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"STUDY OF THE ACOUSTIC INSULATION THROUGH DOMESTIC WINDOWS"

TESIS DE MASTER

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Study of the Acoustic Insulation through Domestic Windows

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Resumen.- En este trabajo se estudia el comportamiento acústico en transmisión de varios tipos de ventanas a través de un experimento llevado a cabo por la *Universidad de Napier, Edimburgo*. En primer lugar se han procesado todos los datos del experimento, extrayendo el valor de la Diferencia de Niveles Estandarizada en tercios de octava para cada tipo de ventana y dependiendo de su área de apertura.

En segundo lugar se ha realizado un estudio experimental del comportamiento acústico de las ventanas, considerando diferentes parámetros como: tipo de ventana y estilo de apertura, área de apertura, dimensiones, ángulo de incidencia, material de construcción y condiciones acústicas de la habitación.

Por último, se ha realizado un modelo numérico, por medio del programa Comsol Multiphysics de Elementos Finitos, en el que se ha simulado un tipo de ventana y se ha comparado con los resultados experimentales anteriormente estudiados. Los resultados obtenidos de la simulación, permiten interpretar los resultados experimentales

Abstract.- This academic work presents the acoustic performance in transmission of various types of windows through an experiment conducted by *Napier University, Edinburgh*. First a processed of the experimental data has been done, extracting the value of the Standardized Level Difference in octaves bands for each type of window and depending on the opening area.

Second has been made an experimental study of the acoustic performance of windows, considering different parameters such as: window type and opening style, area of open, size, angle of source incidence, material and acoustics room condition.

Finally, a numerical model has been done, through Comsol Multiphysics program, Finite Elements, which has been carried out a window simulation and has been compared with the experimental results studied before. The results of the simulation, can interpret the experimental results.

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INDEX

I. Introduction 5
I.1. Background 5
I.2. Objetives 5
II. Theoric introduction 7
II.1. Natural ventilation 7
II.2. External windows 8
II.3. Acoustic and cross ventilation 10
II.3.1 Cross vent to assist with the prevention of noise break-in 10
II.3.2 Acoustic screening to open windows 10
II.4. Airborne sound insulation 11
II.4.1. Method of measurement to BS EN ISO 140-4:1998 12
II.4.2. Method of measurement to BS EN ISO 140-5:1998 13
II.4.3. Method of measurement to BS EN ISO140-3:199 14
III. Experimental method 15
III.1. Introduction to study 15
III.2. Experimental details 15
III.2.1. Specification of window assemblies 16
III.3. Test procedure 18
III.3.1 Receiver room 19
III.3.2 Source room 20
III.3.3 Wall construction 21
III.3.4 Measurement precision 22
III.3.5 Window test arrangements 22
III.4 Results and analysis 23
III.4.1 Measurement objectives 23
III.4.2. Result format 23
III.4.3. Specific parameters 24
III.5. Conclusions 32
IV. Numerical method 34
IV.1. Finite element method 34
IV.1.1. General concepts of method 34
IV.2. Model and numeric simulation results. 34
IV.2.1. Numerical model 35

IV.2.2. Results of the numerical model 37
IV.3 Experimental and numerical method: Comparison 42
IV.3.1 Opening area: $0.10m^2$ 44
IV.3.1 Opening area: $0.20m^2$ 46
IV.4. Conclusions 50
Acknowledgement **51**
References **51**
Appendix............ **52**

I. INTRODUCTION

I.1. BACKGROUND

This project has been realized in the business environment by *Mach Acoustics Ltd* through the Erasmus program. *MachAcoustics* is an acoustic consultancy based in Bristol, England, who work on a large number of schools projects, developing solutions to natural ventilation and cross ventilation in combination with room acoustic treatment, whilst complying with BB93.

When environmental noises are high it can be difficult to achieve natural ventilation if low internal noise levels are required. Different solutions can be adopted like louvres or attenuators, but because of their size, price, space constraints and natural light requirements, an opened window is often the only solution.

Natural ventilation is being adopted in building design to reduce operational energy usage and increasing building occupant comfort. Unfortunately, ventilation openings in interior partitions of naturally ventilated buildings also reduce the noise isolation across the partition, resulting in a poor acoustical environment.

When naturally ventilating a building on a noisy or moderately noisy site the acoustic design of the facade becomes fundamental. It is generally accepted that cross ventilation is the most effective form of natural ventilation. Acoustics plays a key role in the design of a cross ventilated building as air must flow freely through the building whilst maintain privacy across partitions. One of the main difficulties in designing low energy buildings can be the prevention of noise break-in via vented facades. A range of options and details exist, which can be used to reduce environmental noise break-in from numerous noise sources affecting the buildings, including motorways, dual carriageways, trains, aeroplanes and inner city noise.

The orientations of a building and the type of windows have a significant impact upon noise levels at the different facades of the building. For this reason we are going to study the different types of windows and the effect that they are producing to have used in the building construction.

This report presents the findings from a set of laboratory measurements undertaken at the *BUILDING PERFORMANCE CENTER* - *School of the Built Environment, Napier University* and a numerical simulation to investigate the sound insulating performance of windows in their open condition, so to provide additional guidance on related physical factors.

I.2. OBJETIVES

The sound insulation through ventilated window research from Napier University has been read and the data sheets have been summarizing and organized in order to analysing the data results.

Experimental and numerical study has been done to conclude on which are the main factors offering the performance of a window.

The specific goals to the Project are:

- Provide a guidance on the acoustical properties of facades allowing for the requirements of natural ventilation, through either open window. The guidance is intended to be of particular use at the planning state for schools developments; where it can be used in combination with acoustic criteria to assess the scope of noise mitigation works.
- Compare the experimental data and numeric experiment performed. In order to carry out this simulation, a scale model will be built using Comsol Multiphysics.

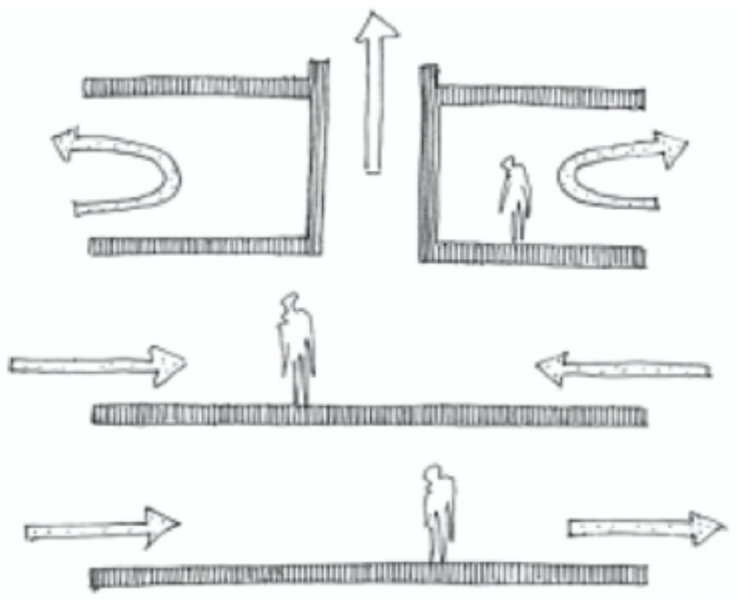
II. THEORIC INTRODUCTION

II.1. NATURAL VENTILATION

Natural ventilation is the process of supplying and removing air through an indoor space without using mechanical systems. It refers to the flow of external air to an indoor space as a result of pressure or temperatures differences.

Natural ventilation systems rely on pressure differences to move fresh air through buildings. The pressure differences can be caused by the buoyancy effect created by temperature differences, by wind, or by differences in humidity. Natural ventilation, unlike fan-forced ventilation, uses the natural forces of wind and buoyancy to deliver fresh air into buildings. Fresh air is required in buildings to alleviate outdoors, to provide oxygen, and to maintain thermal comfort.

The following Figure is illustrating the types of natural ventilation and it is going to explain the them:



1. SINGLE- SIDED VENTILATION

2. CROSS VENTILATION

3. TACK VENTILATION

Fig.1. Building with several natural ventilation systems.

1. SINGLE-SIDED VENTILATION: relies on opening(s) on only one side of the ventilated enclosure. Fresh air enters the room through the same side as used air is exhausted. A typical example is the rooms of a cellular building with openable windows on one side and closed internal doors on the other side.

2. CROSS-VENTILATION: is the case when air flows between two sides of a building envelope by means of wind-induced pressure differentials between the two sides. The ventilation air enters and leaves commonly through windows, hatches or grills integrated in the façades. The ventilation air

moves from the windward side to the leeward side.

3. TACK VENTILATION: occurs where the driving forces promote an outflow from the building, thereby drawing fresh air in via ventilation openings at a lower level. Fresh air typically enters through ventilation openings at a low level, while used and contaminated air is exhausted through high-level ventilation openings.

The method of ventilation as well as the type and location of ventilation openings will affect the overall sound insulation of the building envelope. When external noise levels are higher than $60dBL_{Aeq,30min}$, simple natural ventilation solutions may not be appropriate as the ventilation openings also let in noise. However, it is possible to use acoustically attenuated natural ventilation rather than full mechanical ventilation when external noise levels are high but do not exceed $70dBL_{Aeq,30min}$.

Additional ventilation such as openable windows or vents may be required to prevent summetime overheating.

II.2. EXTERNAL WINDOWS

The airborne sound insulation of windows can be assessed from laboratory measurements of the sound reduction index according to BS EN ISO 140:3. When choosing suitable windows using measured data, care must be taken to differentiate between measured data for glazing and measured data for windows. The reason is that the overall sound insulation performance of a window is affected by the window frame and the sealing the glazing.

To achieve the required sound insulation with thin glass it is often necessary to use two panes separated by an air (or other gas) filled cavity. In theory, the wider the gap between the panes, the greater the sound insulation. In practice, the width of the cavity in double glazing makes relatively little difference for cavity widths between 6mm and 16mm. Wider cavity widths perform significantly better.

In existing buildings, secondary glazing may be installed as an alternative to replacing existing single glazing with double glazing. The effectiveness of secondary glazing will be determined by the thickness of the glass and the width of the air gap between the panes. Another alternative may be to fit completely new double-glazed window the inside of the existing window opening, leaving the original window intact. The use of sound absorbing reveal linings improves the performance of double-glazed windows, but the improvement is mainly in the middle to high frequency region, where it has little effect on road traffic and aircgraft noise spectra.

To achieve their optimum performance, it is essential that the glazing in windows makes an airtight seal with its surround, and that opening lights have effective seals around the perimeter of each frame.

Neoprene compression seals will provide a more artight seal than brush seals. The framing of the window should also be assembled to achieve an airtight construction.

It is equally important that an airtight seal is achieved between the perimeter of the window frame and the opening into which it is to be fixed. The opening should be accurately made to receive the window, and the perimeter packed with sound insulating material prior to application of a continuous seal on both sides.

For partially open single-glazed widows or double-glazed windows with opposite opening panes, the laboratory measured airborne sound insulation is approximately 10-15dB Rw. This increases to 20-25dB Rw in the open position for a secondary glazing system with partially open ventilation openings, with the openings staggered on plan or elevation, and with absorbent lining of the window reveals (*see Fig. 2*). In situ, the degree of attenuation provided by an open window also depends on the spectrum of the noise and the geometry of the situation.

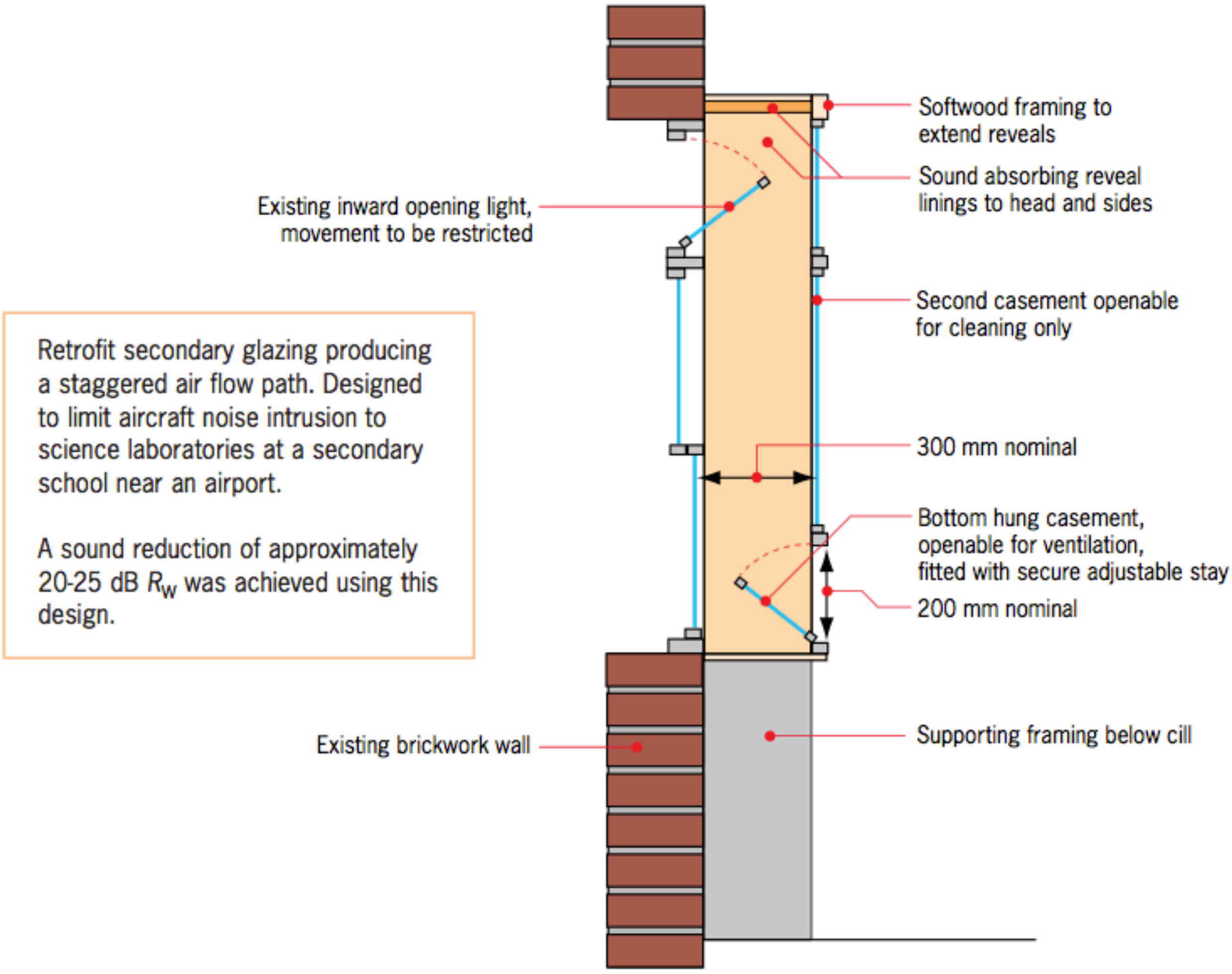


Fig.2. Sound reducing secondary glazing system

II.3. ACOUSTIC AND CROSS VENTILATION

It is generally accepted that cross ventilation is the most effective form of natural ventilation. Acoustics plays a key role in the design of a cross ventilated building as air must flow freely through the building whilst maintaining privacy across partitions.

The orientation of a building has a significant impact upon noise levels at the different facades of the building. It is often the case that facades on the opposite side of a building to a significant noise source, will have considerably lower noise levels than those on the noisy side of the building.

By orientating the building and by locating non-critical spaces on the noisy side of a building, it is possible to form a good acoustic buffer. In these instances, cross vent can be used where the air intake is placed on the quiet side of the building. Cross ventilation to an atrium or circulation zone is then used to provide the air extract. Alternatively, single sided ventilation could be used for sensitive spaces on the quiet side of a building.

Another way to obtain natural ventilation by means of openable windows. It is the cheapest alternative but the most difficult as well.

II.3.1 CROSS VENT TO ASSIST WITH THE PREVENTION OF NOISE BREAK-IN

In instances where a building is located on an exceptionally noisy site, cross ventilation can improve the feasibility of natural ventilation. Cross ventilation has an important advantage over single sided ventilation, in that air inlet vents can be between 25% to 75% smaller than those required for single sided ventilation. This significant reduction in vent size helps considerably in preventing noise break-in, as smaller vents restrict the passage of sound into a building.

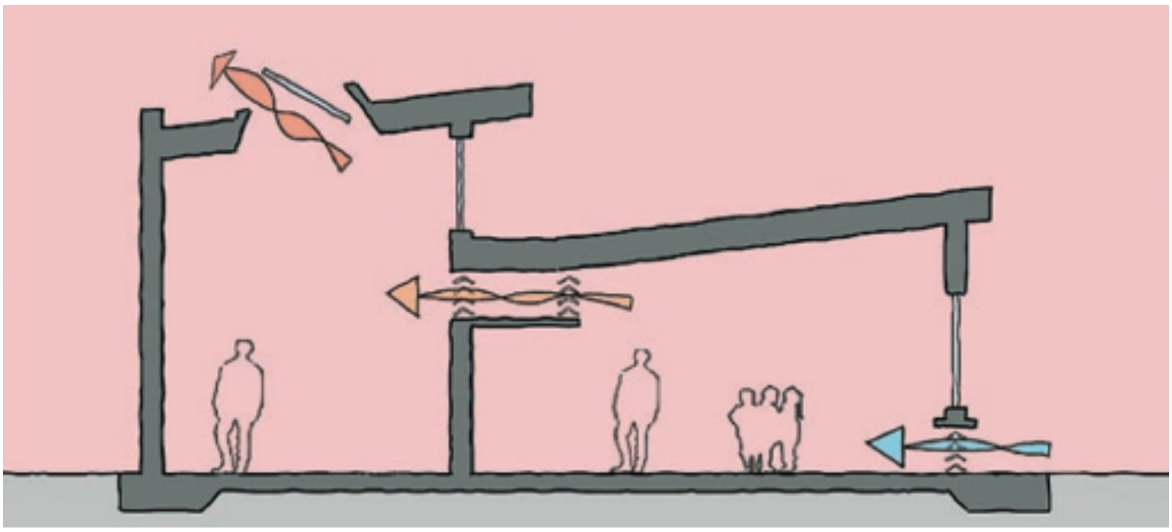


Fig.3. Cross ventilation in a building

II.3.2 ACOUSTIC SCREENING TO OPEN WINDOWS

Acoustic Scaled Models of Vented Facades is a technology which enables the effects of acoustic screens attached directly to the facade of a building to be assessed. Scaled models are typically used to assess the acoustics of auditoria during the design stages. Scaled models are used due to their practical, accurate and cost effective nature. The same principles apply to the design of screened acoustic facades.

The illustration shows two design options where screened facades were proposed in order to add acoustic attenuation to a vented facade of an inner city office block. This method of noise control is simple, cost effective and provides the additional acoustic resistance such to prevent inner city noise being a nuisance within the office accommodation. Screened facades are also a good method of meeting the requirements set out by BREEAM. The drawback of this system is that these screens can only enhance the performance of an open-able window by around 5 to 7 dB, meaning that these facades can only be used when external noise levels are moderately high.

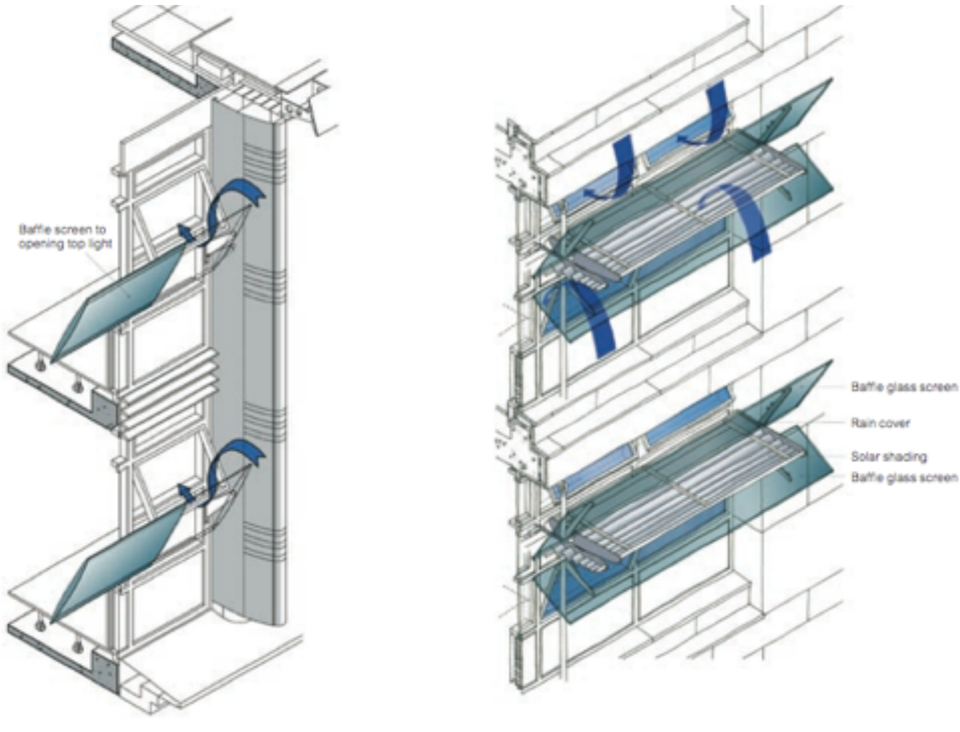


Fig.4. Simple Screened window and Screened window install on solar shanding unit

II.4. AIRBORNE SOUND INSULATION

- *Laboratory measurements*

Laboratory airborne sound insulation measurements are primarily used to compare the sound insulation provided by different test elements and to calculate the sound insulation in situ. The role of field measurements is usually to check that a certain level of sound insulation has been achieved.

A transmission suite for airborne sound insulation measurements comprises two rooms; a source room and a receiving room separated by a test element. At this stage we simply assume that all sound is transmitted via the test element, and that the structure of the transmission suite itself plays no role other than defining the space for the source and receiving rooms.

The transmission coefficient, τ, is defined as the ratio is the sound power transmitted by the test element, W_2, to the sound power inciden to the test element, W_1,

$$\tau = \left(\frac{W_2}{W_1}\right) \tag{1}$$

The sound reduction index, or transmission loss, R, in decibels is defined as

$$R = 10log\left(\frac{1}{\tau}\right) = 10log\left(\frac{W_1.W_{ef}}{W_2.W_{ef}}\right) = 10\log\frac{W_1}{W_{ef}} - \frac{W_2}{W_{ef}} = L_{W1} - L_{W2} = R \tag{2}$$

The sound reduction index R expresses in decibels the inverse of the wall's transmission factor. In the laboratory this index is measured by having separate rooms for emission and reception. R is determined by measuring sound pressure level L_{P1} and L_{P2} in the two rooms. The following is obtained

$$\mathrm{R} = \mathrm{L_{P1}} - \mathrm{L_{p2}} - 10\log\frac{\mathrm{A}}{\mathrm{S}} \tag{3}$$

where A is the equivalent absorption area of the receiving room and S is the area of the Wall under test.

II.4.1. METHOD OF MEASUREMENT TO BS EN ISO 140-4:1998, 'FIELD MEASUREMENTS OF AIRBORNE SOUND INSULATION BETWEEN ROOMS'

Airborne sound insulation measurements were performed according to a prescribed procedure that specifies the sound generated in the source room shall be steady and have a continuous spectrum in the frequency bands of interest. Measurements of the sound levels were made in both source and receiver rooms at the one-third octave intervals from 100 Hz to 5000 Hz as recommended in the Standard. The measurements were made with a moving microphone to obtain a good average of the sound pressure level in each room. Reverberation time measurements were made in the receiver room following the procedures of *British Standard BS EN 20354:1993.*

The Level Difference (D) in decibels (dB) is calculated in each frequency band using the equation:

$$\mathrm{D} = \mathrm{L_1} - \mathrm{L_2}\ (\mathrm{dB}) \tag{4}$$

The Standardized Level Difference (DnT) in decibels (dB) is calculated in each frequency band using the equation:

$$\mathrm{DnT} = \mathrm{L}_1 - \mathrm{L}_2 + 10\log\left(\frac{\mathrm{T}}{\mathrm{T}_0}\right)\ (\mathrm{dB}) \tag{5}$$

where, DnT is the Standardized Level Difference (dB)

L_1 is the average sound pressure level in the source room (dB)

L_2 is the average sound pressure level in the receive room (dB)

T is the average reverberation time of the receive room (seconds)

T_0 is the reference reverberation time of 0.5 (seconds)

The Weighted Standardized Level Difference (DnT,w) and Weighted Level Difference (Dw) in decibels (dB) and the Spectrum Adaptation Terms (C and *Ctr),* also in decibels, are calculated in accordance with *BS EN ISO 717-1:1997* by comparison of the sixteen values of Standardized Level Difference from 100 Hz to 3150 Hz with the relevant reference curves.

II.4.2. METHOD OF MEASUREMENT TO BS EN ISO 140-5:1998, 'FIELD MEASUREMENTS OF AIRBORNE SOUND INSULATION OF FACADE ELEMENTS AND FACADES'

This part of ISO 140 specifies two series of methods (element methods and global methods) for measurement of the airborne sound insulation of façade elements and whole façades, respectively. The element methods aim to estimate the sound reduction index of a façade element, for example a window. The most accurate element method uses a loudspeaker as an artificial sound source. Other, less accurate, element methods use available traffic noise. The global methods, on the other hand, aim to estimate the outdoor/indoor sound level difference under actual traffic conditions. The most accurate global methods use actual traffic as sound source. In addition, a loudspeaker may be used as an artificial sound source.

The element loudspeaker method yields an apparent sound reduction index, which, under certain circumstances, can be compared with the sound reduction index measured in laboratories in accordance with *140-3 or 140-10*. This method is the preferred method when the aim of the measurement is to evaluate the performance of a specified façade element in relation to its performance in the laboratory.

II.4.3 MEASUREMENT OF SOUND INSULATION IN BUILDINGS AND OF BUILDING ELEMENTS BS EN ISO 140-3:1998LABORATORY MEASUREMENTS OF AIRBORNE SOUND INSULATION OF BUILDING ELEMENTS

This part of *ISO 140* specifies a laboratory method for measuring air sound insulation of building elements such as walls, floors, doors, windows, facade elements and facades.

The results obtained can be used in the design of building elements with acoustic properties appropriate to compare the properties of sound insulation of building elements and to classify such items according to their capabilities of acoustic insulation.

The measurements were performed in laboratory facilities where sound transmission through indirect channels is suppressed. The results of measurements made with this part of ISO 140, therefore, not be applied directly in the field without taking into account other factors affecting sound insulation, especially indirect transmissions and loss factor.

Sound reduction index R: It's ten times the logarithm of the ratio of the sound power W1, striking the wall under study and the power transmitted through the sample.

$$R = 10\log\frac{W1}{W2}\,(\text{dB}) \qquad (6)$$

also sound reduction index is evaluated as:

$$R = L_1 - L_2 + 10\log\frac{S}{A}\,(dB) \qquad (7)$$

L_1 is the average sound pressure level in the source room (dB)

L_2 is the average sound pressure level in the receive room (dB)

S is the test area (m^2)

A is the equivalent sound absorption area in the receiver room (m^2)

III. EXPERIMENTAL METHOD

III.1. INTRODUCTION TO STUDY

This section will show the experimental results and study conducted by the department *The Building Performance Centre de School of Built Environment, Napier University* and conduced for Department for Environment, Food and Rural Affairs (DEFRA) in UK.

This publication presents measured data from a set of laboratory measurements made in support of the *Defra (Department for Environment, Food and Rural Affairs)* 'Open/Closed window Research: Sound Insulation Through Ventilated Domestic Windows'.

The data presented are the laboratory measured standardised level difference, defined for the data-set presented as:

$$\mathrm{DnT} = \mathrm{L}_1 - \mathrm{L}_2 + 10 \cdot \log_{10}\left(\frac{\mathrm{T}}{\mathrm{T}_0}\right) \quad (8)$$

L_1 is the averaged sound pressure level in the source room (dB).

L_2 is the averaged sound pressure level in the receiving room (dB).

T is the reverberation time in the receiving room (s).

T_0 is the reverberation time reference (0.5s).

The standard test methodology for laboratory sound insulation testing on panel assembly is contained within *BS ISO EN 140 part 3 'Laboratory measurements of airborne sound insulation of building elements'*. This method uses a test aperture between two highly reverberant environments. The use of a reverberant source environment however would not allow for the investigation of source location or any influence from angled window openings. Therefore it was decided that the test methodology provided *in BS ISO EN 140 part 5: 'Field measurements of airborne sound insulation of façade elements facades'* to be appropriate; although based within a laboratory environment i.e. anechoic chamber.

III.2. EXPERIMENTAL DETAILS

The test laboratory consisted of a 300m^3 anechoic 'Source', chamber connected via a 12m^2 test aperture, to a 38m^3 reverberation 'Receiver', chamber.

The rooms were both structurally isolated and were only coupled at the same aperture. The initial suite layout is shown in *Fig.5*. The facilities also include an external control room with installed cabling runs to/from the anechoic and reverberation chambers.

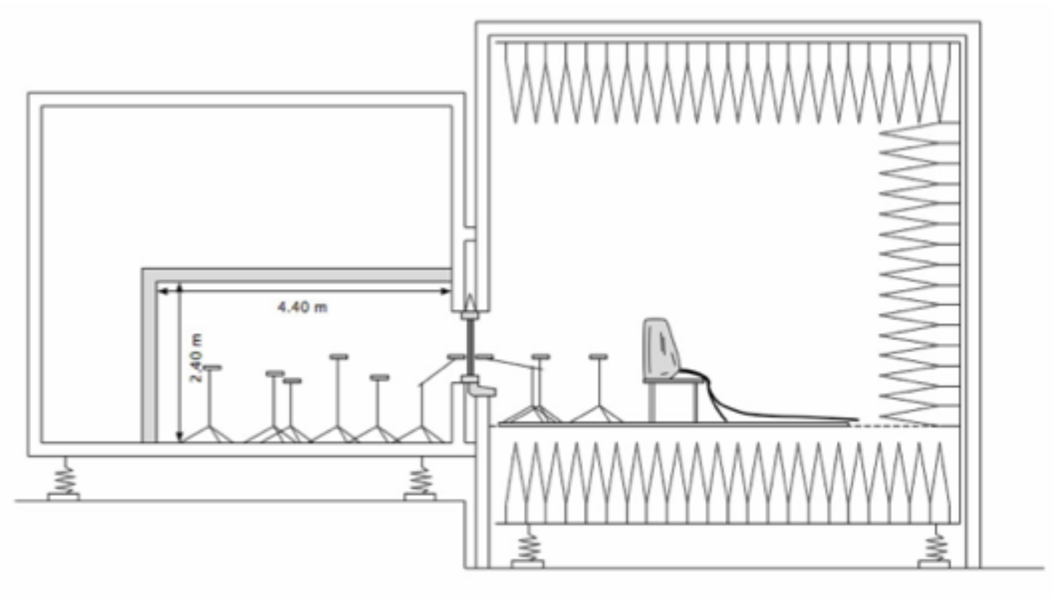


Fig.5. Section through laboratory

III.2.1. SPECIFICATION OF WINDOW ASSEMBLIES

A questionnaire survey of window manufacturers and construction companies was undertaken to identify the range and styles of window units currently being installed in the UK. The units selected were predominately PVCu frames, with the exception of one timber and one aluminium frame.

Fig.6. PVCu frames

Fig.7. Aluminium Frame

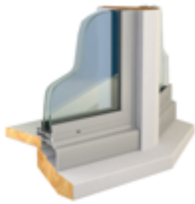


Fig.8. Timber Frame

All window units were specified with sealed double-glazed units of 4mm glass- 16mm air space- 4mm glazing specification, with one frame also having a heavier 4mm glass- 18mm air space-6.4mm laminated replacement pane. A total of five different manufactures were used to source the test units. The range of windows included the most popular frame sizes, materials, opening types, seals and ventilation arrangements. Table 1 shows the physical properties of each window simple included in the test programme.

Sample	Description	Frame dimensions(mm) (area)	Frame depth(mm)	Glass dimensions (mm)	Mass(Kg)	Seals
A	Vent+side hung (double)	2400x1050 (2.54m2)	60	424x834 560x600 464x194 424x834 560x600 464x194	75.6	Foam
B	Reversible	1200x1050 (1.26m2)	71	1004x854	35.2	Rubber
C	Tilt&turn (inwards)	900x1050 (0.95m2)	70	696x846	29.2	Rubber
D	Sliding sash	900x1200 (1.08m2)	135	725x485 725x485	34.8	double brush
E	Top hung London	600x1050 (0.63m2)	70	452x493 403x362	16.9	Rubber
F	Top hung London (Aluminium)	600x1050 (0.63m2)	48	530x473 487x430	16.9	Rubber
G	Side hung (Timber)	600x900 (0.54m2)	94	414x695	18	foam, nylon sheath

Table 1. Properties of windows samples

Several window units were able to open in different configurations, the range of potential openings are shown in *Table 2.*

Description	*Configuration*
Window A. outward opening casement-left hand side	
Window A. outward opening casement- right hand side	
Window A. top hung outward opening casements	
Window B. side swing reversible	
Window C. horizontal inward tilt	
Window C. vertical inward turn	
Window C. laminate glass, bottom hung inward tilt	
Window C. laminate glass, side hung inward tilt	
Window D. sliding sash upper section open	
Window D. sliding sash lower section open	
Window D. bottom hung inward opening	
Window E. top hung outward opening (PVC-U)	
Window F. top hung outward opening (Aluminium)	
Window G. side hung outward tilt (timber)	

Table 2. Window test configuration.

III.3. TEST PROCEDURE

The test methodology followed the function requirements of *BS EN ISO 140-3:1995*. A Brúel&Kjaer Pulse nine channel data acquisition system was used for the testing, with 3 fixed microphones used to characterise the source noise levels and 5 fixed microphones used within the receiver room. A 30 second pink noise signal, generated by the data acquisitions system was used as the acoustic excitation, fed through amplifying loudspeakers. The test signal arrangement is shown in *Fig.9.*

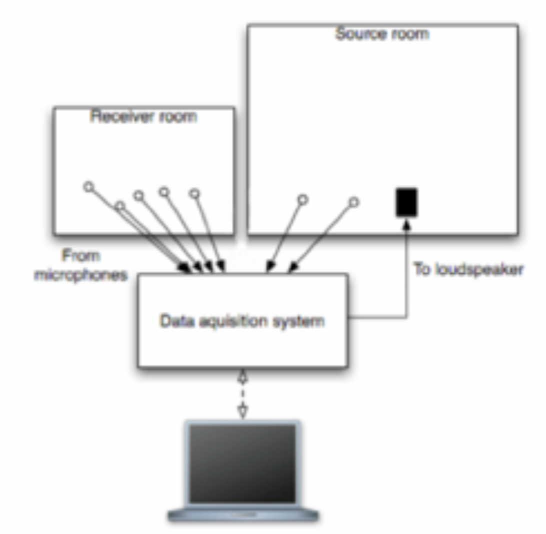


Fig.9. Test system schematic diagram

III.3.1 RECEIVER ROOM

The five microphones in the receiver room, R1 to R5, were positioned at heights between 1.2m and 1.5m and were all at least 700mm away from any other surface or measurement position. The positions are shown graphically in *Fig.10*, with their respective distances shown in *Table 3.*

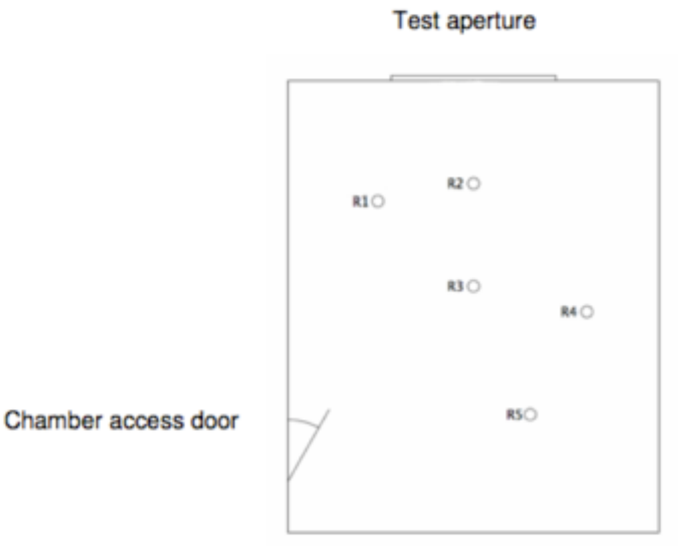


Fig.10. Receiver room microphone positions

Microphone	Height (m)	Distance from centre of window (m)
R1	1.35	1
R2	1.2	2

R3	1.35	2.5
R4	1.5	3.3
R5	1.35	1.5

Table 3. Receiver room microphone positions

III.3.2 SOURCE ROOM

The two microphones located in the source room, *S1 and S2*, were positioned at heights between *1.2m* and *1.5m*. These microphones were rotated around the centre of the test window at fixed radii, depending on the location of the source loudspeaker.

Five loudspeakers configurations, *L1 to L5*, were used at a distance of *2.72m* from the centre of the window specimen and at angles to the centre of *-70º, -35º,0º,+35º and +70º.*

The positions of the source microphones and loudspeaker are shown in *Fig.11*. In *Table 4* is shown the height to microphone and speaker centre and the distance centre of window with their respective distances.

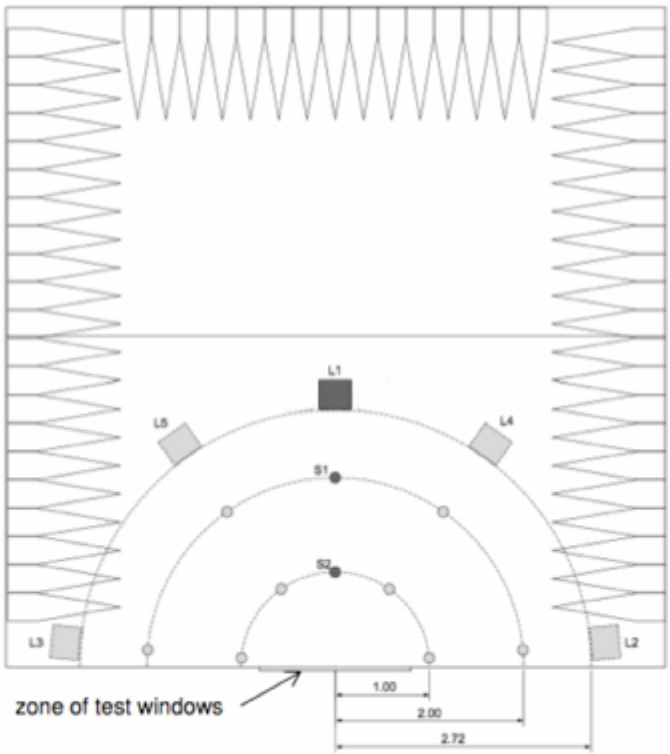


Fig.11. Source room microphones and loudspeakers positions

Microphone/Loudspeaker position	Height to mic/speaker centre (m)	Distance from centre of window (m)	Horizontal angle with the facade
S1	1.20	2.00	-
S2	1.35	1.00	-
L1	1.07	2.72	0º
L2	1.07	2.72	+70º
L3	1.07	2.72	-70º
L4	1.07	2.72	+35º
L5	1.07	2.72	-35º

Table 4. Source room microphones and loudspeakers positions

III.3.3 WALL CONSTRUCTION

A cavity masonry wall, similar to that commonly used in dwellings, was built as the core wall within the test aperture separating the source and receiver test rooms. The construction consisted of two leaves of *100mm* concrete block work, rendered on the source face with *13mm* cement and on the receiving room face with *12.5mm* plasterboard on timber straps. The leaves were separated by a *50mm* cavity, using butterfly wire wall ties. The wall was initially built across the whole test aperture and included a *2.4 m* lintel supported on two masonry piles either side on the infill. The wall was then tested before it was knocked through in order to provide an aperture in which window specimens could be mounted. Throughout the processes of construction and knocking through the wall, care was taken that mortar and debris did not fall into the cavity and thereby cause unrepresentative bridging effects between the two masonry leaves.

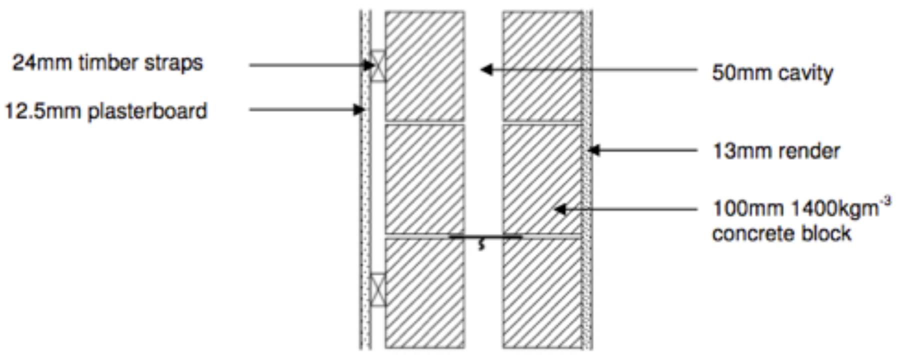


Fig.12. Filler wall construction simulating external Wall characteristics

III.3.4 MEASUREMENT PRECISION

The accuracy of the sound level measurement equipment complied with *class 1* requirements, as defined in *IEC 651 and IEC 804*. At the start of each measurement sequence, all microphones were calibrated at a reference level of *94dB at 100Hz*. The calibrator complied with the requirements of accuracy *class 1* defined in *IEC 942.*

The third-octave band filters in the data acquisition system complied with the requirements defined in *ISO 354.*

The reverberation time measurement equipment complied with the requirements defined in *ISO 354.*

The loudspeaker settings were adjusted to ensure a reasonably flat spectrum across the third-octave bands from *50Hz to 5kHz*, when pink noise was used as an input to the system. Sound emitted from the loudspeakers did not differ in level by more than *6dB* between adjacent third-octave bands, measured 1m from the loudspeaker centre.

Test specimens were stored for more than *24 hours* at the test temperature, which was always between *17ºC and 23ºC.*

III.3.5 WINDOW TEST ARRANGEMENTS

The windows were tested with the window open, at three defined settings:

- $0.05m^2$
- $0.10m^2$
- $0.20m^2$

The size of the openings were measured perpendicular to the potential air flow in the plane of the open area.

An illustration in Fig.13. of the scope of the laboratory testing is given below, indicating the basic parameters that were tested. These include the openable window configurations which were each tested at 5 source locations with 3 distinct window conditions and with the data recorded by 7 microphone channels.

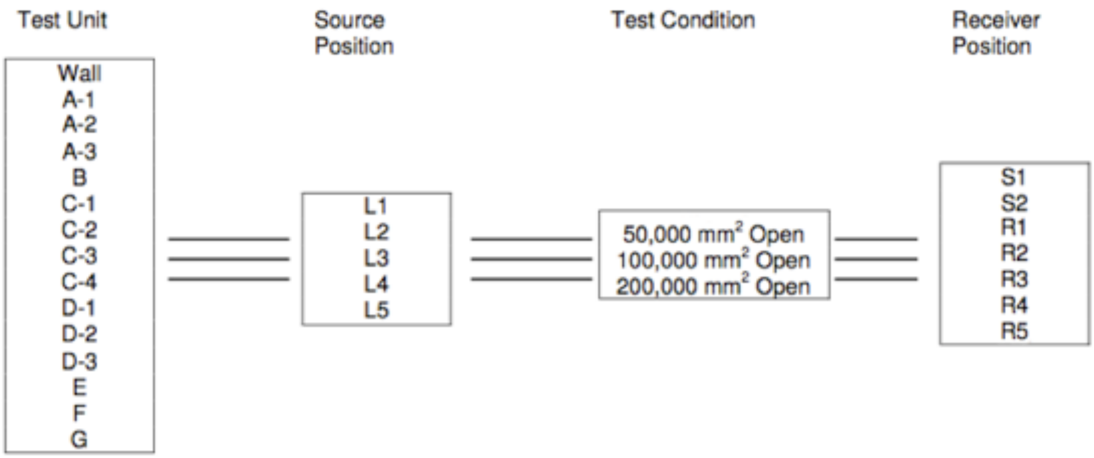


Fig.13. Scope of the laboratory testing

III.4 RESULTS AND ANALYSIS

III.4.1 MEASUREMENT OBJECTIVES

The aim of the laboratory measurements was to facilitate the project objectives empirically. The methodology has therefore been designed to provide comparative data on the variables that are anticipated to have an influence on the acoustic transmission characteristics of domestic windows. The specific parameters considered are:

- *window type/opening style*
- *area of open window*
- *size of window area*
- *angle of source incidence*
- *window frame/seals materials*
- *acoustic room condition*

III.4.2. RESULT FORMAT

A full set of standardised one-third octave level difference results (D_{nT}) are presented in *Appendix 2;* calculated for every experimental set-up for each source measurement position, relative to the averaged receiving room result, standardised to the receiver room reverberation and the *0.5s* T_0 reference. The reverberation time measurement results are shown in *Table 13.*

The calculations used each source microphone results (*S1, S2*) in combination with the logarithmically average receiver spectrum at five receiver room positions (*R1-R5*). These receiver room microphones were located within the specification tolerance given within *BS EN ISO 140-3* for measurement of the receiver room sound field.

III.4.3. SPECIFIC PARAMETERS

- *Window Type/opening style*

Considering that the experiment includes 7 types of windows with 12 different configurations (*see Table 2*), a simplification of them is conduced into windows to take place an experiment simplification. *A, B, C-3, C-4, D-1, D-3 and E* are the windows which taking place in the final experiment. A simplification has been taking place in order to develop the window that are contribute more information.

In order to provide simplified data on the insulating performance of the window openings, the combined results have been reduced into a single set of results for each opening condition. *Table 5, 6 and 7* show the standardised level difference in octaves-band from the final window simplification. The open area values used for the tested windows are approximately $0.05m^2$, $0.10m^2$ and $0,20m^2$.

