ACOUSYS V4
VALIDATION BOOKLET

Version January 2020

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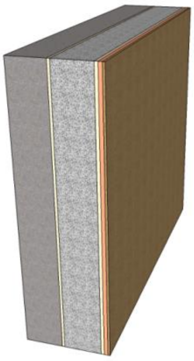
1. Introduction

1.1 General properties

AcouSYS software is based on the Transfer Matrix Method (TMM) approach, initially developed by Munjal in 1992 [1]. It can be used for predicting the acoustic performances of complex multi-layered structures of building, automotive or aeronautic domains.

It is suitable for consultancy firms, industry actors, laboratories, experts or non-experts since it allows quick and complete investigations, optimizations and parametric studies.

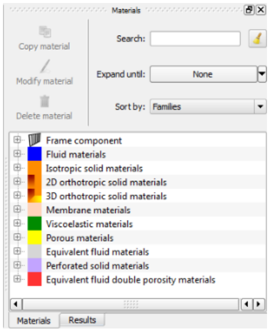


1.1.1 Material database

There are a multitude of materials of several natures in the AcouSYS material database with generic or customizable characteristics.

The different layers of constant thicknesses constituting the structure can be either:

- Fluids - air, water, etc.
- Isotropic solids - plaster, foam, metal, concrete, engineered wood, glass, coating, etc.
- Orthotropic solids - stiffened plates, hollow masonry, etc.
- Viscoelastic materials - adhesive, bitumen, etc.
- Poroelastic materials (Biot-Allard model) – mineral wool, bio-sourced products (wood, hemp, cotton, straws, etc.).
- Double porosity materials – poroelastic materials with inclusions.
- Perforated materials
- Frames – metal sections, wood, etc.



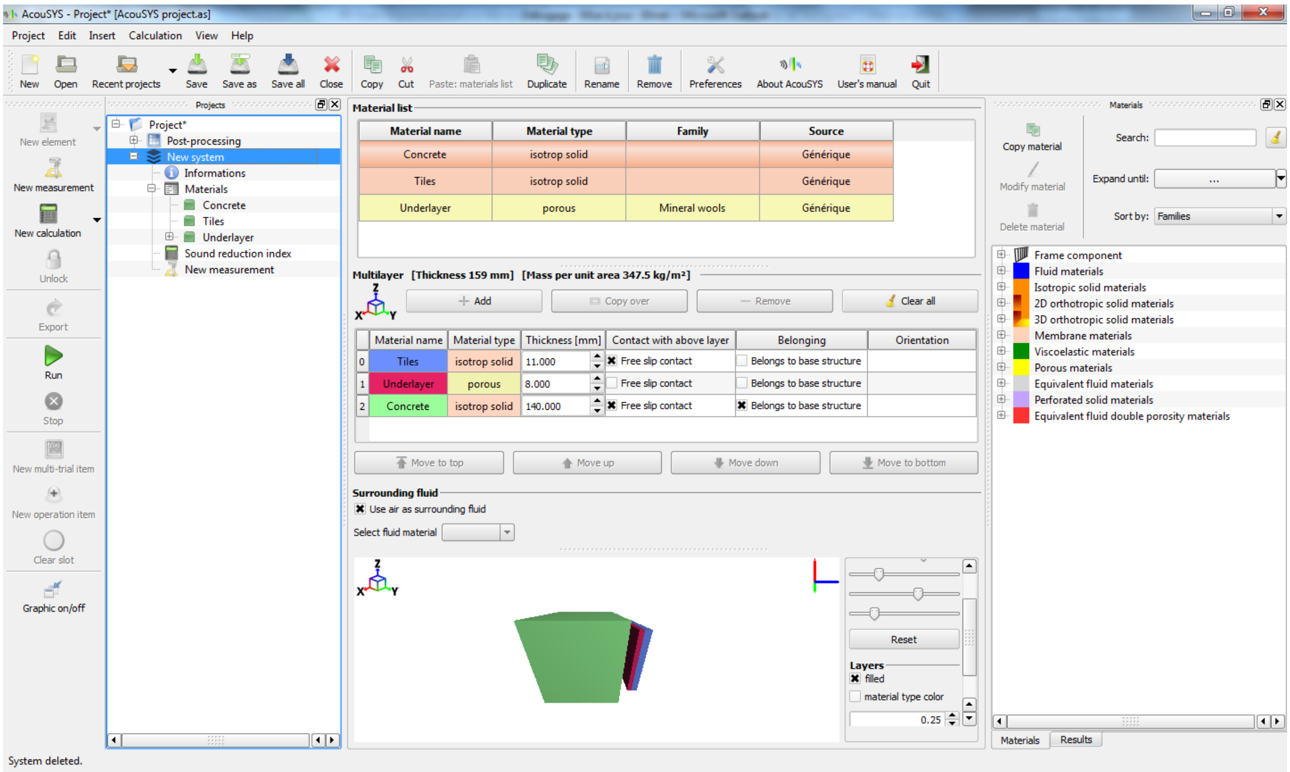
The modelling of porous layers (absorbing materials) follows Biot's theory [2] and includes the propagation of two coupled compressional waves and a shear wave travelling simultaneously in both phases of the porous material (elastic and fluid phase). If the solid phase is rigid and motionless (no strain energy), a porous layer can also be modelled in using an equivalent fluid formalism (model with 5 parameters).

The solid or viscoelastic layers include the propagation of two different wave types (compressional and shear waves).

Perforated elements are can either be modelled according to the work of Atalla and Sgard [3]: the system is treated as porous material with a rigid frame and an equivalent tortuosity.

The orthotropic solids are modelled as thin orthotropic plates [4] (no transverse shear) or thick solids.

Furthermore, the layers can be bounded or unbounded to each other. In practice, this allows to handle situations where materials are either glued or sliding (equivalent to a remaining infinitesimal air layer in between).



1.1.2 Acoustic performance calculations

AcouSYS can be used to predict:

- Sound reduction index R,
- Sound absorption coefficient α_S,
- Impact sound pressure level L_n (normalized tapping machine)
- Rainfall sound intensity level L_i (normalized rainfall)
- Transmission loss R_{TBL} due to a turbulent boundary layer excitation (Corcos model [5])

For transmission and absorption problems, the system can be either excited by a diffuse acoustic field (composed of multiple acoustic plane waves incoming in different directions) or normal incidence plane wave (impedance tube situation). For sound absorption calculation, the system is assumed to rest on a rigid and perfectly reflecting foundation.

A structural excitation (2D delta Dirac distribution) is decomposed into an infinite number of propagating normal stress waves. The velocity field, on the top and bottom interface, evaluated in the wavenumber domain allows calculating the acoustic intensity radiated on both sides of the system leading to

- An impact noise level if tapping machine is used as structural excitation,
- A rainfall noise level if rainfall is the excitation.

The excitation force associated to the tapping machine can be estimated as explained in [6-8] as a function of the: mass and the impact velocity of the hammer, input mobility of the structure studied and the impact frequency of the tapping machine. Note that the excitation force depends on the input mobility of the multi-layered system and must be calculated for each system. The excitation force associated to the rainfall noise can be estimated similarly [8-10].

For a turbulent boundary excitation, the incident intensity for the evaluation of transmission loss is obtained from the integration in the wavenumber domain of the spectrum of the fluctuating boundary layer pressures.

The airborne noise reduction *ΔR* of a wall lining, floor covering or ceiling system can also be deduced from the sound transmission index of the base structure (wall or floor) calculated with and without the lining or covering [11]. In a similar way, the impact noise reduction ΔL of a floor covering can then be deduced from the impact noise level of the base floor calculated with and without the floor covering [12-13].

1.2 Specific properties

1.2.1 Spatial windowing

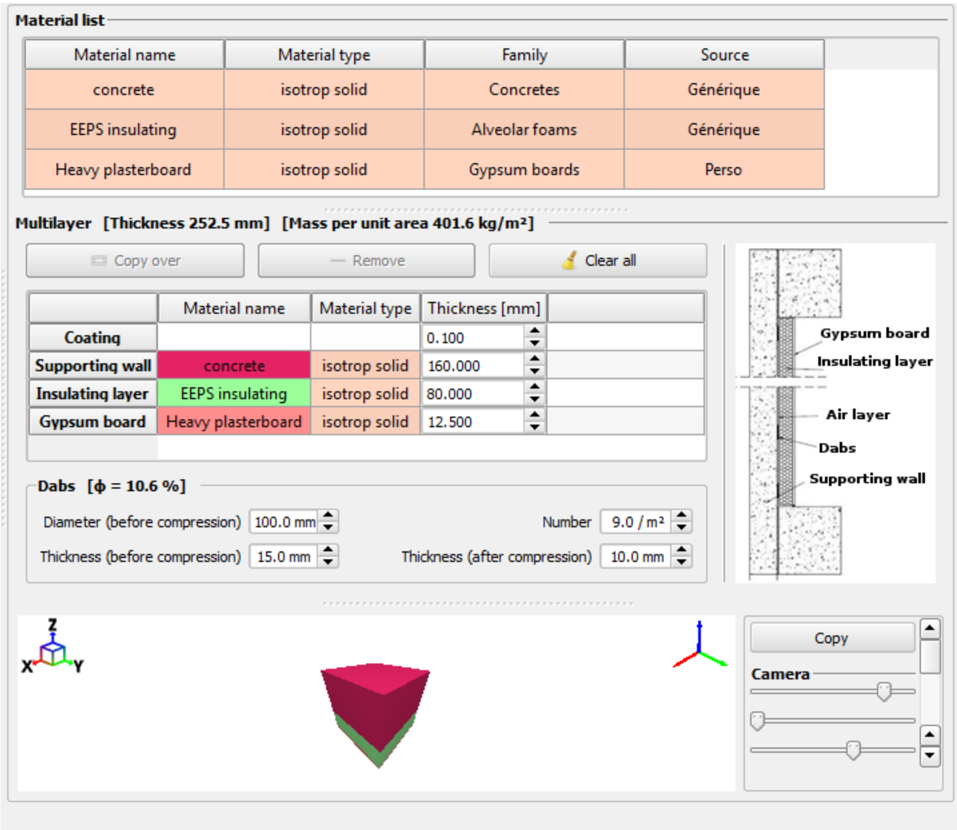
A technique based on a spatial windowing of plane waves presented in [12] is used in order to consider the finite size of a planar structure in sound radiation and sound transmission and absorption problems. This technique leads to prediction results much closer to experimental measurements than the classical wave approach applied to infinite structure. It is a simple method in the case of sound transmission since the associated radiation efficiency depends only on the spatial window considered (i.e. the size of the structure) and can therefore be pre-calculated.

1.2.2 Systems bonded by dabs (thermal lining systems)

One of the novelties in the latest version of the AcouSYS software (Version 4) is the possibility to account for partial contact between two adjacent layers. This allows to model thermal linings bonded by dabs, where mortar dabs are distributed over the wall surface according to the technical document NF DTU 25.42 P1-1 [14]. To this end, an analytical method presented in [15] is implemented.

For closed-cell insulating materials (e.g. EPS), it consists in introducing a fictitious air gap between the supporting wall and the insulation layer. The thickness of this air gap is calculated from the dynamic stiffness of the insulating material, the dimensions of the mortar dabs and the number of dabs per m². The loss factor of the air gap is dependent from the nature of the supporting wall, to account for additional energy dissipation in the case of hollow masonry walls.

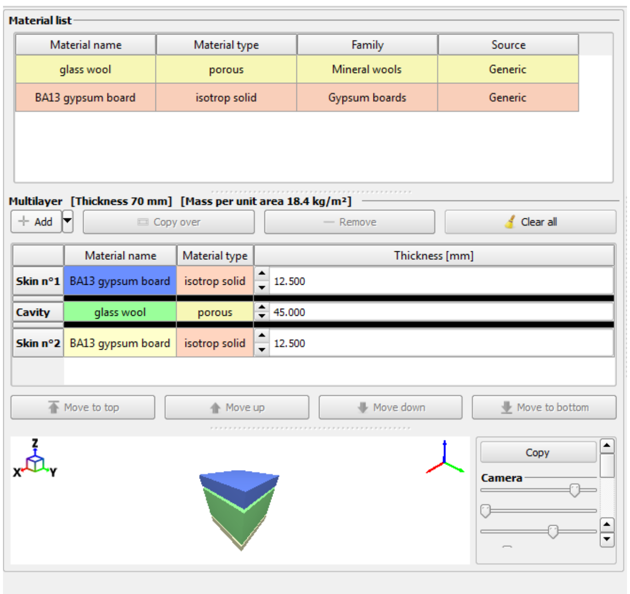
For open-cell or fibrous insulating materials (e.g. mineral wool), the equivalent porous layer approach described in [15] is implemented. In this case, the insulating material is considered glued to the supporting wall. The thickness of the insulation layer and the Young's modulus of its skeleton are modified to account for the stiffnesses of both the solid and the fluid phases.

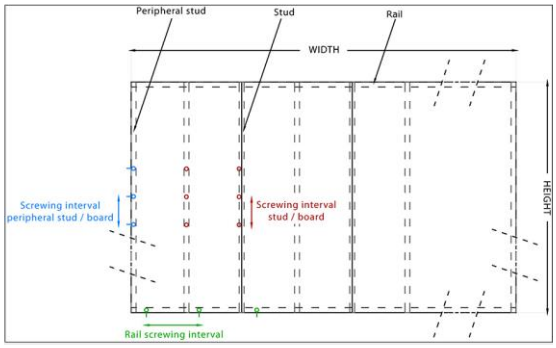


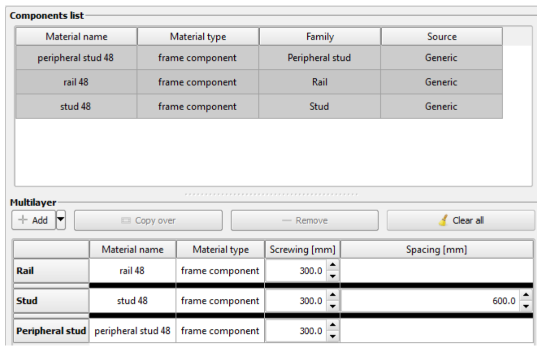
Some examples of thermal linings (bonded by dabs) projects are illustrated § 2.3.

1.2.3 Systems with framework (partition walls)

AcouSYS software is also able to simulate the sound reduction index of single frame partition [16] thanks to an original prediction method based on a mixed approach: the TMM to evaluate the sound reduction index of the partition without frame components (transmission through partitions with cavity only) and a SEA model to evaluate the transmission paths associated to the frame components only. The partition frame components are modelled as punctual springs corresponding to positions of screws fixing the boards on the frame. In the low frequency range, this method is completed by an analytical model where the studs act as periodic translational springs. The transition between the two models appears when the boards' flexural half wavelength is equal to the screws distance.







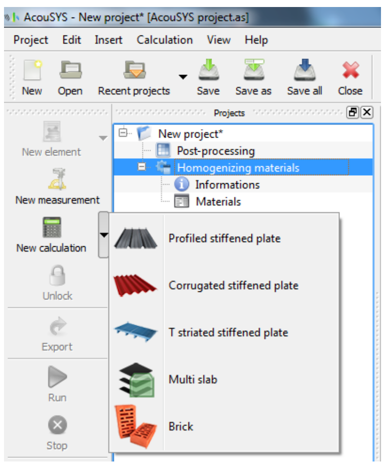
Some examples of partition wall projects are illustrated § 2.4.

1.2.4 Homogenized materials

In some cases, the layers have non-planar or inhomogeneous profiles in thickness. A homogenized element with a constant thickness and equivalent properties/characteristics must be considered. Therefore, it is necessary to go through an intermediate step to homogenize the element.

AcouSYS software creates homogenized equivalent materials to include in a standard system [17] such as:

- Alveolar elements (e.g. hollowed brick [18]; See § 2.2);
- Multi-layered shells (e.g. facing with multi skin in partition wall; See § 2.4.2);
- Stiffened plates [19] (e.g. corrugated/profiled plate or other systems with inhomogeneous profile; See § 2.8).



In the latest version of the AcouSYS software (Version 4), several masonry walls in hollow terracotta bricks from different brickmakers were homogenized and added to the AcouSYS database [15].

1.2.5 Other features

Other properties may be accessible with AcouSYS software, such as:

- Indication of the upper and lower limits included into the database for known products;
- Addition of double porosity materials into the database [20];
- Addition of bio-based materials into the database [21] (Version 4);
- Indication of the North American single number ratings: STC (Sound Transmission Class) [22], IIC (Impact Insulation Class) [23], NRC (Noise Reduction Coefficient) and SAA (Sound Absorption Average) [24].

1.3 Future works

Other specificities have been developed by CSTB but not integrated yet in the current version of AcouSYS software such as:

- An automatic genetic optimization tool which offers an optimal set of parameters in order to get as close as possible to reference results such as test results [25] (e.g. optimized hollow brick; See § 2.2);
- A FEM approach to take into account the modal behaviours of the studied systems at low frequencies [26] (e.g. window with double glazing; See § 2.7).

For more information about the AcouSYS software, the following websites can be visited (in French):

- **https://logiciels.cstb.fr/sante-confort/acoustique-dans-le-batiment/acousys/**
- **https://www.youtube.com/watch?v=5abfNv8DD4E**
- **https://www.youtube.com/watch?v=T1b9h4fNENw**
- **https://boutique.cstb.fr/acoustique/3-acousys.html**

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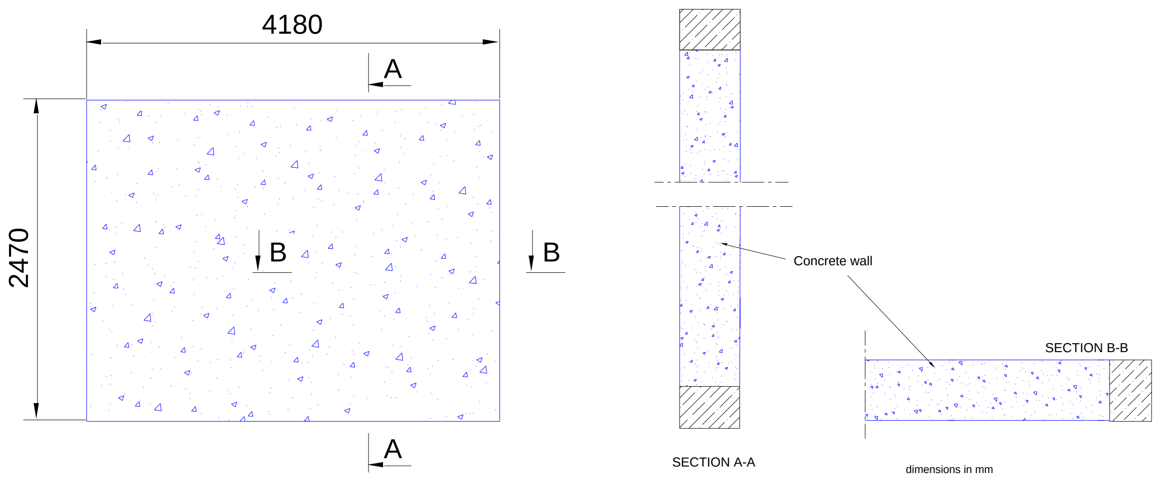
2. Airborne sound insulation calculation of vertical systems

For vertical systems, AcouSYS software can simulate the following acoustic indicators:

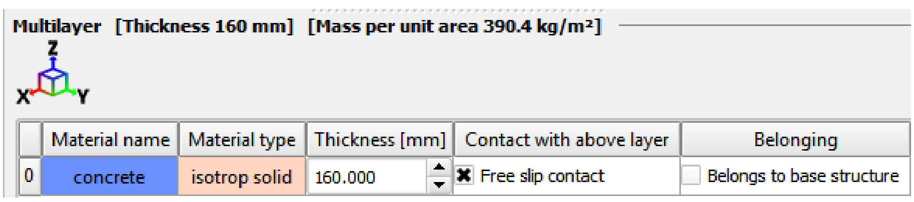
- **The airborne sound insulation R**
- **The improvement of airborne sound insulation ΔR**

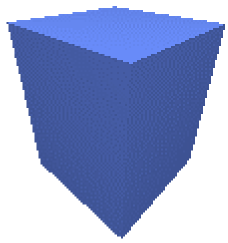
2.1 Concrete wall

❶ **Drawing of the system**



❷ **Description of the multilayer system in AcouSYS**





❸ **Parameters associated with the different system layers**

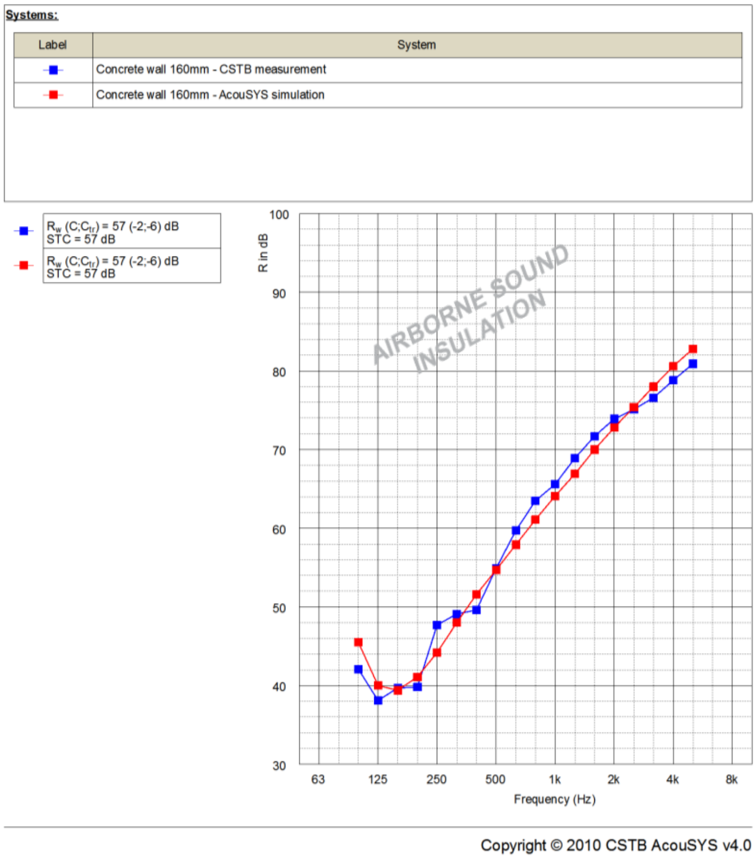
Layer	Name	Type	Parameters
0	Reinforced concrete wall	Isotropic solid	thickness = 160 (mm) ρ = 2 440 (kg/m^3) ν = 0.1 E = 30 000 (MPa) η = 0.07

❹ Spatial windowing

XY system dimensions: [4180; 2470] mm

❺ AcouSYS calculation results

An AcouSYS simulation/measurement comparison of the airborne sound reduction index *R* for a concrete wall of thickness 160 mm is shown in figure below:

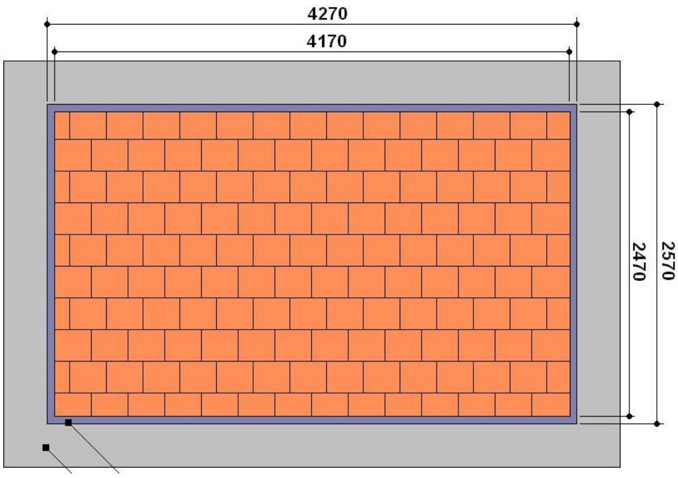


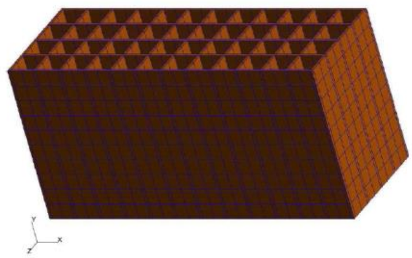
❻ Comments

A good correlation is noticed between AcouSYS simulation and measurement. The drop around the third octave 160 Hz is associated with the critical frequency of the wall.

2.2 Hollow brick wall

❶ **<u>Drawing of the alveolar material included in a system</u>**

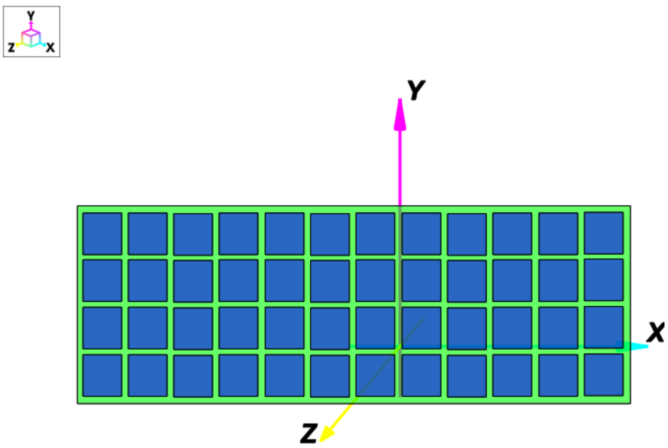


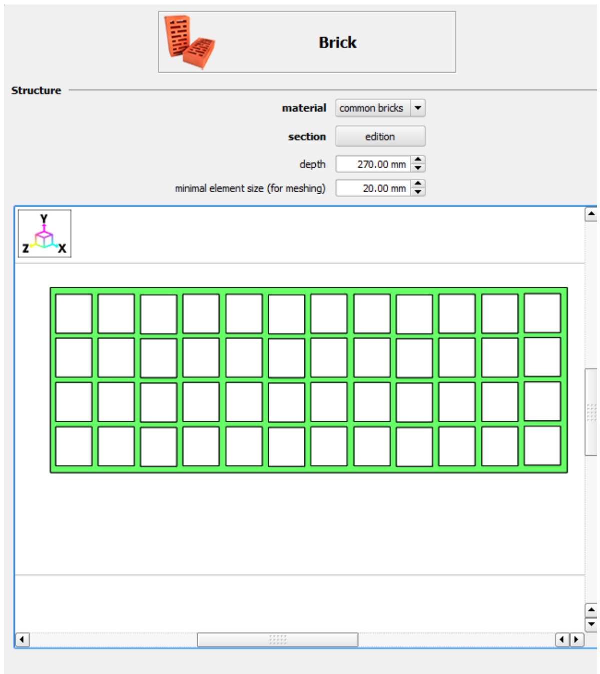


Width (X) = 560 mm
Height (Y) = 270 mm
Thickness (Z) = 200 mm
<u>Cell sizes:</u> x = 39.6 mm; y = 41.9 mm

❷ **<u>Homogenization</u>**

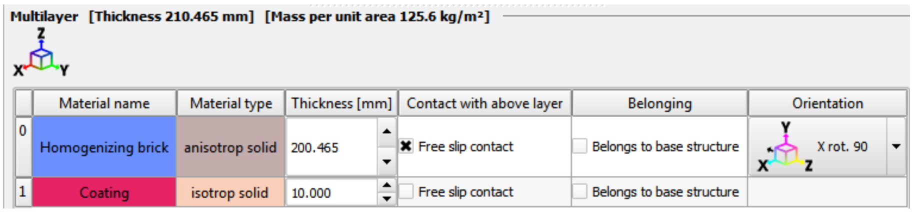
In the case of a hollow brick, the presence of vertical internal cells creates an inhomogeneous profile in its structure. Therefore, it is necessary to go through an intermediate step to homogenize it.

