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Prediction of sound transmission in long spaces using ray tracing and experimental Statistical Energy Analysis

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A R T I C L E I N F O

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A B S T R A C T

Long spaces such as corridors, train carriages and aircraft cabins often have a significant decrease in sound pressure level along their length when a sound source is positioned at one end. However, the more common situation for noise control involves multiple sound sources positioned along their length. In order to use Statistical Energy Analysis (SEA) to predict spatial-average sound pressure levels along a long space when it is subdivided into a series of adjacent subsystems with one or more point sources, this paper combines ray tracing and a general form of experimental SEA (GESEA) to determine the loss factors. Predictive SEA that includes only direct coupling between subsystems (based on the open area) tends to over- or under-predict the decrease in SPL that is determined from ray tracing. This occurs when there is a point source at one end of an elongated cuboid that is either empty, has staggered barriers, or symmetrically-placed barriers. However, SEA using all Coupling Loss Factors (CLFs) determined from GESEA which incorporates indirect coupling and any negative CLFs shows almost exact agreement with ray tracing. This agreement is maintained when the point source is positioned in other subsystems, or point sources are positioned in multiple subsystems. This provides evidence of the importance of indirect coupling in long spaces, as has previously been identified with structure-borne sound transmission along a series of in-line coupled subsystems.

1. Introduction

For the purpose of noise control or the assessment of human perception, it is necessary to predict sound transmission along long spaces such as a corridor, train carriage or an aircraft cabin (see Fig. 1). These long spaces can be categorised into two generic types: (1) empty (see Fig. 1a), or (2) an unobstructed narrow corridor with either full-height barriers that run from floor to ceiling, partial-height barriers that are formed by seating, or a combination of full- and partial-height barriers (see Fig. 1b and c). When the sound source is at one end of the space, there can be a significant decrease in the Sound Pressure Level (SPL) along the length of the space. In addition, there can be zones along the space that have significantly different levels due to different noise sources injecting power at different positions along its length. Hence, subdividing a long space into several coupled volumes potentially allows prediction of sound transmission along a corridor into and out of rooms that are connected via doors, as well as the noise levels near seating positions in trains and aircraft due to mechanical and aerodynamic sources of noise.

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1.1. Review of previous studies on sound transmission in long spaces

Corridors in buildings often show a decrease in the SPL over a distance, d. Early work by Yamamoto [1] developed the following theoretical equation to calculate the decrease in SPL along an infinitely long corridor, ΔL_{inf}, assuming a semi-diffuse sound field in each cross-section:

$$\Delta L_{\mathrm{inf}} = C\frac{U\alpha d}{S} \quad (1)$$

where U is the perimeter of the corridor cross-section ($U = 2w + 2h$ for a rectangular cross-section of width, w, and height, h), $S = wh$, α is the average absorption coefficient of the boundaries that form the corridor cross-section (i.e. side walls, floor, ceiling) and d is the distance travelled along the corridor. In Yamamoto's equation, the constant, $C = 2.17$. However, this appears to be incorrect and caused by use of $20\log_{10}$ rather than $10\log_{10}$ when calculating the decrease in SPL in decibels. Use of $10\log_{10}$ would have resulted in $C = 1.09$. Yamamoto showed close agreement between his image source approach and measurements in a real corridor, but the theoretical model overestimated the measured decrease in SPL by a factor of two and this is attributed to the use of $20\log_{10}$.

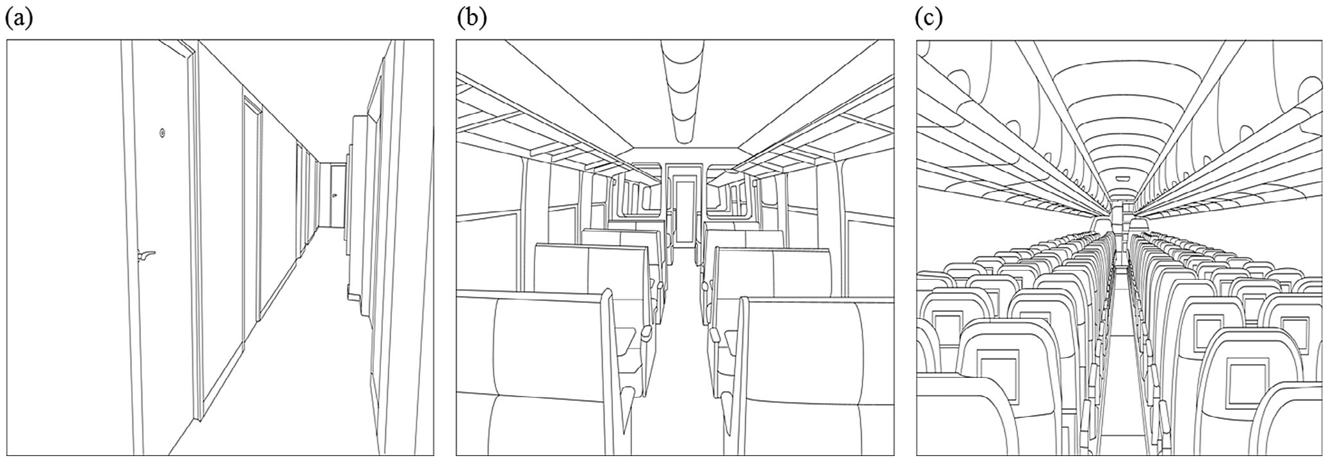

Fig. 1. Illustrations of long spaces: (a) corridor, (b) train carriage and (c) aircraft cabin.

