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FINITE ELEMENT ANALYSIS OF AIRBORNE SOUND TRANSMISSION IN STUD-COUPLED LIGHTWEIGHT WALL SYSTEMS

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ABSTRACT[*]

Lightweight wall systems, widely used in aerospace and construction, offer advantages such as weight efficiency, rapid construction, and ease of replacement. However, the presence of flexible or rigid studs within these systems complicates their acoustic performance, particularly in terms of airborne sound insulation. This study employs an efficient finite element approach to accurately predict the sound transmission loss of stud-coupled double-leaf lightweight walls. This approach offers a cost-effective and time-efficient alternative to experimental and analytical methods while maintaining acceptable precision. A parametric study was conducted to investigate the sensitivity of sound insulation to various parameters, including panel thickness and stud stiffness. The results provide insights into the influence of effective parameters on the acoustic performance of lightweight coupled wall systems, facilitating the design of more acoustically effective solutions for noise-sensitive environments.

Keywords: *lightweight wall systems, sound transmission loss, stud-coupled double-leaf, finite element, parametric study.*

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1. INTRODUCTION

Understanding the impact of studs on the sound insulation of double-leaf walls is relevant for building acoustics [1], [2]. Indeed, double-leaf walls offer improved sound insulation compared to single walls, but their performance may be affected by structural connections like studs, which act as sound bridges [3], [4], coupling the two leaves of the partition. Various approaches have been employed to analyze this effect, including analytical, experimental, and numerical methods [4–8].

Early analytical models simplified the wall system by focusing on airborne transmission through infinite, unconnected leaves, neglecting the influence of studs [9], [10]. Later models attempted to incorporate studs as rigid connections, which proved inadequate for lightweight walls with flexible metal studs [11–13]. To address this, analytical models evolved to include flexible studs, often represented as springs with translational and rotational stiffness [4], [7], [11], [14]. However, these models often required empirically derived stiffness values, limiting their predictive power for new designs [11]. Smeared models offered another analytical approach by distributing stud properties uniformly [7]. Vigran's work [3], reviving and extending Sharp's method, aimed to correct transfer matrix calculations by accounting for stud effects, initially for infinitely stiff studs and later for flexible ones using empirical data. While providing valuable insights into phenomena like mass-spring-mass resonance and coincidence, analytical models often involve simplifications in geometry and boundary conditions [4], [7], [11].

Experimental investigations have been vital for assessing the sound insulation performance of double-leaf walls with various stud configurations [5], [15]. These studies have examined the influence of stud type, spacing, cavity filling,

and the use of resilient elements [15], [16]. Researchers have measured the sound reduction index (R) and weighted sound reduction index (R_w) for different constructions. Studies by Hongisto et al. specifically explored the impact of stud characteristics and resilient channels [5], [8]. While providing real-world data for validation, experimental approaches are resource-intensive and may not offer detailed insights into the dynamic behavior of studs within the assembly [5].
Numerical methods, particularly the Finite Element Method (FEM), offer a more comprehensive approach. FEM allows for detailed modeling of stud geometry, material properties, and the interaction between studs, panels, and the cavity. It can accurately represent fluid-structure interaction (FSI), crucial for understanding sound transmission pathways. But FEM analyses are time consuming and require experts for accurately simulate the complex systems. Numerical models can also incorporate damping and complex boundary conditions. They have demonstrated good agreement with experimental results [2], [17], [18].
This study makes use of a simplified model that efficiently predicts the performance of stud-coupled infinite wall systems with reasonable accuracy while still being time efficient. Moreover, the model is designed to be flexible, allowing for the analysis of various wall configurations and stud shapes. The model tends to be efficient compared to existing FEM or analytical approach while providing acceptable accuracy.

2. FINITE ELEMENT MODELING METHODOLOGY

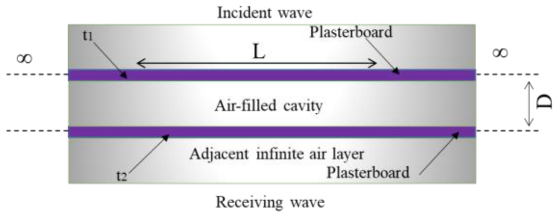
Figure 1 shows the schematic view of un-coupled and coupled wall systems, considering L as periodic unit cell length, t_1 and t_2 are panels thickness and D is cavity thickness. The system is infinite, and an incident plane wave is applied to one side of the panel, while its effect is evaluated in other side by means of nodal displacements. The finite element model uses 1D elements, see Figure 2. The plane strain Euler-Bernoulli beam element has been used to model wall panels. The air inside the cavity and receiving side is modeled using analytical frequency dependent spring, discussed in detail elsewhere [18]. The stud is modeled as equivalent two node bar element. Additionally, infinite panels with a 600 mm stud span are modeled using Bloch–Floquet boundary conditions. The numerical model is organized into two groups, each evaluating wall performance based on panel thickness and stud thickness. Material properties used in the models are listed in Table 1.

