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A LOOK AT COMPONENTS OF SOUND STRENGTH IN CONCERT HALLS THROUGH ACOUSTICAL MEASUREMENTS AND COMPUTER MODELING

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1. INTRODUCTION

This research paper reports current work on the magnitude and variation of Sound Strength (G) in concert halls and reviews its behavior relative to both "classical" and Barron's "revised" theory. Acoustical measurements in various types of halls along with computer modeling have suggested the existence of a design related factor beyond those accounted for in theory which affects the value of G. It is suggested that this added component, along with G itself, may be a factor in the subjective attribute of acoustical intimacy.

2. THE OBJECTIVE PARAMETER G, SOUND STRENGTH

2.1 Sound Strength, G

This objective parameter is commonly defined in the literature and is directly related to the subjective attribute of Loudness in a hall. Being essentially the "acoustical gain" provided by an enclosure relative to a free-field signal, the parameter is normalized to source power and is therefore an absolute value. This allows a direct comparison of Sound Strength between halls. Different integration times define different time sectors of G such as "early," "early reflected," "late," and "total." An excellent history, derivations of the origins of this parameter and its behavior in large rooms is given in papers by Barron [1][2] as well as in his book [3].

2.2 Relationship Between Loudness and Early Reflected Sound

Studies and listening experience have established Sound Strength as a predictor of subjective "loudness" as work by Bradley & Soulodre [4] among others has shown. Also apparent from the literature and listening experience is the contribution of increased Early Reflected Energy to the perception of increased loudness [5][6]. Connecting these relationships, we can say that increased early reflections produce increased sound strength at the receiver. This will be shown empirically.

It is important to note that current formulae based on classical theory do not specifically take this early reflected sound energy into account. This points to the importance of the temporal distribution of reflected sound and the role of room geometry as important design related factors relating to Sound Strength. Also, as yet we have no basis of predicting the increase in G which may be the result of an architectural design approach which increases the early sound field under constant reverberation conditions.

Work by Toyota, et al. [ref. Fig. 1] has further connected the Strength/Early Reflected Energy relationship through their use of the Reflection Energy Cumulative Curve (RECC). In a given hall, they study the buildup of sound energy, excluding the direct sound, at many seat locations, each receiving differing early reflection patterns. They have found that the rank order of the final Sound Strength values between seat locations has already been established at 80 to 100 msec.

They point out the "influence by room shape" on the early cumulative sound energy buildup showing the role of both the early sound field and the room geometry in determining total Sound Strength values. The paper also notes that seats with greater early energy are those where "one can feel intimacy in the hall." Fig. 1 shows Toyota's RECC curves for Suntory Hall in Tokyo.

