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ORIGINAL PAPER

Acoustical properties of the new sandwich structures for aircraft cabin interiors with integrated vacuum insulation

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Abstract
Any modern passenger aircraft must provide a high level of comfort for passengers who spend considerable time inside the cabin. The cabin's climate and interior noise levels contribute to this comfort. Vacuum insulation panels (VIP) have been explored as insulation materials to improve these factors due to their extremely low thermal conductivity. When integrating VIPs into the aircraft cabin's interior, it was discovered that the thermal conductivity of the entire sandwich structure was 3–6 times lower than conventional structures. This finding has generated much interest in using VIPs for aircraft cabin insulation. This article delves into the acoustic properties of these new structures featuring integrated VIPs. Tests were carried out to analyze the sound insulation capabilities of these structures. The results showed that the new interior structures exhibited promising acoustic properties.

Keywords Aircraft cabin · Interior · Vacuum insulation · Acoustic insulation

1 Introduction

The aircraft industry places high importance on creating a comfortable acoustic environment inside the cabin. Achieving sufficient noise reduction is crucial for the health, comfort, and psychological well-being of passengers and cabin crew who spend a lot of time in the cabin during a flight.

Modern aircraft use light materials such as carbon or glass fiber-reinforced plastics instead of aluminum for the fuselage. However, this causes an increase in sound transmission into the cabin from the outside, making noise reduction a significant challenge for aircraft manufacturers, particularly for manufacturers of small private jets, which are lighter than big wide-body aircraft.

Noise in the cabin environment can originate from both external and internal sources. The primary external noise sources are engines and turbulent boundary layers that form between the free stream and the outer side of the fuselage. Jet engine noise covers a wide frequency spectrum, including both low and high frequencies. Low-frequency noise (below 500 Hz) includes engine hum and rumble. High-frequency noise (above 1 kHz) includes whining and screeching sounds. Some aircraft engine noise contains discrete frequencies known as “pure tones.” These tones can be annoying for listeners and affect the assessment of flyover noise [1]. The noise can be transmitted into the cabin through airborne noise, leakage noise, and structure-borne noise [2]. The internal sources of noise in the cabin are the air conditioning and hydraulic systems, avionic ventilation, vacuum toilets, the air extraction system, electrics, passengers, and cabin crew who use the hatracks or galley [3].

The sounds inside an aircraft cabin can be categorized as either continuous or intermittent. Continuous noise levels are those that change according to the movements of the aircraft during takeoff, cruising, and landing. For a typical commercial jet passenger plane, the noise levels prior to takeoff are around 60–65 dB(A), while during flight, the levels rise to 80–85 dB(A), and during landing, they are around

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75–80 dB(A). Intermittent noise levels, on the other hand, also include sounds caused by passengers and flight crew and can reach levels as high as 81–88 dB(A) [4]. The noise levels depend on various factors such as the type of aircraft, flight status, location within the cabin, weather, and can vary at different frequencies. The most critical frequency range, which is identified by different studies [2, 5], is around 100 to 2,000 Hz. In this range, the A-weighted noise levels reach their highest values. Therefore, it is essential to have acoustic insulation that is efficient in this critical frequency range [2].

Conventional acoustical materials used in the aircraft industry include glass wool, as shown in Fig. 1 and Fig. 2, polyimide foam (PI), and polyethylene foam (PE). However, glass wool is not effective as a sound transmission barrier at low frequencies [6]. To improve transmission loss performance at low frequencies, various investigations were conducted. One study integrated an active noise reduction system into an interior panel, which reduced the average sound pressure level by 7–8 dB [6]. However, conventional improvement measures such as the addition of a heavy layer of damping material or soft-touch foam as an absorption material, integration of vibration-damping structural brackets, or sealing of existing leaks are still the most effective acoustical methods.

In a study on optimizing the thermal insulation of aircraft cabin interiors, several sandwich structures with integrated vacuum insulation were proposed [7]. These structures reduced thermal conductivity by 3–6 times compared to conventional structures using insulated materials like glass wool. The new structures with integrated vacuum insulation eliminate the need for conventional glass wool packages, which could change the acoustic properties of interiors. However, the impact of vacuum insulation on the acoustic properties of these new sandwich structures has not been studied yet. This paper aims to address this gap by studying the acoustic properties of the proposed structures and identifying which ones meet the acoustic requirements for use in aircraft cabins.