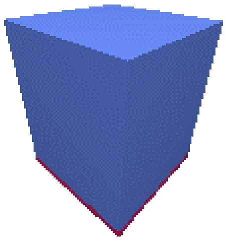




In this case, the axes of the modeling are X = Width, Y = Thickness and Z = Height. Thus, the open cells being vertical. the extrusion (depth) matches the height of the brick.

❸ Description of the multilayer system in AcouSYS





The "Homogenizing brick" element must be reoriented 90° around the X axis in order to correspond to the axes of the wall.

❹ Optimisation

This option is not yet included in AcouSYS version 4 but the optimization of the parameters can be achievable for any kind of systems.

❺ Parameters associated with the different system layers

Layer	Name	Type	Parameters	
	Common brick	Isotropic solid	ρ = 1 860 (kg/m³) v = 0.2 E = 7 000 (MPa) η = 0.01	
0	Hollow brick	Anisotropic solid	thickness = 200 (mm) ρ = 541.5 (kg/m³)	
			v_{xy} (=v_{zx}) = 0.2 v_{yz} = 0.125 v_{zx} (=v_{xy}) = 0.044 E_x = 1 246 (MPa) E_y (=E_z) = 2 038 (MPa) E_z (=E_y) = 1 271 (MPa) G_{xy} (=G_{zx}) = 541 (MPa) G_{yz} = 573 (MPa) G_{zx} (=G_{xy}) = 159 (MPa) η = 0.01	v_{xy} = 0.022 v_{yz} = 0.125 v_{zx} = 0.005 E_x = 10 720 (MPa) E_y = 8 352 (MPa) E_z = 508.4 (MPa) G_{xy} = 2 488 (MPa) G_{yz} = 1 089 (MPa) G_{zx} = 47.64 (MPa) η
1	Cement mortar	Isotropic solid	thickness = 15 (mm) ρ = 2 300 (kg/m³) v = 0.21 E = 28 000 (MPa) η = 0.014	

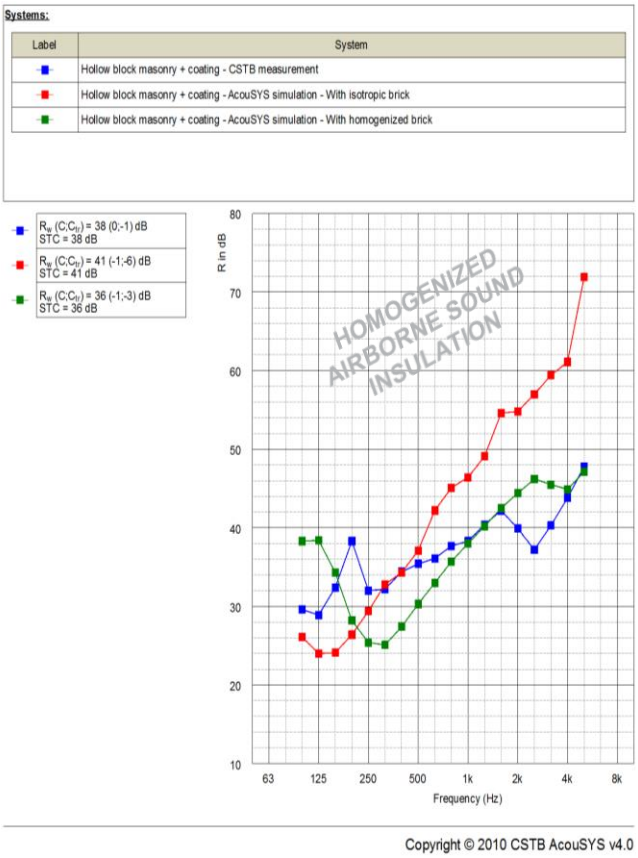
Homogenized parameters
Optimized parameters
Frequency dependent parameter - see values per frequencies in Appendix 1)

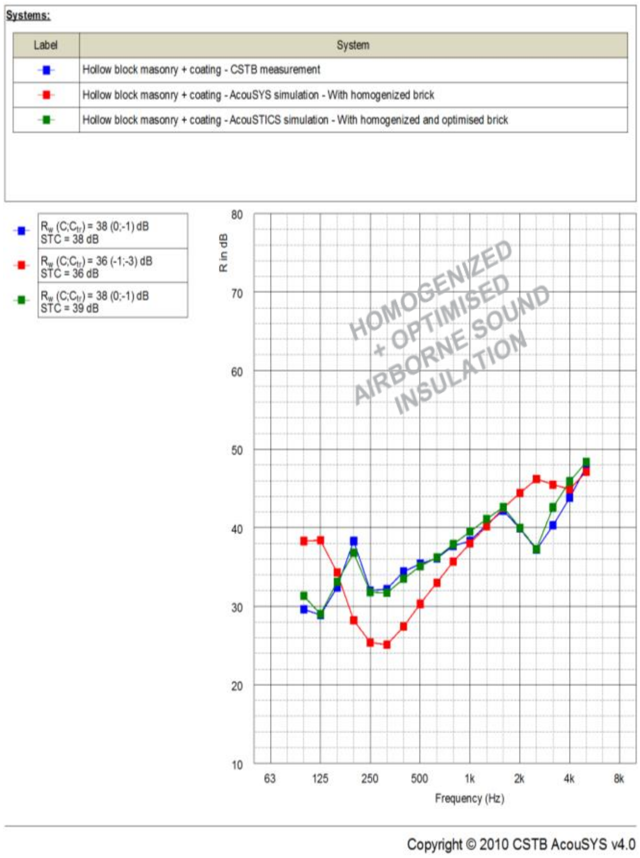
❻ Spatial windowing

XY system dimensions: [4180; 2470] mm

❼ AcouSYS calculation results

AcouSYS simulation/measurement comparisons of the airborne sound insulation R for the brick wall are shown below without and with homogenization (full or hollow brick) then with optimized parameters:





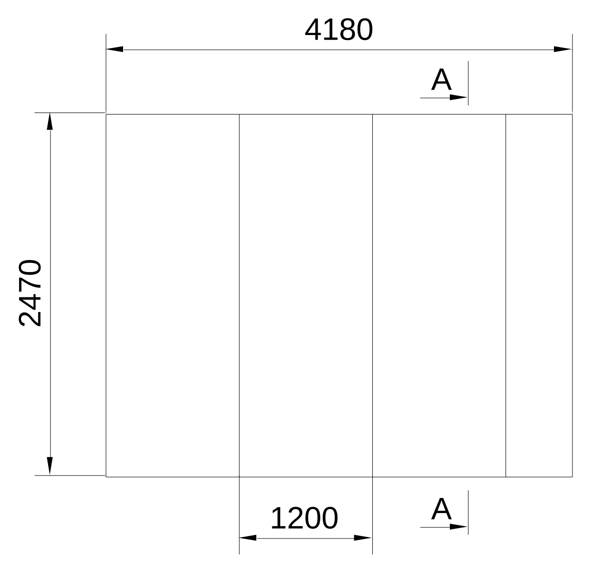
❽ Comments

In a first step, such a simple approach for the evaluation of effective mechanical properties allows to improve correlation between AcouSYS simulation and measurement when the hollowed brick (homogenized material) is used. Moreover, in a second step, the use of the automatic genetic optimization tool allows to correlate with the test results.

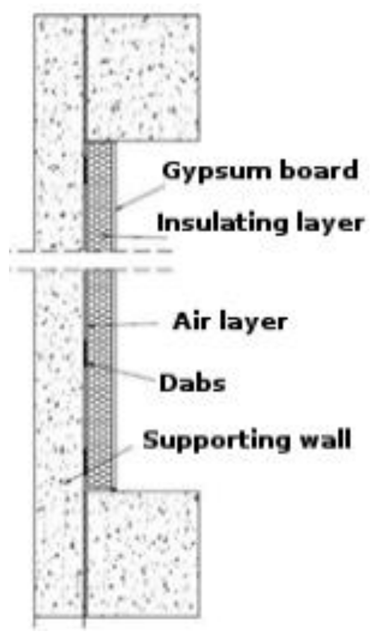
2.3 Thermal lining systems implemented on a supporting wall

2.3.1 EEPS-based thermal lining system 13+80 on a concrete wall

❶ **Drawing of the system**



dimensions in mm



❷ **Description of the multilayer system in AcouSYS**

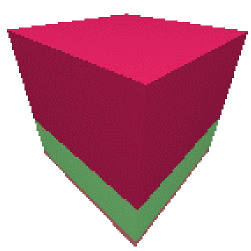
Multilayer [Thickness 252.5 mm] [Mass per unit area 401.6 kg/m²]

	Material name	Material type	Thickness [mm]
Coating			0.100
Supporting wall	concrete	isotrop solid	160.000
Insulating layer	EEPS insulating	isotrop solid	80.000
Gypsum board	Heavy plasterboard	isotrop solid	12.500

Dabs [ϕ = 10.6 %]

Diameter (before compression) 100.0 mm — Number 9.0 / m²

Thickness (before compression) 15.0 mm — Thickness (after compression) 10.0 mm



❸ Parameters associated with the different system layers

Layer	Name	Type	Parameters
Supporting wall	Reinforced concrete wall	Isotropic solid	thickness = 160 (mm) ρ = 2 440 (kg/m^3) ν = 0.1 E = 30 000 (MPa) η = 0.07
Insulating layer	Elastified Expanded Polystyrene (EEPS)	Isotropic solid	thickness = 80 (mm) ρ = 10.94 (kg/m^3) ν = 0.2 E = 0.24 (MPa) η = 0.067
Gypsum board	Plasterboard	Isotropic solid	thickness = 12.5 (mm) ρ = 824 (kg/m^3) ν = 0.1 E = 2 700 (MPa) η = 0.03

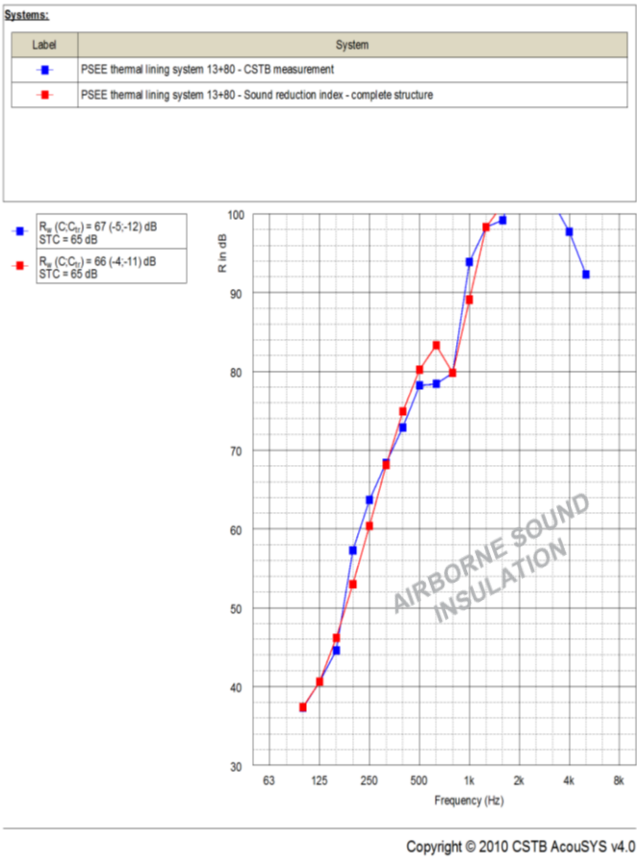
Measured according to standard [28] adapted to the plasterboard issues
Measured according to standard [29]

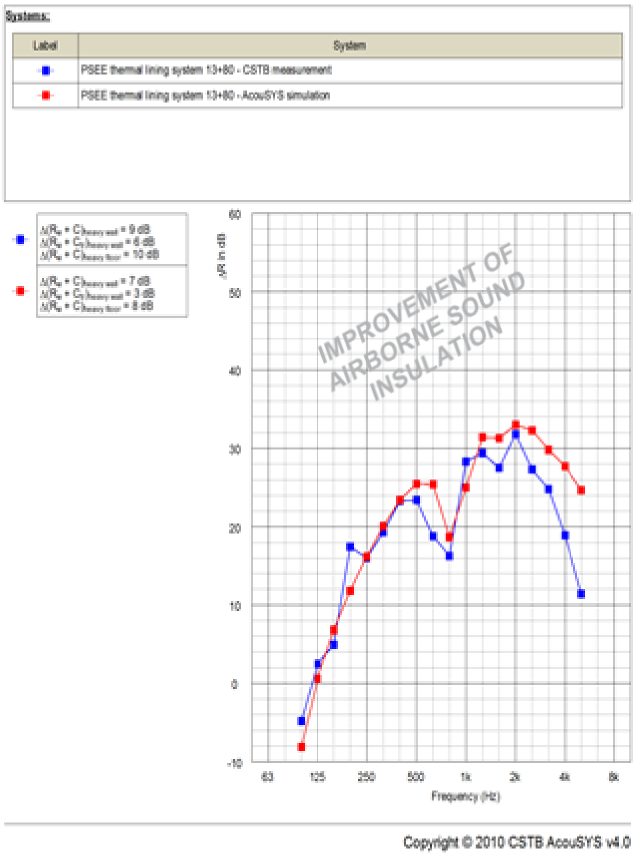
❹ Spatial windowing

XY system dimensions: [4180; 2470] mm

❺ AcouSYS calculation results

AcouSYS simulation/measurement comparisons of the airborne sound insulation R and the improvement of airborne sound insulation *ΔR* for a thermal lining system in EEPS 13+80 implemented on a concrete wall of thickness 160 mm are shown below:





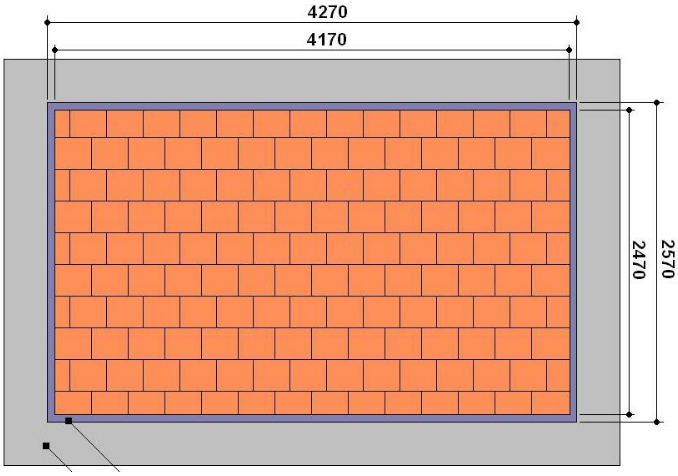
❻ Comments

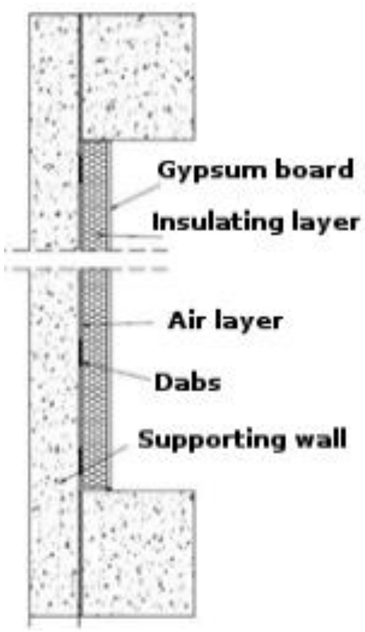
Good correlations are noticed between AcouSYS simulations and measurements. The first thickness resonance of the insulating layer is observed around the third octave 800 Hz. Discrepancies at high frequencies probably come from sound transmission paths not considered in the simulation (direct peripheral structural link or leakage).

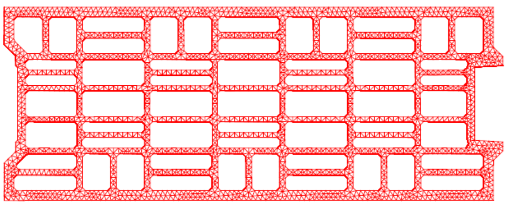
The approach adopted here is valid for a soft (e.g. EEPS) or rigid insulating layer (e.g. EPS, PU). The global equivalent spring is a function of the air and insulating layers' stiffnesses weighted by the bonding rate.

2.3.2 EPS-based thermal lining system 10+80 on a hollow brick wall [25]

❶ **Drawing of the system**







BGV Costo (BOUYER-LEROUX)

Width (X) = 500 mm
Height (Y) = 314 m
Thickness (Z) = 200 mm

❷ **Description of the multilayer system in AcouSYS**

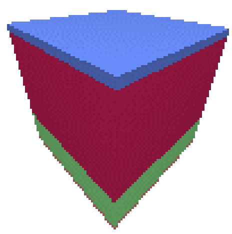
Multilayer [Thickness 304.5 mm] [Mass per unit area 176.2 kg/m²]

	Material name	Material type	Thickness [mm]
Coating	Coating	isotrop solid	15.000
Supporting wall	Hollow brick	anisotrop solid	200.000
Insulating layer	EPS insulating	isotrop solid	80.000
Gypsum board	BA10 gypsum board	isotrop solid	9.500

Dabs [ϕ = 10.6 %]

Diameter (before compression) 100.0 mm — Number 9.0 / m²

Thickness (before compression) 15.0 mm — Thickness (after compression) 10.0 mm



❸ Parameters associated with the different system layers

Layer	Name	Type	Parameters
Coating	Coating	Isotropic solid	thickness = 15 (mm) ρ = 2 640 (kg/m³) ν = 0.25 E = 10 000 (MPa) η = 0.01
Supporting wall	Hollow brick (BGV Costo)	Anisotropic solid	thickness = 200 (mm) ρ = 642 (kg/m³) ν_{xy} = 0.120 ν_{yz} = 0.251 ν_{zx} = 0.026 E_x, E_y, E_z G_{xy}, G_{yz}, G_{zx} η
Insulating layer	Expanded Polystyrene (EPS)	Isotropic solid	thickness = 100 (mm) ρ = 18 (kg/m³) ν = 0.2 E = 2.94 (MPa) η = 0.026
Gypsum board	BA10 plasterboard	Isotropic solid	thickness = 9.5 (mm) ρ = 720 (kg/m³) ν = 0.1 E = 2 000 (MPa) η = 0.02

Optimized frequency dependent parameters (see values per frequencies in Appendix 1)
Measured according to standard [29]

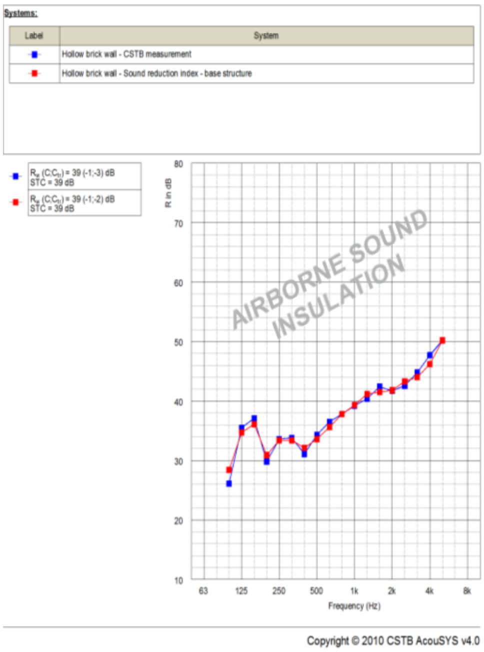
The support wall parameters were obtained using the genetic optimization tool (not included yet in AcouSYS version 4.

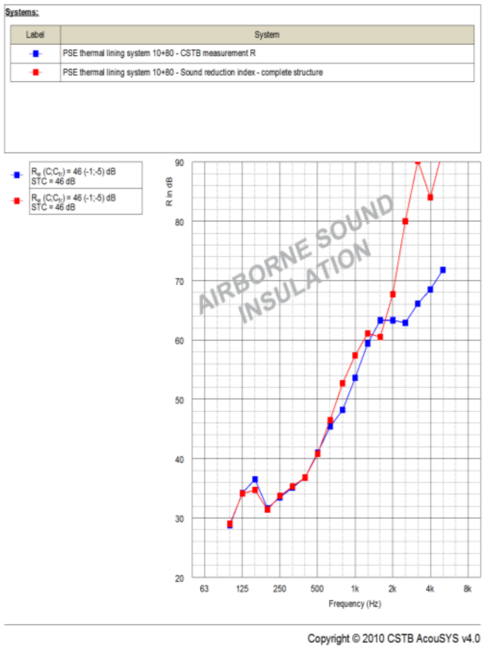
❹ Spatial windowing

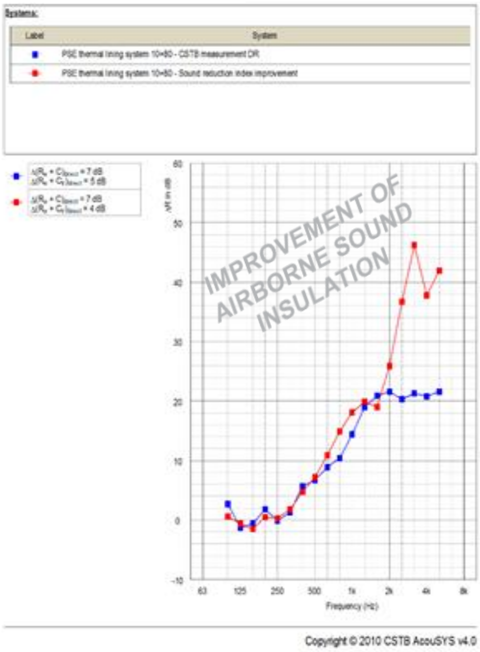
XY system dimensions: [4180; 2470] mm

❺ AcouSYS calculation results

AcouSYS simulation/measurement comparisons of the airborne sound insulation R for the wall without and with thermal lining and the improvement of airborne sound insulation *ΔR* for a thermal lining system in EPS 10+80 implemented on a hollow brick wall of thickness 200 mm with coating are shown after:







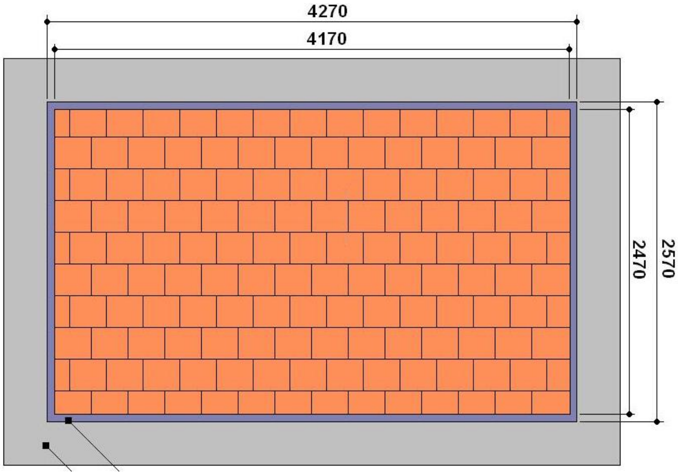
❼ Comments

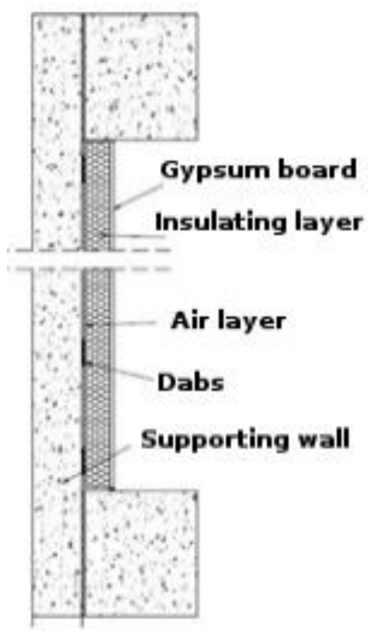
Good correlations are noticed between AcouSYS simulations and measurements. The first thickness resonance of the insulating layer is observed around the third octave 2 500 Hz. Discrepancies at high frequencies probably come from sound transmission paths not considered in the simulation (direct peripheral structural link or leakage).

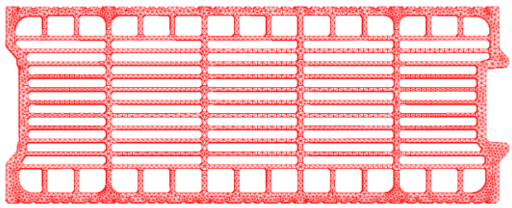
The approach adopted here is valid for a soft (e.g. EEPS) or rigid insulating layer (e.g. EPS, PU). The global equivalent spring is a function of the air and insulating layers' stiffnesses weighted by the bonding rate.

