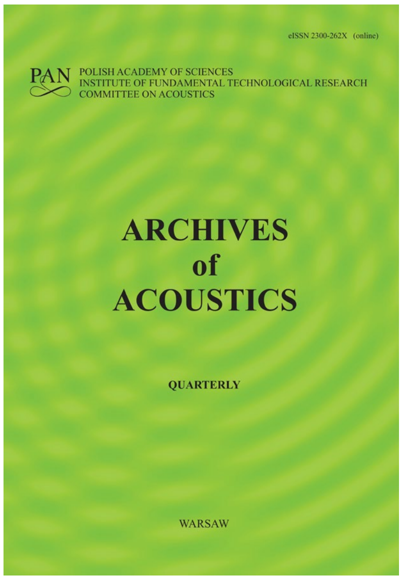
JOURNAL PRE-PROOF

This is an early version of the article, published prior to copyediting, typesetting, and editorial correction. The manuscript has been accepted for publication and is now available online to ensure early dissemination, author visibility, and citation tracking prior to the formal issue publication.

It has not undergone final language verification, formatting, or technical editing by the journal's editorial team. Content is subject to change in the final Version of Record.

To differentiate this version, it is marked as "PRE-PROOF PUBLICATION" and should be cited with the provided DOI. A visible watermark on each page indicates its preliminary status.

The final version will appear in a regular issue of *Archives of Acoustics*, with final metadata, layout, and pagination.



Title: Flanking sound transmission in massive-lightweight connections

Author(s): Agnieszka Wójtowicz, Tadeusz Kamisiński, Jarosław Rubacha

DOI: https://doi.org/10.24423/archacoust.2026.4330

Journal: *Archives of Acoustics*

ISSN: 0137-5075, e-ISSN: 2300-262X

Publication status: In press

Received: 2025-09-11

Revised: 2026-01-08

Accepted: 2026-01-12

Published pre-proof: 2026-01-19

Please cite this article as:

Wójtowicz A., Kamisiński T., Rubacha J. (2026), Ultrasonic Estimation of Pressure Dependent Nonlinearity Index in Liver, *Archives of Acoustics*, https://doi.org/10.24423/archacoust.2026.4330

Flanking sound transmission in massive-lightweight connections

Agnieszka WÓJTOWICZ* https://orcid.org/0009-0004-2943-351X, Tadeusz KAMISIŃSKI https://orcid.org/0000-0002-8580-2402, Jarosław RUBACHA https://orcid.org/0000-0001-7624-8879

AGH University of Krakow, Kraków, Poland

*Corresponding Author: awojtowicz@agh.edu.pl

Assessing the impact of flanking sound transmission is one of the most significant challenges in the process of designing building partitions. Acoustic parameters declared by manufacturers of lightweight systems are subject to errors of up to several decibels – and in the case of inaccurate construction on site, these differences can reach even higher values. One factor contributing to this is the phenomenon called flanking sound transmission, which involves the transmission of acoustic energy through partitions connected to a partition directly dividing two adjacent rooms. For this reason, estimating the resultant acoustic insulation of a partition, taking into account the flanking paths, is crucial early in the design process to ensure compliance with the requirements outlined in standard recommendations and literature. Currently, there are regulations and studies that provide guidance on calculating the estimated reduction in acoustic insulation due to flanking transmission. However, in practice, situations arise that have not yet been addressed in standards or literature. Examples include partitions made of plasterboard, which are among the most common types of partition walls in Poland, yet are not covered by current normative procedures, as well as glass systems. This study aims to explore this topic further by analysing the impact of combining a massive partition with flanking lightweight partitions for selected structures (glass, plasterboard with single or double panelling, with full or partial sound-absorbing material infill, and without infill) and connection types.

Keywords: building acoustics, flanking sound transmission, sound insulation, statistical energy analysis.

1. Introduction

When estimating the sound transmission index of a partition it is essential to take into consideration not only the direct partition between rooms, but also all the alternative paths in which the sound is transferred, known as flanking paths. These paths can significantly decrease the resultant sound insulation of a direct partition, particularly if the flanking partitions provide weaker insulation or have lower density than the direct partition. A methodology for estimating the impact of flanking transmission for several types of partitions is described in the standard

EN 12354-1 (International Organization for Standardization [ISO], 2017); however it does not cover all types of partitions encountered in practice. Although there have been numerous publications on the matter, most of them discuss flanking transmission through timber or CLT partitions (Neusser, Bednar, 2022) which are not among the popular building materials in Poland, where gypsum board partitions prevail. Less frequently other constructions are discussed, such as gypsum board partitions or double walls (Crispin *et al*., 2019; Crispin *et al*., 2017; Gerretsen, 2015; Schoenwald, 2008). This paper, however, examines a previously unstudied case: the use of lightweight gypsum board and glass partitions and their impact on the resultant sound insulation of a massive partition, using Statistical Energy Analysis. Several cases are described – case 1 shows a basic situation of a single concrete partition between two rooms without flanking paths, case 2 includes a single-cladding gypsum-board based flanking partitions and cases 3-5 focus on double-cladding partitions without filling in the cavity between plates, with a cavity partially filled with a sound-absorbing material and with a cavity fully filled with a sound-absorbing material. Case 6 focuses on glass flanking partitions. All of the cases show results for a C, T and H-shaped connections.

