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WHEN IS A CONCERT HALL TOO QUIET?

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ABSTRACT

One of the surprises from analysis of results of an objective and subjective study of British concert halls (1988 *Acustica* **66**, 1-14) was that the subjective judgement of loudness in concert halls is influenced not only by sound level but also by the source-receiver distance. This influence implies that the same sound level is judged louder at positions further from the orchestra platform. Since loudness increases with source-receiver distance roughly the same amount that level decreases with distance in actual halls, loudness is judged more-or-less independent of position in average halls (except at positions close to the platform and seats overhung by balconies). The sound strength G is the sound level in an auditorium normalised to the sound power level of the source; the traditional criterion of acceptability for level is that G > 0 dB. The paper proposes that on the basis of subjective evidence and objective behaviour in auditoria, the criterion for G should not be a particular value of G but rather a function of source-receiver distance.

1. INTRODUCTION

It is a truth almost universally acknowledged that sufficient loudness is an important component of the best concert hall acoustics and that sound level is a major determinant of this subjective effect. The sound level, as determined by the hall design, is measured as the Strength (G dB), now specified in ISO3382 [1]. The lower limit for adequate loudness is generally quoted as $G \geq 0$ dB. This paper proposes that the lower limit should also be a function of source-receiver distance.

To make the case for the change of criterion, it is necessary to discuss the behaviour, as a function of source-receiver distance, of both sound level in halls and subjective loudness. The following discussion uses two frequency ranges: mid-frequency, which is the mean of three octaves 500 Hz, 1000 Hz and 2000 Hz, and full-frequency, which is the mean of five octaves 125 – 2000 Hz.

2. SOUND LEVEL BEHAVIOUR IN CONCERT HALLS

The traditional theory for sound level in rooms containing an omni-directional point source is that two components are considered: the direct and reflected sound. The direct sound is taken to behave according to the inverse square law, while traditionally the reflected component was taken to be constant throughout the space. Barron and Lee [2, 3] presented a revised theory for sound level, which proposed that the reflected component decreases as source-receiver distance increases, Figure 1. The rationale behind the proposal was as follows: at a late time after the direct sound during the decay of sound the instantaneous sound level throughout the space is constant; the total sound level decreases with increasing distance because reflected sound at individual positions cannot arrive at the listener before the direct sound. A simple theory was proposed which predicted the following in the case of the total reflected sound level:

$$L_{refl} = 10.\log\left(\frac{31200.T}{V}\right) - \frac{0\cdot174.r}{T} \text{ dB} \quad (1)$$

where T is the reverberation time, V the auditorium volume and r is the source-receiver distance.

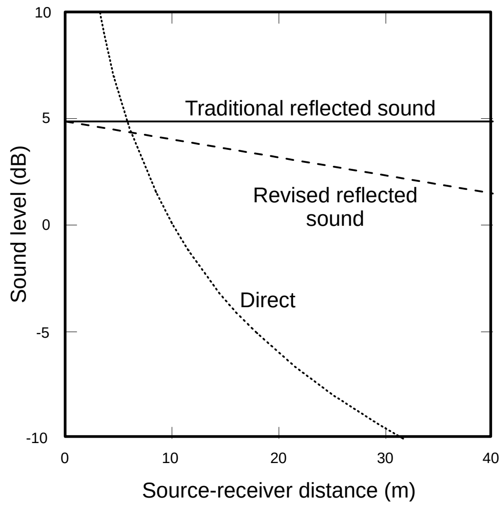

Figure 1. Theory of sound level in a room with a point source.

Figure 2 shows a typical variation of sound level (including the direct sound) with distance in a large concert hall, while Figure 3 shows the agreement between measured and predicted sound level, with the reflected sound level according to equation (1). In Figure 2, under-balcony positions have been omitted as these tend to have lower sound levels than fully exposed positions. The correlation coefficient between measured and theory in Figure 3 is r = 0.94; the root mean square error is 1.1 dB. The revised theory of sound level thus represents average behaviour well.