2.3.3 Mineral wool-based thermal lining system 10+100 on a hollow brick wall [25]

❶ **Drawing of the system**







BGV Thermo+ (BOUYER-LEROUX)

Width (X) = 500 mm
Height (Y) = 249 m
Thickness (Z) = 200 mm

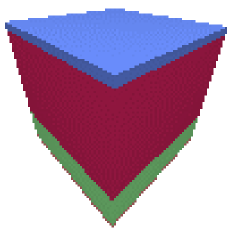
❷ **Description of the multilayer system in AcouSYS**

Multilayer [Thickness 324.5 mm] [Mass per unit area 186.9 kg/m²]

	Material name	Material type	Thickness [mm]
Coating	Coating	isotrop solid	15.000
Supporting wall	Hollow brick	anisotrop solid	200.000
Insulating layer	Mineral wool	porous	100.000
Gypsum board	BA10 gypsum board	isotrop solid	9.500

Dabs [ϕ = 18.3 %]

Diameter (before compression)	130.0 mm	Number	9.2 / m²
Thickness (before compression)	15.0 mm	Thickness (after compression)	10.0 mm



❸ Parameters associated with the different system layers

Layer	Name	Type	Parameters
Coating	Coating	Isotropic solid	thickness = 15 (mm) ρ = 2 550 (kg/m³) ν = 0.25 E = 10 000 (MPa) η = 0.01
Supporting wall	Hollow brick (BGV Thermo+)	Anisotropic solid	thickness = 200 (mm) ρ = 710 (kg/m³) ν_{xy} = 0.120 ν_{yz} = 0.205 ν_{zx} = 0.121 E_x , E_y , E_z G_{xy}, G_{yz}, G_{zx} η
Insulating layer	Mineral wool	Porous	thickness = 100 (mm) σ = 70 000 (Pa.s/m²) α_∞ = 1.00 φ = 0.9 Λ = 60 (µm) Λ' = 150 (µm) ρ = 70 (kg/m³) ν = 0.00 E = 0.240 (MPa) η = 0. 054
Gypsum board	BA10 plasterboard	Isotropic solid	thickness = 9.5 (mm) ρ = 720 (kg/m³) ν = 0.1 E = 2 000 (MPa) η = 0.02

Optimized frequency dependent parameters (see values per frequencies in Appendix 1)
Measured according to standard [29]

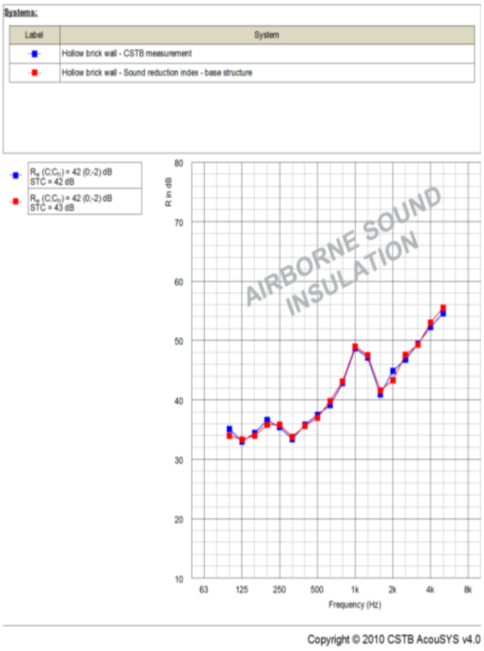
The support wall parameters were obtained using the genetic optimization tool (not included yet in AcouSYS version 4.

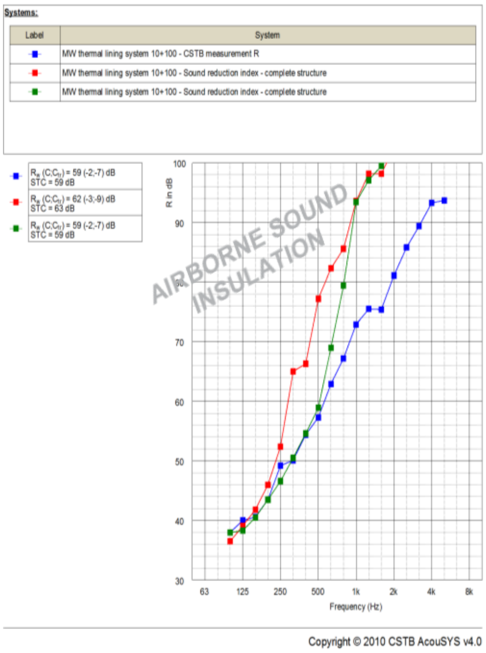
❹ Spatial windowing

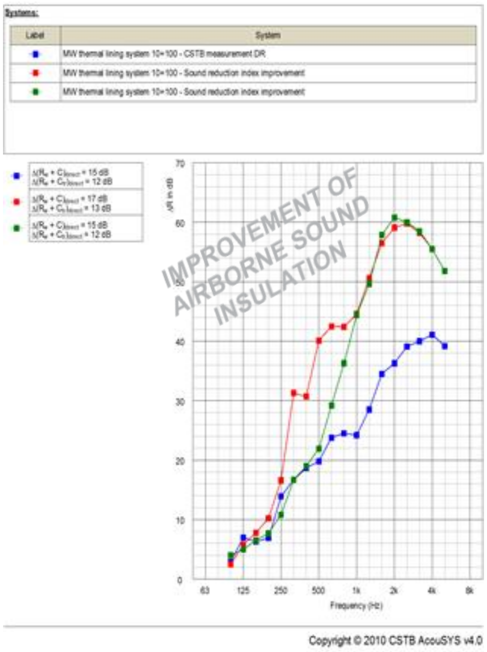
XY system dimensions: [4180; 2470] mm

❺ AcouSYS calculation results

AcouSYS simulation/measurement comparisons of the airborne sound insulation R and the improvement of airborne sound insulation *ΔR* for a thermal lining system in mineral wool 10+100 implemented on a hollow brick wall of thickness 200 mm with coating are shown below with two approach methods.







❼ Comments

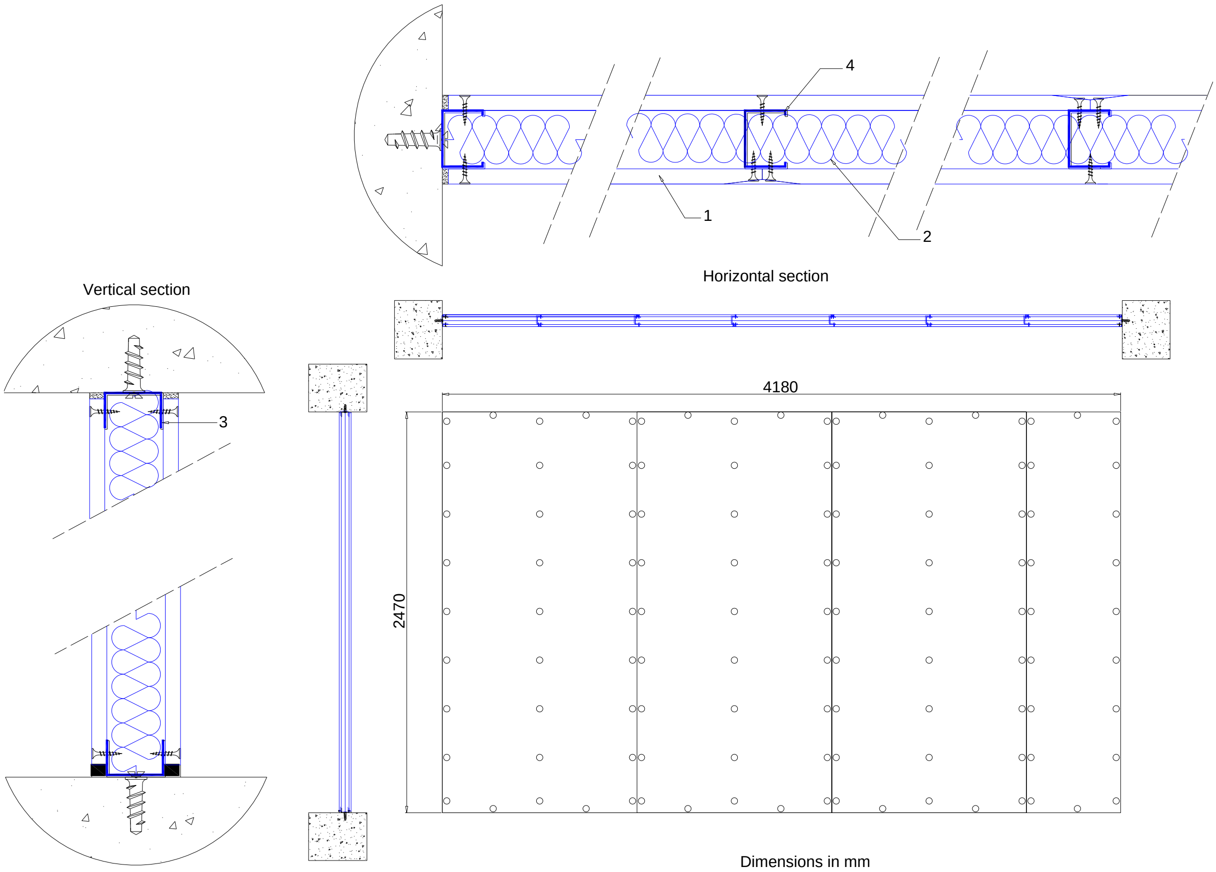
Two methods have been used and presented above. The first one used is the 'systems bonded by dabs' method (see § 1.2.2) and the second one is the classical multilayer method with a 'free contact' between insulating material and the supporting wall (without fictive air gap) which seems to give a better agreement with measurement.

The first method has been validated with a mineral wool-based thermal lining system implemented on a concrete supporting wall [15] but apparently the behaviour is not the same on a porous wall such as a masonry wall. New investigations should be carried out in order to clarify these configurations and the solution will be implemented in a next update of the AcouSYS software.

2.4 Partition walls

2.4.1 Single leaf partition wall with single frame (e.g. 72/48)

❶ **Drawing of the system**



A partition wall system can be divided into two parts:

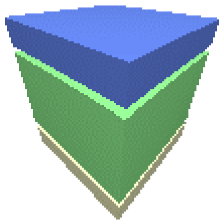
- The plasterboards and the cavity (filled with air or absorbing material)
- A framework

The first part (without structural connections) is simulated using the TMM approach. Next the contribution due to the framework is obtained using the SEA (Statistical Energy Analysis) approach which includes the rail and stud rigidities and the screwing rate.

❷ Description of the multilayer system in AcouSYS and frame

Multilayer [Thickness 70 mm] [Mass per unit area 19.1 kg/m²]

	Material name	Material type	Thickness [mm]
Skin n°1	BA13 gypsum board	isotrop solid	12.500
Cavity	glass wool	porous	45.000
Skin n°2	BA13 gypsum board	isotrop solid	12.500



	Material name	Material type	Screwing [mm]	Spacing [mm]
Rail	rail 48	frame component	300.0	
Stud	stud 48	frame component	300.0	600.0
Peripheral stud	peripheral stud 48	frame component	300.0	

❸ Parameters associated with the different system layers and frame

Layer	Name	Type	Parameters
Skin n°1/2	Plasterboard	Isotropic solid	thickness = 12.5 (mm) ρ = 736 (kg/m³) ν = 0.1 E = 2 700 (MPa) η = 0.03
Cavity	Glass wool	Porous	thickness = 45 (mm) σ = 14 620 (Pa.s/m²) α∞ = 1.00 φ = 0.95 Λ = 60 (μm) Λ' = 150 (μm) ρ = 14.6 (kg/m³) ν = 0.00 E = 0.05 (MPa) η = 0.1

Measured according to standard [28] adapted to the plasterboard issues
Measured according to standard [30]
Measured according to standard [29]

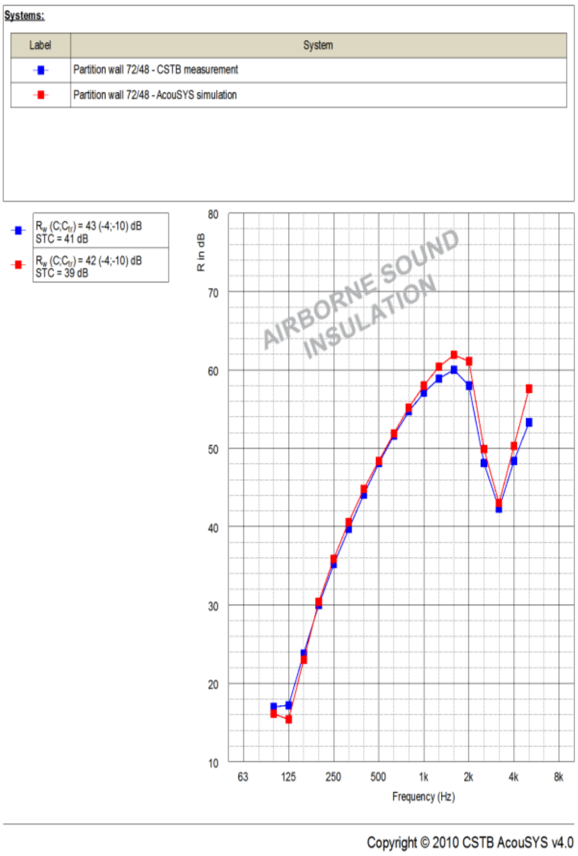
Frame	Name	Type	Parameters
Rail	Rail 48	Frame component	Rigidity = 1 000 (kN/m) Screwing = 300 (mm)
Stud	Stud 48	Frame component	Rigidity = 700 (kN/m) Screwing = 300 (mm) Spacing = 600 (mm)
Peripheral stud	Peripheral Stud 48	Frame component	Rigidity = 1 000 (kN/m) Screwing = 300 (mm)

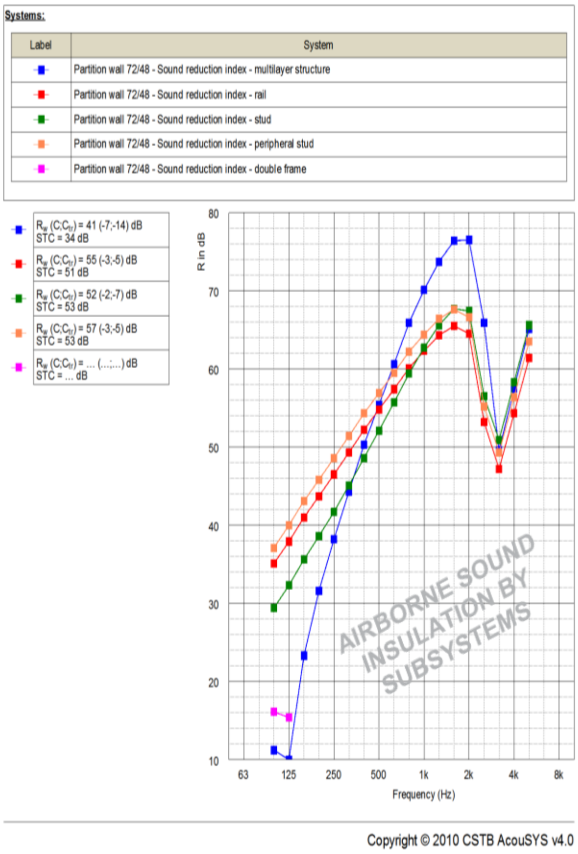
❹ Spatial windowing

XY system dimensions: [4180; 2470] mm

❺ AcouSYS calculation results

An AcouSYS simulation/measurement comparison of the airborne sound insulation *R* for a 72/48 partition is shown below as well as the acoustic contribution of each subsystem (multilayer and framework elements) on the airborne sound insulation R of the partition.





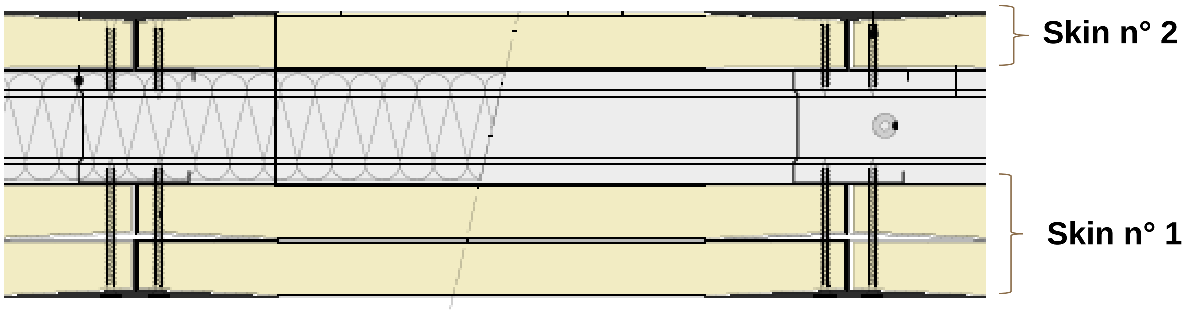
❻ Comments

A good correlation is noticed between AcouSYS simulation and measurement when the framework contribution accounts. The mechanical short circuit is mostly observed in medium and high frequencies. The critical frequency of the plasterboard is observed at the third octave 3150 Hz.

Additional investigations are in progress to extend this hybrid approach (TMM+SEA) to other systems with mechanical connections.

2.4.2 Double leaf partition wall with single frame (e.g. 116/62)

❶ Drawing of the system



❷ Homogenization

Multi slab

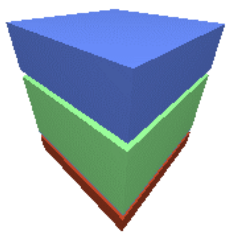
Structure [Thickness 36 mm] [Mass per unit area 34.9 kg/m²]

	Material name	Material type	Thickness [mm]	Contact with above layer	
0	BA18 Plaster	isotrop solid	18.000		
1	BA18 Plaster	isotrop solid	18.000	✖ Free slip contact	
2	No slab				

❸ Description of the multilayer system in AcouSYS

Multilayer [Thickness 116 mm] [Mass per unit area 53.5 kg/m²]

	Material name	Material type	Thickness [mm]
Skin n°1	2xBA18 Homogenizing materials	isotrop solid	36.000
Cavity	Glass wool	porous	60.000
	air	fluid	2.000
Skin n°2	BA18 Plasterboard	isotrop solid	18.000



	Material name	Material type	Screwing [mm]	Spacing [mm]
Rail	rail 62	frame component	300.0	
Stud	stud 62	frame component	250.0	900.0
Peripheral stud	peripheral stud 62	frame component	250.0	

⚠ The indicated screwing matches the apparent skin.

❹ Parameters associated with the different system layers and frame

Layer	Name	Type	Parameters
Skin n°2	Plasterboard	Isotropic solid	thickness = 18 (mm) ρ = 910 (kg/m³) ν = 0.1 E = 4 780 (MPa) η = 0.014
Skin n°1	Homogenized material	Isotropic solid	thickness = 36 (mm) ρ = 910 (kg/m³) ν = 0.1 E (MPa) η
Cavity	Glass wool	Porous	thickness = 60 (mm) σ = 11 000 (Pa.s/m²) α∞ = 1.00 φ = 0.95 Λ = 60 (µm) Λ' = 150 (µm) ρ = 18.3 (kg/m³) ν = 0.00 E = 0.02 (MPa) η = 0.08

Measured according to standard [28] adapted to the plasterboard issues
Homogenized parameters (see E and η values per frequencies in Appendix 1)

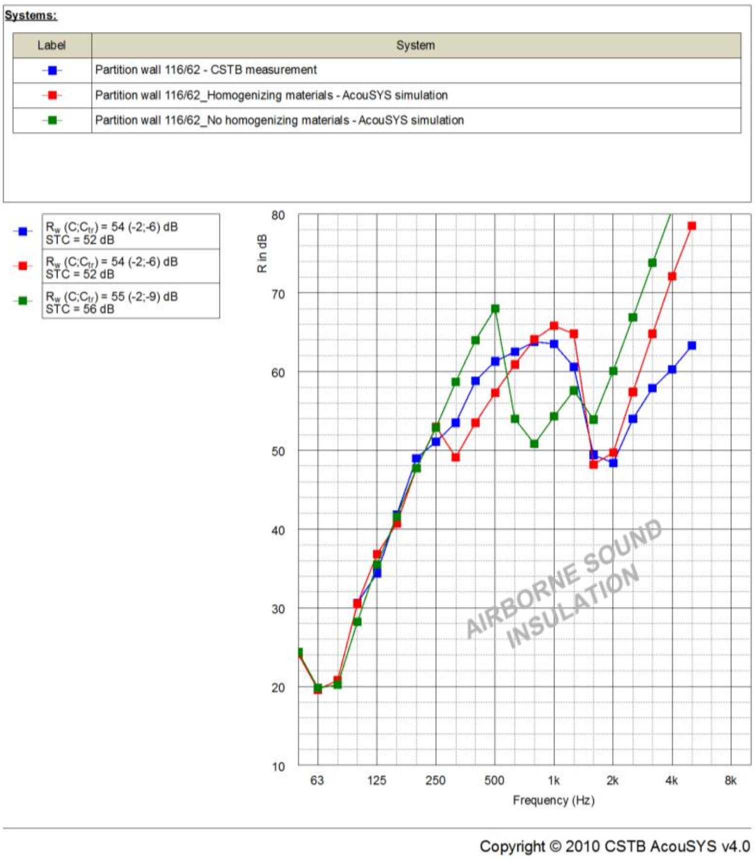
Frame	Name	Type	Parameters
Rail	Rail 62	Frame component	Rigidity = 380 (kN/m) Screwing = 300 (mm)
Stud	Stud 62	Frame component	Rigidity = 330 (kN/m) Screwing = 250 (mm) Spacing = 900 (mm)
Peripheral stud	Peripheral Stud 62	Frame component	Rigidity = 380 (kN/m) Screwing = 250 (mm)

❺ Spatial windowing

XY system dimensions: [4180; 2470] mm

❻ AcouSYS calculation results

AcouSYS simulation/measurement comparisons of the airborne sound insulation *R* for a 116/62 partition are shown below with and without homogenization:

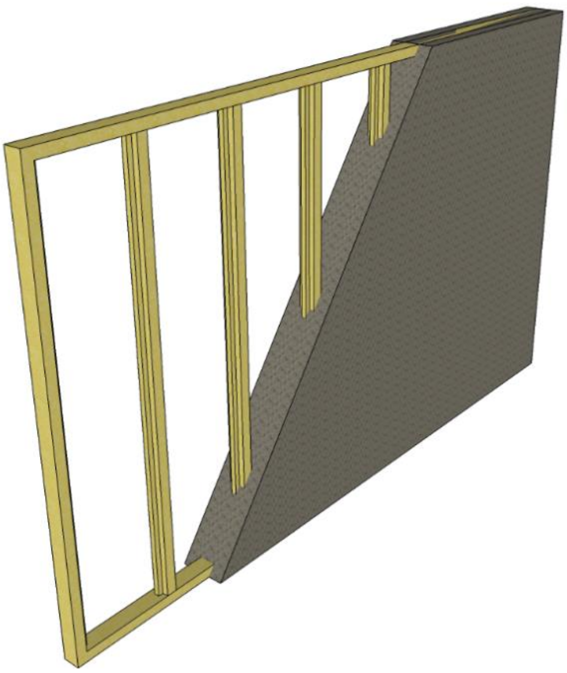


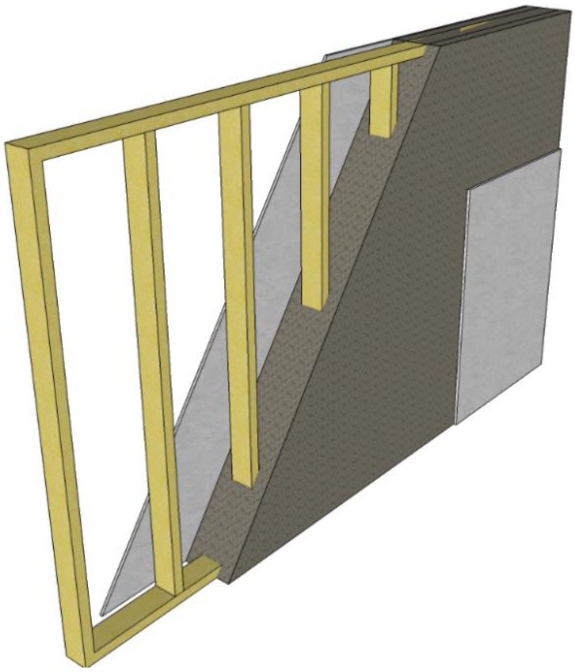
❼ Comments

A better correlation is obtained between AcouSYS simulation and measurement when the homogenized material is used. The critical frequency of the plasterboard is observed at the third octave 1600-2000 Hz.

2.5 Hemp concrete wall (around a wood frame without and with coatings)

❶ **Drawing of the system**

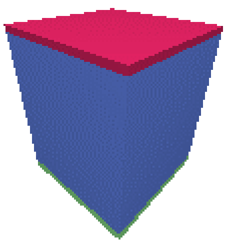




❷ **Description of the system in AcouSYS**

Multilayer [Thickness 353 mm] [Mass per unit area 158.9 kg/m²]

	Material name	Material type	Thickness [mm]	Contact with above layer	Belonging
0	Coating	isotrop solid	13.000	☒ Free slip contact	☐ Belongs to base structure
1	Hemp concrete	porous	320.000	☐ Free slip contact	☐ Belongs to base structure
2	Coating	isotrop solid	20.000	☐ Free slip contact	☐ Belongs to base structure



Here, the wood frame is not considered.