Davies [2] used a modal approach to predict sound fields along a corridor with consideration of open doors along the corridor, and branches off the corridor. Unfortunately the experimental validation was limited to one corridor at one frequency (2 kHz) with estimated values for all absorption coefficients. Redmore and Flockton [3] developed theory using a similar approach to Yamamoto but their equation used $C = 10\pi/(8\ln 10) = 1.71$ which gave reasonable agreement with measurements from three different corridors. Redmore [4] subsequently developed ray image models for corridors which gave close agreement for hard-walled corridors but tended to overestimate levels in corridors containing absorbent surfaces.

To avoid problems estimating absorption coefficients in real corridors, Redmore [5] built scale model corridors where the absorption and cross-section could be altered. Linear regression was used to give an empirical version of Eq. (1) where $C = 1.4$. It was noted that regression with measured data from real corridors gave $C = 1.7$ and this slightly higher value was attributed to a lack of knowledge of the actual absorption coefficients. Hopkins [6] subsequently showed that Redmore's empirical equation could be derived theoretically by considering two-dimensional sound fields in cross-sections along the corridor to give the constant $C = 10/(4\ln 10) = 1.38$; hence in this paper it is referred to as a 'propagating 2D model'. Kang [7] notes that Redmore's empirical equation is likely to be limited to corridors because when used for long enclosures up to 120 m in underground stations, the errors are significant. In corridors, the maximum distance between consecutive sets of fire doors to satisfy building regulations on fire safety [8] is approximately 40 m. In reviewing the different prediction models for sound attenuation in long enclosures, Kang [7] concluded that "...it is still necessary to develop a more practical prediction method". Whilst this also considered long enclosures such as underground tunnels and street canyons with line sources, these are not considered in the current paper. Picaut et al. [9] developed a theoretical model incorporating a diffusion coefficient to predict sound propagation along long spaces with diffusely reflecting boundaries. As real corridors rarely have diffusely reflecting boundaries over the entire building acoustics frequency range, this diffusion coefficient was determined from calculations of the mean free path.

The use of Statistical Energy Analysis (SEA) to predict sound transmission in corridors, train carriages, aircraft cabins and car cabins often involves subdivision of a space into coupled cavity subsystems. Long spaces can potentially be represented by a series of in-line, coupled cavity subsystems linked by large open areas. With reference to car cabins, Fahy [10] noted that subdivision of a space had been criticized because the SEA assumption of 'weak coupling' would not apply to two coupled cavity subsystems without any impedance mismatch at the open boundary between them. No numerical or theoretical analysis was carried out by Fahy, but the qualitative discussion concluded that subdivision could be justified for a cabin when the sound field approximated a diffuse field, although the use of coupled cavities for long spaces might be more problematic.

To model a corridor in SEA, Craik [11] proposed incorporating the Redmore and Flockton equation describing attenuation with distance. This approach essentially 'forces' the Coupling Loss Factor (CLF) to be a function of the Internal Loss Factor (ILF). An advantage of this approach is that it is possible to choose any model that has been validated for the space, such as the Redmore and Flockton equation, the propagating 2D model, or Picaut *et al*'s model.

For a train carriage, Forssén et al. [12] used an SEA model to predict sound transmission along its length (≈22 m) by subdividing it into five coupled cavity subsystems. The predicted energy for each subsystem was distributed along the subsystem length using the Redmore and Flockton equation to account for the decrease in SPL. Measurement of the spatial-average SPL in each cavity subsystem used microphones arranged in a straight line along the aisle at a height of 1.2 m (approximately corresponding to head height when seated). Comparison of measurements from a detailed scale model with ray tracing and SEA showed differences of up to ≈8 dB at 125 Hz but these reduced with increasing frequency to only ≈3 dB at 4 kHz. Differences between SEA and measurements could be attributed to the sole use of sampling positions along the aisle at a fixed height, rather than a random distribution of sampling positions in each subsystem to give a spatial-average SPL representing the entire cavity. Yang and Cheng [13] used a two-subsystem SEA model to determine the sound energy in a long cavity subsystem and, in a similar way to Forssen et al., the energy was distributed along the length of the cavity subsystems using two different approaches. The first approach incorporated the Picaut et al. model. The second approach was the same as Forssén et al. which incorporated the Redmore and Flockton equation. Comparison of both approaches with scale model measurements approach showed agreement within ≈2 dB, except at positions near end walls. The inherent assumption in the approach used by Forssén et al. and Yang and Cheng, is that net power transferred between coupled subsystems remains proportional to the difference in their modal energies, even when there is a large decrease in energy across the subsystem. Whilst this might be reasonable for rain-on-the-roof excitation (i.e. random phase, broadband sound sources with the same power output that are distributed throughout the elongated subsystem), it may not always be reasonable for a point