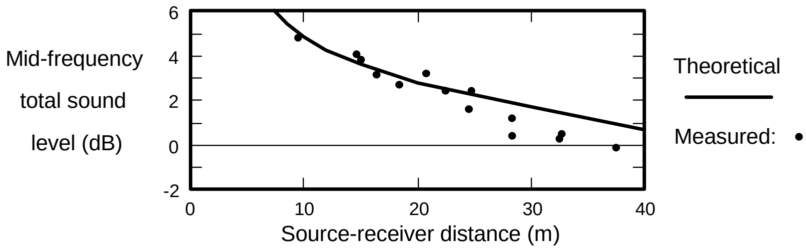

Figure 2. Measured sound level in a large concert hall, compared with revised theory.

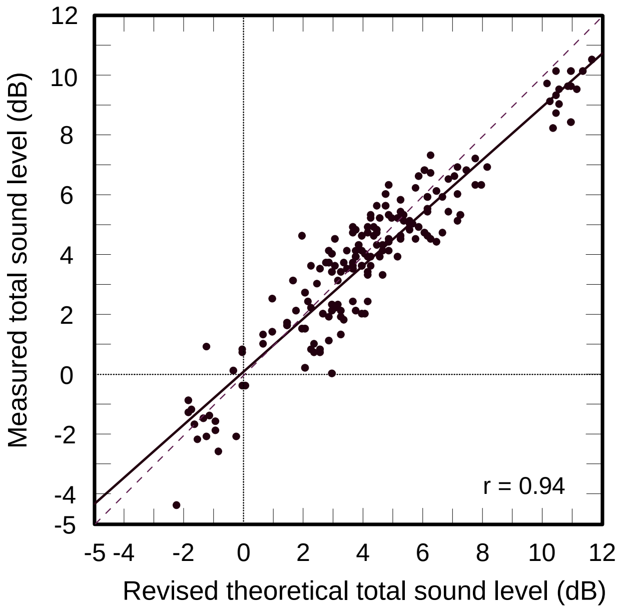

Figure 3. Measured vs. revised theoretical total sound level at mid-frequencies. 174 positions in 17 concert halls.

Thus in a concert hall with a typical reverberation time of 2.0 seconds, for receiver positions well away from the source (where the contribution of the direct sound is no longer significant) the rate of decrease of sound level from equation (1) is 0.087 dB/m.

3. SOUND LEVEL IN PRACTICE

The implication of the $G \geq 0$ dB criterion for Strength in terms of concert hall dimensions is of interest. The reverberation time of most major concert halls is 2.0 seconds. A maximum of 3000 seats is frequently mentioned for concert halls, as is the requirement of $10m^3$/seat. Thus we have a maximum volume of 30,000 m^3. The maximum recommended distance in a concert hall is 40 m from the stage to the farthest seat. These values for T, V and r give a value for G (Direct sound level + L_{refl} from equation (1)) of 0.0 dB. This provides support for the proposed minimum value for Strength.

Though the discussion of sound level in concert halls above has concentrated on behaviour with distance, the prime determinant remains the total acoustic absorption, A m^2 (which from the Sabine equation is proportional to V/T). It is because of this that there is a limit on the number of seats in concert halls. The Royal Albert Hall in London has an audience capacity of over 5000 seats. Figure 4 shows measured values of the total sound level in this hall. At most measurement positions, the measured values are reasonably similar to those predicted by revised theory (given by the solid line). However the high acoustic absorption means that measured values are all below the 0 dB criterion with the exception of the measurement position close to 10 m from the source.