		125 (Hz)	250 (Hz)	500 (Hz)	1000 (Hz)	2000 (Hz)	4000 (Hz)
A		23,3	21,7	20,8	21,2	21,4	23,1
B		22,8	22,5	18,7	18,4	17,9	23,2
C-3		27,1	23,5	16,1	19,7	19,9	24,1
C-4		26,3	23,7	17,4	19,6	19,9	21,7
D-1		26,4	21,0	19,9	20,1	21,3	21,8
D-2		25,0	21,9	17,7	18,3	17,1	23,0
D-3		25,3	23,0	17,3	19,3	18,7	25,3
E		26,4	21,6	23,5	22,8	24,3	26,5

Table 5. D_{nT} in octaves-bands in $0.05m^2$ area of open window

		125 (Hz)	250 (Hz)	500 (Hz)	1000 (Hz)	2000 (Hz)	4000 (Hz)
A		22,2	20,9	19,2	19,3	20,1	20,4
B		21,4	21,1	18,0	16,8	15,9	22,8
C-3		26,3	22,6	15,1	18,2	18,5	23,4
C-4		25,6	22,1	15,2	18,3	19,2	22,3

D-1		24,8	19,0	17,9	20,5	19,2	19,5
D-2		22,5	19,4	15,3	16,5	13,2	17,6
D-3		23,0	20,0	15,3	18,0	17,1	21,6
E		25,2	19,6	21,5	22,3	22,0	24,4

Table 6. D_{nT} in octaves-bands in $0.10m^2$ area of open window

		125 (Hz)	250 (Hz)	500 (Hz)	1000 (Hz)	2000 (Hz)	4000 (Hz)
A		20,6	17,6	17,1	18,6	17,5	18,0
B		19,6	19,3	17,3	15,9	16,6	20,1
C-3		25,0	20,8	13,1	15,4	17,8	23,7
C-4		23,3	19,7	13,0	15,4	19,8	22,8
D-1		22,4	17,0	19,0	17,7	16,1	15,8
D-2		20,2	16,8	13,9	13,9	10,9	14,9
D-3		21,0	17,1	15,4	16,7	14,6	18,2
E		24,2	17,8	19,8	20,6	20,1	21,7

Table 7. D_{nT} in octaves-bands in $0.20m^2$ area of open window

- *Area of open window*

Table 8 ranks the highest performing windows in *Weighted Difference Level* . The results given from the various loudspeaker positions have been averaged to produce the overall *Weighted Standardised Level Difference ($D_{nT,w}$)* for each open area of window. *See in Appendix 1.*

	$0.05m^2$	**$0.10m^2$**	**$0.20m^2$**	**Illustration**
E	26	24	22	
D-1	24	22	20	
A1	23	21	19	
D-3	22	20	19	

C-4	21	20	18	
C-3	21	19	18	
B	21	19	18	
D-2	20	18	16	

Table 8. Weighted Difference Level

The sound insulation is reduced as the window is progressively opened, with the largest single decrease in insulation occurring between 0.10m^2 and 0.20m^2 of open area.

For most window types there was a 2dB reduction from the 0.05m^2 to the 0.10m^2. The exception is the sliding configuration C-4, which exhibits a slightly lower reduction of 1dB.

For most window types there was a 2dB reduction from the 0.10m^2 to the 0.20m^2. The exception is the configuration C-3 and B, which exhibits a lower reduction of 1dB.

The next graph is shown the Ranking depending of the free area and the Dw valour. The blue colour is showing the 0.05m^2 free area, the red 0.10m^2 free area and the green one is showing the 0.20m^2.

Fig.14. shows the ranking of window performance in relation to the open area.

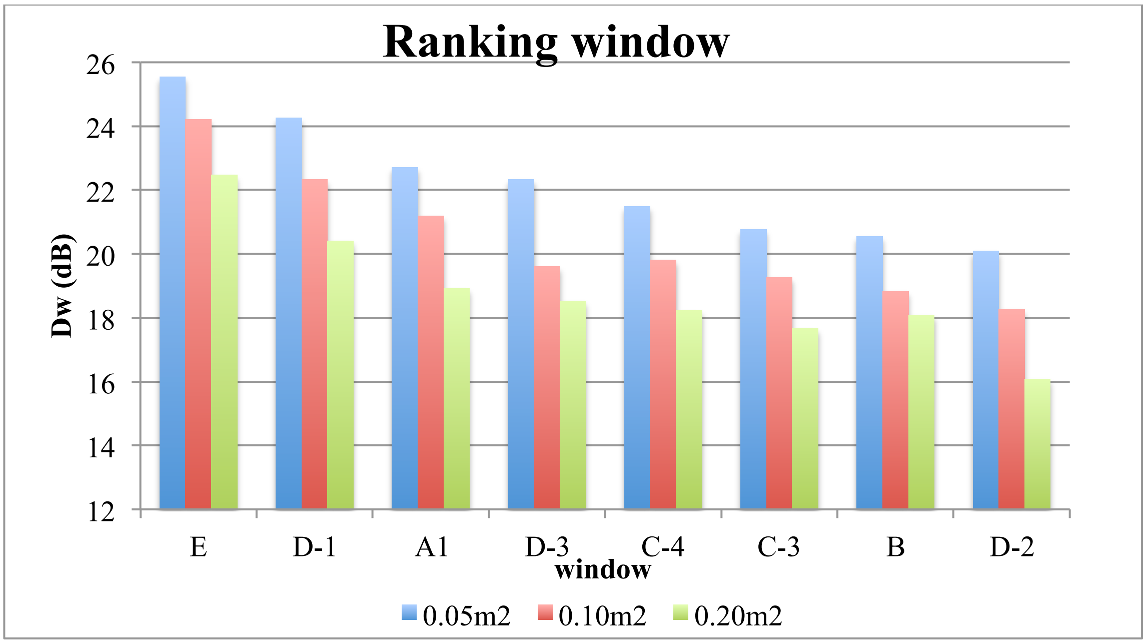


Fig.14. Ranking of the window performance

When the free area is increasing always is true that the level of sound insulation is lower. As expected it is found that the larger the open are, the lower the sound insulation performance.

- *Size of window area*

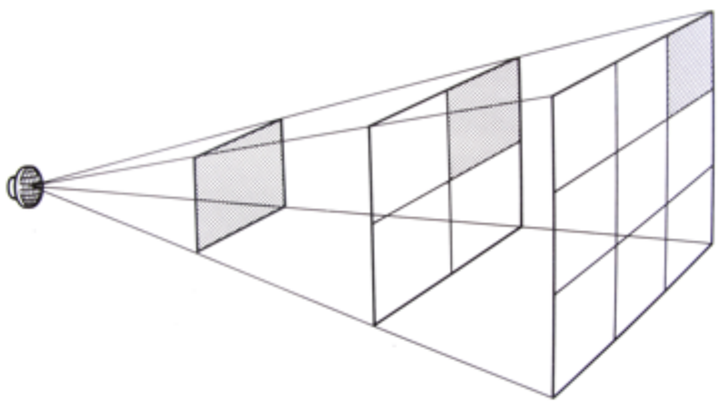
The opening distances for the different types of windows are presented in the Table 9. The opening distance has been calculate for each type of window in the opening configurations.

Window illustration		***Opening distance (m)at 0.05m²***	***Dw 0.05m²***	***Opening distance (m) at 0.10m²***	***Dw 0.10m²***	***Opening distance (m) at 0.20m²***	***Dw 0.20m²***
E		*0,053*	*26*	*0,106*	*24*	*0,212*	*22*
D-1		*0,48*	*24*	*0,96*	*22*	*1,92*	*20*
A-1		*0,040*	*23*	*0,080*	*21*	*0,160*	*19*
D-3		*0,041*	*22*	*0,082*	*20*	*0,164*	*19*
C-4		*0,032*	*21*	*0,064*	*20*	*0,128*	*18*
C-3		*0,032*	*21*	*0,064*	*19*	*0,128*	*18*
B		*0,037*	*21*	*0,074*	*19*	*0,148*	*18*
D-2		*0,48*	*20*	*0,96*	*18*	*1,92*	*16*

Table 9. Size of window area and Dw from free area

If a source is radiating sound equally in all directions, the energy will be spread over an increasing area as the distance from the source increases. This means that for a double distance the sound pressure will be increasing +3dB (inverse square law)

$$\text{SPL decrease} 10\log\frac{1}{2^2} = -6\text{dB per distance doubling} \tag{9}$$



The opening distances for the different types of windows have been calculated in Table 9. The opening configuration is always the double area (0.05m^2, 0.10m^2 and 0.20m^2), however the inverse square law is not apparent in any of the different configurations of windows.

The configurations E, D-1, A-1 and D-2 are increasing 2dB for a double distance. D-1 and D-2 have a rectangular configuration, this can explain the nearest from the inverse square law, and E and A-1 are one of the bigger opening distance before D.

- *Angle of source incidence*

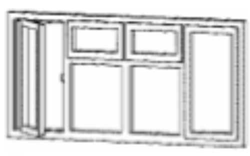
The effect of the angle of incidence on the resulting insulation was tested using five loudspeakers positions arranger to -70º, -35º, 0º, +35º and +70º.

Calculations have been carried out to show the angles of source incidence for every type of window (*see Appendix 2*). *Appendix 2* show the *Weighted Standardised Level Difference* from every window configuration and also has been graphed to show the sound insulation effect through the angle of source incidence and the opening configuration. .

In order to assess the effect of the angle of source incidence and simplify the report, the study has been focused in two windows configuration.

Two specific window configurations have been chosen because they have the least similarity between them. They are made with the same window frame material, PVC(u) but they have different opening configurations so they will have a different sound insulation effect. The A-1 window is describing as outward opening casement- left hand side and the D-1 window as sliding sash upper section open.

A-1 window configuration:



	-70°	**-35°**	**0°**	**+35°**	**+70°**
125	25,5	24,3	22,2	22,8	22,7
250	24,3	22,5	21,5	20,3	20,8
500	20,8	20,2	20,1	20,2	23,2
1k	17,4	23,0	21,8	24,0	23,5
2k	22,7	19,7	20,0	20,9	27,7
4k	20,9	22,4	23,1	24,2	27,5

Table 10. Window A in a size of 0.05m^2 of window area. DnT in octaves-band

Fig. 15 show the apparent façade insulation to be strongly depend on the source angle and, that the response is symmetric with insulation minima generally observed at normal incidence.

There are five angles of the source incidence -70º, -35º, 0º, +35º and +70º . The positive angles are on the right side and the negative angles are in the left side.

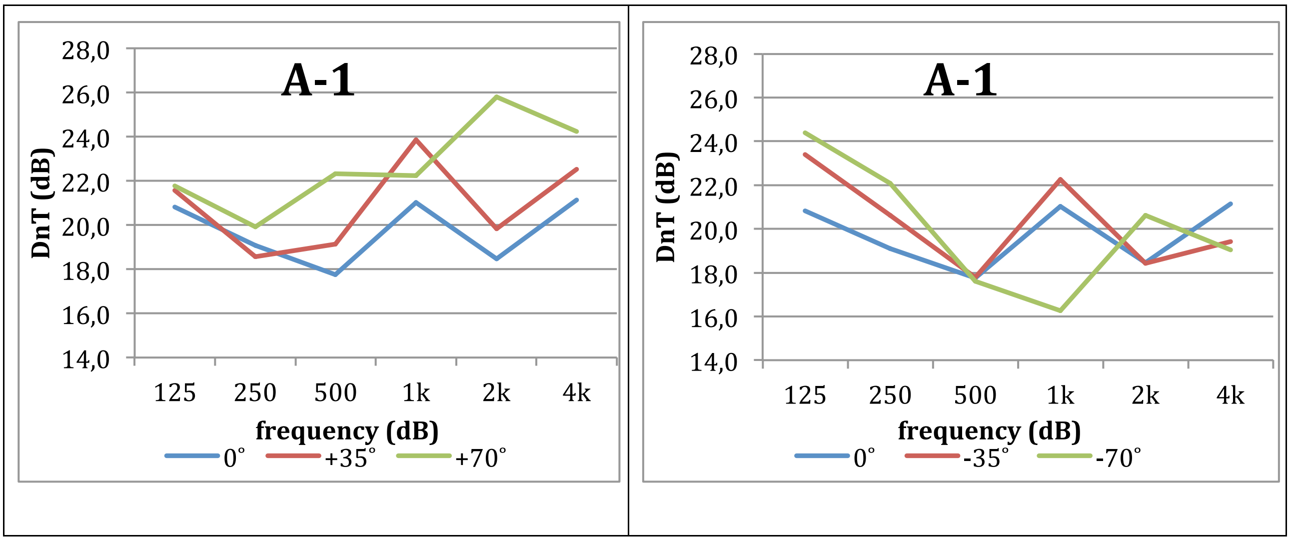


Fig.15. Window A-1. Right (positive) and Left side (negative)

Due to asymmetry in configuration A-1, the source angle at -70º to the window has more free area opened than in the position at +70º, and consequently is a worse result. In +70º the window behaves as a barrier and therefore produces a better result.

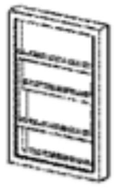
However, in low frequencies, the -70º position is working better than in +70º. This may be due to resonance build up within the system.

It is appearing the diffraction effect in low frequencies and in high frequencies the waves patron is the same like a barrier so the window is working such a barrier.

However, in low frequencies in -70º position is working better than in +70º. Maybe some resonances of the system can build up within the system.

For window D, tests were not carried out for all speaker positions. Data has therefore been repeated for angles beyond 90º, with the assumption that the response exhibited a symmetric pattern.

D-1 window configuration:



	-70˚	-35˚	0˚	+35˚	+70˚
125	26,3	26,5	26,3	-	-
250	25,7	20,7	19,0	-	-
500	24,0	21,3	17,1	-	-
1k	26,4	19,3	18,2	-	-
2k	28,9	20,7	19,1	-	-
4k	23,6	23,3	19,6	-	-

Table 11. Window D-1 in a size of $0.05m^2$ of window area. DnT in octaves-band

D-1 configuration is working like a hole. The sound insulation is better in the -70º position than in the 0º. The sound pressure in the centre is higher because the wave travels in a straight line.

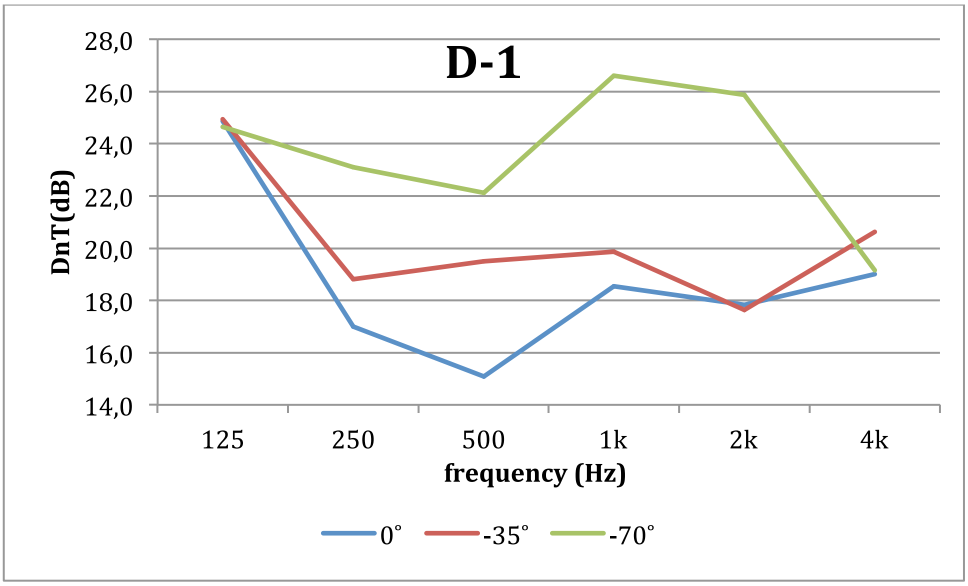


Fig.16. Window D-1

A-1 configuration window depends on the positive and negative angles of incidence of the source while the D-1 configuration depend only in part because of its symmetry. A-1 configuration appears to be producing diffraction within low frequencies, while creating a barrier type effect for higher frequencies.

- *Window frame/sales materials*

The effect of frame type on the measured level difference is shown in *Table 12*. Types tested included PVC-U and aluminium frames. At the same time of testing it was not possible to test a timber window of the exact same type as the PVC(u) and Aluminium frame types. Therefore *Table 12* includes the PVC (E) and Aluminium (F) frames for the same window in an area of 0.05m^2 open window.

	**125**	**250**	**500**	**1k**	**2k**	**4k**
PVCu (E)	27,0	20,6	25,2	20,6	21,2	25,0
Aluminium (F)	26,2	21,9	25,1	22,7	24,5	22,4

Table 12. Frame type. D_{nT} insulation

The window configuration has been made with a PVC(u) frame while the F configuration has been made with an Aluminium frame. Both windows have the same configuration window, a different frame has been used.

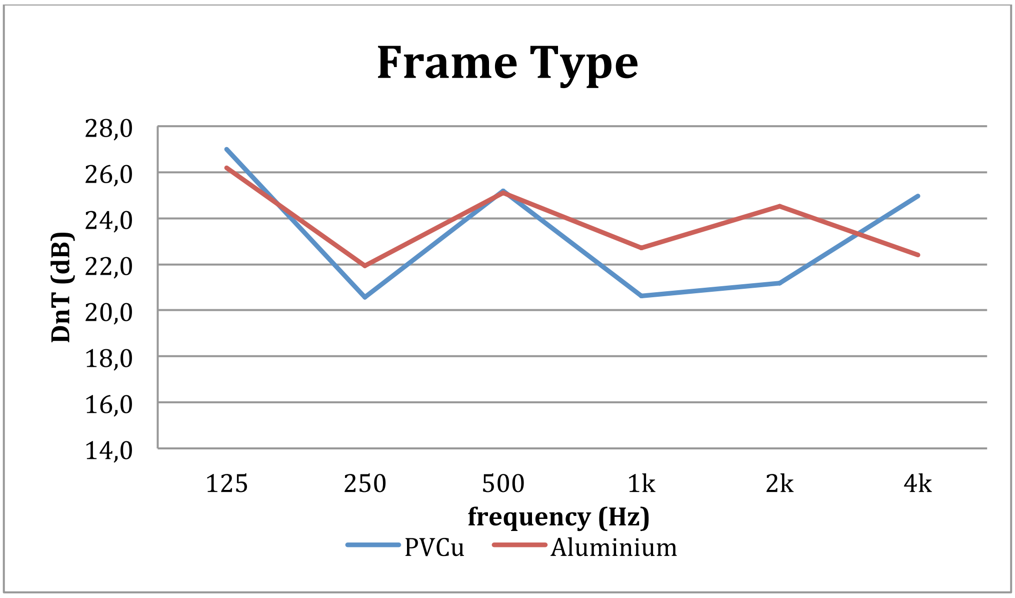


Fig.17. Frame Type

The Results show that the PVC frame type provides a better acoustic insulation performance than the Aluminium frame. However, in most configurations the PVC has been used more than the Aluminium.

Despite the lower sound insulation performance, PVC is typically more practical as it provides increased thermal performance and resistance to corrosion. It comes from the shape of the window, but we can not affirm it because there are not enough measurements made.

- *Acoustic room condition*

Five district room conditions were used to assess the variation in the sound insulation result for the façade. The room changes were created by introducing soft material into the receiver room from condition *D0*, corresponding to the base condition with only bare surfaces exposed. D1 included a soft floor covering, *D2 and D3* included curtains whilst condition *D4* incorporated absorptive material usually used within the anechoic chamber. *Table 13* shown the reverberation time in receiver room in octaves-bands in order to each absorbent condition.

	D0	**D1**	**D2**	**D3**	**D4**
125 (Hz)	0,75	0,80	0,81	0,80	0,49
250 (Hz)	1,05	0,66	0,61	0,60	0,28
500 (Hz)	1,47	0,59	0,54	0,53	0,30
1000 (Hz)	1,49	0,77	0,68	0,64	0,36
2000 (Hz)	1,34	0,79	0,62	0,62	0,31
4000 (Hz)	0,98	0,61	0,49	0,49	0,28

Table 13. Reverberation Time in the receiver room.

A description of the receiver room condition is explained:

D1: soft floor covering

D2: soft floor covering + light curtains

D3: soft floor covering + light curtains + curtains closed

D4: soft floor covering + curtains closed + heavy curtains + absorbent wedges

III.5. CONCLUSIONS

Analysis has been performed on the measurement results to rationalise them into a more functional format and to better quantify each physical variable under consideration.

The analysis is principally based on the measurements results for consider the specific parameters: window type/opening style, area of open window, size of window area, angle of source incidence, window frame/seals materials and acoustic room condition.

The insulation of several windows, have been analysed (see in Appendix 2). The variation range in the single figure weighted insulation results across the different opening styles is consistently between 4 and 6dB. There is therefore a significant affect attributable to the means of opening.

The window opening with the poorest sound insulating performance was Window B, a reversible centre pivoting window whose opening light twisted into the room to allow maintenance access. The method of opening creates the main air paths either side of the opening, these additionally form a channel with sound reflecting off the open light towards the room.

The results do not show any one opening style providing significantly better insulation characteristics. Instead the set of windows with an outward opening, which protects the open void from direct sound generally performed similarly well.

The set of windows with no extending opening lights, namely the inwards turn and tilt Window C and the sliding sash Window D, were also among the best performing open units particularly with angled sources of noise; The lack of an extending openings is potentially advantageous by avoiding further in-bound reflections which effectively reduce the level of noise transmitted through the opening compared to the outward opening windows. The turn and tilt window bettered the 'unprotected' sliding sash window when the source was normal in the façade.

There is a direct relationship between a windows area of opening and its characteristic level of acoustic insulation; larger openings provide poorer acoustic protection. This relationship does not however correlate to a logarithmic ratio of relative opening sizes, with measured weighted sound insulation differences in opening areas being limited to 1 and 2dB for open areas increases from $0.05m^2$ to $0.1m^2$ and from $0.1m^2$ to $0.2m^2$ respectively.

The analysis of source angle incidence found the weighted apparent sound insulation rating to have the lowest value with the source normal to the openings. The movement of the source to wider angles increased the level of insulation.

IV. NUMERICAL METHOD

IV.1. FINITE ELEMENT METHOD

The finite element method (*FEM*) is a numerical technique that allows the resolution problems of physics and engineering by describing a set of partial differential equations. The *FEM* performs a mathematical model that provides an approximate solution obtained from the assembly of independent solutions of the finite elements.

IV.1.1. GENERAL CONCEPTS OF METHOD

The steps against any finite element project are as follows:

STEP 1: Geometric space definition. This space will be called domain and it is where the system is analysed. This rule provides:

- Boundary conditions: known variables that influence the system to act a certain way

- Unknowns: System Variables that are desired (displacements, stresses etc.)

STEP 2: Discretization Domain: To resolve the problem, the finite element method individualizes the domain into small subdomains called elements. This process is called mesh generation. The elements consist of a discrete number of points, called nodes, which connect all the elements.

STEP 3: Calculation variables: The nodes are characterized by a finite number of parameters N, called degrees of freedom. When N goes to infinity, the finite element solutions converge to a solution that is independent of the model and solves the problem. The functions used to calculate equations can be linear or higher order polynomial depending on the geometric location of the nodes. The resolution of these equations is achieved through linear algebraic techniques.

STEP 4: Post-processing : Interpretation of the variables (unknowns) obtained from finite element analysis. In this step, it tests whether the design is responding in a coherent and can be seen that the model is valid. There will be a relationship between changes in design variables and the corresponding changes in the behaviour of the prototype.

IV.2. MODEL AND NUMERIC SIMULATION RESULTS.

In order to compare the experimental and numerical method, a Comsol model is going to be built with the same conditions that Napier University.

This first model is who sets if the numerical simulation performed by the Comsol Multiphysics software is valid and also the results are close to the experimental data as mentioned in the previous section.

To perform this comparison, we model the sample used in the laboratory with the same dimensions and geometry.

The following subsections is shown the modelling process and the results achieved.

IV.2.1. NUMERIC MODEL

The Comsol modelling process consists of the following parts:

- Pre-processing
- Processing
- Post-processing

Here are detailed each one of the bellow parts

1. *Pre-processing*
   - Geometry of the object: The first thing to be sought, is the existence of symmetry. Identify existing planes of symmetry and to define appropriate boundary conditions will significantly reduce the computational cost of the model. To reduce the computational time is necessary to identify symmetry within the problem.
     - Plane symmetry: The symmetry that produces a mirror. The problem can be reduced to half by means of a hard condition (u = 0)
     - Symmetry of revolution axisymmetric symmetry type. A 3D problem can be reduced to a 2D axisymmetric.
   - Dimensions: In Comsol Multiphisycs exists *1D, 2D, 3D* problems

Our model does not have any symmetry and a *2D* dimension is used. The geometry is using rectangles in order to build the model.

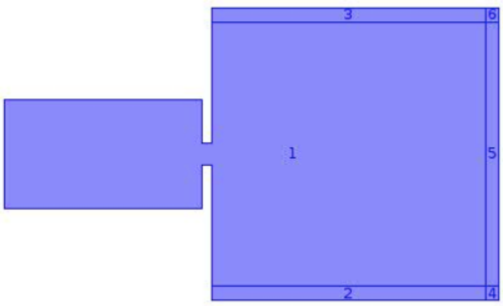


Fig.18. Geometry of the model.

2. *Processing*

- Study: It will conduct a study in harmonic regime.

- Interest frequencies: The frequencies of interest are those between 125Hz and 4000Hz. The experimental data are in third octave but to simplify the problem results have been converted to octave bands.

The results provided by Comsol are in octave bands with which conversions will have to be carried out to achieve third octave octaves bands for comparison with the experimental method.

- Mesh: The frequencies of interest influence the meshing of design, since with them and with the speed of sound is obtained the maximum and minimum wavelength and hence the size of the element according to the following relationship:

$$\lambda = \frac{c}{f} \tag{10}$$

where

λ is wavelength

c is velocity of sound ($340\, m/s$)

f is the interest frequencies.

In order to calculated the mesh length:

$$\Delta x = \frac{\lambda}{16}$$

There is a proportionality between the size of the mesh and the computational time. This model is going to use a commitment to division by 2, because if we use the 16 or 8 or 4 C Comsol program can not cover the computational cost. The maxim element size is:

$\Delta x = 0.0425$

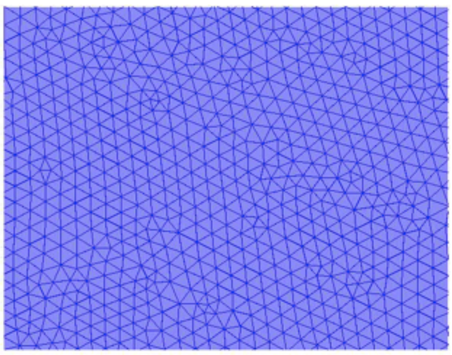


Fig.19. Maxim element size

3. *Post-processing*
   - Pressure Acoustics: In this mode, sound pressure levels in dB are modelled to achieve the finals result. Below are the boundary conditions that have been used to implement the model:
     - Sound Hard Boundary: The sound hard boundary is the Wall that is around the model.
     - Perfectly Matched Layers: Is utilised a Perfectly Matched Layer (PML) to obtain an absorption condition. PML is utilised around the source room because is an absorbent room.
     - Power Point Source: There are 5 point source (in blue) , *see in Figure 11,* that are acting independently. The power per unit length is 0.5W/m.

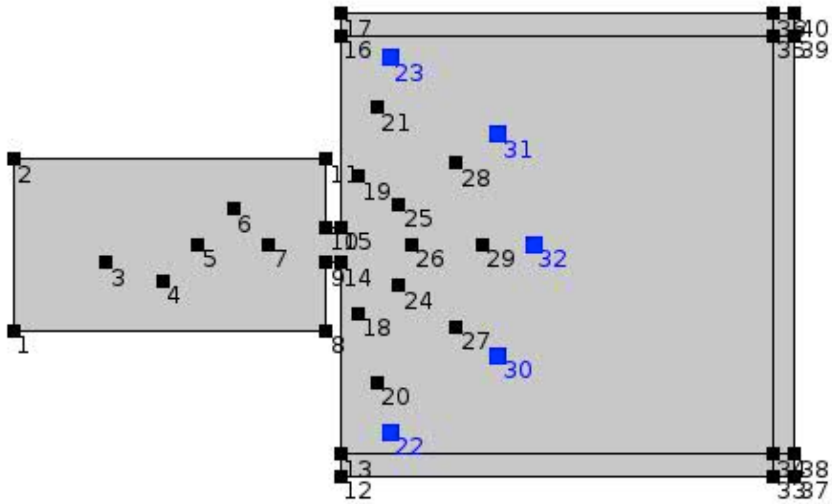


Fig.20. model with the loudspeakers and microphones in the receiver and source room.

Fig.20 illustrates the numerical model. The receiver room, reverberant, is shown with 5 receiver microphones in black, while the source room, absorbent, is shown with 5 source points in blue and 10 receivers microphones in black, that are acting two off them when are opposites to the loudspeaker that is working.

IV.2.2. RESULTS OF THE NUMERICAL MODEL

0.10m² opening area:

The simulation of the Comsol model has been analysed for the window configuration D-1 which is a sliding sash upper section open and a free area configuration of $0.10m^2$ and $0.20m^2$. The analysis of the model in Comsol has been done in a range of frequencies between 125Hz and 4000Hz. In the *Appendix 3* is shown all the simulation for each frequency and opening area. In order to simplify the problem we are going to show the diagrams from the simulation models in the frequency 270Hz.

The effect of the angle of incidence on the resulting insulation has been tested using five loudspeaker positions (see figure 21 in blue) *L-70º, L-35º, L0º, L+35º,L+70.*

The following graphs show the diagrams for every angle of source in 270Hz for a 0.10m^2 of opening area:

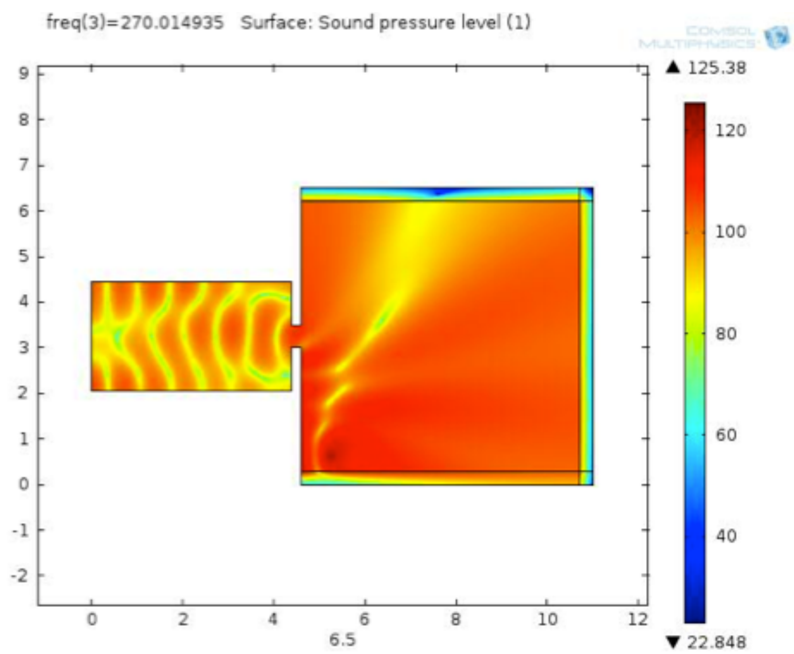


Fig.21. power point source in L+70º 0.10m^{2}opening area

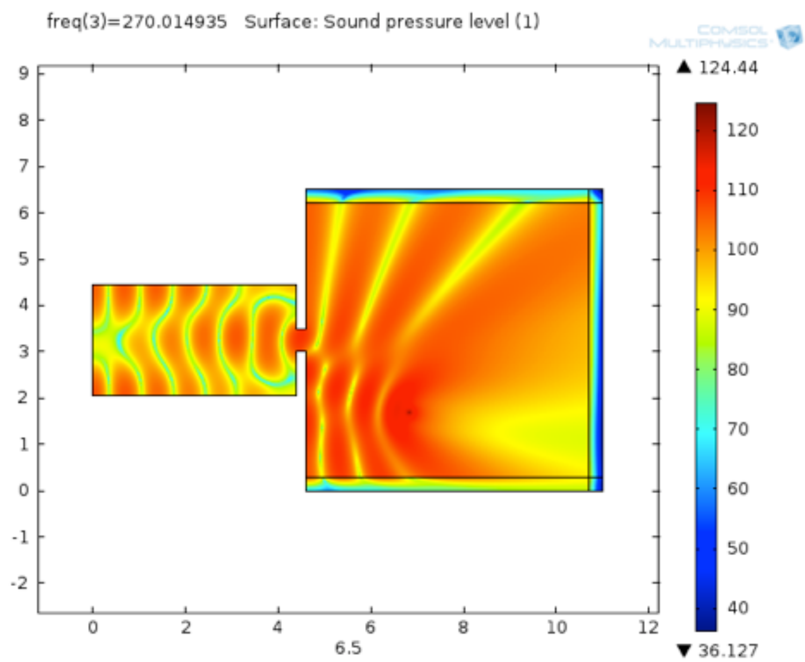


Fig.22. power point source in L+35º0.10m^{2}opening area

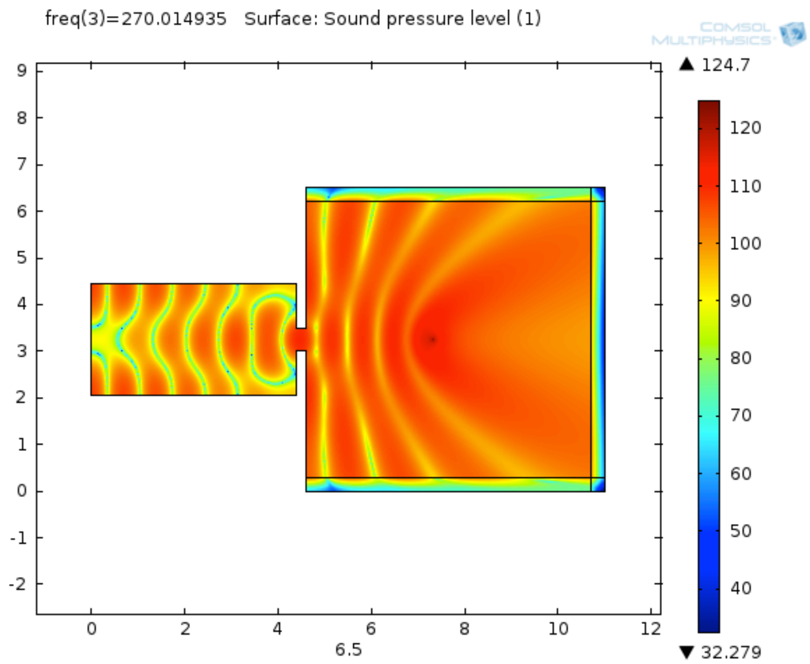


Fig.23. power point source in L0º 0.10m^{2}opening area

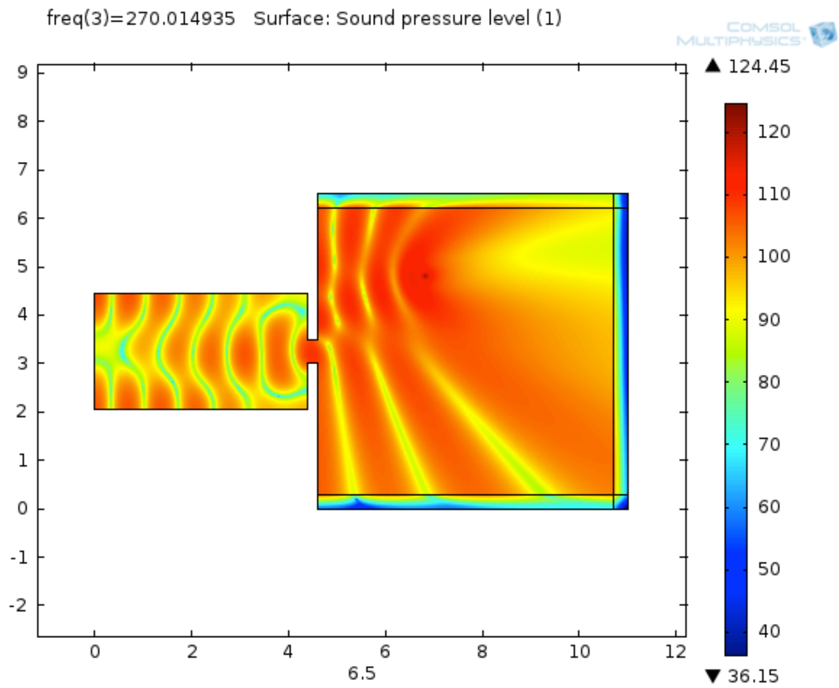


Fig.24. power point source in L -35º 0.10m^{2}opening area

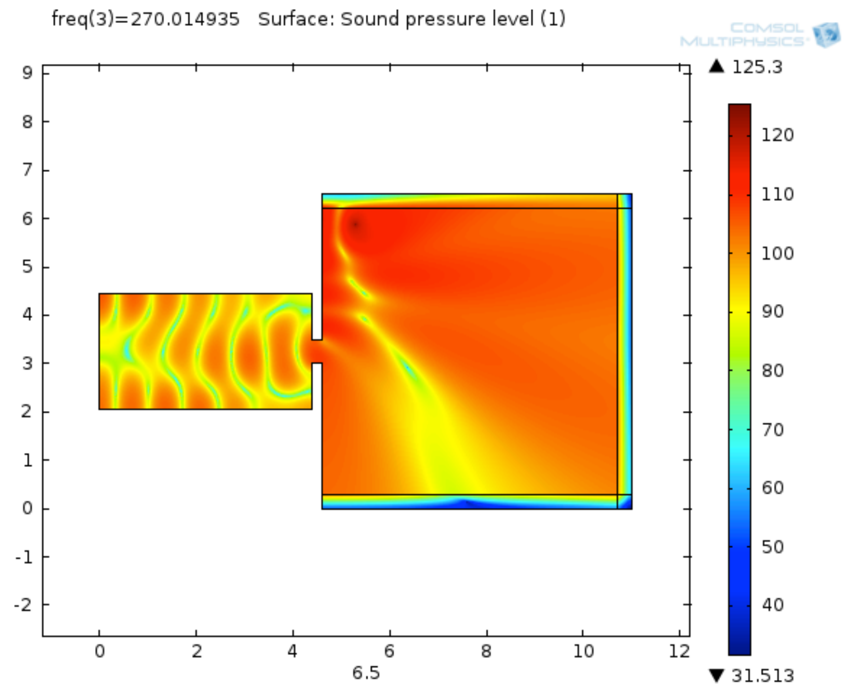


Fig.25. power point source in L -70º 0.10m^{2}opening area

The patterns observed in the last diagrams show the apparent façade insulation to be strongly dependent on the source angle, and, for the closed window case that the response is symmetric with insulation minima generally observed at normal incidences.

Analysis has been performed on the measurement results to rationalise them into a more functional format and to better quantify each physical variable under consideration i.e. window opening size, source directivity and frequency content of source.

0.20m^2 opening area:

A simulation has been carry out to compare the effect of the opening areas.

Three loudspeaker positions have been used *L0º, L+35º,L+70.* We have used three loudspeakers because there is a symmetry in the plane of the source incidence angle.

In the bellow simulation has been study the angle of incidence for every loudspeaker but in this case, we will study the tendency between them.

The following graphs show the diagrams for every angle of source in 270Hz for a 0.20m^2 of opening area:

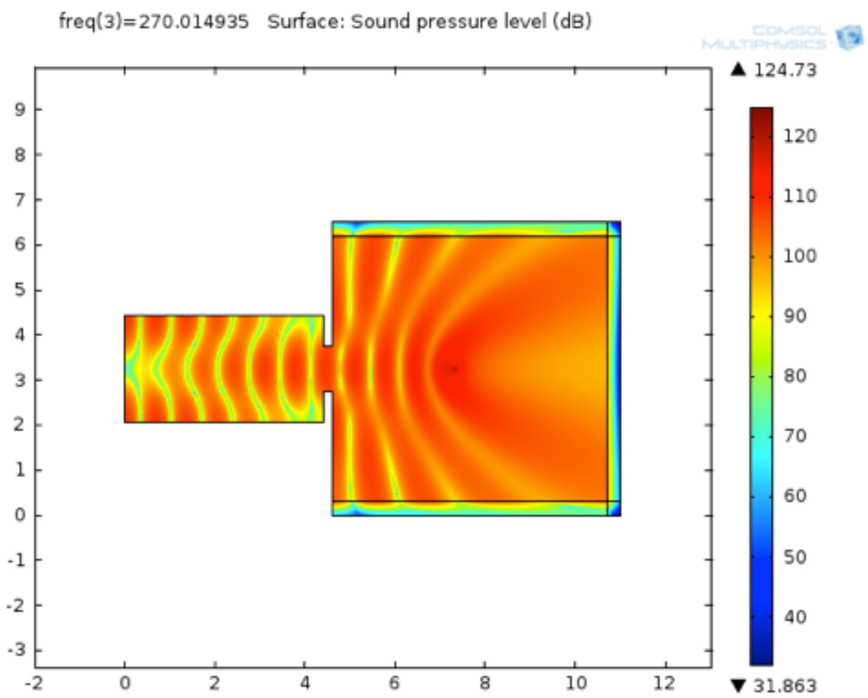


Fig.26. power point source in L0º 0.20m^{2}opening area

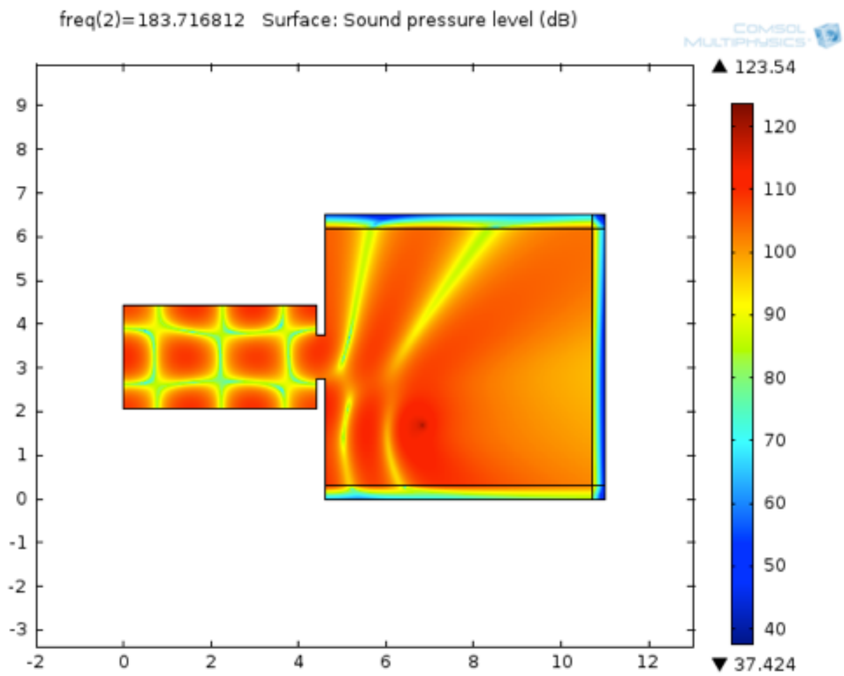


Fig.27. power point source in L35º 0.20m^{2}opening area

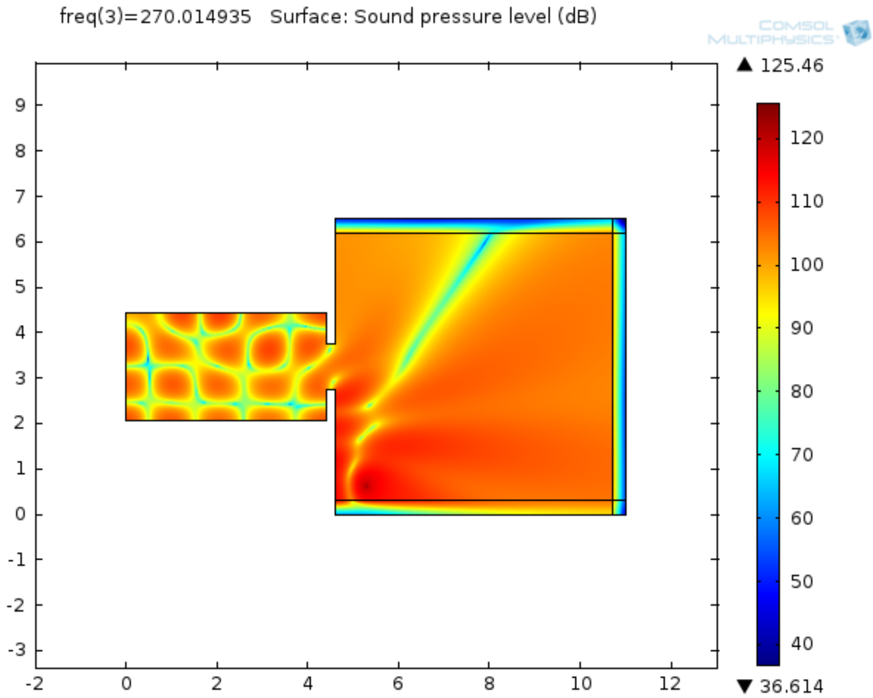


Fig.28. power point source in L75º 0.20m^{2}opening area

IV.3 EXPERIMENTAL AND NUMERICAL METHOD: COMPARISON

In this section is shown a comparison between the experimental and numerical method.

A numerical analysis has been done to obtain the results of the method in order to compare them with the below experimental method.

In order to compare both methods, The experimental results for window configuration D-1 is shown in the following Table 14:

	-70˚	**-35˚**	**0˚**	**+35˚**	**+70˚**
125	-	-	24,9	24,9	24,6
250	-	-	17,0	18,8	23,1
500	-	-	15,1	19,5	22,1
1k	-	-	18,5	19,9	26,6
2k	-	-	17,8	17,6	25,9
4k	-	-	19,0	20,6	19,1

Table 14. Experimental method from D-1 configuration window

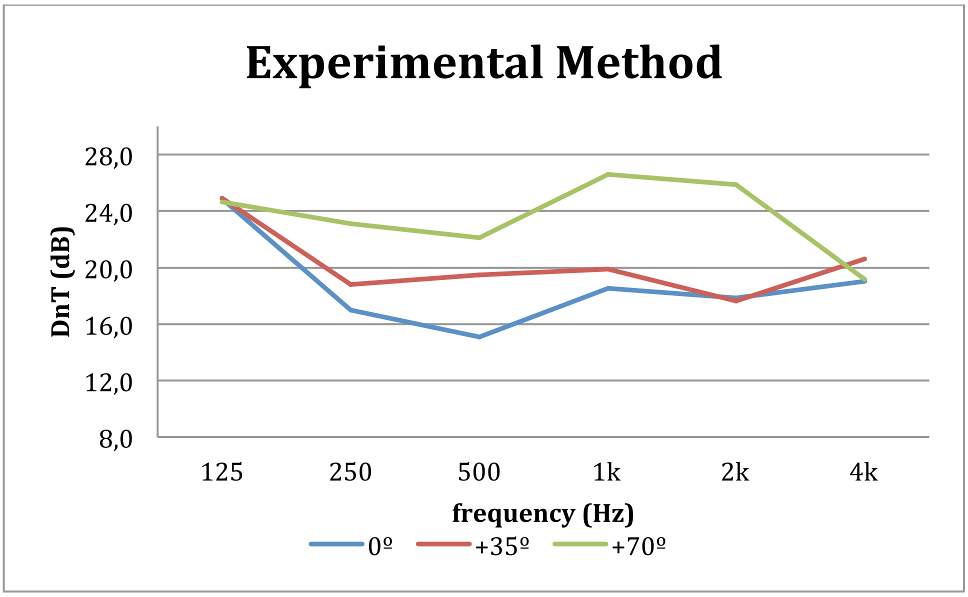


Fig.29. Experimental method

Fig.20. shows the points have been utilized to built the numerical model. In the source room there are five loudspeakers, source (blue) and 10 microphones, receiver (black). In the receiver room there are five microphones, receiver (black.).

