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Sound transmission through triple-panel structures lined with poroelastic materials

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Abstract

In this paper, previous theories on the prediction of sound transmission loss for a double-panel structure lined with poroelastic materials are extended to address the problem of a triple-panel structure. Six typical configurations are considered for a triple-panel structure based on the method of coupling the porous layers to the facing panels which determines critically the sound insulation performance of the system. The transfer matrix method is employed to solve the system by applying appropriate types of boundary conditions for these configurations. The transmission loss of the triple-panel structures in a diffuse sound field is calculated as a function of frequency and compared with that of corresponding double-panel structures. Generally, the triple-panel structure with poroelastic linings has superior acoustic performance to the double-panel counterpart, remarkably in the mid-high frequency range and possibly at low frequencies, by selecting appropriate configurations in which those with two air gaps in the structure exhibit the best overall performance over the entire frequency range. The poroelastic

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lining significantly lowers the cut-on frequency above which the triple-panel structure exhibits remarkably higher transmission loss. Compared with a double-panel structure, the wider range of system parameters for a triple-panel structure due to the additional partition provides more design space for tuning the sound insulation performance. Despite the increased structural complexity, the triple-panel structure lined with poroelastic materials has the obvious advantages over its double-panel counterpart while without the penalties in weight and volume, and is hence recommended as a promising replacement for the widely used double-panel sandwich structure in order to optimise the sound transmission loss.

Keywords: Triple-panel structure, Sound transmission loss, Double-panel sandwich structure, Sound insulation performance, Poroelastic material, Biot's theory

1. Introduction

Double-panel sandwich structures lined with poroelastic materials are widely used for sound insulation purposes in a variety of engineering applications, e.g. automobile, aircraft, and construction industries, due to their superior performance over a wide frequency range and excellent mechanical properties (e.g. stiffness-to-weight ratio, vibration damping) compared with a single panel and other sandwich cores (e.g. air cavity [1–3], corrugated core [4, 5], rib-stiffened core [6–8]). The problem of sound transmission through such a lined panel structure has been studied extensively in literature. Most of these theoretical and experimental studies [9–11] have been restricted to normally incident sound

12 to double-panel structures of infinite lateral extent, though the random
13 incidence transmission loss was considered for double-panels without porous
14 linings [12, 13]. Bolton et al. [14] developed a theoretical model for the
15 prediction of sound transmission through laterally infinite double-panel
16 structures lined with poroelastic materials in a diffuse field. They adapted
17 Biot’s theory [15] in this model to describe wave propagation in two-phase
18 poroelastic media and have validated the model with experimental results.
19 A transfer matrix equation was derived by Bolton et al. [14] to efficiently
20 relate the incident waves to and transmitted waves from the multiple panel
21 system. Numerical studies were also conducted for this problem. For
22 example, Panneton and Atalla [16] and Sgard et al. [17] used finite element
23 method and boundary element method to calculate the normal and random
24 incidence transmission losses through finite double panels with porous linings,
25 respectively.

26 In order to maximise sound transmission loss while minimising total
27 structure mass, double-panel structures with multilayered linings have
28 been applied in many situations. The design of such multilayered panels
29 generally involves a multi-objective optimisation problem [18–20] with regard
30 to material selection, optimal layer thickness and sequencing, and the
31 application of the transfer matrix method to assist the acoustic analysis.
32 Lee et al. [19] used a topology optimisation method for sound transmission
33 through one-dimensional (i.e. normal incidence) multilayered acoustic foams.
34 They applied open surface conditions to the layer interfaces by assuming
35 insignificant difference between bonded and unbonded multilayers, which is
36 contradictory to the finding by other researchers that the coupling method

37 of a double-panel sandwich structure is critical to the sound insulation
38 properties [14, 21]. Tanneau et al. [18] employed a genetic algorithm to solve
39 the optimisation problem for multilayered panels including a combination of
40 solid, fluid, and porous components. However, their model did not consider
41 the case of thin elastic panels in bending [14, 22] whose vibration under the
42 excitation of the stresses exerted by adjacent layers certainly influences the
43 sound insulation of the entire system.

44 A simple multilayer structure can be obtained by adding an extra middle
45 panel between the two facing panels of a double-panel structure. The
46 resulting triple-panel structure has even better mechanical and thermal
47 insulation properties than its double-panel counterpart, and the introduction
48 of an additional partition that consists of panel, porous material and air
49 gap components provides more options for tuning the sound insulation
50 performance. Despite the increased structural complexity, the triple-panel
51 structure has the potential to be a promising substitute for the double-panel
52 structure widely used in practice as sound insulation devices. However,
53 surprisingly very little work has been reported on acoustic insulation
54 properties of this structure, compared with the research efforts into its
55 double-panel counterpart. The most likely reason is the so-called ‘triple
56 leaf effect’ observed for windows and walls that makes this structure
57 unpopular in construction industry. It is well known that a triple-glazing
58 window or a triple-leaf wall without sound absorbent linings exhibits inferior
59 low-frequency soundproof performance to its double-leaf counterpart with
60 the same total weight and total air gap depth [23]. This is because the
61 narrower air gaps and lighter panels in a triple-panel structure drive up the

62 fundamental resonance frequency of the system. Only above a very high
 63 cut-on frequency, $f_{co} = c/2d$ where c is the speed of sound and d is the total
 64 air gap depth, is it possible to achieve a noticeably higher transmission loss
 65 with a triple-panel wall [24, 25].

66 The experiments by Tadeu and Mateus [24] have shown that the triple
 67 glazing gains reasonable improvements over double glazing yet with penalties
 68 in mass and volume. Xin and Lu [26] developed an analytical model to
 69 predict sound transmission of a clamp mounted triple-panel partition and
 70 found that the soundproof performance of a triple-panel partition improves
 71 as panel dimensions decrease. This model was validated by the experimental
 72 results of Brekke [25] but did not consider the effect of poroelastic linings.
 73 Sharp [27] proposed an empirical model for the transmission loss of a
 74 triple-panel wall with absorption equivalent to at least 2 inches of fiberglass
 75 batts in each cavity, and Jones [28] suggested improvements to this model
 76 by correcting several errors in the original theory by Sharp [27]. Moreover,
 77 controversial results exist regarding the performance of a triple-panel wall
 78 below the fundamental resonance frequency f_m . Sharp [27, 29] reported the
 79 same transmission loss below f_m for both double- and triple-wall structures,
 80 whereas Quirt [30] measured a slightly larger transmission loss below f_m for
 81 a triple-glazing window as predicted by Brekke [25].

82 Sound absorbing porous linings will enhance the sound insulation
 83 properties of a multiple-panel structure. It is therefore of interest to explore
 84 how a triple-panel structure lined with poroelastic materials will improve in
 85 sound insulation properties over its double-panel counterpart, for instance
 86 higher transmission loss at lower frequencies. This problem has not been

87 addressed yet to the best of the author’s knowledge and will be a focus of the
88 present study. The prime objective of this paper is three-fold: (i) to extend
89 the theoretical model of Bolton et al. [14] to consider the case of a triple-panel
90 structure by modifying the boundary conditions and the transfer matrix; (ii)
91 to predict the transmission loss of various configurations of the triple-panel
92 structure and examine the sound insulation properties by comparing with the
93 double-panel counterparts; and (iii) to explore the options of sound insulation
94 control for the triple-panel structure through tuning some typical parameters
95 (e.g. thicknesses of porous layers and air gaps, air properties in the gaps)
96 and the potential advantages over the double-panel structure.

97 The remaining paper is organised as follows. In Section 2 the theoretical
98 framework for sound transmission through a triple-panel structure with
99 poroelastic linings is established on the basis of Bolton et al.’s model [14]
100 and Biot’s theory [15], including the boundary conditions, transfer matrix
101 method and random incidence transmission loss. The results of transmission
102 loss, effects of typical parameters for control, and comparison between the
103 double- and triple-panel structures are presented and discussed in Section 3.
104 The conclusions are summarised in the last section along with suggestions
105 for future work.

106 **2. Theoretical formulation**

107 *2.1. General description of the system*

108 The triple-panel structure considered in this study consists of three
109 parallel homogeneous thin panels, poroelastic material linings and air gaps
110 (if any) between the panels, as illustrated in Fig. 1. The layers of the panel,

Figure 1: Schematic of a plane wave transmitting through a triple-panel structure.

111 poroelastic material and air gap have finite thicknesses and are assumed to
 112 be infinite in lateral extent. The structure is situated in ambient air which
 113 is considered to be semi-infinite before the first panel and behind the third
 114 panel. A plane sound wave of unit amplitude is incident on the first panel
 115 and transmits through the system in a direction parallel with the x - y plane.
 116 Following Bolton et al. [14], the problem is formulated in a two-dimensional
 117 form and the velocity potential of the incident wave can be expressed in a
 118 harmonic form as

$$\phi_i = e^{j\omega t - j(k_x x + k_y y)}, \quad (1)$$

119 where the wavenumber $k = \omega/c$, ω is angular frequency, c is the ambient
 120 speed of sound, and the symbol $j = \sqrt{-1}$; the components of k are

$$k_x = k \sin \theta \quad \text{and} \quad k_y = k \cos \theta \quad (2)$$

121 with θ the angle of incidence. On the incident side of the system, the sound
 122 field consists of incident and reflected plane waves, and the velocity potential

123 is written as

$$\phi_1 = \phi_i + \phi_r = e^{j\omega t - jk_x x} (e^{-jk_y y} + R e^{jk_y y}), \quad (3)$$

124 where ϕ_r is the velocity potential of the reflected wave and R is the amplitude
 125 of ϕ_r . On the transmitted side, an anechoic termination allows only a single
 126 plane transmitted wave present, and similarly its velocity potential can be
 127 written as

$$\phi_t = T e^{j\omega t - j(k_x x + k_y y)}, \quad (4)$$

128 where T is the amplitude of ϕ_t and also the transmission coefficient.

The velocity potentials in the two air gaps between the panels are

$$\phi_2 = \phi_{2i} + \phi_{2r} = e^{j\omega t - jk_x x} (I_2 e^{-jk_{2y} y} + R_2 e^{jk_{2y} y}), \quad (5a)$$

$$\phi_3 = \phi_{3i} + \phi_{3r} = e^{j\omega t - jk_x x} (I_3 e^{-jk_{3y} y} + R_3 e^{jk_{3y} y}), \quad (5b)$$

129 respectively, where the coefficients I_2, R_2, I_3, R_3 are the amplitudes of the
 130 incident and reflected wave components within the two air gaps. The air
 131 properties in the two gaps, i.e. ρ_2, c_2, ρ_3, c_3 , can be different from those of
 132 the ambient air (ρ_0, c) , and so the wavenumbers in the air gaps are defined
 133 as $k_2 = \omega/c_2$ and $k_3 = \omega/c_3$. The y -components of k_2 and k_3 are

$$k_{2y} = k_2 \cos \theta_2 \quad \text{and} \quad k_{3y} = k_3 \cos \theta_3, \quad (6)$$

134 where θ_2 and θ_3 are the respective incidence angles of the waves transmitting
 135 in the two air gaps. According to the well-known Snell-Descartes law, the
 136 wavenumbers and incidence angles of waves m and n transmitting in two
 137 adjacent media are related through

$$k_m \sin \theta_m = k_n \sin \theta_n, \quad (7)$$

138 and hence all wave components in the different layers of the system must
 139 share the same trace wavenumber k_x [31].