2 Vacuum insulation panels

Vacuum Insulation Panels (VIPs) are highly efficient insulation packages that consist of a solid porous core. This core is then evacuated, and a gas- and water–vapor-tight envelope

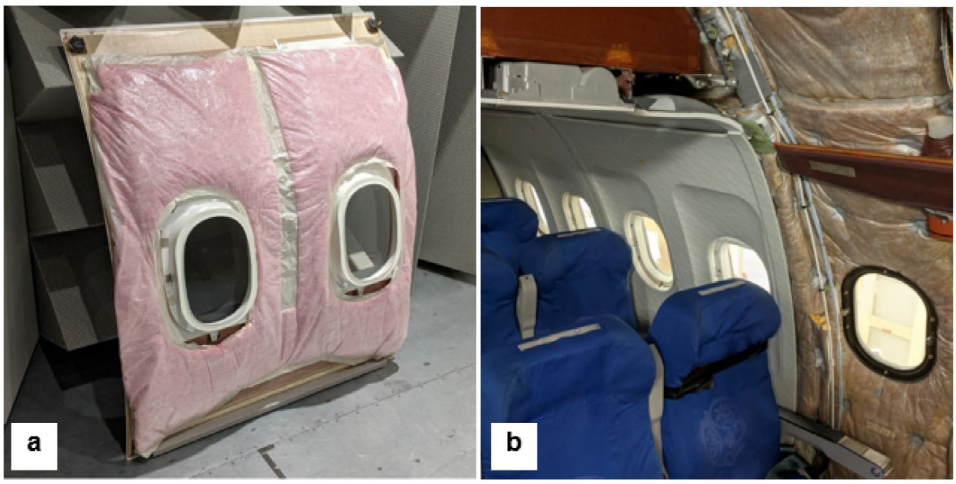

Fig. 1 Example of a sidewall with a secondary insulation: **a** view from the rear side, **b** sidewall installed in the cabin

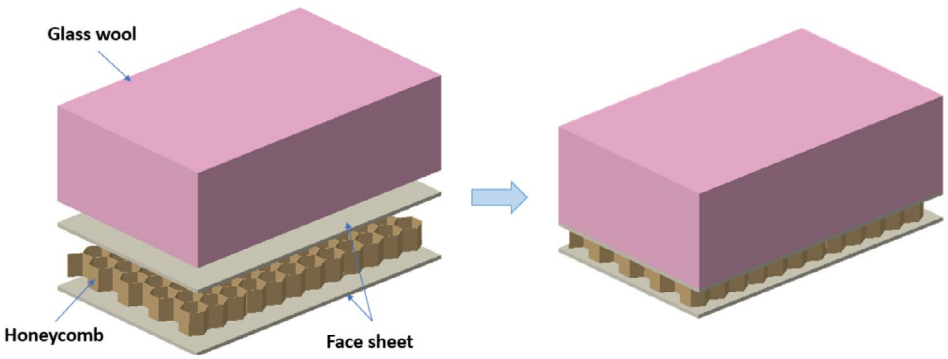

Fig. 2 Conventional sandwich structure with honeycomb core, insulated by glass wool package

Fig. 3 Vacuum insulation panel

is added to prevent any outer gases and vapors from passing into the panel. VIPs have an extremely low thermal conductivity ranging from 0.0035 to 0.008 W/m·K at the center of the panel after production. They possess long-term thermal performance, which makes them 5–10 times more effective than traditional insulation materials [8]. The typical VIP is presented in Fig. 3.

VIPs are used in a variety of industries such as refrigeration units, pharmaceuticals, temperature-controlled transportation, building construction, and other applications requiring low energy loss from heat transfer [9, 10]. However, VIPs have not yet found any applications in the aircraft industry, with the exception of cargo containers, where clinical and pharmaceutical goods are transported [11].

The core material of a panel is chosen based on its ability to endure the external air pressure, which occurs after the panel has been evacuated. Various materials can be used as the core, such as glass fiber [12–14], polyurethane foam [15], and aerogel [12, 16]. However, the most commonly used material is fumed silica [16, 17]. The high-barrier multilayer films used in VIP have three layers: an inner sealing layer of polyethylene (PE), a middle barrier layer of aluminum foil (AF) or metalized polymer film multilayer laminates (MF), and an outer protective layer. Expanded polystyrene (EPS) or extruded polystyrene (XPS) can be applied as the outer layer to enhance fire resistance or panel durability, while polyethylene terephthalate (PET) can be used to withstand transportation and installation handling [18].

VIPs were initially created for use in thermal applications such as the transportation of pharmaceuticals. However, they were not initially considered for use in acoustic applications. As VIPs began to be used for building insulation, research into their acoustic properties became more relevant. But unlike their thermal properties, the acoustic properties of VIPs have not been extensively explored. Initial investigations have shown that VIPs are less effective for acoustic insulation due to their reduced thickness when used alone. However, combining them with thicker and heavier facings can compensate for this. Additionally, placing a rubber layer between the VIP and the facing can further improve results by shifting the coincidence frequency above 3000 Hz [19].