2. Statistical Energy Analysis

Statistical Energy Analysis (SEA), widely described by Craik (1996) as well as Crocker and Price (1969), is one of the methods of calculating sound and vibration transmission through a given acoustic system. The general rule of SEA is to create a model of a system consisting of smaller subsystems, and then determine the equilibrium equations describing the energy flow between them. A subsystem is a set of modes with the same properties and similar modal energy; it represents a physical object, such as a partition, a room or a void. The measure of sound in a room or vibration of a partition in SEA is energy. The value of power transferred from subsystem i to subsystem j (W_{ij}) depends on the sound energy in the transmitting subsystem E_i, the angular frequency ω and the energy loss factor η_{ij} (Formula 1).

$$W_{ij} = E_1 \omega \eta_{ij} \tag{1}$$

Some of the energy leaving the subsystem is lost as heat or transferred to a different partition that is not a part of a system (W_{id}, W_{jd}), and some is radiated and transmitted to other subsystems (W_{ij}, W_{ji}). The energy entering the subsystem includes the external excitation (W_I) and the transmission from other subsystems (W_{ji}, W_{ij}).

In the SEA model, it is assumed that the energy is distributed evenly in all frequency bands, so that each band must contain an appropriate number of modes. The number of modes in a frequency is defined by the mode density *n(f)*, and in a band as the number of modes *ΔN* of the subsystem. The mode density depends on the type of wave and the geometry, material and boundary conditions of the subsystem. The number of modes depends on the width of the frequency band.

All modes in one subsystem and frequency band are excited equally, and their response is independent of the others. The mode density, according to Craik (1996), Kleiner and Tichy (2014) and Schoenwald (2008), is described as follows:

a. for plates:

$$n(f) = \frac{2\pi f S}{c^2} \tag{2}$$

where *S* refers to surface of the room and *c* is the wave speed. For bending waves on thin plates modal density is described as:

$$n(f) = \frac{\pi S f_c}{{c_0}^2} \tag{3}$$

b. for rooms:

$$n(f) = \frac{4\pi f^2 V}{c_0^3} + \frac{\pi f S'}{2c_0^2} + \frac{L'}{8c_0} \tag{4}$$

where *V* is the volume of the room, *S'* is the total surface of the room and *L'* is the total length of all the edges in the room.

c. for cavities:

For thin space of void and for low frequency below the eigenfrequency of the first cross mode, found using formula (5):

$$f_{m,n,o} = \frac{c_0}{2}\sqrt{\frac{m^2}{l_x^2} + \frac{n^2}{l_y^2} + \frac{o^2}{l_z^2}} \tag{5}$$

where *m*, *n*, *o* are positive integers (Craik, 1996; Schoenwald, 2008) and l_x, l_y, l_z are the dimensions of the void, the system is treated as two-dimensional and formula (2) should be used, whereas above that frequency the void is treated like a room, which implies using formula (4).

The number of modes in a given frequency band is calculated using formula (6).

$$N = n(f)\Delta f \tag{6}$$

where

$$\Delta f = 0{,}23 f_m \tag{7}$$

for 1/3 octaves and

$$\Delta f = 0{,}707 f_m \tag{8}$$

for 1/1 octave bands, where f_m is the centre frequency of a given frequency band.

2.1. Damping

The key element of calculating energy in individual subsystems is determining the energy loss coefficients, which define the energy flow between subsystems. The loss coefficient is the fraction of energy lost by the subsystem in one cycle. Damping is described by several types of loss factors: internal loss factors $\eta_{i,d}$, coupling loss factors η_{ij} and total loss factors η_i, where

$$\eta_i = \sum_{j=1}^{n} \eta_{ij} + \eta_{i,d} \tag{9}$$

2.1.1. Coupling Loss Factors (CLF)

The CLF parameter describes the attenuation due to the coupling between subsystems. It is the fraction of energy transferred from one subsystem to another in one cycle, described generally by the formula (10).