140 Finally, the transverse displacements of the three panels excited by the
 141 incident sound wave can be expressed as [14]

$$w_{ti} = W_{ti} e^{j\omega t - jk_x x}, \quad i = 1, 2, 3 \quad (8)$$

142 where W_{ti} are the respective amplitudes of the three panels' transverse
 143 displacement. Similarly, the centre-line, in-plane displacements of the three
 144 panels are given by

$$w_{pi} = W_{pi} e^{j\omega t - jk_x x}, \quad i = 1, 2, 3 \quad (9)$$

145 with W_{pi} being the corresponding amplitudes of w_{pi} .

146 2.2. Biot's theory of waves in porous medium

147 The theory developed by Biot [15] to describe wave propagation in
 148 poroelastic materials is summarised in this section. A more detailed
 149 description of the model can be found in Refs. [14, 15, 21, 22]. According
 150 to Biot's theory, a poroelastic material is modelled as a coupled system
 151 consisting of a solid and a fluid phase with three waves transmitting in
 152 both phases: two longitudinal waves and a transverse wave. The governing
 153 equations for the propagation of the three waves are

$$\nabla^4 e + A_1 \nabla^2 e + A_2 e = 0, \quad (10)$$

154

$$\nabla^2 \boldsymbol{\omega} + k_r^2 \boldsymbol{\omega} = 0, \quad (11)$$

155 where $e = \nabla \cdot \mathbf{u}$ and $\boldsymbol{\omega} = \nabla \times \mathbf{u}$ denote the volumetric and rotational
 156 strains of the solid phase respectively, $\mathbf{u}$ being the displacement vector of the

157 solid phase. The volumetric and rotational strains of the fluid phase can be
 158 obtained via

$$\begin{aligned}\epsilon &= \nabla \cdot \mathbf{U} = \frac{(PR - Q^2)\nabla^2 e + \omega^2(\rho_{11}^* R - \rho_{12}^* Q)e}{\omega^2(\rho_{22}^* Q - \rho_{12}^* R)} \\ \boldsymbol{\Omega} &= \nabla \times \mathbf{U} = -\frac{\rho_{12}^*}{\rho_{22}^*} \boldsymbol{\omega}\end{aligned}\quad (12)$$

159 once the solutions of e and $\boldsymbol{\omega}$ are known, where $\mathbf{U}$ is the fluid displacement
 160 vector. Since Eq. (10) is a fourth-order wave equation, two solutions can
 161 exist, i.e. two dilatational wave types with the wavenumbers given by

$$k_{\text{I,II}}^2 = \left(A_1 \pm \sqrt{A_1^2 - 4A_2} \right) / 2. \quad (13)$$

162 The second-order wave equation (11) indicates the existence of only a single
 163 rotational wave with the wavenumber k_r given by

$$k_r^2 = (\omega^2 / N)(\rho_{11}^* - \rho_{12}^{*2} / \rho_{22}^*). \quad (14)$$

164 In the governing equation (10), the coefficients A_1 and A_2 are written as

$$\begin{aligned}A_1 &= \omega^2(\rho_{11}^* R' - 2\rho_{12}^* Q + \rho_{22}^* P) / (PR' - Q^2), \\ A_2 &= \omega^4(\rho_{11}^* \rho_{22}^* - \rho_{12}^{*2}) / (PR' - Q^2).\end{aligned}\quad (15)$$

165 In the above expression, $P = A + 2N$ with

$$A = \frac{\nu E_1}{(1 + \nu)(1 - 2\nu)}, \quad N = \frac{E_1}{2(1 + \nu)}, \quad (16)$$

166 where N denotes the elastic shear modulus and A the first Lamé constant;
 167 E_1 and ν are the Young's modulus and Poisson's ratio of the solid phase.
 168 E_1 is complex valued: $E_1 = E_m / (1 + j\eta)$, where E_m is the static Young's
 169 modulus and η is the loss factor. The coefficients Q and R' represent the

170 elastic coupling between the volume change of the solid phase and that of
 171 the interstitial fluid,

$$Q = (1 - h)E_2, \quad R' = hE_2, \quad (17)$$

172 where E_2 denotes the bulk modulus of the fluid in pores and h is the porosity
 173 of the porous material. In this model, the interstitial fluid is assumed to be air
 174 and it shares the same air properties (i.e. ρ_f, c_f) as those of the adjacent air
 175 gap (if any). Assuming cylindrical pores, E_2 is related to the bulk modulus
 176 of air as [14, 32, 33]

$$\begin{aligned} E_2 &= E_0 [1 + 2(\gamma - 1)/\lambda \cdot T_c(\lambda)]^{-1}, \\ T_c(\lambda) &= J_1(\lambda)/J_0(\lambda), \\ \lambda &= Pr^{1/2}\lambda_c\sqrt{-j}, \quad \lambda_c^2 = 8\omega\rho_f\epsilon'/h\sigma, \end{aligned} \quad (18)$$

177 where $E_0 = \rho_f c_f^2$, γ is the ratio of specific heats, J_i is the first-kind Bessel
 178 function of order i , Pr is the Prandtl number, ϵ' is the geometrical structure
 179 factor [34] and σ is the steady-state, macroscopic flow resistivity.

180 The complex equivalent densities in Eq. (15) are defined as

$$\begin{aligned} \rho_{11}^* &= \rho_{11} + b/j\omega, & \rho_{11} &= \rho_1 + \rho_a, \\ \rho_{12}^* &= \rho_{12} - b/j\omega, & \rho_{12} &= -\rho_a, \\ \rho_{22}^* &= \rho_{22} + b/j\omega, & \rho_{22} &= \rho_2 + \rho_a, \end{aligned} \quad (19)$$

181 where ρ_1 and $\rho_2 = \rho_f h$ are the bulk densities of the solid and fluid phases
 182 of porous materials, respectively; $\rho_a = \rho_2(\epsilon' - 1)$ is an inertial coupling
 183 parameter between the fluid and solid [22, 35], and ρ_{11}, ρ_{22} represent the
 184 effective densities of the solid and fluid phases [14], respectively. The

185 coefficient b is a viscous coupling factor expressed as [22, 35]

$$b = j\omega\epsilon'\rho_2(\rho_c^*/\rho_f - 1), \quad (20)$$

186 where the complex density

$$\rho_c^* = \rho_f [1 - 2/\lambda_c \sqrt{-j} \cdot T_c(\lambda_c \sqrt{-j})]^{-1} \quad (21)$$

187 for cylindrical pores [11, 32].

The solutions of $e, \boldsymbol{\omega}, \epsilon, \boldsymbol{\Omega}$ have been derived in previous studies [14, 22]. From these solutions the displacement components for the solid and fluid phases can be obtained as [14]

$$u_x = jk_x e^{j\omega t - jk_x x} \left(\frac{C_1}{k_I^2} e^{-jk_{Iy}y} + \frac{C_2}{k_I^2} e^{jk_{Iy}y} + \frac{C_3}{k_{II}^2} e^{-jk_{IIy}y} + \frac{C_4}{k_{II}^2} e^{jk_{IIy}y} \right) - j \frac{k_{ry}}{k_r^2} e^{j\omega t - jk_x x} (C_5 e^{-jk_{ry}y} - C_6 e^{jk_{ry}y}), \quad (22a)$$

$$u_y = j e^{j\omega t - jk_x x} \left(\frac{k_{Iy}}{k_I^2} C_1 e^{-jk_{Iy}y} - \frac{k_{Iy}}{k_I^2} C_2 e^{jk_{Iy}y} + \frac{k_{IIy}}{k_{II}^2} C_3 e^{-jk_{IIy}y} - \frac{k_{IIy}}{k_{II}^2} C_4 e^{jk_{IIy}y} \right) + j \frac{k_x}{k_r^2} e^{j\omega t - jk_x x} (C_5 e^{-jk_{ry}y} + C_6 e^{jk_{ry}y}), \quad (22b)$$

$$U_x = jk_x e^{j\omega t - jk_x x} \left(b_1 \frac{C_1}{k_I^2} e^{-jk_{Iy}y} + b_1 \frac{C_2}{k_I^2} e^{jk_{Iy}y} + b_2 \frac{C_3}{k_{II}^2} e^{-jk_{IIy}y} + b_2 \frac{C_4}{k_{II}^2} e^{jk_{IIy}y} \right) - jg \frac{k_{ry}}{k_r^2} e^{j\omega t - jk_x x} (C_5 e^{-jk_{ry}y} - C_6 e^{jk_{ry}y}), \quad (22c)$$

$$U_y = j e^{j\omega t - jk_x x} \left(b_1 \frac{k_{Iy}}{k_I^2} C_1 e^{-jk_{Iy}y} - b_1 \frac{k_{Iy}}{k_I^2} C_2 e^{jk_{Iy}y} + b_2 \frac{k_{IIy}}{k_{II}^2} C_3 e^{-jk_{IIy}y} - b_2 \frac{k_{IIy}}{k_{II}^2} C_4 e^{jk_{IIy}y} \right) + jg \frac{k_x}{k_r^2} e^{j\omega t - jk_x x} (C_5 e^{-jk_{ry}y} + C_6 e^{jk_{ry}y}), \quad (22d)$$

188 where

$$\begin{aligned} b_1 &= a_1 - a_2 k_I^2, & b_2 &= a_1 - a_2 k_{II}^2, \\ a_1 &= (\rho_{11}^* R' - \rho_{12}^* Q) / (\rho_{22}^* Q - \rho_{12}^* R'), \\ a_2 &= (P R' - Q^2) / [\omega^2 (\rho_{22}^* Q - \rho_{12}^* R')], \end{aligned} \quad (23)$$

189 and

$$k_{I,\Pi y}^2 = k_{I,\Pi}^2 - k_x^2, \quad g = -\rho_{12}^*/\rho_{22}^*. \quad (24)$$

190 The constants C_1 – C_6 represent the complex amplitudes of six wave
 191 components, i.e. positive- and negative-propagating components of the two
 192 longitudinal waves and one transverse wave, and will be determined by
 193 applying appropriate boundary conditions as discussed in Section 2.3.

194 The stresses in the two phases of poroelastic medium can be obtained from
 195 the solutions of e and ϵ . Here only the normal solid stress in the y -direction
 196 σ_y , the fluid stress s , and the solid shear stress in the x - y plane τ_{xy} are
 197 discussed which will be used in the boundary conditions. These stresses are
 198 determined through the relations:

$$\begin{aligned} \sigma_y &= 2Ne_y + Ae + Q\epsilon, \quad s = R'\epsilon + Qe, \\ \tau_{xy} &= \tau_{yx} = N(\partial u_x/\partial y + \partial u_y/\partial x), \end{aligned} \quad (25)$$

and their expressions are in the form [14]:

$$\begin{aligned} \sigma_y &= e^{j\omega t - jk_x x} \left[\left(2N \frac{k_{Iy}^2}{k_I^2} + A + b_1 Q \right) (C_1 e^{-jk_{Iy}y} + C_2 e^{jk_{Iy}y}) \right. \\ &\quad + \left(2N \frac{k_{\Pi y}^2}{k_{\Pi}^2} + A + b_2 Q \right) (C_3 e^{-jk_{\Pi y}y} + C_4 e^{jk_{\Pi y}y}) \\ &\quad \left. + 2N \frac{k_x k_{ry}}{k_r^2} (C_5 e^{-jk_{ry}y} - C_6 e^{jk_{ry}y}) \right], \end{aligned} \quad (26a)$$

$$\begin{aligned} s &= e^{j\omega t - jk_x x} \left[(Q + b_1 R') (C_1 e^{-jk_{Iy}y} + C_2 e^{jk_{Iy}y}) \right. \\ &\quad \left. + (Q + b_2 R') (C_3 e^{-jk_{\Pi y}y} + C_4 e^{jk_{\Pi y}y}) \right], \end{aligned} \quad (26b)$$

$$\begin{aligned} \tau_{xy} &= e^{j\omega t - jk_x x} N \left[\frac{2k_x k_{Iy}}{k_I^2} (C_1 e^{-jk_{Iy}y} - C_2 e^{jk_{Iy}y}) + \frac{2k_x k_{\Pi y}}{k_{\Pi}^2} (C_3 e^{-jk_{\Pi y}y} - C_4 e^{jk_{\Pi y}y}) \right. \\ &\quad \left. + \frac{k_x^2 - k_{ry}^2}{k_r^2} (C_5 e^{-jk_{ry}y} + C_6 e^{jk_{ry}y}) \right]. \end{aligned} \quad (26c)$$

Figure 2: The three configurations of a double-panel structure considered in Ref. [14].

