Airborne sound transmission in fluted PVC panels—properties of materials and structures

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Abstract. Authors present a study on transmission loss and absorption of corrugated PVC panels. Tests were conducted in reverberation room and it has been proven, both theoretically and experimentally, that there is a relationship between the panel type and its transmission loss and absorption. Panel size and thickness was also taken into consideration during testing procedure. Analyses also show that the Hansen model was not perfectly accurate when predicting the transmission loss for some of the tested samples.

Keywords: road accidents, sensors, automotive safety

1. Introduction
One of the main blocks of the European Green Deal is Circular Economy Action Plan (CEAP). The plan targets product design, circular economy processes and sustainable consumption. This causes industry to play a leading role in the ecological transition by reducing its carbon and material footprint. Further actions include implementing circularity across the economy [1], also by management of waste, especially plastics or polymers materials [2]. Due to this fact, the industry uses waste polymers materials more and more for automotive, aeronautics and space applications considering its mechanical properties and low weight [3]. Polyvinyl Chloride (PVC) is one of the most popular polymers in the industry, having a versatile nature and it is broadly applicable to technical solutions including in building, transport, packaging, electrical/electronic and healthcare applications, as well as everyday items. Although recent works have shown that PVC production harms the natural environment and human health [4,5], it is still universally used and will be used in the future.

A critical problem during the design, construction and exploitation of vehicles, buildings or machinery is not only the energy efficiency, but also good fire or sound insulation. Determination of the sound absorption (absorption coefficient - \( \alpha \)) and sound transmission loss (TL, insulation parameter) of materials have become a necessity due to the technical progress and thus increased number of noise sources. Nowadays, noise pollution is one of the world’s most leading environmental problems and about 40 % of the UE residents are always exposed to noise [6]. The latest research has shown, that long-term exposure to noise in urban areas has negative impact on health, causing 12 000 premature deaths and contributes to 48 000 new cases of ischaemic heart disease every year across Europe [7]. Different actions are taken to ensure reduction of noise pollution, for example by correcting the noise...
wave propagation to exposed people, by using panels, barriers and screens to block the direct path of sound. Some of the earliest works focus on PVCs acoustic insulations in different forms: foam or fiber or composites or a mix with additives. Cheng et al., pointed out that the addition of flame retardants polymer composite to PVC does not influence the acoustic insulation[8]. Yang et al., studied the honeycomb weave fabric/PVC composite material, showing that repetitions of weave have great influence on the acoustic insulation [9]. Liu et al., noticed that adding fillers to PVC deteriorates mechanical properties and has little effect on the acoustics [10]. Huang et al. shows that PVC fiber panels can reduce the noise of the air conditioning more effectively, as compared to an only absorption material [11]. Xue et al., found that sound insulation cover made from PVC/PET fiber can effectively reduce the noise of the compressor [12]. Pulgern et al., studied the WPVC composite panels, indicating that those panels reduce sound pressure level by approximately 15-19 dB [13]. The other works focus on sound-absorption and sound insulation of the PVC in different building applications, like floor covering [14], blocks mixed with fine PVC [15], PVC foam materials [16] or PVC windows [17]. This resulted in several papers about PVC capacity for acoustic barriers for machineries or transport system. Fang et al., found that PVC panels caused noise reduction in refrigerators [18]. Agyeman-Prempeh [19] studied the reduction of noise levels of coconut fiber combined with polyvinyl chloride as sound insulating panels. Moreover, the noise insulation system for high-rise building by using PVC foam on wood, concrete and glass were studied [20]. The results for indoor showed that concrete mixed with PVC foam has the highest noise insulation effectiveness. Roschke and Esche examined another acoustics parameter of materials - insertion loss (IL) and have studied various polymer barriers [21]. Mac Bain et al., [22] studied barrier from various recycled plastic and found its performance to be better at lower frequencies (100 to 250 Hz). Combination of tire rubber, PVC grains and nylon fibers with polyurethane as a binder resulted in good absorption coefficient [23]. Another way to improve the performance of noise barrier was to modify its shape by using additional elements on the top of barrier, made from different material, like T-shaped and Y-shaped caps [24,25], cylindrical caps [26,27], multiple-edge caps [28] and tilted caps [29]. All of these design variants changed the effective acoustic length of the barrier or modified the diffraction points of the screen. Also the application of scatters acoustic barriers in cities was studied. Its aim was to reduce the transmitted transport noise that affected buildings [30].

