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Regression curves for vibration transmission across junctions of heavyweight walls and floors based on finite element methods and wave theory

Carl Hopkins [a,*], Charlotte Crispin [b], Jordi Poblet-Puig [c], Catherine Guigou-Carter [d]

[a] Acoustics Research Unit, School of Architecture, University of Liverpool, Liverpool L69 7ZN, United Kingdom
[b] Belgian Building Research Institute – Acoustics Division, Lombardstraat 42, B-1000 Brussels, Belgium
[c] Laboratori de Càlcul Numèric, E.T.S. d'Enginyers de Camins, Canals i Ports de Barcelona, Universitat Politècnica de Catalunya, Campus Nord B1, Jordi Girona 1, E-08034 Barcelona, Spain
[d] Direction Santé Confort, Centre Scientifique et Technique du Bâtiment, Joseph Fourier 24, Saint Martin d'Hères 38400, France

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ABSTRACT

Sound insulation prediction models in European and International Standards use the vibration reduction index to calculate flanking transmission across junctions of walls and floors. These standards contain empirical relationships between the ratio of mass per unit areas for the walls/floors that form the junction and a frequency-independent vibration reduction index. However, calculations using wave theory show that there is a stronger relationship between the ratio of characteristic moment impedances and the transmission loss from which the vibration reduction index can subsequently be calculated. In addition, the assumption of frequency-independent vibration reduction indices has been shown to be incorrect due to in-plane wave generation at the junction. Therefore numerical experiments with FEM, SFEM and wave theory have been used to develop new regression curves between these variables for the low-, mid- and high-frequency ranges. The junctions considered were L-, T- and X-junctions formed from heavyweight walls and floors. These new relationships have been implemented in the prediction models and they tend to improve the agreement between the measured and predicted airborne and impact sound insulation.

1. Introduction

Prediction of airborne and impact sound insulation in heavyweight buildings requires consideration of both direct and flanking transmission because the latter is often critical in determining the *in situ* sound insulation [1]. The International Standards, ISO 15712 Parts 1 and 2 [2] and the identical European Standards, EN 12354 Parts 1 and 2 [3] describe a prediction model to estimate the airborne and impact sound insulation based on the approach from Gerretsen [4]. This model considers flanking transmission paths with vibration transmission across one junction of walls and/or floors using a parameter called the vibration reduction index, K_{ij} [5]. Part 1 of these Standards has an informative annex (Annex E) which contains empirical relationships between K_{ij} and the ratio of mass per unit areas for the walls and floors that form the junction.

Problems concerning the application of these empirical relationships have been discussed in detail by Hopkins [6]. These occur because the relationships were derived from a mixture of theoretical K_{ij} values for isolated junctions and *in situ* measurements of K_{ij} in real buildings. The latter contain unwanted flanking transmission from high-order flanking paths [7], whereas the prediction model only considers first-order flanking paths. This conflicts with the approach prescribed in ISO 10848-1 [8] to provide measured K_{ij} data for the prediction model from isolated junctions of walls and floors in the laboratory (i.e. without high-order flanking paths). Laboratory measurements on isolated heavyweight junctions with rigid connections have shown varying degrees of agreement with the empirical relationships (e.g. see [9,10]). One reason for this is that it has been shown that K_{ij} measurements on heavyweight junctions in both the laboratory and the field will often incur significant errors due to unwanted flanking transmission [7]. Some calculations of airborne and impact sound insulation using the empirical relationships have shown reasonable agreement with existing field sound insulation databases for heavyweight

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* Corresponding author.
E-mail address: carl.hopkins@liverpool.ac.uk (C. Hopkins).

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buildings (e.g. see [4,11]). However, it has also been shown that bias errors up to 10 dB occur in the airborne sound insulation when compared with matrix SEA which considers all possible transmission paths [1,12,13]. Comparisons of measured and predicted single-number quantities for airborne and impact sound insulation do not always show these bias errors (e.g. see [4]). This could be attributed to the fact that single-number quantities often obscure discrepancies in the frequency trends of the sound insulation curves with emphasis on the low- and mid-frequency ranges. Some comparisons do indicate a bias error but this could also be attributed to the input data [14].

To assess the empirical relationships in this informative annex of the European and International Standards, Hopkins [6] used wave theory to calculate the vibration reduction index for L-, T- and X-junctions of solid masonry/concrete walls and floors. A theoretical approach was used because of the problems inherent in K_{ij} measurements with heavyweight junctions [7]. Calculations were carried out assuming only bending wave transmission at the junction, as well as bending and in-plane wave transmission at the junction. For typical heavyweight walls and floors in the low-frequency range, only bending wave transmission is relevant which gives a frequency-invariant K_{ij}. However, it was shown that the frequency-invariant empirical K_{ij} data in the European and International Standards were likely to give rise to errors in the mid- and high-frequency ranges due to the importance of in-plane wave generation at the junction. Regression analysis with wave theory data was used to identify new relationships between K_{ij} and the ratio of mass per unit areas for the walls/floors forming the junction. The results indicated that it was feasible to generate new empirical curves for (a) the low-frequency range (50–200 Hz) using bending wave theory and (b) the mid-frequency range (250 Hz to 1 kHz) and high-frequency range (1.25–5 kHz) using bending and in-plane wave theory.