❸ Physical parameters associated with the different system layers

Layer	Name	Type	Parameters
0 / 2	Coating	Isotropic solid	Thickness (layer 0 / 2) = 13 / 20 (mm) ρ = 1 770 (kg/m³) ν = 0.2 E = 3 770 (MPa) η = 0.01
1	Hemp concrete	Porous	thickness = 320 (mm) σ = 2 000 (Pa.s/m²) α_∞ = 1.15 φ = 0.70 Λ = 155 (μm) Λ' = 250 (μm) ρ = 315 (kg/m³) ν = 0.35 E = 47.5 (MPa) η = 0.06

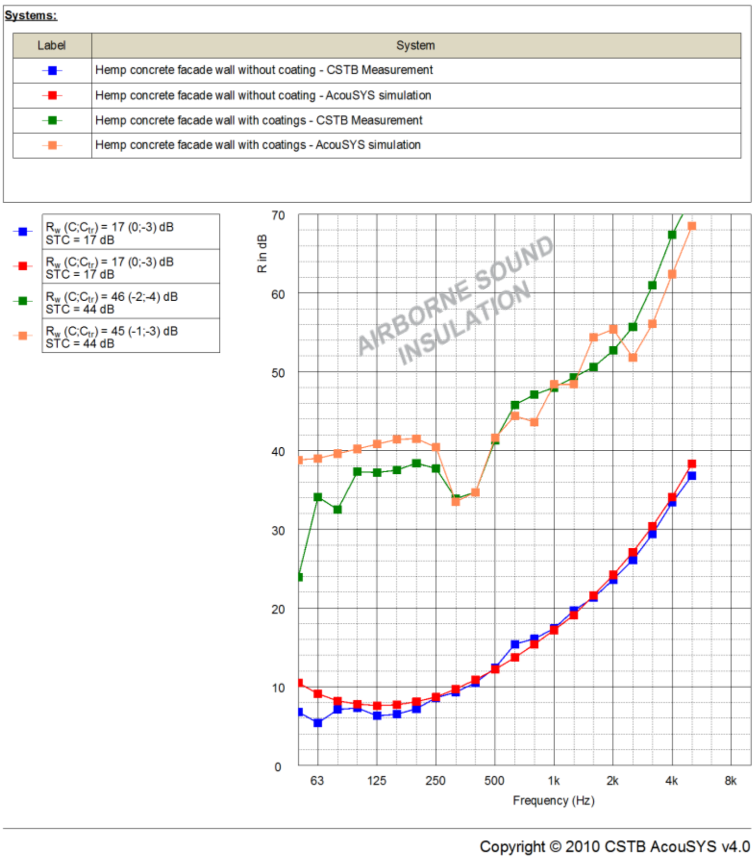
Measured according to standard [31]
Measured according to standard [30]
Measured according to methods [32] [33]
Measured according to method [34]

❹ Spatial windowing

XY system dimensions: [4180; 2470] mm

❺ AcouSYS calculation results

AcouSYS simulation/measurement comparisons of the airborne sound reduction index *R* for the hemp concrete facade wall of thickness 320 mm without and with coatings are shown in figure below:

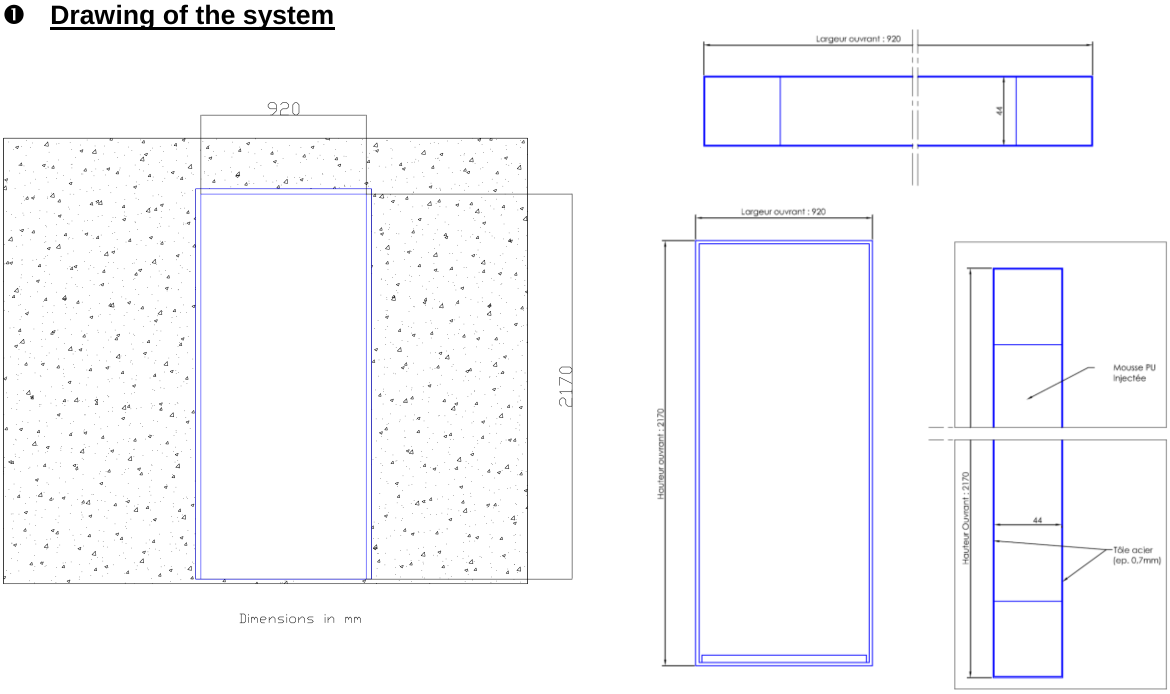


❻ Comments

Good correlations are noticed between AcouSYS simulations and measurements. The drop around the third octaves 315 - 400 Hz is associated with the resonance frequency of the mass/spring/mass system.

2.6 Door sandwich panel

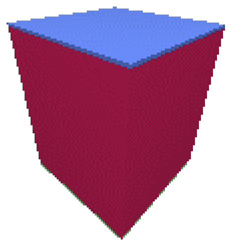
❶ **Drawing of the system**



❷ **Description of the multilayer system in AcouSYS**

Multilayer [Thickness 45.4 mm] [Mass per unit area 12.7 kg/m²]

	Material name	Material type	Thickness [mm]	Contact with above layer	Belonging
0	steel	isotrop solid	0.700	☒ Free slip contact	☐ Belongs to base structure
1	PU insulating	isotrop solid	44.000	☐ Free slip contact	☐ Belongs to base structure
2	steel	isotrop solid	0.700	☐ Free slip contact	☐ Belongs to base structure



Only the central part of the door is modelled. The frame and the peripheral structure can cause leaks are not considered by calculation.

❸ **Parameters associated with the different system layers**

Layer	Name	Type	Parameters
0/2	Steel plate	Isotropic solid	thickness = 0.7 (mm) ρ = 7 800 (kg/m³) ν = 0.3 E = 200 000 (MPa) η = 0.01
1	Polyurethane insulating foam (PU)	Isotropic solid	thickness = 44 (mm) ρ = 40 (kg/m³) ν = 0.2 E = 15 (MPa) η = 0.07

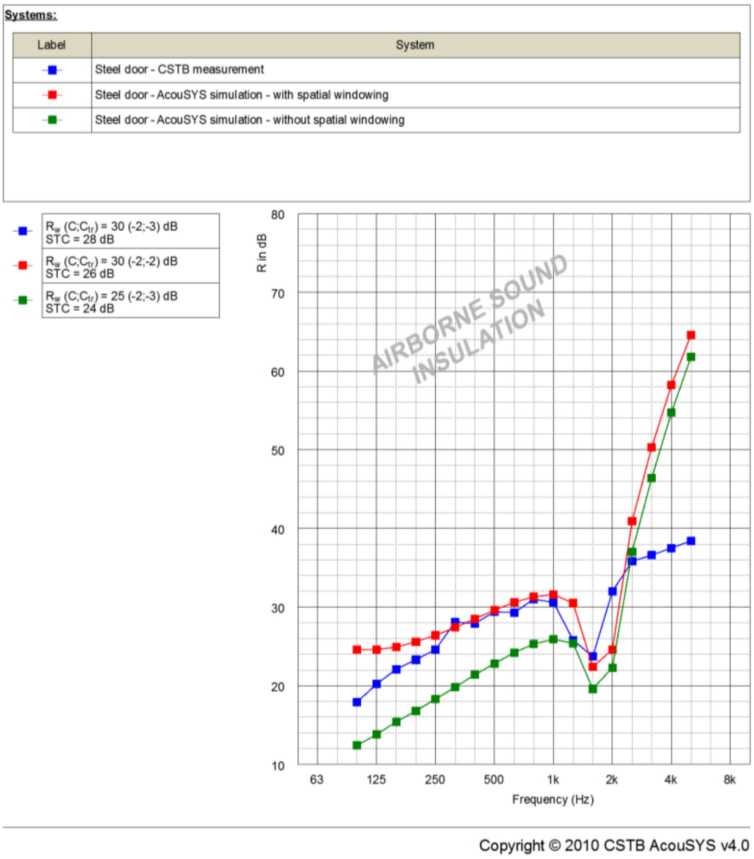
❹ Spatial windowing

XY system dimensions: [2170; 920] mm

Spatial windowing has a strong influence when calculating airborne sound insulation. An example is shown in the figure below.

❺ AcouSYS calculation results

AcouSYS simulation/measurement comparisons of the airborne sound insulation *R* for a door are shown below. The simulation is done with and without taking spatial windowing:



❻ Comments

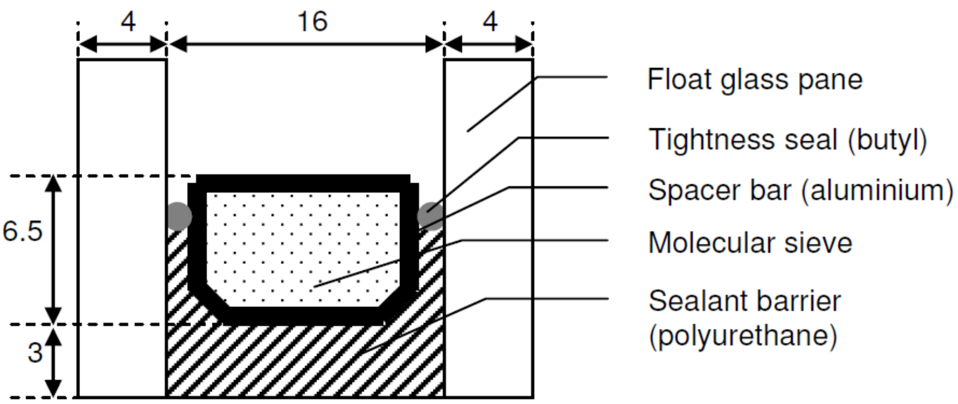
A good correlation is noticed between AcouSYS simulation and measurement when the spatial windowing is taken into account.

The drop around the third octaves 1 600- 2 000 Hz is associated with the resonance frequency of the mass/spring/mass system.

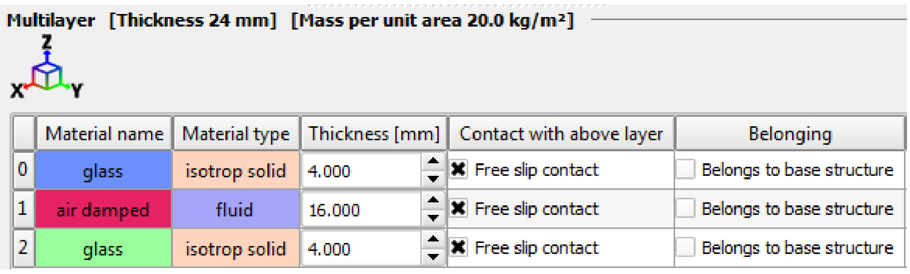
The deviations observed at low frequencies (f < 250 Hz) are due to modal phenomena and at high frequencies (f > 2 kHz) are mainly due to the peripheral leaks and losses by the frame not considered by calculation.

2.7 Double glazing

❶ Drawing of the system

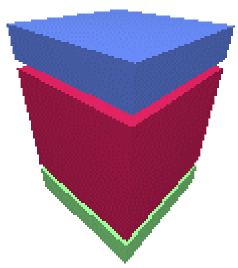


❷ Description of the multilayer system in AcouSYS



Multilayer [Thickness 24 mm] [Mass per unit area 20.0 kg/m²]

	Material name	Material type	Thickness [mm]	Contact with above layer	Belonging
0	glass	isotrop solid	4.000	Free slip contact	Belongs to base structure
1	air damped	fluid	16.000	Free slip contact	Belongs to base structure
2	glass	isotrop solid	4.000	Free slip contact	Belongs to base structure



Only the glass part of the window is modelled. The frame and the peripheral structure can cause leaks are not considered by calculation.

❸ Parameters associated with the different system layers

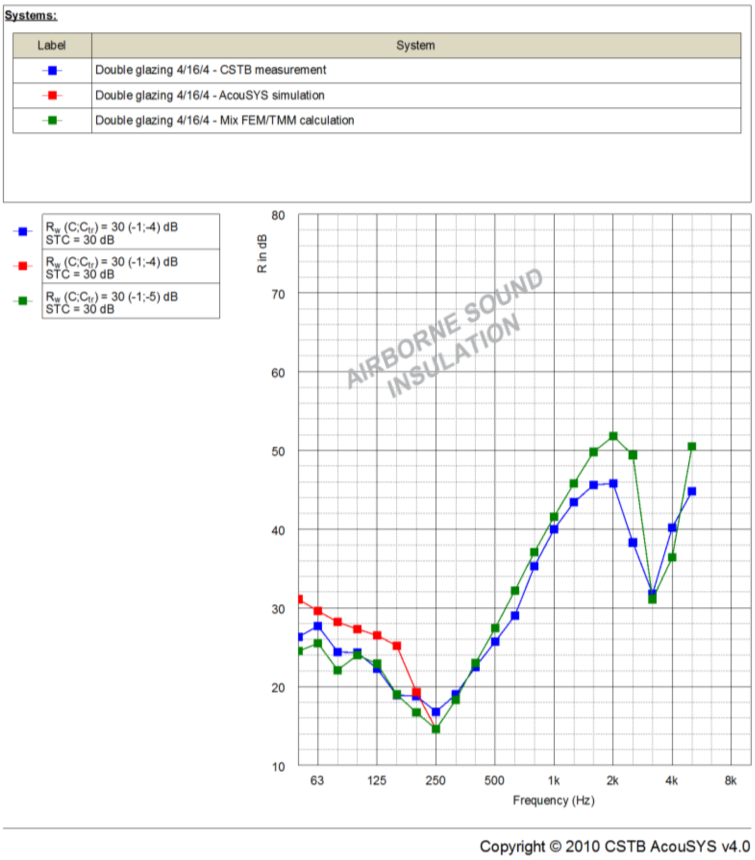
Layer	Name	Type	Parameters
0/2	Glass	Isotropic solid	ρ = 2 500 (kg/m³) ν = 0.22 E = 62 000 (MPa) η = 0.02
1	Air damping	Fluid	ρ = 1.3 (kg/m³) c=342m/s η = 0.01

❹ Spatial windowing

XY system dimensions: [1480; 1230] mm

❺ AcouSYS calculation results

AcouSYS simulation/measurement comparisons of the airborne sound insulation R for a 4/16/4 double glazing are shown below. A FEM method can also be used to take into account the modal behaviour of glazing panel at low frequencies.



❻ Comments

Overall, a good correlation is noticed between AcouSYS simulation and measurement but a TMM approach is not the most appropriate method to simulate glazing components because of their strong modal behaviour at low frequencies. Moreover, the additional edge damping due to the spacer and sealant is not considered in the simulation. A FEM approach could be implemented in an AcouSYS future version to take into account these elements.

2.8 Constructions taken from NRC-CRNC research (IRC IR-818)

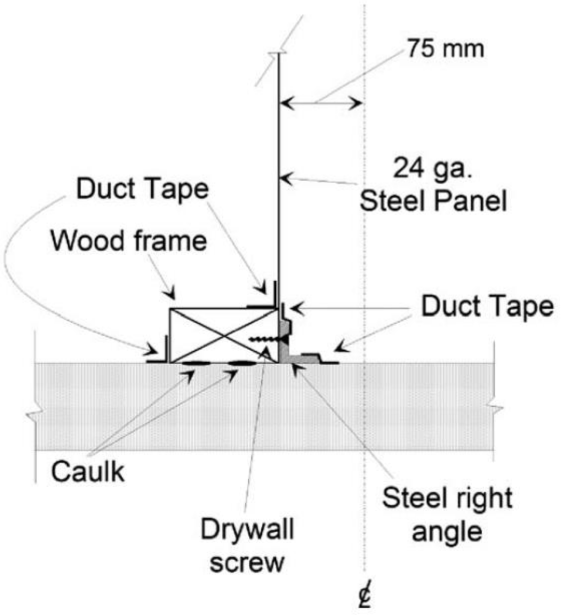
The examples of systems presented below are system with wood frame.

Unlike the other systems presented in this document which come from measurements made in the CSTB acoustic laboratory, these systems have been measured according to descriptions specified in the North American standards. The measurement results come from various document like the American Standard ASTM E 1289-08 (Standard Specification for Reference Specimen for Sound Transmission Loss: Installation A and B) or a NRC-CRNC research report (IRC IR-818: 'Laboratory Measurements of the Sound Insulation of Building Façade Elements' by J.S. Bradley and J.A. Birta).

2.8.1 Galvanized steel sheets with wood frame (Standard ASTM E 1289-08)

❶ <u>Drawing of the system</u>

Installation A



NOTE 1—Wood frame caulked, specimen joints and perimeter taped on both sides.

FIG. 4 Installation of Reference Specimen Showing Caulking of Wood Frame and the Taping of the Specimen Joints and Perimeter on Both Sides

Installation B

(= Installation A with 2 steel sheets spaced by a wood frame (depth 90 mm))

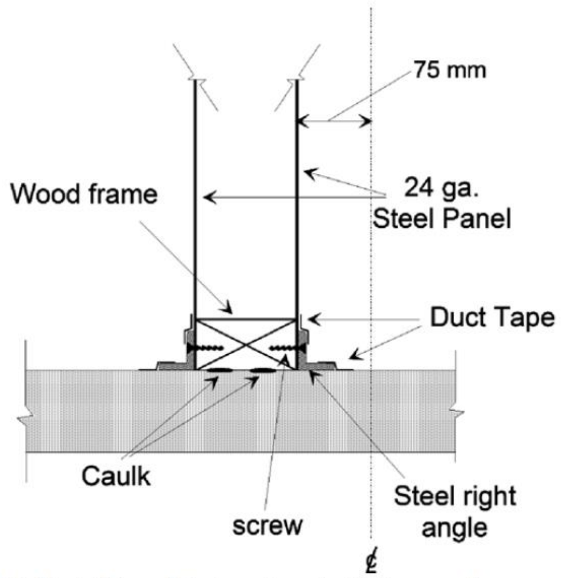


FIG. 5 Installation of Steel panels as double layer specimen on a single wood frame. The centerline symbol, ¢, represents the mid-plane of the test opening between two rooms.

The steel sheets have a nominal thickness 0.63 mm and a weight 5.1 ± 0.7 kg/m².

❷ Performance (from an interlaboratory research)

TABLE 1 Mean and Standard Deviations of Transmission Loss Data on a Single Layer Specimen, Installation A.

One Third Octave Band Center Frequency (Hz)	Average Laboratory Value of Sound Transmission Loss (dB)	Standard Deviation (dB)
50	12.2	1.9
63	12.3	1.2
80	10.8	2.0
100	11.2	1.8
125	12.1	1.2
160	12.9	1.3
200	14.6	1.3
250	15.8	1.3
315	17.6	1.1
400	19.1	1.2
500	20.8	1.1
630	22.6	1.1
800	24.3	1.0
1000	26.0	0.9
1250	28.1	0.8
1600	29.9	0.8
2000	31.7	0.9
2500	33.6	0.8
3150	35.4	1.1
4000	37.1	1.2
5000	38.6	1.4
STC	25.3	0.9
OITC	19.0	0.7

TABLE 2 Mean and Standard Deviations of Transmission Loss Data on a Double Layer Specimen, Installation B

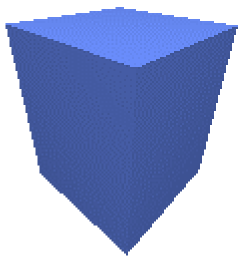
One Third Octave Band Center Frequency (Hz)	Average Laboratory Value of Sound Transmission Loss (dB)	Standard Deviation (dB)
80	11.9	2.5
100	10.4	2.3
125	10.0	1.7
160	11.6	2.0
200	13.5	1.8
250	15.3	2.2
315	18.2	2.0
400	20.9	2.1
500	23.6	1.8
630	27.1	2.0
800	30.8	2.1
1000	34.7	2.2
1250	39.1	3.1
1600	43.5	3.0
2000	46.7	2.7
2500	50.5	2.9
3150	53.5	3.1
4000	55.0	3.7
5000	55.8	5.6
STC	27.3	1.5
OITC	19.1	1.1

❸ Description of systems in AcouSYS

Installation A

Multilayer [Thickness 0.63 mm] [Mass per unit area 5.1 kg/m²]

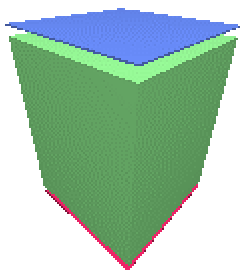
	Material name	Material type	Thickness [mm]	Contact with above layer	Belonging
0	steel	isotrop solid	0.630	☒ Free slip contact	☐ Belongs to base structure



Installation B

Multilayer [Thickness 91.26 mm] [Mass per unit area 10.3 kg/m²]

	Material name	Material type	Thickness [mm]	Contact with above layer	Belonging
0	steel	isotrop solid	0.630	☒ Free slip contact	☐ Belongs to base structure
1	air	fluid	90.000	☒ Free slip contact	☐ Belongs to base structure
2	steel	isotrop solid	0.630	☒ Free slip contact	☐ Belongs to base structure



⚠ Here, the wood frame is not considered.

❹ Parameters associated with the different system layers

Layer	Name	Type	Parameters
0/2	Steel	Isotropic solid	thickness = 0.63 (mm) ρ = 8 095 (kg/m³) ν = 0.3 E = 200 000 (MPa) η = 0.01
1	Air	Fluid	thickness = 90 (mm) ρ = 1.21 (kg/m³) c = 342 (m/s) η_{air} = 18.14e^{-6} (Pa.s) η = 0.00

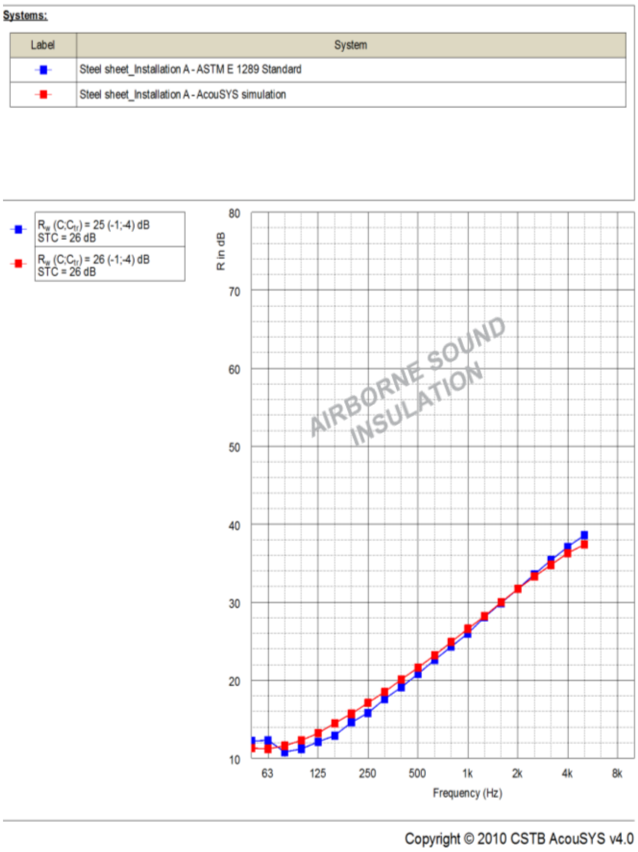
❺ Spatial windowing

XY system dimensions: [2840; 1220] mm

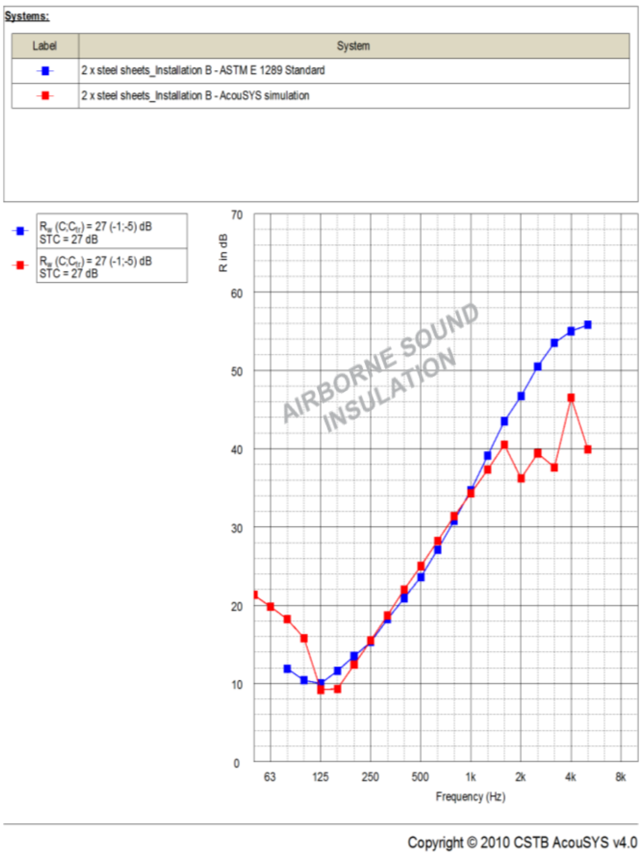
❻ AcouSYS calculation results

AcouSYS simulation/measurement comparisons of the airborne sound insulation R for a simple and double steel sheet (Installation A and B respectively of the standard ASTM E 1289-08) are shown below:

Installation A



Installation B



❼ Comments

Although the presence of the frame is not considered (observed at high frequencies), good correlations are noticed between AcouSYS simulations and measurements according to the North American standards.