3 New sandwich structures with integrated vacuum insulation for the interior

In the early stages of this project, four innovative structures for the interior panels were proposed, considering crucial characteristics such as mechanical properties, thermal performance, production capability, and vacuum maintenance during the interior's lifetime [7]:

- Evacuated honeycomb core filled by micro- or nano-porous powder;
- Sandwich structure with an evacuated VIP in the middle, which is covered by rigid foam and face sheets from both sides;
- Evacuated aerogel core;
- Double sandwich with two core elements, an evacuated VIP and honeycomb.

The novel sandwich structures with integrated vacuum insulation are presented in Fig. 4.

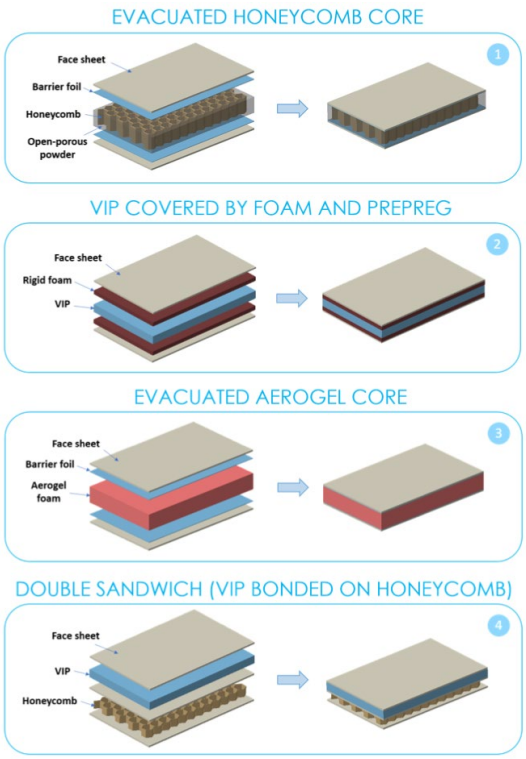

Fig. 4 Novel structure proposals with integrated vacuum insulation

The first structure, the "evacuated honeycomb core," is similar to the conventional one. It uses NOMEX® honeycomb as a core with fiber-reinforced thermosetting pre-impregnated materials (prepregs) as face sheets. A high barrier foil MF4 is placed between the honeycomb and face sheets to prevent gases and water vapor from penetrating the panel. Additionally, the core is filled with pyrogenic silica powder to increase the interior's lifespan. The nanopores in the silica powder reduce the mean free path of air molecules that penetrate the high barrier foil. The entire core system is evacuated to an inner gas pressure of 5 mbar. A thermoplastic nonwoven layer is applied between the MF4 foil and honeycomb core to evacuate the core and bond them together. The prepregs already have a pre-catalyzed resin system, which is impregnated into reinforcement fabrics and has good adhesive properties after curing in the hot molding press.

In the second type of structure, a semi-finished product called va-Q-vip is used as VIP, and it is covered by rigid foams and prepregs from both sides. The semi-finished panel is evacuated to a pressure of 5 mbar. The face sheet is fixed to the foam using the resin in the prepreg. However, an additional adhesive in the form of a thermoplastic nonwoven layer is required to bond the foam and VIP. This research project uses different foam materials that meet aviation-specific requirements for the cabin, including polyether sulfone (PES), polyvinyl chloride (PVC), and polymethacrylimide (PMI).

The third structure is similar to the first but uses a polyurethane-based aerogel board instead of a honeycomb as the core, which is also pumped out to a pressure of 5 mbar. The prepregs with high-barrier foil MF4 are used as face sheets, and a thermoplastic nonwoven layer is placed between the foil and aerogel foam as an adhesive.

In the last structure, called the "double sandwich", two materials are used as a core: the semi-finished vacuum insulation panel va-Q-vip and the honeycomb NOMEX®. Similar to structure solution 2, a semi-finished VIP is used here that is evacuated to 5 mbar. The prepreg layers are used to create two face sheets and an adhesive in the middle between both core elements.

Depending on the required mechanical properties of the panels, it is possible to work with different prepreg materials. Due to the aim of this research to identify the optimal structures, the choice of the skins fell on the lightweight prepregs, which were used in all new proposals except solution 3. During the feasibility study of this proposal, it was found that the optimal bonding degree between the skin and the core is achieved by using a resin-rich epoxy-glass prepreg. Figure 5 presents the manufactured flat panels with the novel sandwich structure solutions 2 and 4.