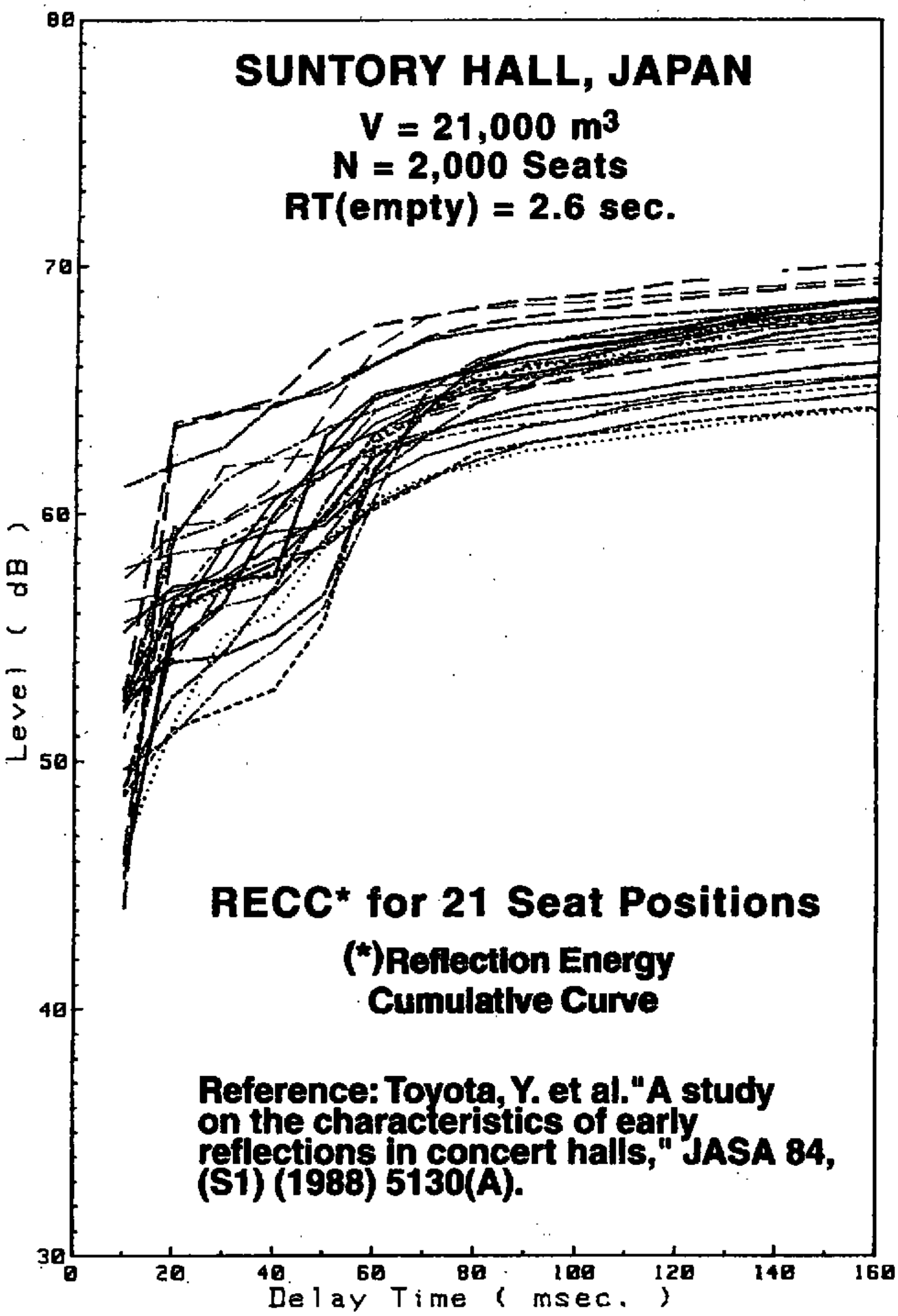
