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Taking account of loudness constancy for the loudness criterion for concert halls

Mike Barron *

Fleming & Barron, Combe Royal Cottage, Bathwick Hill, Bath BA2 6EQ, United Kingdom

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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 response implies that the same sound level is judged louder at positions further from the orchestra platform. Whereas 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). As an observation it ties in with evidence from experimental psychologists for loudness constancy throughout a space. 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 $G \geqslant 0$ dB. The paper proposes that, on the basis of subjective evidence and objective behaviour in auditoria, the criterion for G should not be a unique value of G but rather a function of source–receiver distance.

1. Introduction

It is generally 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]. A lower limit for adequate loudness has been proposed as $G \geqslant 0$ dB. The proposal presented here is that the lower limit should also be a function of source–receiver distance.

The lower limit was put forward in Refs. [2,3] based on experience gained in the author's objective and subjective survey of British concert halls. Previously Lehmann and Wilkens [4], based on their survey of six German concert halls, had proposed a minimum criterion of $G = +3$ dB. This seems excessively severe as it implies that 30% of their chosen seat positions were too quiet. For the British survey, this criterion places 60% of measured positions with inadequate loudness! Evidence gained from the subjective survey of the British halls suggested a criterion for the minimum of 0 dB as acceptable for the total sound level. Ideally this figure of 0 dB refers to the average over the octaves 125–2000 Hz. This limit does not appear to have been challenged in the intervening years.

To make the case for the change of criterion, it is necessary to discuss 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.

The objective situation will be dealt with first, followed by the subjective leading to the relation between the two. The subjective evidence comes first from a study by the author, which is followed by consideration of work from experimental psychologists. An earlier version of this paper was presented at the International Congress on Acoustics in Madrid in 2007 [5].

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 [6] and Barron [2] presented a revised theory for sound level, which proposed that the reflected component decreases as source–receiver distance increases, Fig. 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 reflected sound level decreases therefore with increasing distance because reflected sound at individual positions cannot arrive at the listener before the direct sound. This line of reasoning leads to the following relationship for the total reflected sound level:

$$L_{refl} = 10 \cdot \log\left(\frac{31200 \cdot T}{V}\right) - \frac{0 \cdot 174 \cdot r}{T} \text{ dB} \quad (1)$$

* Tel.: +44 1225 580188.
E-mail address: m.barron@flemingbarron.co.uk

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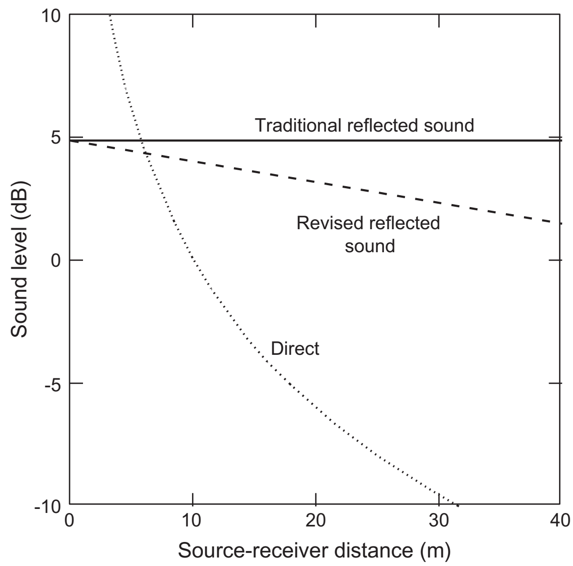

Fig. 1. Theory of sound level in a room with a point source.

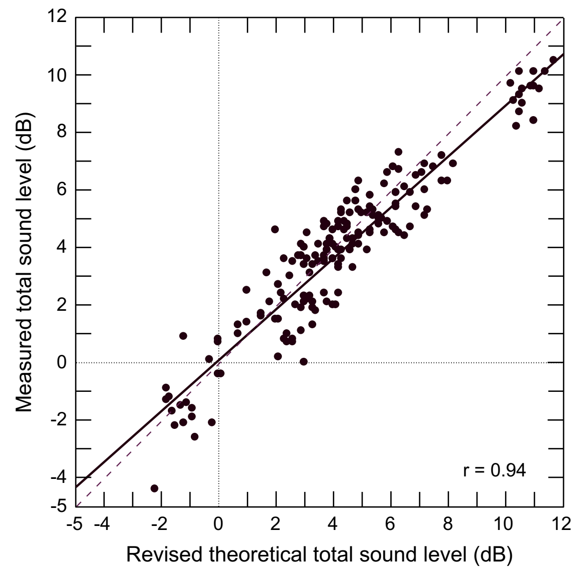

Fig. 3. Measured vs. revised theoretical total sound level at mid-frequencies. 174 Positions in 17 concert halls, omitting under-balcony locations.

where T is the reverberation time (RT), V the auditorium volume and r is the source–receiver distance.

Fig. 2 shows a typical variation of sound level (including the direct sound) with distance in a large concert hall. Fig. 3 shows the agreement between measured and predicted sound levels in 17 concert halls, with the direct sound according to the inverse square law and reflected sound level according to Eq. (1). In Figs. 2 and 3, under-balcony positions have been omitted as these tend to have lower sound levels than fully exposed locations. The correlation coefficient between measured and theory in Fig. 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.

Thus in a concert hall with a typical reverberation time of 2.0 s, 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 Eq. (1) is 0.087 dB/m.

3. Sound level in practice

The implication of the $G \geqslant 0$ dB criterion for strength in terms of the limits for concert hall dimensions is of interest. The reverberation time of most major concert halls is around 2.0 s. A maximum of 3000 seats is frequently mentioned for concert halls, as is the requirement of 10 m^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 Eq. (1)) of 0.0 dB. Thus general values for reverberation time and volume per seat for large concert halls, plus maximum values for seat capacity and distance lead to $G = 0$, which 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. Fig. 4 shows measured values of the total sound level in this hall, which have been corrected from the unoccupied reverberation time at the time of measurement to the occupied value. 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.

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 heads made in a range of concert halls. The Göttingen group [7] were using paired comparisons by

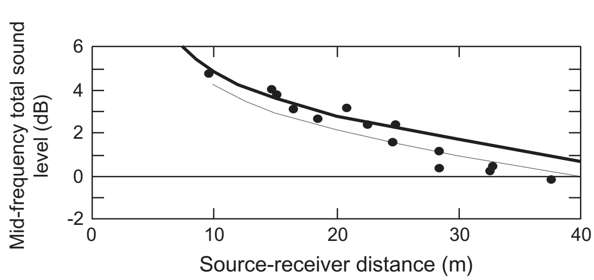

Fig. 2. Measured sound level in a large concert hall, compared with revised theory (solid line). Positions under balcony overhangs have been omitted. Measured values have been corrected to occupied conditions for the RT change. Dotted line is the new minimum criterion.

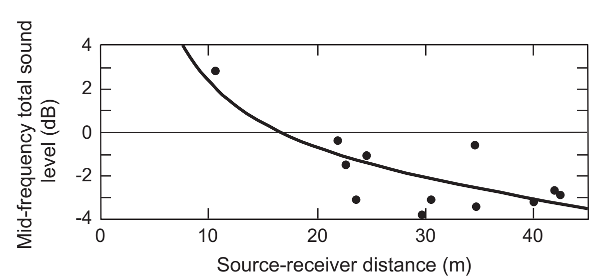

Fig. 4. Measured total sound level at mid-frequencies in the Royal Albert Hall, London. Measured values have been corrected to occupied conditions for the RT change. Solid line gives revised theory predictions.