Corrugated or fluted panels have experienced increasing number of application as construction elements for roofs, claddings and walls of modern industrial buildings as well as acoustics road panels. The range of profile shapes may be large and intended for different situations. As corrugated and fluted panels are so widely used for industrial applications, its acoustics parameters are of considerable interest. Engineers need this information to estimate expected community noise levels at the building or construction design stage. The corrugated or fluted panels are generally referred to as orthotropic because they are more stiff along one direction than the other. Heckl’ [31,32] analyzed sound transmission through orthotropic panels. He derived some approximate solutions for transmission coefficient for panels of infinite extent with the effects of panel damping neglected. The earliest works focus on the calculation of moments of area of the profiled metal sheet [33], on the sound absorption and TL of single metal skin cladding with varying profiling and thickness [34] or on the dependences of the profiling to critical frequency [35] or application the finite element and boundary element analysis to predict the TL of a corrugated and fluted steel sheet [36].

Due to the development of the plastics processing industry, those materials are used even more frequently. Manufacturing specifics and material additives caused the acoustical parameters for different type of plastics to remain in the cognitive phase. Therefore, the main goal of this paper is study the absorption coefficient and sound insulation of fluted PVC panels, taking into account the panel size and thickness. Measured results are also compared with the theoretical model. The acoustical analysis of a single fluted PVC panels could be the next step to find a method for improving their sound insulation capacity.
2. Materials and methods

2.1. Analytical model infinite and finite homogeneous orthotropic panel

According to Hansen [38] for thin, homogeneous, orthotropic panels, the wave impedance $Z_{\text{orth}}$ can be expressed by:

$$Z_{\text{orth}} = j\omega m \left[ 1 - \left( \frac{f}{f_{c1}} \cos^2 \varphi + \frac{f}{f_{c2}} \sin^2 \varphi \right) \sin^4 \theta \left( 1 + jn \right) \right],$$  \hspace{1cm} (1)

where:

$$f = \frac{\omega}{2\pi},$$ \hspace{1cm} (2)

$$f_{c1} = \frac{c^2}{2\pi} \frac{m}{B_x},$$ \hspace{1cm} (3)

$$f_{c2} = \frac{c^2}{2\pi} \frac{m}{B_y},$$ \hspace{1cm} (4)

The panel loss factor is $n$, the frequency of the panel is $\omega$, the mass per unit area of the panel is $m$, the speed sound in air is $c$ and the angles $\theta$ and $\varphi$ are defined in Figure 1.

![Figure 1. Panel coordinate system showing incident wave.](image)

The $f_{c1}$ and $f_{c2}$ are known as the critical frequencies, at which the speed of bending wave propagation is equal to the speed of acoustic wave propagation in the surrounding medium. The corrugated panel commonly found in constriction engineering are stiffer along the direction of the ribs than across the ribs. Orthotropic panels are characterized by a range of bending wave speeds caused by the two different values of the cross-sectional second moment of area per unit width. Therefore, for thin corrugated trapezoidal panel the bending stiffness about X and Y axis, $B_x$ and $B_y$, in Equation (3) and (4) are given by:

$$B_x = \frac{Eh}{(1 - \nu^2)L} \sum_n b_n \left[ z_n^2 + \frac{h^2 + b_n^2}{24} + \frac{h^2 - b_n^2}{24} \cos^2 \theta \right],$$ \hspace{1cm} (5)

$$B_y = \frac{Eh^3}{(1 - \nu^2)L} \sum_n b_n,$$ \hspace{1cm} (6)

where $L$ and $b_n$ are defined in Figure 2, and $\nu$ is Poisson’s ratio, $z_n$ is the distance from the neutral axis of the panel cross section to the center of the panel segment $n$, where neutral axis is defined such that:

$$\sum_n b_n z_n = 0,$$ \hspace{1cm} (7)
The transmission coefficient for a wave incident at angle ($\theta, \varphi$) to the panel is given in terms of the panel impedance by

$$\tau_{\theta \varphi} = \left[1 + \frac{Z_{\text{arch}} \cos \theta}{Z_{\rho \rho}}\right]^{-2},$$