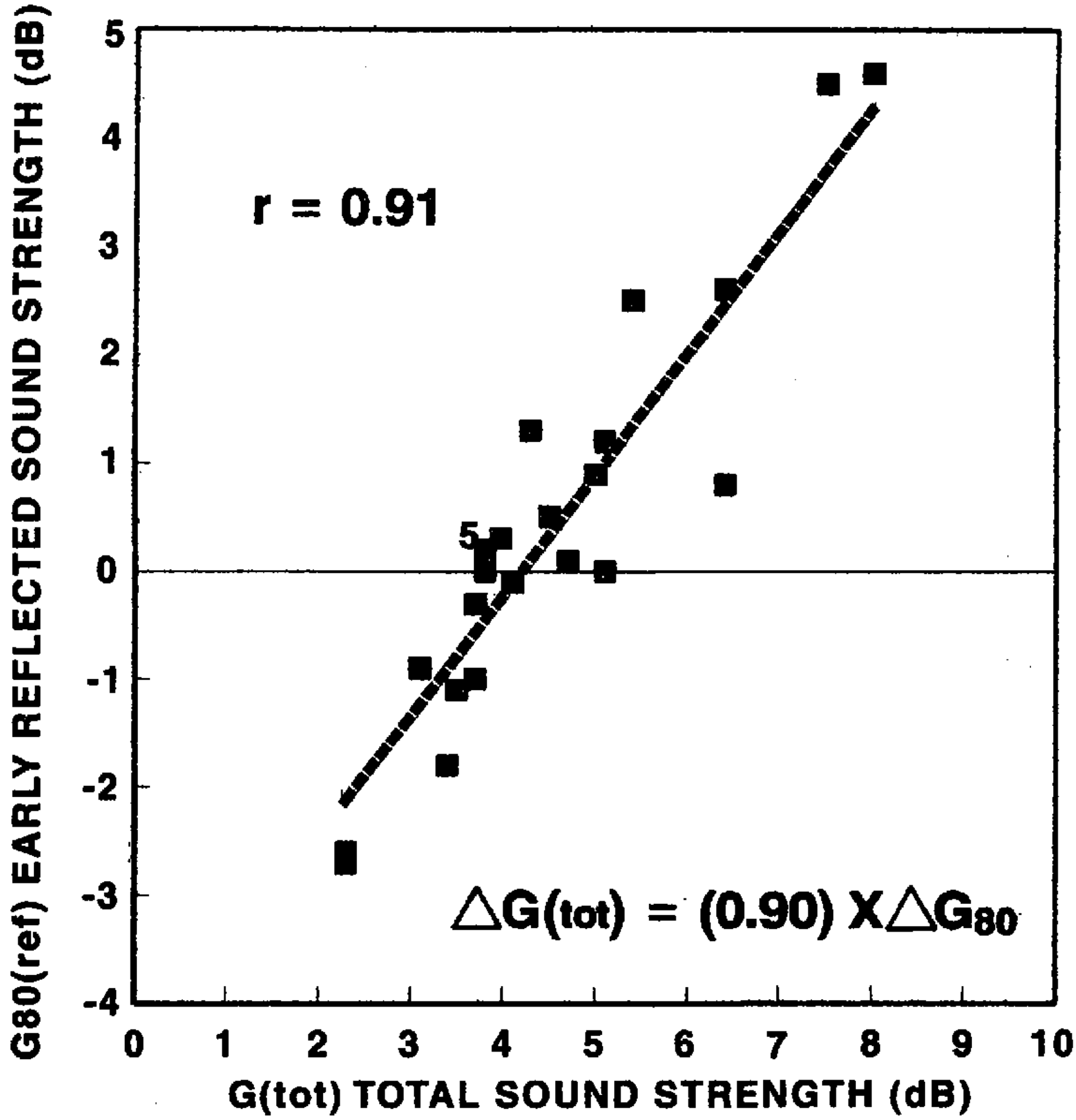