$$\eta_{ij} = \frac{W_{ij}}{E_i \omega} \tag{10}$$

The formulas for connections between different types of subsystems are as follows:

a) energy transfer from a room to a partition

$$\eta_{ij} = \frac{\rho_0 c_0^2 S_j f_{c,j} \sigma_j}{8\pi f^3 V_i \rho_{s,j}} \tag{11}$$

b) energy transfer from a partition to a room

$$\eta_{ij} = \frac{\rho_0 c_0 \sigma_i}{\omega \rho_{s,i}} \tag{12}$$

c) energy transfer between partitions

$$\eta_{ij} = \frac{l_{ij} c_{g1} \tau_{ij}}{\omega \pi S_i} \tag{13}$$

d) energy transfer from a cavity to a partition

$$\eta_{ij} = \frac{\rho_0 c_0 f_{c,j} \sigma_j}{4\pi f^2 \rho_{s,j}} \tag{14}$$

e) energy transfer from a cavity to a room

$$\eta_{ij} = \frac{\tau_{ij}}{4\pi} \tag{15}$$

f) energy transfer between rooms

$$\eta_{ij} = \frac{c_0 S \tau_{ij}}{8\pi f V_i} \tag{16}$$

where $f_{c,j}$ – critical frequency for the *j*-element, S_j is the surface of the *j*-element, V_i is the volume of the source room, σ_j is the resonant radiation efficiency of the *j*-element, $\rho_{s,i/j}$ is the surface mass of element *i*/*j*, τ_{ij} is the transmission coefficient from element *i* to *j*, $c_{g,i}$ is the corrected group velocity and l_{ij} is the length of the connection between elements *i* and *j*.

If the coupling loss factor from subsystem *i* to *j* is known, the energy flow from subsystem *j* to *i* can also be calculated using formula (17).

$$\eta_{ji} = \frac{\eta_i \eta_{ij}}{\eta_j} \tag{17}$$

Transmission coefficient can be calculated using formula (18) as stated by Craik (1996).

$$\begin{aligned}\tau_{ij} = \left(\frac{\rho_0 c_0}{\pi f \rho_j (1-\mu^{-4})}\right)^2 \Bigg\{ & \ln\left(\frac{2\pi f \sqrt{S}}{c_0}\right) + 0.16 + U(l_x, l_y) \\ & + \frac{1}{4\mu^6}\left[(2\mu^2-1)(\mu^2+1)^2 \ln(\mu^2-1)\right. \\ & \left. + (2\mu^2+1)(\mu^2-1)^2 \ln(\mu^2+1) - 4\mu^2 - 8\mu^6 \ln(\mu)\right] \Bigg\}\end{aligned} \tag{18}$$

where $U(l_x,l_y)$ is a shape function that can be omitted if $0.1<l_x,l_y<10$ and μ is a square root of f_c/f where f_c being critical frequency.

2.1.2. Internal Loss Factors (ILF)

The Internal Loss Factor (ILF) represents the amount of energy lost by a subsystem and converted into heat or transferred to another structure, not included in the model, in one cycle, as described by Formula (19).

$$\eta_{id} = \frac{W_{id}}{E_i \omega} \tag{19}$$

Internal loss factors for common material types can be found in Table 1.

Table 1. Internal loss factors of common materials

Material	**Internal loss factor $\eta_{id} \cdot 10^{-3}$**
Steel	~0.1
Aluminium	~0.1
Glass	0.6-2
Concrete	4-8
Lightweight concrete	10-20
Autoclaved aerated concrete	10-20
Gypsum plate	10-15
Chipboard	10-30

2.1.3. Total Loss Factors (TLF)

The total energy loss factor, denoted as η_i, is the sum of the energy loss due to coupling of subsystems (CLF) and the internal losses of a given subsystem. Formulas for each type of subsystem are specified below.

a) TLF of a room

$$\eta_i = \frac{2.2}{T_{60,i} f} \tag{20}$$

b) TLF of a cavity

$$\eta_i = \frac{c_0 \sum l\alpha'}{2\pi^2 f S_i} \tag{21}$$

c) TLF of a partition

$$\eta_i = \frac{c_g L\alpha}{2\pi^2 f S} \tag{22}$$

whereas for massive partitions it can be assumed that:

$$\eta_i \approx \frac{1}{\sqrt{f}} + 0.015 \tag{23}$$

and for a lightweight partition:

$$\eta_i = \frac{c_0}{f\pi^2\sqrt{\frac{f_{ref}}{f}}} \tag{24}$$

where $T_{60,i}$ is the reverberation time of the i-element, f is frequency, c_0 – speed of sound in the air, l – the length of the cavity, α' is the average sound absorption coefficient in the void, S_i is the surface of the i-element, c_g is the group velocity and f_{ref} = 1000 Hz. Group velocity, which describes the velocity at which the energy is transported, is described by formula (25).