(8)

The transmission coefficient for normal incidence, $\tau_n$, is found by substituting $\theta=0$ in Equation (5). The diffuse field transmission coefficient, $\tau_d$, is found by determining a weighted average for $\tau(\theta, \varphi)$ over all angles of incidences using the following relationship:

$$\tau_d = \frac{1}{\pi} \int_0^{2\pi} \int_0^{\pi/2} \tau(\theta, \varphi) \cos \theta \sin \theta d\theta.$$

(9)

The $\cos \theta$ term accounts for the projection of the cross-section area of the panel wave that is incident upon a unit area of wall at an angle, $\theta$, to the wall normal. The $\sin \theta$ term is a metrical coefficient, which arises from the use of spherical coordinates. For orthotropic panel Equation (3) becomes:

$$\tau_d = \frac{2}{\pi} \int_0^{\pi/2} \int_0^1 \tau(\theta, \varphi) d(sin^2 \theta),$$

Substituting Equation (5) into (7) gives for the diffuse field transmission coefficient for an infinite panel, like given by Heckl [33]:

$$\tau_d = \frac{2}{\pi} \int_0^{\pi/2} \int_0^1 \frac{d(sin^2 \theta)}{1 + \frac{Z_{\rho \rho}}{Z_{\text{arch}} \cos \theta}} d\varphi.$$

(11)

The transmission loss is commonly observed by means of testing in a reverberation room. The transmission loss is usually measured by placing the panel in a window between two adjacent reverberant rooms. Noise is introduced into one of the rooms (source room) and part of the sound energy is transmitted through the test panel into the second room (receiver room). So, during measurements, panels are not of infinite extent.

It is possible to perform numerical integration of the Equation (11) for various range of frequency and transmission loss can then be calculated by substituting $\tau_d$ for $\tau$ in Equation (12), considering that the angle $\theta$ is dependent on the size of the panel (and $\theta=0$ - the acoustic wave is in the direction angle $\theta$ to the normal to the panel surface). So, to reduce the extent of the numerical calculations the various approximation can be made [34]. At frequency $f = f_c/2$, it may be assumed that the panel behaves as a limp mass and transmission loss $TL$ can be calculated from:

$$TL = 20\log_{10} f_{c1} m - 54, (dB)$$

(12)

For $f_{c1} < f < f_c$ the following approximation can be used:

$$TL = 20\log_{10} f + 10 \log_{10} m - 10 \log_{10} f_{c1} - 20\log_{10} \left[\log_{10} \frac{f}{f_{c1}}\right] - 13.2, (dB)$$

(13)

For $f=2f_c$ transmission loss TL is calculated from:

$$TL = 10\log_{10} m + 10\log_{10} f_{c2} - 17, (dB)$$

(14)

Above $2f_c$ the TL is given by:

$$TL = 20\log_{10} f + 10\log_{10} m - 5\log_{10} f_{c1} - 5\log_{10} f_{c2} - 23, (dB)$$

(15)

The transmission loss between $0.5f_{c1}$ and $f_{c1}$ and also between $0.5f_{c2}$ and $2f_{c2}$ is approximated by connecting points corresponding to frequency with a straight line. It is generally accepted that these formulas provide reasonably accurate results and are satisfactory for most commonly used orthotropic building panels, like corrugated or fluted panels.
2.2. Studied panels

The transmission loss between $0.5f_{c1}$ and $f_{c1}$ and also between $0.5f_{c2}$ and $2f_{c2}$ is approximated by connecting points corresponding to frequency with a straight line. It is generally accepted that these formulas provide reasonably accurate results and are satisfactory for most commonly used orthotropic building panels, like corrugated or fluted panels.