FIGURE 1

2.3 Measured Values of "Early" and Total Sound Strength

The author has previously reported [7] the measurement of G and C_{80} (Clarity Index) in a large hall where the distance to all measurement positions is the same, thus normalizing both parameters to the same direct sound level. It is no surprise that a strong and positive relationship between the two is found; the greater the C_{80} (and the early reflected energy), the greater the value G. In subsequent measurements at random seats, the early reflected Sound Strength G_{80} (ref) was derived from the measurement data giving the highly correlated relationship shown in Fig. 2.

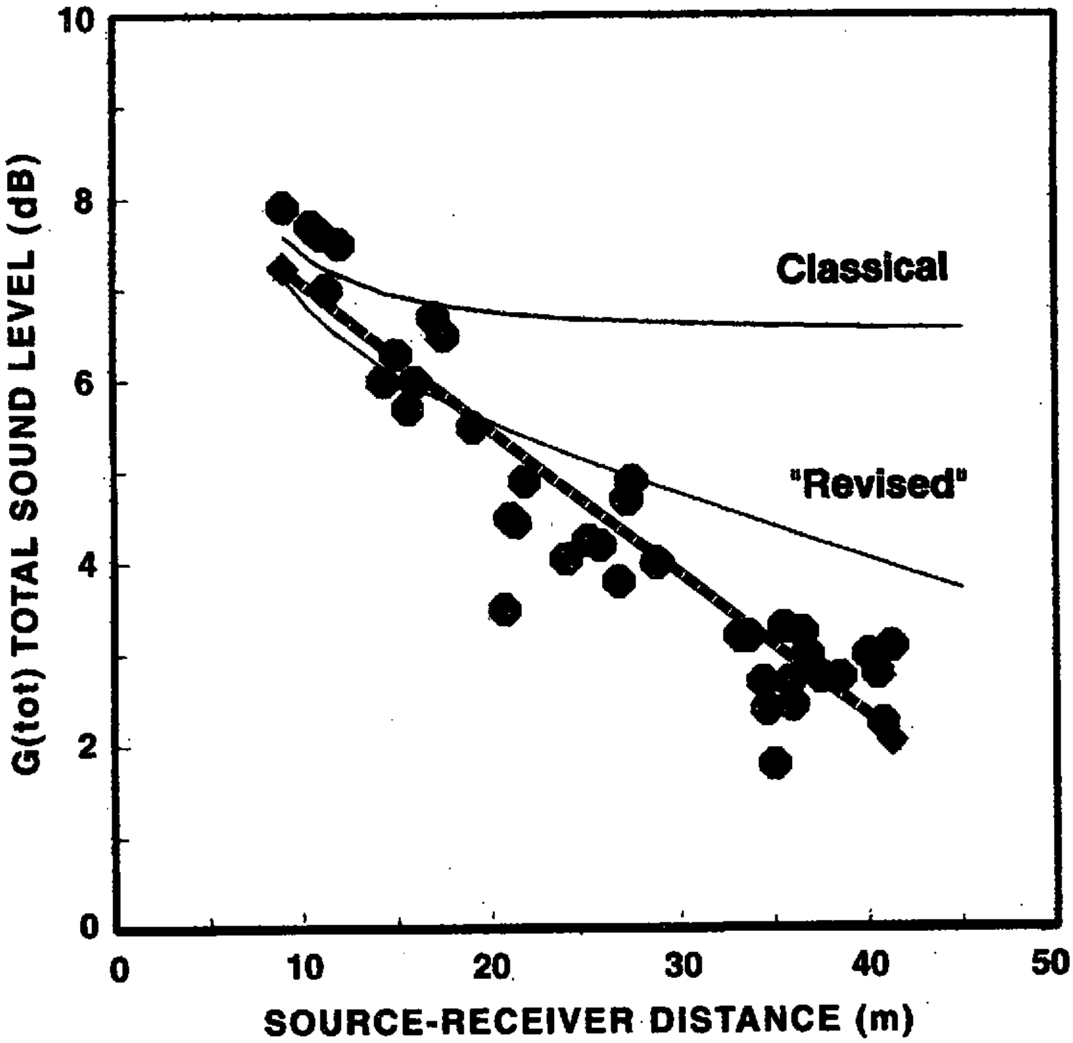


Total Sound Strength vs. Early Reflected Sound
Segerstrom Hall, Orange Co., @ 1kHz (Hyde, 1994)

FIGURE 2

2.4 Statistical Theories and Measurement Results

Sound Strength is an important factor in concert halls. Since the design related early sound field augments this factor, it seems problematic that current theories don't take this important non-statistical energy contribution into account. The classical theory predicts a relatively constant G with distance once beyond the reverberation radius. Barron corrects this relationship [8] by including in the derivation the reduction in reflected energy with distance. This "revised" calculation more accurately approximates the actual behavior of G in halls in that it provides a decrease in level with distance. Both theories, however, involve only two independent variables, namely, distance from the source and the room constant as determined by the measurement of reverberation time (RT). These two theories are applied to Boston Symphony Hall data in Fig. 3.



Boston Symphony Hall - G(tot) vs Distance Measured Values @ 1 kHz (from J.S. Bradley)

FIGURE 3

Early reflections from surfaces specifically applied as part of the architectural design constitute non-statistical energy, and classical theory, indeed, does not take this early reflected energy into account. Therefore, as halls become larger, the need arises for adequate early energy (and laterally if possible), and "theory" requires acknowledgement of this additional factor. As a rule, concert halls consistently produce G values less than those predicted by "revised theory," even for halls which are quite reverberant. A case in point is Boston Symphony Hall (BSH), the measurement values of which are shown in Fig. 3. This measurement by Bradley was taken in the empty hall with an RT=2.7 sec; the regression line shows a drop-off in level of 1.6 dB/10 m.

As a further example, measurements of the reduction in G with distance have been reported by the author [8] in a large highly reverberant volume (V=5,180 m^3, a=0.09, RT=3.5 sec.) which show the values of G further below the "revised" prediction than those of BSH. Why this drop in G with distance occurs is a matter of conjecture; one might ask the question, "why not?"

3.0 COMPUTER MODEL REFLECTION STUDIES

3.1 Reflection Experiment in a 500 Seat Theater

While taking acoustical measurements in a theater, a simple reflection experiment was devised by the author to illustrate the inability of theory to account for early reflections in the computation of G. A small reflector was placed to increase early reflections in a test seat area. G was measured in this seat area with and without the reflector. At seat C15l, the early level G50(ref) at 2 kHz increased by around 3.0 dB while G increased by around 0.7 dB under the relatively reverberant conditions of the empty theater (V=1,700 m^3, a=0.16, RT=1.4 sec.). The result is obvious in this case. There is no theory to predict the addition of this non-statistical reflection whilst the reverberation time upon which the calculation of G is dependent doesn't change.

