Journal of Sound and Vibration 341 (2015) 138–161

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Analysis of bending wave transmission using beam tracing with advanced statistical energy analysis for periodic box-like structures affected by spatial filtering

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A R T I C L E I N F O

Article history:
Received 12 April 2014
Received in revised form
3 November 2014
Accepted 20 December 2014
Handling Editor: D. Juve
Available online 14 January 2015

A B S T R A C T

For bending wave transmission across periodic box-like arrangements of plates, the effects of spatial filtering can be significant and this needs to be considered in the choice of prediction model. This paper investigates the errors that can occur with Statistical Energy Analysis (SEA) and the potential of using Advanced SEA (ASEA) to improve predictions. The focus is on the low- and mid-frequency range where plates only support local modes with low mode counts and the in situ modal overlap is relatively high. To increase the computational efficiency when using ASEA on large systems, a beam tracing method is introduced which groups together all rays with the same heading into a single beam. Based on a diffuse field on the source plate, numerical experiments are used to determine the angular distribution of incident power on receiver plate edges on linear and cuboid box-like structures. These show that on receiver plates which do not share a boundary with the source plate, the angular distribution on the receiver plate boundaries differs significantly from a diffuse field. SEA and ASEA predictions are assessed through comparison with finite element models. With rain-on-the-roof excitation on the source plate, the results show that compared to SEA, ASEA provides significantly better estimates of the receiver plate energy, but only where there are at least one or two bending modes in each one-third octave band. Whilst ASEA provides better accuracy than SEA, discrepancies still exist which become more apparent when the direct propagation path crosses more than three nominally identical structural junctions.

1. Introduction

Many engineering structures are regular in form, with repeating cellular units across which it is necessary to be able to predict bending wave transmission. For some periodic structures the bending wavelength of interest is much larger than the structural dimension between adjacent units. However, there is also a class of engineering problems where all the constituent structural elements that form the cellular unit, such as beams or plates, support local bending modes of vibration. In these situations it is usually assumed that the vibration field on the source subsystem approximates a diffuse field when the response to broadband excitation is multimodal in frequency bands. Under this assumption, Statistical Energy Analysis (SEA) is often used to predict structure-borne sound transmission [1]. However, even when there is an

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http://dx.doi.org/10.1016/j.jsv.2014.12.029

approximation to a diffuse field on the source subsystem, successive structural junctions between cellular units will filter the range of wave angles that are transmitted, leading to non-diffuse fields on the subsystems that form more distant cellular units.

To account for spatial filtering and the existence of non-diffuse vibration fields, Langley [2,3] proposed an alternative to SEA for the prediction of high-frequency vibration, Wave Intensity Analysis (WIA). A finite Fourier series was used to represent the directional dependency of the wave intensity. The application of power balance at the junction between plates leads to a set of simultaneous equations which can be solved to give the plate energy levels. Heron [4] proposed an alternative approach using ray tracing, which was referred to as Advanced Statistical Energy Analysis (ASEA). This was primarily developed to allow the inclusion of tunnelling mechanisms between indirectly-connected subsystems but as with WIA it also accounts for spatial filtering, non-diffuse vibration fields and propagation losses. Note that ASEA and WIA both converge on the same result. Heron noted that implementation of ASEA for coupled plates "could well turn out to be computationally expensive" compared with classical SEA (i.e. using wave theory to calculate the coupling loss factors) due to the ray tracing requirement. For this reason an alternative approach, referred to as 'beam tracing' is introduced in this paper to reduce computation times. The structures used for validation were a linear chain of rods with ASEA [4] and linear chains of plates with WIA [2,3]. These were essentially waveguides that were not representative of typical automotive, aeronautic, marine or building structures. Engineering constructions that are used for noise control tend to be formed from coupled plates where all or most plate edges are coupled to other plates to form open or closed box-like structures. Hence this paper focuses on systems consisting of a large number of plates in a box-like arrangement.

For coupled plate structures, Bercin [5] compared WIA and SEA against an exact approach based on dynamic stiffness to assess the importance of in-plane wave generation at junctions. It was noted that the structures were limited to those where two opposite plate edges were simply supported because of the requirements of the dynamic stiffness technique. However, the results confirmed that WIA gave better agreement with exact results from the dynamic stiffness technique than SEA, particularly with a linear chain of 15 coupled plates.

ASEA was used by Yin and Hopkins [6] to investigate tunnelling on an L-junction comprising a periodic ribbed plate with symmetric ribs and an isotropic homogeneous plate. Indirect coupling was significant at high frequencies where bays on the ribbed plate can be treated as individual subsystems. With excitation of the isotropic homogeneous plate, classical SEA gave significant underestimates in the energy of the bays due to the absence of tunnelling mechanisms. In contrast, ASEA gave close agreement with Finite Element Methods (FEM) and laboratory measurements. The errors incurred with SEA rapidly increased as the bays become more distant from the source subsystem. ASEA provided significantly more accurate predictions by accounting for the spatial filtering that led to non-diffuse vibration fields on more distant bays.

This paper investigates the effect of spatial filtering with periodic box-like structures formed from plates to demonstrate the errors that can occur when using SEA and assesses the potential of using ASEA to improve predictions. The focus is on the low- and mid-frequency range where (a) the plates support bending modes without any in-plane wave generation at the junctions, (b) low mode counts can cause problems with the application of SEA [7,8] and (c) the in situ modal overlap is relatively high due to the plates that form the boxes being coupled to several other plates. Previous comparisons of SEA with measurements on box-like structures have tended to show reasonable agreement [9,10] but conclusions cannot always be drawn due to the confounding effects of non-diffuse in-plane wave fields as well as unquantifiable variation in plate properties and junction properties [9], or relatively complex junctions with sufficient uncertainty in the damping that it was not possible to definitively validate the model [10]. To overcome this issue, this paper uses FEM models which have previously been validated against measurements on heavyweight walls and floors [11]. This avoids ambiguity about the internal damping and the coupling condition at the junction as these are prescribed in the FEM model.

2. Periodic box-like structures

2.1. Example structures for the FEM, SEA and ASEA models

Two periodic box-like structures are considered for the numerical experiments in linear and cuboid formats as shown in Fig. 1. These structures represent buildings where the room volumes are 33.6 m^3. To assess the implications of spatial filtering for the modelling of sound transmission in buildings, all the plates that form these two structures represent heavyweight walls and floors. Similar types of repeating box-like structure has previously been used to assess aspects of structure-borne sound transmission in multi-occupancy types of residential accommodation [12,13]. Based on previous work [14], the absence of apertures (i.e. windows and doors) that would occur in a real building is assumed to make negligible difference for small apertures that are distant from the junction lines. Table 1 contains the plate dimensions and the material properties for the masonry walls and concrete floors that were taken from previous measurements [15]. All analysis is carried out between 50 Hz and 1 kHz.

The FEM, SEA and ASEA models exclude radiation coupling, i.e. the plates are in vacuo. For this reason, the rooms are not included as subsystems in the SEA and ASEA models and the resulting models for the linear and cuboid box-like structures have 26 and 36 plate subsystems respectively.