![Figure 3. Panel’s profiles studied in this work.](image)

Table 1. The parameters of studied fluted PVC panels.

| Panel | Panel thickness [mm] | Commercial mark | Young’s modulus [GPa] | Poisson’s Ratio | Cross-sectional panel height [mm] |
|-------|----------------------|-----------------|-----------------------|----------------|----------------------------------|
| GW270 | 3.5                  | light           | 2.4                   | 0.4            | 0.150                            |
| GW300 | 5.5                  | light           | 2.4                   | 0.4            | 0.115                            |
| GW580 | 7.0 Z-type           |                 | 2.4                   | 0.4            | 0.240                            |
| GW700 | 9.0 Z-type           | Strengthened*   | 2.4                   | 0.4            | 0.250                            |
| GW4100| 12.0 Z type          |                 | 2.4                   | 0.4            | 0.254                            |

Studied commercial fluted plastic panels are manufactured in the process of molding, otherwise known as co-extrusion of polyvinyl chloride with additive substances refining its parameters (toughness modifiers, UV and thermal stabilizers etc.). The sheet are manufactured using extrusion molding method as monolithic profiles or co-extrusion method, where core is made from a recycled construction type PVC with an outer layer of the default PVC material. Interlocking connections at the edges allow for producing panels of various width.

2.3. Transmission loss measurements

The studies were done in reverberation rooms of the Institute of Power Engineering, OTC – Thermal Technology Branch „ITC” in Lodz. The panels were tested by mounting in an aperture between two reverberant test chambers. The measurement were carried out in accordance with the current ISO standard: 10140-2:2021 Acoustics — Laboratory Measurement of Sound Insulation of Building
Elements — Part 2: Measurement of Airborne Sound Insulation and 10140-4:2021 Acoustics — Laboratory measurement of sound insulation of building elements — Part 4: Measurement procedures and requirements. Both of the source and receiving rooms were constructed to give a reverberant sound field with volumes of $V=237 \text{m}^3$ and area of 231.5 $\text{m}^2$ for each.

The tested PVC panels (size $1 \times 1 \text{m}$) in a frame were fixed to an aperture opening between the two reverberation rooms. Panels had to be cut down to fit the aperture opening dimension. Edges of each specimen were sealed tightly by means of sound-proof silicone sealant.

A white noise was produced by using all-in-one DO 203 omnidirectional noise source, including a dodecahedron loudspeaker with a power amplifier and a noise generator. Measured parameters were sound pressure level-in both rooms and reverberation time ($\text{RT}_{60}$) in the receiver room. $\text{RT}$ is defined as the time required for the sound source to reduce to a level of 60 dB when it is turned off in a closed room. Reverberation times have been measured in the frequency range of 50Hz to 10000Hz. Sound pressure levels in the rooms were sampled by means of two sets of 1/2 inch microphones, each coupled with a pre-amplifier and fed to SVAN 958 analyzer for 1/3 octave band spectrum analysis. The background level was measured and calibrated using the Bruel & Kjaer 4231 calibrator before and after the measurement procedure. Moreover, the environmental conditions were also monitored by recording the temperature, relative humidity and atmospheric pressure.

Transmission loss was obtained using the equation for the transmission of sound between two reverberant spaces:

$$TL = \bar{L}_s - \bar{L}_r - 10 \log \left( \frac{S}{A} \right) \, (dB)$$

where:

- $\bar{L}_s$ - spatial average sound pressure level in the source room, dB
- $\bar{L}_r$ - spatial average sound pressure level in the receiver room, dB
- $TL$ - reverberant field transmission loss, dB
- $S$ - area of the transmitting surface, $\text{m}^2$
- $A$ - room constant in the receiver room, using the Sabine equation: $A=0,16 \times (V/\text{RT}_{60})$, $\text{m}^2$

2.4. Sound absorption measurements

Second phase of test considered examination of absorption coefficient of studied PVC panels. For every test around 10 $\text{m}^2$ of panel were placed on the floor of the reverberation chamber according to standard ISO 354:2005 - Acoustics — Measurement of sound absorption in a reverberation room. Interlocking connections allowed to build the PVC sheet of approximately 5m in width. Prior to testing, panels were inserted into reverberation room for 24 hours to acclimatize to the atmospheric conditions in chamber - Figure 4. The measurements were done using rotating microphone boom Nor265 with an integration time of 30s for each microphone position. The 1/3 octave bands were measured using Nor140. Microphone was calibrated before the acoustic test.