Figure 3: Six typical configurations of a triple-panel structure considered in this study.

199 2.3. Triple-panel configurations and boundary conditions

200 Bolton et al. [14] considered two basic methods of coupling a porous layer
 201 to an elastic panel, i.e., 1) “bonded” (B): the porous layer is bonded directly
 202 to the facing panel, and 2) “unbonded” (U): the porous layer is separated
 203 from the panel by an air gap. Based on these two coupling methods,
 204 they studied three different cases, as shown in Fig. 2, for a double-panel
 205 structure: 1) a bonded-bonded (BB) configuration where the porous foam
 206 is bonded to the two panels on both sides, 2) a bonded-unbonded (BU)
 207 configuration where the porous foam is bonded to the first panel on one
 208 side whereas unbonded to the second panel on the other side, and 3) an
 209 unbonded-unbonded (UU) configuration where the porous foam is unbonded
 210 to the two panels on both sides.

211 In the case of a triple-panel structure, the introduction of an extra
 212 partition comprised of panel, porous material and air gap (where applicable)
 213 leads to the coupling of two porous layers and three panels and hence more
 214 configurations than its double-panel counterpart. Figure 3 illustrates six
 215 typical configurations for a triple-panel structure considered in this study
 216 which are denoted as BBBB, BBBU, BUBB, BUBU, BUUB and UBBU,
 217 respectively. According to the number of air gaps between the panel and
 218 porous layer (i.e. the number of U coupling methods), these different
 219 configurations can be divided into three categories, i.e.,

- 220 • **Category (i):** no air gap (BBBB),
- 221 • **Category (ii):** a single air gap (BBBU and BUBB),
- 222 • **Category (iii):** two air gaps (BUBU, BUUB and UBBU).

223 As will be shown in Section 3.3, the soundproof performance of a triple-panel
 224 configuration depends, to a great extent, on the number of air gaps existing
 225 in the structure and behaves distinctly across the three categories.

226 Appropriate boundary conditions (BC) are needed to determine the
 227 constants C_1 – C_6 in Eqs. (22) and (26). These constants of wave amplitudes in
 228 the porous material will be doubled (i.e. C_1 – C_{12}) for the case of a triple-panel
 229 configuration due to the extra porous layer. Bolton et al. [14] proposed three
 230 types of BC for a double-panel structure at the surfaces of a porous layer and
 231 a panel, which also apply to a triple-panel structure and will be introduced
 232 respectively. A fourth type of BC required for a triple-panel structure will
 233 also be defined. The first type of boundary conditions, BC (I), applies to the
 234 open surface of a porous layer and is related to any configurations that include
 235 an unbonded (U) coupling between the foam and panel (e.g. BU, BUBB,
 236 BUBU). The four conditions for BC (I) to be satisfied are, respectively:

$$\begin{aligned} & \text{(i) } -hp = s, \quad \text{(ii) } -(1-h)p = \sigma_y, \\ & \text{(iii) } v_y = (1-h)\frac{\partial u_y}{\partial t} + h\frac{\partial U_y}{\partial t}, \quad \text{(iv) } \tau_{xy} = 0, \end{aligned} \tag{27}$$

237 where p and v_y are the acoustic pressure and the normal component of the
 238 acoustic particle velocity in the exterior medium at the interface and can be
 239 simply obtained from the velocity potential ϕ of the sound waves propagating
 240 in the exterior medium, i.e.

$$p = \rho \frac{\partial \phi}{\partial t} = j\omega\rho\phi, \quad v_y = -\frac{\partial \phi}{\partial y}, \tag{28}$$

241 ρ being the density of the exterior fluid. The first two conditions relate the
 242 acoustic pressure in the exterior medium to the normal stresses acting on
 243 the fluid and solid phases of the poroelastic material, respectively. The

244 third condition is the continuity relation of normal velocity between the
 245 exterior and porous media. The last condition represents no shear stress
 246 at the interface because an inviscid exterior fluid is assumed.

247 The second type of boundary conditions, BC (II), applies to a panel
 248 bonded to poroelastic material on one side and open to the exterior medium
 249 on the other side, for example, both panels in BB, the first panel in BBBU,
 250 and the first two panels in BUBB and BUBU, as shown in Figs. 2 and 3. Six
 251 conditions must be satisfied for BC (II):

$$\begin{aligned}
 & \text{(i)} \ v_y = \frac{\partial w_t}{\partial t}, \quad \text{(ii)} \ u_y = w_t, \quad \text{(iii)} \ U_y = w_t, \\
 & \text{(iv)} \ u_x = w_p \mp \frac{h_p}{2} \frac{\partial w_t}{\partial x}, \\
 & \text{(v)} \ \pm \tau_{yx} = (D_p k_x^2 - \omega^2 m_s) w_p, \\
 & \text{(vi)} \ \pm p \mp q_p - j k_x \frac{h_p}{2} \tau_{xy} = (D k_x^4 - \omega^2 m_s) w_t,
 \end{aligned} \tag{29}$$

252 where h_p denotes the panel thickness, D and D_p the flexural and longitudinal
 253 stiffness per unit width of the panel respectively, m_s the panel mass per unit
 254 area, and $q_p = -\sigma_y - s$ the normal stress exerted by the poroelastic material
 255 on the panel. The first three conditions represent the continuity of normal
 256 velocity and normal displacement at the interface of the porous material
 257 and panel. The fourth condition equates the tangential displacement of the
 258 porous material's solid phase to the centre-line in-plane displacement of the
 259 panel vibrating in flexure [36]. The conditions (v) and (vi) represent the
 260 panel in-plane and transverse accelerations under the excitation of the shear
 261 and normal stresses, respectively, where Eq. (29vi) is the Euler-Bernoulli
 262 transverse panel equation with the distributed moment due to the in-plane
 263 shear force taken into account. In BC (II) (iv)–(vi), the first and second

signs are taken for the porous material attached to the panel on the positive and negative y -facing surfaces, respectively.

The third type of boundary conditions, BC (III), applies to a panel unbonded to a porous layer on both sides, for example, the two panels in UU, the last panel in BBBU and BUBU, and the middle panel in BUUB (see Figs. 2 and 3). Three boundary conditions should be satisfied for BC (III) at the centre line of the panel:

$$\begin{aligned} \text{(i)} \quad v_{1y} &= \frac{\partial w_t}{\partial t}, \quad \text{(ii)} \quad v_{2y} = \frac{\partial w_t}{\partial t}, \\ \text{(iii)} \quad p_1 - p_2 &= (Dk_x^4 - \omega^2 m_s) w_t, \end{aligned} \tag{30}$$

where $p_{1,2}$ and $v_{1,2y}$ are the acoustic pressures and normal acoustic particle velocities at the two surfaces of the panel.

For a triple-panel structure, the presence of a middle panel results in a fourth type of boundary conditions, BC (IV). This type of boundary conditions applies to a middle panel bonded to poroelastic materials on both sides, and is required for the configurations in Fig. 3 using the BB coupling at the middle panel, i.e. BBBB, BBBU and UBBU. Similar to BC (II), eight boundary conditions must be satisfied for BC (IV), i.e.

$$\begin{aligned} \text{(i)} \quad u_{y1} &= w_t, \quad \text{(ii)} \quad U_{y1} = w_t, \quad \text{(iii)} \quad u_{y2} = w_t, \quad \text{(iv)} \quad U_{y2} = w_t, \\ \text{(v)} \quad u_{x1} &= w_p + \frac{h_p}{2} \frac{\partial w_t}{\partial x}, \quad \text{(vi)} \quad u_{x2} = w_p - \frac{h_p}{2} \frac{\partial w_t}{\partial x}, \\ \text{(vii)} \quad \tau_{yx2} - \tau_{yx1} &= (D_p k_x^2 - \omega^2 m_s) w_p, \\ \text{(viii)} \quad q_{p1} - q_{p2} - jk_x \frac{h_p}{2} (\tau_{xy1} + \tau_{xy2}) &= (Dk_x^4 - \omega^2 m_s) w_t. \end{aligned} \tag{31}$$

The first four conditions simply require that the normal displacements of the solid and fluid phases of the two adjacent porous layers are equal to the panel

transverse displacement. The conditions (v) and (vi) are an application of Eq. (29iv) with the sign taken appropriately for the two porous layers bonded on both surfaces of the middle panel. The seventh condition is a variant of BC (II) (v) where the shear stress τ_{yx} is updated as a sum of the shear stresses exerted by the two adjacent porous layers. Similarly, the last condition is the variant Euler-Bernoulli transverse panel equation for the BB middle panel which includes the contributions of normal and shear stresses from both porous layers acting on the panel but ignores the acoustic pressure owing to the sealed surfaces of the middle panel without any air gap.

2.4. Transfer matrix equation and transmission loss

A transfer matrix equation can be derived by applying the appropriate types of boundary conditions BC (I)–(IV) for a specific configuration and rearranging the equations into a matrix form,

$$\mathbf{A}_n \mathbf{C}_n = \mathbf{B}_n, \quad (32)$$

where $\mathbf{A}_n$ is a $n \times n$ transfer coefficient matrix, $\mathbf{C}_n$ is a $n \times 1$ vector of unknown amplitudes, and $\mathbf{B}_n$ is a $n \times 1$ forcing vector. The i th row of the matrix equation (32) corresponds to the i th boundary condition, and n is the total number of equations. Substituting the various solutions for $u_x, u_y, U_x, U_y, \sigma_y, s, \tau_{xy}$ given in Eqs. (22) and (26) into BC (I)–(IV), the resulting transfer matrix equation includes the unknown complex wave amplitudes in the porous materials (C_1 – C_{12}), facing panels ($W_{t1,2,3}, W_{p1,2,3}$), and air gaps ($I_{2,3}, R_{2,3}$ where applicable) along with the reflected and transmitted wave amplitudes (R, T) that are needed for calculating the transmission loss of the system. The number of unknown amplitudes in

Table 1: The vector $\mathbf{C}$ of unknown wave amplitudes for the six typical configurations of a triple-panel structure.