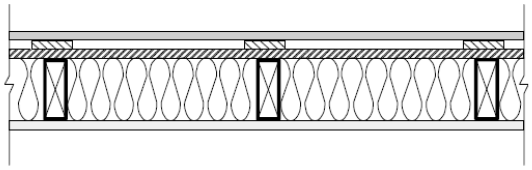
2.8.2 Facade construction with wood frame (Standard ASTM E 1289-08)

❶ **Drawing of the system**

National Research Council Canada

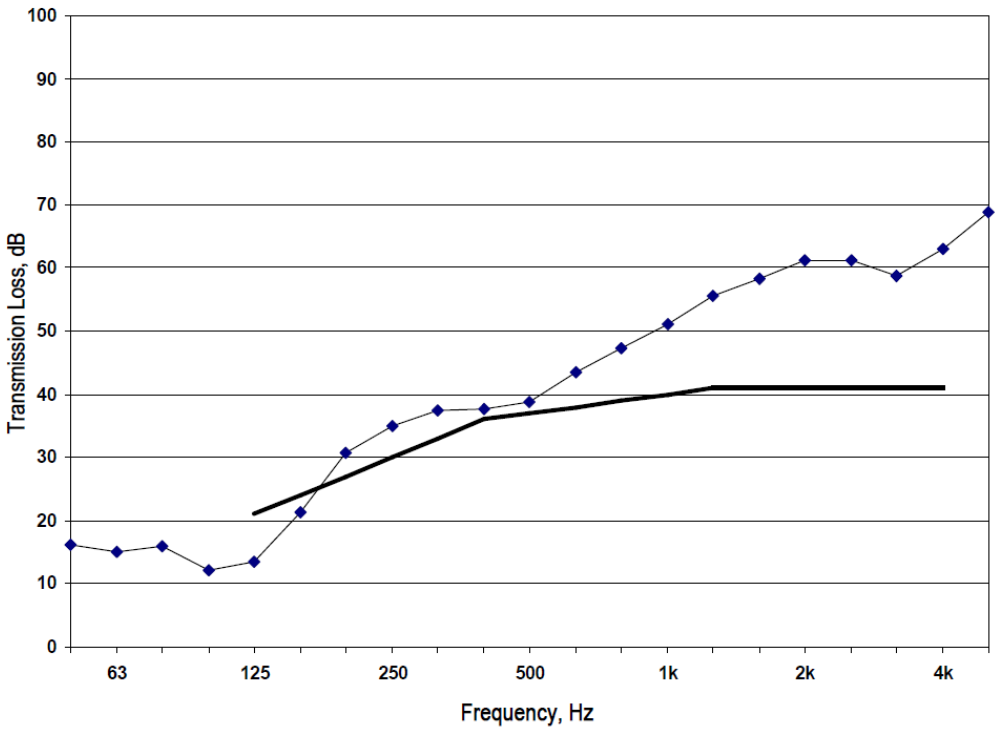
Element	Description
1	1 mm thick vinyl siding
2	19 mm thick wood furring at 406 mm on centre
3	13 mm thick wood fibre board
4	140 mm deep wood stud at 406 mm on centre
5	152 mm thick glass fibre insulation in cavity
6	13 mm thick regular gypsum board

TLA-99-106a
VIN1_WFUR19(406)_WFB13_WS140(406)_GFB152_G13
Construction Type: wall



❷ **Performance**

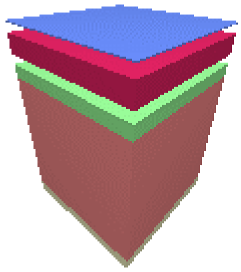
Freq, Hz	TL, dB
50	16
63	15
80	16
100	12
125	13
160	21
200	31
250	35
315	37
400	38
500	39
630	44
800	47
1000	51
1250	56
1600	58
2000	61
2500	61
3150	59
4000	63
5000	69
STC	37
OITC	25



❸ Description of the multilayer system in AcouSYS

Multilayer [Thickness 185.5 mm] [Mass per unit area 12.9 kg/m²]

	Material name	Material type	Thickness [mm]	Contact with above layer	Belonging
0	soft viscoelastic	viscoelastic	1.000	☒ Free slip contact	☐ Belongs to base structure
1	air	fluid	19.000	☒ Free slip contact	☐ Belongs to base structure
2	fibre board	isotrop solid	13.000	☒ Free slip contact	☐ Belongs to base structure
3	glass wool	porous	140.000	☐ Free slip contact	☐ Belongs to base structure
4	BA13 gypsum board	isotrop solid	12.500	☐ Free slip contact	☐ Belongs to base structure



Here, the wood frame is not considered.

❹ Parameters associated with the different system layers

Layer	Name	Type	Parameters
0	Vinyl siding	Viscoelastic	thickness = 1 (mm) ρ = 400 (kg/m^3) ν = 0.3 E (MPa) G (MPa) η
1	Air	Fluid	thickness = 19 (mm) ρ = 1.21 (kg/m^3) c = 342 (m/s) η_{air} = 18.14e^{-6} (Pa.s) η = 0.00
2	Wood fibre board	Isotropic solid	thickness = 13 (mm) ρ = 270 (kg/m^3) ν = 0.1 E = 4 600 (MPa) η = 0.02
3	Glass fibre	Porous	thickness = 140 (mm) σ = 50 000 (Pa.s/m^2) α_∞ = 1.00 φ = 0.95 Λ = 60 (µm) Λ' = 150 (µm) ρ = 9.2 (kg/m^3) ν = 0.00 E = 0.09 (MPa) η = 0.25
4	Gypsum board	Isotropic solid	thickness = 12.5 (mm) ρ = 615 (kg/m^3) ν = 0.1 E = 1 800 (MPa) η = 0.03

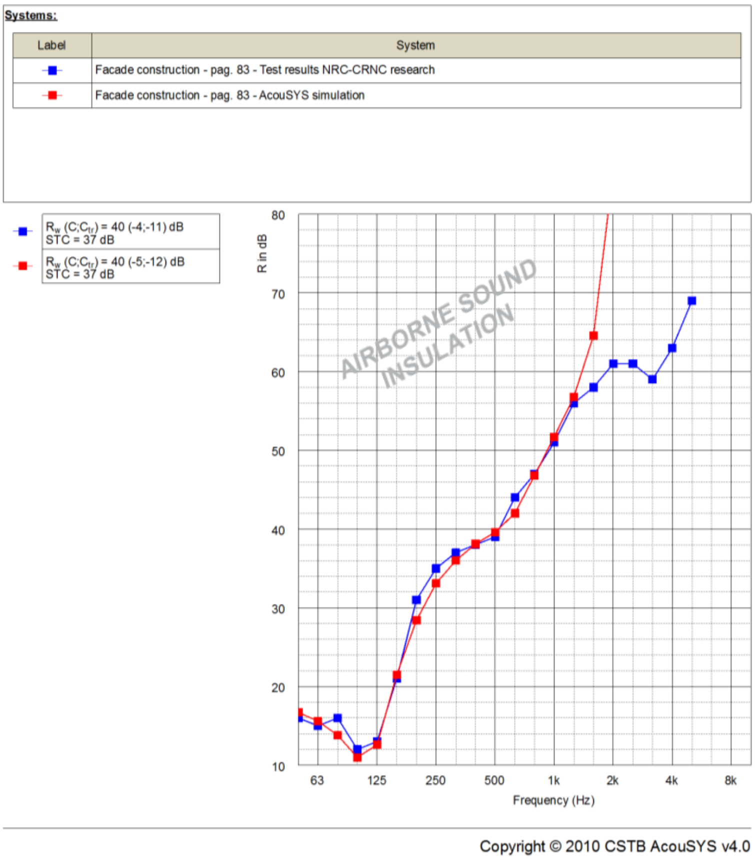
Frequency dependent parameter (see default values in the database "Materials" of AcouSYS software)

❺ Spatial windowing

XY system dimensions: [3660; 2440] mm

❻ AcouSYS calculation results

An AcouSYS simulation/measurement comparison of the airborne sound insulation R for a façade construction with wood frame is given below:



❼ Comments

No information is specified on the mechanical or acoustical properties of materials.

Although the wood frame (furring and stud) is not considered in calculation (observed at high frequencies), a good correlation is noticed between AcouSYS simulation and measurement.

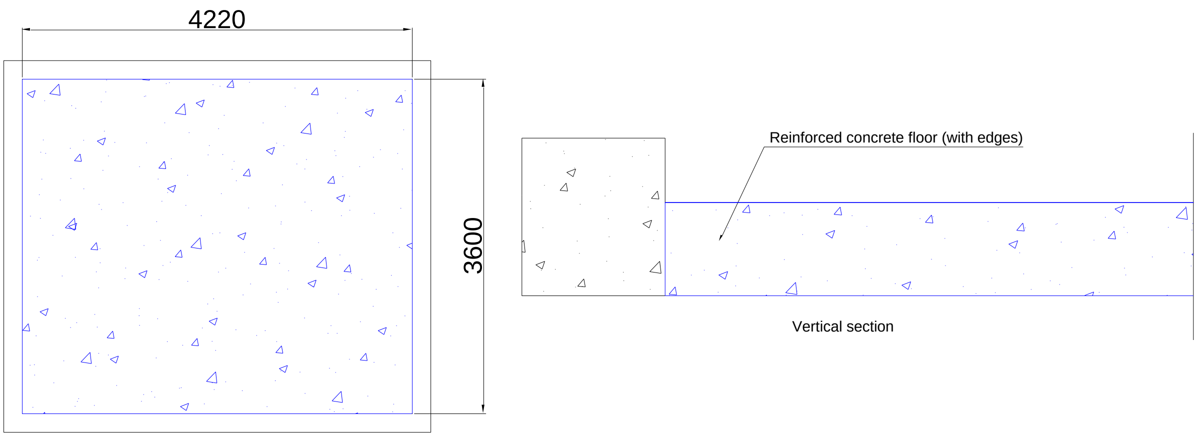
3. Airborne/impact sound insulation and rainfall noise calculation of horizontal systems

For horizontal systems, AcouSYS software can simulate the following acoustic indicators:

- **The airborne sound insulation R (and the improvement of airborne sound insulation ΔR)**
- **The impact sound pressure level Ln** generated by a standardized tapping machine (and **the improvement of impact sound insulation ΔL)**
- **The sound intensity level L_i** of rainfall noise

3.1 Concrete slab

❶ **Drawing of the system**

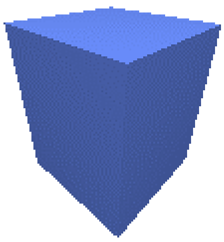


dimensions in mm

❷ **Description of the multilayer system in AcouSYS**

Multilayer [Thickness 140 mm] [Mass per unit area 350.0 kg/m²]

	Material name	Material type	Thickness [mm]	Contact with above layer	Belonging
0	Concrete	isotrop solid	140.000	Free slip contact	Belongs to base structure



❸ Parameters associated with the different system layers

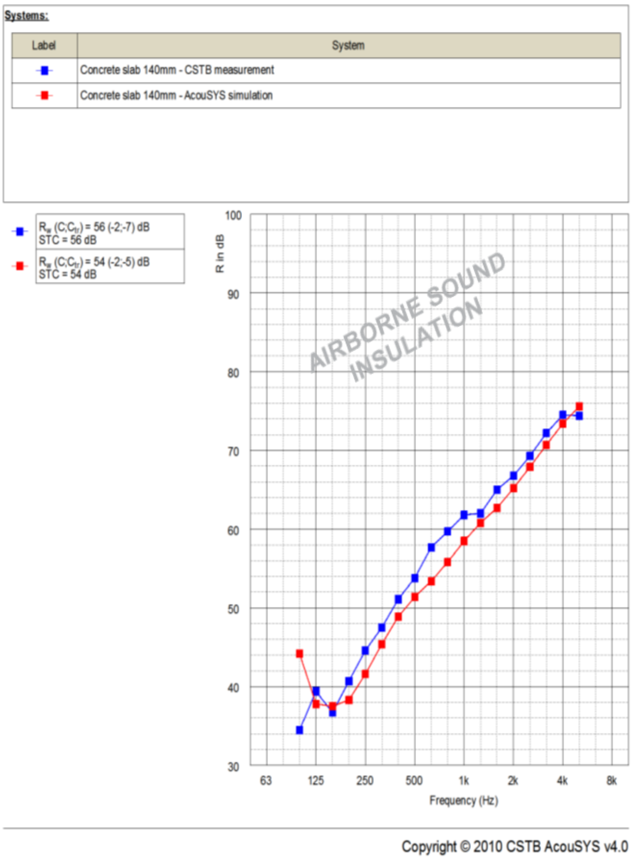
Layer	Name	Type	Parameters
0	Reinforced concrete slab	Isotropic solid	Thickness = 140 (mm) ρ = 2 500 (kg/m³) ν = 0.1 E = 37 000 (MPa) η = 0.015

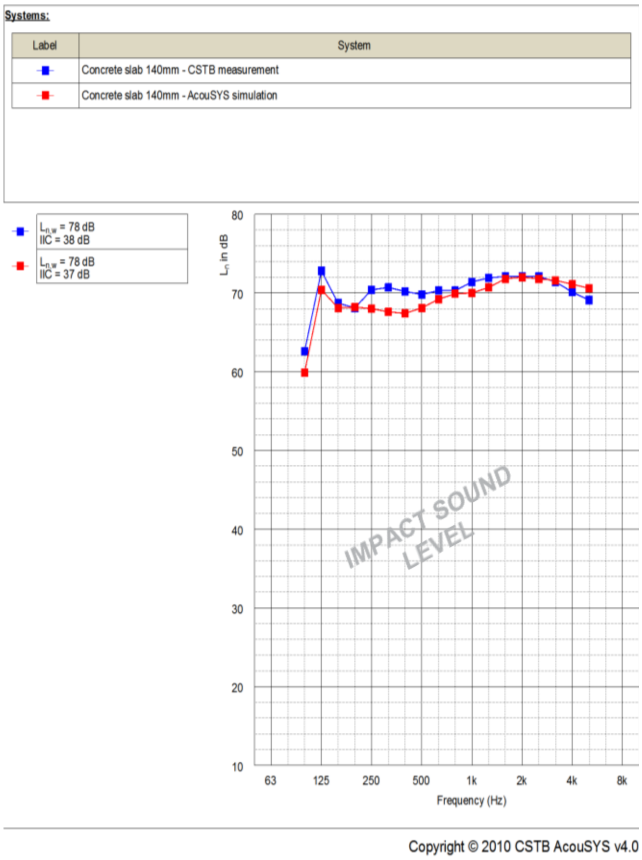
❹ Spatial windowing

XY system dimensions: [4220; 3600] mm for airborne sound insulation (Infinite dimensions for impact sound pressure level).

❺ AcouSYS calculation results

AcouSYS simulation/measurement comparisons of the sound reduction index R and the impact sound pressure level L_n for a concrete slab of thickness 140 mm are shown below:



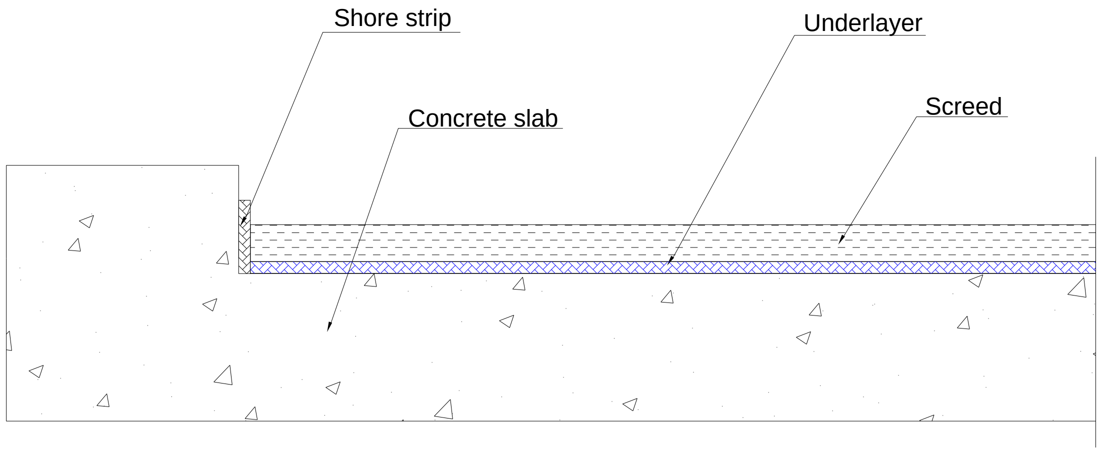


❻ Comments

Good correlations are noticed between AcouSYS simulations and measurements.

3.2 Underscreed system

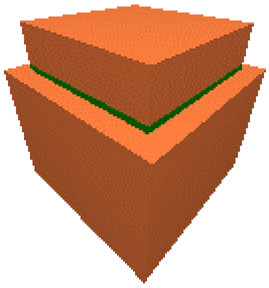
❶ **Drawing of the system**



❷ **Description of the multilayer system in AcouSYS**

Multilayer [Thickness 186 mm] [Mass per unit area 440.2 kg/m²]

	Material name	Material type	Thickness [mm]	Contact with above layer	Belonging
0	Screed	isotrop solid	40.000	☒ Free slip contact	☐ Belongs to base structure
1	Underlayer	viscoelastic	6.000	☐ Free slip contact	☐ Belongs to base structure
2	Concrete	isotrop solid	140.000	☐ Free slip contact	☒ Belongs to base structure



❸ **Parameters associated with the different system layers**

Layer	Name	Type	Parameters
0	Screed	Isotropic solid	Thickness = 40 (mm) ρ = 2 250 (kg/m³) ν = 0.15 E = 20 000 (MPa) η = 0.02
1	Underlayer	Viscoelastic	Thickness = 6 (mm) ρ = 32 (kg/m³) ν = 0.2 E = 0.702 (MPa) G = 0.4 (MPa) η = 0.15
2	Reinforced concrete slab	Isotropic solid	Thickness = 140 (mm) ρ = 2 500 (kg/m³) ν = 0.1 E = 27 000 (MPa) η = 0.015

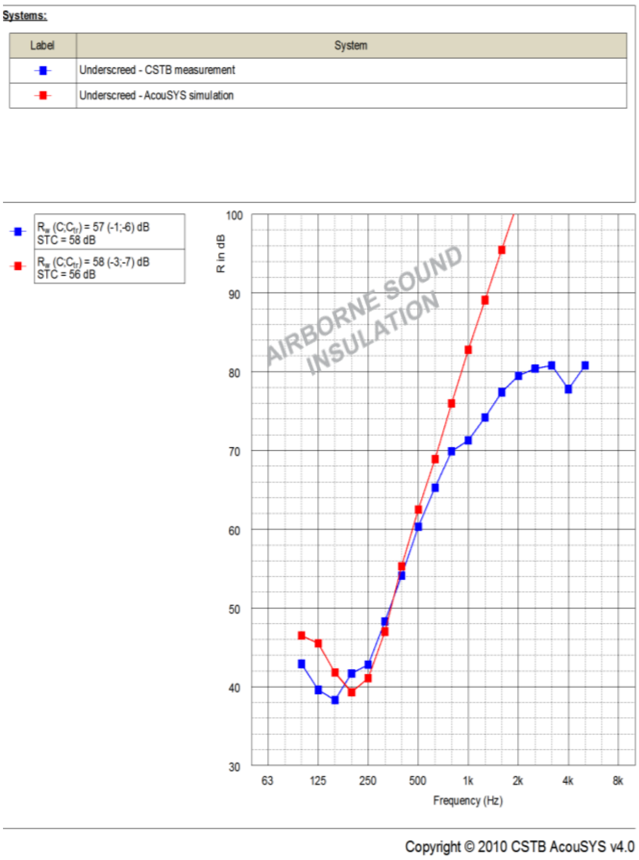
Measured according to standard [29]

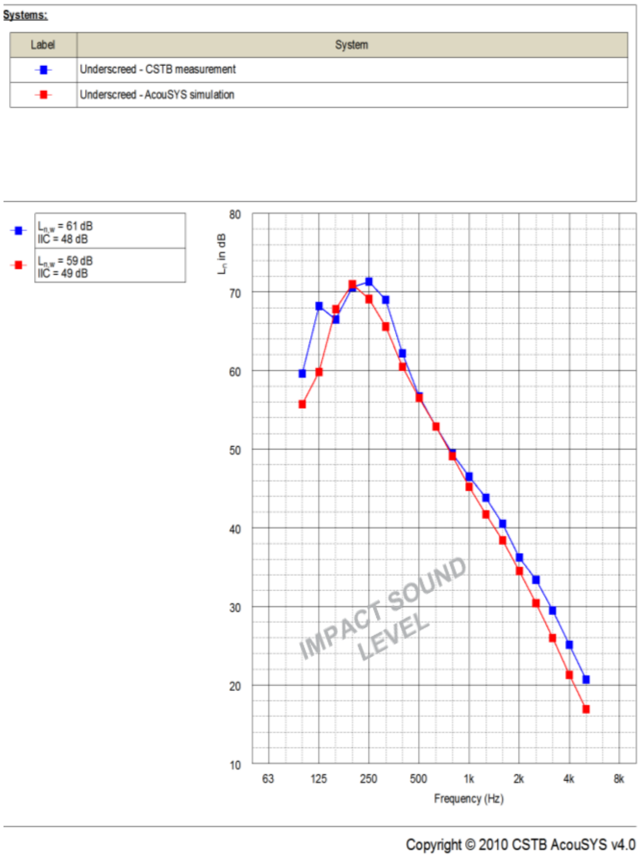
❹ Spatial windowing

XY system dimensions: [4220; 3600] mm for airborne sound insulation (Infinite dimensions for impact sound pressure level).

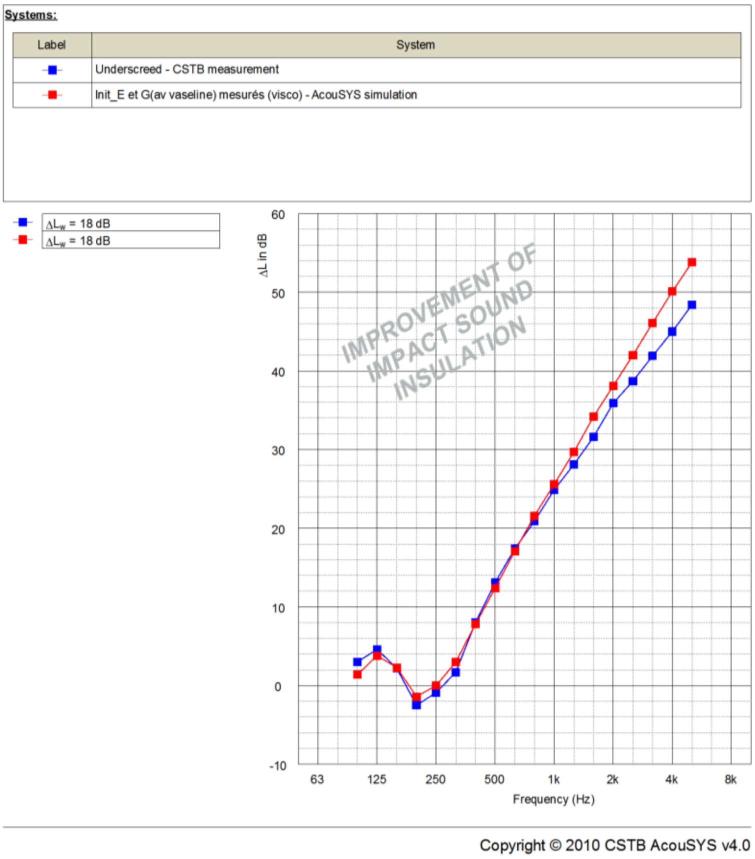
❺ AcouSYS calculation results

AcouSYS simulation/measurement comparisons of the airborne sound insulation *R* and the impact sound pressure level L_n for an underscreed mounted on a concrete slab of thickness 140 mm and a screed of thickness 40 mm are shown below:





It is also possible to determine the acoustic performance of the underscreed only by calculating the improvement of impact sound insulation *ΔL*.



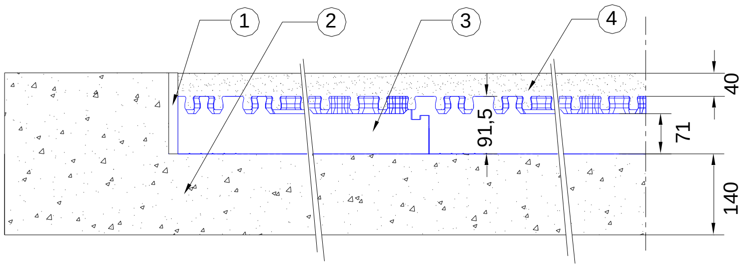
❻ Comments

Good correlations are noticed between AcouSYS simulations and measurements.

The resonance observed around the third octave 200 Hz is a mass/spring/mass phenomenon (the insulating material acts like a spring while the screed and slab act like masses).

3.3 Underfloor heating system

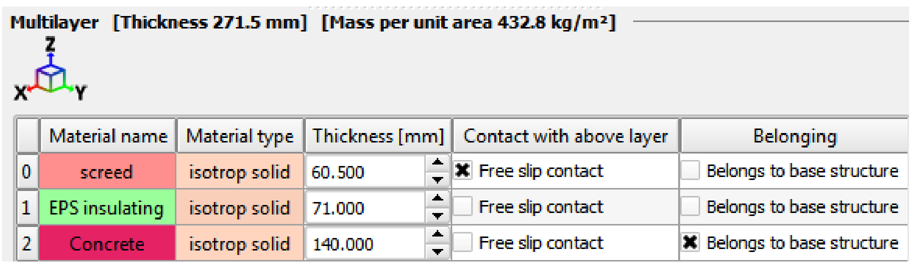
❶ **Drawing of the system**



1 Shore strip
2 Concrete slab
3 Underfloor heating
4 Screed

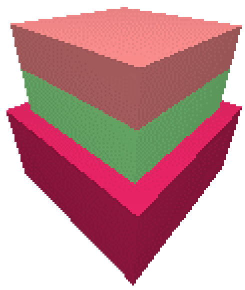
Dimensions in mm

❷ **Description of the multilayer system in AcouSYS**



Multilayer [Thickness 271.5 mm] [Mass per unit area 432.8 kg/m²]

	Material name	Material type	Thickness [mm]	Contact with above layer	Belonging
0	screed	isotrop solid	60.500	☒ Free slip contact	☐ Belongs to base structure
1	EPS insulating	isotrop solid	71.000	☐ Free slip contact	☐ Belongs to base structure
2	Concrete	isotrop solid	140.000	☐ Free slip contact	☒ Belongs to base structure



The insulation panels used are often built with supporting studs of a given height (for installation of heating pipes). These are not taken into account in the panel thickness.

