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Sound transmission loss properties of truss core extruded panels

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ABSTRACT

The car body structures of modern trains are often formed of extruded aluminium panels. Their acoustic properties, particularly the sound transmission loss, have an important influence on the interior acoustic environment. In order to study the acoustic performance of extruded panels, their Sound Transmission Loss (STL) is studied using the coupled Wavenumber Finite Element method (WFE) and Wavenumber Boundary Element method (WBE). The damping of a typical structure is first measured in the laboratory to give suitable input values for the model. The predicted STL is compared with corresponding measurements of the sample panel, with good agreement above 400 Hz. Based on the validated model, an extensive parametric study is carried out to investigate the effect of different reinforcement rib styles on the STL. The effect of using extruded panels with rectangular, triangular and trapezoidal truss-core sections is studied in detail. Among the parameters studied, the number of bays in a given width has a great influence on the sound insulation. Considering practical use, both the mass and stiffness of each case are also considered. To give increased understanding of the STL behaviour, the dispersion curves are also studied. It is found that structures with better STL usually have fewer free wavenumbers below the acoustic wavenumber. For the same number of structural bays, a panel with triangular stiffening has the highest strength but also the largest mass, whereas a structure with rectangular stiffening has the least strength and lowest mass. In the evaluation, the weighted STL R_w and the spectral adaptation term C_{tr} are considered. The results are also considered relative to a mass law adjustment of the STL. It is found that the three cases which give the best results are a triangular rib panel with 4 or 5 bays in a 1 m width, and a trapezium case with 5 bays and inclination angle 25°. These have an R_w that is 2–6 dB better than the reference panel, a smaller mass and a higher stiffness.

1. Introduction

With the increase of train speeds, interior noise has become an important issue to be resolved in the further development of high speed trains [1,2]. Most high-speed trains are constructed from truss core extruded aluminium panels as these provide high strength for a low weight. These panels play an important role in the transmission of noise to the vehicle interior through both airborne and structure-borne paths [3,4]. Their acoustic performance has been widely studied and is known to be relatively poor, giving higher sound transmission than a homogeneous panel of the same mass [5].

Due to the complexity of the rib-stiffened built-up panel structure, a number of different methods have been investigated for studying their acoustic performance [6]. Conventional finite element methods (FEM) can only be used at relatively low frequencies due to the short bending wavelengths in the face plates. Shaw [5] and Xie et al. [7] therefore estimated the sound transmission behaviour of extruded panels using statistical energy analysis (SEA). Besides the extruded panel, Orrenius [8] also used SEA to evaluate the STL of a train floor, including a floating floor assembly. SEA is also effective in predicting the interior noise of the whole railway vehicle at middle and high frequencies [9]. However, the SEA method has limitations at low frequencies where the modal density and mode count of the structures are low. To overcome these limitations, Langley & Bremner [10] introduced a hybrid FEM and SEA method, and Cotoni et al. [11] extended it to periodic structures with applications to the STL simulation of various panels. The periodic cell method is also an effective way to simulate the STL of large periodic or near periodic structures. Kohrs [12–14] used the periodic cell method to study the structure-borne noise and dispersion characteristics of extruded panels. Cotoni et al. [11] and Orrenius et al. [15]

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compared these various methods for determining the STL loss of extruded railway floor panels and stiffened aircraft fuselage structures. Wang et al. [16] calculated the STL of infinite panels with regular vertical stiffeners based on a wave method. Lu et al. [17] used a space-harmonic method to study the transmission loss of orthogonally rib-stiffened panels with regular vertical reinforcement as well as the sound transmission across sandwich structures with periodic corrugated cores.

The Wavenumber Finite Element and Wavenumber Boundary Element (WFE-WBE) method has also been used to calculate the sound insulation of extruded sections. The WFE method uses finite elements to simulate the finite-width structure in a two-dimensional (2D) cross-section and uses a wave method to simulate the infinite structure in the third direction. Therefore, this method can simulate both different boundary conditions and irregular stiffening forms in the 2D cross-section, and can also consider the response in the third direction assuming invariant geometry and a long length. The number of degrees of freedom and the calculation effort are much reduced compared with a fully 3D method. The sound radiation and transmission can be studied by coupling the WFE model with WBE. Prasetiyo [18] used this method to calculate the STL of a semi-infinite single panel, double panel and a structure with vertical stiffeners as used in lightweight building structures. Nilsson et al. [19] and Kim et al. [20] further considered irregularly reinforced structures, and established a model of the sound insulation of a section of train floor, which gave good agreement with measurements.

The reinforcement style of a ribbed panel is essential in the structural design of an extruded panel. On the basis of this WFE-WBE model [19–22], this paper aims to investigate the dependence of the sound insulation on the different types of rib style. The sound insulation properties are investigated of extruded panels with regular rectangular, triangular and trapezoidal stiffeners in various configurations. Before performing the parameter study, the damping of a sample of extruded aluminium panel was first measured, as discussed in Section 2. Following this, the WFE-WBE model is validated in Section 3 by comparing the calculated STL with measurements. The parameter study of the effect of different rib styles on the STL is presented in Section 4.

2. Measurement of damping loss factor

The damping loss factor of the structure is an input required by the model. To find practical values, the damping of an extruded panel is investigated experimentally. More details of the experimental methods are given in Appendix A.