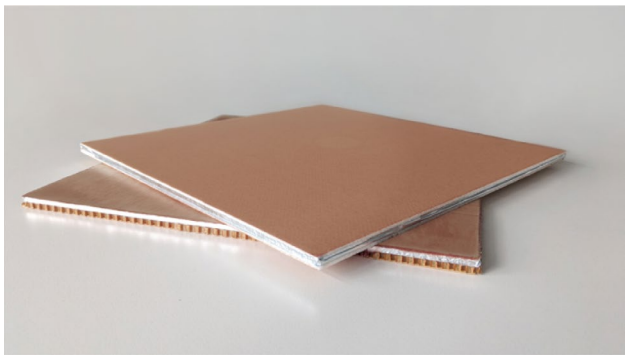

Fig. 5 Examples of the new sandwich structures with integrated vacuum insulation panels

4 Experimental analysis

For this project, an experimental research method was used to analyze the acoustic behavior of new structures. All the new solutions were tested for sound transmission loss and compared with two conventional sandwich panels, one with glass wool insulation and one without. The comparison was made in accordance with the DIN EN ISO 15186–1 standard [20], which involves measuring the sound insulation of building elements using sound intensity. This comparison was used to ensure that the new structures met the acoustic requirements set by conventional structures for wide-body aircraft. In addition, a semi-finished VIP was tested as a stand-alone insulation panel with and without a vacuum to analyze the influence of vacuum on its acoustic properties.

The tests were conducted in the acoustical laboratory at the Diehl Aviation facility located in Laupheim (Fig. 6). The test samples were fixed in a window between the receiving and source rooms. Three globe source dodecahedron loudspeakers were used to create diffuse sound excitation, and the sound was measured using a rotating microphone boom. The source room had a volume of 900 m^3 and the test parts were installed into the test stand using a wooden adapter frame covered by 5 mm thick rubber foil. This was done to enhance its transmission loss and prevent flanking noise. The sound intensity level was measured using scanning methodology, and a sound intensity probe was used during the tests.

The semi-anechoic test chamber was built using a double-wall design and the inner chamber was decoupled from the ground floor and outer walls to prevent noise transfer. The edges of the window cut-out were covered with felt material and taped airtight to prevent any structure-borne noise transfer from the wooden adapter to the test part.

The sound power level on the semi-anechoic side is calculated from the averaged sound intensity of the measured surfaces enclosing the test part and transmission loss according to the following formula:

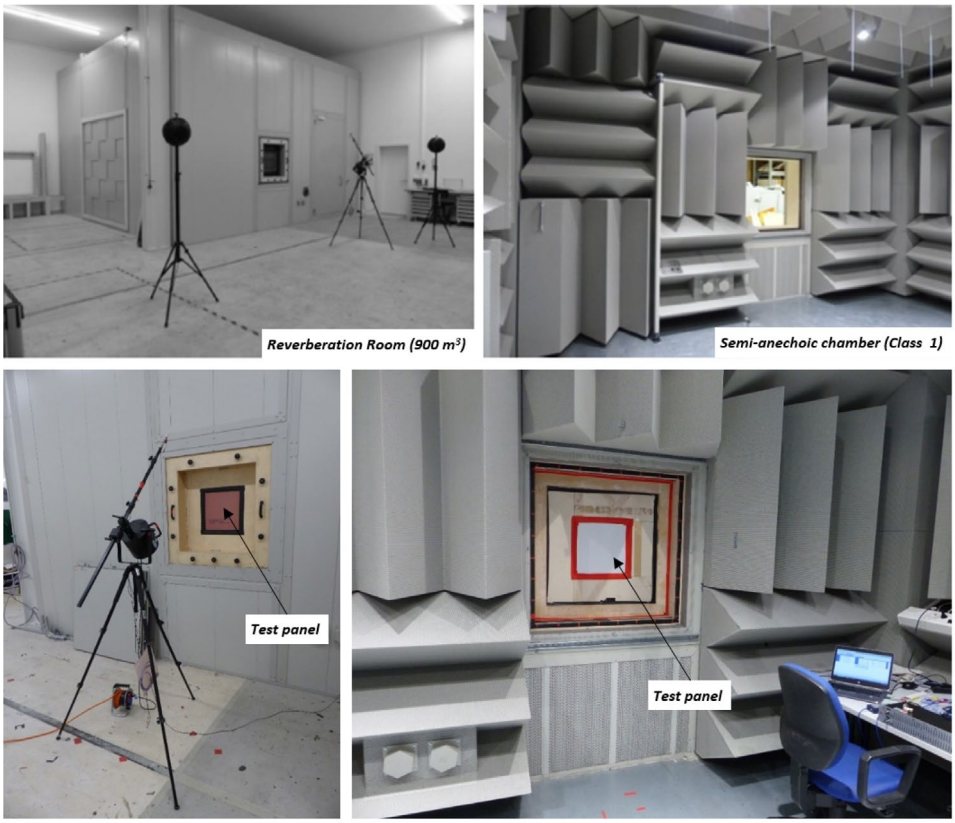

Fig. 6 Acoustical laboratory at Diehl Aviation facilities, Source: Diehl Aviation Laupheim