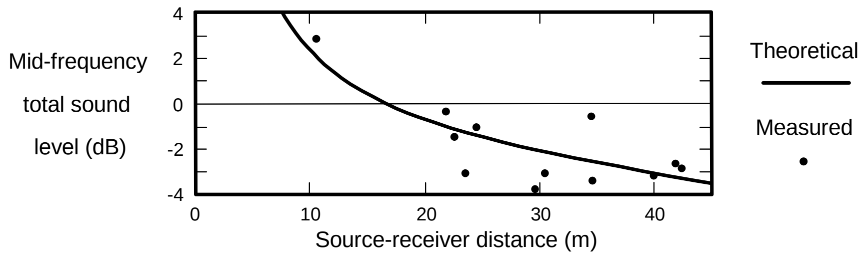

Figure 4. Measured total sound level at mid-frequencies in the Royal Albert Hall, London.

4. LOUDNESS IN CONCERT HALLS

Evidence that loudness was an important issue for concert hall listening emerged in two German subjective studies in the late 1960s and early ‘70s. Both groups were conducting experiments using recordings via dummy head made in a range of concert halls. The Göttingen group [4] were using paired comparisons by subjects and found that the sound level dominated the results; they therefore eliminated loudness differences from their experiments! The Berlin study involved subjects completing questionnaires; factor analysis indicated that ‘loudness’ was one of three subjective factor scales. Perceived loudness was found to be strongly correlated with total sound level (r = 0.82) [5, p.603].

In this author’s subjective study [6], in which listeners completed questionnaires during actual concert performances, both subjective ‘intimacy’ and ‘loudness’ were found to be correlated to measured total sound level. Interestingly ‘intimacy’ was better correlated with ‘overall acoustic impression’, the subjective measure of preference. The following is based on the results of this study regarding ‘loudness’. Several results presented here have already been quoted in reference [7]. As in the latter paper, the regression coefficients quoted here are slightly different to those quoted in [6]. The data set in [6] used a minimum of three questionnaires per seat position. Further subjective tests were conducted later in some of the concert halls and data presented here is from the data set with a minimum of four questionnaires per position. This revised data set contains results from 34 positions in 11 large British concert halls. Both data sets lead to the same conclusions regarding loudness.

Figure 5 shows the relationship for the author’s data between subjective loudness and full-frequency sound level, with a correlation coefficient of r = 0.77 (the correlation coefficient with mid-frequency level was r = 0.70). These coefficients are comparable to that quoted for the Berlin study above.

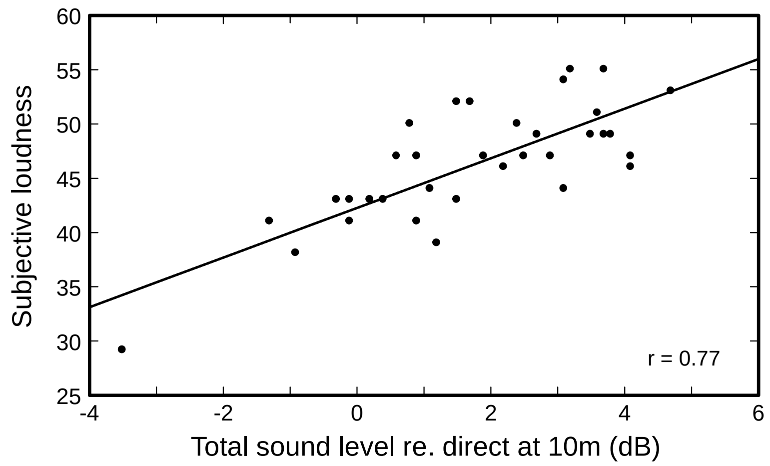

Figure 5. Subjective loudness plotted against measured sound level at frequencies 125–2000Hz.

5. LOUDNESS AND DISTANCE

For the same data set, objective measured full-frequency sound level is correlated with source-receiver distance (r = -0.66). Loudness however is not significantly correlated with source-receiver distance, Figure 6 (r = -0.31). This is slightly surprising.