To calculate the numerical D_{nT} were exported the sound pressure levels data for each points shown in Figure 20. Equation (4) has been used to calculate the value of D_{nT}. D0 and D4 reverberation time conditions have been taken because are they provide the largest difference between them. D4 is the most absorbent condition while D0 is the least absorbent.

Comsol Multyphysics calculations do not work in frequency bands., although it can produce a logarithmic scan, which can be applied to 10 frequencies between 125Hz and 4000Hz (10^range(log10(125),(log10(4000)-log10(125)/9, log10(4000)).

The experimental method is using frequency bands, an average between those frequencies have been calculated in order to show the octave band frequencies for the experimental and numerical method.

Comsol calculation is not working in frequencies bands. Comsol do a logarithmic scan and this model has done a scan for 10 frequencies between 125Hz and 4000Hz (10^range(log10(125),(log10(4000)-log10(125)/9, log10(4000)).

Comsol model show 10 frequencies. The experimental method is using frequencies, an average between those frequencies have done in order to show octaves band frequencies for the experimental and numerical method.:

125	183-270	396-583	857-1259	1851-2721	4000
125	250	500	1000	2000	4000

IV.3.1 OPENING AREA: 0.10m²

D_{nT} values for the D4 test results are shown in the followings tables. The results of the numerical method in octaves bands have been calculated through the pressure level points in the source and receiver room.

DnT (dB)			
	0º	**+35º**	**+70º**
125	11,5	14,9	7,6
250	11,8	10,5	9,0
500	4,2	3,1	8,5
1k	11,4	9,7	11,0
2k	12,4	11,8	9,9
4k	9,9	10,8	11,4

Table 15. Standardised Level Difference in every source angle.

The numerical results are not exactly the same than the experimental method. As we can see the amplitude is smaller, for this reason a shifting has been done for all the numerical data with a constant to compare if both method are following the same tendency.

	0º	**+35º**	**+70º**
125	24,9	24,9	24,6
250	25,2	20,5	26,0
500	17,6	13,1	25,5
1000	24,8	19,8	28,0
2000	25,7	21,8	26,9
4000	23,2	20,8	28,4

Table 16. Numerical data shift

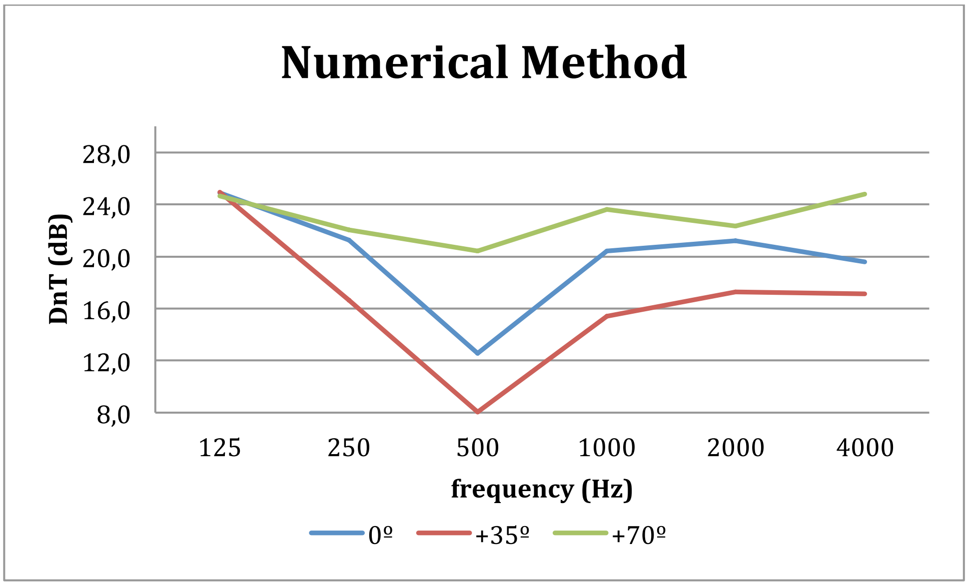


Fig.30. Numerical method

To conclude with this chapter a comparison between Experimental and Numerical Method has been carried out:

In this section we are going to Compare both method for every angle source position:

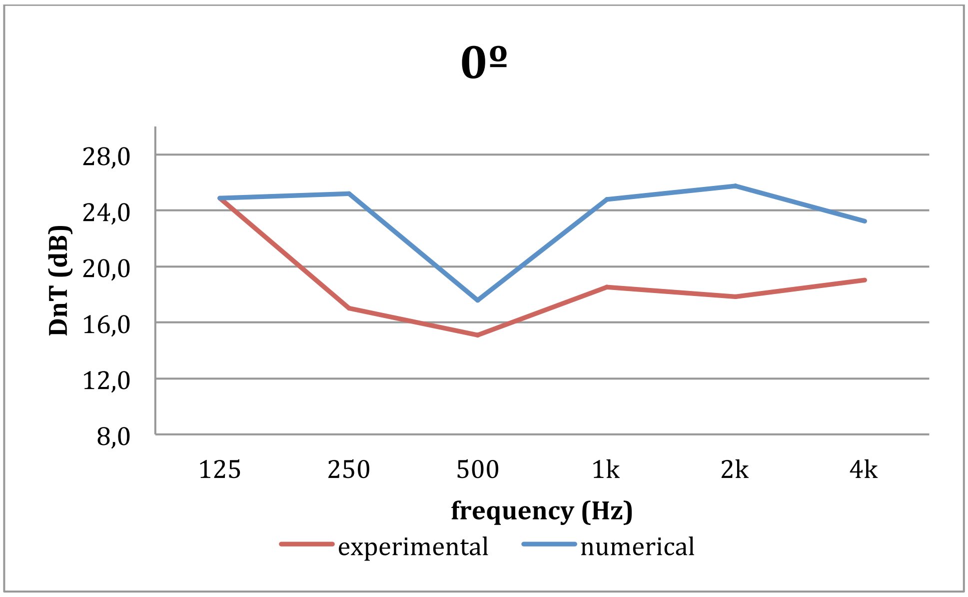


Fig.31. Experimental and numeric method comparison from a source angle of 0º

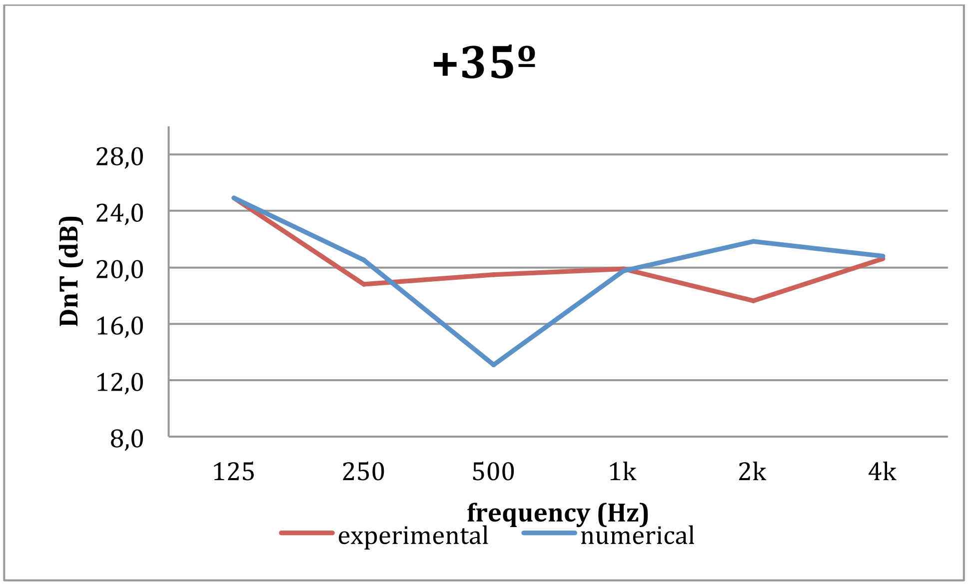


Fig.32. Experimental and numeric method comparison from a source angle of +35º

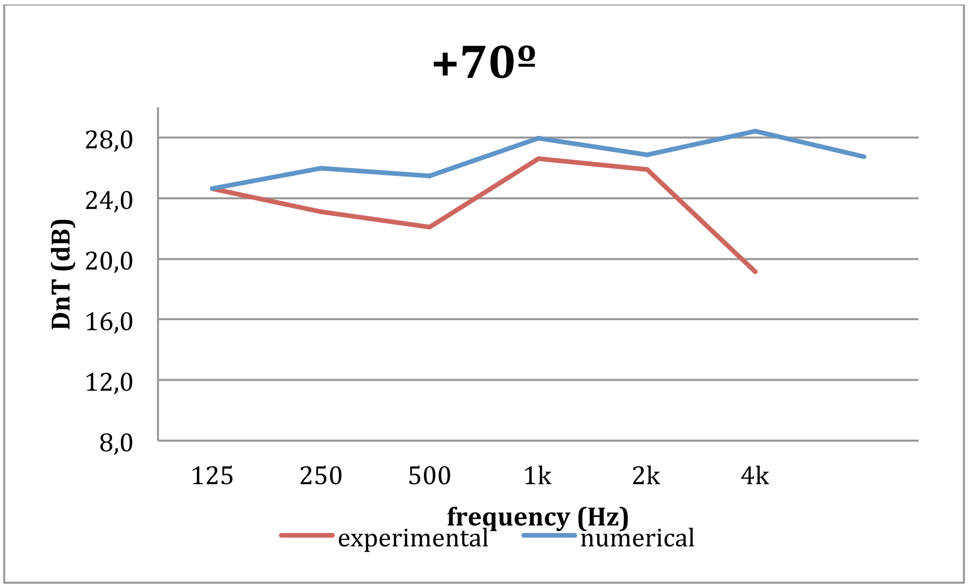


Fig33. Experimental and numeric method comparison from a source angle of +70º

In the graphs we can see that there is a symmetry in +35 ° and -35 °, this should happen in the same position of +70 ° and -70 °, but possibly not with the same effect because the receiver positions are not the same height for each position microphone.

500Hz is noted that there is a resonance which may be due to diffraction.

IV.3.1 OPENING AREA: 0.20m²

Here is the analysis for the opening area of 0.20m². A shifting has been done, because it is happening the same as the 0.10m² opening area result simulation. The amplitude is not helping in the results.

	0º	+35º	+70º
125	6,2	9,9	11,0
250	10,0	7,3	4,9
500	5,9	2,7	11,4
1000	14,2	13,5	11,5
2000	0,2	8,4	10,9
4000	2,5	6,0	10,7

Table 17. Standardised Level Difference in source angle.

	0º	+35º	+70º
125	24,9	24,9	24,6
250	28,6	22,3	18,6
500	24,6	17,7	25,1
1000	32,8	28,5	25,2
2000	18,9	23,4	24,6
4000	21,2	21,0	24,4

Table 18. Numerical data shift

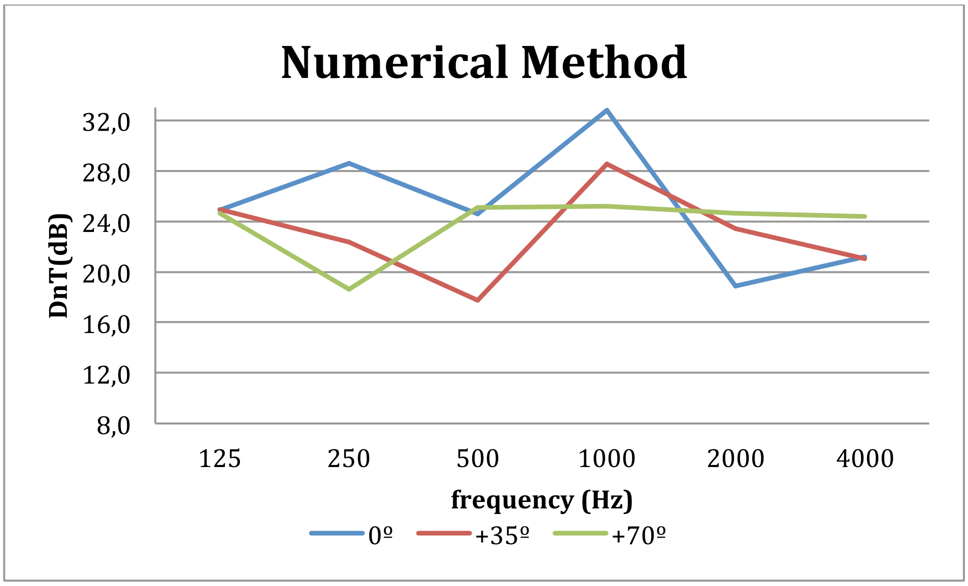


Fig.34. Numerical method

We are going to compare both numerical experiments in the opening areas for 0.10m^2 and 0.20m^2 for the angle source incidence in 0º, +35º and +70º in order to observe the tendency they are following:

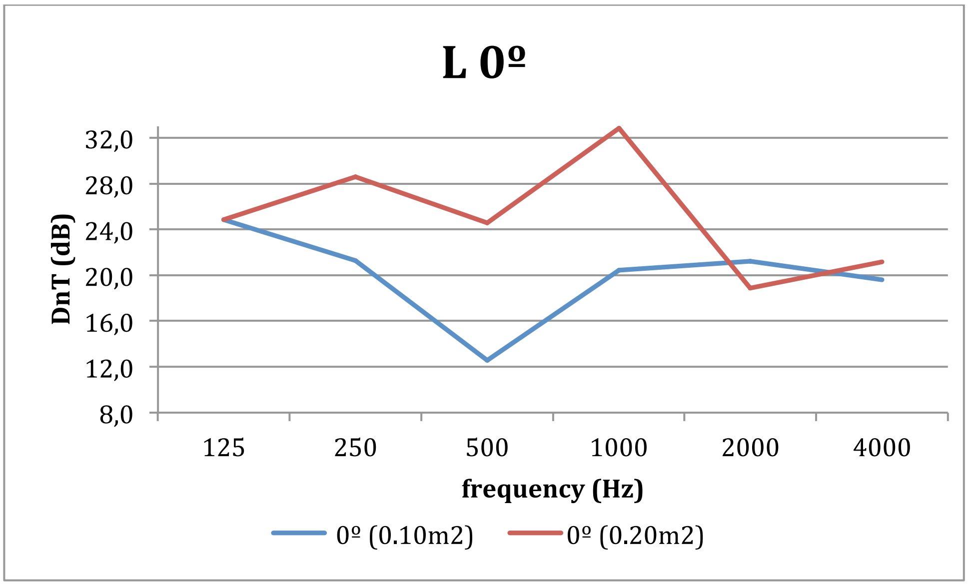


Fig.35. Numerical method comparison from a source angle of +0º

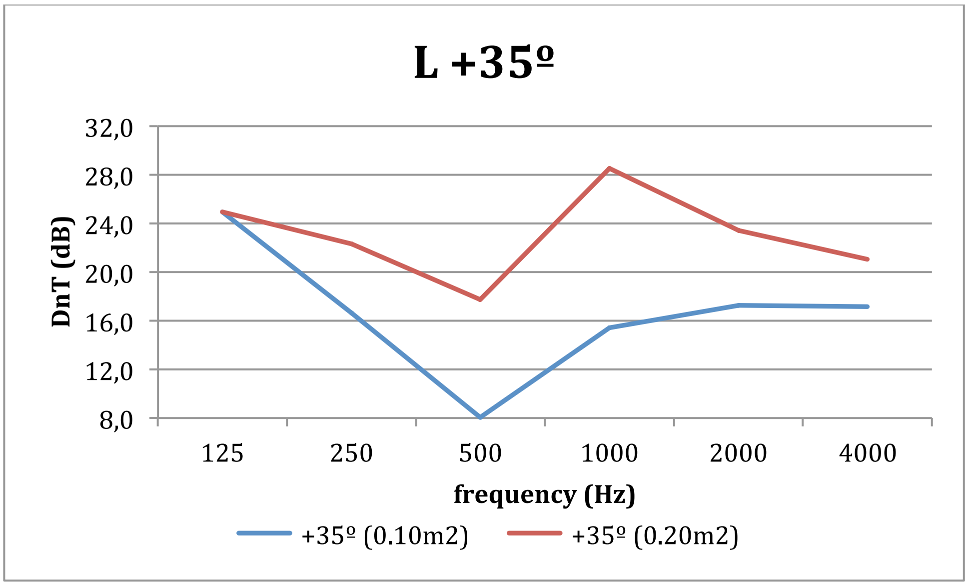


Fig.36. Numerical method comparison from a source angle of +35

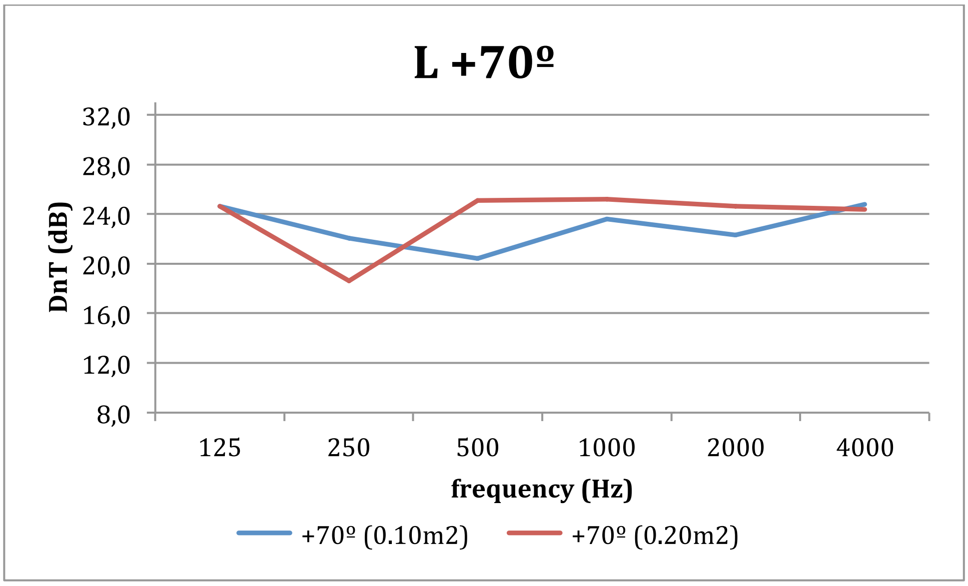


Fig37. Numerical method comparison from a source angle of +70º

A shifting has been done for the numerical results in order to compare the tendency between experimental and numerical method because the insulation valour amplitude is not helping us in the numerical method.

Independently of the amplitude, a tendency is following in 0º and +35º, a resonance is happening in 500Hz in both opening area caused by the reflexion of the system. However, in +70º is observed the opening distance does not depend of the distance, the result is following a tendency and the amplitude is not changing. I t make sense because the angle source is in +70º so the source is further from the opening area window

IV.4. CONCLUSIONS

One of the objectives of this project was to compare two methods, the experimental and numerical. After comparing the numerical results with the experimental, we have realized that we have not achieved the results we expected. We have calculated the sound insulation in Comsol. We have used 2D modelling and built a model as same as the experiment performed.

The model has been simulated with similar contour conditions to the experiment but the numerical method does works however it can be improved in several aspects:

- The boundary conditions are not the same as the experiment was performed in 3D while our model is 2D, so affect the positions x, y, z.

- Comsol do not works with octave bands. The experimental results have been made in octave bands while the numerical results were made using a logarithmic sweep and then we have calculated an average to obtain octave bands.

-TR has been used experimentally to obtain the numerical DnT. The conditions are totally reverberant receiving room and in our model we used the reverberation time used in the experimental method.

To compare the results we have plotted the experimental and numerical results and as you can see they do not follow the same pattern.

The conclusion is that if we use the 2D model can not get the same experimental results but we can study the effects that are produced in different setups.

Moreover, a comparison between the opening areas for 0.10m2 and 0.20m2 has been carried out. The tendency is not following in the position 0º and +35º but in +70º we can observed that the tendency is pretty much similar.

We can conclude that the numerical model is not helping to obtain a valour to the window insulation, but its useful to study the physic effect is happening in the several windows.

ACKNOWLEDGEMENT

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REFERENCES

[1] Open/Closed window research. The building performance Centre. School of the built environment Napier University (2007).

[2] Acoustics and Noise Control. R. J. Peters. B.J. Smith

[3] Fundamentals of Acoustics Lawrence E. Kinsler. Austin R. Frey. Alan B. Coppens, James V Sandes.

[4] Sound Insulation of an open window: Novel measurement to achieve ventilation and sound insulation by Gavin Irvine

[5] Sound Insulation. Carl Hopkins.

[6] Sustainable Acoustics. Sustainable Acoustics scheme designs from MachAcoustics. Ze Nunes (2011).

[7] The measurement os airborne sound insulation using acoustic scale models by M.W. Simons

[9] Building Acoustics. Tor Erik Vigran

[10] Industrial Noise and Control. Lewis H. Bell. Douglas H. Bell.

[11] Noise Control from Concept to Apllication. Colin Hansen

[12] Apuntes de Aislamiento acústico en la edificación. Jesus Alba (2010).

[13] Insulating Buildings Against Aircraft Noise. Bradley, J.S.

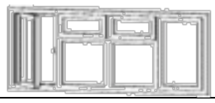
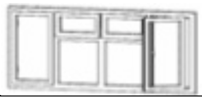
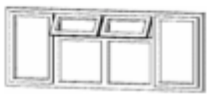
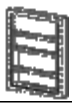
[14] Introducción al método de los elementos finitos. A. Carnicero,

[15] The finite element method: basic concepts and applications. Juan C. Heinrich,

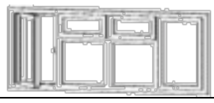
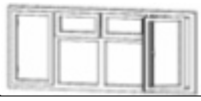
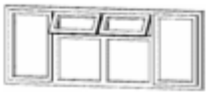
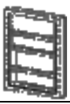
[16] Barna Aladár Szabó, "Finite element analysis". Ivo Bsabuska (2003)

APPENDIX

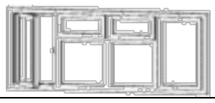
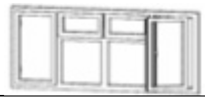
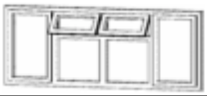
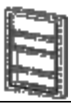
APPENDIX 1. Weight Level Difference is shown in the following tables:

	-70˚	-35˚	0˚	+35˚	+70˚	min	max	average
	21	21	21	22	26	21	26	23
	*26*	*22*	21	*21*	*21*	21	26	23
	-	-	20	-	-	-	-	13
	22	16	17	20	22	16	22	20
	-	23	19	-	23	19	23	20
	21	20	19	22	26	19	22	22
	*22*	*20*	19	20	22	19	23	21
	17	22	19	20	25	17	25	21
	27	21	19	*21*	*27*	18	27	24
	23	16	15	*16*	*23*	15	23	20
	25	19	18	*19*	*25*	17	25	22
	*27*	*25*	22	25	27	22	27	26
	*25*	*24*	24	24	25	23	25	24
	22	22	22	22	22	20	22	22

Weighted Level Difference. Open window (0.05m² free area).

	-70˚	-35˚	0˚	+35˚	+70˚	min	max	average
	19	20	20	21	24	19	24	21
	24	21	20	*20*	*19*	19	24	21
	-	-	19	-	-	-	-	12
	21	16	16	17	21	16	21	*19*
	*21*	21	18	*21*	21	18	21	21
	19	20	18	21	23	19	21	20
	*19*	*20*	18	20	19	18	22	19
	17	20	17	19	23	17	23	20
	25	19	18	*19*	*25*	16	25	22
	21	15	13	15	21	13	21	18
	22	17	16	17	22	15	22	20
	26	23	21	23	26	21	26	24
	24	22	22	22	24	21	24	23
	19	22	21	22	22	18	22	21

Weighted Level Difference. Open window (0.10m^2 free area).

	-70˚	-35˚	0˚	+35˚	+70˚	min	max	average
	17	17	18	20	21	17	21	19
	21	20	18	17	17	17	21	19
	17	-	17	-	-	-	-	13
	20	17	15	16	20	15	20	18
	18	18	16	18	18	16	19	18
	17	18	16	19	20	16	18	18
	18	18	16	18	18	16	20	18
	17	18	16	19	20	16	20	18
	23	17	17	17	23	15	23	20
	19	12	11	12	19	11	19	16
	21	16	14	16	21	14	21	19
	24	22	18	22	24	18	24	22
	23	20	20	20	23	19	23	21
	13	20	21	21	22	13	22	20

Weighted Level Difference. Open window (0.20m^2 free area)

APPENDIX 2. Standardised Level Difference in octaves-bands for each condition and for all type of window with every opening configuration.

WINDOW A

Window A-1. Outward opening casement-left hand side

Window A-1

Open Window (0.05m² free area)

	-70˚	-35˚	0˚	+35˚	+70˚
125	25,5	24,3	22,2	22,8	22,7
250	24,3	22,5	21,5	20,3	20,8
500	20,8	20,2	20,1	20,2	23,2
1k	17,4	23,0	21,8	24,0	23,5
2k	22,7	19,7	20,0	20,9	27,7
4k	20,9	22,4	23,1	24,2	27,5

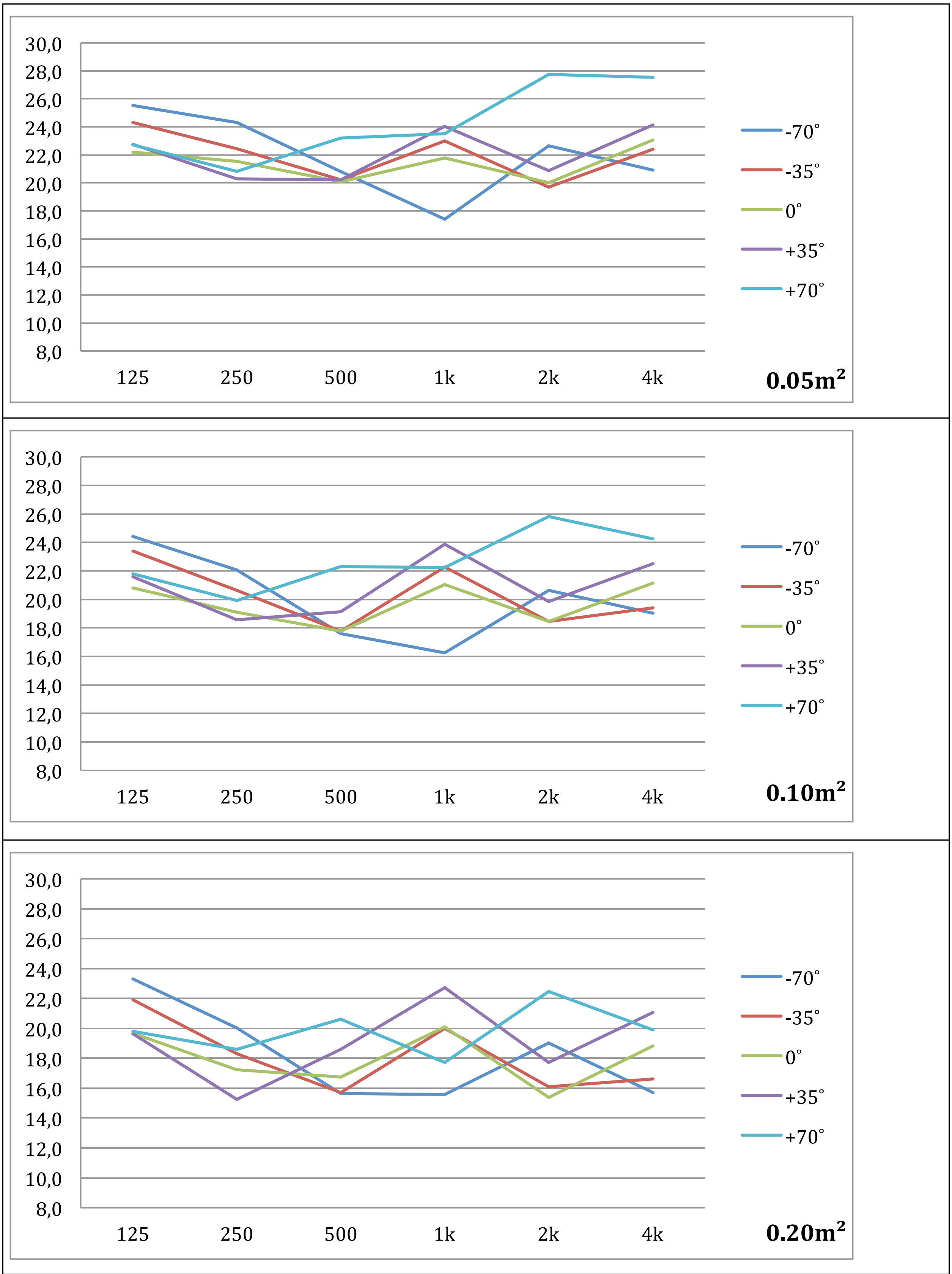
Open Window (0.10m² free area)

	-70˚	-35˚	0˚	+35˚	+70˚
125	24,4	23,4	20,8	21,6	21,8
250	22,1	20,6	19,1	18,6	19,9
500	17,6	17,8	17,8	19,1	22,3
1k	16,2	22,3	21,0	23,9	22,3
2k	20,6	18,4	18,5	19,8	25,8
4k	19,0	19,4	21,1	22,5	24,2

Open Window (0.20m² free area)

	-70˚	-35˚	0˚	+35˚	+70˚
125	23,3	21,9	19,7	19,6	19,8
250	20,0	18,3	17,2	15,3	18,6
500	15,6	15,7	16,7	18,6	20,6
1k	15,6	20,0	20,1	22,7	17,7
2k	19,0	16,1	15,4	17,7	22,5
4k	15,7	16,6	18,8	21,1	19,9

Standardised Level Difference in octaves-bands (dB)


30,0
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.05m²
0.10m²
0.20m²

Window A-2. Outward opening casement-right hand side

Window A-2

Open Window (0.05m² free area)

	-70˚	-35˚	0˚	+35˚	+70˚
125	22,7	22,8	22,4	24,3	25,5
250	20,8	20,3	21,8	22,5	24,3
500	23,2	20,2	19,8	20,2	20,8
1k	23,5	24,0	21,6	23,0	17,4
2k	27,7	20,9	20,6	19,7	22,7
4k	27,5	24,2	22,1	22,4	20,9

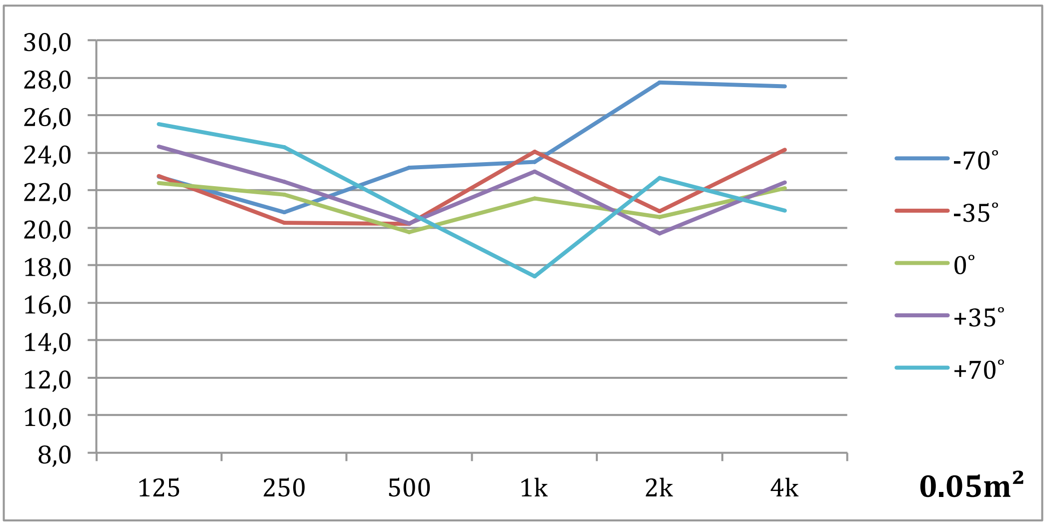
Open Window (0.10m² free area)

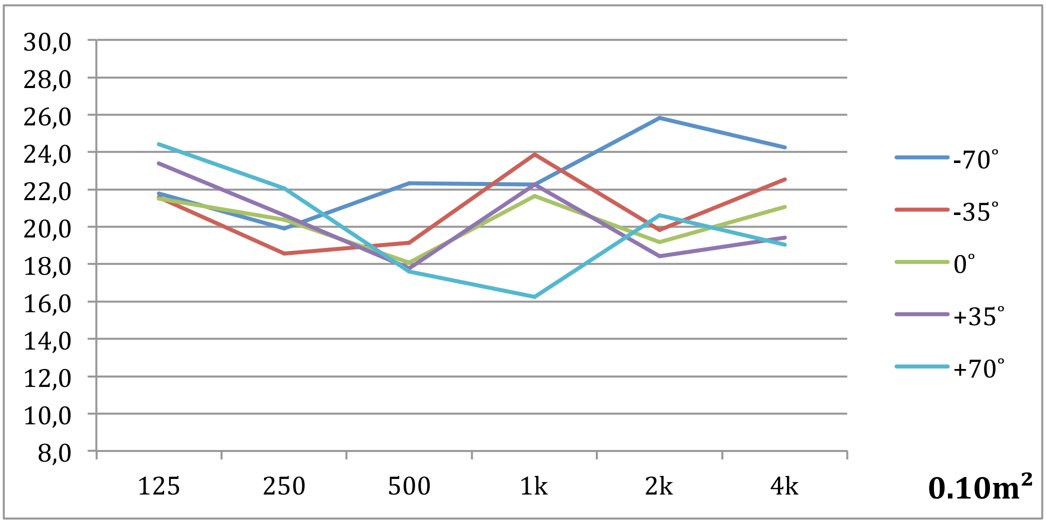
	-70˚	-35˚	0˚	+35˚	+70˚
125	21,8	21,6	21,5	23,4	24,4
250	19,9	18,6	20,4	20,6	22,1
500	22,3	19,1	18,1	17,8	17,6
1k	22,3	23,9	21,6	22,3	16,2
2k	25,8	19,8	19,2	18,4	20,6
4k	24,2	22,5	21,0	19,4	19,0

Open Window (0.20m² free area)

	-70˚	-35˚	0˚	+35˚	+70˚
125	19,8	19,6	19,9	21,9	23,3
250	18,6	15,3	17,7	18,3	20,0
500	20,6	18,6	16,2	15,7	15,6
1k	17,7	22,7	20,2	20,0	15,6
2k	22,5	17,7	15,5	16,1	19,0
4k	19,9	21,1	18,0	16,6	15,7

Standardised Level Difference in octaves-bands (dB)


30,0
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.05m²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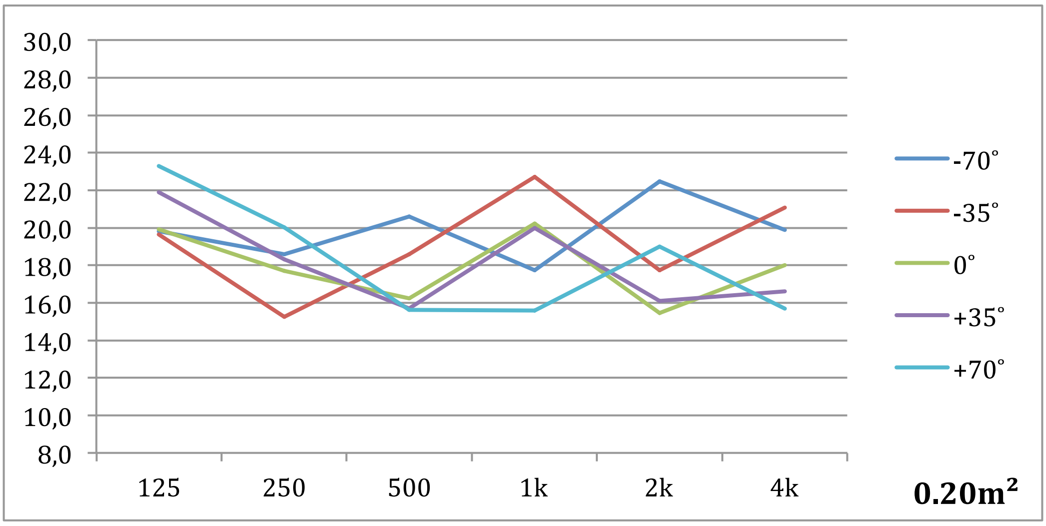
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.10m²


30,0
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.20m²

WINDOW B

Window B. Side swing reversible

Window B

Open Window (0.05m² free area)

	-70˚	-35˚	0˚	+35˚	+70˚
125	24,1	22,5	21,5	22,4	24,1
250	24,1	21,1	21,3	22,5	24,3
500	20,9	17,5	17,1	18,6	20,9
1k	17,8	18,0	18,7	19,3	18,6
2k	24,2	13,8	16,5	19,7	24,3
4k	28,1	23,4	20,2	22,2	26,5

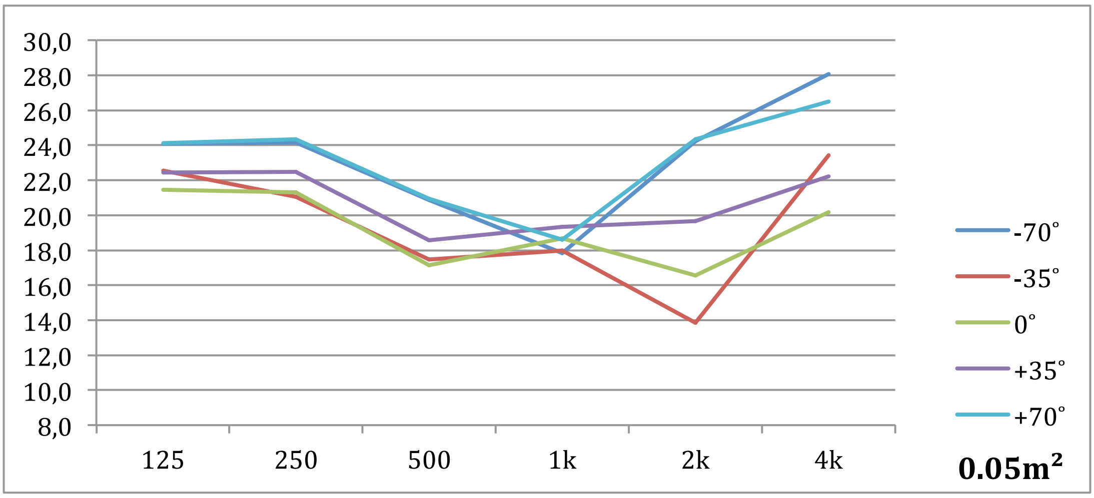
Open Window (0.10m² free area)

	-70˚	-35˚	0˚	+35˚	+70˚
125	23,0	21,2	19,9	20,9	23,0
250	23,0	19,7	19,7	21,4	23,3
500	19,5	17,6	16,4	17,7	19,8
1k	16,9	16,6	17,0	16,1	17,8
2k	23,2	12,9	14,4	14,8	23,3
4k	26,4	24,5	19,0	23,5	25,0

Open Window (0.20m² free area)

	-70˚	-35˚	0˚	+35˚	+70˚
125	21,6	19,2	17,6	19,0	21,7
250	21,5	18,1	17,4	19,5	21,7
500	17,8	18,0	15,5	17,7	18,0
1k	16,5	16,6	14,8	15,3	16,6
2k	22,6	16,6	14,1	14,3	22,0
4k	25,5	18,0	18,8	19,4	23,0

Standardised Level Difference in octaves-bands (dB)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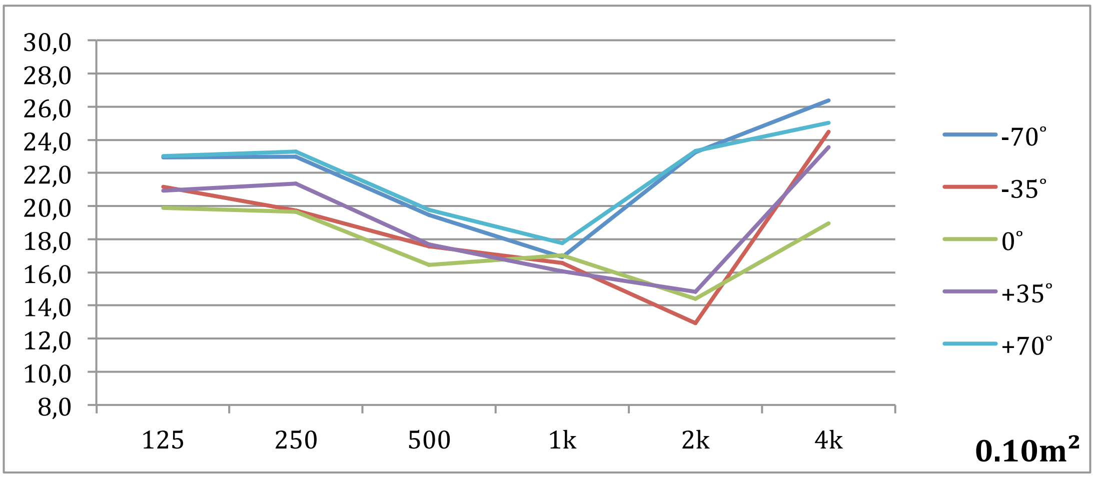
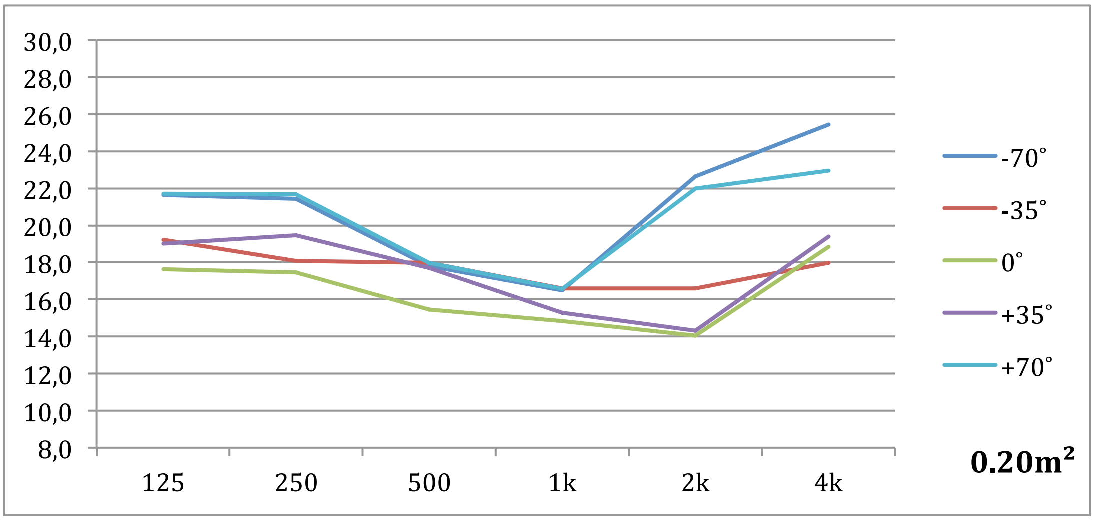
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.05m²


30,0
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.10m²


30,0
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.20m²

WINDOW C

Window C-1. Horizontal inward tilt

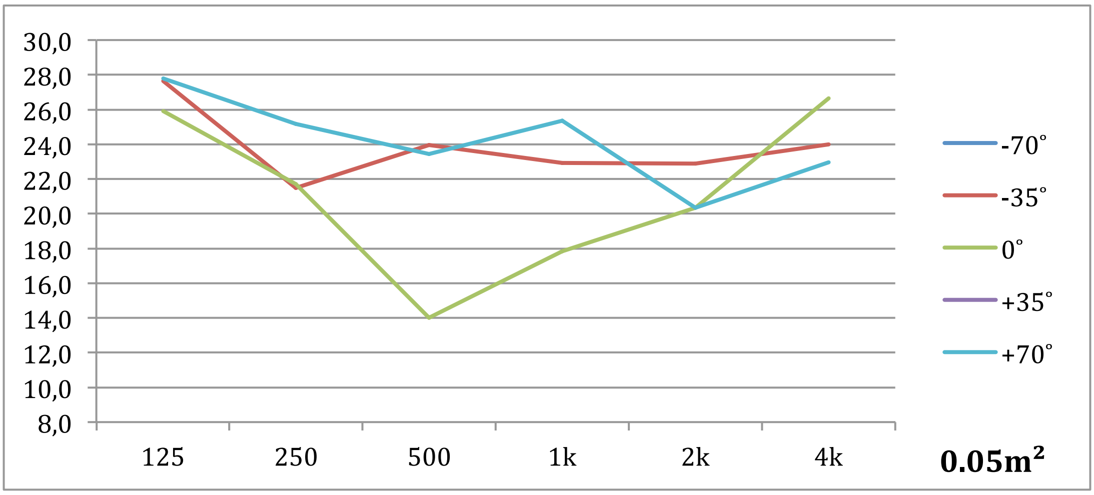
Window C-1

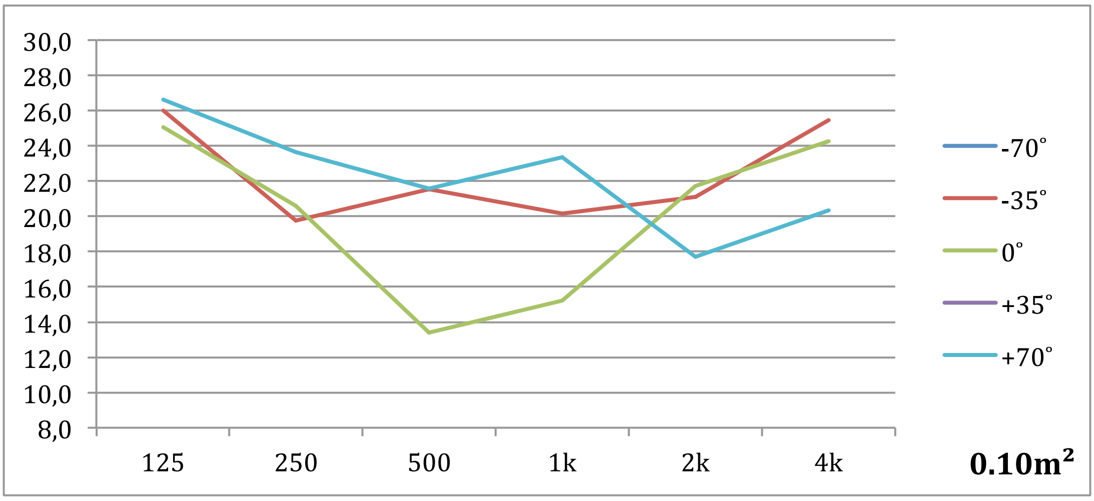
	Open Window (0.05m² free area)				
	-70°	-35°	0°	+35°	+70°
125	-	27,7	25,9	-	27,8
250	-	21,5	21,7	-	25,2
500	-	24,0	14,0	-	23,4
1k	-	22,9	17,8	-	25,4
2k	-	22,9	20,4	-	20,3
4k	-	24,0	26,7	-	23,0