$$TL = \left(L_p - 6\right) - \left[L_I + 10\log_{10}\left(\frac{S_m}{S}\right)\right]\text{dB} \quad (1)$$

where TL = transmission loss [dB], L_p = the average sound pressure level within a reverberant room [dB], L_I = the average intensity level of the measured surfaces enclosing the test part [dB], S_m = the sum area of all measured surfaces in the semi-anechoic room [m^2], S = the area of the best component on the source side [m^2].

For every structure solution, one test sample with the size of 400 × 400 mm^2 was manufactured, as shown in Fig. 7. The thickness and surface weight differed for each solution, as presented in Table 1.

Due to different surface weights, an additional analysis was performed for the new structure solutions with aligned masses. The masses were corrected in alignment with the surface weight of 1,6 kg/m^2 of the reference panel with the glass wool insulation. The mass alignment was conducted in accordance to the mass law:

$$R = 20 \times \lg\left(\frac{\pi \cdot f \cdot m''}{\rho \cdot c}\right)^2 \text{dB} - 3\text{dB}$$

where R = the sound reduction index [dB], f = the frequency [Hz], m'' = the mass per unit area [kg/m^2], ρ = the density of air [kg/m^3], c = the speed of sound [m/s].

$$\Delta R = 20 \times \lg\left(\frac{m''_{\max}}{m''_{\min}}\right)\text{dB}$$

where $m''_{\max}$ = maximum weight per unit area when comparing several components [kg/m^2], $m''_{\min}$ = minimum weight per unit area when comparing several components [kg/m^2].

The experimental results were utilized to analyze new structures to achieve the required acoustic properties and identify any necessary changes if the structure's performance did not meet the desired standards.

5 Results and discussion

Before conducting the acoustic analysis on the novel sandwich structures with integrated vacuum insulation, an experimental analysis was conducted to determine the effect of vacuum on acoustic values. Noise and vibration energy can be transmitted to the receiver through two different paths—airborne and structure-borne. In this study, the airborne path of the noise flow can be blocked by a vacuum. If the core has a porous structure with open nanoparticles, the noise energy will flow only through the connection points between the powder particles and, therefore, will be limited. To confirm this hypothesis, the semi-finished vacuum insulation panel

Fig. 7 Examples of the test samples: solutions 1, 2a, 3 and reference panel with a glass wool insulation

Table 1 Thickness and surface weight of the test specimens

Sandwich structure	Thickness, mm	Surface weight, kg/m^2
Solution 1 (evacuated honeycomb)	6.5	1.9
Solution 2a (VIP + PES foam)	8.6	2.7
Solution 2b (VIP + PVC foam)	9.0	3.3
Solution 2c (VIP + PMI foam)	8.3	2.8
Solution 3 (Evacuated aerogel)	9.5	3.6
Solution 4 (Double sandwich)	8.2	3.1
Reference panel with glass wool	6.0 + 25 *(glass wool thickness)*	1.6
Reference panel without glass wool	6.0	1.4

was tested for transmission loss, both with and without a vacuum inside the core.

Figure 8 illustrates the significant impact of the evacuated core on transmission loss performance. From 160 Hz and above, the difference in transmission loss values for panels with and without vacuum shows a consistent increase. For instance, at 200 Hz, the difference is 1 dB; at 500 Hz, it's 2 dB; at 1250 Hz, it's 4 dB; and at 2000 Hz, it reaches 9 dB. The evacuated structure reaches its peak effectiveness at 2500 Hz, with a maximum difference of 9.4 dB. After this point, the difference begins to decrease, indicating the limit of the evacuated core's effectiveness. This trend underscores the evacuated structure's effectiveness, not only in the critical frequency area but also in the high-frequency region beyond it.

After verifying the effectiveness of vacuum insulation, the novel sandwich structures with integrated vacuum insulation were analyzed for transmission loss and compared with a conventional structure with and without glass wool insulation.