3.2 Addition of Large Reflectors vs Theory

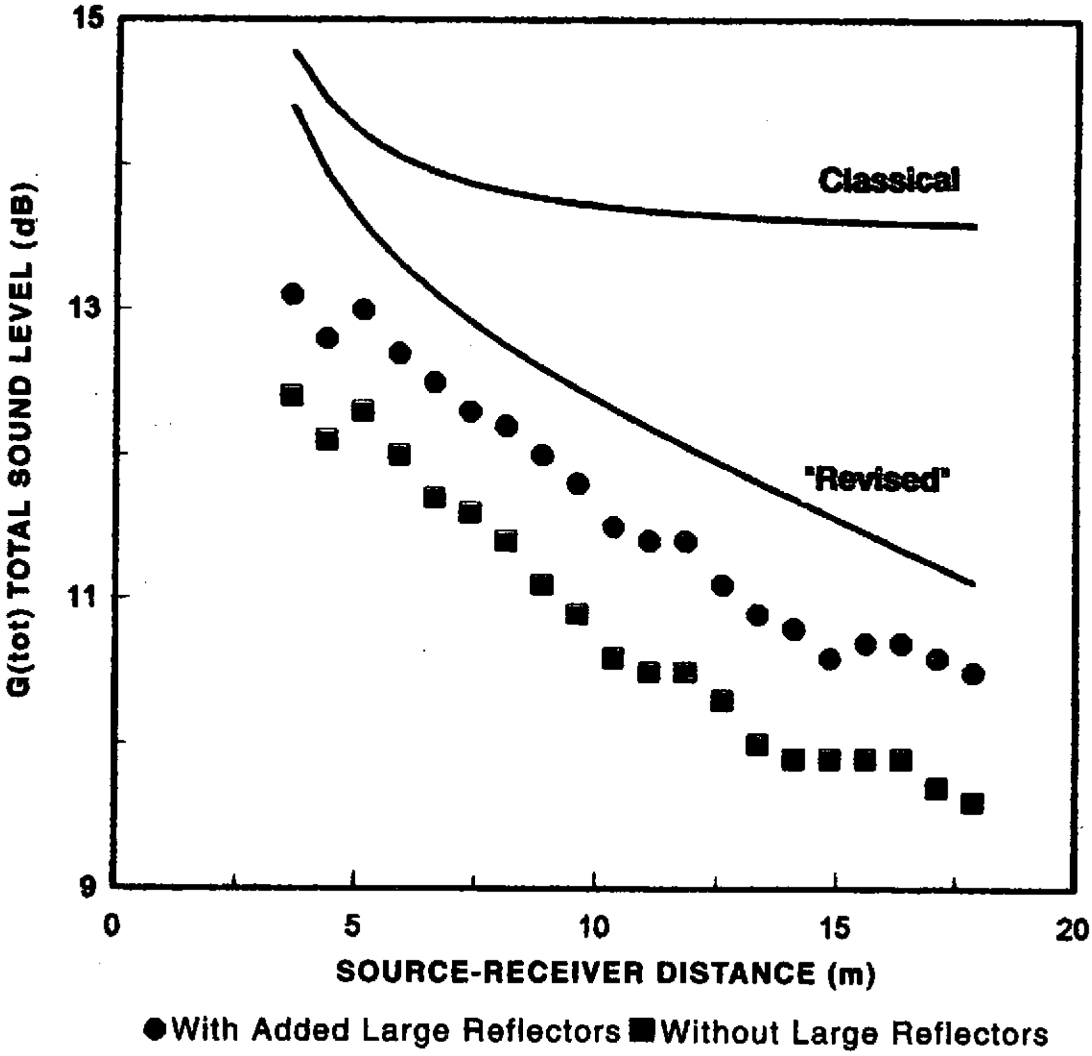
If much larger reflectors are added at the sides of the same room, directing early sound energy down upon the seating area, one might expect similar results for a majority of the seats. How might this affect the overall value of G as averaged over the seating plane, and how would the addition of such reflectors affect the reverberation time used in predicting G?