$$c_g = \frac{d\omega}{dk} \tag{25}$$

2.2 Transfer matrix

In order to calculate energy in each of the subsystems, first equilibrium equations need to be formed, based on the assumption that the energy entering the subsystem is equal to the energy leaving it. Using those equations a transfer matrix is formed (formula 26).

$$\begin{bmatrix} -\eta_1 & \eta_{21} & \eta_{31} & \eta_{41} & \cdots \\ \eta_{12} & -\eta_2 & \eta_{32} & \eta_{42} & \cdots \\ \eta_{13} & \eta_{23} & -\eta_3 & \eta_{43} & \cdots \\ \eta_{14} & \eta_{24} & \eta_{34} & -\eta_4 & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \\ \cdots \end{bmatrix} = \begin{bmatrix} -W_1/\omega \\ 0 \\ 0 \\ 0 \\ \cdots \end{bmatrix} \tag{26}$$

2.3 Analysed cases

For each analysed case the same initial conditions were assumed, as presented in Table 2.

Table 2. Initial conditions assumed for the calculations

Parameter	Symbol	Unit	Value
Initial power	W_1	*W*	0.005
Speed of sound in the air	c_0	*m/s*	343
Density of air	ρ_0	kg/m^3	1.2
Air temperature	*T*	℃	20

The assumption was that both the source and the receiving rooms were the same in terms of their dimensions and reverberation time. The assumed parameters of rooms are listed in Table 3.

Table 3. Parameters of the source and receiving rooms, assumed for the calculations

Parameter	Symbol	Unit	Value
Width	W_R	m	3
Length	L_R	m	5
Height	H_R	m	4
Volume	V_R	m^3	60
Reverberation time	$T_{60,R}$	s	0.6

The main partition between the source room and the receiving room is a massive concrete wall. Flanking partitions were assumed as gypsum board or glass based. Their parameters are specified below in Table 4.

Table 4. Parameters of the walls

Parameter	Symbol	Unit	Value		
			Massive wall	Gypsum board panel	Glass panel
Width	W	m	3	3	3
Thickness	T	m	0.15	0.012	0.0066
Height	H	m	4	4	4
Surface	S	m^2	12	12	12
Perimeter	P	m	14	14	14
Density	ρ	kg/m^3	2400	720	2500
Surface mass	m'	kg/m^2	360	8.64	16.5
Critical frequency	f_c	Hz	110	2846	1808
Young's modulus	E	N/m^2	3.6e+10	2.4e+9	7.2e+10
Poisson's ratio	μ	-	0.2	0.3	0.2
Bending stiffness	B	Nm	3.1e+6	380	1.8e+4

The cavity between the gypsum board or glass panels is assumed to be 0.05 m deep.

The description of cases analysed in the study is presented in Table 5.

Table 5. Description of analysed cases

Case number	Description
1	Basic model with no flanking partitions – source and receiving rooms divided by a 15 cm thick concrete wall
2	One, two or four flanking partitions, composing of a single gypsum board cladding with no absorptive filling; three connection types (“T”, “C”, “H”)
3	One, two or four flanking partitions, composing of a double gypsum board cladding with no absorptive filling; three connection types (“T”, “C”, “H”)
4	One, two or four flanking partitions, composing of a double gypsum board cladding; cavity filled with an absorptive material in 50%; three connection types (“T”, “C”, “H”)
5	One, two or four flanking partitions, composing of a double gypsum board cladding; cavity fully filled with an absorptive material; three connection types (“T”, “C”, “H”)

The connection shapes are presented in Figure 1.