Due to the fact that the tested panels had different surface weights, the so-called "mass alignment" of the new structures to the reference structure with the glass wool insulation was carried out, which is indicated by a dotted line on the graph. The aligned values make it possible to understand within which acoustic characteristics the new structures lie if their weight coincides with the conventional structure. First of all, the critical range of frequencies between 100 and 2000 Hz was analyzed to determine the acoustic properties of the novel sandwich structures. As stated earlier, the A-weighted noise levels are highest in this range. Thus, attaining transmission loss values that are higher or equal to those of traditional structures is crucial.

Figure 9 shows the transmission loss values of the "evacuated honeycomb" solution in comparison to reference panels with and without glass wool insulation. The glass wool insulation, mounted on the back of the reference panel, only starts to improve its acoustical properties from 1000 Hz, making it almost ineffective at low frequencies. In contrast, the new structure displays efficiency from low frequencies and outperforms both conventional structures with and without insulation up to 1800 Hz. Between 1800 and 4000 Hz, the new solution slows down the pace of growth, performing between the references with and without glass wool insulation. Solution 1 shows the ideal transmission loss curve with

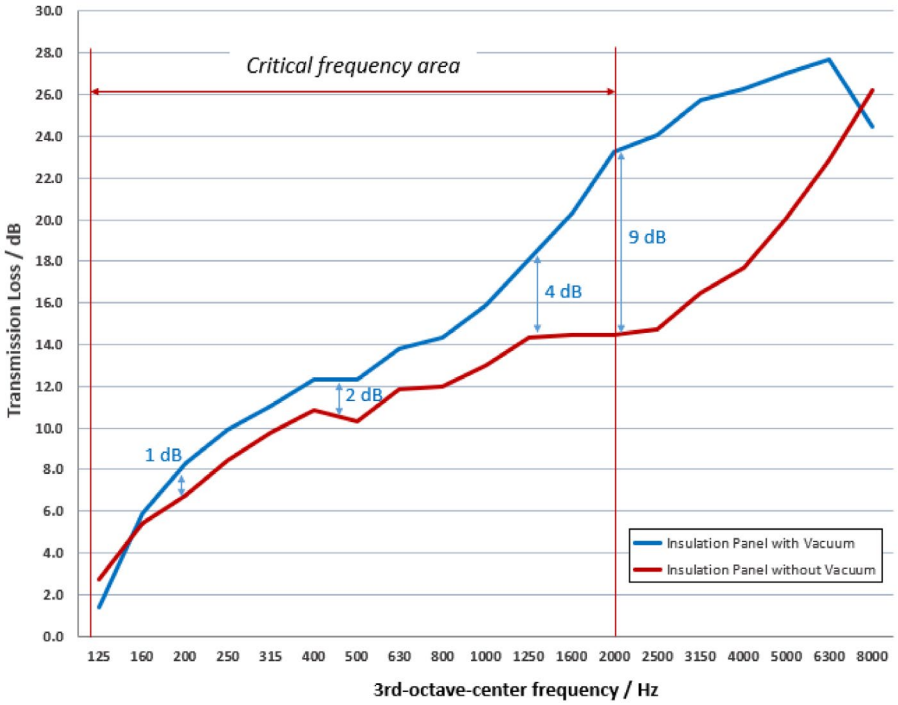

Fig. 8 Transmission loss for insulation panel with and without vacuum

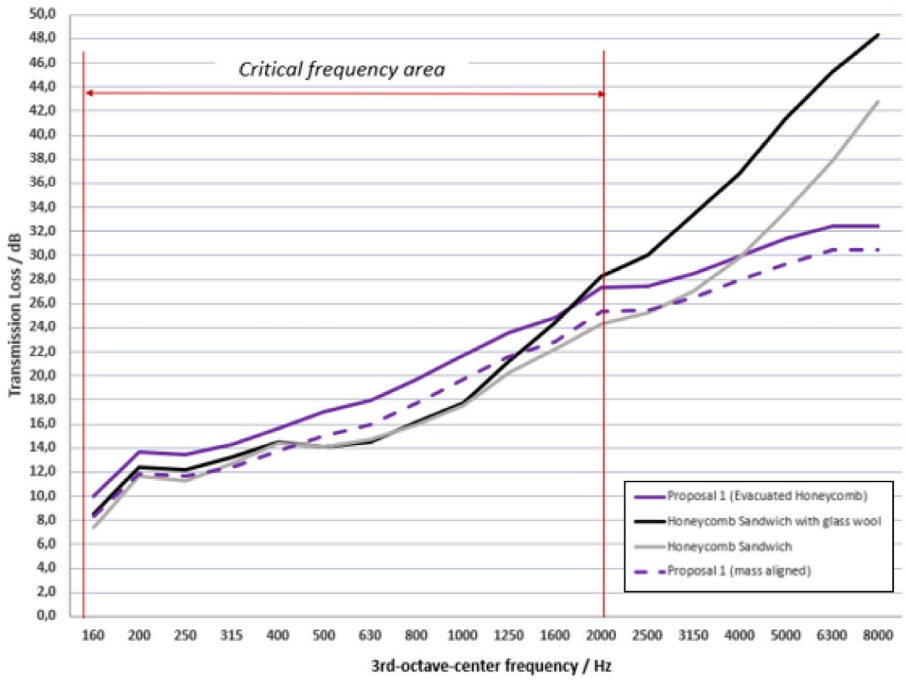

Fig. 9 Transmission loss for solution 1 (evacuated honeycomb)