The panels' thickness is considered in two cases of identical (0.0125mm) and nonsymmetrical panels (0.0125-0.025 m). the cavity thickness is considered 0.05 m, verification models based on [7] except for experimental studies.

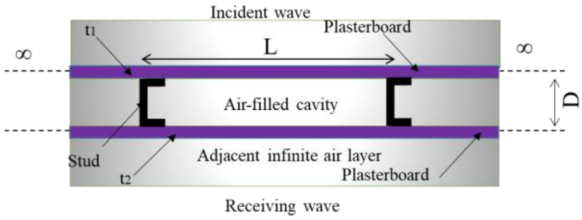
Table 1. material properties

Element	Properties		
Panels	$\rho_p = 790 kg/m^3$	$v_p = 0.3$	$E_p = 2.5e9 Pa$
Stud	$\rho_s = 7850 kg/m^3$	$v_s = 0.28$	$E_s = 2.1e11 Pa$
Air	$\rho_a = 1.21 kg/m^3$	$c = 343 m/s$	

* ρ is density, v is Poisson ratio and E is module of elasticity. Air density and speed of sound are indicated by ρ_a and c, respectively.



a) Un-coupled wall system



b) Coupled wall system

Figure 1. Schematic view of the wall.

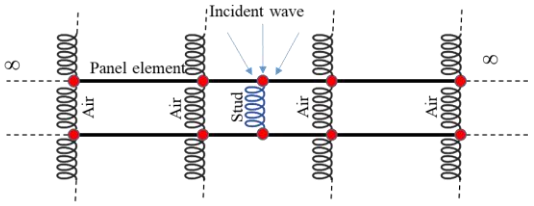


Figure 2. FE model scheme.

3. MODEL VERIFICATION AND VALIDATION

The proposed simulation approach is compared with an existing analytical model [7] in normal and 45 degrees incident angle for un-coupled system (Figures 3 and 4) and coupled systems either analytical or experimental studies (Figures 5-7). For verification, the proposed model is compared against two analytical models [7], [19] and then validated with two experimental studies [3], [19].

The comparison between the proposed numerical model and the analytical model from [7] shows excellent agreement for both 45° and normal incidence (Figures 3 and 4).

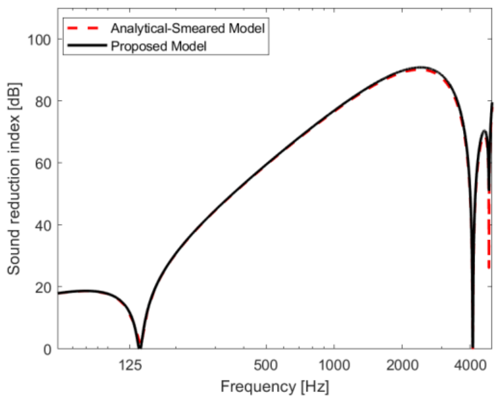


Figure 3. Comparison of Un-coupled proposed model and analytical smeared model ($\varphi = 45^o$).

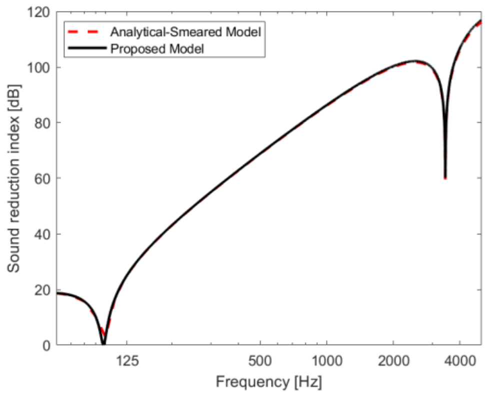


Figure 4. Comparison of Un-coupled proposed model and analytical smeared model ($\varphi = 90^o$).