Configuration	$\mathbf{C}_n^T$	n
BBBB	$[C_1-C_{12} \ W_{t1} \ W_{t2} \ W_{t3} \ W_{p1} \ W_{p2} \ W_{p3} \ R \ T]$	20
BBBU	$[C_1-C_{12} \ I_3 \ R_3 \ W_{t1} \ W_{t2} \ W_{t3} \ W_{p1} \ W_{p2} \ R \ T]$	21
BUBB	$[C_1-C_{12} \ I_2 \ R_2 \ W_{t1} \ W_{t2} \ W_{t3} \ W_{p1} \ W_{p2} \ W_{p3} \ R \ T]$	22
BUBU	$[C_1-C_{12} \ I_2 \ R_2 \ I_3 \ R_3 \ W_{t1} \ W_{t2} \ W_{t3} \ W_{p1} \ W_{p2} \ R \ T]$	23
BUUB	$[C_1-C_{12} \ I_2 \ R_2 \ I_3 \ R_3 \ W_{t1} \ W_{t2} \ W_{t3} \ W_{p1} \ W_{p3} \ R \ T]$	23
UBBU	$[C_1-C_{12} \ I_2 \ R_2 \ I_3 \ R_3 \ W_{t1} \ W_{t2} \ W_{t3} \ W_{p2} \ R \ T]$	22

the vector $\mathbf{C}_n$ depends on the particular configuration of the triple-panel structure. The forms of the unknown vector $\mathbf{C}$ are provided in Table 1 for the six typical triple-panel configurations shown in Fig. 3. An example solution for the BBBU configuration can be found in Appendix A which gives the elements of the transfer coefficient matrix $\mathbf{A}$ and the forcing vector $\mathbf{B}$.

By solving the matrix equation (32) for any specific frequencies, one obtains the solution for the complex wave amplitudes in $\mathbf{C}$ including the transmitted wave amplitude T . Since in a diffuse sound field random incident waves can be from all directions, the solution of T can be expressed as a function of frequency ω and incidence angle θ . The power transmission coefficient is defined simply as the square of the modulus of the pressure transmission coefficient, i.e. $\tau = |T|^2$ since the incident sound is of unit amplitude. In the case of a diffuse sound field, incident angles are assumed to be uniformly distributed over a range $[0, \theta_m]$, where θ_m is the maximum

angle above which no incidence sound exists. The average of the power transmission coefficient τ over all possible angles of incidence is then obtained by integrating over the range of incidence angle [31]:

$$\bar{\tau} = 2 \int_0^{\theta_m} \tau(\theta) \sin \theta \cos \theta \, d\theta. \quad (33)$$

The maximum incidence angle θ_m is an empirical parameter dependent on the experimental setup for measuring the transmission loss. Mulholland et al. [37] suggested the value of θ_m varying between 70° and 85° , and Bolton et al. [14] chose the value of 72° by matching their theoretical predictions to experimental results for an unlined single panel. This value of $\theta_m = 72^\circ$ is used in the present study to calculate the transmission loss for the triple-panel structures. The integral of Eq. (33) is evaluated numerically using Simpson's rule in steps of 2° , and finally the random incidence transmission loss in a diffuse field is calculated through

$$\text{TL} = 10 \log (1/\bar{\tau}) . \quad (34)$$

3. Results and discussion

3.1. Parameters of the system

To compare the performance of sound insulation between the double- and triple-panel structures, the double-panel parameters used in Ref. [14] are taken in this paper to calculate transmission loss for the triple-panel structures, unless stated otherwise. In the experiments of Bolton et al. [14], aluminium sheets were used for the two elastic panels and a polyurethane foam slab as the porous material layer. The parameters of the aluminium panels and the polyurethane porous material are given in Table 2. Moreover,

Table 2: Parameters used for the system [14].

Symbol	Description	Value
<i>Panel properties</i>		
ρ_p	material density	2700 kg m ⁻³
E_p	Young's modulus	7×10^{10} Pa
ν_p	Poisson's ratio	0.33
<i>Porous material properties</i>		
ρ_1	bulk density of solid phase	30 kg m ⁻³
E_m	bulk Young's modulus	8×10^5 Pa
ν	bulk Poisson's ratio	0.4
η	loss factor	0.265
σ	flow resistivity	25×10^3 MKS Rayls m ⁻¹
ϵ'	geometrical structure factor	7.8
h	porosity	0.9

the parameters relevant to the ambient air properties of standard atmosphere are: density $\rho_0 = 1.225$ kg m⁻³, ratio of specific heats $\gamma = 1.4$, Prandtl number $Pr = 0.71$, and speed of sound $c = 340.3$ m s⁻¹. The two air gaps will take the ambient air parameters initially unless in the parametric study of Section 3.5.

The dimensions of the triple-panel structures will be different from those of the double-panel structures tested by Bolton et al. [14]. For these double-panel structures, the thickness of the first panel on the incident side is $h_{p1} = 1.27$ mm, and the second panel on the transmitted side is

348 $h_{p2} = 0.76$ mm in thickness; the thickness of the polyurethane foam is
 349 $L = 27$ mm; the air gap of the BU configuration is $\delta = 14$ mm in depth, and
 350 the depths of the air gaps for the UU configuration are 2 mm and 6 mm on the
 351 incident and transmitted sides, respectively (see Fig. 2). For the triple-panel
 352 structures shown in Fig. 3, the thicknesses of the three panels are denoted
 353 by h_{p1} – h_{p3} , the two porous layers have thickness of L_1, L_2 , and the two air
 354 gaps are δ_1, δ_2 in depth, respectively. To ensure a fair comparison of sound
 355 insulation performance, the total mass per unit area and total thickness of
 356 a triple-panel structure must be kept the same as those of its double-panel
 357 counterpart. This is achieved by satisfying equal total thicknesses of panel,
 358 foam and air gap respectively, for the two structures, i.e.

$$\begin{aligned}
 {}^2h_{p1} + {}^2h_{p2} &= {}^3h_{p1} + {}^3h_{p2} + {}^3h_{p3}, \\
 L &= L_1 + L_2, \quad \delta = \delta_1 + \delta_2,
 \end{aligned} \tag{35}$$

359 where the left superscripts 2, 3 denote a double- or a triple-panel structure.
 360 Following the conditions (35), the dimensions of a triple-panel structure is
 361 simply taken as: panel thickness, $h_{p1} = h_{p3} = 0.76$ mm, $h_{p2} = 0.51$ mm; foam
 362 thickness, $L_1 = L_2 = L/2 = 13.5$ mm; air gap depth, $\delta_1 = \delta_2 = \delta/2 = 7$ mm.
 363 However for Category (ii) with only a single air gap, the depth remains the
 364 same as that of BU, i.e. $\delta = 14$ mm.

365 3.2. Model validation

366 Two test cases are considered in order to validate the theoretical model
 367 and the numerical code employed in this study. Firstly, the results of a
 368 triple-panel structure without porous lining in the case of normal sound
 369 incidence are compared with the model predictions of Xin and Lu [26], as

Figure 4: Comparison of transmission loss for a triple-panel structure without porous lining between current predictions and a previous model by Xin and Lu [26]. Panel and air gap dimensions are $\delta_1 = \delta_2 = 0.1$ m and $h_{p1} = h_{p2} = h_{p3} = 0.002$ m.

370 shown in Fig. 4. Two kinds of resonances were observed in their study, i.e.,
 371 the ‘mass-spring’ resonance and the standing-wave resonance. The resonance
 372 frequencies of the equivalent ‘mass-air-mass-air-mass’ system were derived
 373 as [26]:

$$f_{m1,2} = \frac{\sqrt{2}}{4\pi} \sqrt{\frac{\lambda_1 + \lambda_2 \mp \sqrt{(\lambda_1 - \lambda_2)^2 + 4\kappa_1\kappa_2m_{s1}^2m_{s3}^2}}{m_{s1}m_{s2}m_{s3}}}}, \quad (36)$$

374 where $\lambda_1 = \kappa_1m_{s3}(m_{s1} + m_{s2})$ and $\lambda_2 = \kappa_2m_{s1}(m_{s2} + m_{s3})$ are the
 375 equivalent stiffness of the two air gaps, respectively; $\kappa_{1,2} = \rho_0c^2/\delta_{1,2}$,
 376 and m_{si} ($i = 1, 2, 3$) are the mass per unit area of the three panels,
 377 respectively. The standing-wave resonance occurs when the air gap depth
 378 matches integer numbers of the half wavelength of the incident sound, and

the n -th standing-wave resonance frequency can be expressed as [38]:

$$f_{s,n} = \frac{nc}{2\delta}, \quad (n = 1, 2, 3, \dots) \quad (37)$$

where in this test case the depth is $\delta = 0.1$ m for both air gaps.

As illustrated in Fig. 4, the present predictions agree excellently with those by Xin and Lu [26] particularly the resonance frequencies, which validates the theoretical model of the present study. The mass-spring resonance frequencies calculated from the formula in Eq. (36) are 82 Hz and 142 Hz for f_{m1} and f_{m2} , respectively, and they are reproduced by both the present theory and the previous model in Ref. [26]. The standing-wave resonances occur at higher frequencies, i.e. $f_{s,n} = 1715, 3430, 5145, 6860$ Hz from Eq. (37) for $n = 1, 2, 3, 4$ respectively, which are also captured accurately by the model predictions.

Secondly, the predictions of Bolton et al. [14] for double-panel structures lined with poroelastic materials were reproduced for the three configurations BB, BU and UU. Figure 5 shows the predictions of the current study and Bolton et al. [14] as well as the experimental results in Ref. [14] for comparison. The excellent agreement between the three sets of results, in particular the prediction data, for all three configurations provides validation for the numerical code which will be applied to calculate the transmission loss for the triple-panel structures. The fundamental resonance frequency (i.e. mass-spring resonance frequency) of the classic problem of a double-panel structure without porous materials can be expressed as [12, 21]:

$$f_m = \frac{1}{2\pi} \sqrt{\frac{\rho_0 c^2}{\delta} \frac{m_{s1} + m_{s2}}{m_{s1} m_{s2}}} \quad (38)$$

Figure 5: Comparison of double-panel transmission loss between current predictions and the predicted and experimental results of Bolton et al. [14]. (a) BB, (b) BU, (c) UU.

under normal incidence of sound. The values of f_m for the BB, BU and UU configurations are calculated from Eq. (38) as 322 Hz, 262 Hz and 283 Hz, respectively. As shown in Fig. 5, despite the effects of porous lining and random incidence, the fundamental resonance frequencies of the BU and UU cases are consistent with the predicted values from Eq. (38), whereas the BB resonance frequency increases to about 1000 Hz due to the stiffening effect of the directly attached porous lining on both sides [14]. These resonance dips, however, are well damped due to the sound attenuation by the porous foam and the averaging effect in a diffuse sound field.

3.3. Comparison between double- and triple-panel structures

A focus of this paper is to examine how a triple-panel structure performs in sound insulation compared with its double-panel counterpart. As aforementioned in Section 1, a triple-panel structure without porous linings offers a marked improvement only above a high cut-on frequency, i.e. the triple leaf effect. Two special cases, called the AA and AAAA configurations, in which only air gaps exist between the panels (i.e. $\delta = 2\delta_1 = 2\delta_2 = 41$ mm) are hence considered to demonstrate this effect. The TL spectra of the two configurations are shown in Fig. 6 for comparison. The AA configuration retains the double-panel fundamental resonance frequency from Eq. (38) (i.e. $f_m = 262$ Hz). The mass-spring resonance frequencies of the AAAA configuration are calculated from Eq. (36) as $f_{m1} = 292$ Hz and $f_{m2} = 584$ Hz, respectively, and they are reproduced in the TL spectrum by the prediction model. However, the resonance dips are significantly damped due to random incidence effect in which the dip of f_{m2} nearly disappears.