The reverberation time of the room was measured in two conditions:

- when the reverberation room was empty;
- when the studied panels were inside.

In general, once material is placed into the reverberation room, a lower reverberation time can be observed. The difference in reverberation times is a measure of the amount of absorption caused by the studied panels.
Figure 4. Reverberation room with studied panel.

3. Results and discussion

3.1. Transmission loss

Figure 5 shows the measured TL values for the studied fluted PVC panels. For single panels, the transmission loss is influenced by four factors: size, stiffness, mass, and damping. In Figure 5 similar TL spectrums are observed. In the low and medium frequencies, the three visible peaks are observed: around 100Hz, 160Hz and 315Hz and dips at 125Hz and 200Hz. These dips can be interpreted as specific vibrational mode of the panel or the lowest acoustic coincidence of the panels. At very low frequencies the transmission depends heavily on stiffness, as it can be observed for GW700 panel under 63Hz. With greater bending stiffness and shorter span, the transmission loss is the highest. But the measured transmission loss of all fluted panels shows no distinct lower critical frequency shift with the change of panel shape. The low-frequency response of panels of different depths is similar. However, at the frequency of the incident, the wave increases and the panels will resonate mechanically at a series of frequencies, like resonance or eigenfrequencies. This is because of the fact that the panels have a finite boundary and edge fixing. The resonance frequencies consist of a fundamental frequency and integer multiples of this fundamentally called harmonics. At the fundamental resonance, \( f_{1,1} \), the sound transmission through the panel is enhanced and the transmission loss drops significantly. Adding the damping material to the panel usually reduces the resonance amplitude. The fundamental resonance frequencies, \( f_{1,1} \), of a supported rectangular orthotropic panel of width \( a \) and length \( b \) were calculated according to:

\[
f_{1,1} = \frac{n}{2m_{1/2}} \sqrt{\left(\frac{B_a m^4}{a^4} + \frac{B_b n^4}{b^4} + \frac{B_{ab} k^2 n^5}{a^2 b^2}\right)},
\]

(17)

\[
B_{ab} = \frac{1}{2} (B_a \nu + B_b \nu + G h^3 / 3),
\]

(18)

where, \( G = E/(2(1+\nu)) \) is material modulus rigidity, \( E \) is Young’s modulus, \( \nu \) is Poisson’s ratio, \( a \) and \( b \) are panel dimension (Table 3).
Above 800 Hz the sound transmission depends on the mass inertia of panels and is independent of its stiffness. In this frequency region, part of the acoustic energy is transmitted through the panel and the remainder is reflected. A direct relationship exists between panels' weight and the resulting transmission loss. If the structure of panels is of considerable weight, the sound insulation could not be improved only by a small increase in mass. However, increasing panel mass lowers resonance frequencies and raises the critical frequencies. For the studied panels, as an orthotropic panel, two critical frequencies were calculated, according to Hansen, and shown in Table 2.

For these type of panels the critical frequency is dependent on the direction of the incident acoustic wave. The range of critical frequencies is bounded at the lower end by the critical frequency corresponding to a wave travelling in the panel most stiff direction and at the upper end by the critical frequency corresponding to a wave propagating in the least stiff direction.

