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Effects of external and gap mean flows on sound transmission through a double-wall sandwich panel

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ABSTRACT

This paper studies analytically the effects of an external mean flow and an internal gap mean flow on sound transmission through a double-wall sandwich panel lined with poroelastic materials. Biot's theory is employed to describe wave propagation in poroelastic materials, and the transfer matrix method with three types of boundary conditions is applied to solve the system simultaneously. The random incidence transmission loss in a diffuse field is calculated numerically, and the limiting angle of incidence due to total internal reflection is discussed in detail. The numerical predictions suggest that the sound insulation performance of such a double-wall panel is enhanced considerably by both external and gap mean flows particularly in the high-frequency range. Similar effects on transmission loss are observed for the two mean flows. It is shown that the effect of the gap mean flow depends on flow velocity, flow direction, gap depth and fluid properties and also that the fluid properties within the gap appear to influence the transmission loss more effectively than the gap flow. Despite the implementation difficulty in practice, an internal gap flow provides more design space for tuning the sound insulation performance of a double-wall sandwich panel and has great potential for active/passive noise control.

1. Introduction

The reduction of the noise transmitted into high-speed transportation vehicles such as aircraft, trains and even cars has been a long lasting issue in the past decades. The major sources of acoustic nuisance during long-haul flights are due to the noise from the engine exhaust situated a few metres away from the cabin and the turbulent boundary layer as a result of the external flow over the fuselage. Double-wall sandwich panels have been widely used for this application owing to the superior sound insulation performance over a wide frequency range compared to their single-wall counterparts. The problem of sound transmission through such a double-wall structure has been the object of many previous studies. For example, Bolton et al. [1] studied the sound insulation properties of double-panel structures lined with poroelastic materials using Biot's theory [2] to describe wave propagation in the porous medium. They developed a theoretical model to predict sound transmission through the double-panel structures in the absence of any flow and have validated the model experimentally.

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The effect of an exterior convective flow on sound transmission through a flat or curved wall, which is encountered in many practical applications, has also been well researched in previous literature. Tang et al. [3,4] considered an external mean flow in their model of sound transmission through an infinite cylindrical shell and two infinite concentric cylindrical sandwich shells, and have shown an improvement in transmission loss of these structures as the flow velocity increases. Koval [5] studied the sound insulation properties of an infinite single-wall panel and found that external flow, panel curvature and internal pressurisation have significant effects on the transmission loss of the system. Xin et al. [6] extended Koval's work [5] to a double-leaf aeroelastic panel, and Xin and Lu [7] modelled the sound transmission across a finite aeroelastic panel with mean flows on both sides; both studies recognised the significance of the limiting angle of incidence due to total reflection of sound waves on the panel. Xin and Lu [8,9] also studied the effects of mean flow on sound radiation and transmission of orthogonally rib-stiffened aeroelastic plates, and Meng et al. [10] studied the external mean flow effects for a double-leaf sandwich panel with porous absorptive materials. Zhou et al. [11,12] considered a mean flow on the external side of double-wall panels lined with poroelastic materials for flat and curved plates as well as cylindrical shells. Similar to the findings of Tang et al. [3,4], they have shown that the external flow increases the transmission loss of these structures with poroelastic linings. Zhou et al. [13] also reported a bi-objective optimisation study for the insulation performance of such double-wall panels in which they attempted to simultaneously minimise the weight while maximising the transmission loss of the system.

The study in this paper is motivated by the observations of enhanced sound transmission loss due to a mean flow in exterior fluid medium. An external mean flow experienced over a flat or curved panel is beneficial to the sound insulation properties. However, such a fluid flow is inherently uncontrollable as a result of the moving fluid relative to the panel external surface which always exists on the aircraft fuselage during a flight. It is therefore of interest to explore how a convective flow in between a double-wall sandwich panel would influence the sound insulation properties. If the sandwich core is separated from the facing plate by a gap, it is feasible to introduce a fluid flow into the interior of a double-wall sandwich panel. In most cases it is convenient to simply use air as the fluid medium within this gap, and hence the present work will focus on the case of an air gap. This internal gap flow may yield similar improvement in sound insulation as the external flow, and more importantly such a gap flow can be controlled through a range of parameters (i.e. velocity, direction, gap depth and fluid properties) and hence provides more options for tuning the sound insulation properties. Despite the implementation difficulty in practice, a double-wall sandwich panel equipped with an internal gap flow has the potential for the purpose of active/passive noise control. Furthermore, an internal air flow within a sandwich panel has practical implications for active cooling of sound insulation or absorption liners working in high temperature environment, for example those on jet engine nozzles.

Active/passive control of vibration and noise transmission has been studied by many researchers in the past. The passive insulation of sound transmission generally involves lining sound absorptive porous materials [1,10–16] or other sandwich cores (e.g. corrugated core [17,18], rib-stiffened core [19–21]) within a double-wall panel. These passive methods have been successful in reducing noise transmission to some extent but not very effective in the low-frequency range. Hence active control approaches were considered to overcome this drawback. Fuller [22] and Metcalf et al. [23] actively controlled the sound radiation from vibrating circular plates by oscillating forces applied directly to the structure. Sas et al. [24] used small loudspeakers inside the air gap of a double-panel system as active noise control sources. Their experimental results match the theoretical analysis and show an improvement in transmission loss. Pan and Bao [25] applied this principle to insulate the sound transmission into a room with a double wall by using two acoustic sources in the room and the air gap of the double wall. Clark and Frampton [26] designed a static, constant-gain compensator to improve the sound insulation properties of a panel subjected to a mean flow. Maury et al. [27,28] investigated theoretically and experimentally the active control of flow-induced noise transmitting across single and double panels.

The primary objectives of the present study, therefore, are to address the problem of sound transmission through a double-wall sandwich panel in the presence of both external and gap mean flows, and to explore the potential of the internal gap flow for controlling the sound insulation properties through various gap flow parameters. Moreover, the altered acoustic impedance of the fluid medium in the gap due to the convective gap flow causes additional total internal reflection which further complicates the description of the limiting incident angle of sound waves transmitting through the panel. Hence one of the main focuses of this paper is to determine the overall limiting angle of the system analytically (see Section 2.5). The remaining paper is organised as follows. In Section 2, a theoretical model of the problem is formulated on the basis of previous studies [1,2,11] that includes descriptions of the system, Biot's theory, boundary conditions and transfer matrix equation, random incidence transmission loss and limiting angles of incidence. The predicted results of transmission loss, comparison with previous predictions [1,11], effects of the external and gap flows, and a parametric study of gap flow properties are presented and discussed in Section 3. The conclusions and suggestions for further work are summarised in the last section.

2. Theoretical modelling

2.1. Description of the system

As illustrated in Fig. 1, the double-wall sandwich panel system consists of two parallel homogeneous thin plates lined with poroelastic materials. An air gap exists between the poroelastic layer and the facing plate. The lateral dimensions of the