As shown in Fig. 6, the transmission losses of AA and AAAA are almost

Figure 6: Transmission loss of a double- (AA) and a triple-panel (AAAA) structures without porous linings.

425 the same below f_m , consistent with the observation by Sharp [27, 29], and
 426 they follow approximately a mass-law behaviour based on the same total mass
 427 per unit area. However, because of the increased fundamental resonance
 428 frequency for AAAA, the double-panel configuration AA outperforms its
 429 triple-panel counterpart AAAA in most of the low-mid frequency range.
 430 From about 2000 Hz the transmission loss of AAAA starts to climb at a
 431 dramatic rate and it finally exceeds that of AA around 2500 Hz. In this case,
 432 the cut-on frequency is equal to the first standing-wave resonance frequency
 433 of AA, i.e. $f_{co} = f_{s,1}^2 = c/2\delta = 4146$ Hz from Eq. (37), and it is confirmed
 434 from Fig. 6 that above f_{co} the transmission loss of AAAA is noticeably higher
 435 than that of AA. In addition, the first standing-wave resonance frequency of

AAAA (second resonance frequency for AA), i.e. $f_{s,1}^3 = f_{s,2}^2 = 8293$ Hz from Eq. (37), is also well captured by the model in Fig. 6.

The results of predicted transmission loss for the six typical triple-panel configurations are shown in Fig. 7. It is obvious that the sound insulation performance of the triple-panel configurations depends critically on the foam-panel coupling method (B or U), or more specifically on the number of air gaps in the structure. Therefore the three categories of triple-panel configurations, as defined in Section 2.3, exhibit distinct TL behaviours throughout the entire frequency range. The configurations of Category (ii) (BBBU and BUBB) show only one mass-spring resonance frequency because the ‘BB’ bonding in one of the partitions reduces the structure to an equivalent ‘mass-air-mass’ system. This resonance frequency occurs around 300 Hz, not much different from the theoretical value of $f_m = 262$ Hz for a double-panel structure. The Category (iii) configurations (BUBU, BUUB and UBBU) retain the two mass-spring resonance frequencies with well-damped resonance dips, typical of a triple-panel structure lined with poroelastic materials, which are close to the theoretical predictions $f_{m1} = 292$ Hz and $f_{m2} = 584$ Hz. Moreover, the reduced thickness of the foam layer and air gap for these triple-panel configurations results in very large standing-wave resonance frequencies (the lowest one above the frequency bound of 10000 Hz), and hence these resonances will not be discussed hereafter.

With regard to the level of transmission loss, the BBBB case shows the highest transmission loss at low frequencies below 500 Hz, but its high-frequency performance of sound insulation is evidently inferior to other

Figure 7: Transmission loss of six typical triple-panel structures.

461 configurations. This is because the direct foam-panel bonding at each
 462 interface makes the structure behaves as an entire mass system which has the
 463 highest overall stiffness and hence the best performance in the low-frequency
 464 range. For the same reason, the BBBB configuration retains the increased
 465 fundamental resonance frequency of the BB configuration around 1000 Hz as
 466 shown in Fig. 5(c). The BBBB configuration is favourable to the transmission
 467 of frame waves but not airborne waves since the frame wave in the foam layer
 468 is the dominant wave in such a configuration [14].

469 On the other hand, Category (iii) of configurations BUBU, BUUB and
 470 UBBU shows very close transmission loss throughout the entire frequency
 471 range except in the low-frequency band $[f_{m1}, f_{m2}]$ where BUUB shows a slight
 472 improvement of about 3 dB and 6 dB over the other two cases. The similar

473 coupling methods of these configurations (i.e. two air gaps in the structure)
474 account for the slight difference in their sound insulation performance. The
475 relative higher transmission loss of BUUB within $[f_{m1}, f_{m2}]$ is owing to the
476 enhanced stiffness of the two facing panels and hence the entire structure. In
477 contrast to the BBBB configuration, Category (iii) shows poor low-frequency
478 performance: below f_{m2} its transmission loss is lower than that of BBBB by
479 up to 16 dB. The two air gaps separate the structure physically into three
480 detached elements, as shown in the bottom row of Fig. 3, which reduces the
481 overall stiffness of the system and hence the low-frequency TL.

482 However, the striking feature for this category of configurations is
483 the remarkably superior performance of sound insulation in the mid-high
484 frequency range. As can be seen in Fig. 7, above 700 Hz the transmission
485 loss of Category (iii) is distinctly higher than those of Categories (i) and (ii)
486 by up to 53 dB and 35 dB, respectively, and it displays a sharp 45 dB/octave
487 slope except for the troughs around 3500 Hz and 7700 Hz. The existence
488 of two narrow air gaps in Category (iii) configurations increases the number
489 of layers in the structure and as a result more wave reflections occur at the
490 layer interfaces, which ultimately enhances the attenuation of high-frequency
491 sound within the poroelastic materials. Moreover, the configurations BBBU
492 and BUBB in Category (ii) also show similar TL spectra which lie between
493 those of the other two categories in almost the entire frequency range.
494 Considering the sound insulation performance over the entire frequency
495 range, therefore, Category (iii) in particular BUUB may be the overall best
496 structure since this category provides the highest transmission loss in the
497 mid-high frequency range yet with an acceptable sacrifice of performance in

Figure 8: Comparison of transmission loss between typical double- and triple-panel structures.

the low-frequency range.

The next step is to compare the sound insulation properties of the double- and triple-panel structures lined with poroelastic materials. Figure 8 shows the transmission loss of the three double-panel configurations (BB, BU and UU) and three typical triple-panel configurations from Categories (i)–(iii), i.e. BBBB, BBBU and BUUB. The comparison is drawn between each triple-panel category and its double-panel counterpart, respectively. At low frequencies the BBBB configuration is still the most efficient structure which outperforms its double-panel counterpart BB in TL by about 3.5 dB below 600 Hz. Although both configurations, BBBB and BB, have the same mass per unit area, the extra middle panel of BBBB improves the

509 system stiffness and hence the low-frequency performance. The BBBB
 510 configuration also shows higher transmission loss than BB by up to 28 dB at
 511 frequencies above 2300 Hz which is almost halved compared with the cut-on
 512 frequency for the case of AAAA vs. AA. This is because the middle panel of
 513 BBBB induces extra reflected waves (and hence more absorption) within the
 514 porous material and the thin foam layers are favourable to high-frequency
 515 reflection. Note that the fundamental resonance frequency of BBBB is
 516 supposed to be increased by the stiffening effect but remains unchanged at
 517 1000 Hz because the dramatic climb of transmission loss at high frequencies
 518 apparently elevates the TL values in the neighbouring mid-frequency range.

519 Consider next the configurations BU and BBBU. The TL trends of the
 520 two configurations appear very similar. However, the fundamental resonance
 521 frequency of BBBU shifts upward to 310 Hz because the structure is
 522 reinforced somewhat by the extra middle panel, which results in a TL 7–12 dB
 523 lower than that of BU from the resonance frequency to 1000 Hz. The two
 524 configurations then take the lead in TL alternatively, and at high frequencies
 525 above 3300 Hz the configuration BBBU outperforms BU significantly due
 526 to the enhanced multiple wave reflections and the reduced size of the foam
 527 layers by the middle panel, as have been explained for the case of BBBB
 528 and BB. Finally, the UU configuration shows similar TL as BU [14], and the
 529 BUUB configuration still yields the best high-frequency performance; above
 530 900 Hz (22% of the cut-on frequency for AAAA and AA) the transmission
 531 loss of BUUB is higher than those of UU and BU by up to 44 dB.

532 To sum up, in general the sound transmission loss of a triple-panel
 533 configuration is higher than that of its double-panel counterpart in the

534 mid-high frequency range. The porous lining is capable of lowering the
 535 cut-on frequency where the triple-panel configurations noticeably outperform
 536 their double-panel counterparts and hence extends the applicability of
 537 a triple-panel structure to lower frequencies. The high-frequency TL
 538 of the triple-panel configurations are hence remarkably increased by the
 539 combination of the triple-panel structure and the porous lining. In addition, a
 540 triple-panel configuration can also outperform its double-panel counterpart
 541 at low frequencies, for example BBBB vs. BB and BBBU vs. BU. The
 542 different methods of attaching the porous lining to the panel (i.e. bonded
 543 or unbonded) yield a variety of triple-panel configurations. In practice,
 544 an appropriate configuration with the optimal overall performance can be
 545 selected according to the target frequency range of sound insulation, which
 546 is an obvious advantage of a triple-panel structure over a double-panel
 547 structure.

548 *3.4. Effect of foam and air gap thicknesses*

549 The effects of material parameters on the transmission loss of the
 550 double-panel structures have been presented in Ref. [14]. The parametric
 551 effects on a triple-panel structure will be similar to the double-panel results
 552 provided the porous materials are uniform in both layers. A simple example
 553 is the effect of foam thickness on the transmission loss of the double-
 554 and triple-panel configurations: BB, BU, BBBB and BUBU. For BB and
 555 BBBB, the total foam thickness L varies from 15 mm to 39 mm in step of
 556 4 mm and equal thickness is assumed for the two foam layers of BBBB, i.e.
 557 $L_1 = L_2 = L/2$. For BU and BUBU, the same variation of foam thickness
 558 is applied and the total thickness of the structure remains unchanged as

that in previous analysis (41 mm), i.e. the air gap depth is decreasing correspondingly as the foam thickness increases; equal air gap depth is assumed for BUBU, i.e. $\delta_1 = \delta_2 = \delta/2$.

Figures 9(a)–9(d) show the transmission loss of the four configurations with varying foam thickness (and air gap depth). As expected, the TL variation of a triple-panel structure appears similar to that of the double-panel counterpart. For the configurations BB and BBBB, the increasing foam thickness shifts the TL curves to lower frequencies because the fundamental resonance frequency is reduced due to the enlarged depth between the two facing panels. Hence as the foam thickness increases, the soundproof performance of BB and BBBB is improved at high frequencies but with a slight TL reduction in the low-frequency range of 400–1000 Hz. For the configurations BU and BUUB, however, the resonance frequency is nearly unaffected by the varying foam thickness since the total thickness of the structure is fixed as 41 mm. The increasing foam thickness (and decreasing air gap depth) also shifts the TL curves downward in frequency along with the reduced magnitude of the local peaks. This effect is more evident for the BUUB configuration. As shown in Figs. 9(b) and 9(d), the first peak of BU falls from 1600 Hz to 650 Hz by 18 dB when the foam thickness varies from 15 mm to 39 mm, whereas for BUUB the drop occurs from 3300 Hz to 1250 Hz by 30 dB. It is therefore more effective to tune the acoustic performance of a triple-panel structure by simply varying the ratio of foam thickness to air gap depth. Note that even when the total air gap is extremely thin, i.e. $\delta = 2$ mm, the configurations BU and BUUB still greatly outperform BB and BBBB at frequencies from about 400 Hz,

Figure 9: Transmission loss of the (a) BB, (b) BU, (c) BBBB and (d) BUUB configurations with varying foam thickness.

