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Wave modelling in predictive vibro-acoustics: Applications to rail vehicles and aircraft

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HIGHLIGHTS

- We show significance and potential of wave modelling for industrial problems.
- Three methods are presented based on their applicability to industrial structures.
- Combinations of FE and wave models are shown to be numerically very effective.
- Calculation potential is illustrated using industrially relevant examples.

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ABSTRACT

Three different predictive methods based on wave descriptions of the acoustic field are presented and used to calculate transmission and radiation properties of typical rail and aerospace structures. First, a transfer matrix method assesses the sound transmission and wavenumbers of composite sandwich fuselage structures in a wide frequency range. The method is computationally effective and can be used for numerical optimization of sandwich lay-ups common in rail and aerospace engineering. Further, an approach for which a small finite element model of a periodic cell is applied to create a statistical model of a near periodic structure is shown to determine transmission and radiation properties of stiffened fuselage structures and an extruded train floor structure. Finally, a novel combination of the waveguide FE method with the Rayleigh–Ritz method is applied to: (i) calculate the transmission through a double wall structure; (ii) again assess the sound transmission of an extruded floor structure and also (iii) determine the sound pressure inside a large section of a rail car excited by external sound sources. All three methods presented can be used to effectively support decision making in the design process of trains and aircraft.

1. Introduction

1.1. Industrial need for prediction tools

As the pace of product development is increasing, the need for validated prediction tools becomes gradually more pronounced. Such tools should be able to assist in finding design solutions that meet specifications without adding cost and

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weight more than necessary. The principal application is to support decision-making in the engineering process, preferably in its early stages when the design still can be influenced without major cost and project time losses. For this reason, the model that the tool is based on should be able to correctly resolve the effects of design alterations that have an impact on acoustic transmission, including dedicated noise control treatments such as introduction of damping layers and stiffness alterations. In addition, models can be used to explain physical phenomena.

Industrial acoustic predictions have come a long way in the last decade. More powerful computers together with enhanced numerical algorithms and methodologies have much advanced what is possible to calculate in terms of, e.g., sound transmission through structures and associated radiation properties. Traditionally, methods applied in industry are based on either Statistical Energy Analysis (SEA) [1] or Finite Elements (FE) [2], sometimes combined with Boundary Elements (BE) [3]. For large structures at audio frequencies, however, the fluid–structure FE–BE models become numerically expensive, if at all feasible. The SEA methodology is suitable for vibro-acoustic analysis of large structures, like those of aircraft and trains, and successful predictions of interior aircraft and railway noise are reported in Refs. [4–6]. These applications, however, mainly consider transmission *through* the structures (i.e. air-borne transmission) whereas transmission *along the* structures (i.e. structure-borne transmission) is not straightforward using standard SEA. Such transmission analysis typically requires more advanced methodology, for example coupled FE–SEA [7,8], using FE modelling of sub-structures with a low modal density or on which structural loads are acting.

1.2. Wave based modelling techniques in predictive acoustics

Methods based on wave analysis are useful when at least one dimension of the investigated structure is large compared to the wavelength; for a car this would be in the mid-audio frequency range while for aircraft and trains it is the case for all but the lowest frequency bands of interest. Wave methods in vibro-acoustics naturally divide into methods for calculating waves in complex structures, e.g. [9–16] and methods for forced response calculations based on wave functions. Wave models may explain fluid–structure and structure–structure couplings over interfaces; they support qualitative assessment and may be the basis for design guidelines. In many ways they add to the understanding of how and why a structure behaves like it does, much like vibration modes for smaller structures at lower frequencies.

Methods for forced response calculations based on wave solutions in one-axial systems are rather straightforward and have been available for a long time [17–19]. The extension to two and three dimensional problems can be based upon exact or approximate expressions for the waves that travel within sub-structures and conditions at interfaces and boundaries. The BEM falls within this class of methods that also could be based on, e.g., Trefftz methods [20], eikonal approximations [21] and variational formulations [22,23].

For problems that are separable in space, additional strategies for the extension are available, e.g., (A) direct solution of a combination of Fourier methods and FE methods [24]; (B), FE discretization in two dimensions and postulating harmonic motion along a third dimension [25,26]; (C) FE discretization in two dimensions provides one-dimensional differential equations that have exponential (near field or harmonic) solutions and are useful for intermediate manipulations [27]; (D) FE discretization of a cell in a periodic structure and an assumption of harmonic phase lag between cells provides "wave solutions" [16,28]. A homogeneous structure divided into equal cells is in this perspective periodic [13,14].

The present work aims at displaying how wave based modelling can support development of industrial products, like trains and aircraft. For these products the size of the structures, together with the need for full audio frequency range predictions, limits the use of standard 3D discretization schemes as applied in FE based procedures. In addition, the structural layout typical of both aircraft fuselage and train car-bodies, together with the shift from stiffened metallic structures to multifunctional multi-material panel design in, e.g. sandwich materials, makes wave based modelling techniques attractive. This trend is further enhanced by that these "new" materials and structures often have frequency dependent elastic and damping properties that vary within the structures, which makes conventional FE based modal procedures less efficient, while the cost for direct methods is not much increased.

Out of the fairly large number of wave based modelling concepts discussed above, only a few have to date matured to such a level that they are used for industrial predictions. Apart from the capabilities of a method to accurately predict parameters of interest, typically sound transmission and radiation parameters, the flexibility to address various materials and structural configurations is of key importance. In this context it is essential that a method can predict effects of design changes critical for the acoustic performance.

1.3. Outline of the present work

Based on the authors experience using acoustic predictions to support the design of industrial products combined with a broad knowledge of wave based methods available, three different methods are chosen and discussed in view of their prediction capability for aircraft and rail structures. Two of them, the transfer matrix method [29,30] and the periodic cell method [7,16] are fairly mature and currently used in industrial practice. The third is in development and should be viewed as a research method, but is judged to have high potential regarding computational efficiency. In Section 2 the modelling concepts applied in the three methods are summarized and in Section 3 their respective merits and limitations for analysis of structures typical of train and aircraft are illustrated by means of a few selected calculation examples. Finally, in Section 4 the