA, Seattle, 2141-2142, (1998).
4. X. Pelorson, et. al., 'On the variability of room acoustical parameters: Reproducability and statistical validity', Appl. Acoust., 399-406, (1988).
5. J.S. Bradley, 'A comparison of three classical concert halls', J. Acoust. Soc. Of America, 89(3), 1176, (1991).
6. ISO 3382: 'Acoustics- Measurement of the reverberation time of rooms with reference to other acoustical parameters' (1997).

7. J. Wang & G. Jiang, 'Early sound distribution in an auditorium', Proc. of the 15th ICA, Seattle, 2141-2142, (1998).
8. Y. Toyota, et. al., 'Study on characteristics of early reflections in concert halls', J. Acoust. Soc. Of America, 84 (Suppl. 1.S130), (1988).
9. J.R. Hyde, 'Sound strength in concert halls I: role of the early sound field with objective and subjective measures, Proc. of the 15th ICA, Seattle, 9-10, (1998).
10. M. Barron & L-J Lee, 'Energy relations in concert auditoriums', J. Acoust. Soc. Of America, 84(2), 618-628, (Aug 1998).
11. C.A. Weitze & A.C. Gade, 'Acoustics and geometry of concert halls', Proc. Nordic Acoust. Meeting, Roros, Norway, (May 2000).
12. A.C. Gade, 'Investigations of musicians' room acoustic conditions in concert halls', Acustica 69, 193-203 & 249-262, (1989).