584 which emphasises the importance of the air gap to the sound insulation of
 585 a multiple-panel structure. Additionally, if there is no constraint on the
 586 total thickness of the structure, it is anticipated that a thicker structure will
 587 further improve the low-frequency soundproof performance.

588 An advantage of a triple-panel structure is that the foam and air
 589 properties in the two partitions can vary independently. For instance,
 590 assuming that $L_1 = 2L_2$ and $\delta_1 = 2\delta_2$ while keeping other relations (e.g.
 591 variations of L and δ) as in the previous case, the effect of foam thickness
 592 (and air gap depth) on the transmission loss of the BBBB and BUUB
 593 configurations is shown in Fig. 10. The results of BBBB are nearly unchanged
 594 compared to those in Fig. 9(c), which indicates that the position of the
 595 middle panel has minor effect on the soundproof performance of a triple-panel
 596 structure. The transmission loss of BUUB in Fig. 10(b) shows little variation
 597 to that in Fig. 9(d), neither, at low frequencies below 1000 Hz since the total
 598 foam thickness and total air gap depth are varying identically between the
 599 two figures. However, the non-uniform thicknesses of foam and air gap in the
 600 two partitions appear to attenuate significantly the local peaks (and troughs)
 601 observed in Fig. 9(d), resulting in much less oscillatory TL behaviours in the
 602 high-frequency range. Furthermore, alternative methods are also available to
 603 achieve various control effects according to the target of sound insulation; for
 604 example the foam thickness can increase in one partition whereas decrease in
 605 the other partition. Therefore, the extra partition of a triple-panel structure
 606 with air gaps provides more design space for tuning the sound insulation
 607 performance at high frequencies.

(a)

(b)

Figure 10: Transmission loss of the (a) BBBB and (b) BUUB configurations with different varying thicknesses of the two foam layers.

Table 3: The properties of air at various altitudes [39] to be applied in the air gaps.

Altitude (m)	Density (kg m^{-3})	Sound speed (m s^{-1})	Prandtl number
3000	0.909	328.6	0.715
6000	0.660	316.5	0.720
10000	0.414	299.5	0.729

608 3.5. Effect of air gap pressure

609 Apart from the thicknesses of the foam layers and air gaps, the porous
610 material parameters can be varied to adjust the transmission loss and the
611 results for the double-panel structures can be found in Ref. [14]. Compared
612 with the material parameters, altering the air properties and hence the
613 acoustic impedance in the air gaps (and within the interior of adjacent
614 porous layers) is relatively easy to implement in practice for the purpose
615 of active control. The mismatch of acoustic impedance between the air gap
616 and ambient air on the incident and transmitted sides has been observed
617 to increase the transmission loss [20, 40, 41]. In this section, the effect of
618 pressure in the air gaps is studied by considering air properties at different
619 altitudes as shown in Table 3, while the ambient air remains the standard
620 atmosphere at sea level. The triple-panel dimensions discussed in Section 3.1
621 are employed in the numerical calculation. Note that in this case all incident
622 waves will transmit through the air gaps because the decreased acoustic
623 impedance of the air gaps reduces the incidence angle according to the
624 Snell-Descartes law in Eq. (7).

625 Figures 11(a)–11(d) show the effect of air gap pressure on the transmission

Figure 11: Transmission loss of the (a) BU, (b) UU, (c) BBBU and (d) BUUB configurations with different air gap pressures.

626 loss of the double- and triple-panel configurations, i.e. BU, UU, BBBU
 627 and BUUB . The air properties at higher altitudes reduce the acoustic
 628 impedance and hence the fundamental resonance frequency. As a result of
 629 the mismatch of acoustic impedance, the TL curve for air properties at sea
 630 level is shifted downward to lower frequencies and the TL levels are elevated
 631 significantly from the resonance frequencies. As can be observed in Fig. 11,
 632 the effect of air gap pressure on the TL variations appears to be very similar
 633 among the configurations BU, UU and BBBU. It is obvious that the BUUB
 634 configuration benefits more from the impedance mismatch than the other
 635 three configurations, which is a merit of the triple-panel structure with two
 636 air gaps. As the pressure in the air gap decreases from sea level to an altitude
 637 of 10000 m, the TL level increases by about 5–17 dB for BU, 11–22 dB for
 638 UU, 5–20 dB for BBBU and 9–33 dB for BUUB, respectively. Moreover,
 639 the TL troughs observed for the air properties at sea level, characteristic
 640 of the BUUB configuration, are disappearing gradually with lower air gap
 641 pressures, which results in an even higher increase of transmission loss at
 642 these frequencies.

643 The two air gaps in the BUUB configuration also allow air with different
 644 properties existing in them, and similarly it is supposed to provide an
 645 additional option for the control of sound insulation. However, Fig. 11(d)
 646 shows that using different air properties at altitudes of 3000 m and 10000 m
 647 in the two air gaps does not gain extra benefits. Below 3000 Hz the TL
 648 of this case is very close to that of air properties at 3000 m and then it
 649 approximates the TL of air properties of 6000 m at very high frequencies. As
 650 aforementioned, the improvement of sound insulation performance depends

on the difference of acoustic impedance between the air gaps and ambient air. Compared with the case of uniform air properties of 10000 m in both air gaps, applying properties of air at 3000 m and 10000 m in the two air gaps separately diminishes the overall degree of impedance mismatch and hence the transmission loss falls off. In addition, the application of different air gap pressures further increases the system complexity and is therefore not recommended as an effective control method to implement in practice.

4. Conclusions

In this work, a theoretical model [14] to predict the transmission loss of a double-panel structure lined with poroelastic materials has been extended to the case of triple-panel structures. Biot's theory [15] has been applied in the model to describe wave propagations in poroelastic materials. The extended model has been validated by reproducing the predicted and measured transmission losses of the double-panel configurations in Ref. [14]. Based on the methods of mounting the foam layers to the panels, a triple-panel structure with an extra partition provides more configurations than its double-panel counterpart. Six typical triple-panel configurations were considered in this study and they can be divided into three categories according to the number of 'unbonded' coupling in the structure. It has been confirmed that the foam-panel coupling method, or more specifically the number of air gaps in a triple-panel structure, has a profound influence on the sound insulation performance. The configurations in Category (iii), i.e. BUBU, BUUB and UBBU, yield the optimal overall performance with the remarkably high transmission loss in the mid-high frequency range, whereas

675 the BBBB configuration shows better performance at low frequencies; the
676 transmission loss of Category (ii) with a single air gap falls between the
677 results of the other two categories.

678 Compared with a double-panel structure having the same total mass per
679 unit area and total thickness, a triple-panel structure generally exhibits better
680 soundproof performance in the high-frequency range and the porous lining
681 extends this advantage to significantly lower frequencies, which eliminates
682 the drawback of a triple-panel wall with a noticeable improvement in
683 TL only above a high cut-on frequency, i.e. the triple leaf effect. A
684 triple-panel structure can also outperform its double-panel counterpart in
685 the low-frequency range if the appropriate configurations are selected. The
686 variety of configurations provided by a triple-panel structure hence provides
687 more design space to meet a target frequency range of sound insulation in
688 practice, and there is always a triple-panel configuration superior to the
689 double-panel counterpart throughout the entire frequency range.

690 The properties of the foam layers and air gaps can be varied to tune the
691 sound insulation performance of a triple-panel structure. Varying the foam
692 and air gap thicknesses is observed to be more effective for a triple-panel
693 structure than for a double-panel structure. It has also been shown that air
694 properties of higher altitudes in the air gaps produce higher transmission
695 loss and a triple-panel structure is more sensitive to this effect than its
696 double-panel counterpart. The triple-panel structure also allows the foam
697 and air properties to vary independently in the two partitions, which provides
698 more control options for its soundproof performance. However, applying
699 different air properties in the two air gaps is not recommended as it reduces

700 the average impedance difference between the air gaps and ambient air
701 without additional benefit.

702 Although complexity is an inherent drawback, the triple-panel structure
703 with poroelastic linings has great potential to replace the double-panel
704 sandwich structure widely used in practice without the penalty in weight or
705 volume because this structure has superior performance of sound insulation,
706 particularly in the mid-high frequency range, and provides more space for
707 control purpose. It can be anticipated that better performance at higher
708 frequencies yet with a greater TL sacrifice in the low-frequency range can
709 be achieved through a multiple-panel structure with even more layers when
710 necessary. In this case, an optimisation study using a transfer matrix
711 method needs to be carried out to maximise the transmission loss within
712 the imposed constraints of weight and volume. The presence of external
713 mean flow and air gap flow has a profound influence on sound transmission
714 through a realistic multiple-panel structure and turns the system into a
715 three-dimensional problem, which will be addressed in future work.

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Figure A.1: Schematic of sound transmission through the BBBU configuration.

Appendix A. An example of the transfer matrix equation

The BBBU configuration is chosen as an example to demonstrate in detail the derivation of the matrix equation and the transfer coefficients using appropriate boundary conditions. This configuration requires all four types of boundary conditions discussed in Section 2.3, including BC (IV) which is characteristic of a triple- or multiple-panel structure. Figure A.1 illustrates schematically sound transmission through the BBBU configuration.

The different types of boundary conditions to be satisfied for the BBBU configuration are listed as follows.

BC (II) at $y = 0$:

$$\begin{aligned}
 (1) \quad v_{y1} &= -\frac{\partial \phi_1}{\partial y} = j\omega W_{t1}, & (2) \quad u_{y1} &= W_{t1}, & (3) \quad U_{y1} &= W_{t1}, \\
 (4) \quad u_{x1} &= W_{p1} - jk_x \frac{h_{p1}}{2} W_{t1}, & (5) \quad \tau_{yx1} &= (D_{p1}k_x^2 - \omega^2 m_{s1}) W_{p1}, \\
 (6) \quad p_1 + \sigma_{y1} + s_1 - jk_x \frac{h_{p1}}{2} \tau_{yx1} &= (D_1k_x^4 - \omega^2 m_{s1}) W_{t1}.
 \end{aligned} \tag{A.1}$$

733 BC (IV) at $y = L_1$:

$$\begin{aligned}
(7) \quad u_{y1} &= W_{t2}, \quad (8) \quad U_{y1} = W_{t2}, \quad (9) \quad u_{y2} = W_{t2}, \quad (10) \quad U_{y2} = W_{t2}, \\
(11) \quad u_{x1} &= W_{p2} + jk_x \frac{h_{p2}}{2} W_{t2}, \quad (12) \quad u_{x2} = W_{p2} - jk_x \frac{h_{p2}}{2} W_{t2}, \\
(13) \quad \tau_{yx2} - \tau_{yx1} &= (D_{p2} k_x^2 - \omega^2 m_{s2}) W_{p2}, \\
(14) \quad (\sigma_{y1} + s_1) - (\sigma_{y2} + s_2) - jk_x \frac{h_{p2}}{2} (\tau_{xy1} + \tau_{xy2}) &= (D_2 k_x^4 - \omega^2 m_{s2}) W_{t2}.
\end{aligned} \tag{A.2}$$

734 BC (I) at $y = L_1 + L_2$:

$$\begin{aligned}
(15) \quad -h p_3 &= -h(j\omega \rho_3 \phi_3) = s_2, \\
(16) \quad -(1-h)p_3 &= -(1-h)(j\omega \rho_3 \phi_3) = \sigma_{y2}, \\
(17) \quad v_{y3} &= -\frac{\partial \phi_2}{\partial y} = j\omega(1-h)u_{y2} + j\omega h U_{y2}, \quad (18) \quad \tau_{xy2} = 0.
\end{aligned} \tag{A.3}$$

735 BC (III) at $y = L_1 + L_2 + \delta$:

$$\begin{aligned}
(19) \quad v_{y3} &= -\frac{\partial \phi_3}{\partial y} = j\omega W_{t3}, \quad (20) \quad v_{y4} = -\frac{\partial \phi_t}{\partial y} = j\omega W_{t3}, \\
(21) \quad p_3 - p_4 &= j\omega(\rho_3 \phi_3 - \rho_0 \phi_t) = (D_3 k_x^4 - \omega^2 m_{s3}) W_{t3}.
\end{aligned} \tag{A.4}$$

736 In the above BC equations, the velocity potentials ϕ_1, ϕ_3, ϕ_t have been
737 expressed in Eqs. (3)–(5) that includes the reflection and transmission
738 coefficients R and T ; the transverse and in-plane displacements of the
739 three panels, $W_{t1,2,3}$ and $W_{p1,2,3}$, can be found in Eqs. (8) and (9); the
740 solutions of $u_{x1,2}, u_{y1,2}, U_{x1,2}, U_{y1,2}, \sigma_{y1,2}, s_{1,2}, \tau_{xy1,2}$ containing the constants
741 C_1 – C_{12} for the two foam layers were given by Eqs. (22) and (26). Substituting
742 these equations into the boundary conditions (A.1)–(A.4), a transfer matrix
743 equation can be obtained as

$$\mathbf{A}_{21} \mathbf{C}_{21} = \mathbf{B}_{21}, \tag{A.5}$$

744 where the i th row of equation corresponds to the i th boundary condition.