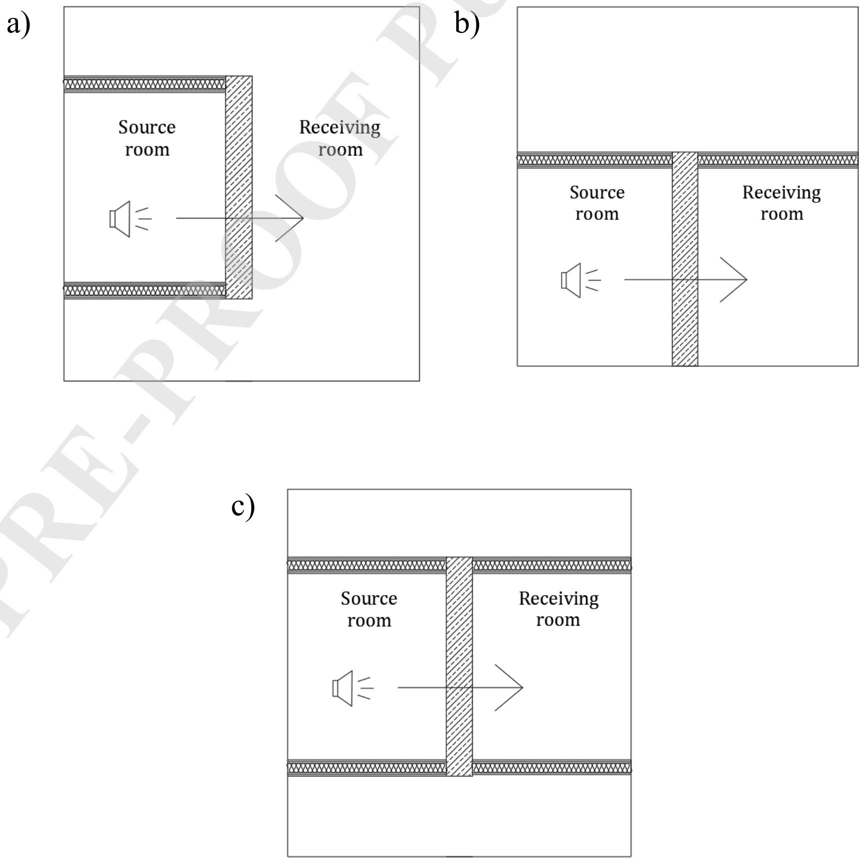


Fig. 1. Schematic layout of analysed connections in case 2: a) C-shaped connection, b) T-shaped connection, c) H-shaped connection.

2.3.1 Subsystems

The connections between subsystems were assumed according to Fig. 2-6. For cases 2-6 the connections are identical as double-cladding of gypsum board walls is considered as one subsystem.

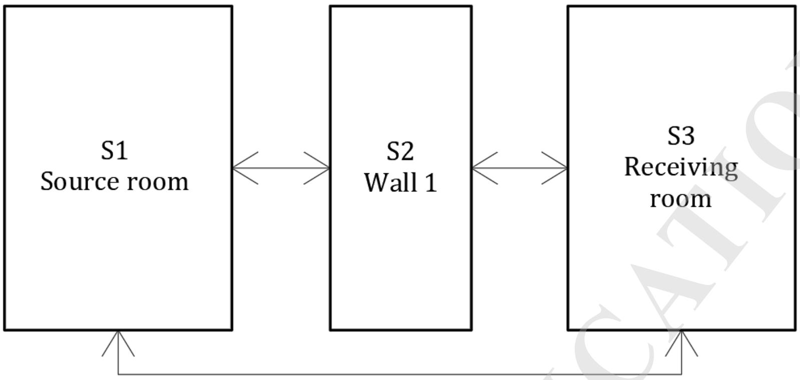


Fig. 2. Energy flow scheme between subsystems for case 1.

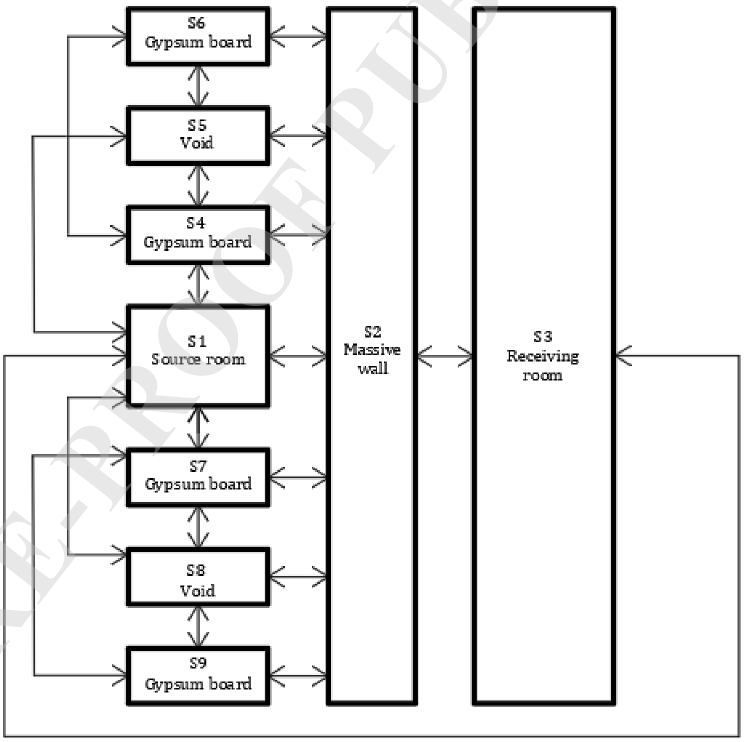


Fig. 3. Energy flow scheme between subsystems for C-shaped connections.