a linear increase in the mass-controlled area, a dip or at least a flattening above the coincidence frequency, and a subsequent increase. The new solution, with aligned mass, also performs well in the critical frequency area, proving that even a lightweight structure can be considered an acoustically promising construction.

As depicted in Fig. 10, the second structure, in which three different rigid foams were tested in combination with the semi-finished VIP, yielded rather varied results, but what they had in common was the presence of a coincidence dip. To achieve good results, it is important to have the coincidence region outside the critical area. While the dip of

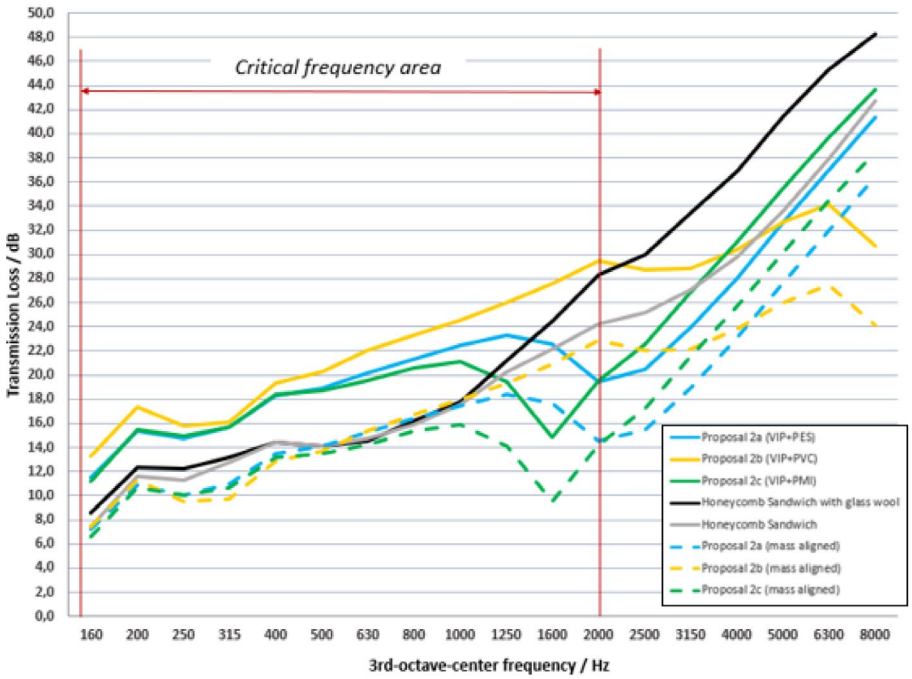

Fig. 10 Transmission loss for solutions 2a, b, and c (VIP + rigid foams)

structure 2b is outside of it, structures 2a and 2c have a dip in the critical area. Comparing these three structures, structure 2c yields the best results, as its transmission loss values with the original mass exceeded those of conventional structures in the critical region. Outside of this area, where the coincidence region begins, the values remain at a sufficient level. The "mass-aligned" structure also showed promising performance, but in some places, its transmission loss values were lower than those of reference structures. Therefore, it is recommended to use a higher surface weight than for a conventional structure, so that the transmission loss values lie between the two yellow continuous and dashed lines. This will enable a competitive solution to the reference panel in the future. Structures 2a and 2c need to be modified to meet the acoustical requirements, and their coincidence dips should be moved to the high frequencies. These modifications are possible if the structures with greater surface weight and lower stiffness are manufactured.

Figure 11 shows that structure proposal 3 with the original surface weight exhibits high transmission loss values across all frequencies. It outperforms a reference panel with glass wool insulation up to 3150 Hz and without insulation up to 6300 Hz. Even with aligned mass, it still yields good results. However, in order to meet the transmission loss requirements for wide-body aircraft, it is necessary to work with a higher surface weight than that of the reference structure or to use a sandwich construction with lower stiffness.