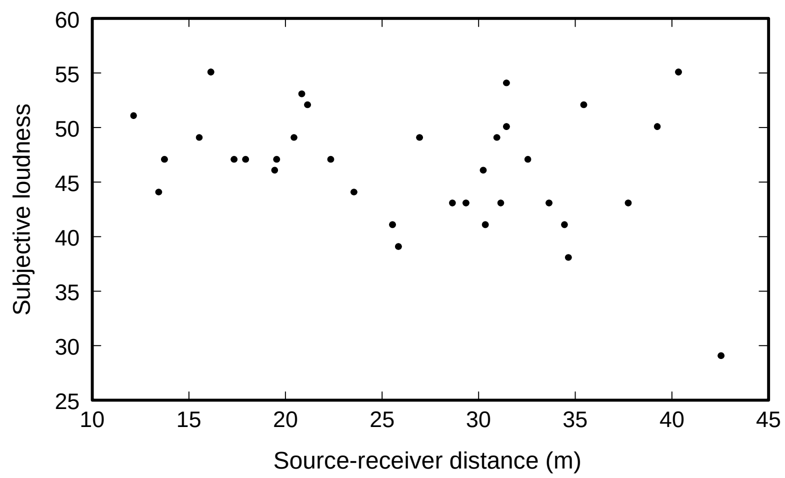

Figure 6. Subjective loudness plotted against source-receiver distance.

If a multiple regression is performed on loudness, it is found that the coefficient is improved from r = 0.77 to r = 0.82 if both sound level and distance are included. The regression equation is:

$$\text{Loudness} = 2.96 \times (\text{Full-freq. sound level} + 0.076 \times \text{Distance}) + 35 \qquad (2)$$

The crucial observation here is the sign of the coefficient for distance: loudness apparently <u>increases</u> with distance. Since sound level decreases with distance, we might have expected the relationship between loudness and distance to be the other way round. There is no obvious objective behaviour which explains loudness increasing with distance. The most persuasive explanation is the subjective one: that listeners relate their judgement of loudness to how far they judge themselves to be distant from the stage. This is therefore an example of acoustic judgement being influenced by a visual cue. There is an extensive literature in the experimental psychology field concerned with such interactions, such as [8]. Figure 7 shows the correlation between loudness and (Full-freq. sound level + 0.076 × Distance). Both this regression and that with sound level alone are significant at the 0.1% level.

From equation (2) the trade-off between level and distance is 0.076 dB/m. This is similar to the rate of level drop-off in halls of 0.087 dB/m, quoted in section 2 above. The accuracy of the first of these numbers is not high, based as it is on subjective data. It is therefore a reasonable assumption that listeners judge the loudness as roughly constant throughout a hall with the possible exception of positions close to the stage. We would also expect loudness to be judged lower at positions adversely influenced by design features, such as seats overhung by balconies.

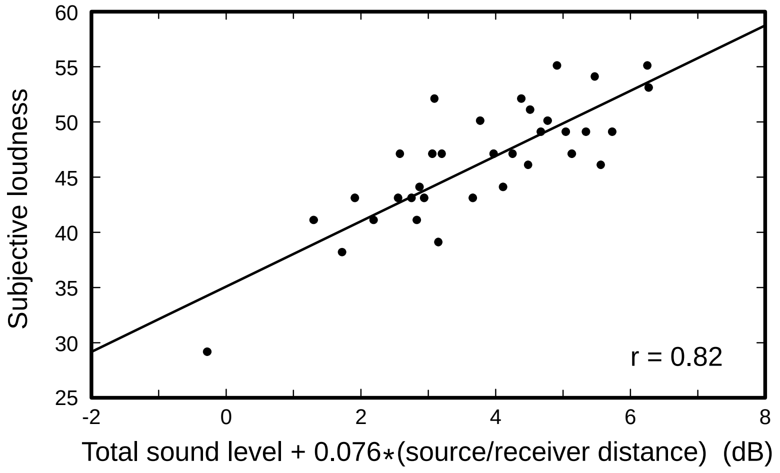

Figure 7. Subjected loudness plotted against total sound level and a contribution from distance.