❸ **Parameters associated with the different system layers**

Layer	Name	Type	Parameters
0	Screed	Isotropic solid	Thickness = 60.5 (mm) ρ = 1 800 (kg/m³) ν = 0.15 E = 20 000 (MPa) η
1	Polyethylene insulating foam	Isotropic solid	Thickness = 71 (mm) ρ = 27 (kg/m³) ν = 0.2 E = 12.94 (MPa) η = 0.16
2	Reinforced concrete slab	Isotropic solid	Thickness = 140 (mm) ρ = 2 300 (kg/m³) ν = 0.1 E = 37 000 (MPa) η

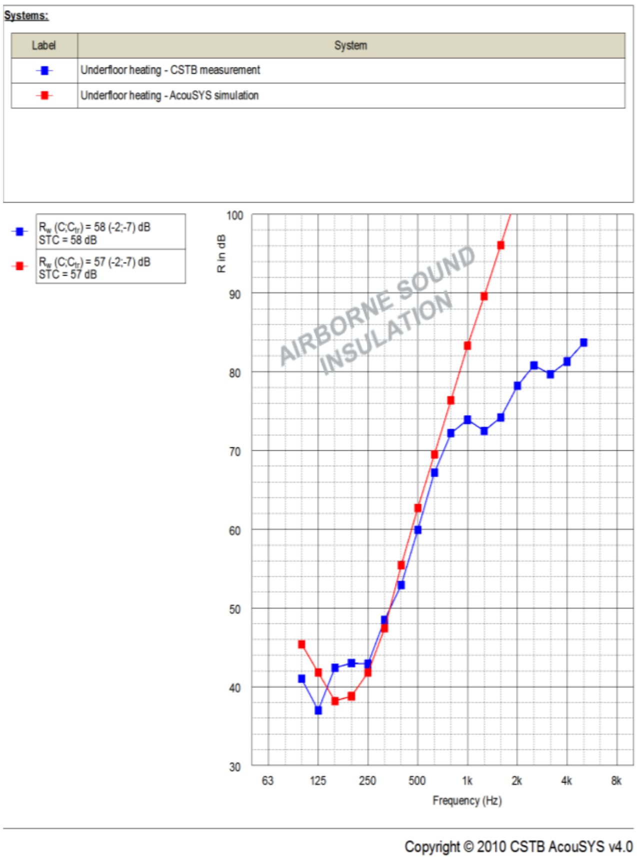
Measured according to standard [29]
Frequency dependent parameter (see values per frequencies in Appendix 1)

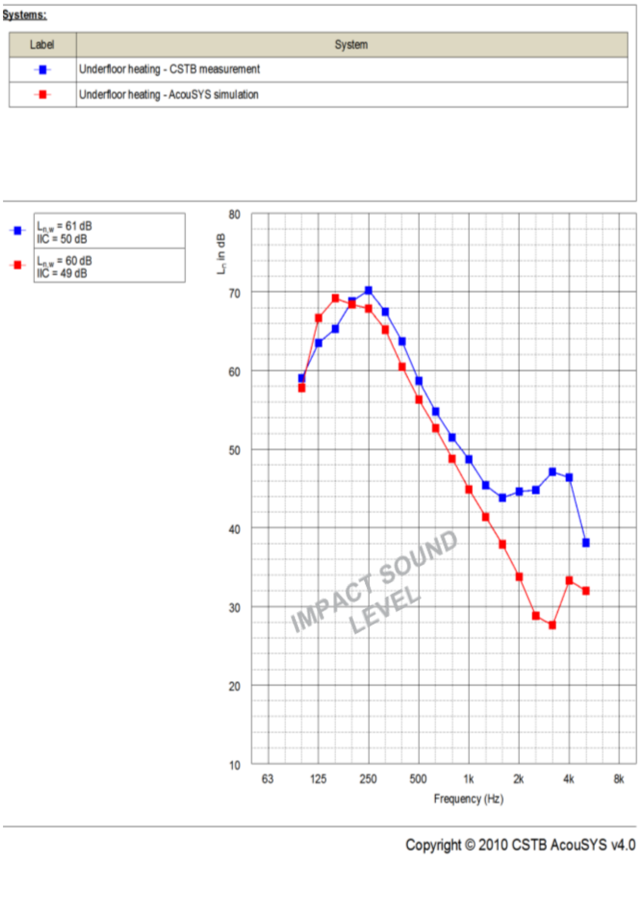
❹ Spatial windowing

XY system dimensions: [4220; 3600] mm for airborne sound insulation (Infinite dimensions for impact sound pressure level)

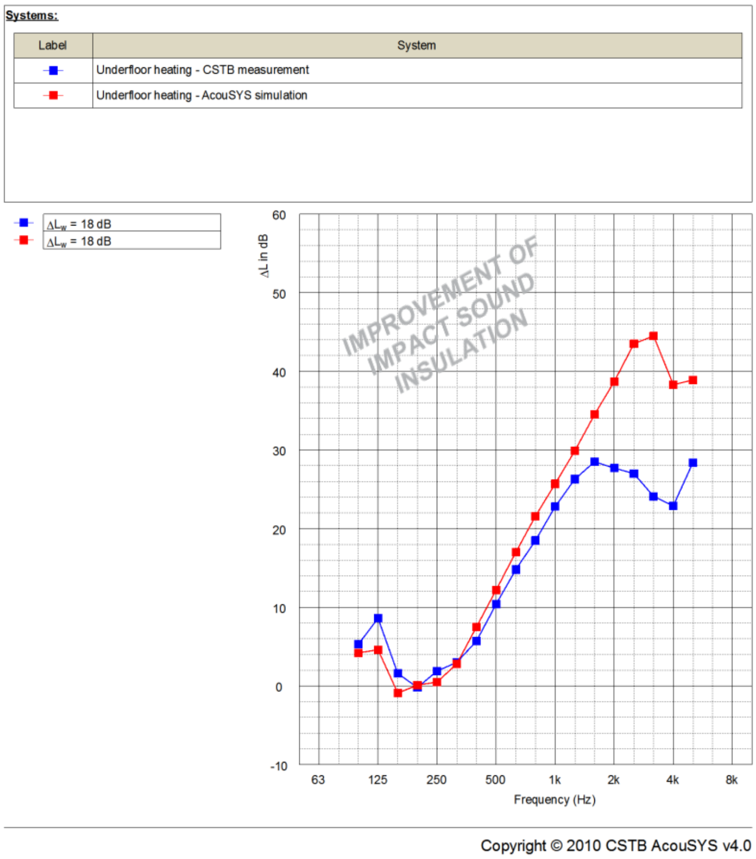
❺ AcouSYS calculation results

AcouSYS simulation/measurement comparisons of the airborne sound insulation R and the impact sound level L_n for an underfloor heating system implemented on a concrete slab of thickness 140 mm and a screed of thickness 40 mm are shown below:





It is also possible to determine the acoustic performance of the underfloor heating system only by calculating the improvement of impact sound insulation *ΔL*.



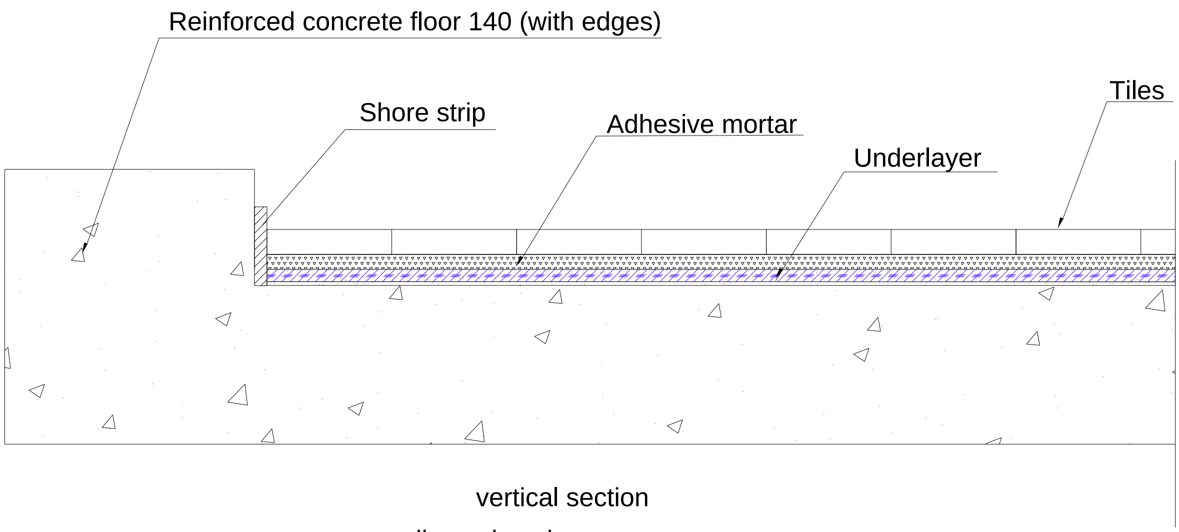
❻ Comments

Good correlations are noticed between AcouSYS simulations and measurements.

The resonance observed around the third octave 200 Hz is a mass/spring/mass phenomenon (the insulating material acts like a spring while the screed and slab act like masses).

3.4 Under tiles system

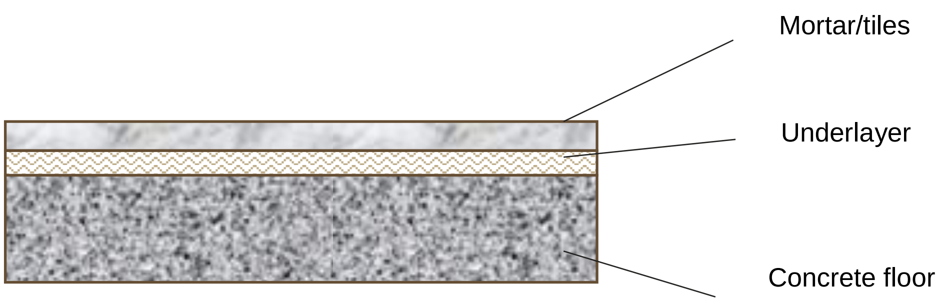
❶ Drawing of the system



vertical section

dimensions in mm

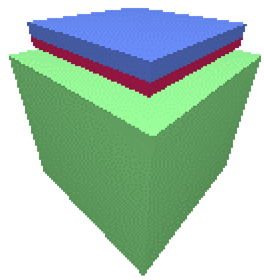
The tiles and mortar are considered as a single equivalent layer. The whole system is simulated with AcouSYS as a three-layer system (see figure below).



❷ Description of the multilayer system in AcouSYS

Multilayer [Thickness 159 mm] [Mass per unit area 348.8 kg/m²]

	Material name	Material type	Thickness [mm]	Contact with above layer	Belonging
0	Tiles	isotrop solid	11.000	☒ Free slip contact	☐ Belongs to base structure
1	Underlayer	porous	8.000	☐ Free slip contact	☐ Belongs to base structure
2	Concrete	isotrop solid	140.000	☐ Free slip contact	☒ Belongs to base structure



For an under tiles system, the influence of the contact with the concrete slab can be important. In practice, the underlayer is more or less glued to the slab. So, the measurement results can be between the simulation results with (glued) and without (free) contact.

❸ Parameters associated with the different system layers

Layer	Name	Type	Parameters
0	Tiles + Mortar	Isotropic solid	Thickness = 7 + 4 = 11 (mm) ρ = 2 000 (kg/m^3) ν = 0.1 E = 33 000 (MPa) η = 0.05
1	Under tiles	Porous	Thickness = 8 (mm) σ = 124 000 (Pa.s/m^2) α_∞ = 1.00 φ = 0.93 Λ = 60 (µm) Λ' = 120 (µm) ρ = 168 (kg/m^3) ν = 0.4 E = 1.7 (MPa) η = 0.065
2	Reinforced concrete slab	Isotropic solid	Thickness = 140 (mm) ρ = 2 325 (kg/m^3) ν = 0.1 E = 25 000 (MPa) η = 0.1

Measured according to standard [30]
Measured according to standard [29]

❹ Spatial windowing

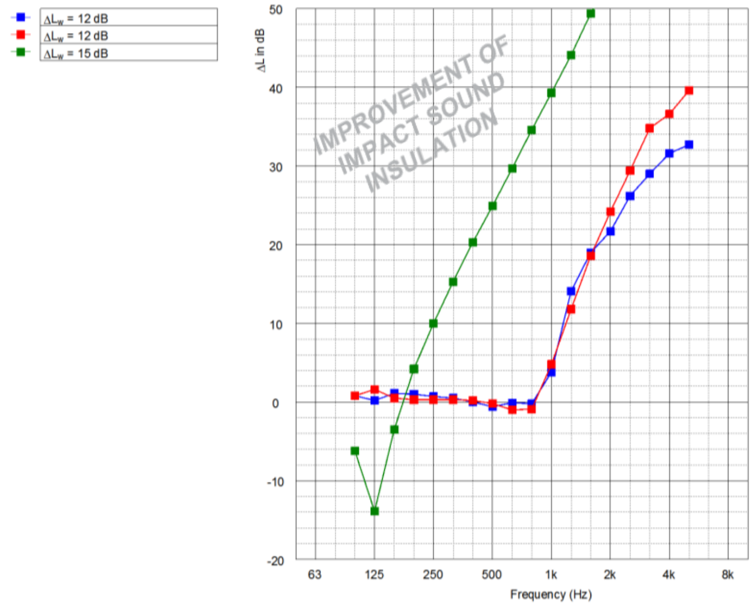
XY system dimensions: Infinite

❺ AcouSYS calculation results

AcouSYS simulation/measurement comparisons of the improvement of impact sound insulation ΔL for an under tiles system implemented on a concrete slab of thickness 140 mm and a mortar/tiles set of thickness 11mm are presented below. The simulation is done with and without taking contact into account:

Systems:

Label	System
blue	Under tiles - CSTB measurement
red	Under tiles - AcouSYS simulation - Glued
green	Under tiles - AcouSYS simulation - Not glued

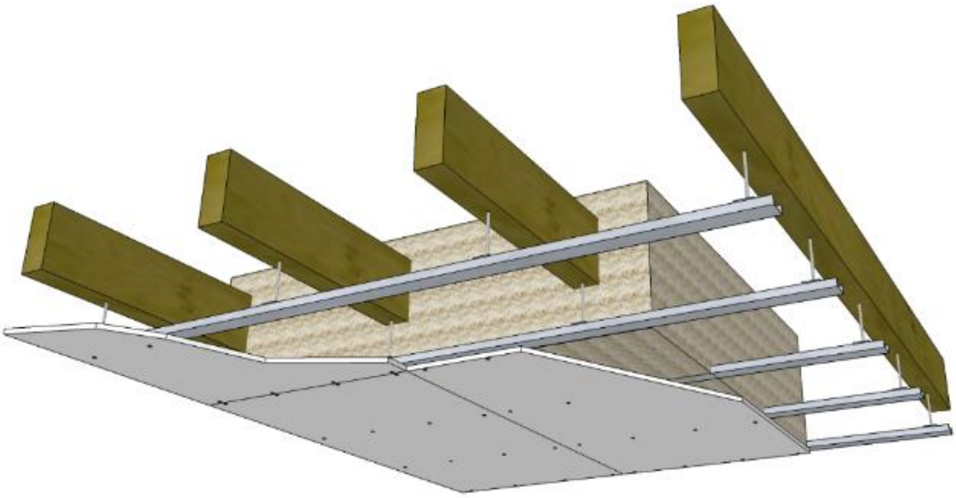


❻ Comments

A good correlation is noticed between AcouSYS simulation and measurement when the underlayer is glued to the concrete slab.

3.5 Ceiling below undeveloped attic with a loose filling bio-based insulation material

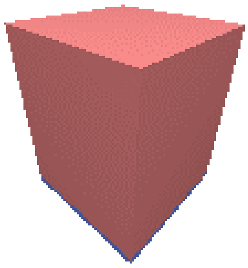
❶ **Drawing of the system**



❷ **Description of the system in AcouSYS**

Multilayer [Thickness 362.5 mm] [Mass per unit area 16.4 kg/m²]

	Material name	Material type	Thickness [mm]	Contact with above layer	Belonging
0	Hemp-cotton fibres	porous	350.000	☒ Free slip contact	☐ Belongs to base structure
1	BA13 plasterboard	isotrop solid	12.500	☐ Free slip contact	☐ Belongs to base structure



Here, the beams and the metallic frame of the ceiling are not considered.

❸ Physical parameters associated with the different system layers

Layer	Name	Type	Parameters
0	Hemp/cotton fibres (Loose)	Porous	thickness = 350 (mm) σ = 1 000 (Pa.s/m²) α∞ = 1.00 φ = 0.90 Λ = 200 (µm) Λ' = 1 000 (µm) ρ = 21 (kg/m³) ν = 0.00 E = 0.033 (MPa) η = 0.07
1	Plasterboard	Isotropic solid	thickness = 12.5 (mm) ρ = 725 (kg/m³) ν = 0.1 E = 3 000 (MPa) η = 0.03

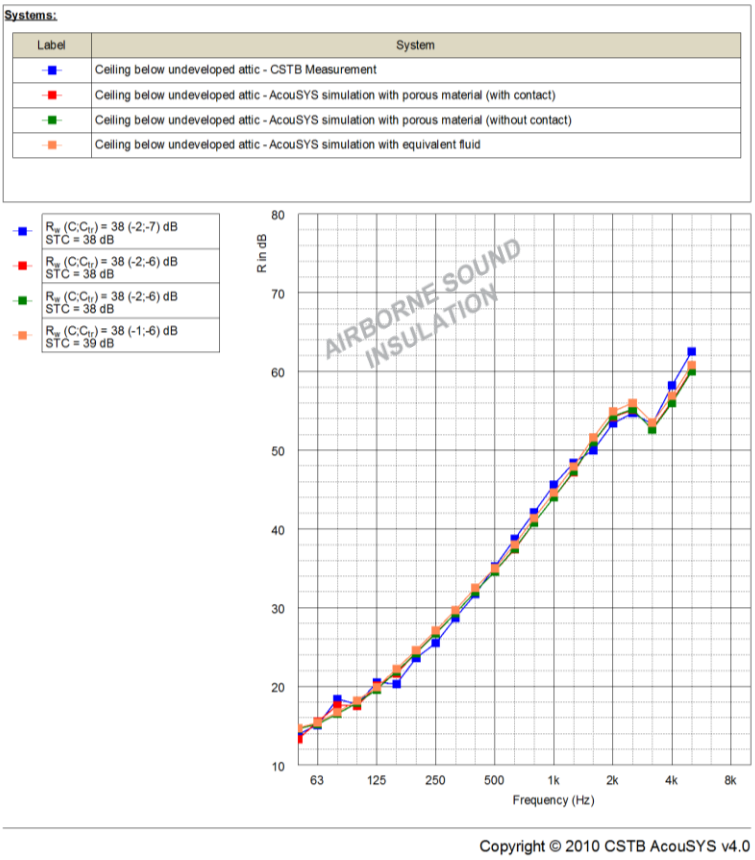
Measured according to standard [30]
Measured according to methods [32] [33]
Measured according to method [34]
Measured according to standard [28] adapted to the plasterboard issues

❹ Spatial windowing

XY system dimensions: [4220; 3600] mm

❺ AcouSYS calculation results

AcouSYS simulation/measurement comparisons of the airborne sound insulation R for a ceiling below undeveloped attic are shown below for different model not considered by calculations:



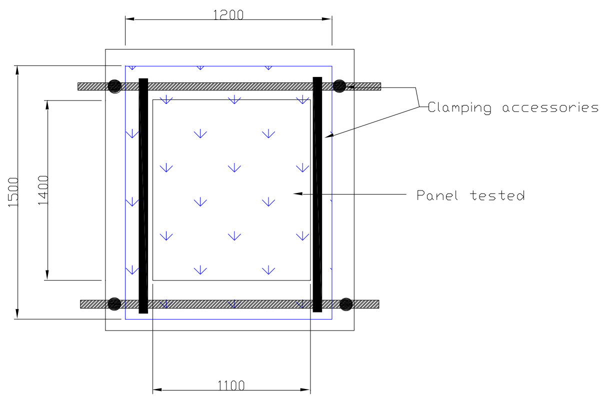
❻ Comments

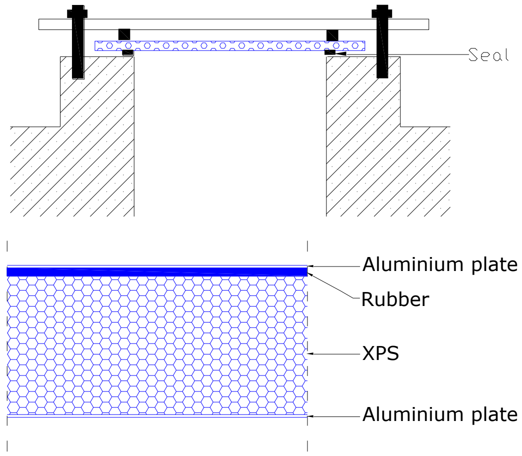
A good correlation is noticed between AcouSYS simulation and measurement.

In this case, the bio-based insulation used is a loose filling material and the mechanical parameters are difficult to obtain. So, three types of models were considered: porous material (with or without contact with the lower layer) and an equivalent fluid. A better correlation is noted in low frequencies when the porous material is considered with contact (since the insulation material rests on the plasterboards layer) because the skeleton of the porous material is excited, but the impact is tiny.

3.6 Roof sandwich panel

❶ Drawing of the system

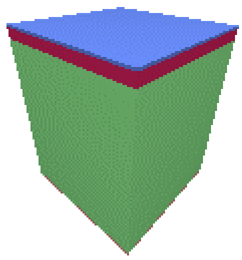




❷ Description of the multilayer system in AcouSYS

Multilayer [Thickness 54.4 mm] [Mass per unit area 7.4 kg/m²]

	Material name	Material type	Thickness [mm]	Contact with above layer	Belonging
0	aluminium	isotrop solid	0.700	☒ Free slip contact	☐ Belongs to base structure
1	soft viscoelastic	viscoelastic	3.000	☐ Free slip contact	☐ Belongs to base structure
2	XPS insulating	isotrop solid	50.000	☐ Free slip contact	☐ Belongs to base structure
3	aluminium	isotrop solid	0.700	☐ Free slip contact	☐ Belongs to base structure



❸ Parameters associated with the different system layers

Layer	Name	Type	Parameters
0/3	Aluminium facing	Isotropic solid	Thickness = 0.7 (mm) ρ = 2 700 (kg/m³) ν = 0.33 E = 71 000 (MPa) η = 0.01
1	Soft viscoelastic	Viscoelastic	Thickness = 3 (mm) ρ = 700 (kg/m³) ν = 0.3 E (MPa) G (MPa) η
2	Extruded polystyrene insulating foam (XPS)	Isotropic solid	Thickness = 50 (mm) ρ = 30 (kg/m³) ν = 0.2 E = 30 (MPa) η = 0.08

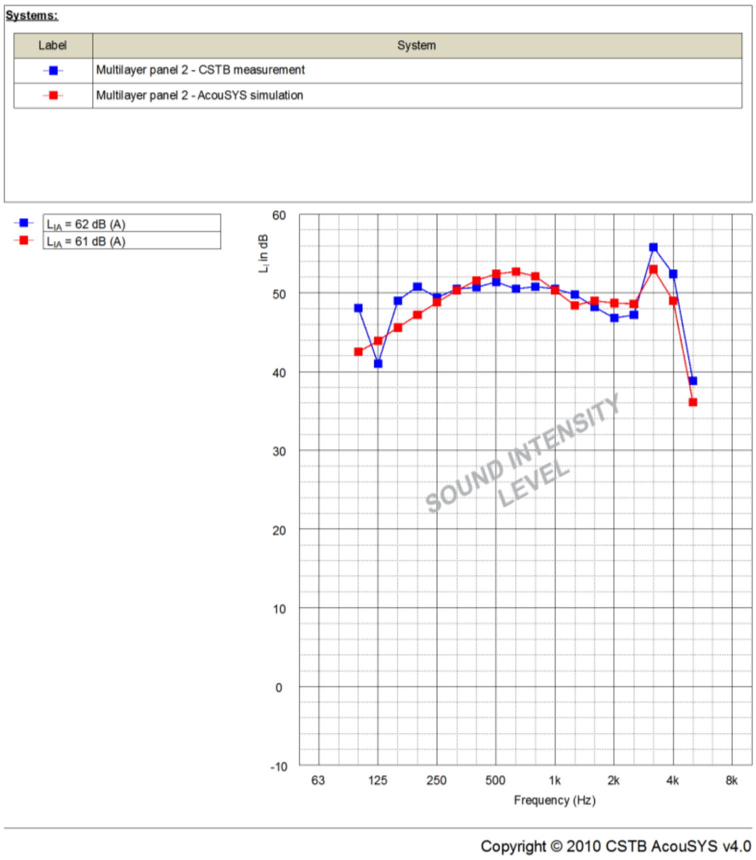
Frequency dependent parameter (see default values in the database "Materials" of AcouSYS software)
Measured according to standard [29]

❹ Spatial windowing

XY system dimensions: Infinite

❺ AcouSYS calculation results

An AcouSYS simulation/measurement comparison of the sound intensity level L_i for a roof sandwich panel is shown in figure below:

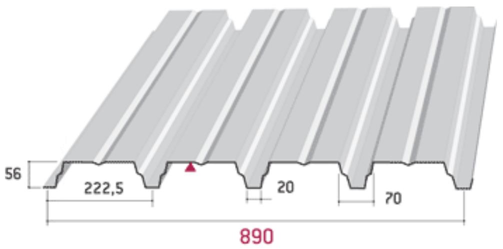


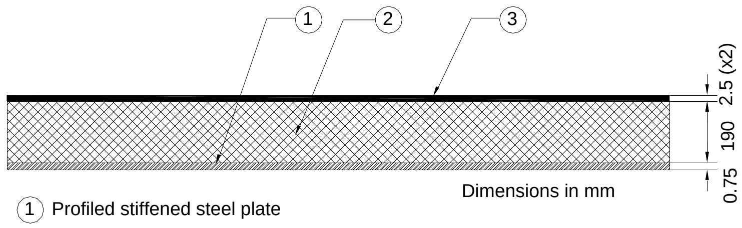
❻ Comments

A good correlation is noticed between AcouSYS simulation and measurement.