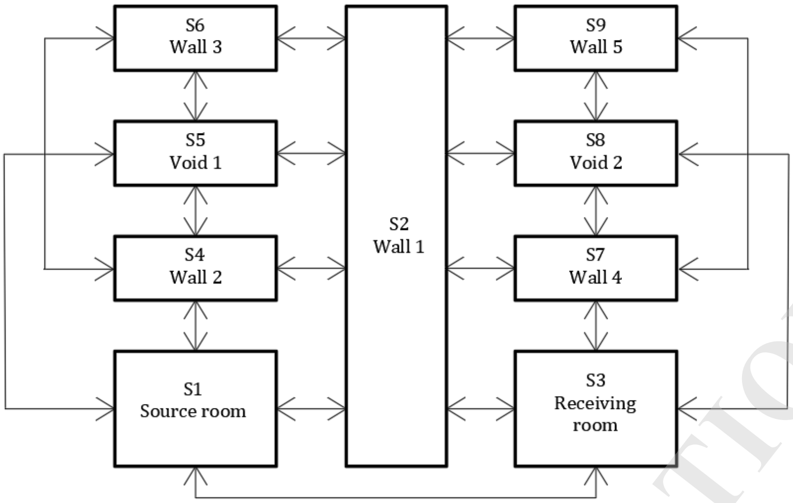


Fig. 4. Energy flow scheme between subsystems for T-shaped connections.

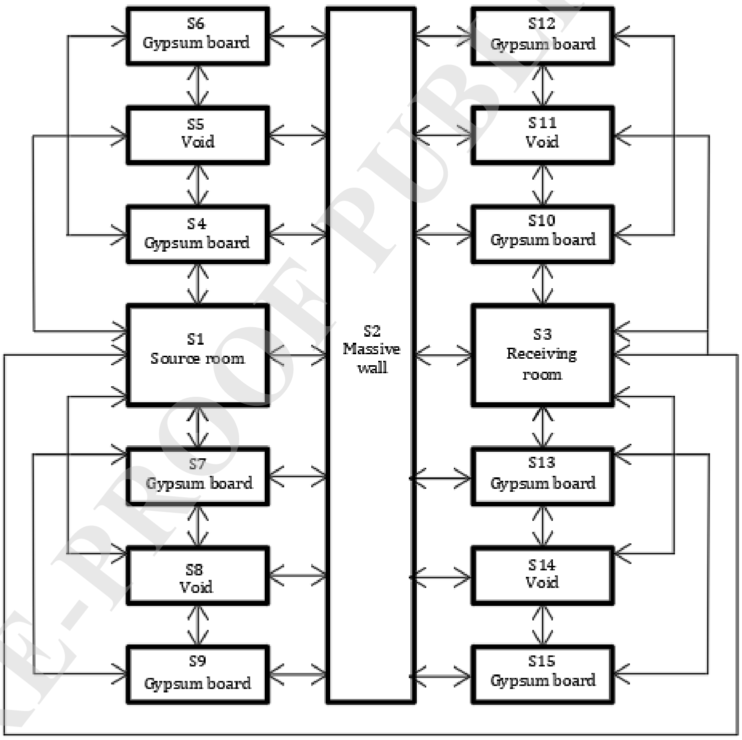


Fig. 5. Energy flow scheme between subsystems for H-shaped connections.

3. Results

For each case and each connection type the energy in every subsystem was calculated. The results obtained for cases 2-6 were then compared to the basic situation (case 1) in order to show the difference between the resultant sound insulation of the massive wall with no flanking paths and the one obtained after adding lightweight partitions. The results are presented in Fig. 6-7.

