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A modal-spectral model for flanking transmissions

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ABSTRACT

A model for the prediction of direct and indirect (flanking) sound transmissions is presented. It can be applied to geometries with extrusion symmetry. The structures are modelled with spectral finite elements. The acoustic domains are described by means of a modal expansion of the pressure field and must be cuboid-shaped. These reasonable simplifications in the geometry allow the use of more efficient numerical methods. Consequently the coupled vibroacoustic problem in structures such as junctions is efficiently solved. The vibration reduction index of T-junctions with acoustic excitation and with point force excitation is compared. The differences due to the excitation type obey quite general trends that could be taken into account by prediction formulas. However, they are smaller than other uncertainties not considered in practice. The model is also used to check if the sound transmissions of a fully vibroacoustic problem involving several flanking paths can be reproduced by superposition of independent paths. There exist some differences caused by the interaction between paths, which are more important at low frequencies.

1. Introduction

Predictions of the direct and indirect (flanking) sound transmission are important in order to make proper acoustic designs of buildings, ships or train wagons. But the simulations done by means of the finite element method (FEM), the boundary element method (BEM) or other deterministic techniques based on space discretisation are often time consuming and computationally expensive due to several reasons: the need to cover a wide frequency range of audible noise, the mandatory use of smaller elements when frequency increases, the large dimensions of the physical domains to be considered or the big number of situations to be analysed in order to understand the problem and provide practical design rules.

This is especially critical in the field of building acoustics where numerical simulations are often restricted to the low-frequency range and/or two-dimensional problems. Very often the interest is focused to describe the behaviour of a single component (*i.e.* sound transmission through a single wall, vibration response of a junction). However, the problem of flanking transmission is global in the sense that it affects several acoustic domains and more or less complex and big structures. It causes computational requirements to be larger and quite often unaffordable.

The use of semi-analytical models or statistical techniques such as Statistical Energy Analysis (SEA) [1] whose hypotheses are valid only at high frequencies is very common in order to complement and cover the whole frequency range of interest. An important example is the global model proposed in the EN-12354 [2]. It accounts for all transmission

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types (direct and flanking) and it is based on a first-order SEA formulation [3,4]. The main input required by the model in order to deal with flanking transmissions is the vibration reduction index. Recent researches try to provide practical design data by studying the structural junctions in the laboratory [5,6], by means of finite element models [7], using wave approach [8], or wave-based or spectral finite elements (SFEM) [9–11]. All of them are restricted to the study of vibration transmissions through the junction.

In the present work, a model is formulated and implemented in a computer software in order to complement these simulations but including now the acoustic part of the problem (*i.e.* rooms that are separated by the junction). The starting point is the model developed in [9]. The vibroacoustic problem to be analysed is restricted to geometries with extrusion symmetry where the acoustic domains are cuboid-shaped. This allows the attainment of a computationally efficient formulation. It uses spectral finite elements [12–14] for the structure part and expand the pressure field in the acoustic domains in terms of the analytical expression of the eigenfunctions. All these keep the model general enough to deal with a great variety of junctions and structures. The results obtained are fully equivalent to a FEM simulation. So, they are valid for all frequencies and are not subjected to hypotheses of physical nature such as the ones required by SEA (they are only satisfied when the frequency is high enough in order to guarantee large modal density of each subsystem among other aspects). Since the model is oriented to reduce the computational costs of FEM or BEM for problems satisfying the restrictions mentioned above, a larger frequency range can be simulated. Moreover, an ensemble of situations can be considered as an attempt to reproduce the uncertainty and statistical nature of the physical phenomenon at mid-frequencies where the modal overlap starts to be important.

The contributions of the research are:

- Formulation, implementation and testing of a deterministic model accounting for extrusion symmetry vibroacoustic problems in a wide frequency range with smaller computation costs than other element-based methods
- Coupling of the SFEM for shells with the modal expansion of cuboid acoustic domains.
- Computation of the vibration reduction indices for heavy junctions with acoustic excitation (instead of mechanical or point forces).

Both components of the model presented here: the use of modal analysis to describe the pressure field in acoustic cavities or rooms and the derivation of spectral or wave-based elements are not new. However, to the best of the author's knowledge a model combining these techniques and its application to the problem of flanking transmissions has not been presented before.

Analytical modal expansion of the pressure field in cavities is a good option when: (i) the shape of the domains to be studied is simple but the dimensions large; (ii) the computational costs must be optimised at maximum; (iii) it is important to cover a wide frequency range to gain knowledge on the physics of the problem and (iv) the coupling is weak enough in order to consider the *in vacuo* modes of each sub-domain of the problem. This technique, recently reviewed in [15], has been considered in the study of a cuboid-shaped cavity coupled with a rectangular plate [16–18], the sound transmission between cuboid-shaped rooms separated by a single wall [19–27], a double wall [28,29], cavities of double walls [30], slits and holes [31] or the transmissions between continuous plates coupled to rooms [32]. Other models combine a modal description in one plane with a description in function of plane waves propagating in positive and negative direction normal to the modal plane which helps in order to impose the continuity of normal velocity. See for example [33] with an application to the sound transmission through cross sections that can be composed of an aperture and flexible structures, [23,34,35] for sound transmission problems, or [36] where in a problem of the sound transmission through a single wall, the direction orthogonal to the wall is infinite.

The most common option is to consider normal modes (case of rigid walls or null normal velocity in all the boundaries), see the general theory in [37]. Their analytical expression is simple, they have interesting orthogonality properties and provide good approximation when the absorption or damping is not very high. This is the option chosen here. However, other options better adapted to satisfy the absorbing (Robin) boundary conditions [38] or the pressure field around a point source [39] exist.

The dynamic stiffness methods and the SFEM are also a good option to deal with the study of structural vibration in a wide frequency range. They have been used, among others, to predict the vibration behaviour of structures composed of panels [40]. Most of these methods require the assumption of some geometry simplification. But recent formulations try to extend their use to more general structures, for example composed of rectangular plates [41–43].

The manuscript is organised as follows. The model is presented in Section 2. The interest is focused on the way how the SFEM and the modal expansion of the acoustic domains are coupled. The numerical examples are shown in Section 3, including a comparison with the finite strip method (FSM) and the parametric analysis of the T-shaped junction. The discussion of the results and possible future improvements is done in Section 4 and the paper is finished with the conclusions of Section 5.