	Open Window (0.10m² free area)				
	-70°	-35°	0°	+35°	+70°
125	-	26,0	25,1	-	26,6
250	-	19,7	20,6	-	23,6
500	-	21,5	13,4	-	21,6
1k	-	20,2	15,2	-	23,4
2k	-	21,1	21,7	-	17,7
4k	-	25,4	24,3	-	20,4

	Open Window (0.20m² free area)				
	-70°	-35°	0°	+35°	+70°
125	-	23,6	23,8	-	23,7
250	-	16,3	18,9	-	19,1
500	-	18,9	11,8	-	18,2
1k	-	14,6	12,2	-	17,2
2k	-	20,1	20,9	-	16,4
4k	-	21,8	23,9	-	21,2

Standardised Level Difference in octaves-bands (dB)


30,0
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.05m²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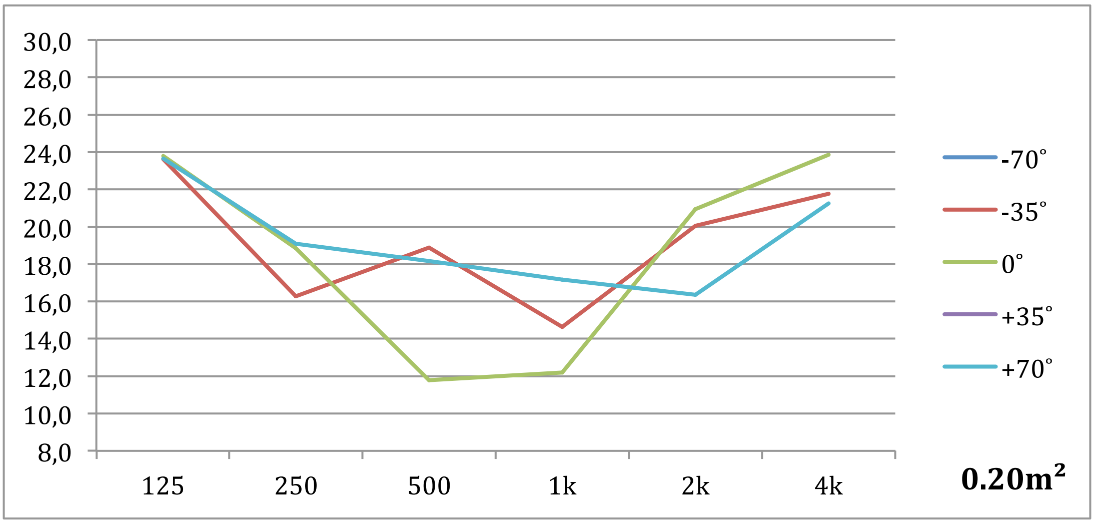
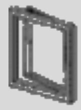
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.10m²


30,0
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.20m²

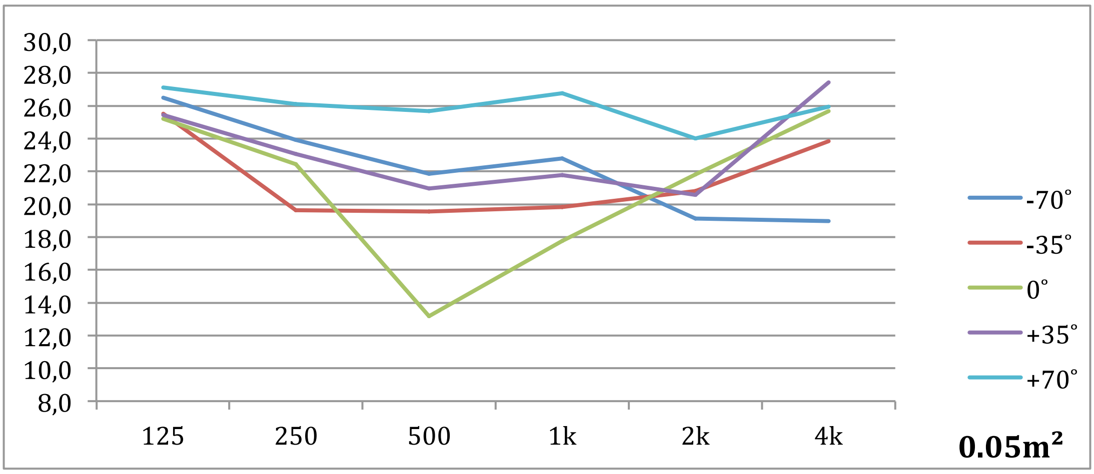
Window C-2. Vertical inward turn

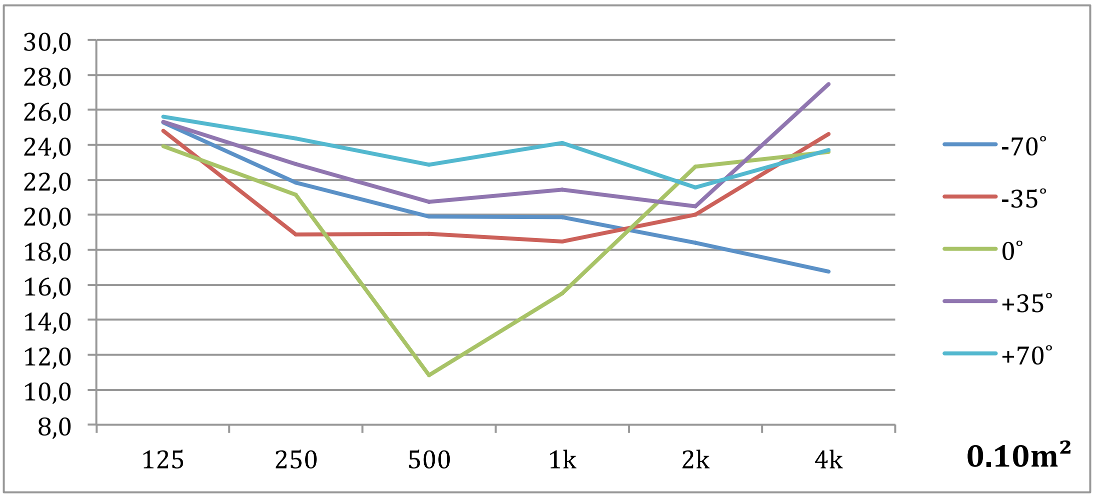
Window C-2

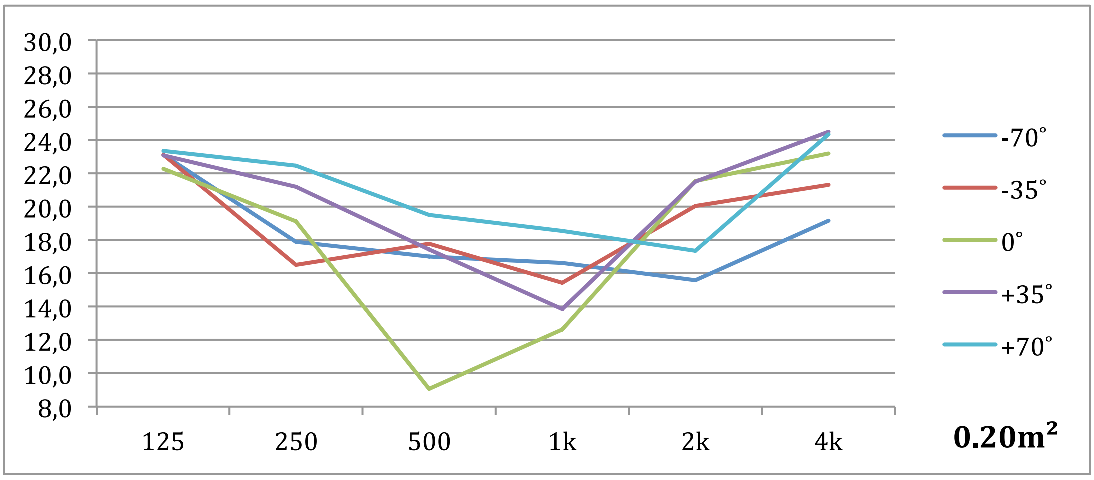


	Open Window (0.05m² free area)				
	-70°	-35°	0°	+35°	+70°
125	26,5	25,5	25,2	25,5	27,1
250	23,9	19,7	22,4	23,1	26,1
500	21,9	19,6	13,2	20,9	25,7
1k	22,8	19,8	17,7	21,8	26,8
2k	19,1	20,8	21,8	20,6	24,0
4k	19,0	23,8	25,7	27,4	25,9
	Open Window (0.10m² free area)				
	-70°	-35°	0°	+35°	+70°
125	25,3	24,8	23,9	25,3	25,6
250	21,8	18,9	21,1	22,9	24,4
500	19,9	18,9	10,8	20,7	22,9
1k	19,9	18,5	15,5	21,4	24,1
2k	18,4	20,0	22,7	20,5	21,6
4k	16,8	24,6	23,6	27,5	23,7
	Open Window (0.20m² free area)				
	-70°	-35°	0°	+35°	+70°
125	23,1	23,1	22,3	23,1	23,4
250	17,9	16,5	19,1	21,2	22,5
500	17,0	17,8	9,1	17,4	19,5
1k	16,6	15,4	12,6	13,9	18,6
2k	15,6	20,1	21,5	21,5	17,4
4k	19,2	21,3	23,2	24,5	24,4

Standardised Level Difference in octaves-bands (dB)

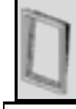

30,0
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.05m²


30,0
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.10m²


30,0
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.20m²

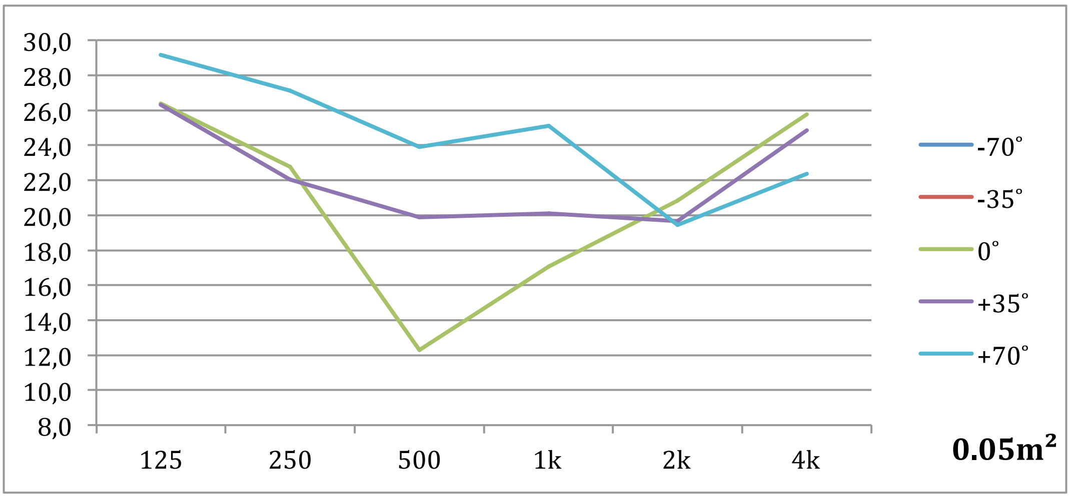
Window C-3. Laminate glass, bottom hung inwards tilt

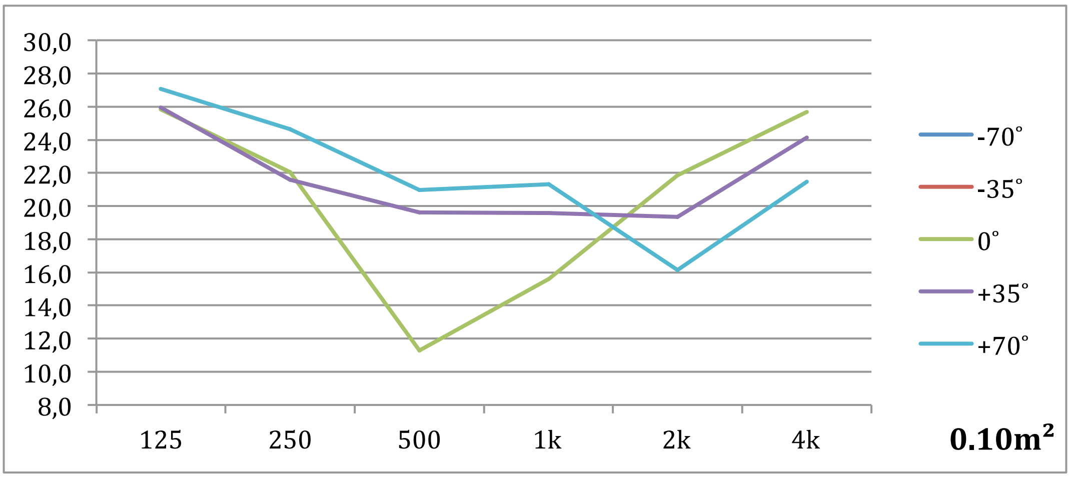
Window C-3

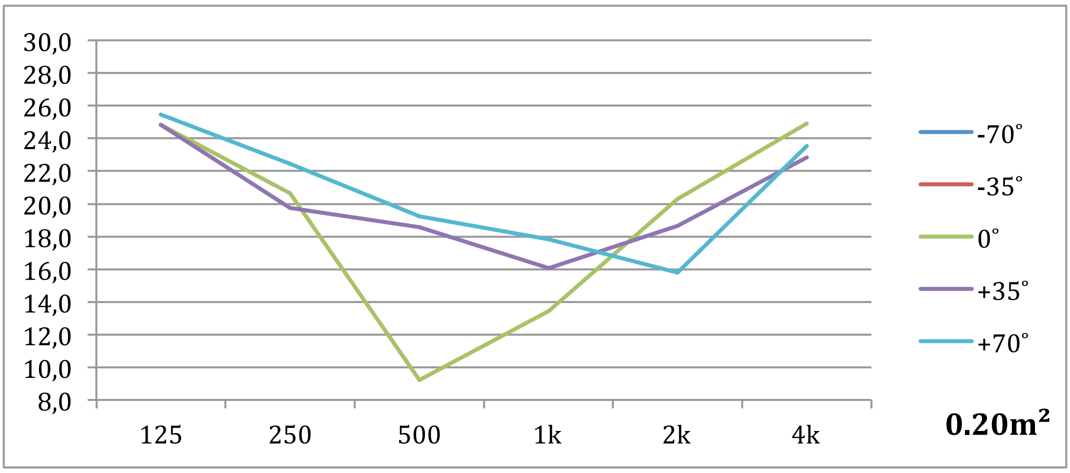


	-70°	-35°	0°	+35°	+70°
Open Window (0.05m² free area)					
125	-	-	26,4	26,3	29,2
250	-	-	22,8	22,1	27,1
500	-	-	12,3	19,9	23,9
1k	-	-	17,1	20,1	25,1
2k	-	-	20,8	19,7	19,4
4k	-	-	25,8	24,8	22,4
Open Window (0.10m² free area)					
	-70°	-35°	0°	+35°	+70°
125	-	-	25,9	26,0	27,1
250	-	-	22,0	21,6	24,7
500	-	-	11,3	19,6	21,0
1k	-	-	15,6	19,6	21,3
2k	-	-	21,9	19,3	16,1
4k	-	-	25,7	24,1	21,5
Open Window (0.20m² free area)					
	-70°	-35°	0°	+35°	+70°
125	-	-	24,8	24,9	25,5
250	-	-	20,6	19,7	22,5
500	-	-	9,2	18,6	19,3
1k	-	-	13,4	16,1	17,8
2k	-	-	20,3	18,6	15,8
4k	-	-	24,9	22,8	23,5

Standardised Level Difference in octaves-bands (dB)


30,0
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.05m²


30,0
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.10m²


30,0
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.20m²

Window C-4. Laminate glass, side hung inward tilt

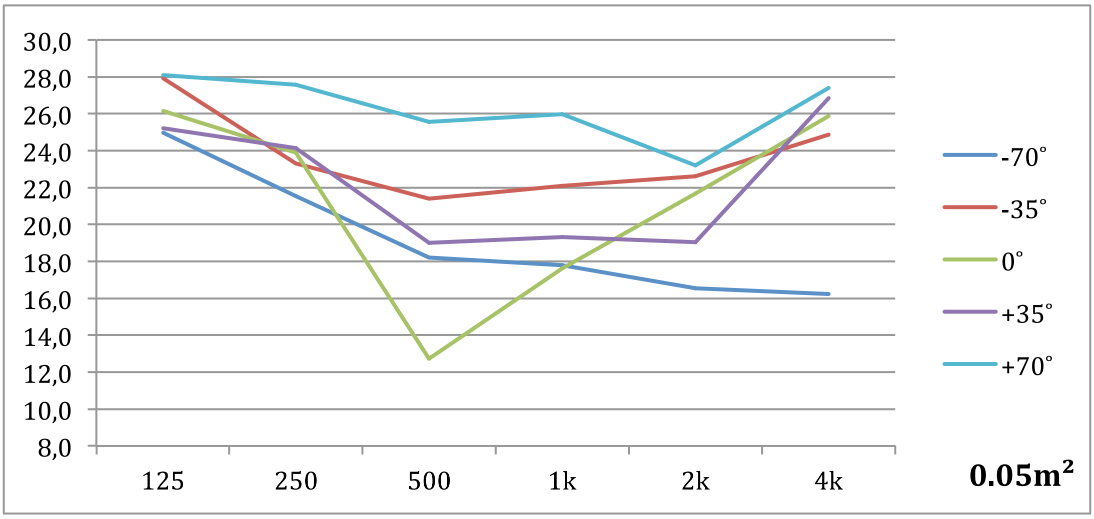
Window C-4

	Open Window (0.05m² free area)				
	-70°	-35°	0°	+35°	+70°
125	25,0	27,9	26,2	25,2	28,1
250	21,5	23,3	23,9	24,2	27,6
500	18,2	21,4	12,7	19,0	25,6
1k	17,8	22,1	17,6	19,3	26,0
2k	16,5	22,6	21,7	19,0	23,2
4k	16,2	24,9	25,9	26,8	27,4

	Open Window (0.10m² free area)				
	-70°	-35°	0°	+35°	+70°
125	24,4	26,5	24,8	26,0	26,9
250	20,2	21,7	22,5	21,6	26,3
500	17,3	19,2	9,8	19,6	23,9
1k	17,1	20,2	15,3	19,6	24,0
2k	15,6	20,6	22,5	19,3	21,4
4k	18,6	23,8	23,2	24,1	25,2

	Open Window (0.20m² free area)				
	-70°	-35°	0°	+35°	+70°
125	22,6	24,1	23,0	22,7	24,2
250	17,0	18,4	20,4	22,1	24,3
500	15,1	17,3	8,0	14,4	20,2
1k	15,6	15,8	13,0	16,4	17,4
2k	17,4	19,8	20,8	22,3	20,4
4k	20,9	21,1	23,3	24,6	26,2

Standardised Level Difference in octaves-bands (dB)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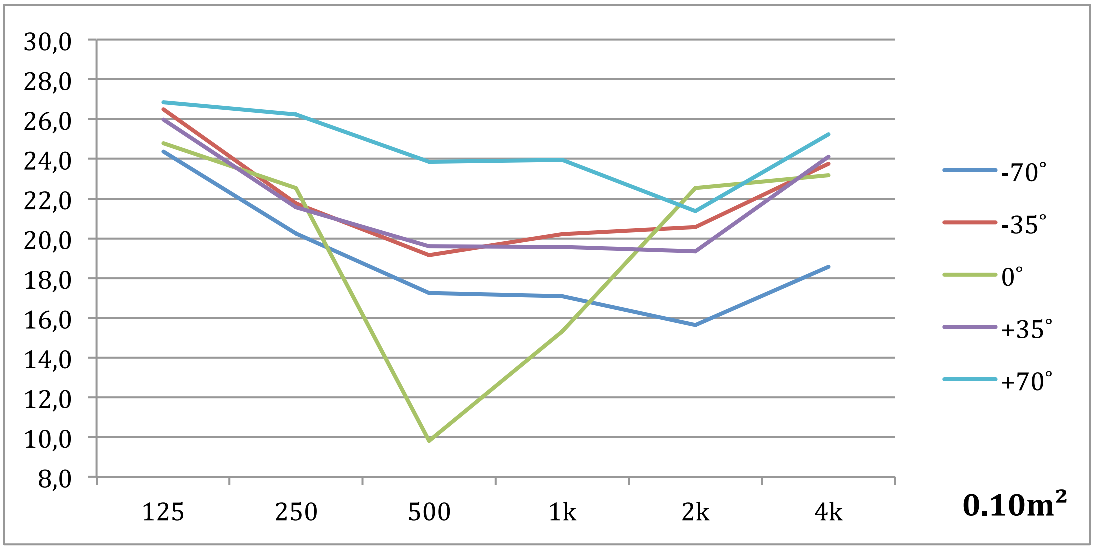
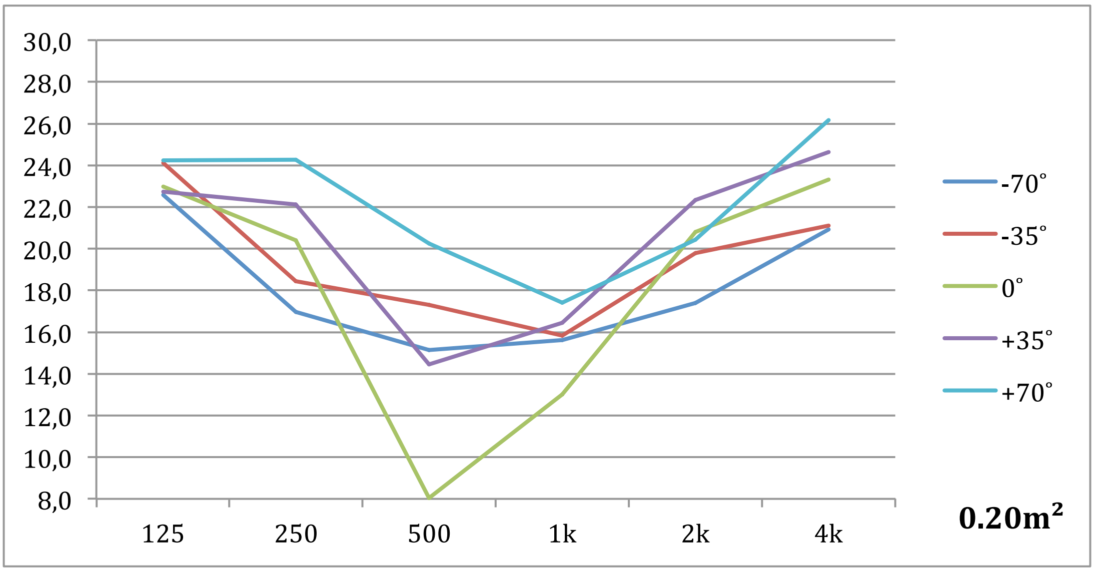
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.05m²


30,0
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.10m²


30,0
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.20m²

WINDOW D

Window D-1. Sliding sash upper section open.

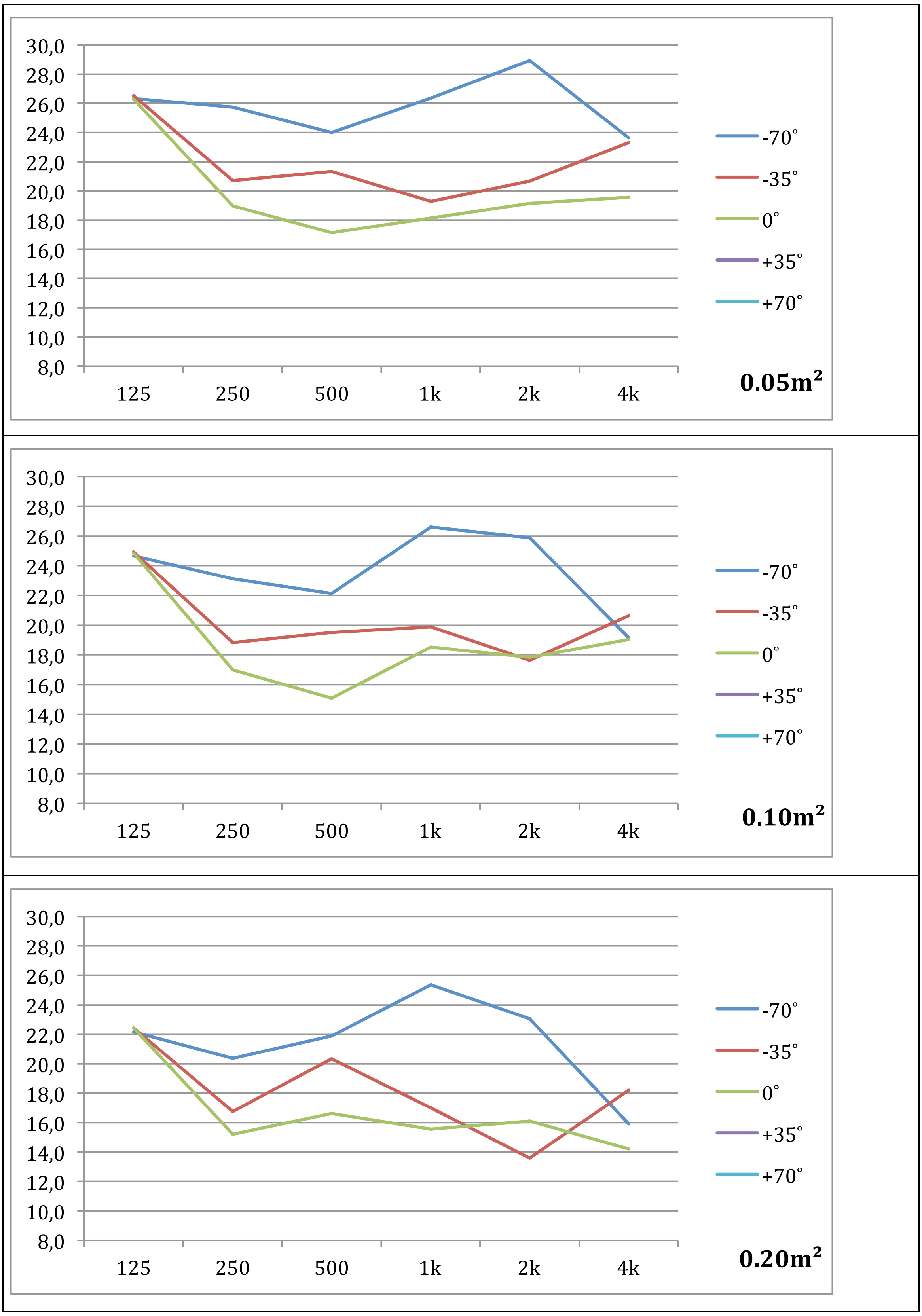
Window D-1

Open Window (0.05m² free area)	-70°	-35°	0°	+35°	+70°
125	-	-	26,3	26,5	26,3
250	-	-	19,0	20,7	25,7
500	-	-	17,1	21,3	24,0
1k	-	-	18,2	19,3	26,4
2k	-	-	19,1	20,7	28,9
4k	-	-	19,6	23,3	23,6

Open Window (0.10m² free area)	-70°	-35°	0°	+35°	+70°
125	-	-	24,9	24,9	24,6
250	-	-	17,0	18,8	23,1
500	-	-	15,1	19,5	22,1
1k	-	-	18,5	19,9	26,6
2k	-	-	17,8	17,6	25,9
4k	-	-	19,0	20,6	19,1

Open Window (0.20m² free area)	-70°	-35°	0°	+35°	+70°
125	-	-	22,4	22,5	22,2
250	-	-	15,2	16,8	20,4
500	-	-	16,6	20,3	21,9
1k	-	-	15,6	17,0	25,4
2k	-	-	16,1	13,6	23,1
4k	-	-	14,2	18,2	15,9

Standardised Level Difference in octaves-bands (dB)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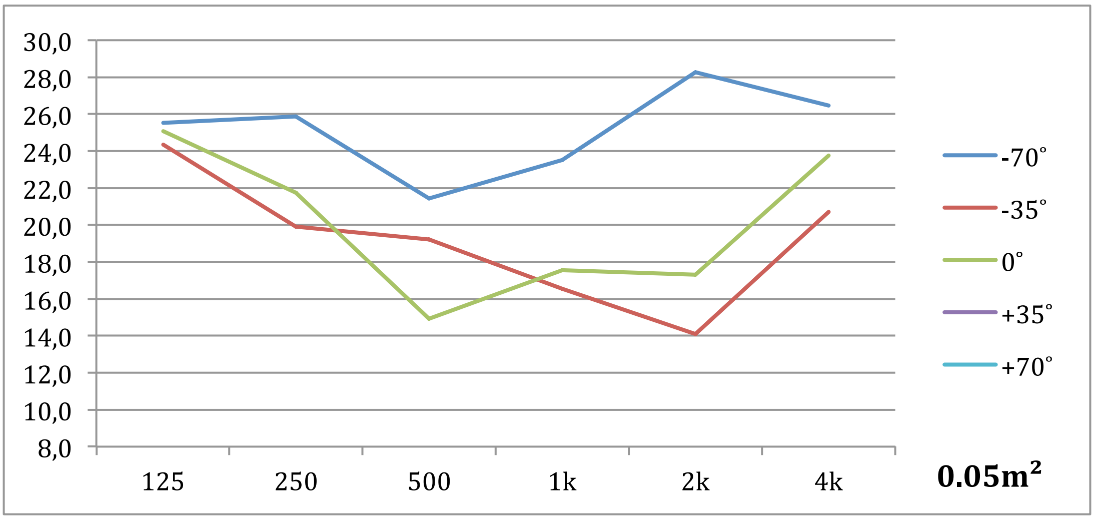
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.05m²
0.10m²
0.20m²

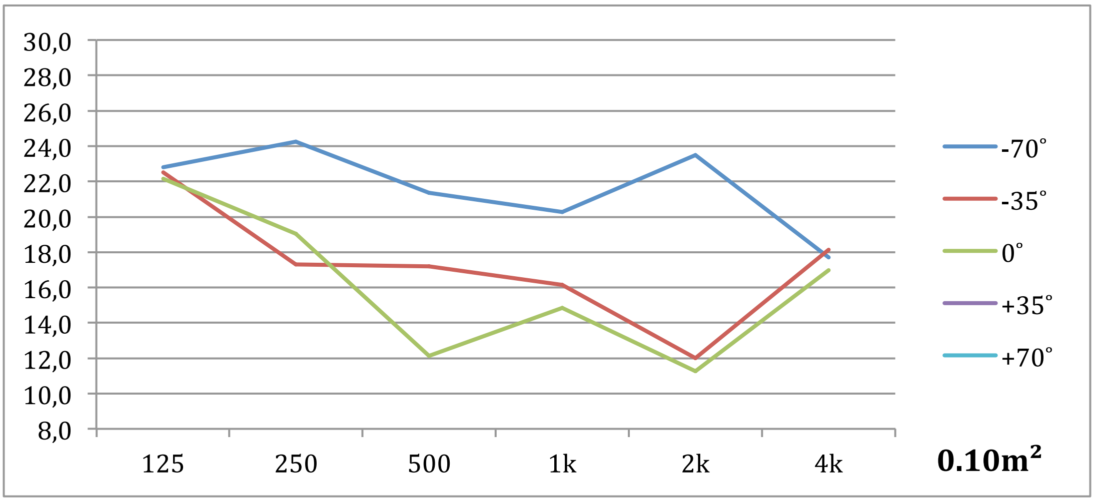
Window D-2. Sliding sash lower section open

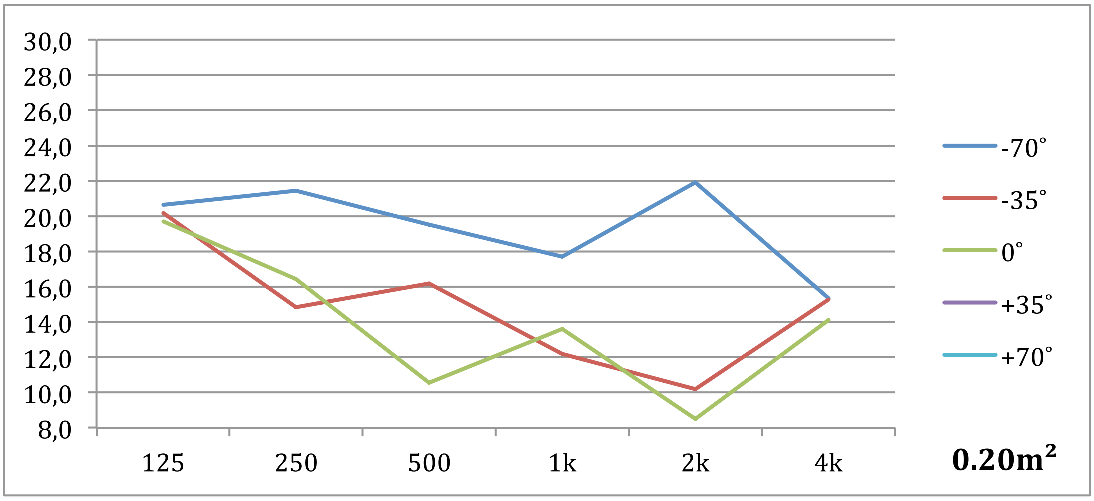
Window D-2

	Open Window (0.05m² free area)				
	-70˚	-35˚	0˚	+35˚	+70˚
125	-	-	25,1	24,3	25,5
250	-	-	21,8	19,9	25,9
500	-	-	14,9	19,2	21,4
1k	-	-	17,6	16,6	23,5
2k	-	-	17,3	14,1	28,3
4k	-	-	23,8	20,7	26,5
	Open Window (0.10m² free area)				
	-70˚	-35˚	0˚	+35˚	+70˚
125	-	-	22,2	22,5	22,8
250	-	-	19,0	17,3	24,2
500	-	-	12,1	17,2	21,4
1k	-	-	14,8	16,1	20,3
2k	-	-	11,3	12,0	23,5
4k	-	-	17,0	18,1	17,7
	Open Window (0.20m² free area)				
	-70˚	-35˚	0˚	+35˚	+70˚
125	-	-	19,7	20,2	20,7
250	-	-	16,4	14,8	21,5
500	-	-	10,6	16,2	19,5
1k	-	-	13,6	12,2	17,7
2k	-	-	8,5	10,2	21,9
4k	-	-	14,1	15,3	15,3

Standardised Level Difference in octaves-bands (dB)


30,0
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.05m²


30,0
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.10m²


30,0
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.20m²

Window D-3. Bottom hung inward opening

Window D-3

Open Window (0.05m² free area)

	-70˚	-35˚	0˚	+35˚	+70˚
125	-	-	25,1	25,3	25,5
250	-	-	21,8	22,5	25,9
500	-	-	14,9	17,7	21,4
1k	-	-	17,6	18,8	23,5
2k	-	-	17,3	16,9	28,3
4k	-	-	23,8	26,1	26,5

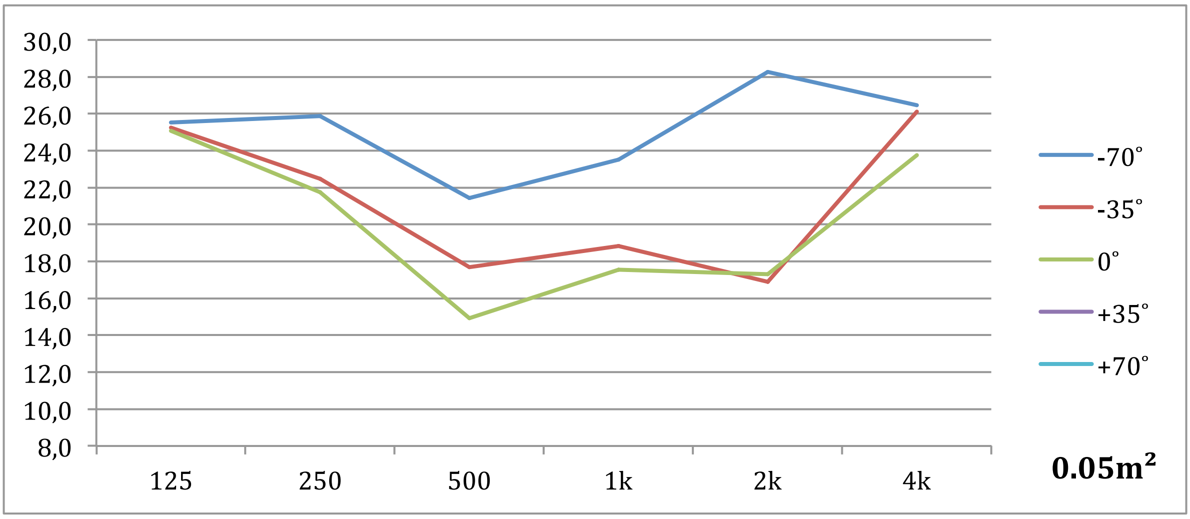
Open Window (0.10m² free area)

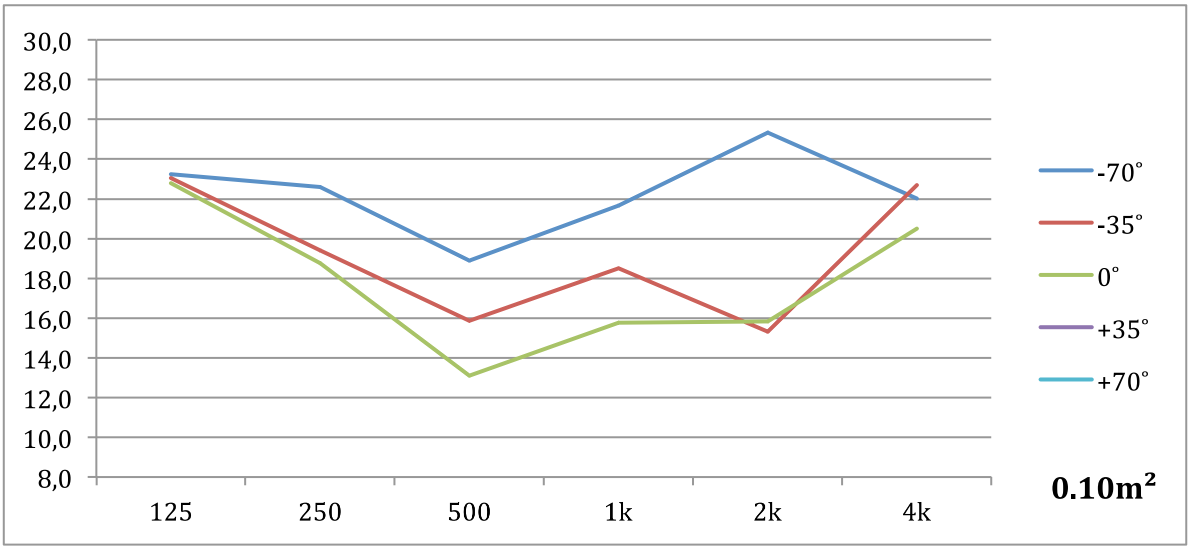
	-70˚	-35˚	0˚	+35˚	+70˚
125	-	-	22,8	23,0	23,3
250	-	-	18,8	19,4	22,6
500	-	-	13,1	15,9	18,9
1k	-	-	15,8	18,5	21,7
2k	-	-	15,8	15,3	25,3
4k	-	-	20,5	22,7	22,0

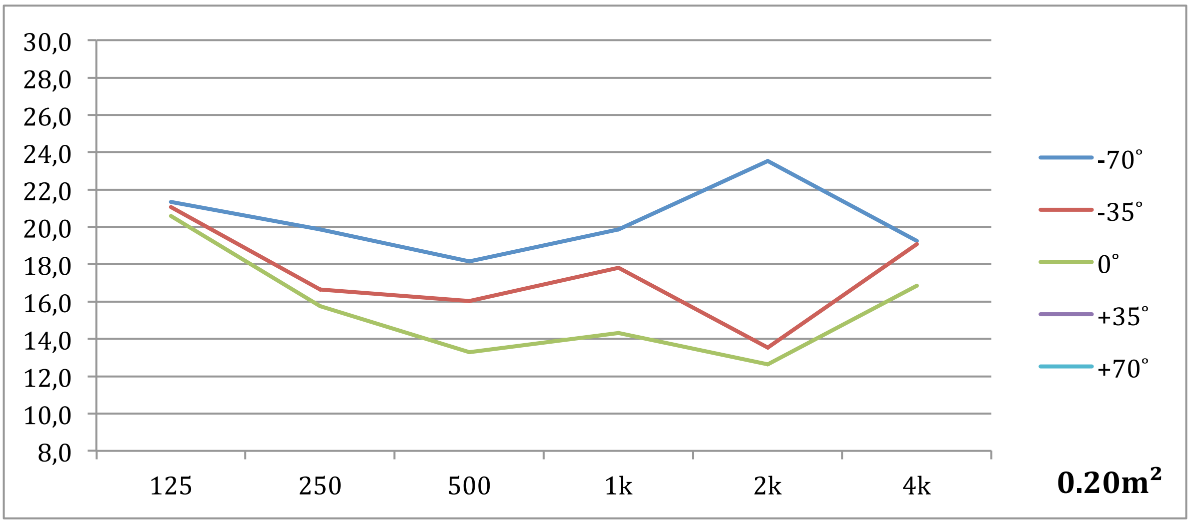
Open Window (0.20m² free area)

	-70˚	-35˚	0˚	+35˚	+70˚
125	-	-	20,6	21,0	21,4
250	-	-	15,7	16,6	19,9
500	-	-	13,3	16,0	18,1
1k	-	-	14,3	17,8	19,9
2k	-	-	12,6	13,5	23,5
4k	-	-	16,8	19,1	19,2

Standardised Level Difference in octaves-bands (dB)


30,0
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.05m²


30,0
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.10m²


30,0
28,0
26,0
24,0
22,0
20,0
18,0
16,0
14,0
12,0
10,0
8,0
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.20m²

WINDOW E

Window E. Top hung inward opening

Window E

Open Window (0.05m² free area)

	-70˚	-35˚	0˚	+35˚	+70˚
125	-	-	27,0	26,2	26,1
250	-	-	20,6	21,2	23,7
500	-	-	25,2	22,7	22,9
1k	-	-	20,6	23,3	26,1
2k	-	-	21,2	26,2	29,6
4k	-	-	25,0	27,3	27,8

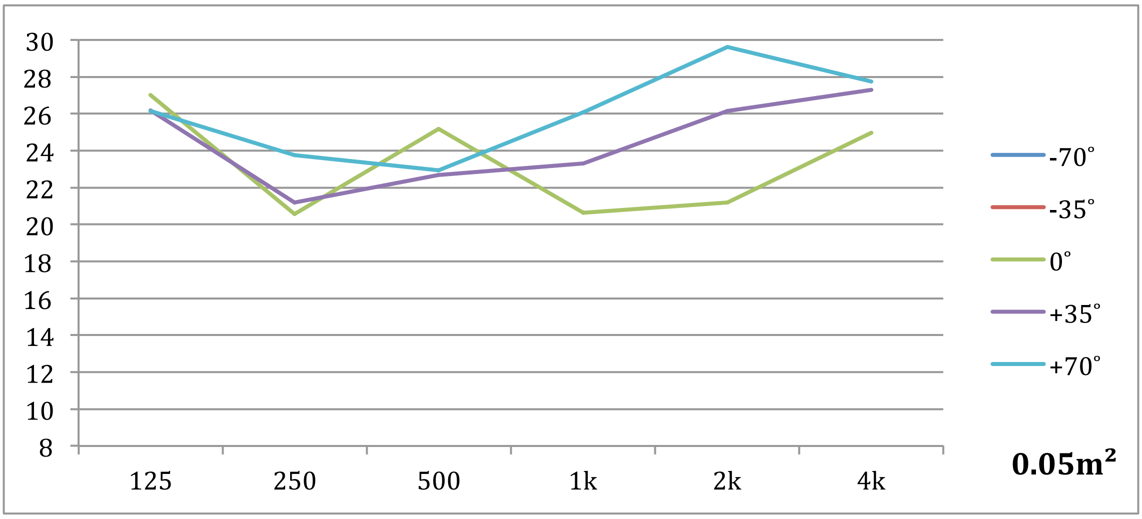
Open Window (0.10m² free area)