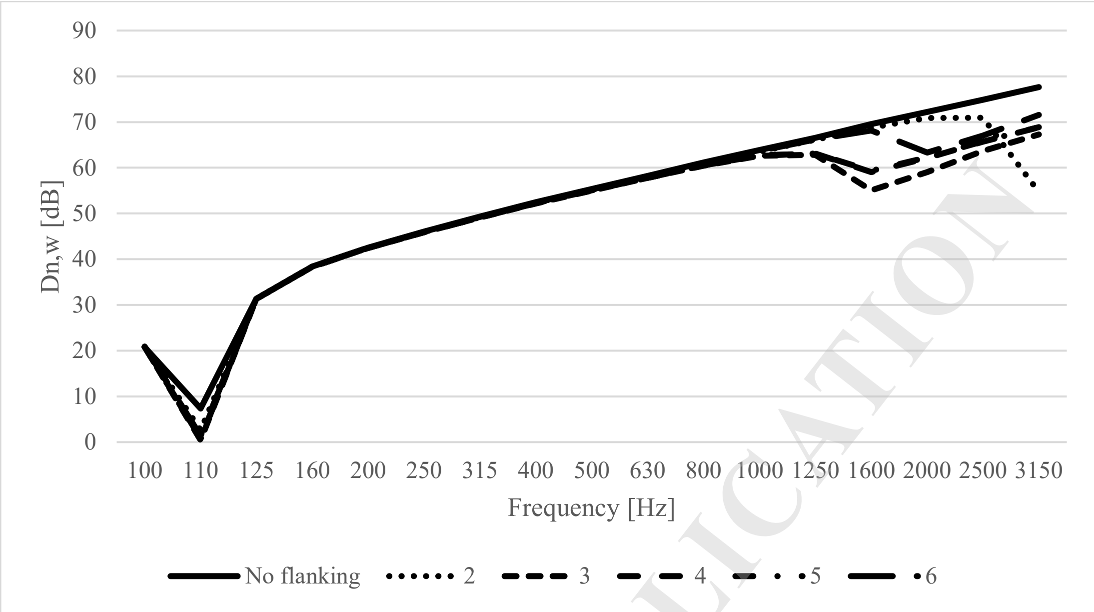


Fig. 6. Weighted sound reduction indexes for H-shaped connections (cases 1-6)

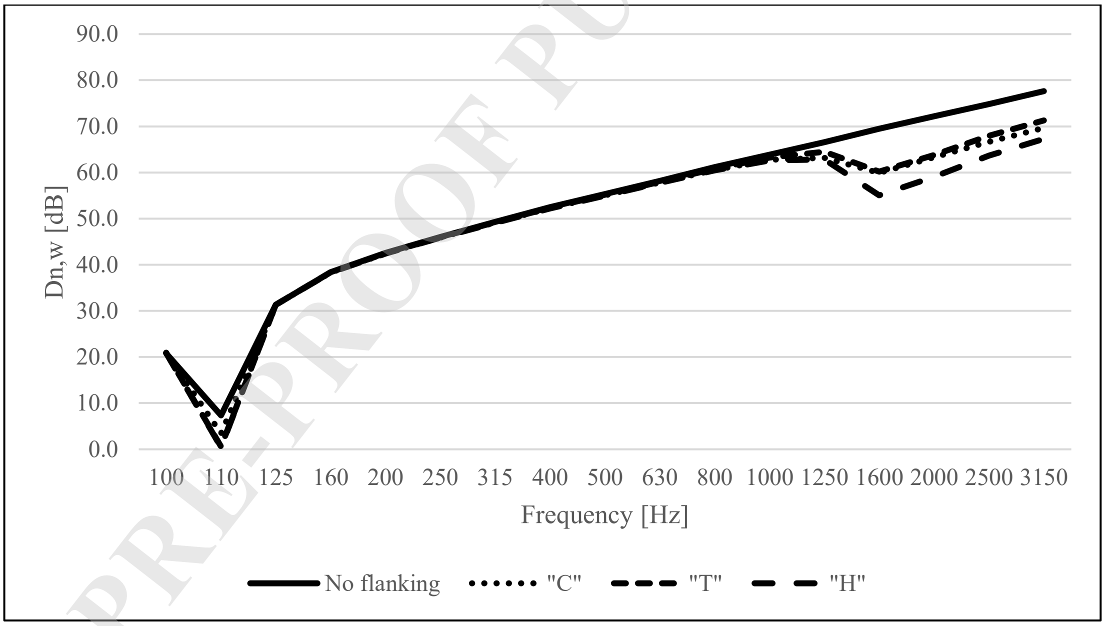


Fig. 7. Weighted sound reduction indexes for case 3 and three connection shapes.

The differences in sound insulation of H-shaped connections between the massive wall and a gypsum wall with no filling, partial filling and fully filled cavities are presented in Table 6.

Table 6. Sound insulation difference between 3 of the analysed cases

Frequency [Hz]	$D_{n,e,w}$ [dB] - Case 3	$D_{n,e,w}$ [dB] - Case 4	$D_{n,e,w}$ [dB] – Case 5
100	20.9	20.9	20.9
125	31.3	31.3	31.3
160	38.4	38.4	38.4
200	42.4	42.4	42.4
250	45.9	45.9	45.9
315	49.1	49.1	49.1
400	52.2	52.2	52.2
500	55.0	55.0	55.0
630	57.8	57.8	57.8
800	60.4	60.5	60.5
1000	62.6	62.7	62.7
1250	62.8	63.1	63.1
1600	55.1	59.1	59.3
2000	59.1	62.1	62.3
2500	63.7	65.7	65.7
3150	67.3	68.8	68.9

The results show that the sound reduction index, compared to case 1, decreases above the critical frequency of the gypsum/glass board. In the case of a single-cladding, the reduction can be observed above 2500 Hz, while in the case of double-cladding the sound insulation decreases above 1250 Hz. In case of glass flanking partitions the decrease occurs above ca. 1850 Hz. The highest reduction of sound insulation can be observed for the H-shaped connections, as they include the most flanking partitions.