The measurements have been performed on a sample of an extruded aluminium panel of a train floor structure with dimensions of 1.0 × 1.5 × 0.07 m. The cross-section is shown in Fig. 1. The specimen consists of two face plates and 18 rib plates. The thickness of the various plates has been measured as 2.54 ± 0.2 mm. One of the face plates additionally has a 4 mm thick rubber layer attached to it. The bare face plate (face plate 1) is divided into six main bays by the stiffening plates, while the face plate with the rubber layer (face plate 2) is divided into eight bays, as indicated in Fig. 1.

Results are obtained for each bay, as shown in Figs. 2 and 3 and for the two sides of the panel.

The damping loss factor of the bare face plate lies in the range 0.001–0.1, while that of the face plate with attached rubber layer lies between 0.01 and 1. In addition to the rubber layer, the proximity to the stiffeners has a great influence on the damping loss factor of each bay. Thus, for example, bays P1-3 and P1-4 have much lower loss factors than P1-2 and P1-5 even though they are all on the bare face plate P1. This illustrates that large variations are possible, although it would appear that this is related to the particular features of the panel under test. In particular there is a joint between the vertical stiffeners between P1-2 and P1-3 and between P1-4 and P1-5 which may be a source of additional damping. There is a small separation between the diagonal stiffener and the vertical one at the outer edge of P1-3 and P1-4 which appears to isolate them from the influence of the joint, leading to lower damping in these strips.

3. STL of extruded panel

Extruded panels used in train construction are complex built-up structures. A WFE-WBE model of the extruded panel is built and used to study the STL property of the panel through simulations. First, the WFE-WBE method is briefly introduced.

3.1. WFE-WBE theory

An example of a single panel, infinite in one direction (the x direction), is shown in Fig. 4. Using the WFE method, each plate element has four degrees of freedom (DOF) at each node. They are three displacements u, v, w, in the x, y, z directions respectively, and the rotation ϕ around the x axis [19–22].

For a structure excited by a force vector $\mathbf{F}$ at angular frequency ω, the equation of motion is:

$$\left[\mathbf{K}_4\frac{\partial^4}{\partial x^4} + \mathbf{K}_2\frac{\partial^2}{\partial x^2} + \mathbf{K}_1\frac{\partial}{\partial x} + \mathbf{K}_0 - \omega^2\mathbf{M}\right]\mathbf{W}(x) = \mathbf{F}(x) \tag{1}$$

where $\mathbf{K}_j$ (j = 0, 1, 2, 4) are stiffness matrices, $\mathbf{M}$ is the mass matrix and $\mathbf{W}$ is the displacement vector. Applying Fourier transforms with respect to x to both the displacement and force gives

$$\widetilde{\mathbf{W}}(\kappa) = \int_{-\infty}^{\infty}\mathbf{W}(x)e^{i\kappa x}dx \tag{2}$$

$$\widetilde{\mathbf{F}}(\kappa) = \int_{-\infty}^{\infty}\mathbf{F}(x)e^{i\kappa x}dx \tag{3}$$

where κ is the structural wavenumber in the x direction. Applying this to Eq. (1), the wavenumber finite element equation is obtained:

$$[(-i\kappa)^4\mathbf{K}_4 + (-i\kappa)^2\mathbf{K}_2 + (-i\kappa)\mathbf{K}_1 + \mathbf{K}_0 - \omega^2\mathbf{M}]\widetilde{\mathbf{W}}(\kappa) = \widetilde{\mathbf{F}}(\kappa) \tag{4}$$

which can also be written as:

$$[\mathbf{K}(\kappa) - \omega^2\mathbf{M}]\widetilde{\mathbf{W}}(\kappa) = \widetilde{\mathbf{F}}(\kappa) \tag{5}$$

with

$$\mathbf{K}(\kappa) = \sum_{j=0,1,2,4}\mathbf{K}_j(-i\kappa)^j \tag{6}$$

When coupled with the wavenumber boundary element equations this becomes:

$$\{\mathbf{K}(\kappa) - \omega^2\mathbf{M}\}\widetilde{\mathbf{W}}(\kappa) = \widetilde{\mathbf{F}}(\kappa) + i\omega\rho_0\mathbf{C}_1\widetilde{\mathbf{\Psi}} \tag{7}$$

$$\mathbf{H}\widetilde{\mathbf{\Psi}} - \mathbf{G}\frac{\partial\widetilde{\mathbf{\Psi}}}{\partial\mathbf{n}} = \frac{\widetilde{\mathbf{P}}_{in}}{i\omega} \tag{8}$$

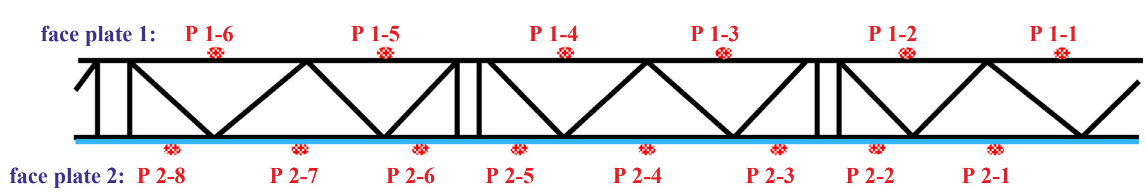

Fig. 1. Sectional view of point mobility measurement of each bay.