745 The vector of unknown amplitudes is:

$$\mathbf{C}_{21}^T = [C_1, C_2, \dots, C_{12}, I_3, R_3, W_{t1}, W_{t2}, W_{t3}, W_{p1}, W_{p2}, R, T]. \quad (\text{A.6})$$

The non-zero elements of the forcing vector $\mathbf{B}$ are $\mathbf{B}(1) = k_y$ and $\mathbf{B}(6) = -j\omega\rho_0$. The non-zero elements of the transfer coefficient matrix $\mathbf{A}$ are:

$$\begin{aligned} \mathbf{A}(1, 15) &= \omega, \quad \mathbf{A}(1, 20) = k_y; \quad \mathbf{A}(2, 1) = k_{Iy}/k_I^2, \quad \mathbf{A}(2, 2) = -k_{Iy}/k_I^2, \\ \mathbf{A}(2, 3) &= k_{IIy}/k_{II}^2, \quad \mathbf{A}(2, 4) = -k_{IIy}/k_{II}^2, \quad \mathbf{A}(2, 5) = k_x/k_r^2, \quad \mathbf{A}(2, 6) = k_x/k_r^2, \\ \mathbf{A}(2, 15) &= j; \quad \mathbf{A}(3, 1) = (k_{Iy}/k_I^2)b_1, \quad \mathbf{A}(3, 2) = -(k_{Iy}/k_I^2)b_1, \\ \mathbf{A}(3, 3) &= (k_{IIy}/k_{II}^2)b_2, \quad \mathbf{A}(3, 4) = -(k_{IIy}/k_{II}^2)b_2, \quad \mathbf{A}(3, 5) = (k_x/k_r^2)g, \\ \mathbf{A}(3, 6) &= (k_x/k_r^2)g, \quad \mathbf{A}(3, 15) = j; \quad \mathbf{A}(4, 1) = k_x/k_I^2, \quad \mathbf{A}(4, 2) = k_x/k_I^2, \\ \mathbf{A}(4, 3) &= k_x/k_{II}^2, \quad \mathbf{A}(4, 4) = k_x/k_{II}^2, \quad \mathbf{A}(4, 5) = -k_{ty}/k_r^2, \quad \mathbf{A}(4, 6) = k_{ty}/k_r^2, \\ \mathbf{A}(4, 15) &= -k_x h_{p1}/2, \quad \mathbf{A}(4, 18) = j; \quad \mathbf{A}(5, 1) = 2k_{Iy}k_x/k_I^2, \quad \mathbf{A}(5, 2) = -2k_{Iy}k_x/k_I^2, \\ \mathbf{A}(5, 3) &= 2k_{IIy}k_x/k_{II}^2, \quad \mathbf{A}(5, 4) = -2k_{IIy}k_x/k_{II}^2, \quad \mathbf{A}(5, 5) = (k_x^2 - k_{ry}^2)/k_r^2, \\ \mathbf{A}(5, 6) &= (k_x^2 - k_{ry}^2)/k_r^2, \quad \mathbf{A}(5, 18) = (\omega^2 m_{s1} - D_{p1}k_x^2)/N; \\ \mathbf{A}(6, 1) &= 2Nk_{Iy}^2/k_I^2 + A + Q + b_1E_2 - jNh_{p1}k_x^2k_{Iy}/k_I^2, \\ \mathbf{A}(6, 2) &= 2Nk_{Iy}^2/k_I^2 + A + Q + b_1E_2 + jNh_{p1}k_x^2k_{Iy}/k_I^2, \\ \mathbf{A}(6, 3) &= 2Nk_{IIy}^2/k_{II}^2 + A + Q + b_1E_2 - jNh_{p1}k_x^2k_{IIy}/k_{II}^2, \\ \mathbf{A}(6, 4) &= 2Nk_{IIy}^2/k_{II}^2 + A + Q + b_1E_2 + jNh_{p1}k_x^2k_{IIy}/k_{II}^2, \\ \mathbf{A}(6, 5) &= 2Nk_xk_{ry}/k_r^2 - jNh_{p1}k_x(k_x^2 - k_{ry}^2)/(2k_r^2), \\ \mathbf{A}(6, 6) &= -2Nk_xk_{ry}/k_r^2 - jNh_{p1}k_x(k_x^2 - k_{ry}^2)/(2k_r^2), \\ \mathbf{A}(6, 15) &= \omega^2 m_{s1} - D_1k_x^4, \quad \mathbf{A}(6, 20) = j\omega\rho_0; \\ \mathbf{A}(7, 1) &= (k_{Iy}/k_I^2)e^{-jk_{Iy}L_1}, \quad \mathbf{A}(7, 2) = -(k_{Iy}/k_I^2)e^{jk_{Iy}L_1}, \end{aligned}$$

$$\begin{aligned}
\mathbf{A}(7, 3) &= (k_{\text{Iy}}/k_{\text{II}}^2)e^{-jk_{\text{Iy}}L_1}, \quad \mathbf{A}(7, 4) = -(k_{\text{Iy}}/k_{\text{II}}^2)e^{jk_{\text{Iy}}L_1}, \\
\mathbf{A}(7, 5) &= (k_x/k_r^2)e^{-jk_{ry}L_1}, \quad \mathbf{A}(7, 6) = (k_x/k_r^2)e^{jk_{ry}L_1}, \quad \mathbf{A}(7, 16) = j; \\
\mathbf{A}(8, 1) &= (k_{\text{Iy}}/k_{\text{I}}^2)b_1e^{-jk_{\text{Iy}}L_1}, \quad \mathbf{A}(8, 2) = -(k_{\text{Iy}}/k_{\text{I}}^2)b_1e^{jk_{\text{Iy}}L_1}, \\
\mathbf{A}(8, 3) &= (k_{\text{Iy}}/k_{\text{II}}^2)b_2e^{-jk_{\text{Iy}}L_1}, \quad \mathbf{A}(8, 4) = -(k_{\text{Iy}}/k_{\text{II}}^2)b_2e^{jk_{\text{Iy}}L_1}, \\
\mathbf{A}(8, 5) &= (k_x/k_r^2)ge^{-jk_{ry}L_1}, \quad \mathbf{A}(8, 6) = (k_x/k_r^2)ge^{jk_{ry}L_1}, \quad \mathbf{A}(8, 16) = j; \\
\mathbf{A}(9, 1) &= (k_x/k_{\text{I}}^2)e^{-jk_{\text{Iy}}L_1}, \quad \mathbf{A}(9, 2) = (k_x/k_{\text{I}}^2)e^{jk_{\text{Iy}}L_1}, \\
\mathbf{A}(9, 3) &= (k_x/k_{\text{II}}^2)e^{-jk_{\text{Iy}}L_1}, \quad \mathbf{A}(9, 4) = (k_x/k_{\text{II}}^2)e^{jk_{\text{Iy}}L_1}, \\
\mathbf{A}(9, 5) &= -(k_{ry}/k_r^2)e^{-jk_{ry}L_1}, \quad \mathbf{A}(9, 6) = (k_{ry}/k_r^2)e^{jk_{ry}L_1}, \quad \mathbf{A}(9, 16) = k_x h_{p2}/2, \\
\mathbf{A}(9, 19) &= j; \quad \mathbf{A}(10, 7) = (k_{\text{Iy}}/k_{\text{I}}^2)e^{-jk_{\text{Iy}}L_1}, \quad \mathbf{A}(10, 8) = -(k_{\text{Iy}}/k_{\text{I}}^2)e^{jk_{\text{Iy}}L_1}, \\
\mathbf{A}(10, 9) &= (k_{\text{Iy}}/k_{\text{II}}^2)e^{-jk_{\text{Iy}}L_1}, \quad \mathbf{A}(10, 10) = -(k_{\text{Iy}}/k_{\text{II}}^2)e^{jk_{\text{Iy}}L_1}, \\
\mathbf{A}(10, 11) &= (k_x/k_r^2)e^{-jk_{ry}L_1}, \quad \mathbf{A}(10, 12) = (k_x/k_r^2)e^{jk_{ry}L_1}, \quad \mathbf{A}(10, 16) = j; \\
\mathbf{A}(11, 7) &= (k_{\text{Iy}}/k_{\text{I}}^2)e^{-jk_{\text{Iy}}L_1}, \quad \mathbf{A}(11, 8) = -(k_{\text{Iy}}/k_{\text{I}}^2)e^{jk_{\text{Iy}}L_1}, \\
\mathbf{A}(11, 9) &= (k_{\text{Iy}}/k_{\text{II}}^2)e^{-jk_{\text{Iy}}L_1}, \quad \mathbf{A}(11, 10) = -(k_{\text{Iy}}/k_{\text{II}}^2)e^{jk_{\text{Iy}}L_1}, \\
\mathbf{A}(11, 11) &= (k_x/k_r^2)e^{-jk_{ry}L_1}, \quad \mathbf{A}(11, 12) = (k_x/k_r^2)e^{jk_{ry}L_1}, \quad \mathbf{A}(11, 16) = j; \\
\mathbf{A}(12, 7) &= (k_x/k_{\text{I}}^2)e^{-jk_{\text{Iy}}L_1}, \quad \mathbf{A}(12, 8) = (k_x/k_{\text{I}}^2)e^{jk_{\text{Iy}}L_1}, \\
\mathbf{A}(12, 9) &= (k_x/k_{\text{II}}^2)e^{-jk_{\text{Iy}}L_1}, \quad \mathbf{A}(12, 10) = (k_x/k_{\text{II}}^2)e^{jk_{\text{Iy}}L_1}, \\
\mathbf{A}(12, 11) &= -(k_{ry}/k_r^2)e^{-jk_{ry}L_1}, \quad \mathbf{A}(12, 12) = (k_{ry}/k_r^2)e^{jk_{ry}L_1}, \\
\mathbf{A}(12, 16) &= -k_x h_{p2}/2, \quad \mathbf{A}(12, 19) = j; \\
\mathbf{A}(13, 1) &= -2k_{\text{Iy}}k_x/k_{\text{I}}^2e^{-jk_{\text{Iy}}L_1}, \quad \mathbf{A}(13, 2) = 2k_{\text{Iy}}k_x/k_{\text{I}}^2e^{jk_{\text{Iy}}L_1}, \\
\mathbf{A}(13, 3) &= -2k_{\text{Iy}}k_x/k_{\text{II}}^2e^{-jk_{\text{Iy}}L_1}, \quad \mathbf{A}(13, 4) = 2k_{\text{Iy}}k_x/k_{\text{II}}^2e^{jk_{\text{Iy}}L_1}, \\
\mathbf{A}(13, 5) &= -(k_x^2 - k_{ry}^2)/k_r^2e^{-jk_{ry}L_1}, \quad \mathbf{A}(13, 6) = -(k_x^2 - k_{ry}^2)/k_r^2e^{jk_{ry}L_1}, \\
\mathbf{A}(13, 7) &= 2k_{\text{Iy}}k_x/k_{\text{I}}^2e^{-jk_{\text{Iy}}L_1}, \quad \mathbf{A}(13, 8) = -2k_{\text{Iy}}k_x/k_{\text{I}}^2e^{jk_{\text{Iy}}L_1},
\end{aligned}$$