6. A CRITERION FOR SOUND LEVEL

In halls we thus have sound levels that decrease with distance, whereas loudness remains basically constant, as sketched in Figure 8. If the criterion of G ≥ 0 dB is applied to the position with the lowest sound level, which is at a source-receiver distance around 40 m, then to maintain loudness at positions nearer to the stage, it is necessary for the sound levels, G, to be greater than 0 dB at distances less than 40 m. Only in this way will the loudness be judged as adequate. It is however fair to add that loudness judgements close to the source (stage) may not remain constant with distance; the subjective situation becomes more complex here with the varying distance to different members of the orchestra.

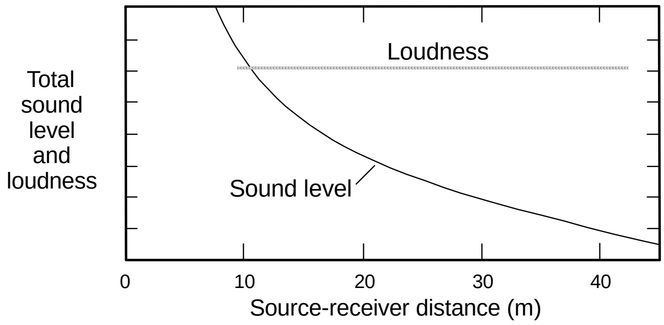

Figure 8. Behaviour of subjective loudness and total sound level as a function of distance.

This line of argument therefore leads directly to a modified sound level criterion. In section 3, the sound level in a hall with reverberation time of 2 seconds and a volume of 30,000 m^3 is predicted to be 0 dB at 40 m. The criterion then becomes the predicted sound level for this particular hall, as shown in Figure 9. The equation of this line is:

$$L = 10.\log(100/r^2 + 2{\cdot}08.e^{-0.02r}) \qquad (3)$$

7. CONCLUSIONS

Objective measurements in concert halls have shown that sound level, relative to a standard sound power source, decreases with distance more than had been traditionally believed. On the other hand, assessment of subjective loudness indicates that loudness judgement is almost independent of distance from the stage, which suggests that listeners are compensating their judgement of loudness on the basis of visual information. These two results lead to a criterion for the minimum sound level in concert halls, which instead of being a single value, G ≥ 0 dB, is a function of distance, as shown in Figure 9.

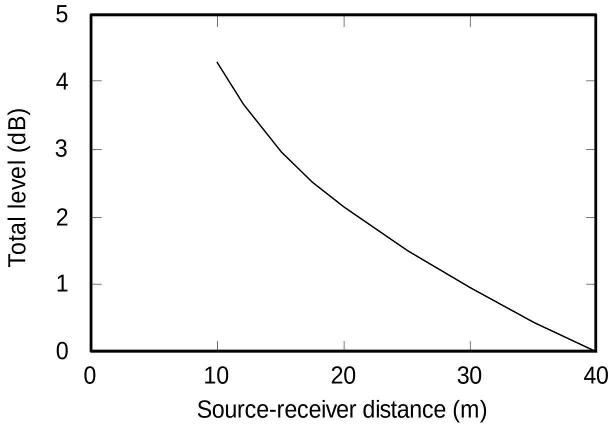

Figure 9. Proposed minimum value for Strength (G) as a function of source-receiver distance.

It is valuable, with a result such as this, for it to be confirmed by subjective observation. Loudness judgements are needed from listeners at seats where the measured level G is greater than 0 dB but less than the curve in Figure 9, to establish whether in fact sound here is judged as too quiet.

The usual concern in large concert halls is for the loudness to be sufficient. Loudness overload does in fact also occur, particularly when a professional orchestra plays in smaller halls (less than 1000 seats). There is a strong case for some variable absorption in these halls.

This paper has been concerned with loudness perception and its link to sound level in halls. A closely related subjective phenomenon is 'intimacy', which is also found to be related to measured sound level [6], though not to distance in the same way as loudness. Some uncertainties remain regarding objective correlates of 'intimacy'; Hyde [9] has provided an interesting discussion of this.

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