It is hypothesized that by taking what would otherwise be "late" energy and redirecting it, the benefit of having greater Sound Strength occurs by virtue of the added early reflected sound, before energy absorption occurs due to multiple reflections. On the other hand, application of this situation to current statistical theories might actually predict that Sound Strength would <u>decrease</u>. This is because by directing the reflections onto an absorptive seating plane, the effective absorption (room constant) of the space is increased, thereby reducing RT and the predicted level of G. This illustrates that without recognition of the contributions of the early sound field, at least in certain types of acoustical design, existing theory can lead to erroneous results in the prediction and behavior of Sound Strength in concert halls.

3.3 Addition of Large Reflectors to Computer Model

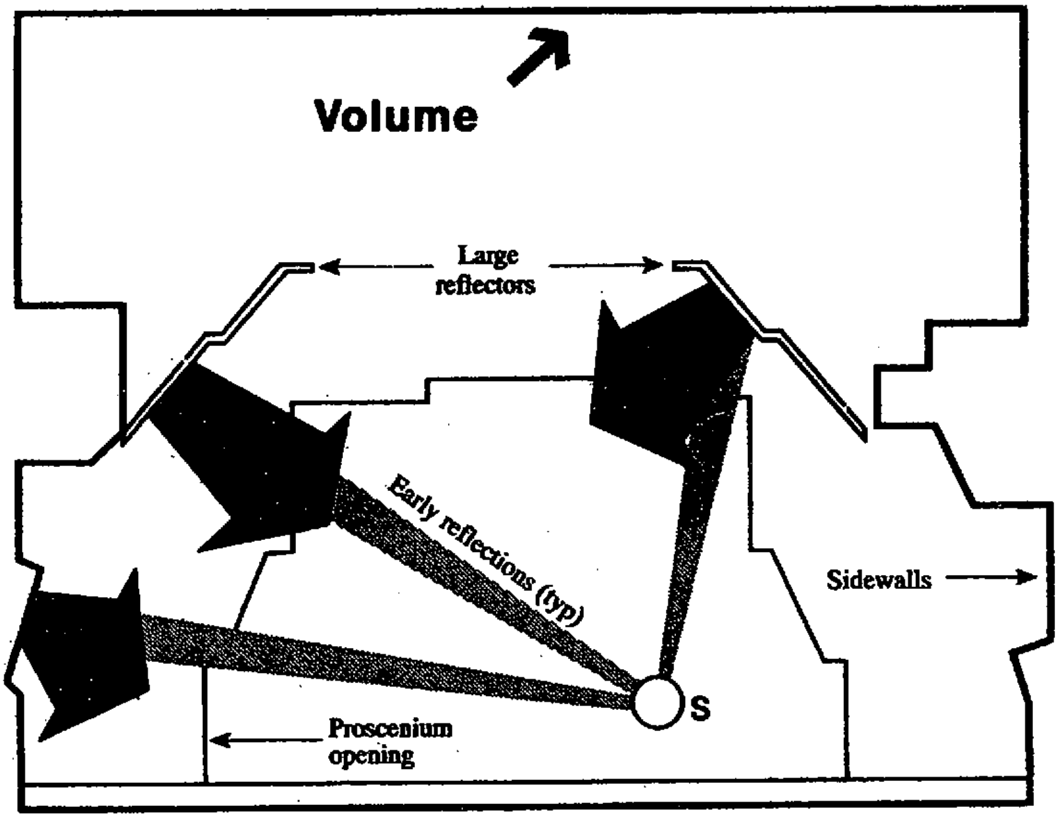
The same 500 seat theater reported above has had a full battery of acoustical measurements as well as having been computer modeled using ODEON. Using the measured data of all acoustical parameters, the computer model was calibrated to yield the same results for reverberation time. Large acoustical reflectors (3 m in width and 8 m long) were then added to both of the upper front corners at the sides (symmetrically), and angled in such a way as to reflect early lateral reflections to the center seating section plus the seating section across the aisle on the far side. The results are given in Fig. 4, showing the increase in total Sound Strength G for the large reflector condition as compared to the bare room without the artificial reflector modification. This increase of 0.8 dB on average for a front-to-back line of seats occurs even though the reverberation time is calculated by ODEON to remain the same for both conditions (the empty seats are not upholstered).