3.7 Roof system with profiled stiffened plate

❶ Drawing of the profiled plate included in a system



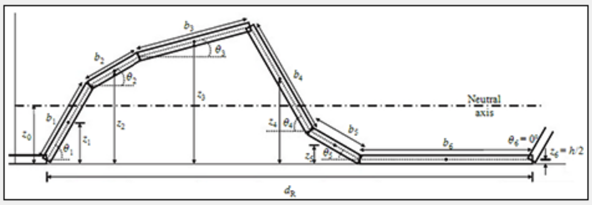


1 Profiled stiffened steel plate
2 Insulating material (stone wool)
3 Viscoelastic sealing coating (double thickness)

❷ Homogenization

Profiled stiffened plate

Ref : "Sound Insulation : Theory into Practice" - Carl Hopkins (p 135 to 140)



material steel

sheet thickness (h) 0.75 mm

wave length (d_R) 222.50 mm

elements

	bi (mm)	zi (mm)	θi (°)		
1	20	0.38	0	+	-
2	61.33	28	65.94	+	-
3	152.5	55.63	0	+	-
4	61.33	28	65.94	+	-

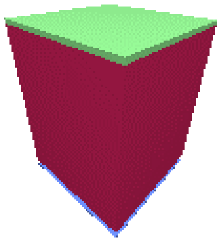
Results

Young modulus Ex =	**2 269 119 382. 02 MPa**
Young modulus Ey =	**150 765. 686 41 MPa**
Shear modulus Gxy =	**10 137 835. 265 3 MPa**
Critical frequency 1 =	**154 Hz**
Critical frequency 2 =	**18875 Hz**
Thickness =	**0.75 mm**
Equivalent mass per unit area (m_{UA}) =	**7.76 kg/m²**
Equivalent density (ρ) =	**10347.18 kg/m³**

❸ Description of the multilayer system in AcouSYS

Multilayer [Thickness 195.75 mm] [Mass per unit area 31.5 kg/m²]

	Material name	Material type	Thickness [mm]	Contact with above layer	Belonging
0	soft viscoelastic	viscoelastic	5.000	☒ Free slip contact	☐ Belongs to base structure
1	rock wool 100	porous	190.000	☐ Free slip contact	☐ Belongs to base structure
2	Stiffened plate (steel)	orthotrop solid	0.750	☒ Free slip contact	☐ Belongs to base structure



❹ Parameters associated with the different system layers

Layer	Name	Type	Parameters
	Steel material	Isotropic solid	thickness = 0.75 (mm) ρ = 7 800 (kg/m³) ν = 0.3 E = 200 000 (MPa) η = 0.01
0	Soft viscoelastic	Viscoelastic	thickness = 5 (mm) ρ = 800 (kg/m³) ν = 0.3 E (MPa) G (MPa) η
1	Stone wool	Porous	thickness = 190 (mm) σ = 70 000 (Pa.s/m²) α∞ = 1.00 φ = 0.9 Λ = 60 (µm) Λ' = 150 (µm) ρ = 104 (kg/m³) ν = 0.00 E = 1.00 (MPa) η = 0.05
2	Stiffened plate (steel)	Orthotropic solid	thickness = 0.75 (mm) ρ = 10 347 (kg/m³) ν_{xy} = 0.3 E_x ~ 2.3 x 10^9 (MPa) E_y = 150 765 (MPa) G_{xy} ~ 10.1 x 10^6 (MPa) η = 0.02

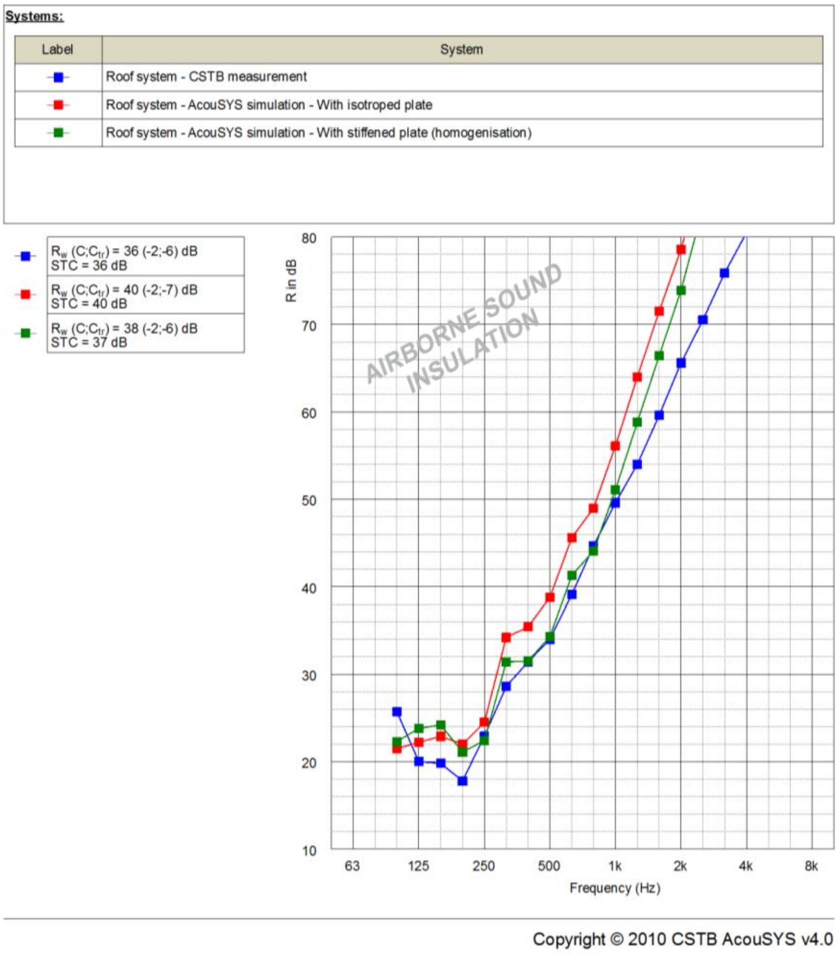
Frequency dependent parameter (see default values in the database "Materials" of AcouSYS software)
Homogenized parameters

❺ Spatial windowing

XY system dimensions: [4220; 3600] mm

❻ AcouSYS calculation results

AcouSYS simulation/measurement comparisons of the airborne sound insulation *R* for a roof system with a steel plate are shown below with and without homogenization:



❼ Comments

A better correlation is obtained between AcouSYS simulation and measurement when the stiffened plate (homogenized material) is used.

The resonance observed around the third octave 200 Hz is a mass/spring/mass phenomenon (the porous material acts like a spring while the steel plate and viscoelastic layer act like masses).

3.8 Constructions taken from NRC-CRNC research (IRC IR-818)

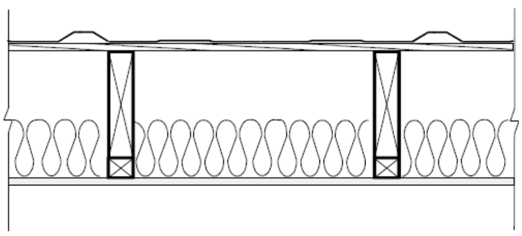
3.8.1 Roof construction with wood frame (Standard ASTM E 1289-08)

❶ **Drawing of the system**

NRC-CNRC National Research Council Canada

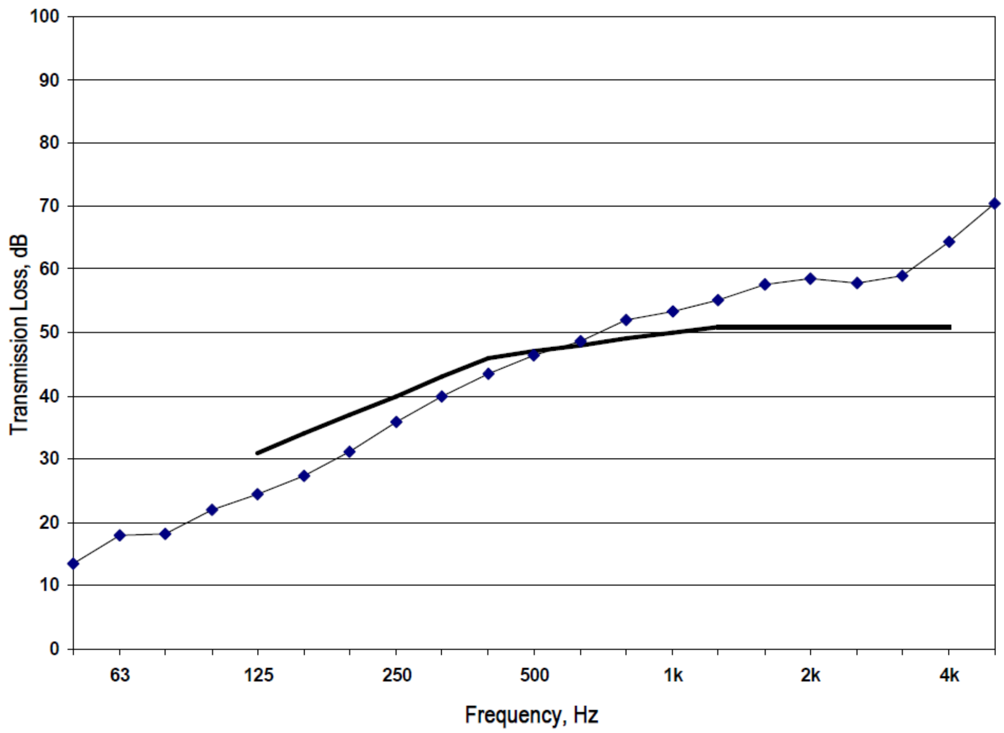
Element	Description
1	0.3 mm of steel decking
2	19 mm thick wood furring at 406 mm on centre
3	1626 mm deep raised heel wood truss
4	152 mm thick glass fibre insulation in cavity
5	13 mm thick regular gypsum board

TLF-98-131a
STE0.3_WFUR19(406)_RHWT1626_GFB152_G13
Construction Type: roof



❷ **Performance**

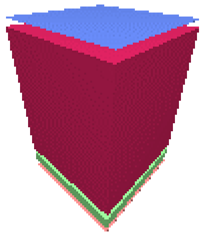
Freq, Hz	TL, dB
50	13
63	18
80	18
100	22
125	24
160	27
200	31
250	36
315	40
400	44
500	46
630	49
800	52
1000	53
1250	55
1600	58
2000	58
2500	58
3150	59
4000	64
5000	70
STC	47
OITC	33



❸ Description of the multilayer system in AcouSYS

Multilayer [Thickness 1638.3 mm] [Mass per unit area 13.9 kg/m²]

	Material name	Material type	Thickness [mm]	Contact with above layer	Belonging
0	steel	isotrop solid	0.300	✖ Free slip contact	Belongs to base structure
1	air damped	fluid	1473.000	✖ Free slip contact	Belongs to base structure
2	glass wool	porous	152.000	✖ Free slip contact	Belongs to base structure
3	BA13 gypsum board	isotrop solid	13.000	✖ Free slip contact	Belongs to base structure



⚠ Here, the wood frame is not considered.

❹ Parameters associated with the different system layers

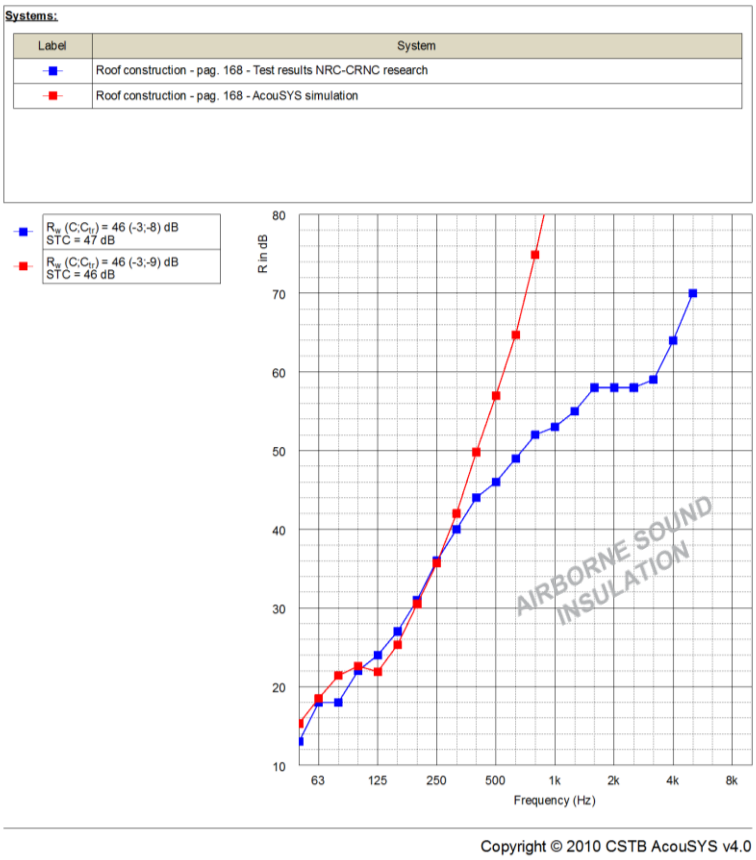
Layer	Name	Type	Parameters
0	Steel	Isotropic solid	thickness = 0.3 (mm) ρ = 9 330 (kg/m^3) ν = 0.3 E = 200 000 (MPa) η = 0.01
1	Air damped	Fluid	thickness = 1 473 (mm) ρ = 1.21 (kg/m^3) c = 342 (m/s) η_{air} = 18.14e^{-6} (Pa.s) η = 0.05
2	Glass fibre	Porous	thickness = 152 (mm) σ = 50 000 (Pa.s/m^2) α_∞ = 1.00 φ = 0.95 Λ = 60 (µm) Λ' = 150 (µm) ρ = 9.86 (kg/m^3) ν = 0.00 E = 0.09 (MPa) η = 0.3
3	Gypsum board	Isotropic solid	thickness = 12.5 (mm) ρ = 592 (kg/m^3) ν = 0.1 E = 1 800 (MPa) η = 0.03

❺ Spatial windowing

XY system dimensions: [4700; 3785] mm

❻ AcouSYS calculation results

An AcouSYS simulation/measurement comparison of the airborne sound insulation R for a roof construction is given below:



❼ Comments

No information is specified about of the mechanical or acoustical properties of materials as well as the stiffened plate profile (an isotropic solid has been used).

Furthermore, although the wood frame (wood furrings and studs) is not considered in calculation (observation at high frequencies), a good correlation is noticed between AcouSYS simulation and measurement.

4. Sound absorption calculation of absorbing materials

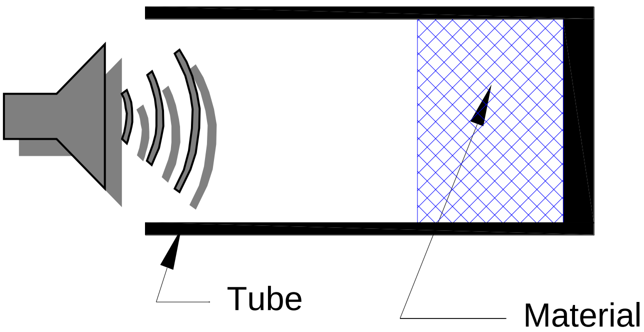
AcouSYS can be used to simulate the sound absorption coefficient in different conditions:

- **In normal incidence α_n** (related to impedance tube measurements)
- **In diffuse field α_S** (related to reverberant room measurements)

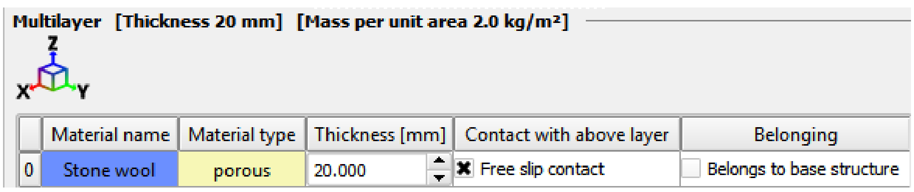
4.1 Normal incidence cases (impedance tube)

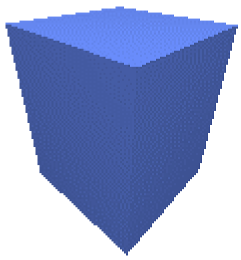
4.1.1 Mineral wool

❶ <u>**Drawing of the system**</u>



❷ <u>**Description of the multilayer system in AcouSYS**</u>





❸ <u>**Parameters associated with the different system layers**</u>

Layer	Name	Type	Parameters
0	Stone wool	Porous	thickness = 20 (mm) σ = 70 600 (Pa.s/m^2) α_∞ = 1.00 φ = 0.9 Λ = 60 (µm) Λ' = 150 (µm) ρ = 100 (kg/m^3) ν = 0.00 E = 0.400 (MPa) η = 0.1

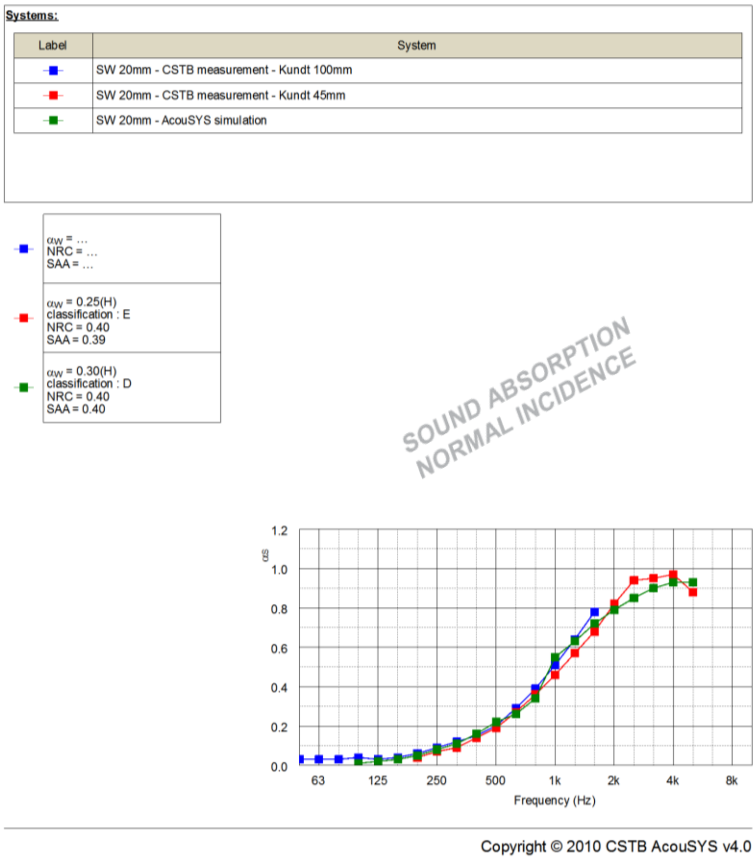
Measured according to standard [30]
Measured according to standard [29]

❹ Spatial windowing

XY system dimensions: Infinite

❺ AcouSYS calculation results

An AcouSYS simulation/measurement comparison of the sound absorption in normal incidence α_n for stone wool is shown below. The measurements are done with an impedance tube of diameter 100 mm and 45 mm (cut-on frequencies fixed to 1600Hz and 4500 Hz, respectively):

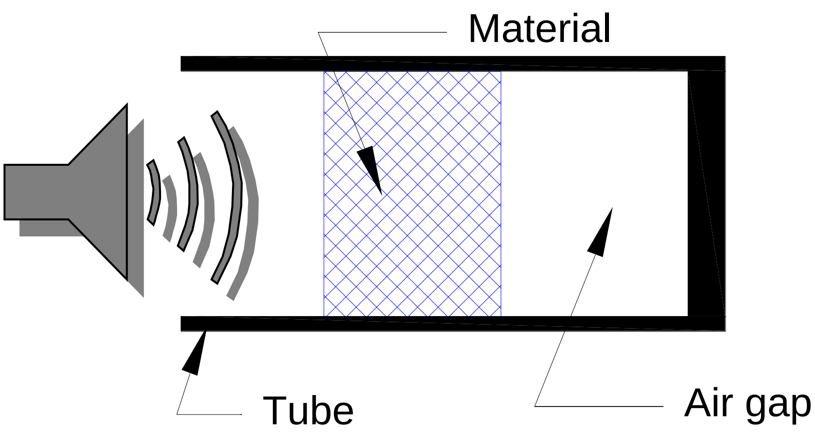


❻ Comments

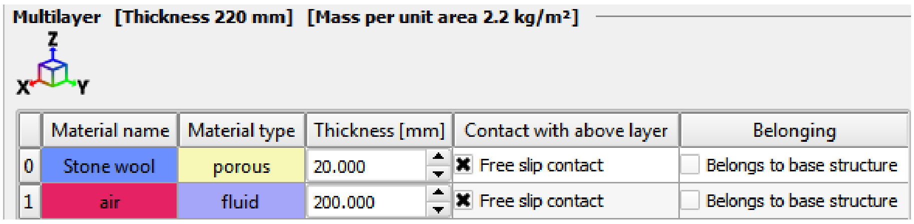
A good correlation is noticed between AcouSYS simulation and measurements.

4.1.2 Mineral wool with air gap

❶ **Drawing of the system**

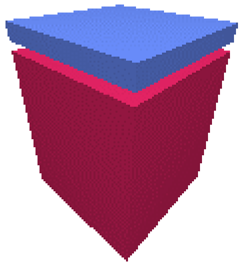


❷ **Description of the multilayer system in AcouSYS**



Multilayer [Thickness 220 mm] [Mass per unit area 2.2 kg/m²]

	Material name	Material type	Thickness [mm]	Contact with above layer	Belonging
0	Stone wool	porous	20.000	Free slip contact	Belongs to base structure
1	air	fluid	200.000	Free slip contact	Belongs to base structure



❸ **Parameters associated with the different system layers**

Layer	Name	Type	Parameters
0	Stone wool	Porous	thickness = 20 (mm) σ = 50 000 (Pa.s/m²) α_∞ = 1.00 φ = 0.9 Λ = 60 (µm) Λ' = 150 (µm) ρ = 100 (kg/m³) ν = 0.00 E = 0.800 (MPa) η = 0.05
1	Air	Fluid	thickness = 200 (mm) ρ = 1.3 (kg/m³) c = 342 (m/s) η_{air} = 18.14e^{-6} (Pa.s) η = 0.00

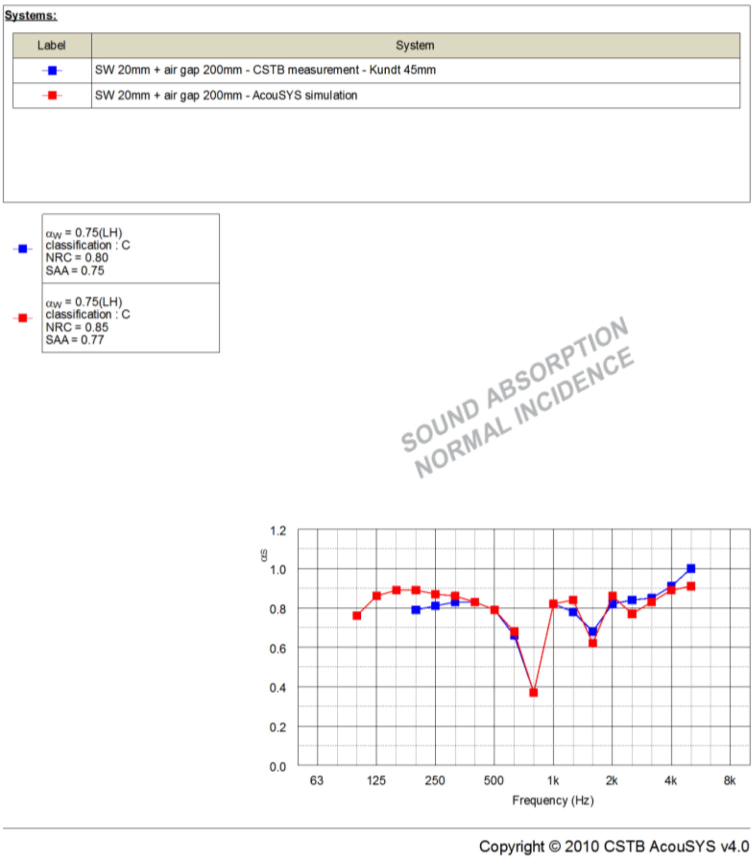
Measured according to standard [30]
Measured according to standard [29]

❹ Spatial windowing

XY system dimensions: Infinite

❺ AcouSYS calculation results

An AcouSYS simulation/measurement comparison of the sound absorption in normal incidence α_n for stone wool with air gap is shown below. The measurement is done with an impedance tube of diameter 45 mm (cut-on frequencies fixed from [200 - 4500 Hz]):

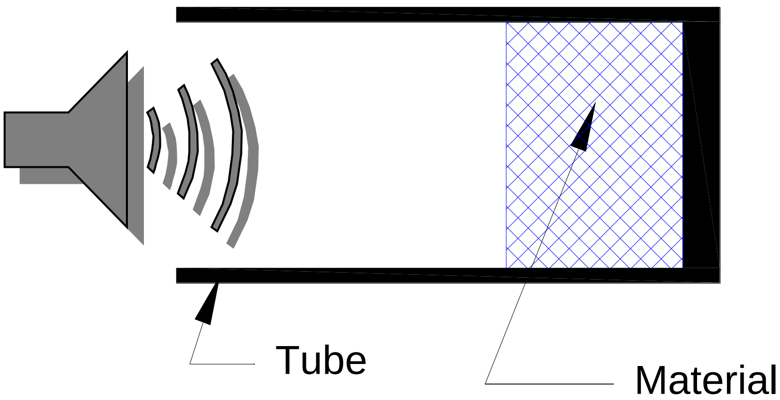


❻ Comments

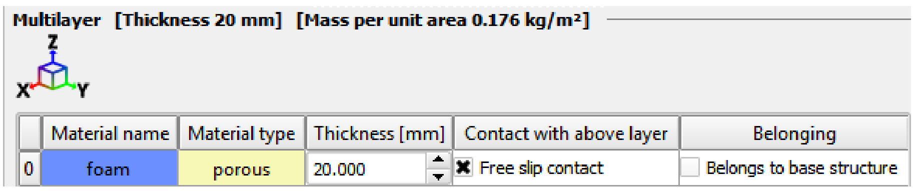
A good correlation is noticed between AcouSYS simulation and measurement.

4.1.3 Melamine foam

❶ **Drawing of the system**

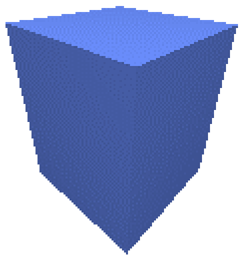


❷ **Description of the multilayer system in AcouSYS**



Multilayer [Thickness 20 mm] [Mass per unit area 0.176 kg/m²]

	Material name	Material type	Thickness [mm]	Contact with above layer	Belonging
0	foam	porous	20.000	Free slip contact	Belongs to base structure



❸ **Parameters associated with the different system layers**

Layer	Name	Type	Parameters
0	Open foam	Porous	thickness = 20 (mm) σ = 15 300 (Pa.s/m²) α∞ = 1.02 φ = 0.96 Λ = 105 (µm) Λ' = 205 (µm) ρ = 9 (kg/m³) ν = 0.40 E = 0.100 (MPa) η = 0.10

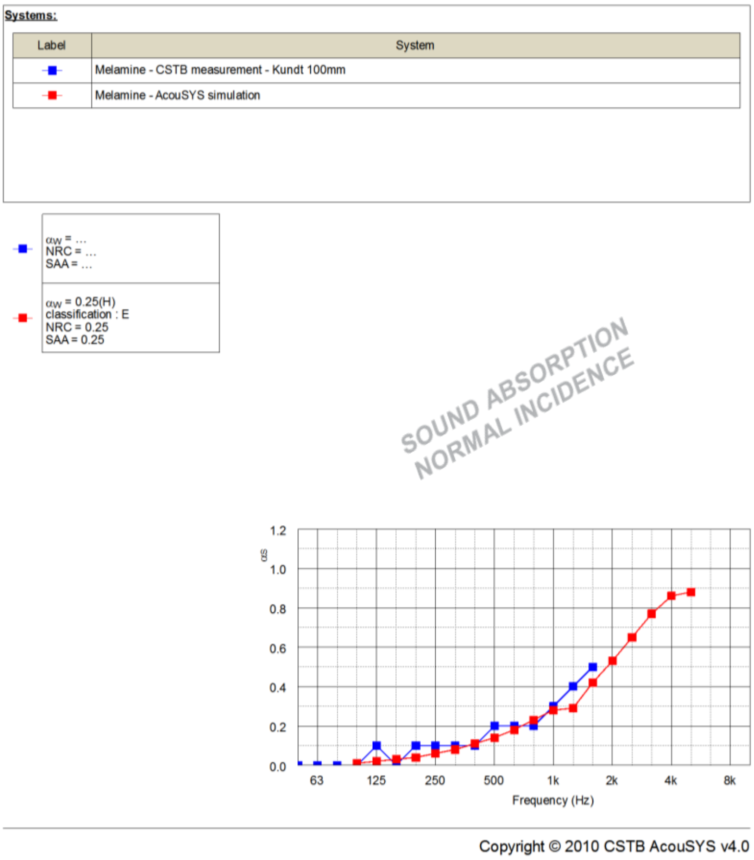
Measured according to standard [30]
Measured according to standard [29]

❹ **Spatial windowing**

XY system dimensions: Infinite

❺ AcouSYS calculation results

An AcouSYS simulation/measurement comparison of the sound absorption in normal incidence α_n for melamine foam is shown in figure below. The measurement is done with an impedance tube of diameter 100mm (cut-on frequencies fixed from [50 - 1600 Hz]):



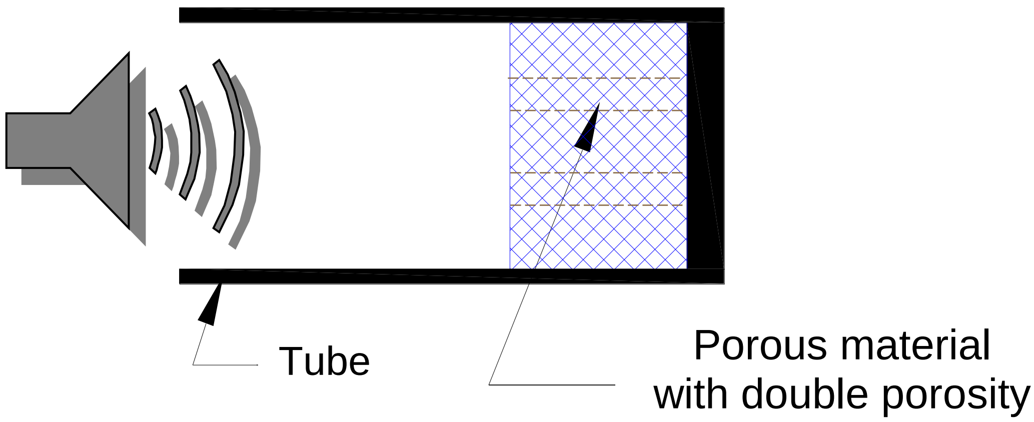
❻ Comments

A good correlation is noticed between AcouSYS simulation and measurement.