Figure 5 compares the proposed numerical model with the analytical smeared model from [7]. Despite some differences, the numerical model follows the same trend, predicted the coincidence frequency, and shows acceptable agreement. Moreover, from Figure 6, comparisons with experimental studies (Vigran [3]) reveal that the model accurately predicts the mass–air–mass and coincidence frequencies, although with differences of about 5 dB in high frequency ranges. It also agrees well with the experimental and analytical results of Godinho et al. [19], even though there is an approximate 10 dB difference in the low frequency range (Figure 7).

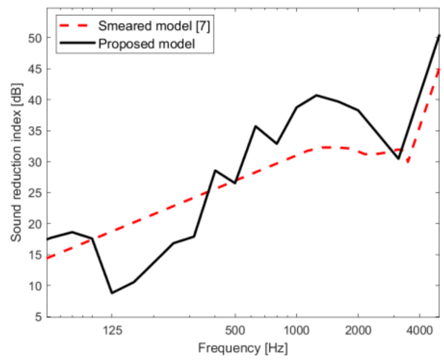


Figure 5. Comparison of proposed model and analytical smeared model (diffuse field).

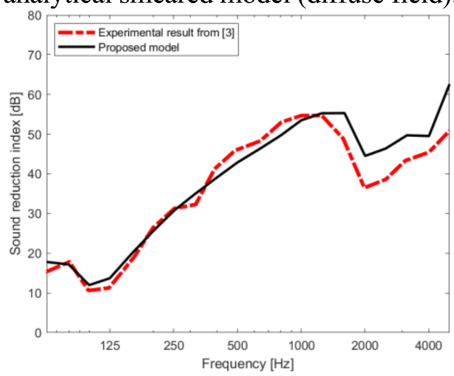


Figure 6. Comparison of proposed model and Experiment [3].

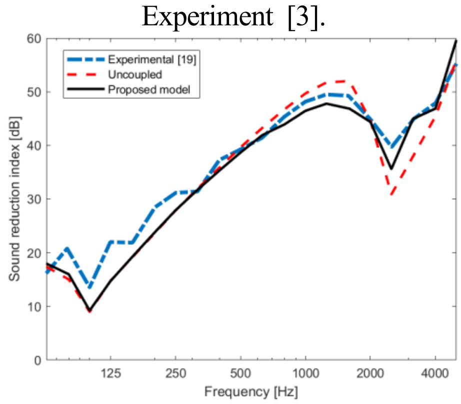
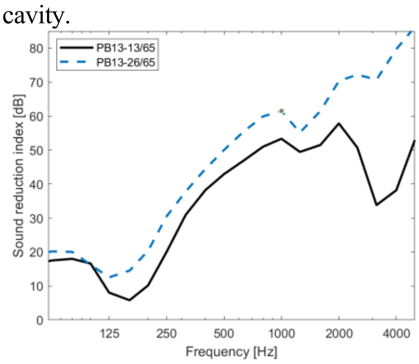


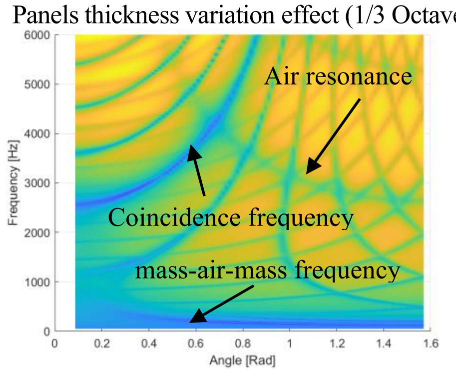
Figure 7. Comparison of proposed model and results of [19].

4. PARAMETRIC STUDY

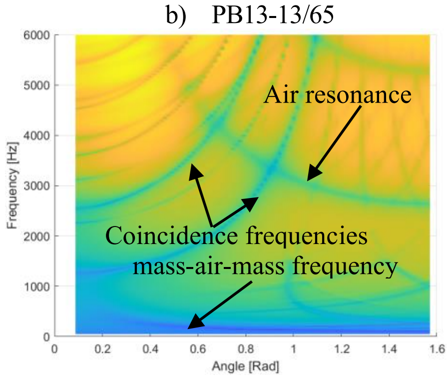
The first part of the parametric study evaluates the effect of wall panel thickness on the model. As expected, using asymmetric panel thicknesses leads to different coincidence resonances. Figure 8 illustrates this effect by comparing configurations with 13 mm and 26 mm panels, both with a 65 mm air gap. The material properties for the panels and studs are provided in Table 1. In this notation, "PB 13-13/65" denotes a wall consisting of two 13 mm panels with a 65 mm cavity.