Based on laboratory measurements of the vibration reduction index, Crispin and Ingelaere [15] noted that the ratio of mass per unit areas might not be the optimal parameter to establish empirical relationships for K_{ij}. In their seminal work on structure-borne sound, Cremer et al. [16] identified the ratio of characteristic moment impedances as the independent variable that described the bending wave transmission loss across L-, T- and X-junctions. Crispin et al. [17] proposed that this ratio of characteristic moment impedances would be a more suitable independent variable than a ratio of mass per unit areas when establishing empirical relationships for K_{ij}. This was assessed by using Finite Element Methods (FEM) with T- and X-junctions to calculate K_{ij} as a single frequency-average value between 200 Hz and 1.25 kHz. These results indicated that K_{ij} data tend to cluster more closely together when using the ratio of characteristic moment impedances rather than the ratio of mass per unit areas. Subsequent numerical experiments by Poblet-Puig and Guigou-Carter [18] used the spectral element method to investigate junctions of solid masonry/concrete walls and floors which opened up the possibility of much faster and efficient calculations than traditional FEM. These numerical simulations also resulted in frequency-dependent K_{ij} as was observed with wave theory [6] for which average results were presented in the low-, mid- and high-frequency ranges.

The revision of ISO 15712 and EN12354 led by CEN TC126 WG2 (Chairman: Michel Villot) began in 2013, and at the meeting in 2014 the working group proposed that based on their recent research, the authors of the present paper should collaborate to use prediction models to produce new K_{ij} relationships for the informative annex. This gave the authors an opportunity to consider whether it might be advantageous to determine relationships between transmission loss (rather than K_{ij}) and the ratio of characteristic moment impedances, from which K_{ij} could subsequently be calculated. There was an additional impetus to introduce relationships for K_{ij} that were relevant to the low-frequency range (particularly below 100 Hz) because of recent changes to European and International Standards on field sound insulation measurement which introduced a new low-frequency procedure in order to allow more repeatable and reproducible measurements [19].

In this paper, numerical experiments with FEM, Spectral Finite Element Methods (SFEM) and wave theory were used to (a) optimise the choice of variables to determine K_{ij} where the prime candidate for the independent variable is the ratio of characteristic moment impedances, and (b) develop new relationships to determine K_{ij} for the low-, mid- and high frequency ranges. The focus was on solid, heavyweight walls and floors which were rigidly connected to form L-, T- and X-junctions (see Fig. 1). FEM and SFEM calculations were able to account for the finite size of typical walls and floors and captured modal features of K_{ij}, particularly in the low-frequency range. However, the FEM and SFEM results were specific to the damping that was assumed for the plates in the FEM or SFEM model [18]. Diffuse field wave theory was used to calculate the diffuse field transmission loss for junctions of semi-infinite plates and gives a generic result which is independent of wall and floor dimensions and damping. This approach not only applies to walls and floors with diffuse vibration fields, but it has been shown that it gives a reasonable estimate for the average of many junctions of heavyweight walls and floors with low mode counts and low modal overlap [20]. The final stage was to assess the implications of using the new K_{ij} relationships when estimating the sound insulation by inserting them in the prediction model in the European and International Standards.

2. Methodology

Numerical experiments were used with FEM, SFEM and wave theory to determine the vibration reduction index which is defined as [2,3]

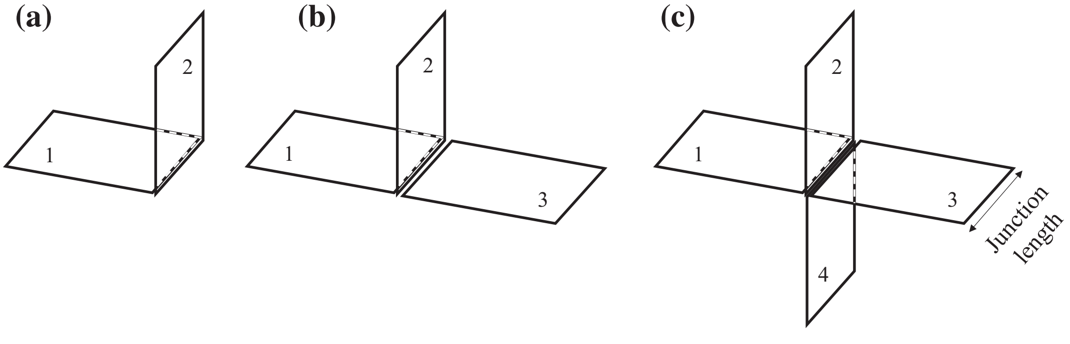

Fig. 1. Junction types: (a) L-junction, (b) T-junction and (c) X-junction.