Figure 12 displays the transmission loss values for the fourth solution, "double sandwich." The structure with the original surface weight yields satisfactory results for

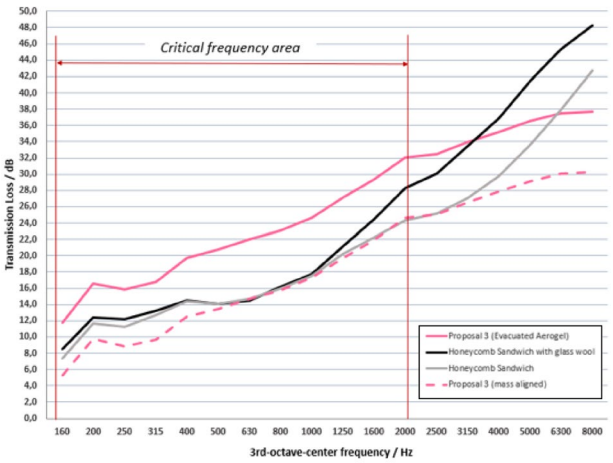

Fig. 11 Transmission loss for solution 3 (evacuated aerogel)

transmission loss, which are higher than the reference panel in the critical frequency area. After the critical area, it enters its coincidence region from 2000 Hz and reaches its coincidence dip at 2500 Hz. The fourth solution with aligned mass drops by approximately 6 dB in comparison to the original mass structure, but still yields good results in the critical frequency area. To move its coincidence-dip to higher frequencies, the lightweight version could undergo the same modifications as increasing the surface weight and decreasing the stiffness of the sandwich structure.

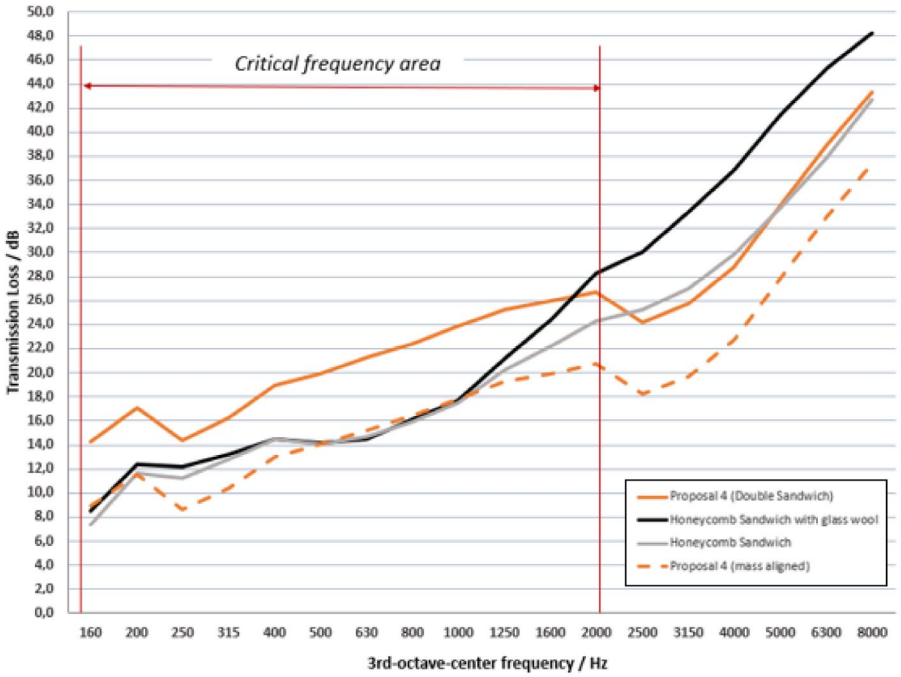

Fig. 12 Transmission loss for solution 4 (double sandwich)

6 Conclusion

Several new structures have been developed to integrate the vacuum insulation concept into the interior structures of the aircraft cabin, with the intention of improving the thermal and acoustic situation in the aircraft. This article presents the acoustical analysis of the novel compounds, in particular, the experimental analysis of their transmission loss. According to the study, creating a vacuum inside the core can enhance transmission loss values, particularly at high frequencies. This method proves to be effective in achieving the necessary acoustic properties.

The new structure solutions demonstrated competitive results in transmission loss in comparison to the conventional interiors with glass wool insulation. Solutions 1 (evacuated honeycomb), 2b (VIP + PVC foam), 3 (evacuated aerogel), and 4 (double sandwich) can be identified as structures that are able to fulfill the transmission loss requirements for a wide-body aircraft. The other structures should be modified to move their coincidence-dip to the high frequencies. The feasible modifications that can be implemented include an increase in the surface weight and a decrease in the stiffness of the sandwich structure.

Author contribution V.L. wrote the main manuscript text. All authors reviewed the manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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