a) Panels thickness variation effect (1/3 Octave band)



b) PB13-13/65

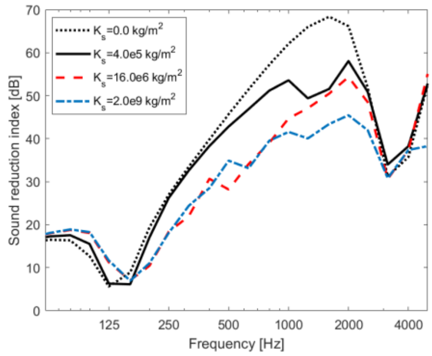


c) PB 13-26/65

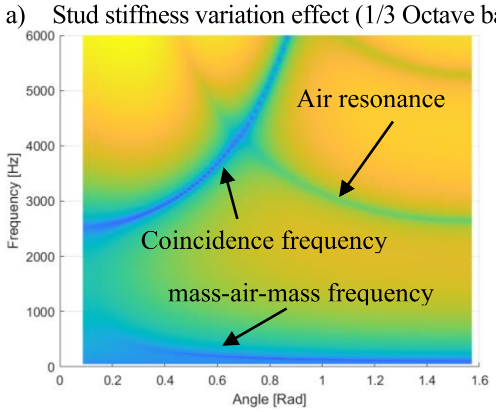
Figure 8. sound transmission index variations of double leaf wall due to geometry differences.

Asymmetric panel thickness produces two distinct coincidence frequencies (Figures 8b and 8c) because each panel responds differently due to its unique mass and stiffness. In accordance with the mass law, an increase in mass and stiffness generally improves sound insulation. Figure 8a illustrates that while the performance is similar at low frequencies—where the response is largely governed by mass—the stiffer, heavier configuration delivers significantly enhanced insulation at higher frequencies, achieving improvements of up to 5–20 dB. This is due to the reduced vibrational transmission and more favorable behavior of the stiffer system.

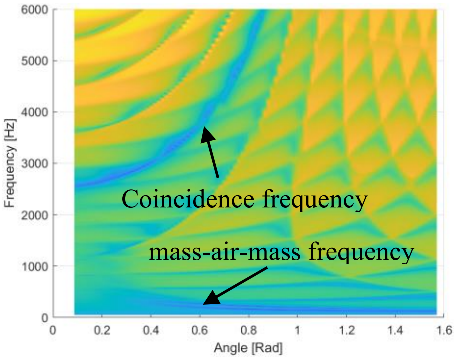
To evaluate the effect of stud stiffness on sound insulation, four cases were examined: one without a stud, two with intermediate and standard steel stud stiffness, and one with a relatively rigid stud ($K_s = 2e9kg/m^2$, similar to wood studs). Figure 9 presents one-third octave band plots of the sound reduction index for these cases, comparing uncoupled and rigid boundary conditions across various incident angles.



a) Stud stiffness variation effect (1/3 Octave band)



b) Un-coupled system



c) Rigid stud

Figure 9. sound transmission index variations of double leaf wall due to stud stiffness.

Figure 9a shows that as stud stiffness increases, the wall's sound insulation deteriorates. For example, around 1000 Hz, an un-coupled wall achieves roughly 62 dB, while a wall with a softer stud reaches about 53 dB; this gap widens to 10–20 dB with intermediate or rigid studs. At low frequencies, all configurations perform similarly because the system's mass dominates the response. However, at higher frequencies, the increased stiffness in stud-coupled systems enhances vibrational transmission, thereby reducing insulation. Figure 9b displays the resonance frequencies of the un-coupled system, where both mass–air–mass and air resonances are evident. In contrast, Figure 9c—representing a rigid stud-coupled system—exhibits significant oscillations across all frequencies, with only the mass–air–mass and coincidence resonances clearly visible. This behavior indicates that a stiffer connection introduces additional dynamic effects, ultimately compromising sound insulation in the medium and high frequency ranges.

5. CONCLUSIONS

This study presents a simplified FEM-based model that combines finite element analysis with an analytical formulation for the fluid medium. The model shows good agreement with existing analytical and experimental data. Our findings indicate that key design parameters—such as panel thickness and stud stiffness—significantly influence the acoustic performance of stud-coupled double-wall systems. Thicker panels improve performance by increasing mass and introducing asymmetry, while more flexible studs enhance insulation in the medium to high-frequency range. Overall, the model is both efficient and accurate, and it can be further developed to incorporate cavity absorbers or extend to triple-wall systems.

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