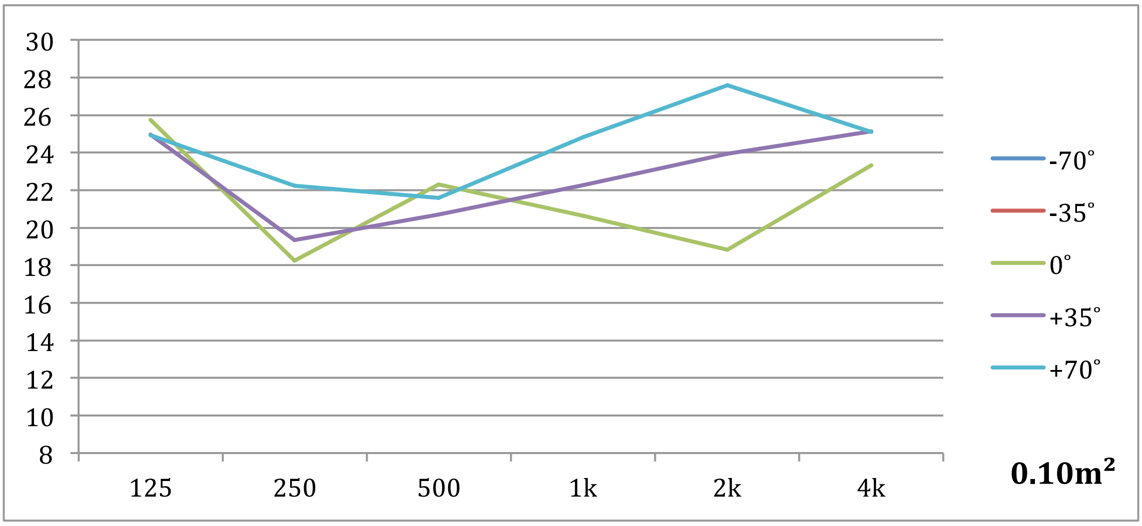
	-70˚	-35˚	0˚	+35˚	+70˚
125	-	-	25,8	25,0	24,9
250	-	-	18,2	19,3	22,2
500	-	-	22,3	20,7	21,6
1k	-	-	20,6	22,3	24,8
2k	-	-	18,8	23,9	27,6
4k	-	-	23,3	25,1	25,1

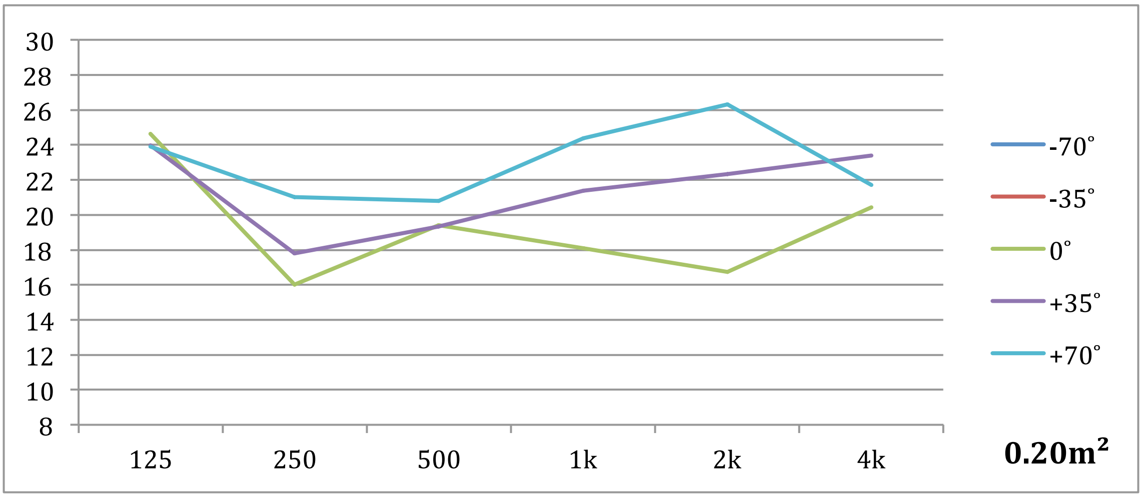
Open Window (0.20m² free area)

	-70˚	-35˚	0˚	+35˚	+70˚
125	-	-	24,6	24,0	23,9
250	-	-	16,0	17,8	21,0
500	-	-	19,4	19,4	20,8
1k	-	-	18,1	21,4	24,4
2k	-	-	16,7	22,3	26,3
4k	-	-	20,4	23,4	21,7

Standardised Level Difference in octaves-bands (dB)


30
28
26
24
22
20
18
16
14
12
10
8
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.05m²


30
28
26
24
22
20
18
16
14
12
10
8
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.10m²


30
28
26
24
22
20
18
16
14
12
10
8
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.20m²

WINDOW F

Window F. Top hung outward opening (PVC-U)

Window F 

Open Window (0.05m² free area)

	-70°	-35°	0°	+35°	+70°
125	-	-	26,2	25,7	25,2
250	-	-	21,9	19,3	23,5
500	-	-	25,1	22,8	22,0
1k	-	-	22,7	21,3	24,6
2k	-	-	24,5	25,8	27,0
4k	-	-	22,4	23,1	28,4

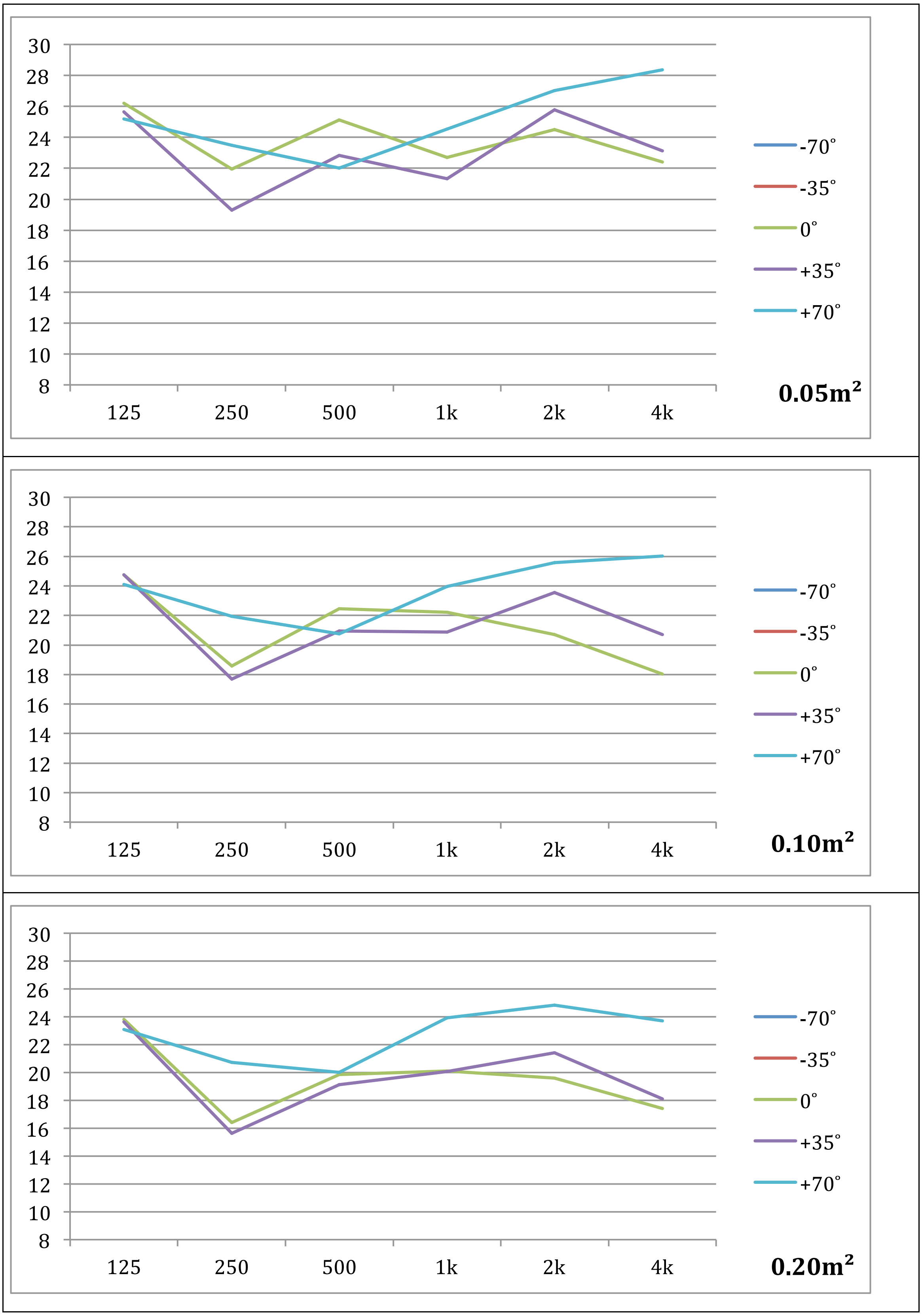
Open Window (0.10m² free area)

	-70°	-35°	0°	+35°	+70°
125	-	-	24,8	24,7	24,1
250	-	-	18,6	17,7	21,9
500	-	-	22,5	21,0	20,8
1k	-	-	22,2	20,9	24,0
2k	-	-	20,7	23,6	25,6
4k	-	-	18,0	20,7	26,0

Open Window (0.20m² free area)

	-70°	-35°	0°	+35°	+70°
125	-	-	23,8	23,7	23,1
250	-	-	16,4	15,6	20,7
500	-	-	19,9	19,1	20,0
1k	-	-	20,1	20,1	23,9
2k	-	-	19,6	21,4	24,9
4k	-	-	17,4	18,1	23,7

Standardised Level Difference in octaves-bands (dB)


30
28
26
24
22
20
18
16
14
12
10
8
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.05m²
0.10m²
0.20m²

WINDOW G

Window G. Side hung outward tilt (timber)

Window G 

Open Window (0.05m² free area)

	-70˚	-35˚	0˚	+35˚	+70˚
125	-	-	25,2	25,3	25,1
250	-	-	23,3	23,5	23,9
500	-	-	23,8	21,0	21,4
1k	-	-	22,7	23,1	18,2
2k	-	-	20,8	22,3	23,7
4k	-	-	20,5	18,5	21,3

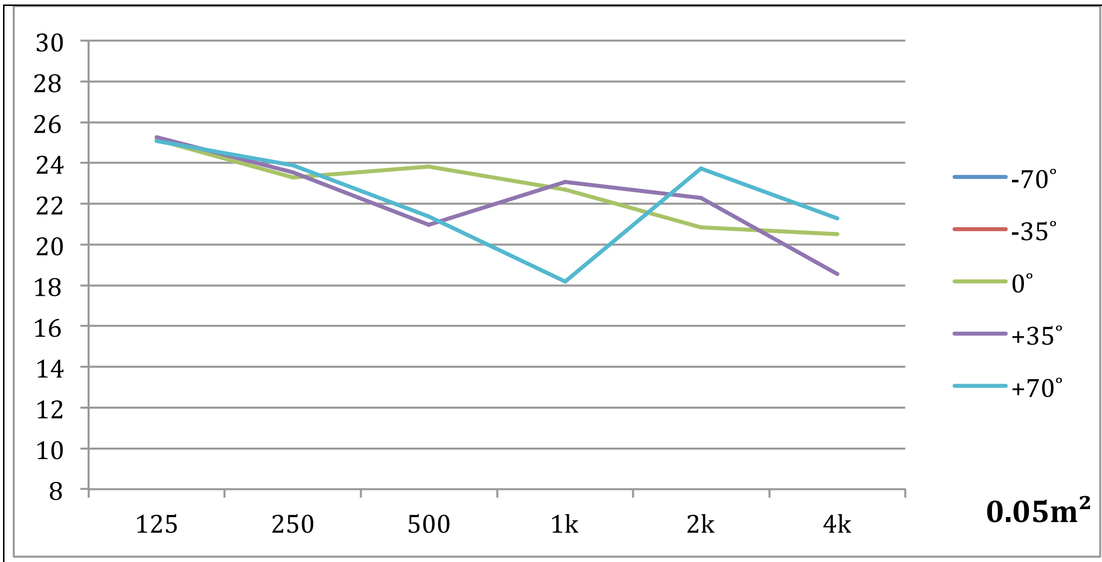
Open Window (0.10m² free area)

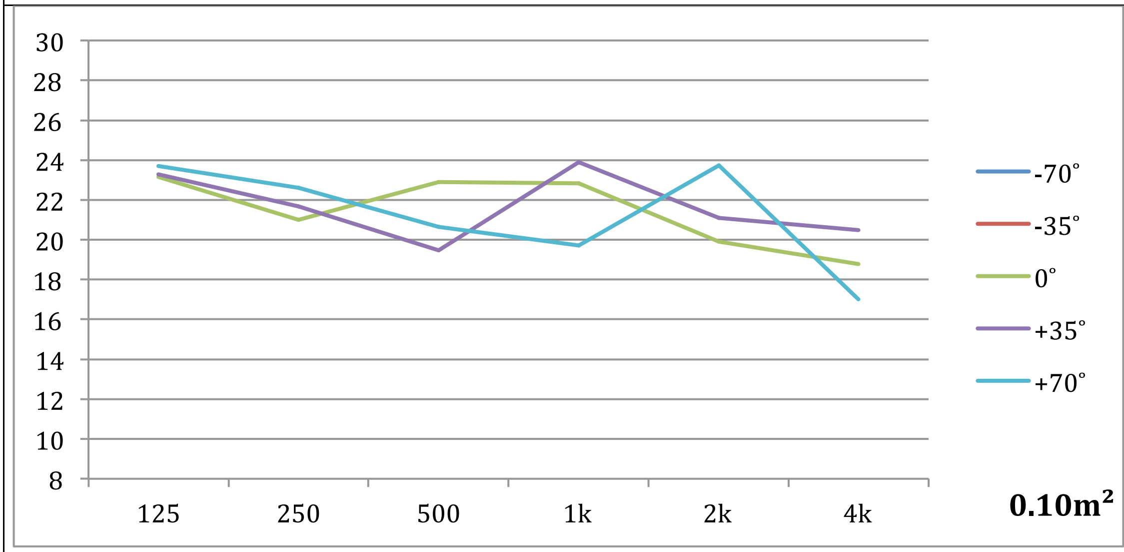
	-70˚	-35˚	0˚	+35˚	+70˚
125	-	-	23,2	23,3	23,7
250	-	-	21,0	21,7	22,6
500	-	-	22,9	19,5	20,6
1k	-	-	22,8	23,9	19,7
2k	-	-	19,9	21,1	23,7
4k	-	-	18,8	20,5	17,0

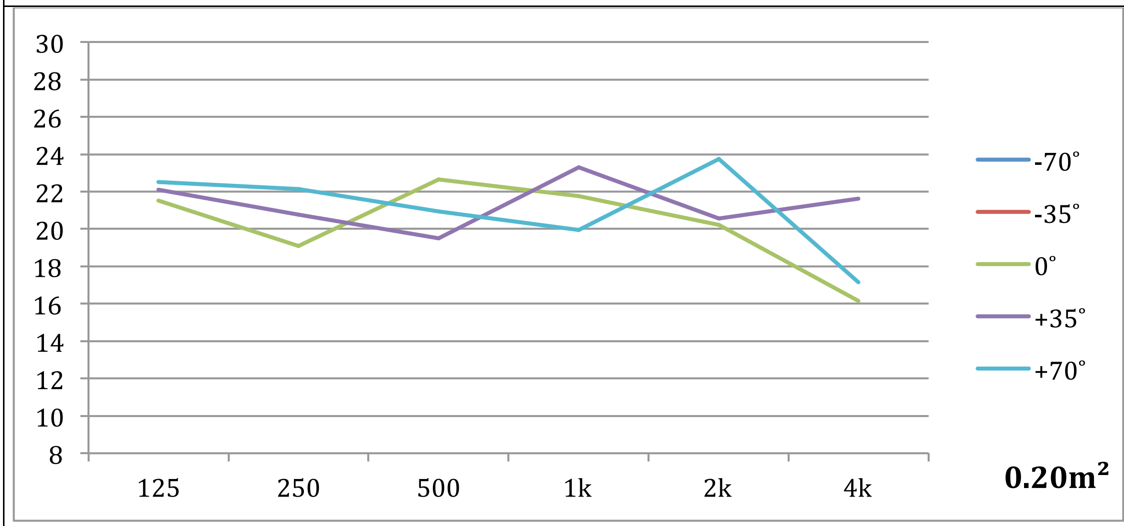
Open Window (0.20m² free area)

	-70˚	-35˚	0˚	+35˚	+70˚
125	-	-	21,5	22,1	22,5
250	-	-	19,1	20,8	22,1
500	-	-	22,6	19,5	20,9
1k	-	-	21,8	23,3	20,0
2k	-	-	20,2	20,6	23,7
4k	-	-	16,2	21,6	17,1

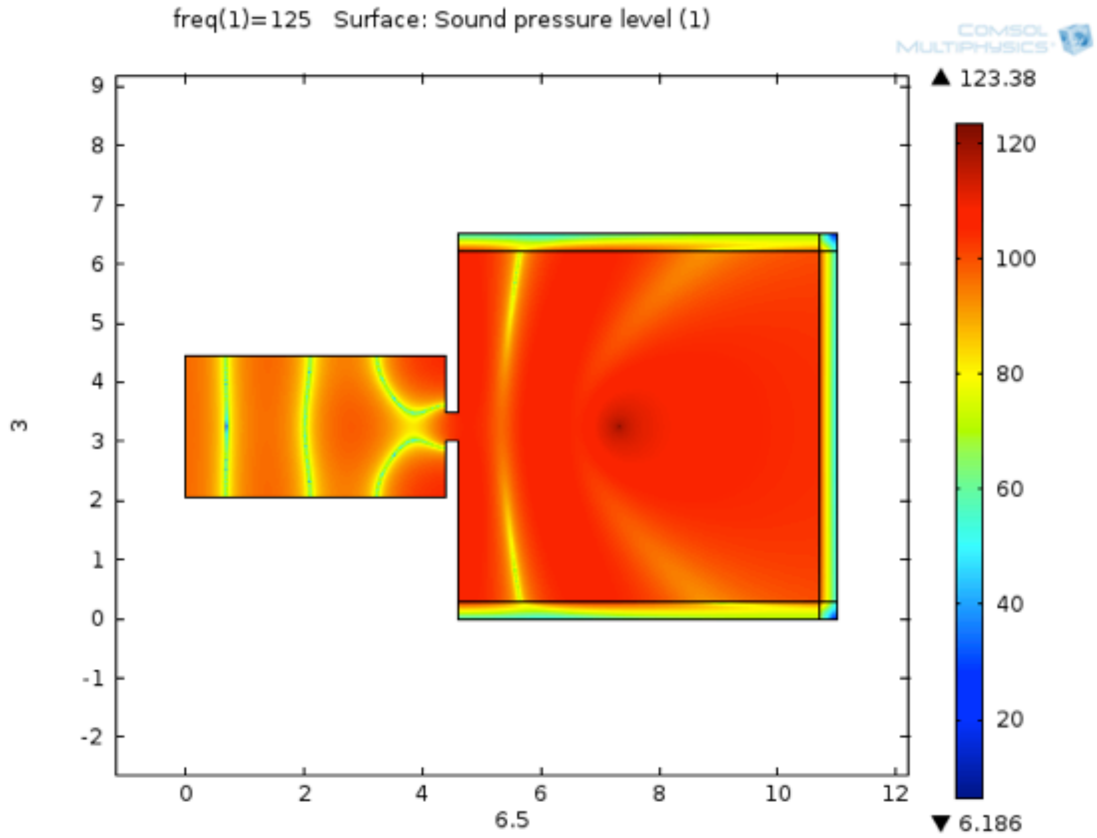
Standardised Level Difference in octaves-bands (dB)

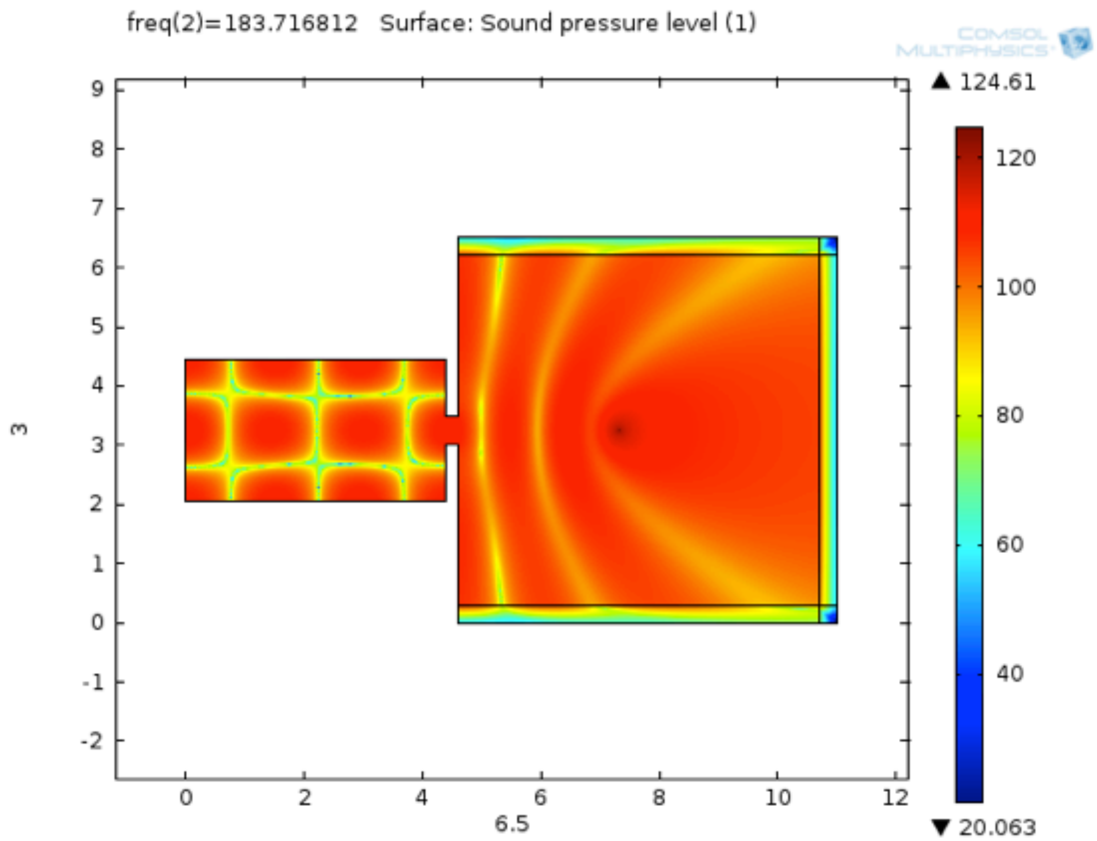

30
28
26
24
22
20
18
16
14
12
10
8
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.05m²

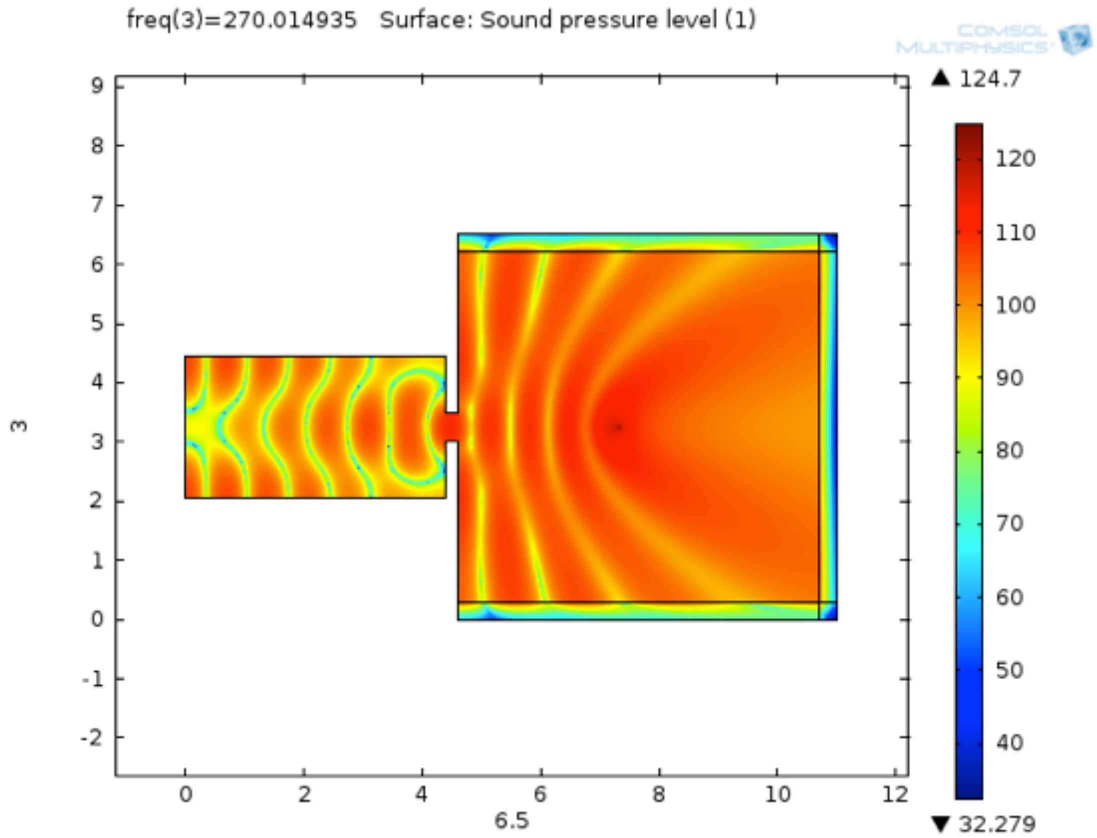

30
28
26
24
22
20
18
16
14
12
10
8
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.10m²

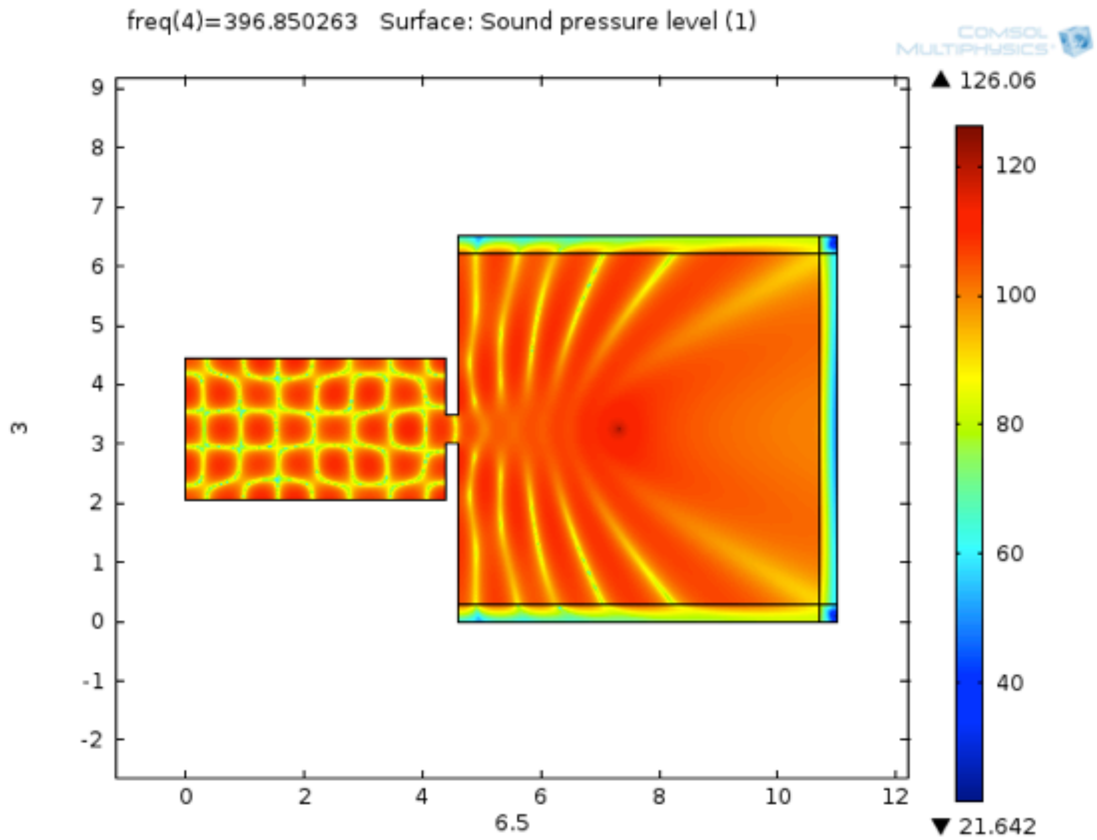

30
28
26
24
22
20
18
16
14
12
10
8
125
250
500
1k
2k
4k
-70°
-35°
0°
+35°
+70°
0.20m²

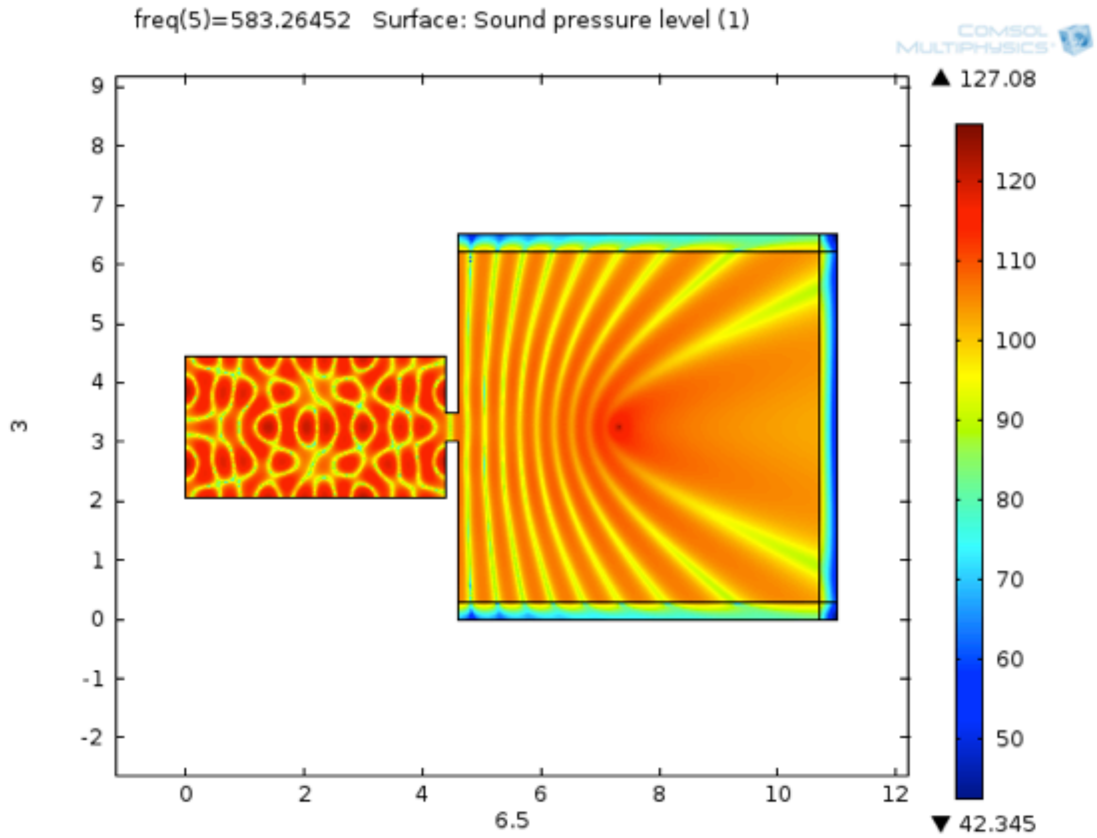
APPENDIX 3. Comsol simulation for an angle of source incidence in 0º and 0.10m^2 free area:

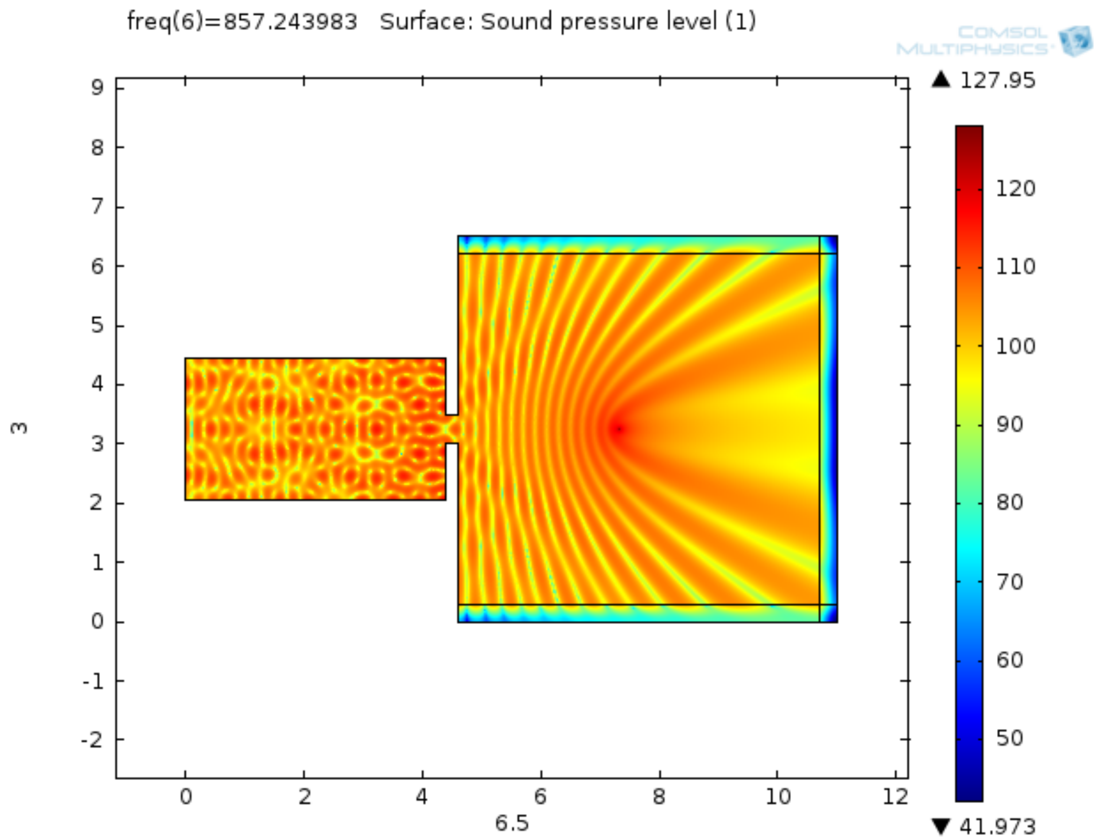


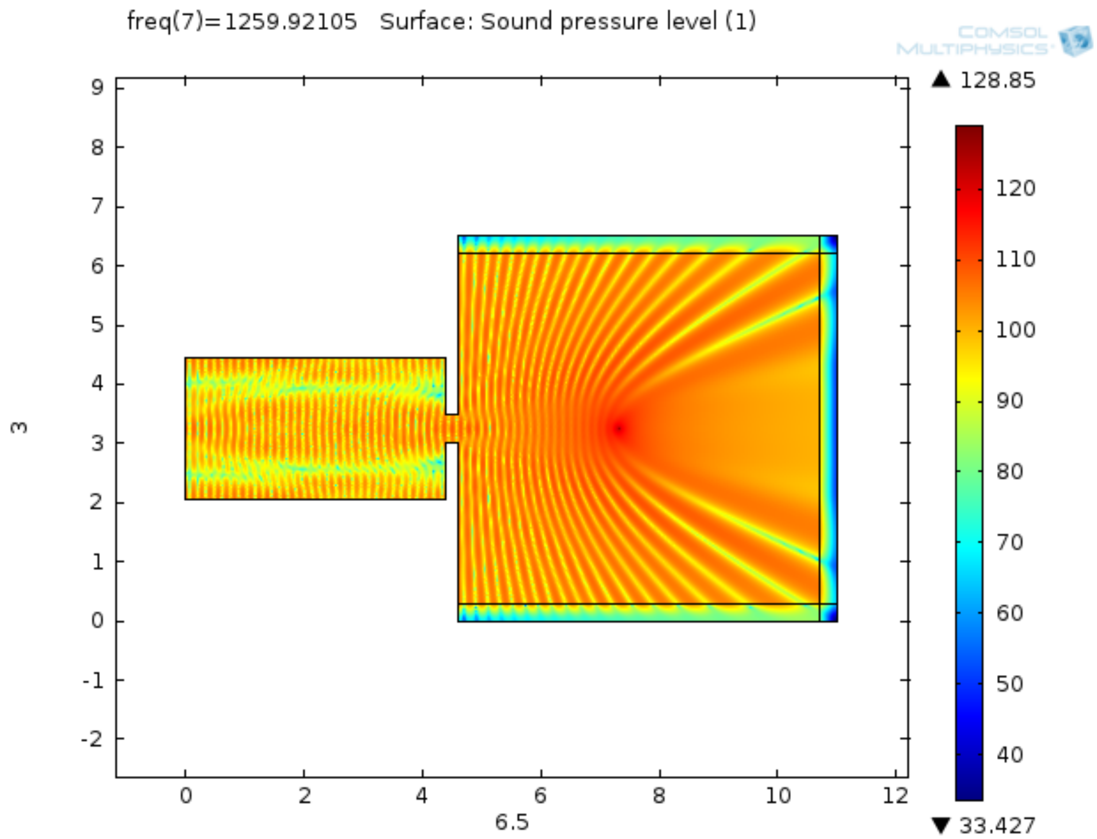


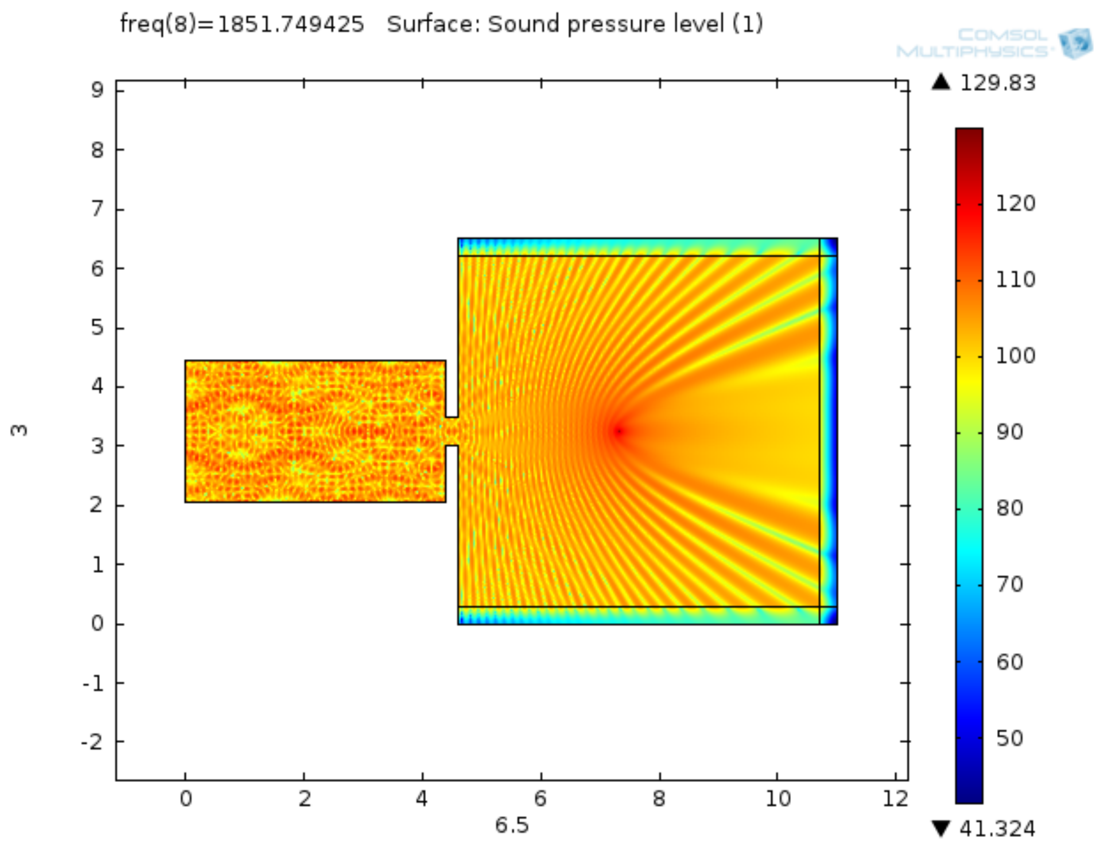

freq(3)=270.014935 Surface: Sound pressure level (1)
▲ 124.7
120
110
100
90
80
70
60
50
40
▼ 32.279
9
8
7
6
5
4
3
2
1
0
-1
-2
3
0
2
4
6
8
10
12
6.5

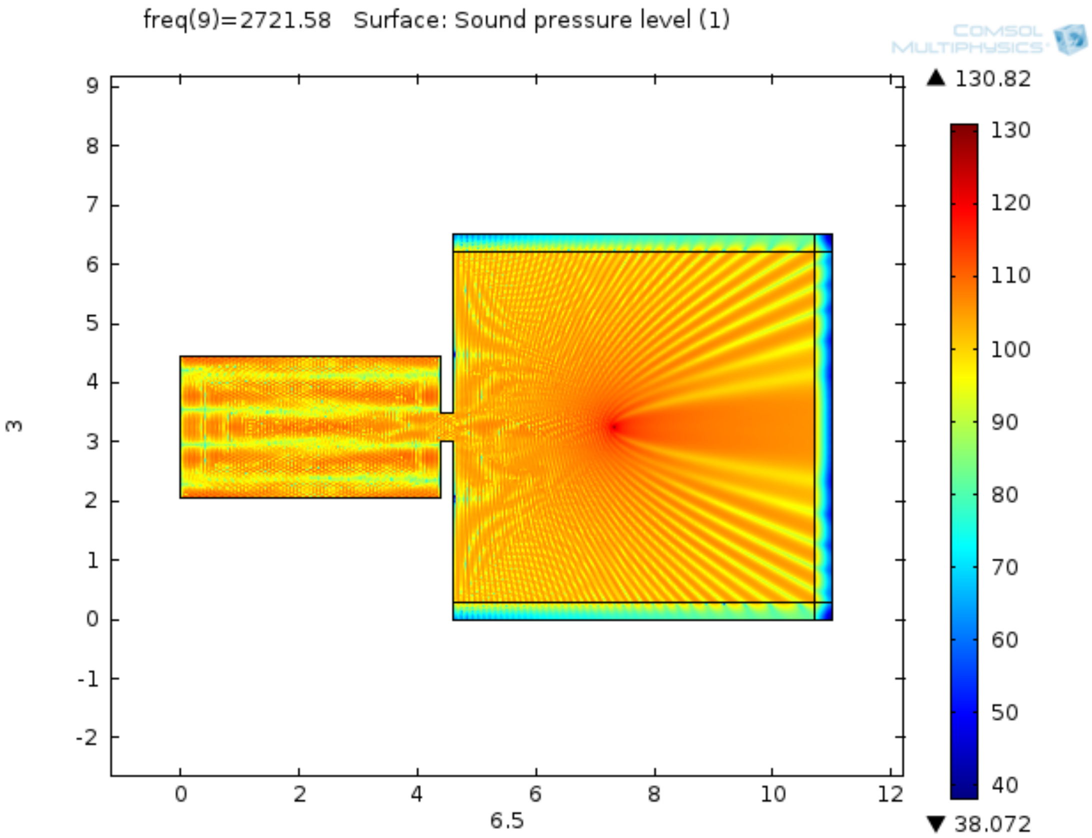

freq(4)=396.850263 Surface: Sound pressure level (1)
▲ 126.06
120
100
80
60
40
▼ 21.642
9
8
7
6
5
4
3
2
1
0
-1
-2
3
0
2
4
6
8
10
12
6.5

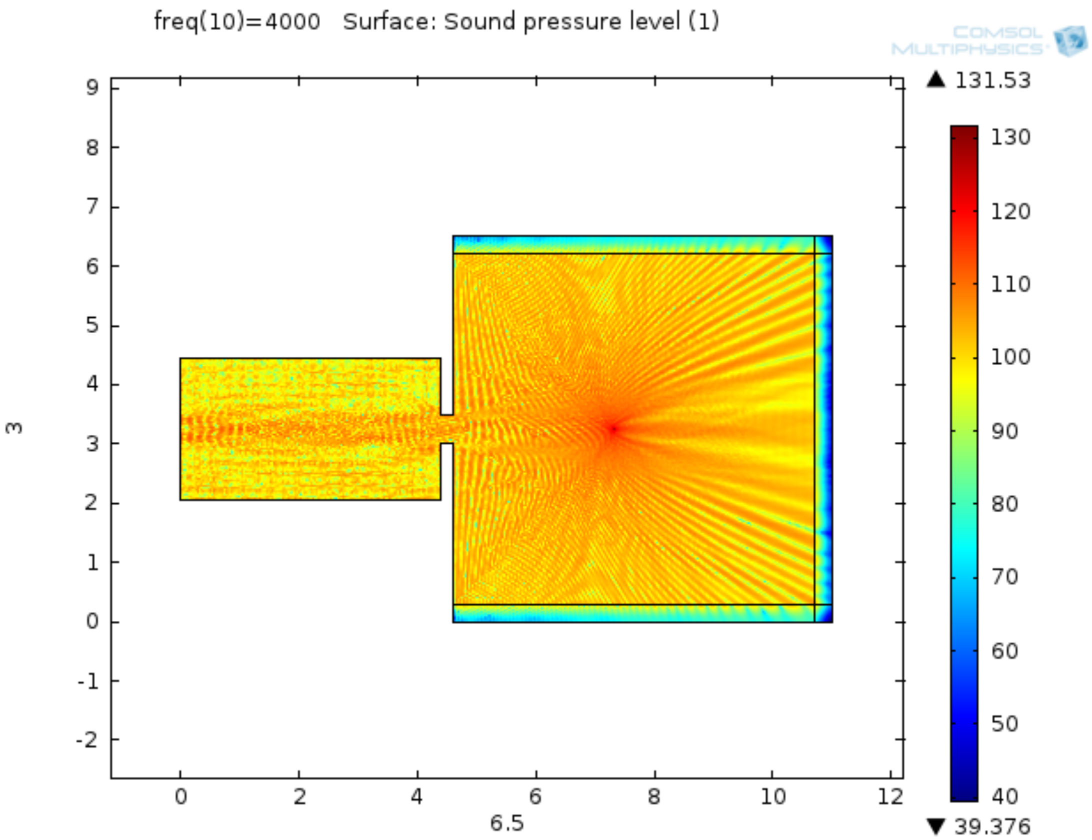

freq(5)=583.26452 Surface: Sound pressure level (1)
COMSOL MULTIPHYSICS
▲ 127.08
▼ 42.345
6.5
3


freq(6)=857.243983 Surface: Sound pressure level (1)
COMSOL MULTIPHYSICS
▲ 127.95
▼ 41.973
6.5
3