Table 2. Calculated properties of fluted (orthotropic) PVC panels.

| Panel type | Surface weight [kg/m²] | Bending stiffness [kgxm²/s²] | Effective bending stiffness [kgxm²/s²] | Critical frequencies [Hz] | First resonance frequency [Hz] |
|------------|------------------------|------------------------------|--------------------------------------|--------------------------|-------------------------------|
| GW270      | 7.2                    | 44599                        | 13.7 780.5                           | 238                      | 13594 136                    |
| GW300      | 14.3                   | 35282                        | 65.8 1523.8                          | 377                      | 8728 86                      |
| GW580      | 23.6                   | 224863                       | 142.45659.6                          | 192                      | 7621 168                     |
| GW700      | 29.4                   | 255173                       | 282.98496.1                          | 201                      | 6036 161                     |
| GW610      | 22.6                   | 219878                       | 266.87658.5                          | 190                      | 5450 170                     |
| GW448      | 30.7                   | 529198                       | 692.219139.6                          | 143                      | 3943 227                     |

For these type of panels the critical frequency is dependent on the direction of the incident acoustic wave. The range of critical frequencies is bounded at the lower end by the critical frequency corresponding to a wave travelling in the panel most stiff direction and at the upper end by the critical frequency corresponding to a wave propagating in the least stiff direction.

Calculated panels properties allowed for a comparison of the theoretical values and measurements result – as shown in Figure 6. It can be seen that the Hansen’s scheme provides a reasonable TL prediction in agreement with measured results for studied GW270 and GW300. For the rest of the panels, the predictions differ from the measurement overestimating at higher frequencies. There are also differences between theory and experiment at very low frequencies. The first resonance frequency of the studied panels varies from 80Hz to 230Hz. As this theory is only applicable to frequencies well above the first
resonance frequency of the panel, some discrepancies are expected. However, this approach that was developed by Hansen is unable to account for localized vibration effects. The following behavior is especially to be noted. A very stiff construction tends to move the first resonance to higher frequencies but, at the same time, the frequency of coincidence tends to move to lower frequencies. Thus, the extent of the mass law region depends on the stiffness of the panel.

The orthotropic plate theory predicts a shift of critical frequency (especially $f_{c2}$), which would make the TL below the critical frequency higher. Such case was not observed in experimental data. The transmission loss of orthotropic panels is strongly affected by the existence of a critical frequency range. In this case the coincidence region may extend over two decades for common fluted panels. Therefore, this type of panels should be avoided where noise control is crucial. Although it can be shown that damping of these panels can improve by adding a damping material.

3.2. Absorption coefficient

The results of the absorption coefficients are given in at Figure 7 in 1/3-octave bands. The results are the arithmetic average of the three measurements and calculations. The studied panels have a good acoustic absorption properties in selected frequencies. If the material’s sound absorption coefficient is above 0.4, it is considered to have good noise absorbing properties. For studied panel, some dependencies between absorbing coefficient and their construction were found. It can be argued that the shape of panel matters here. The similar spectrum for GW700, GW610 and GW580 were observed, with $\alpha \approx 0.4 \div 0.45$ at 125Hz. For GW610 panel, the second peak was observed at 200Hz ($\alpha \approx 0.3$), similar to

![Figure 6. Measured and predicted transmission loss (TL) of studied PVC panels](image)
GW710 ($\alpha \approx 0.25$ at 315Hz). For GW710 panel, an increase in the absorption coefficient is observed between 2000-8000Hz. For GW270, GW300 and GW448 poor absorption was observed below this range ($\alpha \approx 0.3$). However, an advantage here is an increased absorption in the range of 100-400Hz. Higher absorption coefficient was observed in the frequency range with a decrease of transmission loss. The absorption properties of the studied fluted PVC panels are strictly connected with its resonance. In studied cases, this dip could correspond to the resonance frequency associated with the space between the ribs and wave propagation in the plane of the panel. This frequency is independent of panel size, and although it can be calculated reasonably accurately, the magnitude of the corresponding dip cannot be calculated at this research stage.

Figure 7. Measured absorption coefficient of studied PVC panels

4. Conclusions
This paper discusses the PVC fluted panels and its transmission loss as well as absorption coefficient. Authors proved that those two quantities are dependent on the type of panel, both theoretically and experimentally. At low frequencies, there were minor differences between the Hansen model and experimental data. Authors managed also to observe a weakness of the Hansen model when it comes to localized vibration effects—recorded sound spectrum was not in line with the orthotropic plate theory.

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