$$\begin{aligned}
\mathbf{A}(13, 9) &= 2k_{\text{I}y}k_x/k_{\text{I}}^2 e^{-jk_{\text{I}y}L_1}, \quad \mathbf{A}(13, 10) = -2k_{\text{I}y}k_x/k_{\text{I}}^2 e^{jk_{\text{I}y}L_1}, \\
\mathbf{A}(13, 11) &= (k_x^2 - k_{ry}^2)/k_r^2 e^{-jk_{ry}L_1}, \quad \mathbf{A}(13, 12) = (k_x^2 - k_{ry}^2)/k_r^2 e^{jk_{ry}L_1}, \\
\mathbf{A}(13, 19) &= (\omega^2 m_{s2} - D_{p2}k_x^2)/N; \\
\mathbf{A}(14, 1) &= (-2Nk_{\text{I}y}^2/k_{\text{I}}^2 + A + Q + b_1E_2 - jNh_{p2}k_x^2k_{\text{I}y}/k_{\text{I}}^2) e^{-jk_{\text{I}y}L_1}, \\
\mathbf{A}(14, 2) &= (-2Nk_{\text{I}y}^2/k_{\text{I}}^2 + A + Q + b_1E_2 + jNh_{p2}k_x^2k_{\text{I}y}/k_{\text{I}}^2) e^{jk_{\text{I}y}L_1}, \\
\mathbf{A}(14, 3) &= (-2Nk_{\text{I}y}^2/k_{\text{I}}^2 + A + Q + b_2E_2 - jNh_{p2}k_x^2k_{\text{I}y}/k_{\text{I}}^2) e^{-jk_{\text{I}y}L_1}, \\
\mathbf{A}(14, 4) &= (-2Nk_{\text{I}y}^2/k_{\text{I}}^2 + A + Q + b_2E_2 + jNh_{p2}k_x^2k_{\text{I}y}/k_{\text{I}}^2) e^{jk_{\text{I}y}L_1}, \\
\mathbf{A}(14, 5) &= [-2Nk_xk_{ry}/k_r^2 - jNh_{p2}k_x(k_x^2 - k_{ry}^2)/(2k_r^2)] e^{-jk_{ry}L_1}, \\
\mathbf{A}(14, 6) &= [2Nk_xk_{ry}/k_r^2 - jNh_{p2}k_x(k_x^2 - k_{ry}^2)/(2k_r^2)] e^{jk_{ry}L_1}, \\
\mathbf{A}(14, 7) &= (2Nk_{\text{I}y}^2/k_{\text{I}}^2 + A + Q + b_1E_2 - jNh_{p2}k_x^2k_{\text{I}y}/k_{\text{I}}^2) e^{-jk_{\text{I}y}L_1}, \\
\mathbf{A}(14, 8) &= (2Nk_{\text{I}y}^2/k_{\text{I}}^2 + A + Q + b_1E_2 + jNh_{p2}k_x^2k_{\text{I}y}/k_{\text{I}}^2) e^{jk_{\text{I}y}L_1}, \\
\mathbf{A}(14, 9) &= (2Nk_{\text{I}y}^2/k_{\text{I}}^2 + A + Q + b_2E_2 - jNh_{p2}k_x^2k_{\text{I}y}/k_{\text{I}}^2) e^{-jk_{\text{I}y}L_1}, \\
\mathbf{A}(14, 10) &= (2Nk_{\text{I}y}^2/k_{\text{I}}^2 + A + Q + b_2E_2 + jNh_{p2}k_x^2k_{\text{I}y}/k_{\text{I}}^2) e^{jk_{\text{I}y}L_1}, \\
\mathbf{A}(14, 11) &= [2Nk_xk_{ry}/k_r^2 - jNh_{p2}k_x(k_x^2 - k_{ry}^2)/(2k_r^2)] e^{-jk_{ry}L_1}, \\
\mathbf{A}(14, 12) &= [-2Nk_xk_{ry}/k_r^2 - jNh_{p2}k_x(k_x^2 - k_{ry}^2)/(2k_r^2)] e^{jk_{ry}L_1}, \\
\mathbf{A}(14, 16) &= \omega^2 m_{s2} - D_2k_x^4; \\
\mathbf{A}(15, 7) &= (Q + b_1R')e^{-jk_{\text{I}y}(L_1+L_2)}, \quad \mathbf{A}(15, 8) = (Q + b_1R')e^{jk_{\text{I}y}(L_1+L_2)}, \\
\mathbf{A}(15, 9) &= (Q + b_2R')e^{-jk_{\text{I}y}(L_1+L_2)}, \quad \mathbf{A}(15, 10) = (Q + b_2R')e^{jk_{\text{I}y}(L_1+L_2)}, \\
\mathbf{A}(15, 13) &= j\omega\rho_3he^{-jk_{3y}(L_1+L_2)}, \quad \mathbf{A}(15, 14) = j\omega\rho_3he^{jk_{3y}(L_1+L_2)}; \\
\mathbf{A}(16, 7) &= (2Nk_{\text{I}y}^2/k_{\text{I}}^2 + A + b_1Q) e^{-jk_{\text{I}y}(L_1+L_2)}, \\
\mathbf{A}(16, 8) &= (2Nk_{\text{I}y}^2/k_{\text{I}}^2 + A + b_1Q) e^{jk_{\text{I}y}(L_1+L_2)}, \\
\mathbf{A}(16, 9) &= (2Nk_{\text{I}y}^2/k_{\text{I}}^2 + A + b_2Q) e^{-jk_{\text{I}y}(L_1+L_2)},
\end{aligned}$$

$$\begin{aligned}
\mathbf{A}(16, 10) &= (2Nk_{\text{II}y}^2/k_{\text{II}}^2 + A + b_2Q) e^{jk_{\text{II}y}(L_1+L_2)}, \\
\mathbf{A}(16, 11) &= 2N(k_x k_{ry}/k_r^2) e^{-jk_{ry}(L_1+L_2)}, \quad \mathbf{A}(16, 12) = -2N(k_x k_{ry}/k_r^2) e^{jk_{ry}(L_1+L_2)}, \\
\mathbf{A}(16, 13) &= j\omega\rho_3(1-h) e^{-jk_{3y}(L_1+L_2)}, \quad \mathbf{A}(16, 14) = j\omega\rho_3(1-h) e^{jk_{3y}(L_1+L_2)}; \\
\mathbf{A}(17, 7) &= -\omega(1-h+hb_1)(k_{\text{I}y}/k_{\text{I}}^2) e^{-jk_{\text{I}y}(L_1+L_2)}, \\
\mathbf{A}(17, 8) &= \omega(1-h+hb_1)(k_{\text{I}y}/k_{\text{I}}^2) e^{jk_{\text{I}y}(L_1+L_2)}, \\
\mathbf{A}(17, 9) &= -\omega(1-h+hb_2)(k_{\text{II}y}/k_{\text{II}}^2) e^{-jk_{\text{II}y}(L_1+L_2)}, \\
\mathbf{A}(17, 10) &= \omega(1-h+hb_2)(k_{\text{II}y}/k_{\text{II}}^2) e^{jk_{\text{II}y}(L_1+L_2)}, \\
\mathbf{A}(17, 11) &= -\omega(1-h+hg)(k_x/k_r^2) e^{-jk_{ry}(L_1+L_2)}, \\
\mathbf{A}(17, 12) &= -\omega(1-h+hg)(k_x/k_r^2) e^{jk_{ry}(L_1+L_2)}, \\
\mathbf{A}(17, 13) &= -jk_{3y} e^{-jk_{3y}(L_1+L_2)}, \quad \mathbf{A}(17, 14) = jk_{3y} e^{jk_{3y}(L_1+L_2)}; \\
\mathbf{A}(18, 7) &= (2k_x k_{\text{I}y}/k_{\text{I}}^2) e^{-jk_{\text{I}y}(L_1+L_2)}, \quad \mathbf{A}(18, 8) = -(2k_x k_{\text{I}y}/k_{\text{I}}^2) e^{jk_{\text{I}y}(L_1+L_2)}, \\
\mathbf{A}(18, 9) &= (2k_x k_{\text{II}y}/k_{\text{II}}^2) e^{-jk_{\text{II}y}(L_1+L_2)}, \quad \mathbf{A}(18, 10) = -(2k_x k_{\text{II}y}/k_{\text{II}}^2) e^{jk_{\text{II}y}(L_1+L_2)}, \\
\mathbf{A}(18, 11) &= [(k_x^2 - k_{ry}^2)/k_r^2] e^{-jk_{ry}(L_1+L_2)}, \quad \mathbf{A}(18, 12) = [(k_x^2 - k_{ry}^2)/k_r^2] e^{jk_{ry}(L_1+L_2)}; \\
\mathbf{A}(19, 13) &= jk_y e^{-jk_y(L_1+L_2+\delta)}, \quad \mathbf{A}(19, 14) = -jk_y e^{jk_y(L_1+L_2+\delta)}, \quad \mathbf{A}(19, 17) = -j\omega; \\
\mathbf{A}(20, 17) &= -j\omega, \quad \mathbf{A}(20, 21) = jk_y e^{-jk_y(L_1+L_2+\delta)}; \\
\mathbf{A}(21, 13) &= j\omega\rho_0 e^{-jk_y(L_1+L_2+\delta)}, \quad \mathbf{A}(21, 14) = j\omega\rho_0 e^{jk_y(L_1+L_2+\delta)}, \\
\mathbf{A}(21, 17) &= \omega^2 m_{s3} - D_3 k_x^4, \quad \mathbf{A}(21, 21) = -j\omega\rho_0 e^{-jk_y(L_1+L_2+\delta)}.
\end{aligned}$$

746 Note that the above elements of $\mathbf{A}$ are for two foam layers with identical
747 poroelastic material properties. If the two foam layers are different including
748 the case of different interstitial air properties, the relevant coefficients must
749 be calculated separately using material parameters of each individual foam
750 layer.

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