As for the absorptive material in the cavities, the resultant sound reduction difference between cases 3, 4 and 5 can be seen above the critical frequency of the gypsum board, which for the double-cladded wall is around 1400 Hz. The differences in higher frequencies are clearly noticeable and impact the overall resultant single number sound insulation of the wall. The difference between cases 4 and 5, which represent the wall a partially filled cavity and a wall with a fully filled cavity, can also be noted, however the resultant single number sound reduction index is equal (R_{A1} = 48 dB). For case 3 the sound reduction index is equal to R_{A1} = 45 dB.

4. Conclusions

Statistical Energy Analysis, when applied correctly, can be an effective method of calculating sound transmission of a partition, including flanking paths. While most recent publications focus on timber or massive constructions when discussing flanking transmission, this research analyses the connections between gypsum-board-based or glass partitions and massive partitions, which commonly occur in Poland. The results for 6 different cases were presented, starting with a standard situation with no flanking transmission. Cases 2-5 represent connections between a massive wall and a gypsum board wall, considering 3 different shapes of connections (C-shaped, T-shaped and H-shaped), taking into account both single and double-cladded walls. Filling of the cavity with an absorptive material was also taken into consideration. Case 6 represents the situation when the flanking partitions are glass systems for the same types of connections between partitions as in the case of gypsum board partitions.

The results indicate a noticeable impact of flanking paths on the resultant sound insulation of a massive wall. The reduction of sound insulation occurs above the critical frequency of a gypsum or glass board. For this reason the damping in case 2, where the flanking walls have single-cladding and hence have a higher critical frequency, is smaller than in cases 3-6. The shape of the connection is also significant, with H-shaped connections resulting in the highest reduction among all the analysed cases as they include the most flanking partitions.

One additional factor that has an impact on the sound insulation is the filling of the cavity between gypsum boards with an absorptive material. The calculations imply that the more attenuation there is in the cavity, the higher the sound insulation of the massive partition, hence the smaller impact it has.

FUNDINGS

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHORS' CONTRIBUTION

Agnieszka Wójtowicz performed the analysis and contributed to data interpretation. Tadeusz Kamisiński and Jarosław Rubacha conceptualized the study and contributed to data interpretation. All authors reviewed and approved the final manuscript.

References

1. International Organization for Standardization (2017), Building acoustics — Estimation of acoustic performance of buildings from the performance of elements. Part 1: Airborne sound insulation between rooms (ISO Standard No. ISO 12354-1:2017), https://www.iso.org/standard/70242.html.
2. Craik R.J.M. (1996), *Sound transmission through buildings: using statistical energy analysis*, Gower.
3. Crispin C., Mertens C., Dijckmans A. (2019), Simplified prediction of the vibration reduction indices of double wall junctions, [in:] *Proceedings of 23rd International Congress on Acoustics*, https://doi.org/10.18154/RWTH-CONV-239666.
4. Crispin C., Mertens C., Dijckmans A. (2017), Detailed analysis of measurement results of flanking transmission across a junction composed of double walls carried out on a half scaled test bench, [in:] *24th International Congress on Sound and Vibration 2017*, https://doi.org/10.1016/j.jsv.2020.115850.
5. Crocker M.J., Price A.J. (1969), Sound transmission using Statistical Energy Analysis, *Journal of Sound and Vibration,* **9**(3): 469-486.
6. Gerretsen E. (2015), Extending EN 12354 sound insulation modelling to composed, light weight building systems, [in:] *44th International Congress and Exposition on Noise Control Engineering*.
7. Kleiner M., Tichy J. (2014), *Acoustics of Small Rooms*, Taylor & Francis Group, Boca Raton.
8. Neusser M., Bednar T. (2022), Measurement and estimation of the flanking impact sound transmission in timber frame building constructions, [in:] *Proceedings of the 24th International Congress on Acoustics.*
9. Schoenwald S. (2008), *Flanking sound transmission through lightweight framed double leaf walls : prediction using statistical energy analysis*. Ph.D. Thesis, Built Environment, Technische Universiteit Eindhoven, https://doi.org/10.6100/IR637821.