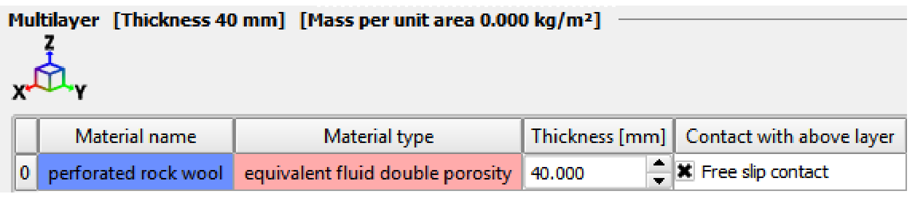
4.1.4 Porous material with double porosity

A porous material with a double porosity is a porous material in which a second scale of porosity was added (example with perforations), the first scale being the porosity of the initials pores in the porous material). This second scale of porosity may improve the acoustic absorption at some frequency range.

❶ **Drawing of the system**

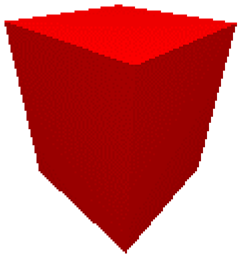


❷ **Description of the multilayer system in AcouSYS**



Multilayer [Thickness 40 mm] [Mass per unit area 0.000 kg/m²]

	Material name	Material type	Thickness [mm]	Contact with above layer
0	perforated rock wool	equivalent fluid double porosity	40.000	Free slip contact



❸ **Parameters associated with the different system layers**

Layer	Name	Type	Parameters
0	Stone wool	Equivalent fluid double porosity	thickness = 40 (mm) σ = 30 590 (Pa.s/m^2) α_∞ = 1.0 φ = 0.9 Λ = 60 (µm) Λ' = 150 (µm) perforation rate = 20 (%) perforation diameter = 43 (mm) (ρ = 100 (kg/m^3)) (ν = 0.0) (E = 0.400 (MPa)) (η = 0.30)

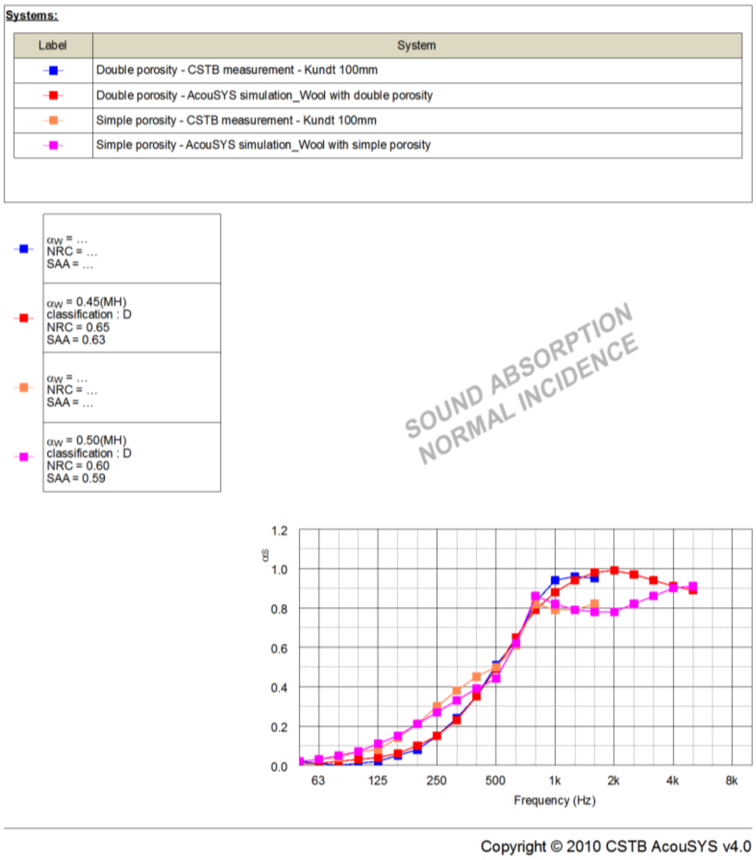
Measured according to standard [30]
Measured according to standard [29]

❹ <u>Spatial windowing</u>

XY system dimensions: Infinite

❺ <u>AcouSYS calculation results</u>

An AcouSYS simulation/measurement comparison of the sound absorption in normal incidence α_n for a porous material with double porosity is shown in figure below. The measurements are done with an impedance tube of diameter 100 mm and 45 mm (cut-on frequencies fixed to 1600Hz and 4500 Hz, respectively):



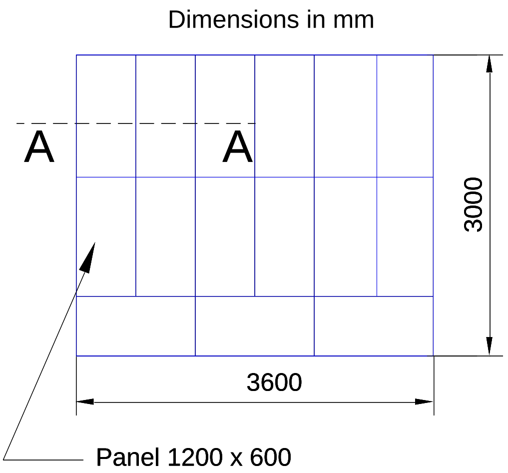
❻ <u>Comments</u>

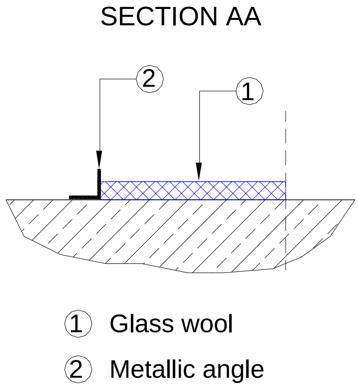
A good correlation is noticed between AcouSYS simulations and measurements.

4.2 Diffuse field cases (reverberant room)

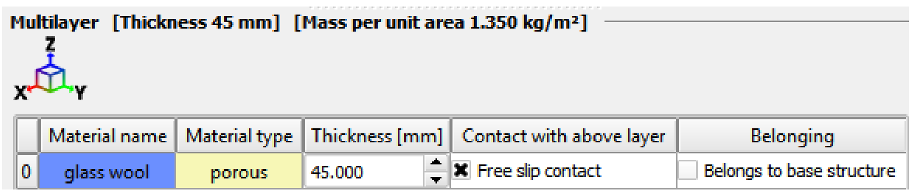
4.2.1 Glass wool

❶ **Drawing of the system**

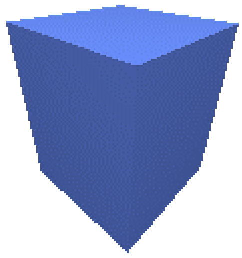




❷ **Description of the multilayer system in AcouSYS**


Multilayer [Thickness 45 mm] [Mass per unit area 1.350 kg/m²]

	Material name	Material type	Thickness [mm]	Contact with above layer	Belonging
0	glass wool	porous	45.000	Free slip contact	Belongs to base structure



❸ **Parameters associated with the different system layers**

Layer	Name	Type	Parameters
0	Glass wool	Porous	thickness = 45 (mm) σ = 120 000 (Pa.s/m²) α_∞ = 1.00 φ = 0.98 Λ = 13 (µm) Λ' = 52 (µm) ρ = 30 (kg/m³) ν = 0.00 E = 0.025 (MPa) η = 0.3

Measured according to standard [30]
Measured according to standard [29]

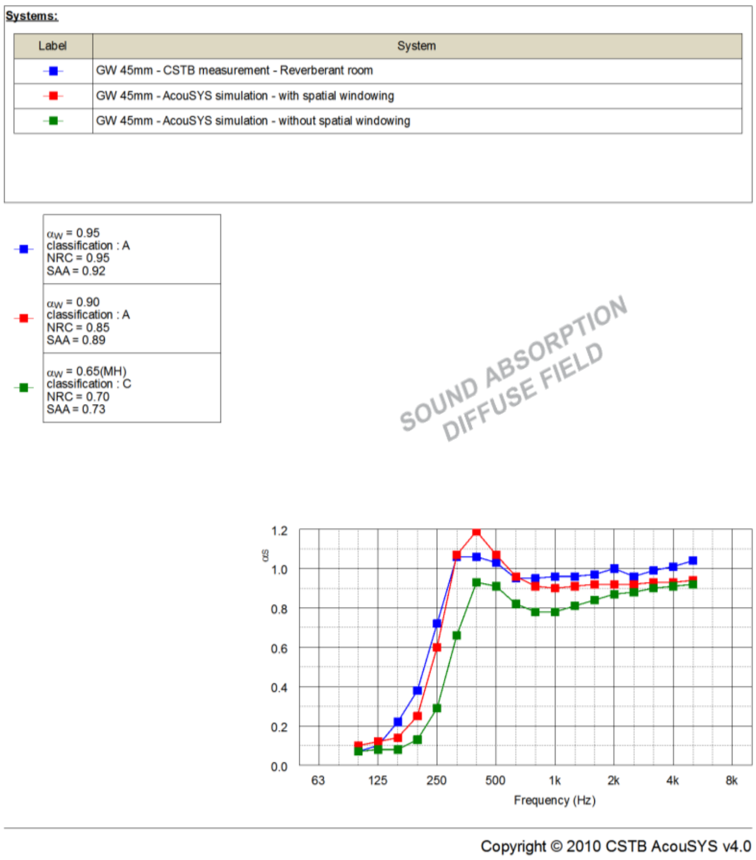
❹ Spatial windowing

XY system dimensions: [3600; 3000] mm

Spatial windowing has a strong influence when calculating sound absorption in diffuse field conditions. An example is shown in the figure below.

❺ AcouSYS calculation results

AcouSYS simulation/measurement comparisons of the sound absorption in diffuse field condition α_S for glass wool are given below. The simulations are done with and without taking spatial windowing into account:

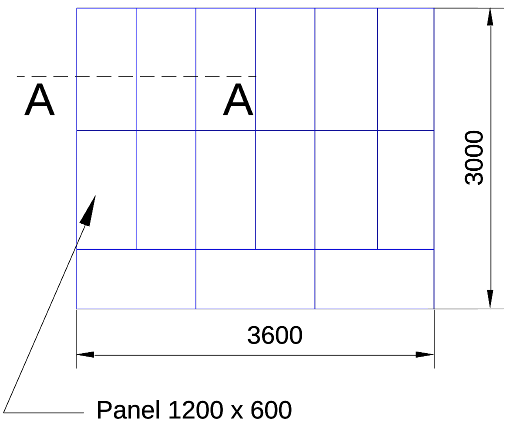


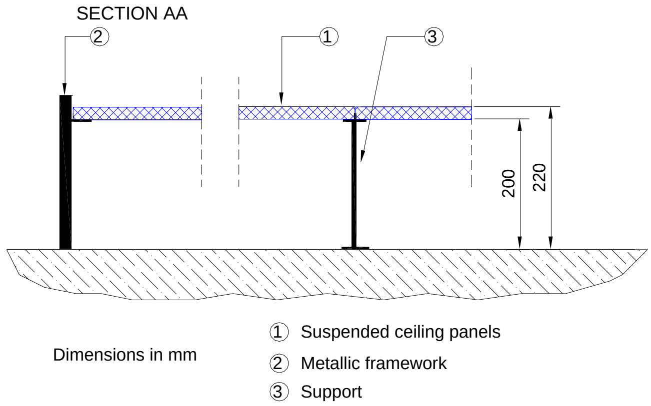
❻ Comments

The correlation between AcouSYS and measurement is good, especially when spatial filtering is added. The difference observed at high frequencies is due to edge effects on the sample during measurements which are not considered in simulation.

4.2.2 Ceiling panels with air gap

❶ **Drawing of the system**

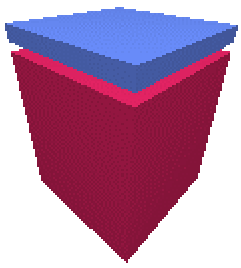




❷ **Description of the multilayer system in AcouSYS**

Multilayer [Thickness 240 mm] [Mass per unit area 2.3 kg/m²]

	Material name	Material type	Thickness [mm]	Contact with above layer	Belonging
0	LDR nue EKLA recale	porous	20.000	✖ Free slip contact	☐ Belongs to base structure
1	air	fluid	220.000	✖ Free slip contact	☐ Belongs to base structure



❸ **Parameters associated with the different system layers**

Layer	Name	Type	Parameters
0	Stone wool	Porous	thickness = 20 (mm) σ = 30 590 (Pa.s/m²) α_∞ = 1.00 φ = 0.9 Λ = 60 (µm) Λ' = 150 (µm) ρ = 100 (kg/m³) ν = 0.00 E = 0.400 (MPa) η = 0.3
1	Air	Fluid	thickness = 200 (mm) ρ = 1.21 (kg/m³) c = 342 (m/s) η_{air} = 18.14e^{-6} (Pa.s) η = 0.00

Measured according to standard [30]
Measured according to standard [29]

❹ Spatial windowing

XY system dimensions: [3600; 3000] mm

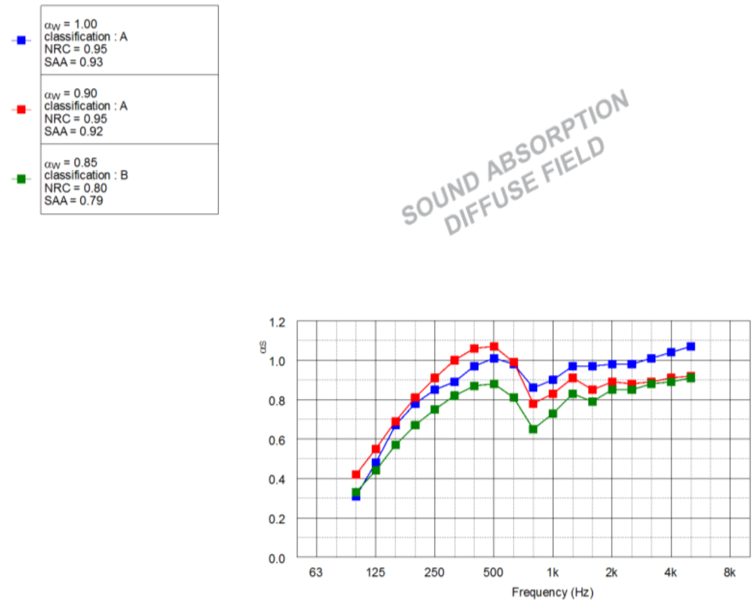
Spatial windowing has a strong influence when calculating sound absorption in diffuse field conditions, absorption result depends on surface area of sample. An example is shown in the figure below.

❺ AcouSYS calculation results

AcouSYS simulation/measurement comparisons of the sound absorption in diffuse field condition α_S for suspended ceiling are given below. The simulations are done with and without taking spatial windowing into account:

Systems:

Label	System
blue	Ceiling panels + air gap - CSTB measurement - Reverberant room
red	Ceiling panels + air gap - AcouSYS simulation - with spatial windowing
green	Ceiling panels + air gap - AcouSYS simulation - without spatial windowing

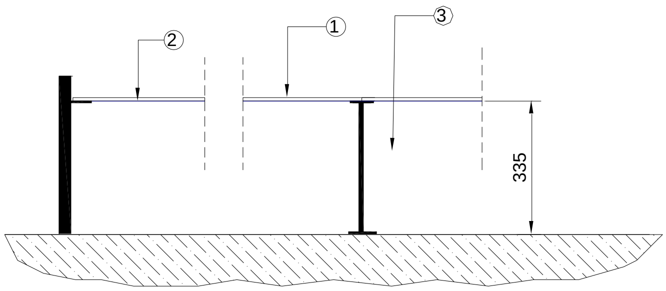


❻ Comments

A reasonable agreement between simulation and measurement is observed, especially when spatial windowing is applied. A resonance frequency due to the air cavity is observed at 800 Hz. The difference observed at high frequencies is due to edge effects on the sample during measurements which are not taken into account in simulation.

4.2.3 Perforated panels with a highly resistive thin veil on back side and air gap

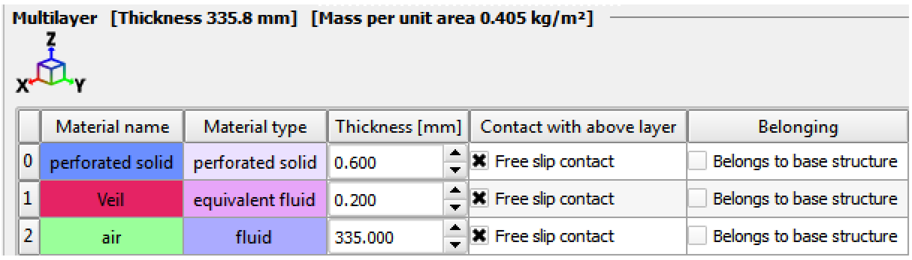
❶ **Drawing of the system**



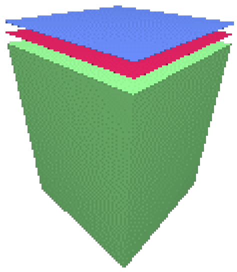
Dimensions in mm

① Perforated panels
② Thin veil
③ Air gap

❷ **Description of the multilayer system in AcouSYS**


Multilayer [Thickness 335.8 mm] [Mass per unit area 0.405 kg/m²]

	Material name	Material type	Thickness [mm]	Contact with above layer	Belonging
0	perforated solid	perforated solid	0.600	Free slip contact	Belongs to base structure
1	Veil	equivalent fluid	0.200	Free slip contact	Belongs to base structure
2	air	fluid	335.000	Free slip contact	Belongs to base structure



❸ **Parameters associated with the different system layers**

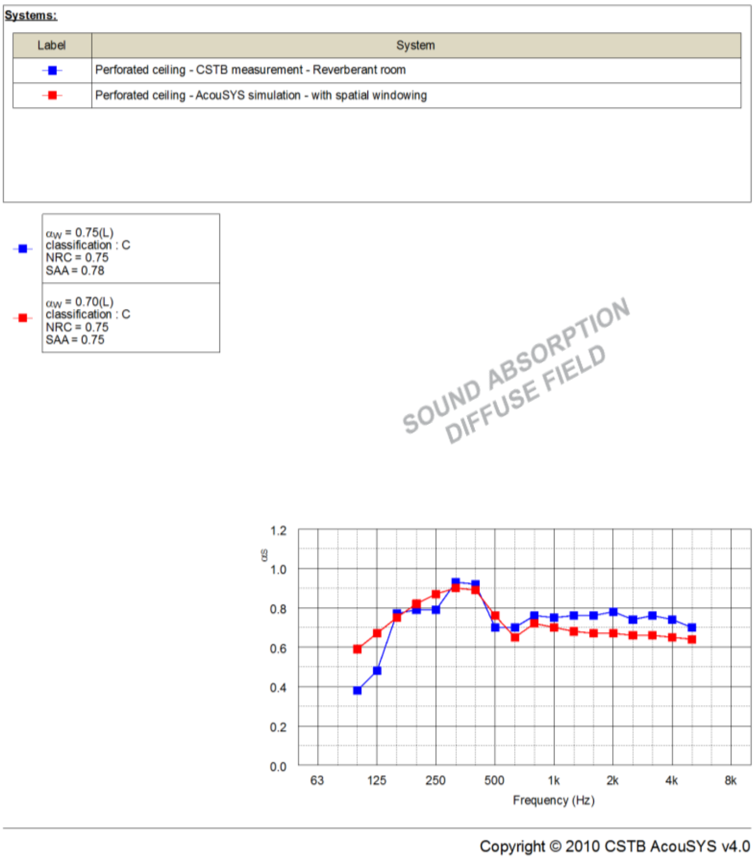
Layer	Name	Type	Parameters
0	Perforated solid	Perforated solid	thickness = 0.6 (mm) perforation rate = 11% perforation diameter = 1.50 (mm)
1	Highly resistive veil	Equivalent fluid	thickness = 20 (mm) σ = 5 000 000 (Pa.s/m^2) α_∞ = 1.00 φ = 0.95 Λ = 100 (µm) Λ' = 100 (µm)
2	Air	Fluid	thickness = 200 (mm) ρ = 1.21 (kg/m^3) c = 342 (m/s) η_{air} = 18.14e^{-6} (Pa.s) η = 0.00

❹ **Spatial windowing**

XY system dimensions: [3600; 3000] mm

❺ AcouSYS calculation results

An AcouSYS simulation/measurement comparison of the sound absorption in diffuse field condition α_S for perforated panels with a highly resistive thin veil on back side and air gap is given below:



❻ Comments

A reasonable agreement between simulation and measurement is observed. A resonance frequency due to the air cavity is observed at around 500 Hz. The difference observed at high frequencies is due to edge effects on the sample during measurements which are not considered in simulation.

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Annexe 1 - Frequency dependent parameters

- **Hollow block masonry – Hollowed brick (p.12)**

η (homogenised)

Frequency [Hz]	Value []
100.0	0.05
101.0	0.04
300.0	0.04
301.0	0.03
500.0	0.03
501.0	0.016
1000.0	0.016
1001.0	0.008
2000.0	0.008
2001.0	0.005
5000.0	0.005

η (optimised)

Frequency [Hz]	Value []
100.0	0.018
125.0	0.01
160.0	0.1
200.0	0.3
250.0	0.025
500.0	0.025
630.0	0.02
1600.0	0.022
2500.0	0.005
3150.0	0.02

- **Hollow block masonry – Hollowed brick (p.18)**

	E_x	E_y	E_z	G_{xy}	G_{yz}	G_{zx}
Frequency [Hz]	Value [MPa]	Value [MPa]	Value [MPa]	Value [MPa]	Value [MPa]	Value [MPa]
100.0	933.8	20860.0	6140.0	2187.0	5359.0	1303.0
250.0	933.8	20860.0	6140.0	2187.0	5359.0	1303.0
315.0	524.53	1198.055	481.201	288.536	265.674	150.827
5000.0	524.53	1198.055	481.201	288.536	265.674	150.827

	η
Frequency [Hz]	Value []
100.0	0.002
125.0	0.12
160.0	0.15
200.0	0.01
250.0	0.035
315.0	0.035
400.0	0.0232
500.0	0.04
1000.0	0.0232
2000.0	0.0232
3150.0	0.01

- **Hollow block masonry – Hollowed brick (p. 21)**

	E_x	E_y	E_z	G_{xy}	G_{yz}	G_{zx}
Frequency [Hz]	Value [MPa]	Value [MPa]	Value [MPa]	Value [MPa]	Value [MPa]	Value [MPa]
100.0	16600.0	2960.0	3930.0	2830.0	4020.0	1770.0
200.0	16600.0	2960.0	3930.0	2830.0	4020.0	1770.0
250.0	707.8	1471.7	340.2	423.4	280.2	222.2
5000.0	707.8	1471.7	340.2	423.4	280.2	222.2

	η
Frequency [Hz]	Value []
100.0	0.08
200.0	0.1
250.0	0.08
315.0	0.04
400.0	0.08
500.0	0.05
630.0	0.05
800.0	0.0525
1000.0	0.17
1600.0	0.02
3150.0	0.01
5000.0	0.01

- **Multi skin (Partition wall - p.27)**

	E	η
Frequency [Hz]	Value [MPa]	Value []
100.0	1189.15171	0.0147
125.0	1187.43817	0.0147
160.0	1184.90615	0.0142
200.0	1183.31445	0.0138
250.0	1179.23482	0.0142
315.0	1175.15804	0.0142
400.0	1170.30392	0.0141
500.0	1163.82598	0.0141
630.0	1155.8271	0.0141
800.0	1146.19202	0.0144
1000.0	1134.10191	0.0143
1250.0	1119.94718	0.0145
1600.0	1099.71529	0.0146
2000.0	1077.46798	0.0146
2500.0	1050.40614	0.0147
3150.0	1017.09883	0.015
4000.0	975.4622	0.0154
5000.0	929.28026	0.0157

- **Underfloor heating system – Reinforced concrete slab and screed (p. 49)**

	η (screed)
Frequency [Hz]	Value []
100.0	0.04
200.0	0.03
800.0	0.02

	η (slab)
Frequency [Hz]	Value []
100.0	0.1
125.0	0.04
160.0	0.08
200.0	0.05
400.0	0.05
630.0	0.03
800.0	0.025
1000.0	0.025
1600.0	0.015
3150.0	0.015

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