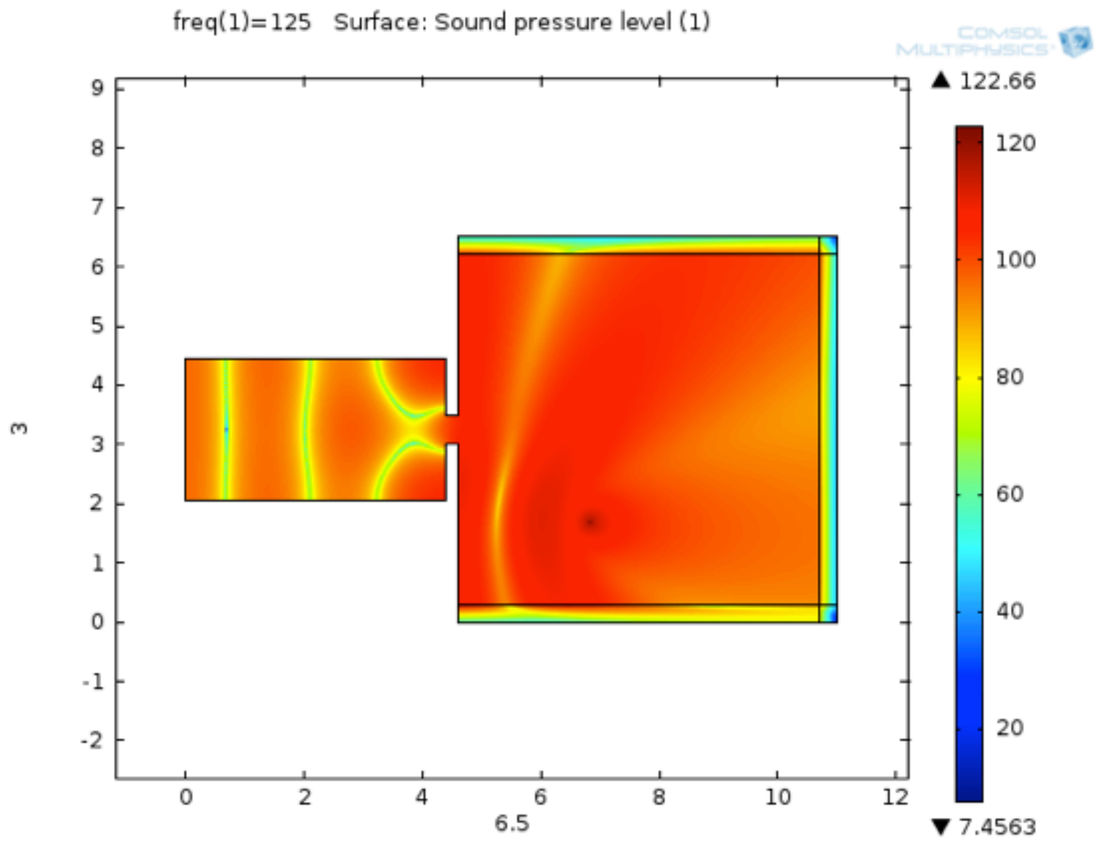

freq(7)=1259.92105 Surface: Sound pressure level (1)
▲ 128.85
▼ 33.427
120
110
100
90
80
70
60
50
40
9
8
7
6
5
4
3
2
1
0
-1
-2
0
2
4
6
8
10
12
6.5
3

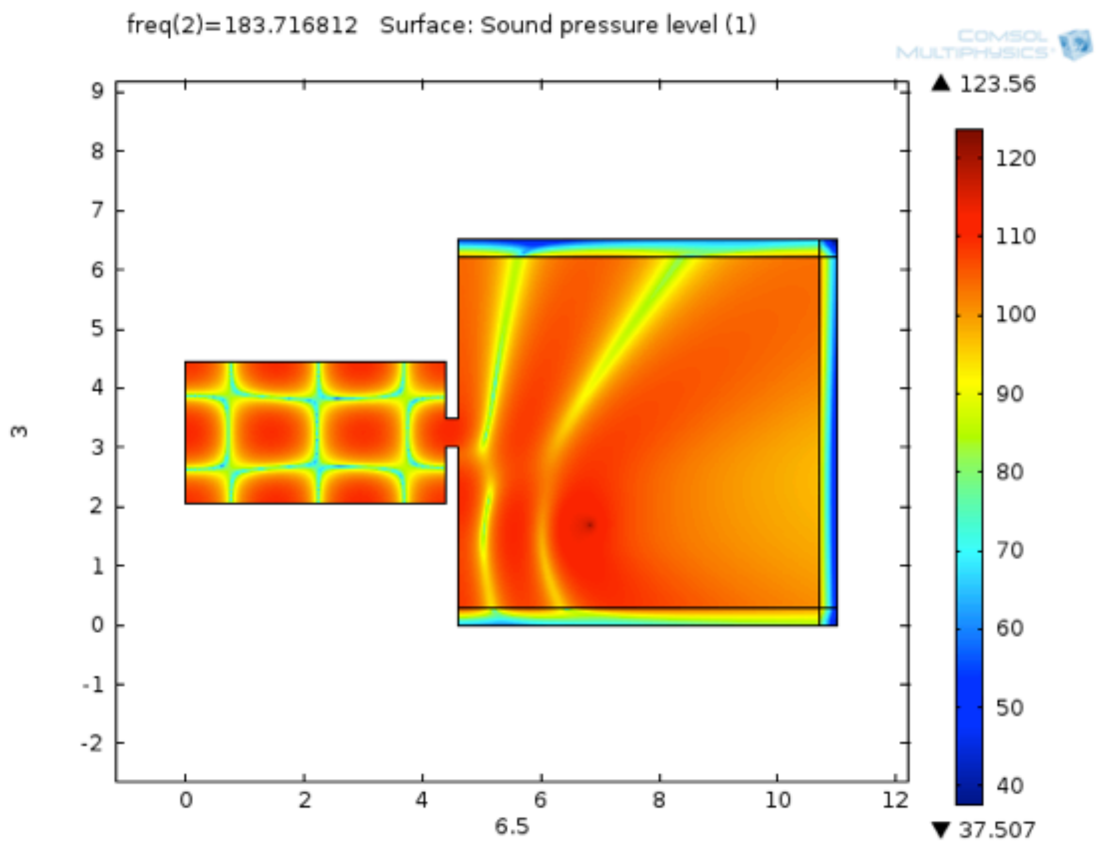

freq(8)=1851.749425 Surface: Sound pressure level (1)
▲ 129.83
▼ 41.324
120
110
100
90
80
70
60
50
9
8
7
6
5
4
3
2
1
0
-1
-2
0
2
4
6
8
10
12
6.5
3

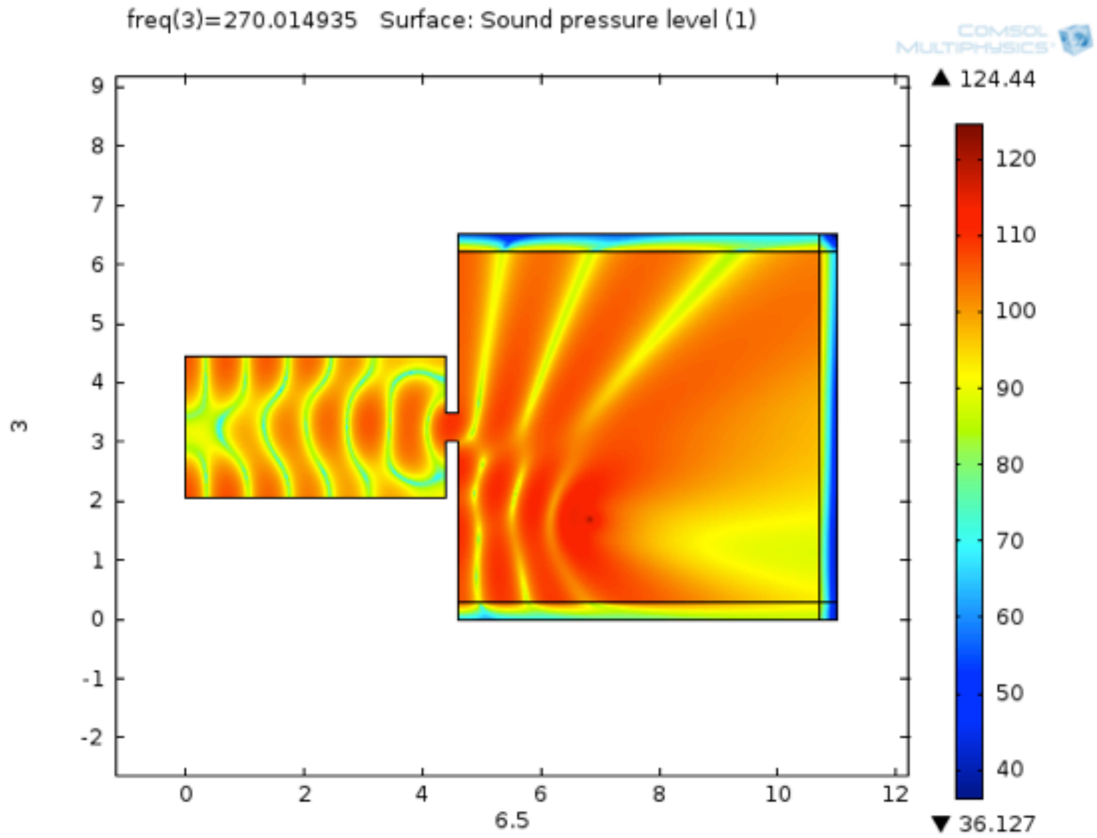

freq(9)=2721.58 Surface: Sound pressure level (1)
COMSOL MULTIPHYSICS
▲ 130.82
▼ 38.072
130
120
110
100
90
80
70
60
50
40
9
8
7
6
5
4
3
2
1
0
-1
-2
0
2
4
6
8
10
12
6.5
3

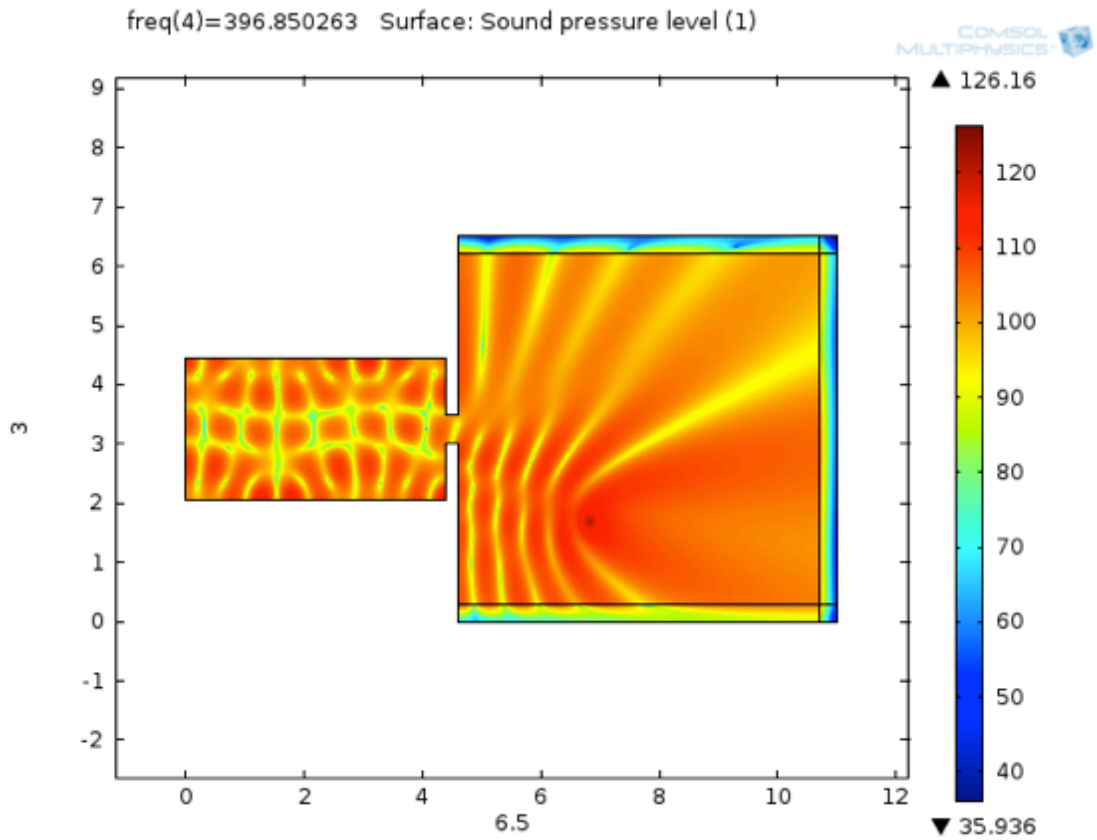

freq(10)=4000 Surface: Sound pressure level (1)
COMSOL MULTIPHYSICS
▲ 131.53
▼ 39.376
130
120
110
100
90
80
70
60
50
40
9
8
7
6
5
4
3
2
1
0
-1
-2
0
2
4
6
8
10
12
6.5
3

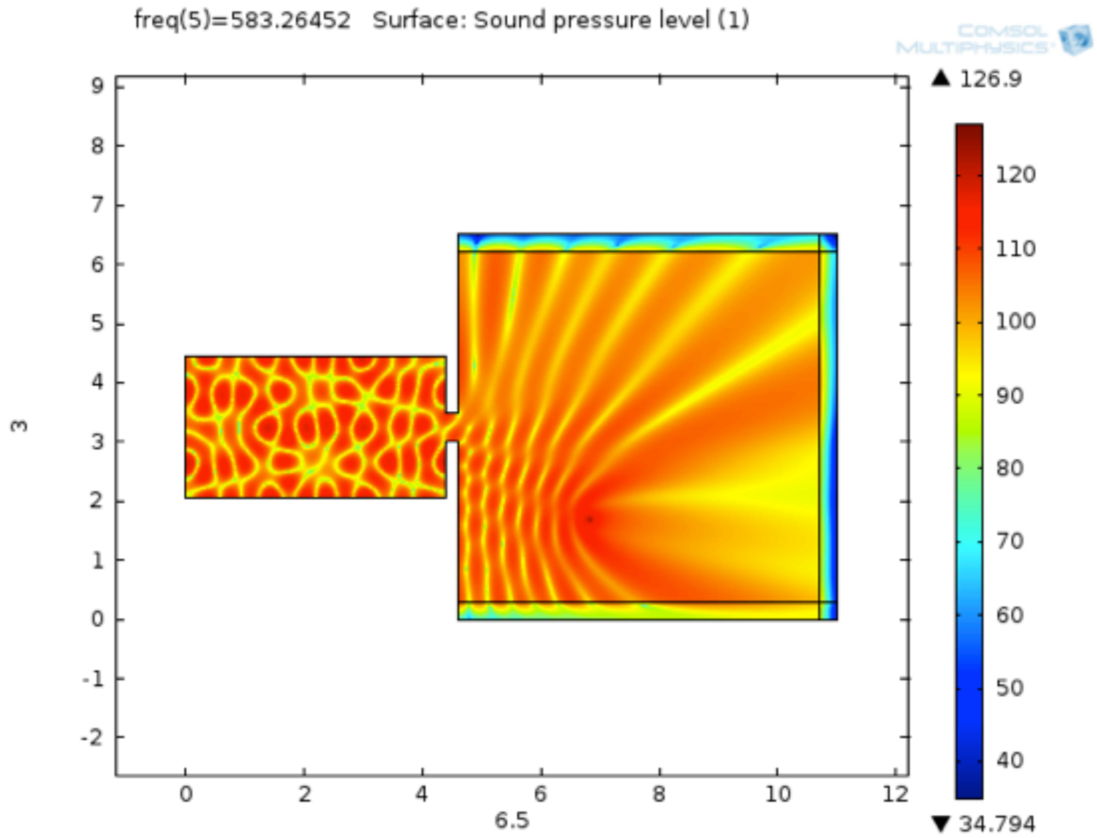
COMSOL SIMULATION for an angle of source incidence +35º and 0.10m² free area

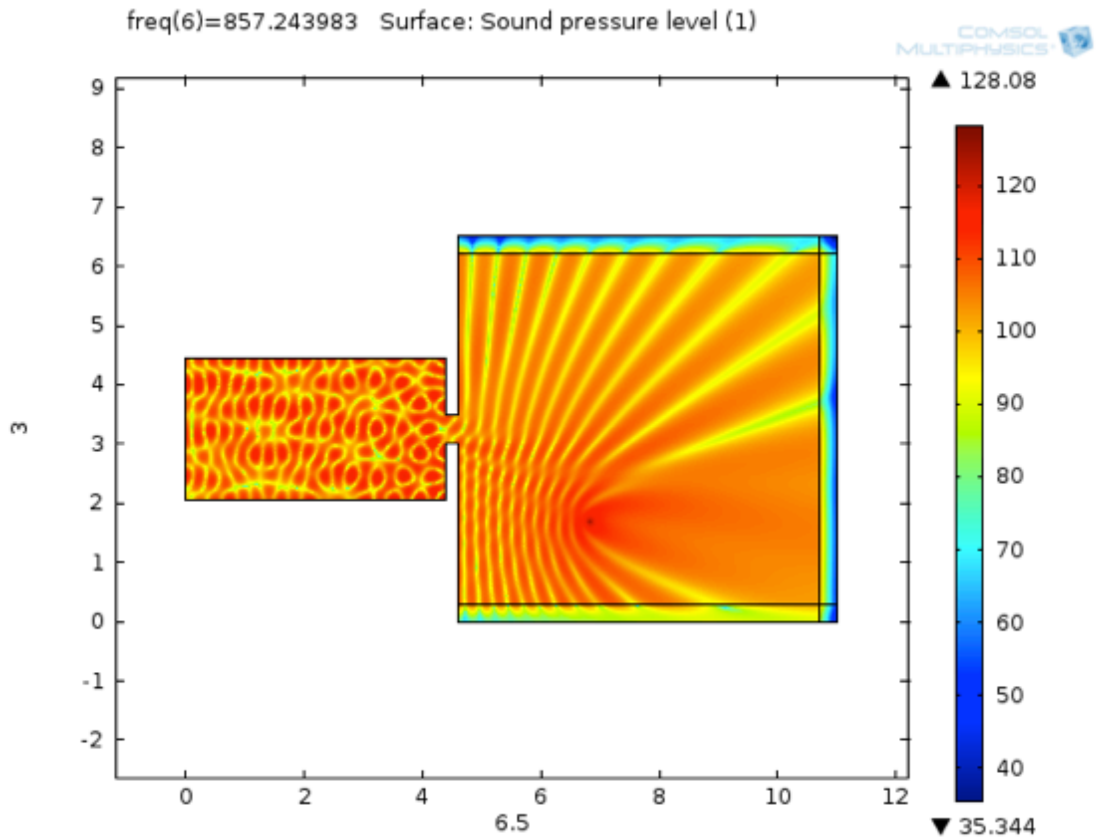


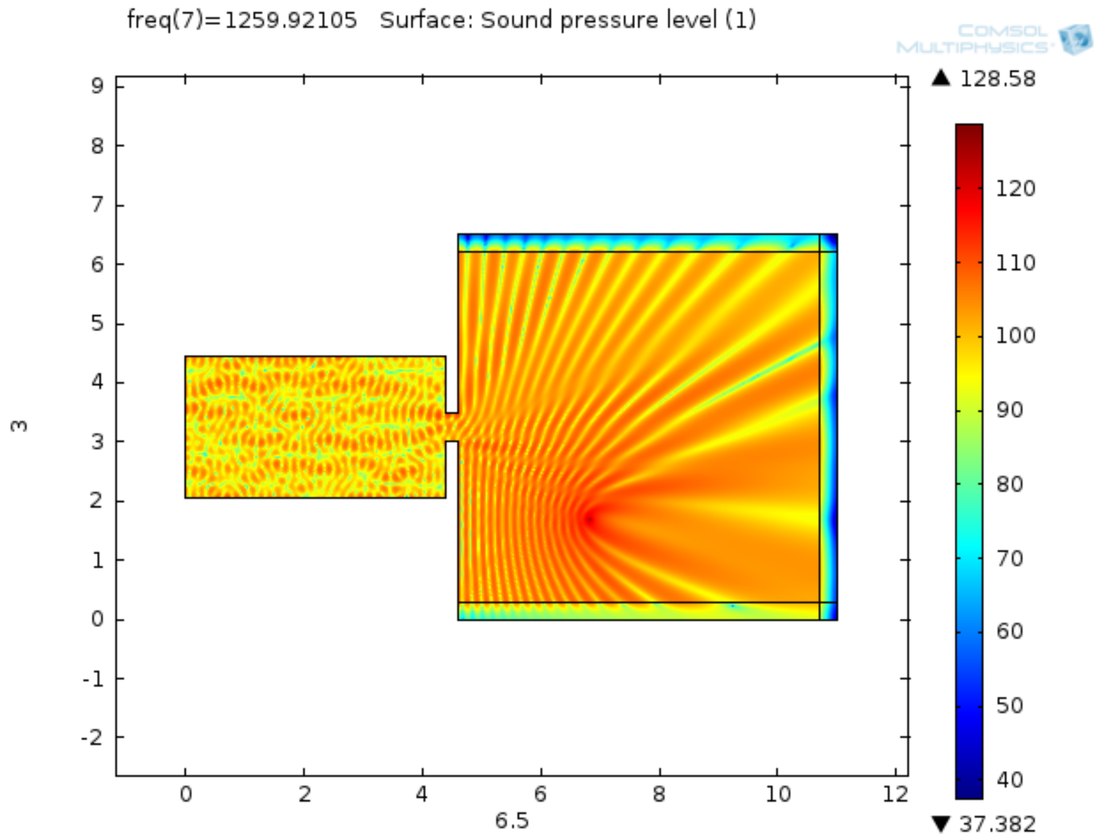


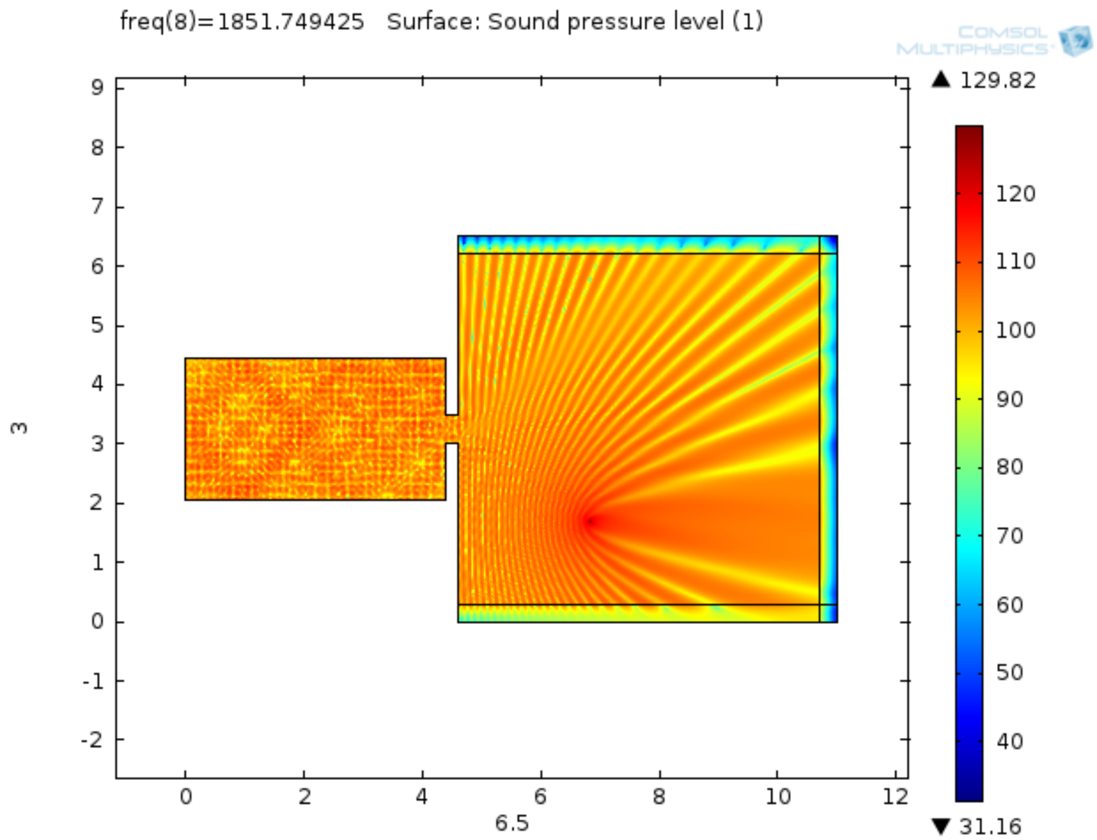

freq(3)=270.014935 Surface: Sound pressure level (1)
▲ 124.44
▼ 36.127
6.5
3

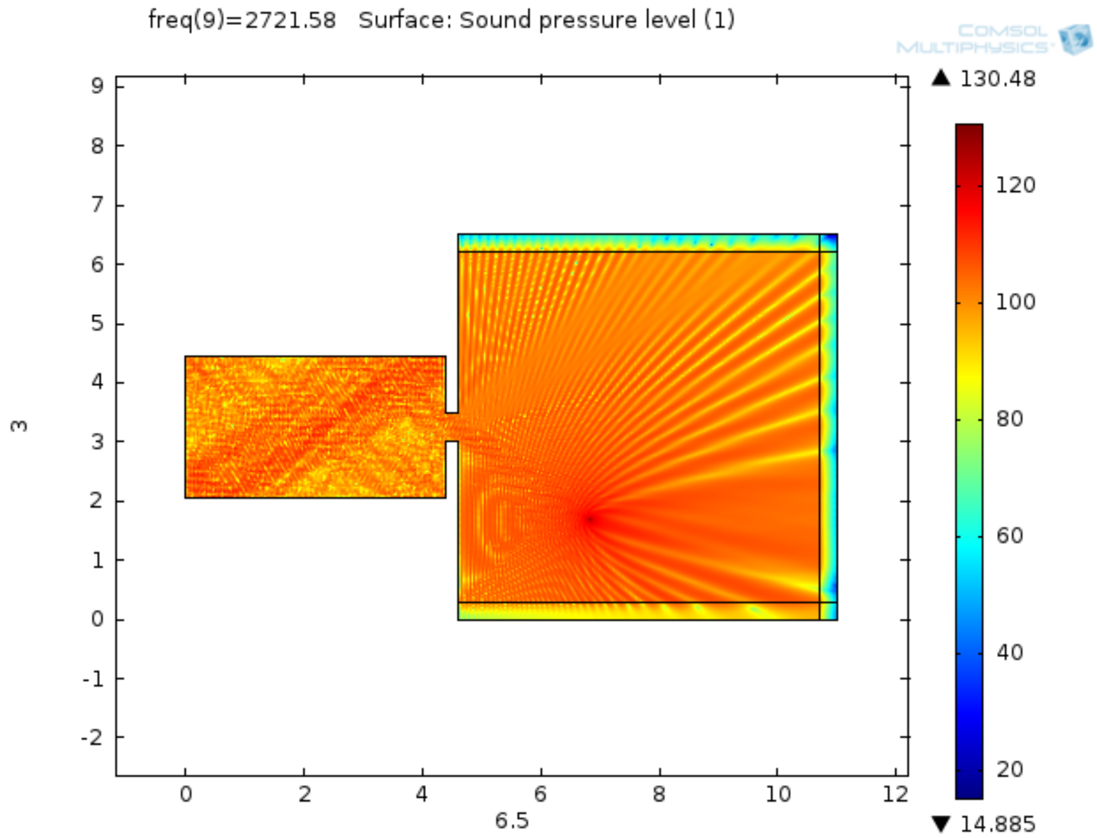

freq(4)=396.850263 Surface: Sound pressure level (1)
▲ 126.16
▼ 35.936
6.5
3

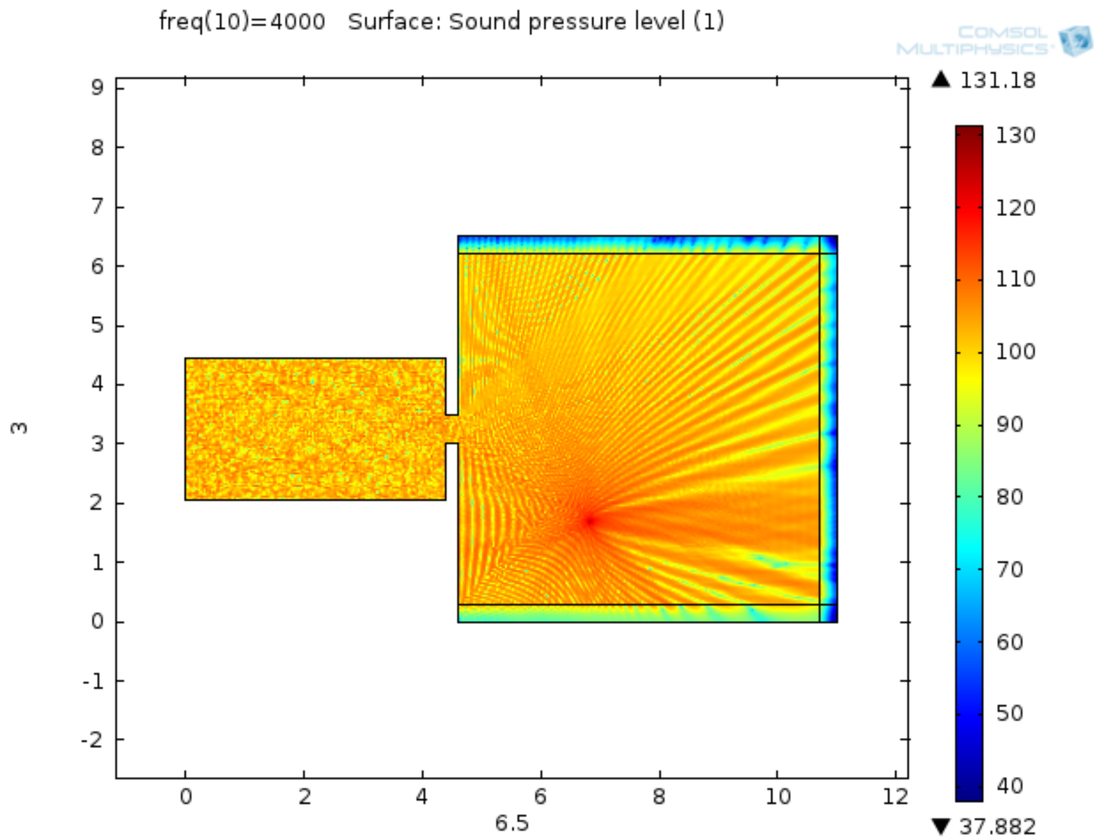

freq(5)=583.26452 Surface: Sound pressure level (1)
COMSOL MULTIPHYSICS
▲ 126.9
▼ 34.794
120
110
100
90
80
70
60
50
40
9
8
7
6
5
4
3
2
1
0
-1
-2
0
2
4
6
8
10
12
6.5
3


freq(6)=857.243983 Surface: Sound pressure level (1)
COMSOL MULTIPHYSICS
▲ 128.08
▼ 35.344
120
110
100
90
80
70
60
50
40
9
8
7
6
5
4
3
2
1
0
-1
-2
0
2
4
6
8
10
12
6.5
3

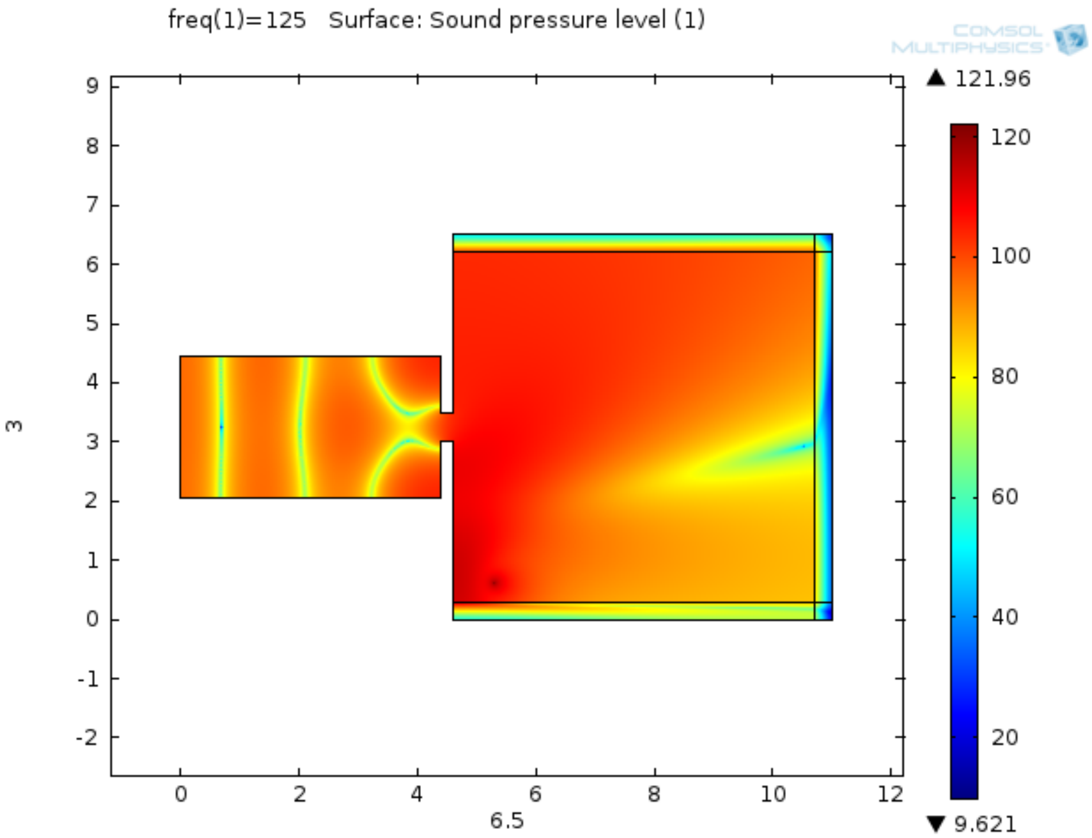

freq(7)=1259.92105 Surface: Sound pressure level (1)
COMSOL MULTIPHYSICS
▲ 128.58
120
110
100
90
80
70
60
50
40
▼ 37.382
9
8
7
6
5
4
3
2
1
0
-1
-2
0
2
4
6
8
10
12
6.5
3

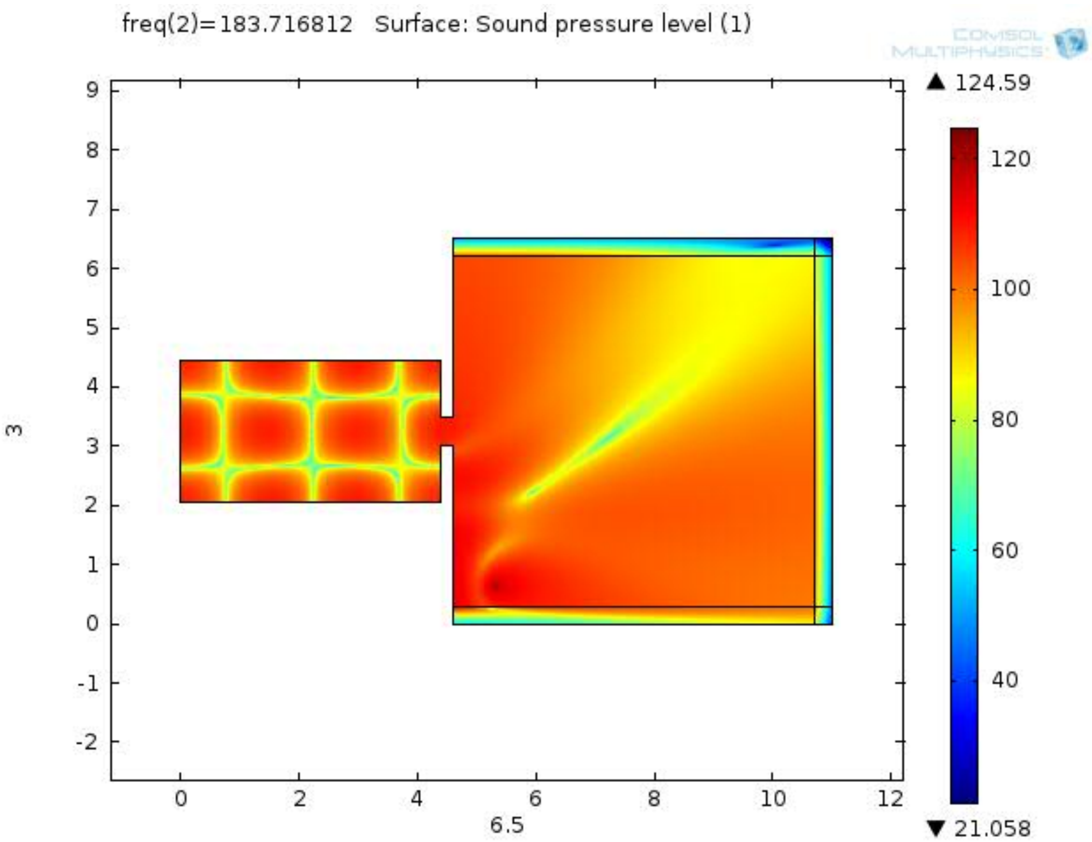

freq(8)=1851.749425 Surface: Sound pressure level (1)
COMSOL MULTIPHYSICS
▲ 129.82
120
110
100
90
80
70
60
50
40
▼ 31.16
9
8
7
6
5
4
3
2
1
0
-1
-2
0
2
4
6
8
10
12
6.5
3

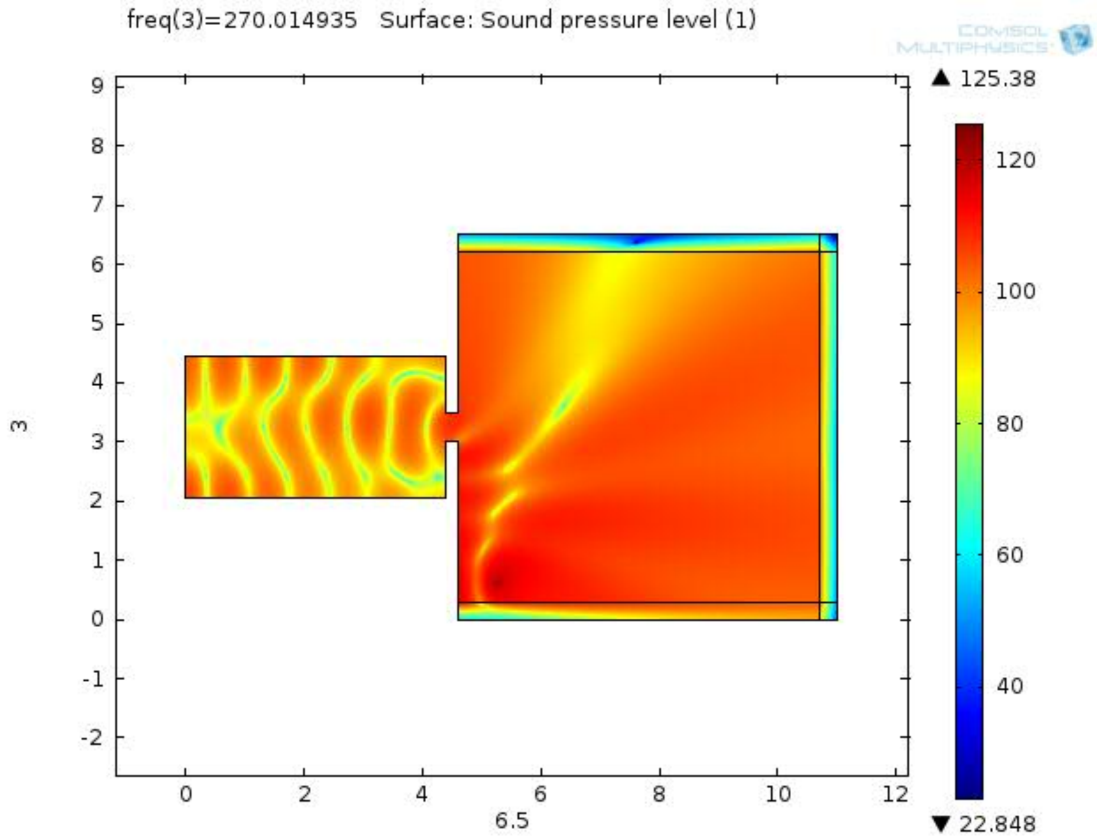


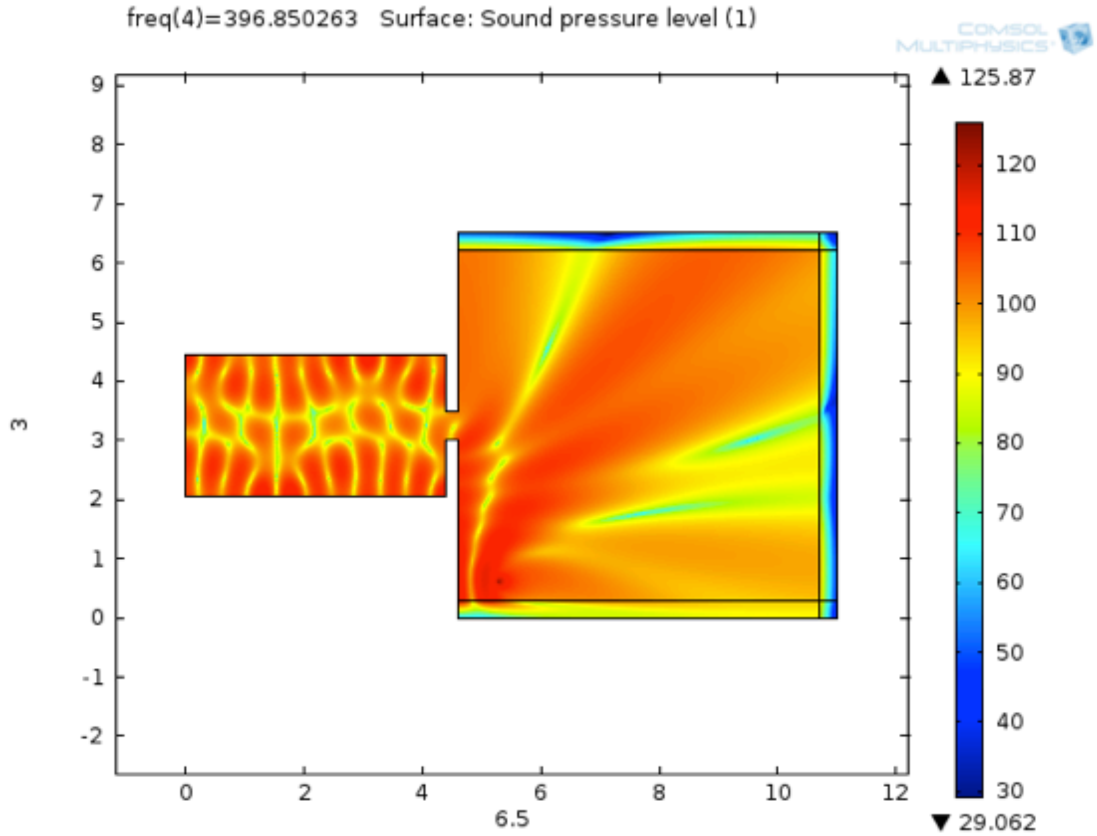


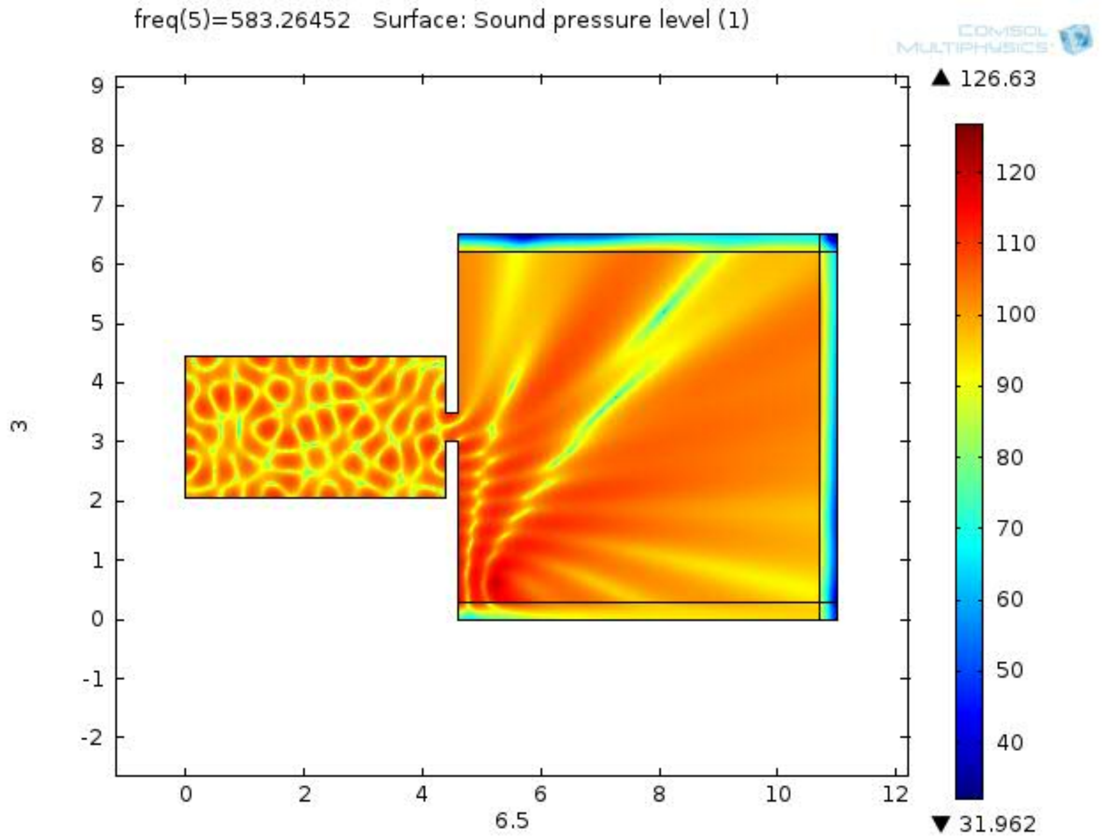
COMSOL SIMULATION for an angle of source incidence +75º and $0.10m^2$ free area:

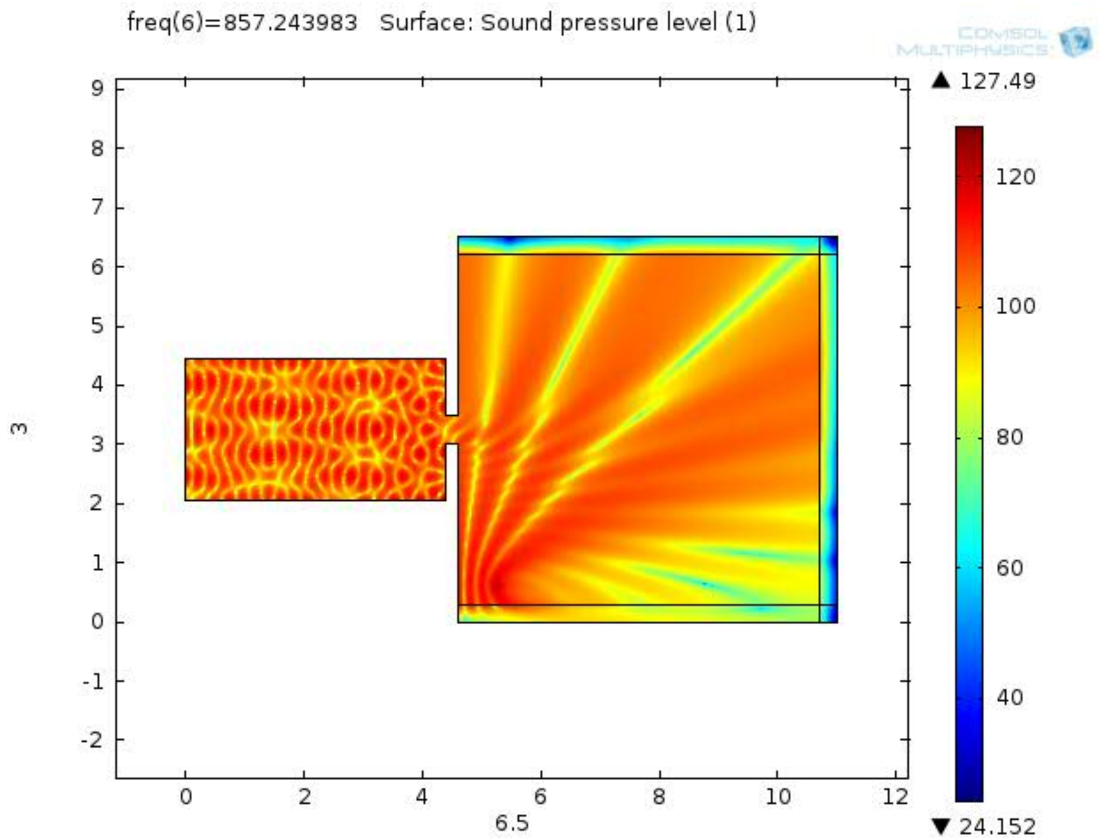

freq(1)=125 Surface: Sound pressure level (1)
COMSOL MULTIPHYSICS
▲ 121.96
▼ 9.621
6.5
3

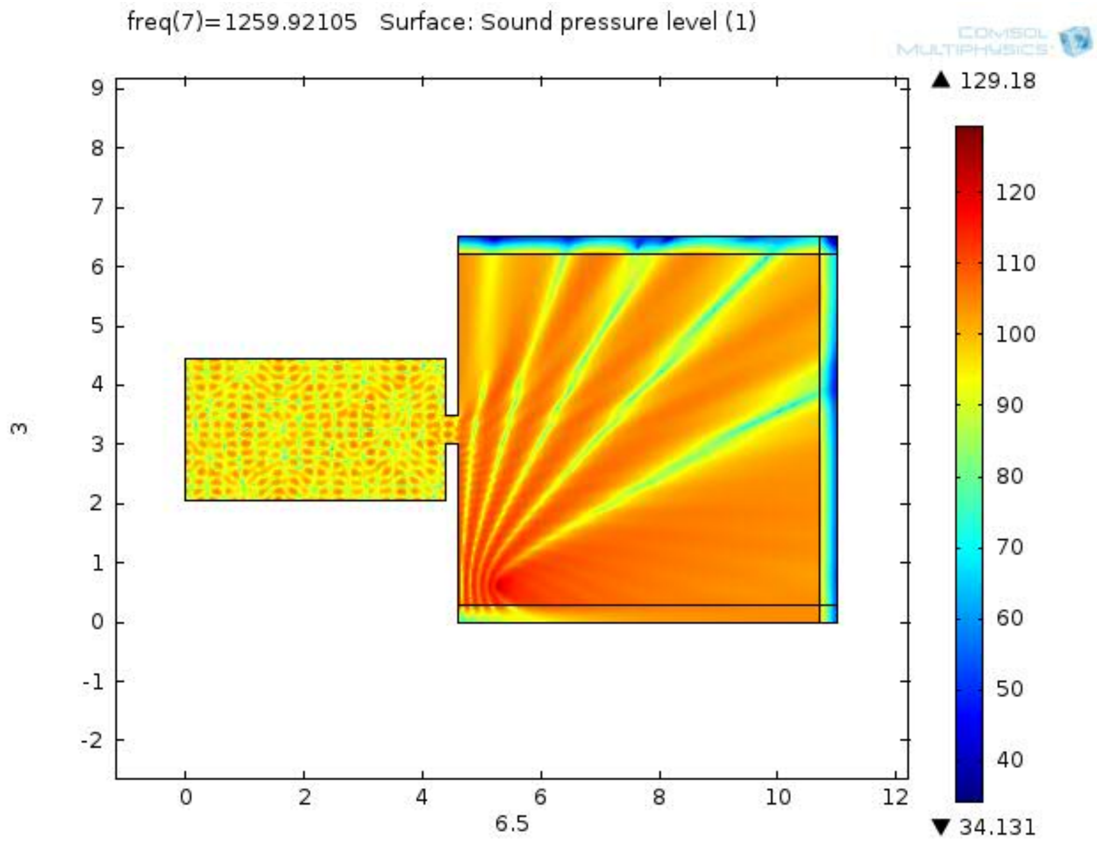

freq(2)=183.716812 Surface: Sound pressure level (1)
COMSOL MULTIPHYSICS
▲ 124.59
▼ 21.058
6.5
3

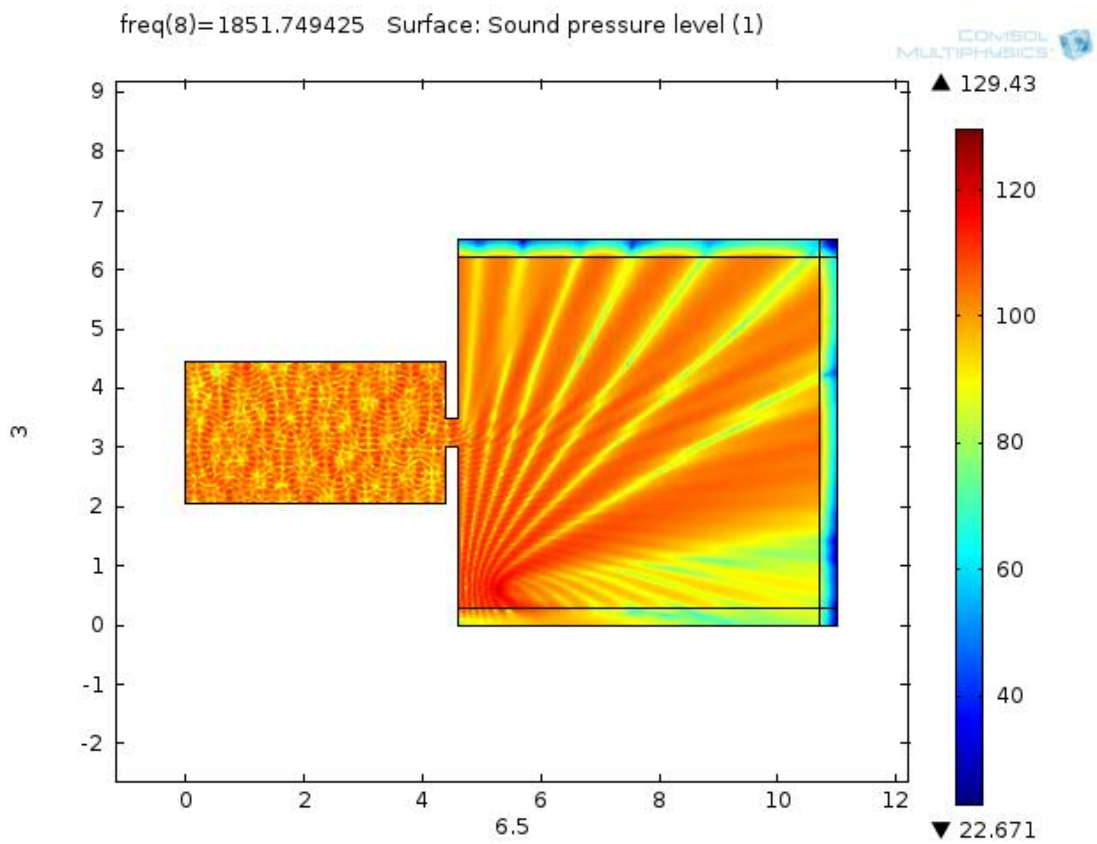

freq(3)=270.014935 Surface: Sound pressure level (1)
COMSOL MULTIPHYSICS
▲ 125.38
▼ 22.848
6.5
3

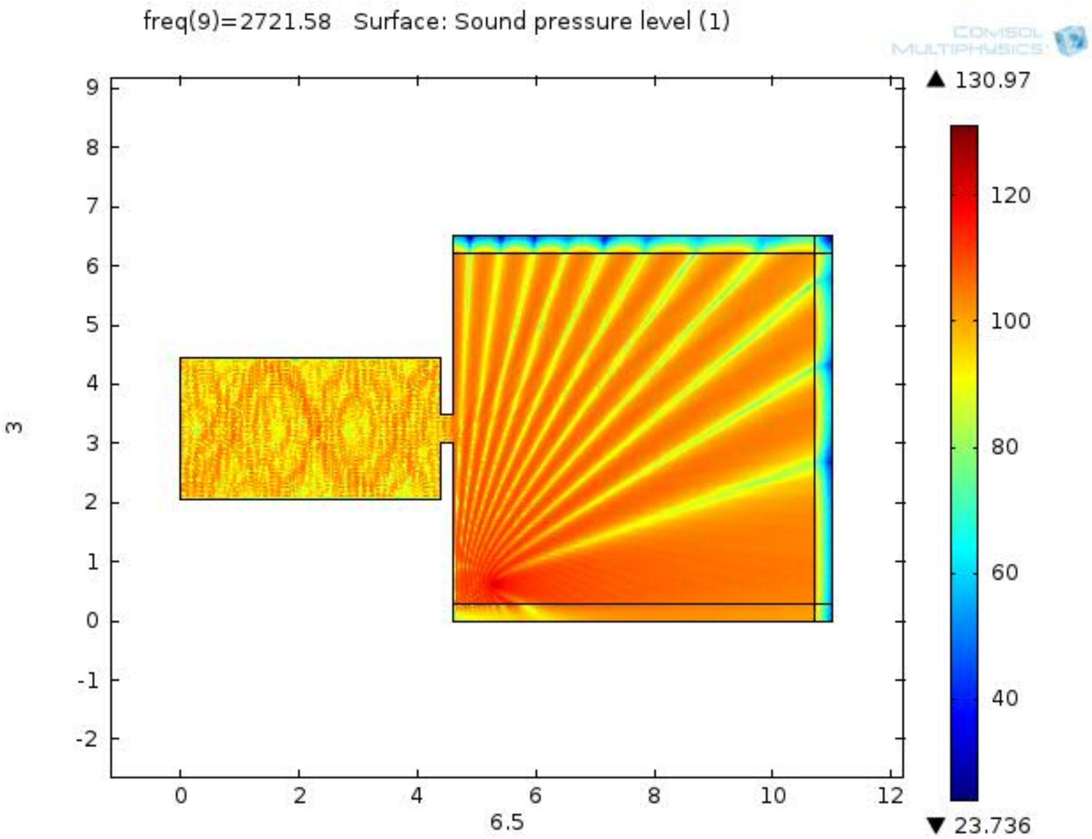

freq(4)=396.850263 Surface: Sound pressure level (1)
COMSOL MULTIPHYSICS
▲ 125.87
▼ 29.062
6.5
3

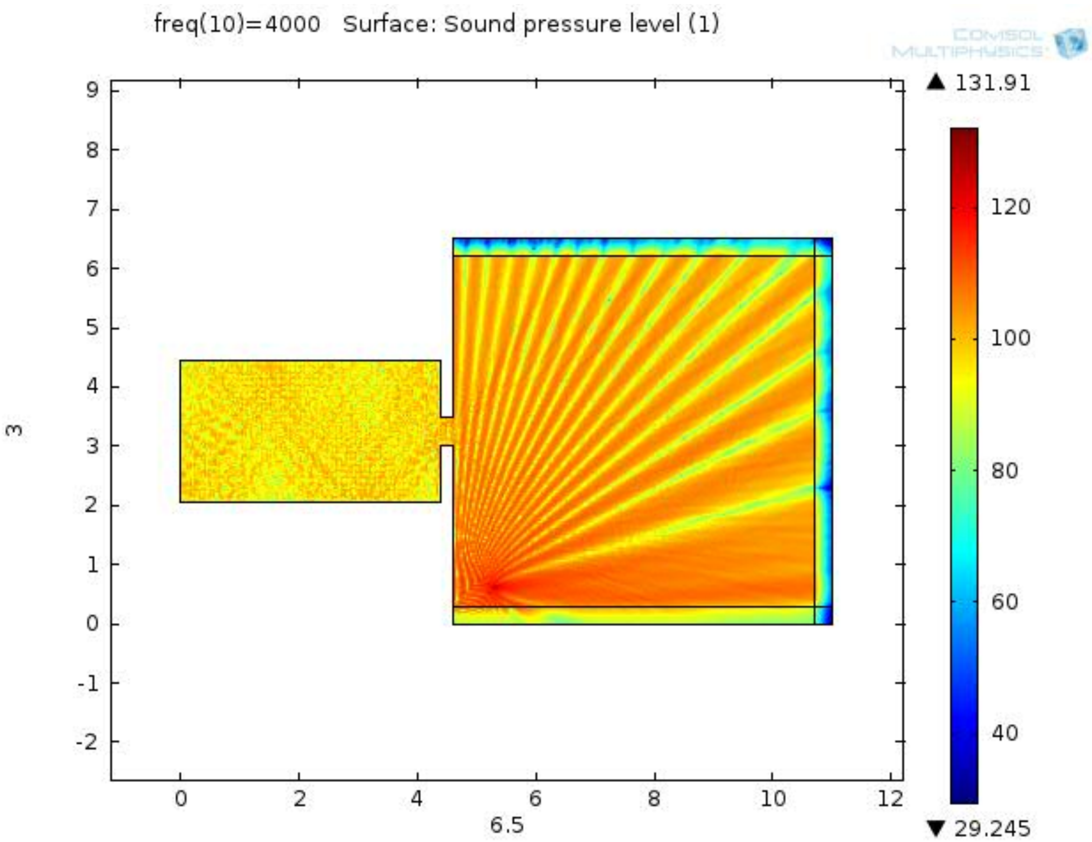

freq(5)=583.26452 Surface: Sound pressure level (1)
COMSOL MULTIPHYSICS
▲ 126.63
▼ 31.962
6.5
3


freq(6)=857.243983 Surface: Sound pressure level (1)
COMSOL MULTIPHYSICS
▲ 127.49
▼ 24.152
6.5
3

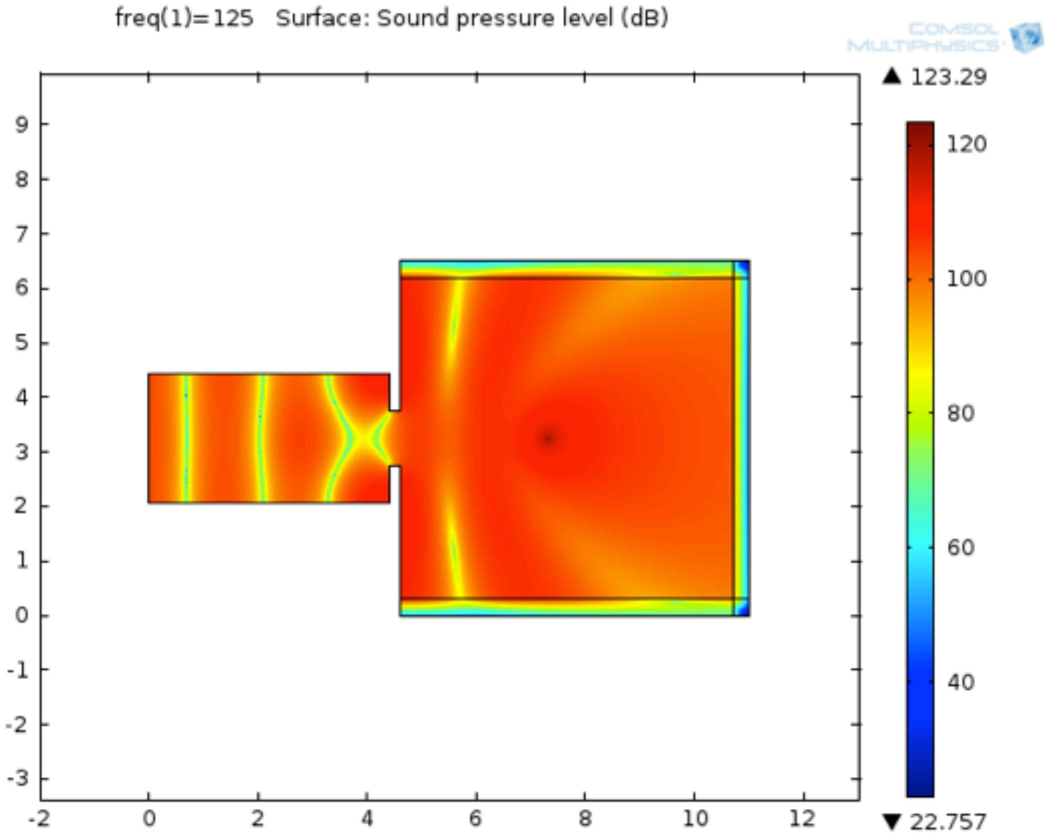

freq(7)=1259.92105 Surface: Sound pressure level (1)
▲ 129.18
▼ 34.131
6.5
3

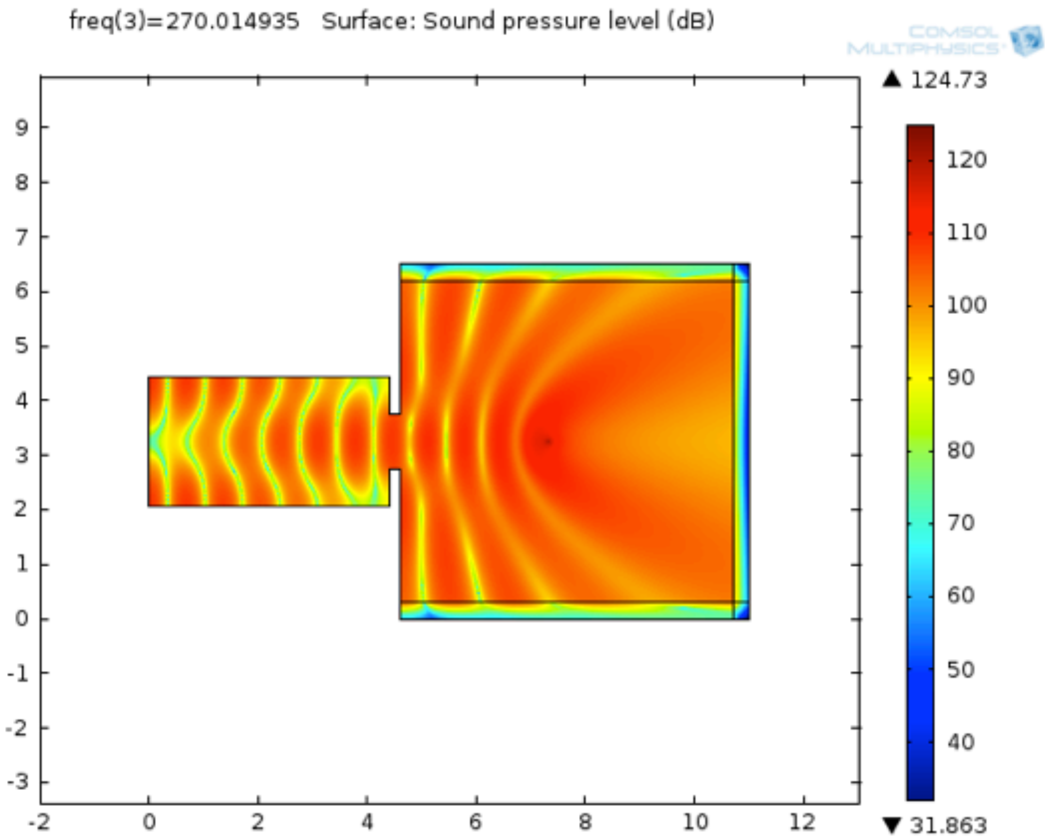

freq(8)=1851.749425 Surface: Sound pressure level (1)
▲ 129.43
▼ 22.671
6.5
3

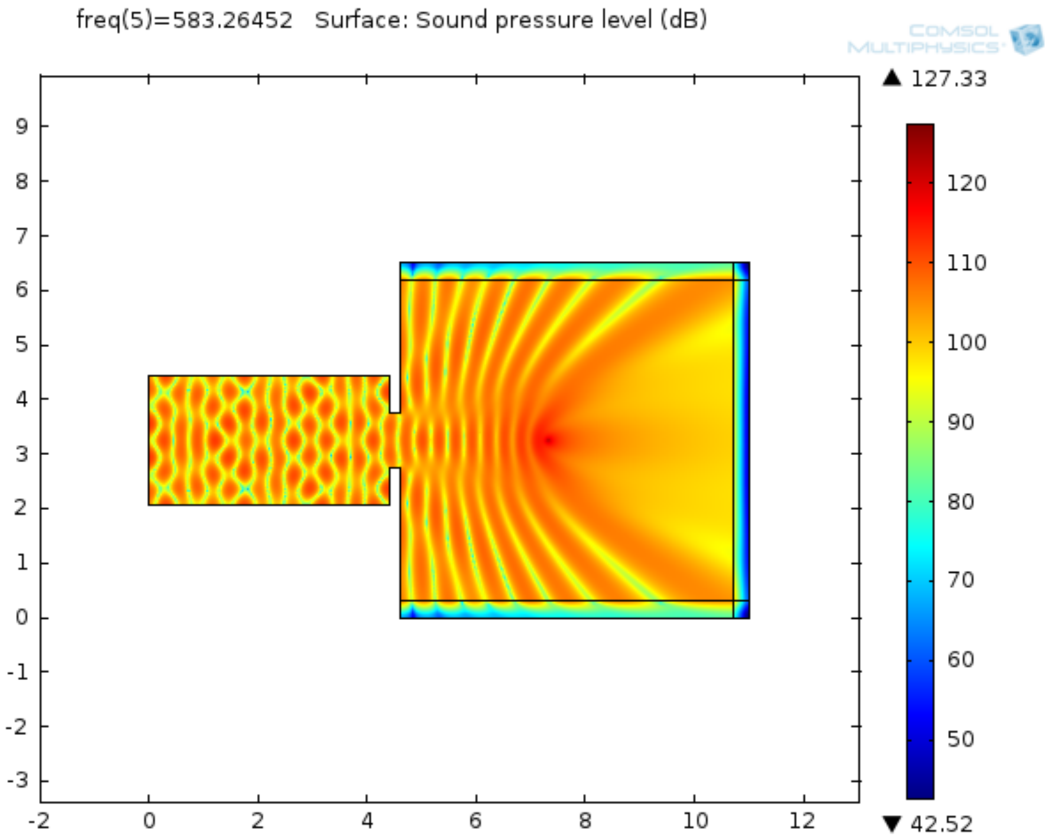

freq(9)=2721.58 Surface: Sound pressure level (1)
▲ 130.97
▼ 23.736
120
100
80
60
40
3
6.5
9
8
7
6
5
4
2
1
0
-1
-2
0
2
4
6
8
10
12

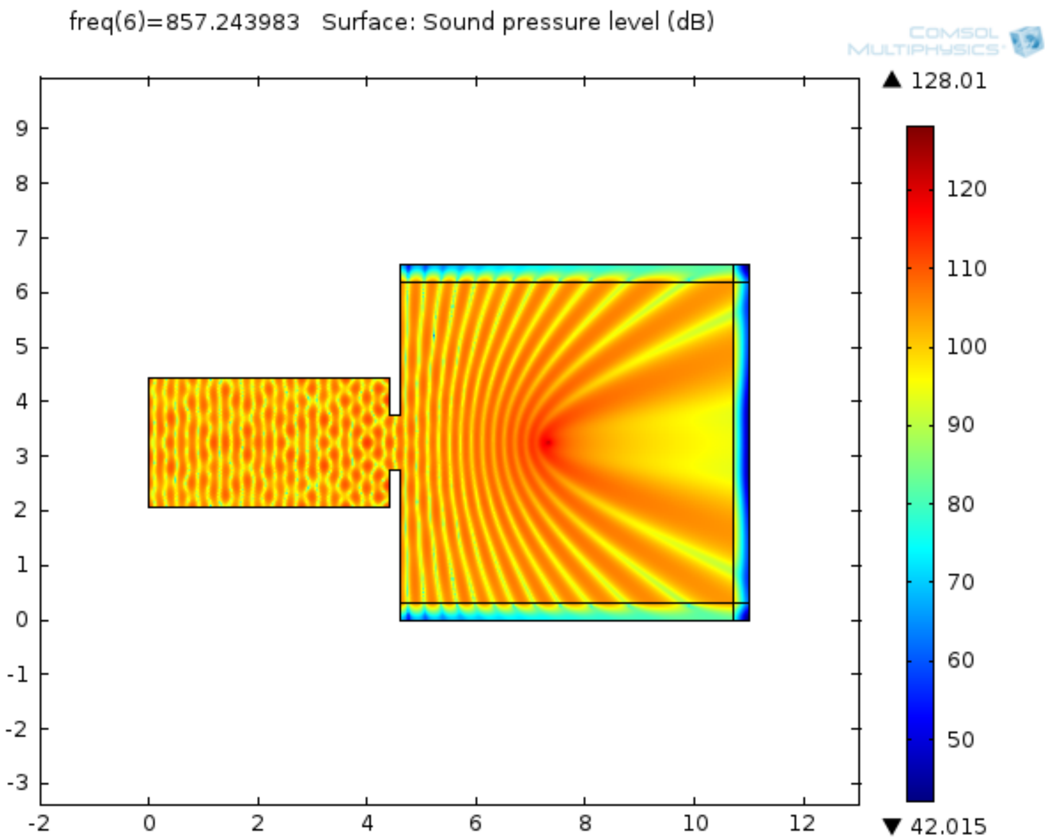

freq(10)=4000 Surface: Sound pressure level (1)
▲ 131.91
▼ 29.245
120
100
80
60
40
3
6.5
9
8
7
6
5
4
2
1
0
-1
-2
0
2
4
6
8
10
12

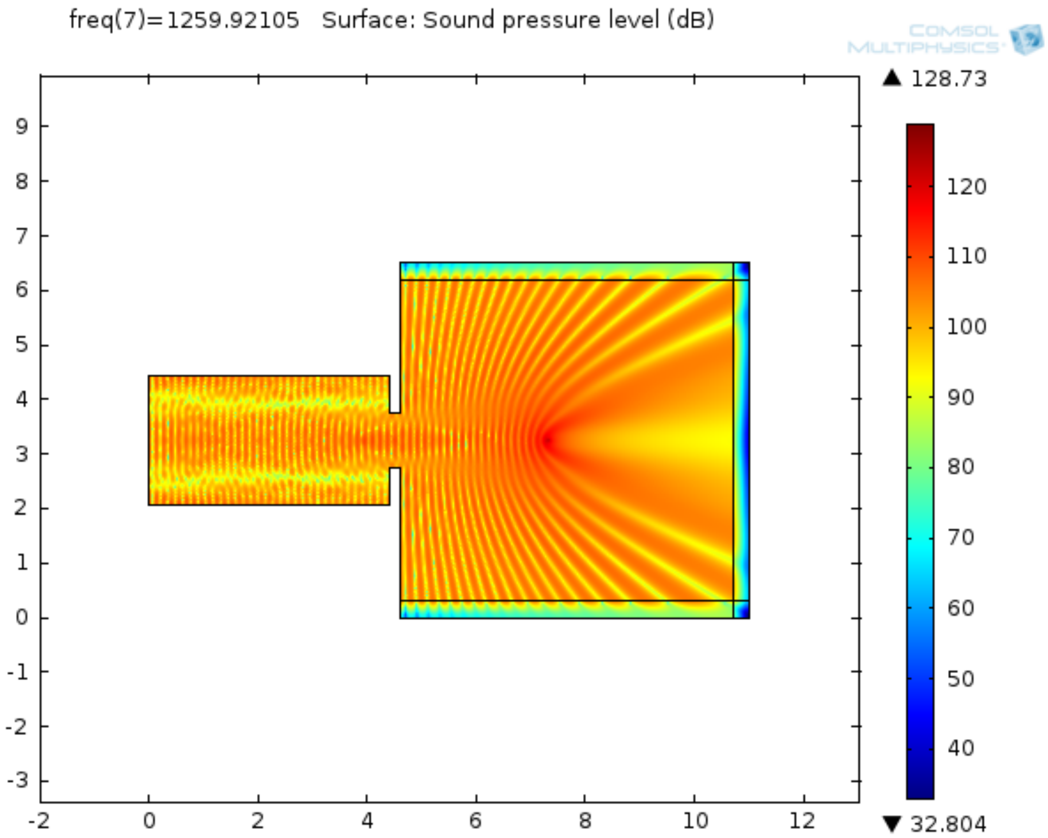
COMSOL SIMULATION for an angle of source incidence +0º and 0.20m² free area:

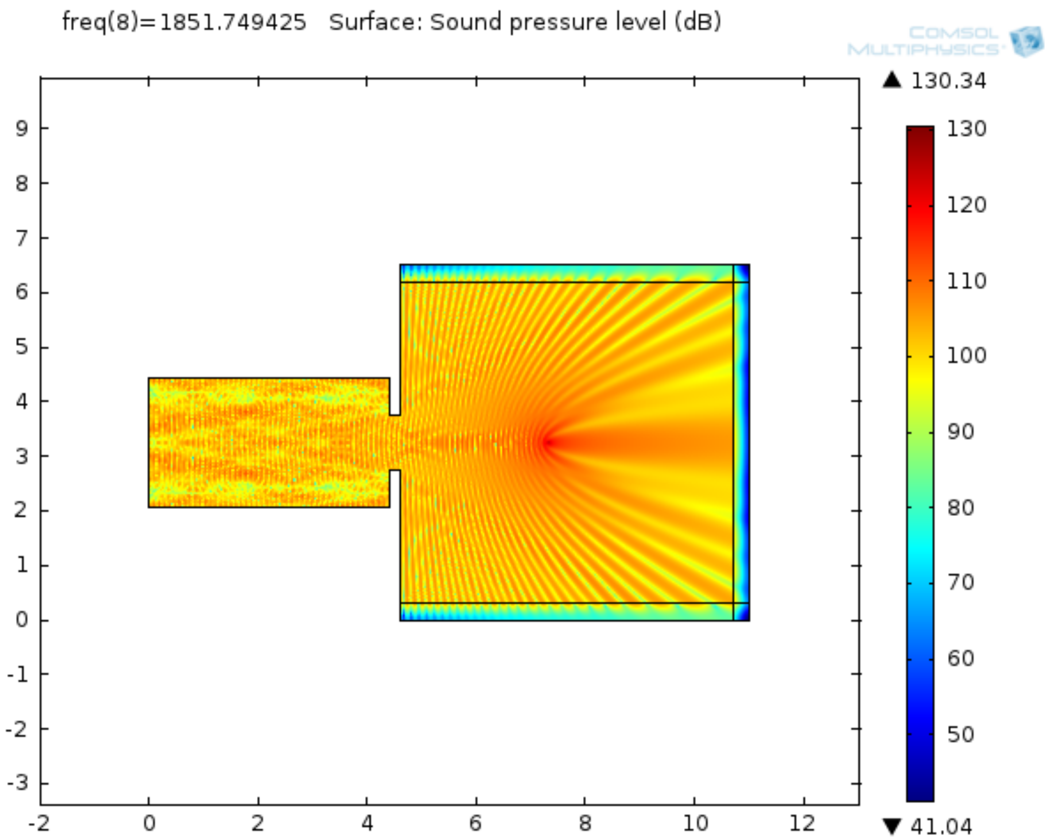


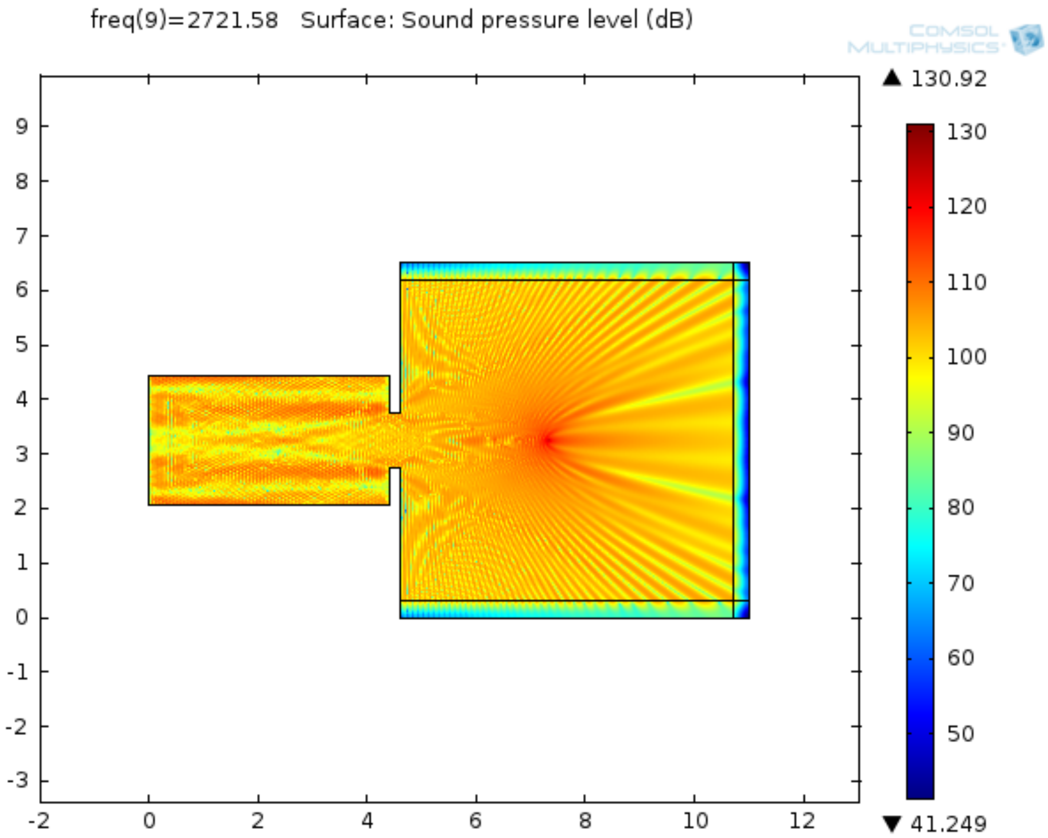


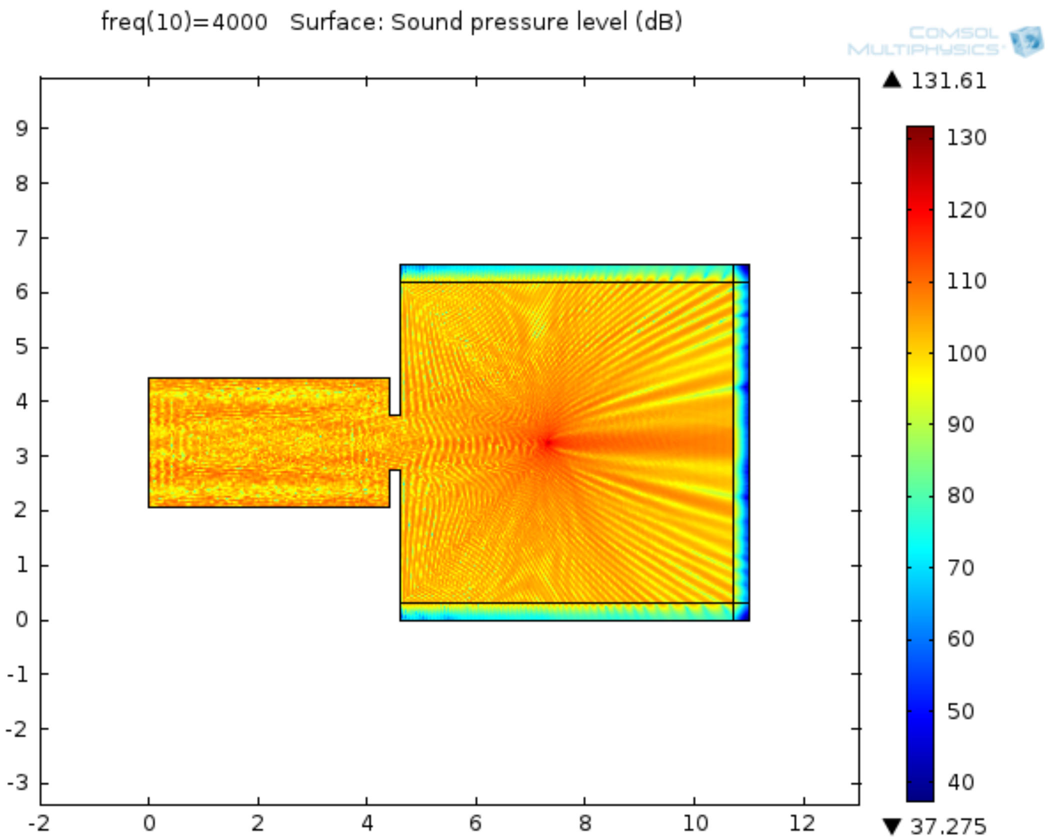

freq(5)=583.26452 Surface: Sound pressure level (dB)
▲ 127.33
120
110
100
90
80
70
60
50
▼ 42.52
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-2
0
2
4
6
8
10
12


freq(6)=857.243983 Surface: Sound pressure level (dB)
▲ 128.01
120
110
100
90
80
70
60
50
▼ 42.015
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-2
0
2
4
6
8
10
12

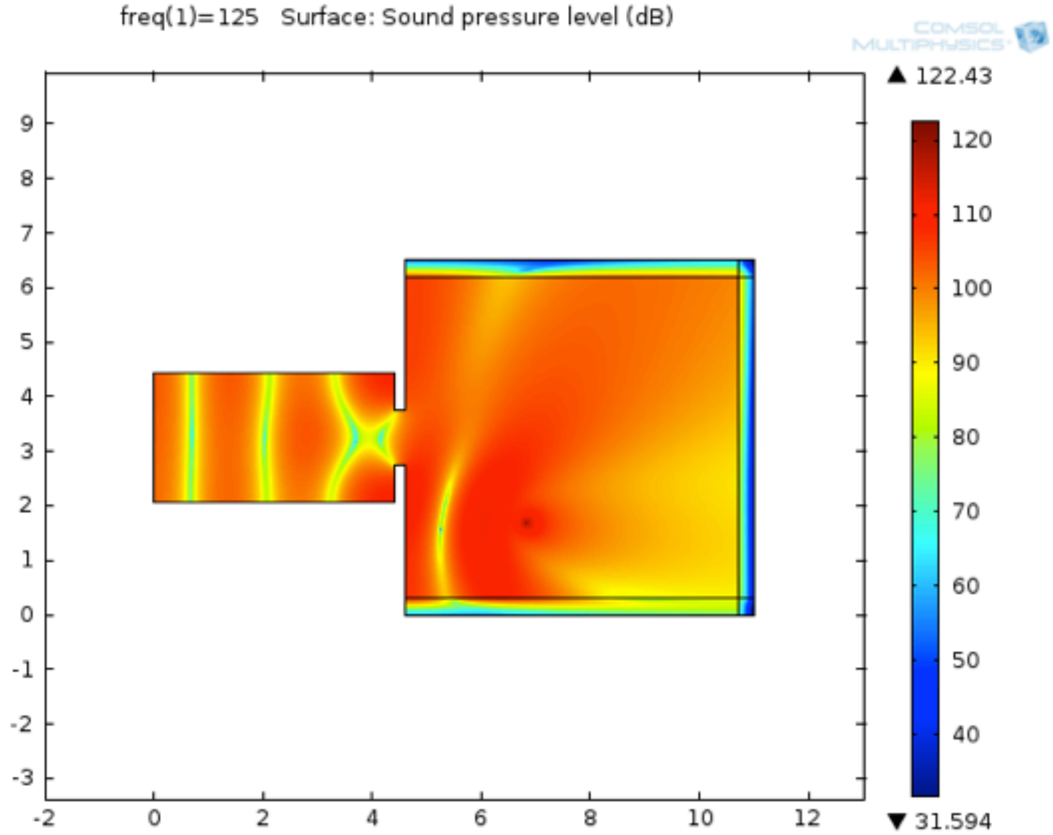

freq(7)=1259.92105 Surface: Sound pressure level (dB)
COMSOL MULTIPHYSICS
▲ 128.73
▼ 32.804
120
110
100
90
80
70
60
50
40
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-2
0
2
4
6
8
10
12

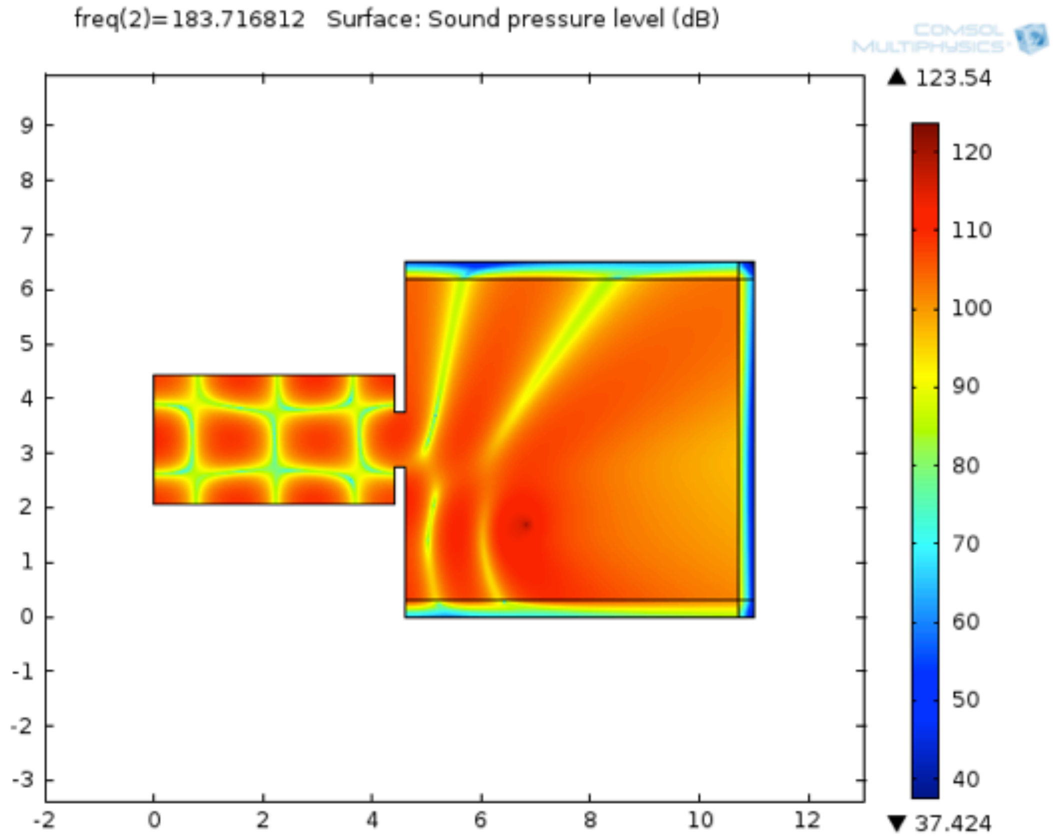

freq(8)=1851.749425 Surface: Sound pressure level (dB)
COMSOL MULTIPHYSICS
▲ 130.34
▼ 41.04
130
120
110
100
90
80
70
60
50
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-2
0
2
4
6
8
10
12

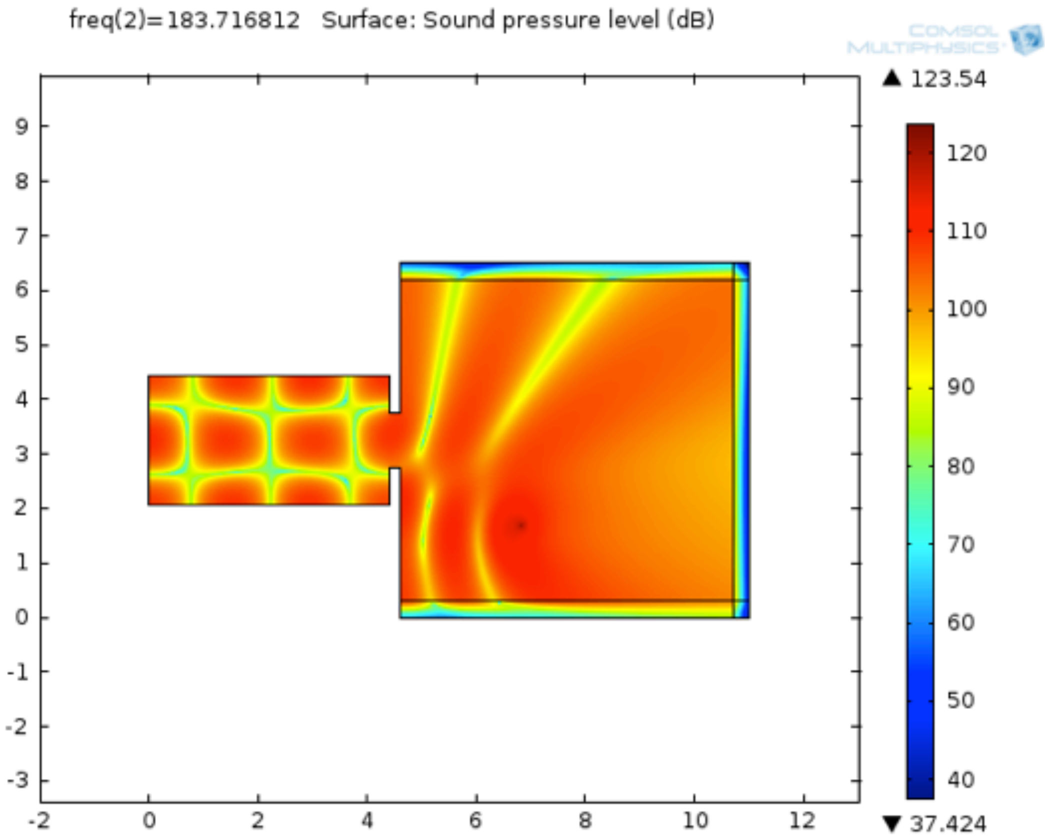

freq(9)=2721.58 Surface: Sound pressure level (dB)
COMSOL MULTIPHYSICS
▲ 130.92
▼ 41.249
130
120
110
100
90
80
70
60
50
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-2
0
2
4
6
8
10
12