Averaging G over the theater's entire center seating plane (a total of 160 grid measurement positions) yields values at 500 Hz of G(no reflectors) = 10.9 dB and G(large reflectors) = 11.6 dB. The increase in G of 0.7 dB over all of the seats due to the reflectors is not an insignificant outcome. Statistical theories would say that there is no difference in G between the two physically different conditions, since calculation of G is based solely on distance and reverberation time (room constant), these being the same in both cases. In adding the reflectors, the calculated average C_{80} remaines the same while the average lateral energy fraction increases from LEF = 0.24 to 0.26.



SHES 500 Seat Shoebox Theater - G(tot) vs Distance
ODEON Calculated Values @ 500 Hz (J.R.Hyde, 9/99)

FIGURE 4



TRANSVERSE SECTION
Segerstrom Hall, Orange County PAC

FIGURE 5

4.0 SEGERSTROM HALL AS AN EXCEPTION TO THE USUAL RESULTS

The acoustical design of Segerstrom Hall, at the Orange County Performing Arts Center in Costa Mesa, California has been widely reported in papers [9] and in recent books by Barron [3] and Beranek [10] among others. It is of the Directed Reflection Sequence (DRS) design type, utilizing large reflectors within the boundaries which define the reverberant volume, as shown in Fig. 5. Variable acoustical curtains can be drawn into this upper space to further reduce the effective volume and reverberation time. The uniqueness of the design also includes the completely asymmetrical seating trays, effectively subdividing the larger plan into smaller seating domains.

The distribution of Sound Strength with distance has also been reported [3][8] with the exceptional results that virtually all measurement seats have G values significantly greater than those predicted by "revised" theory, and some even greater than those predicted by "classical" theory up to 30 m from the source. Refer to Fig. 3 showing the Boston Symphony Hall results by comparison. The results from Segerstrom are a good full scale example of the role of early reflections, through the architectural geometry, as a component of Sound Strength.

5.0 ACOUSTICAL INTIMACY AND RELATED FACTORS

The subjective attribute of acoustical intimacy is not as easily connected to objective parameters as are, for instance, reverberance and clarity. It can be defined as being the degree of identification between the listener and the performance. Is the listener involved or detached? Does the room sound small or large compared to the perception of its size? We see from the definition that intimacy is an abstract concept linking experiential and perceptual dimensions with the sound field.

Increased acoustical intimacy has been linked with low Initial Time Delay Gap (ITDG) [10], while Barron's studies [3][11] have shown a significant link between subjective intimacy and three factors: 1) source-receiver distance, 2) high early sound level and 3) high total level. These findings present significant evidence linking acoustical intimacy with high levels of early sound energy. Note also the work by Toyota et al. and their conclusions on intimacy discussed in Section 2.2.

Data from Barron's surveys [11] plus the author's measurement and listening experience have drawn attention to there being visual aspects to intimacy. This relationship seems evident when the Sound Strength and early reflected energy are greater (the sound is louder) than what would be expected from the visual cues of distance from major surfaces and from the sound source. There is clearly much work to be done to better understand this multidimensional attribute.

6.0 CONCLUSIONS

It is important to acknowledge the early sound field as a component of total Sound Strength G. This raises the question as to how this non-statistical effect might be accounted for in calculation strategies. A "room geometry" term needs to be considered. This appears to be a situation that can be researched through the use of computer modeling, ultimately with full scale confirmation. While "revised" theory remains a valid tool for estimating Sound Strength G in halls, the knowledge that the early sound field affects the magnitude of G yields the prospect of better prediction. Sound Strength and therefore loudness in concert halls can be manipulated both by designing a room with good "reverberant efficiency" [12] and by supplying the necessary early reflections (additionally required for Clarity). The results can be tested by computer modeling. Maximum mean G values for large halls have been previously suggested [3][9][12]. The addition of early energy from lateral positions also doubly increases the room's spatial impression, by both increasing the lateral energy fraction as well as the sound level. Listening experience and research show that this increased level through early reflections can relate to increased acoustical intimacy and presence.

7.0 REFERENCES & ACKNOWLEDGMENTS

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