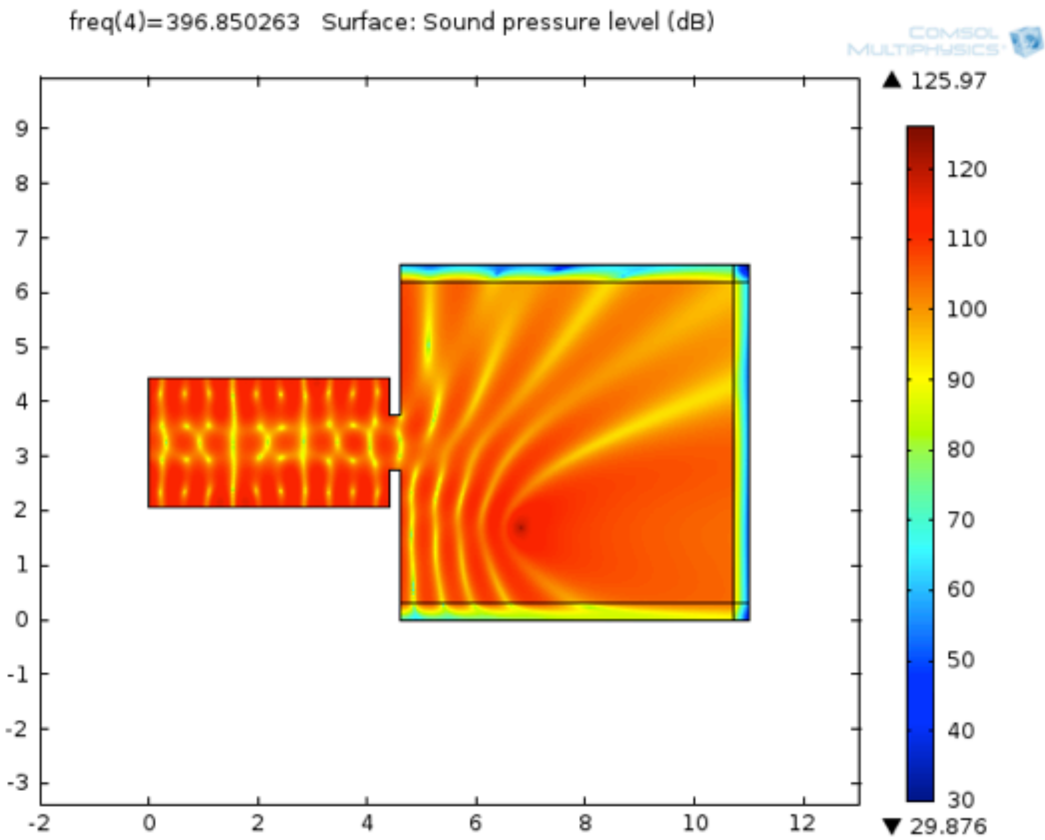

freq(10)=4000 Surface: Sound pressure level (dB)
COMSOL MULTIPHYSICS
▲ 131.61
▼ 37.275
130
120
110
100
90
80
70
60
50
40
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-2
0
2
4
6
8
10
12

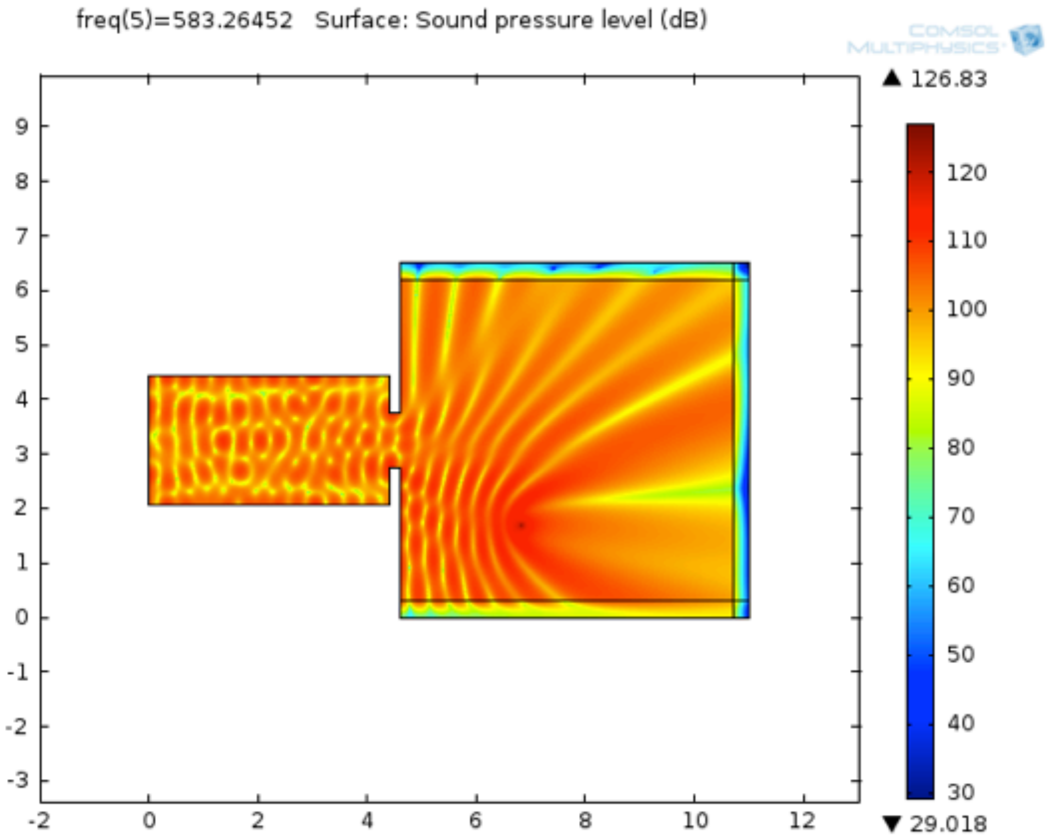
COMSOL SIMULATION for an angle of source incidence +35º and 0.20m^2 free area:

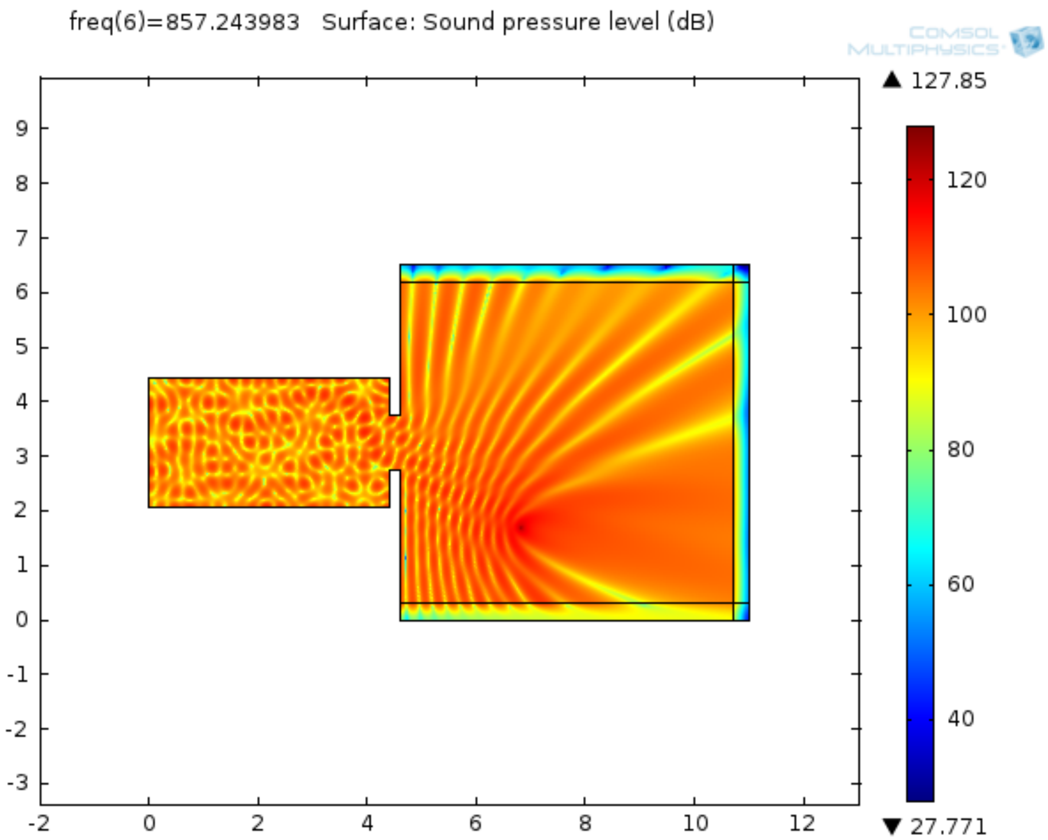


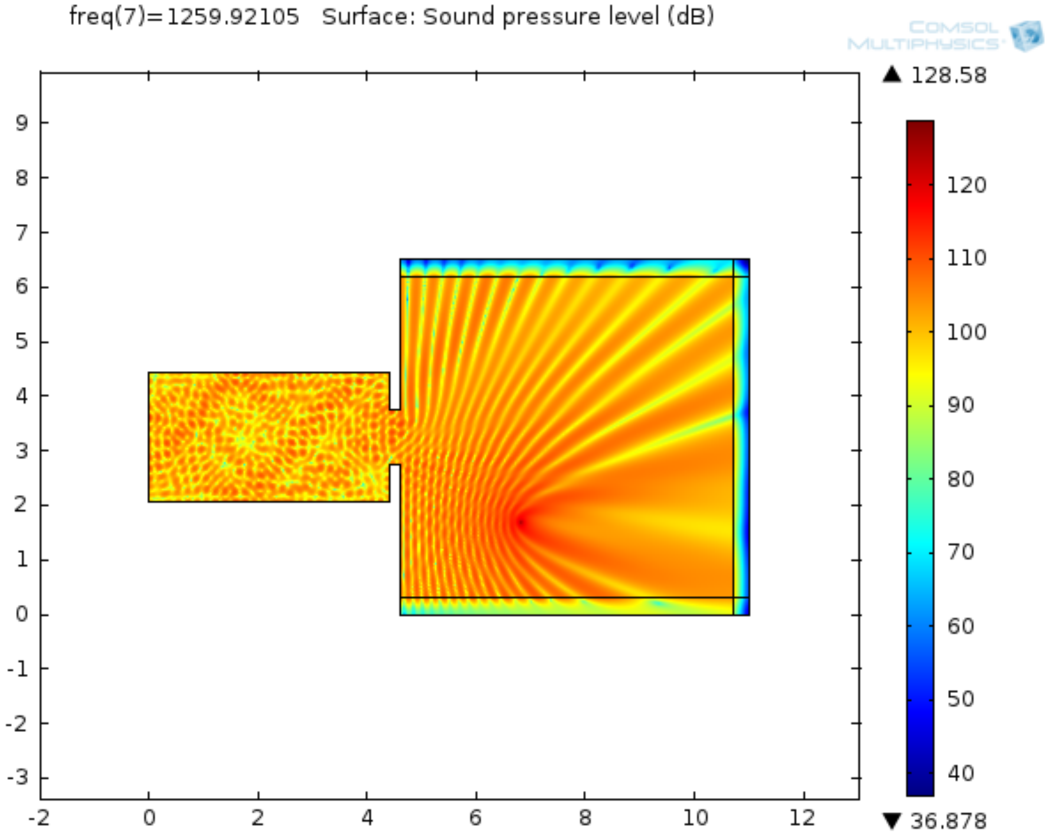


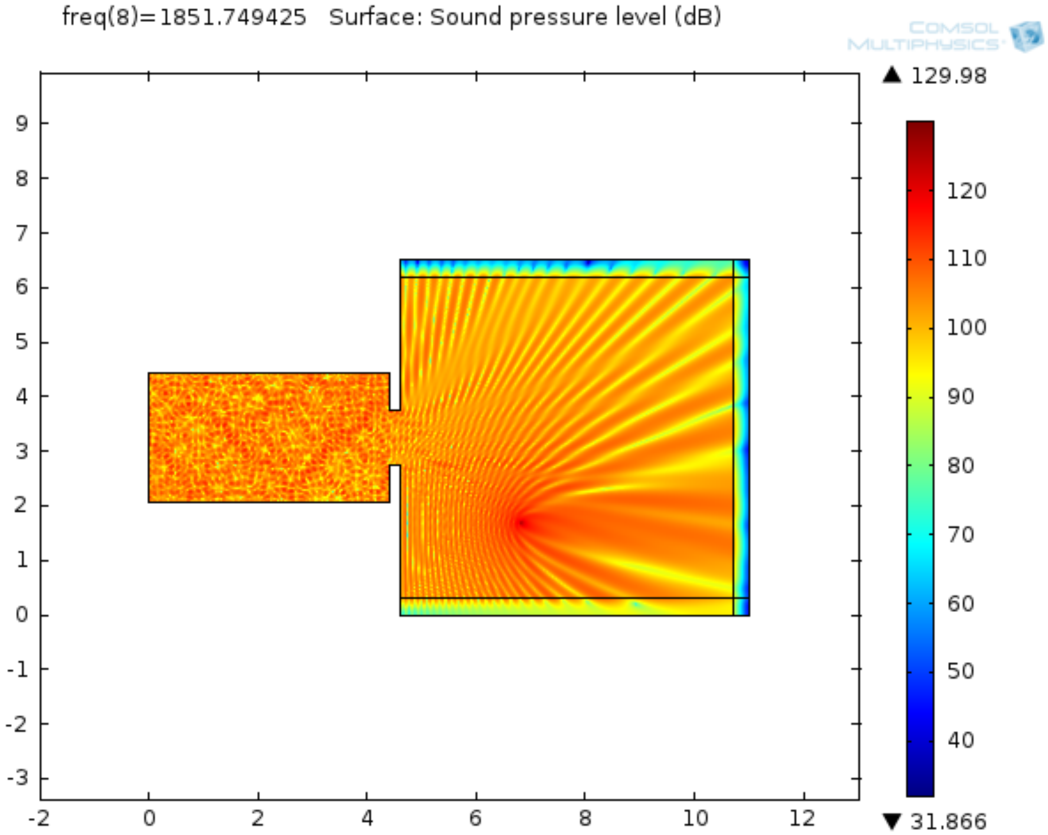

freq(2)=183.716812 Surface: Sound pressure level (dB)
▲ 123.54
120
110
100
90
80
70
60
50
40
▼ 37.424
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-2
0
2
4
6
8
10
12

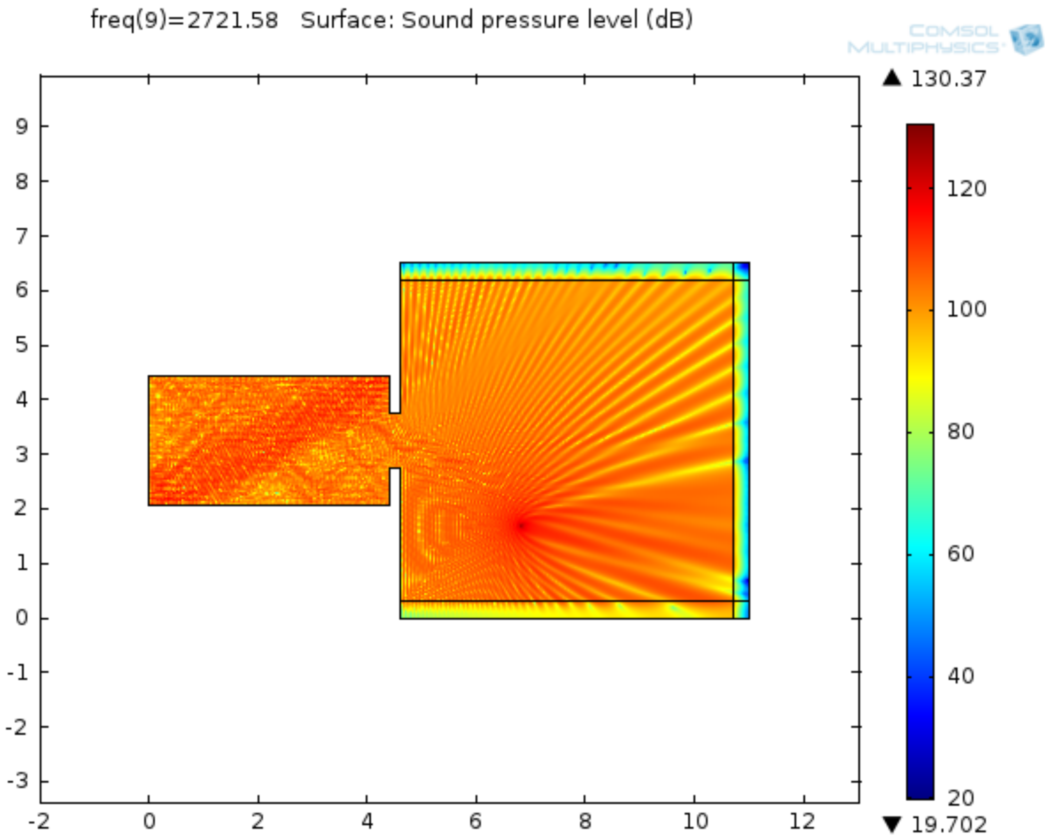

freq(4)=396.850263 Surface: Sound pressure level (dB)
▲ 125.97
120
110
100
90
80
70
60
50
40
30
▼ 29.876
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-2
0
2
4
6
8
10
12

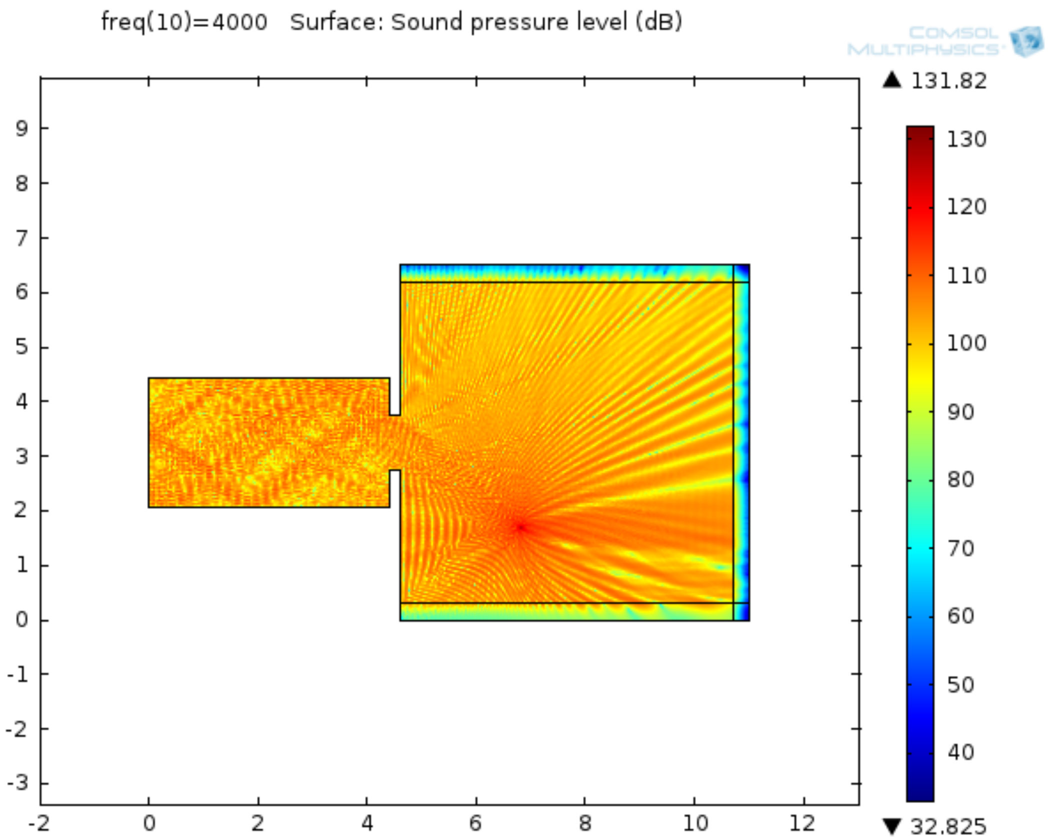

freq(5)=583.26452 Surface: Sound pressure level (dB)
▲ 126.83
▼ 29.018
120
110
100
90
80
70
60
50
40
30
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-2
0
2
4
6
8
10
12


freq(6)=857.243983 Surface: Sound pressure level (dB)
▲ 127.85
▼ 27.771
120
100
80
60
40
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-2
0
2
4
6
8
10
12

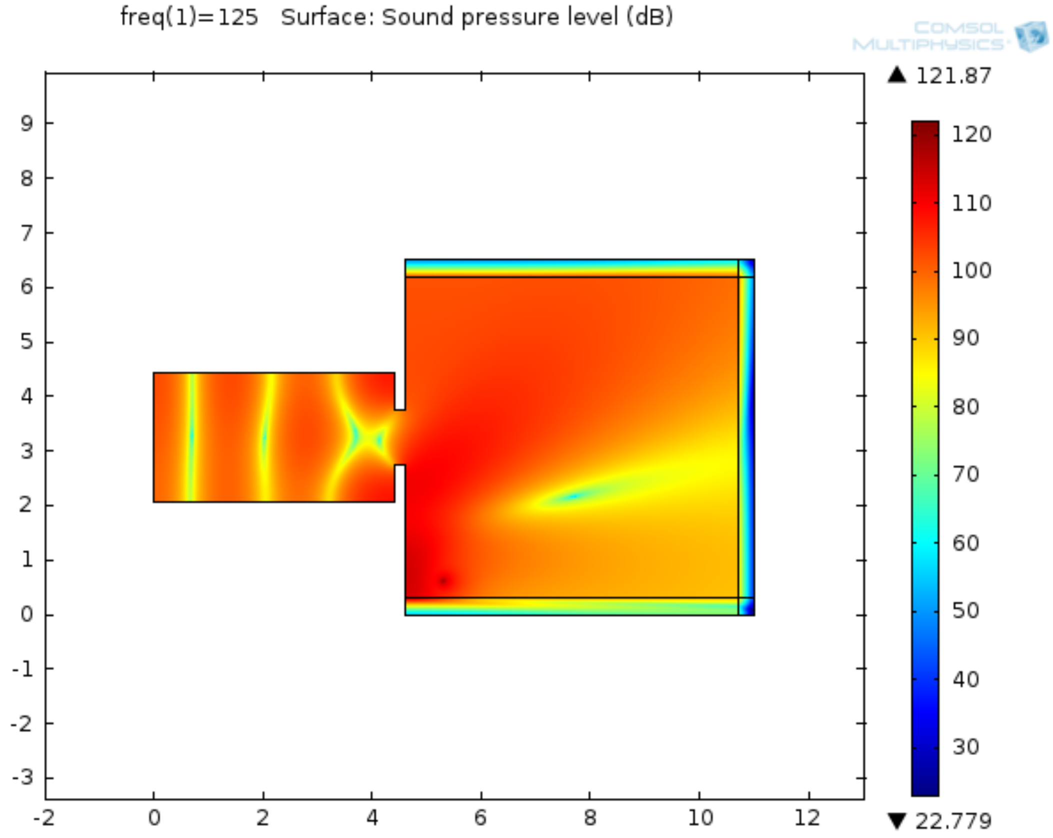

freq(7)=1259.92105 Surface: Sound pressure level (dB)
▲ 128.58
120
110
100
90
80
70
60
50
40
▼ 36.878
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-2
0
2
4
6
8
10
12

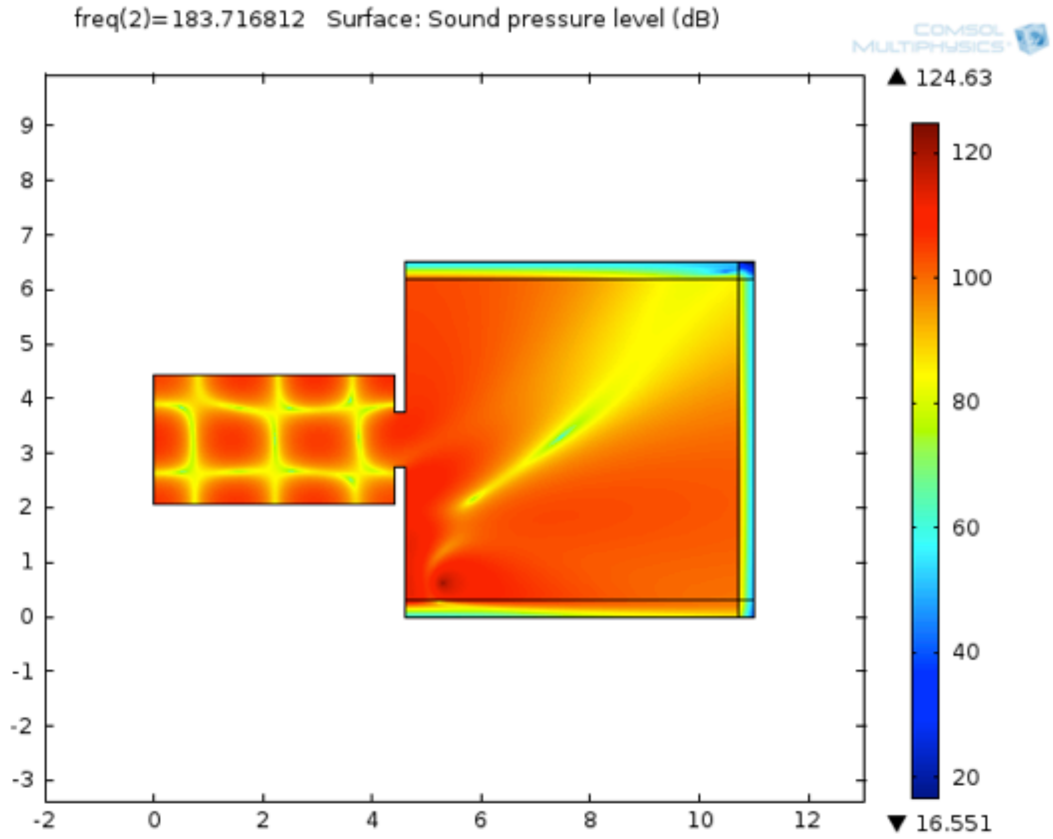

freq(8)=1851.749425 Surface: Sound pressure level (dB)
▲ 129.98
120
110
100
90
80
70
60
50
40
▼ 31.866
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-2
0
2
4
6
8
10
12

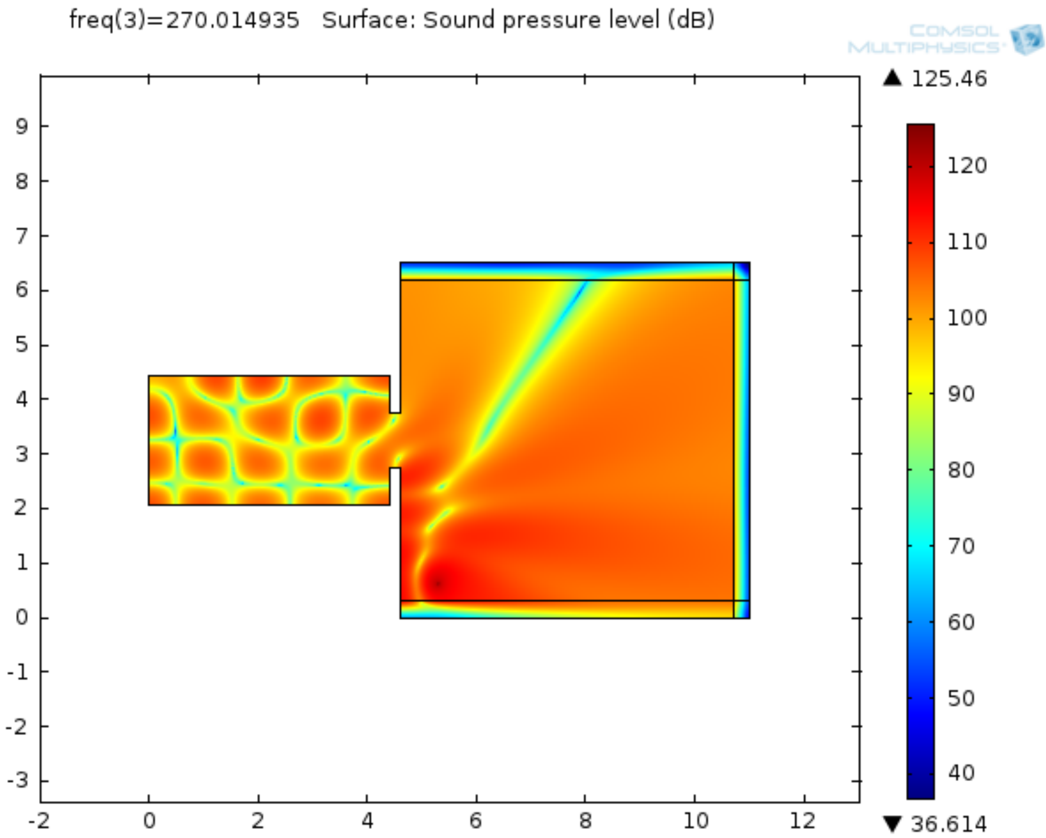

freq(9)=2721.58 Surface: Sound pressure level (dB)
COMSOL MULTIPHYSICS
▲ 130.37
▼ 19.702

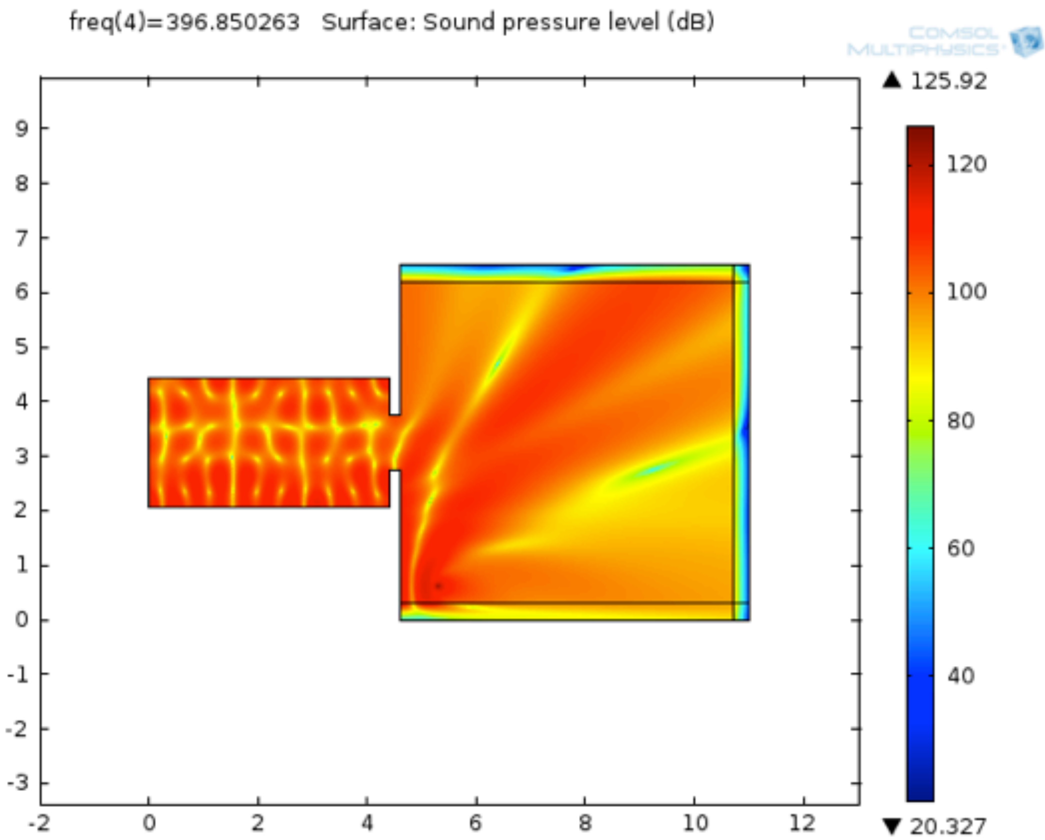

freq(10)=4000 Surface: Sound pressure level (dB)
COMSOL MULTIPHYSICS
▲ 131.82
▼ 32.825

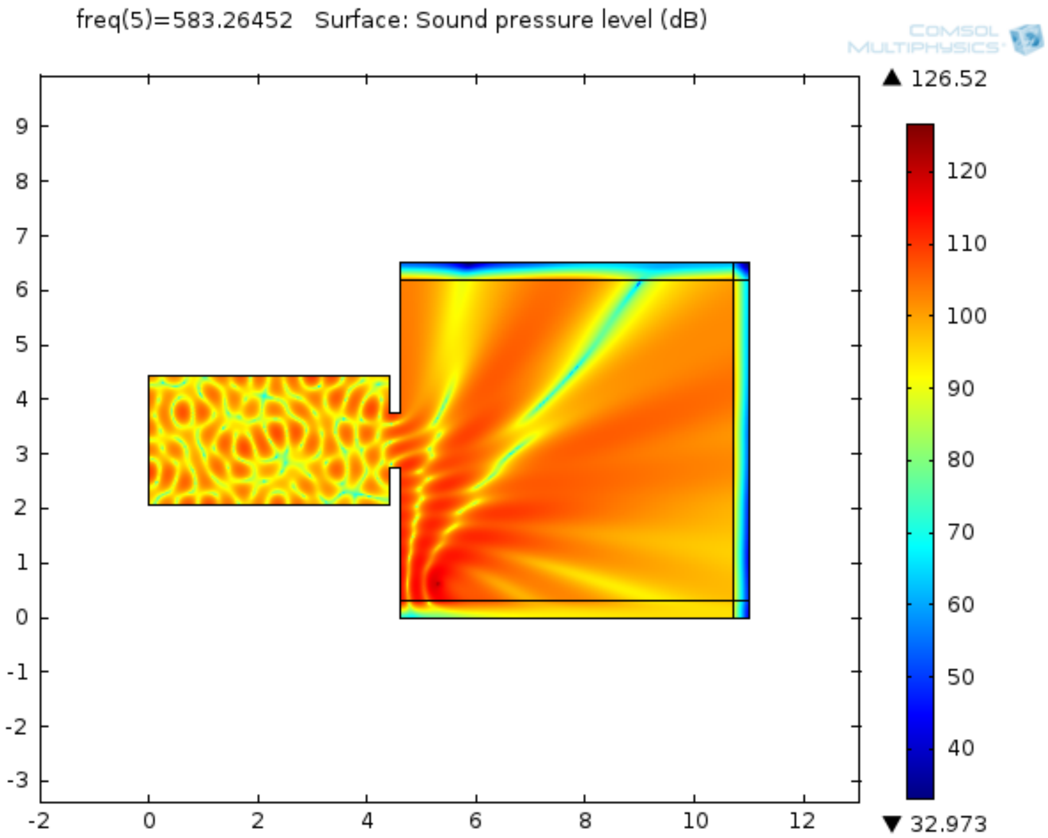
COMSOL SIMULATION for an angle of source incidence +70º and $0.20m^2$ free area:

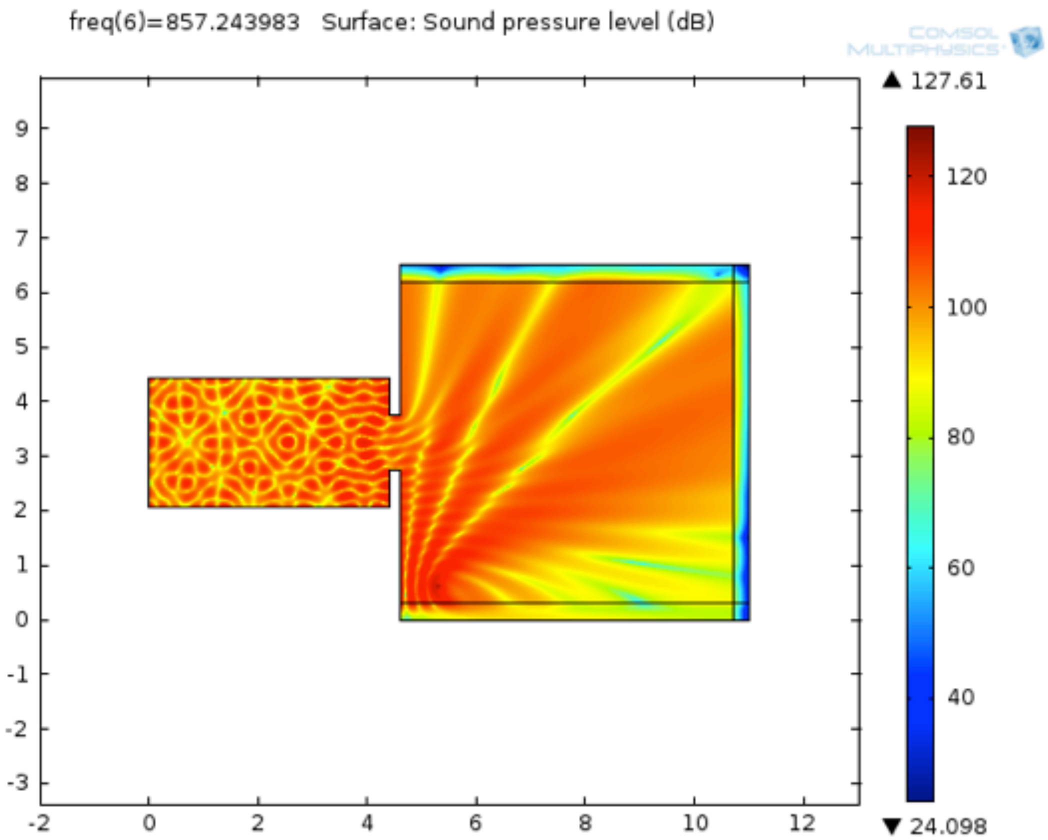


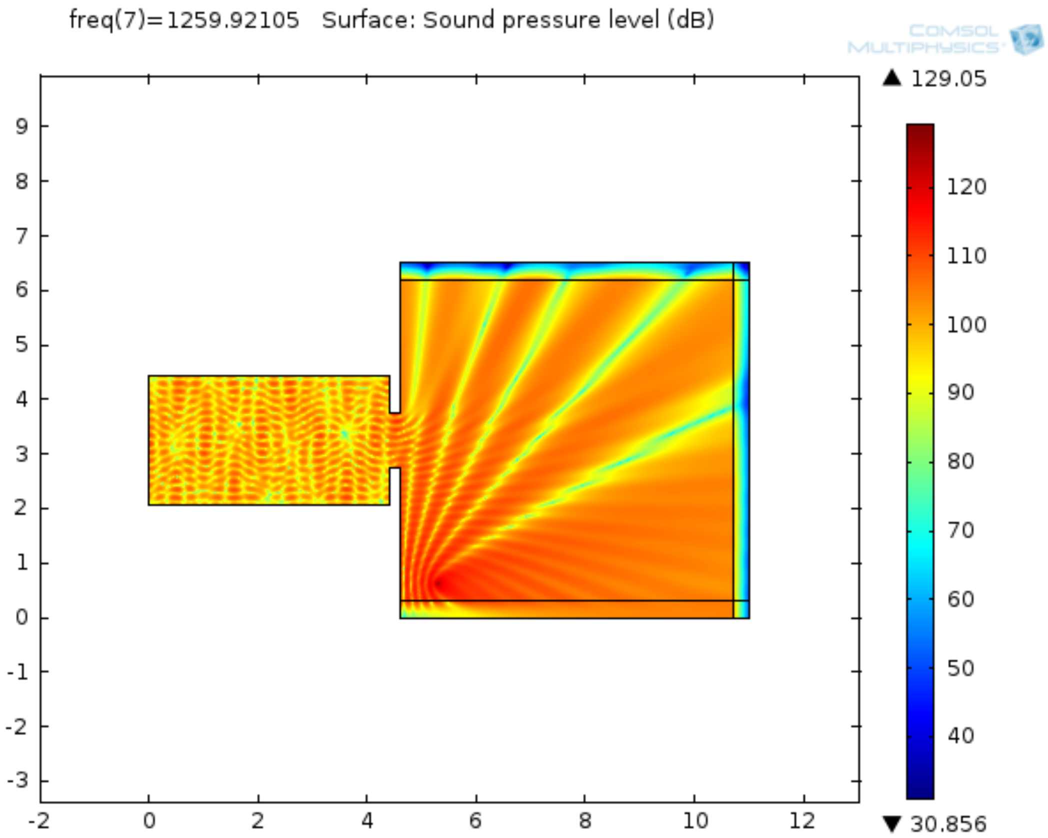


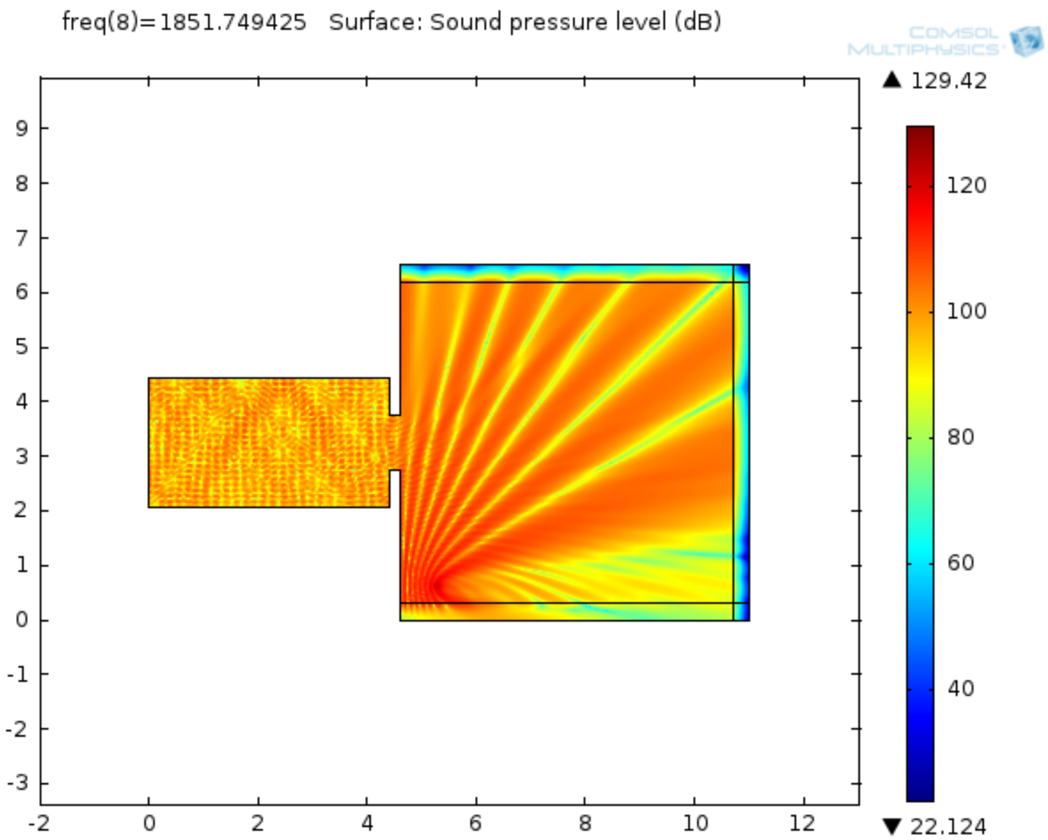

freq(3)=270.014935 Surface: Sound pressure level (dB)
▲ 125.46
▼ 36.614
120
110
100
90
80
70
60
50
40
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-2
0
2
4
6
8
10
12

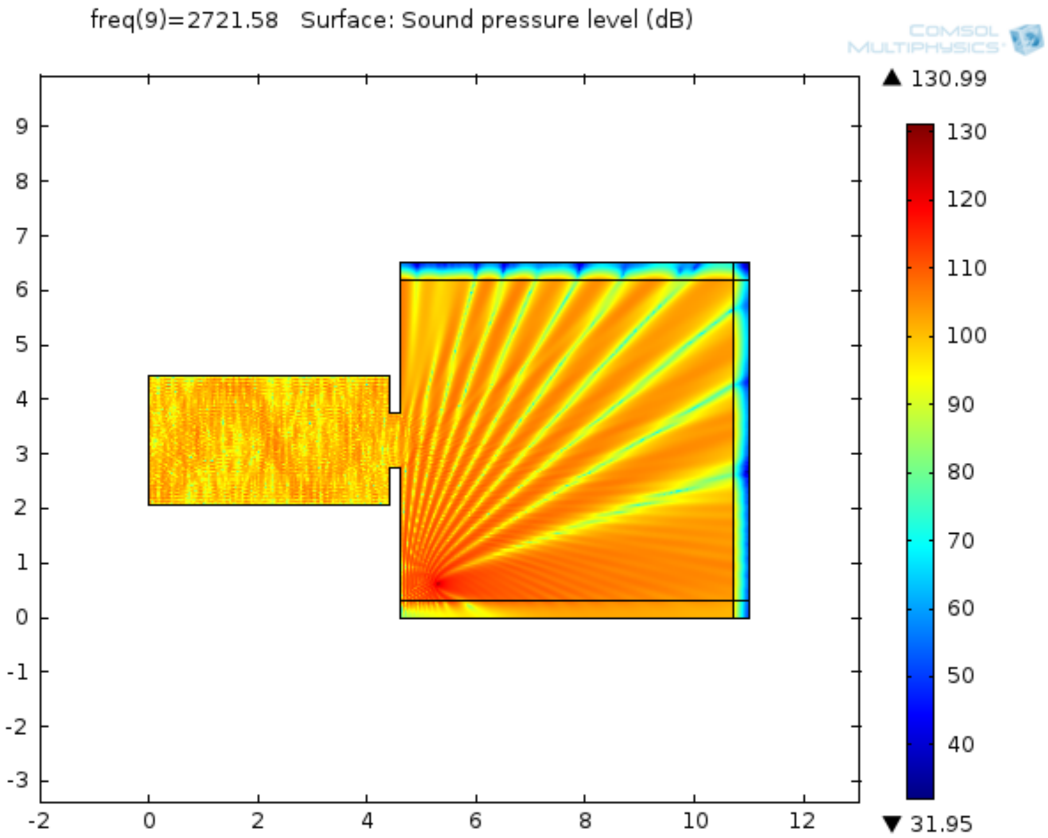

freq(4)=396.850263 Surface: Sound pressure level (dB)
▲ 125.92
▼ 20.327
120
100
80
60
40
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-2
0
2
4
6
8
10
12

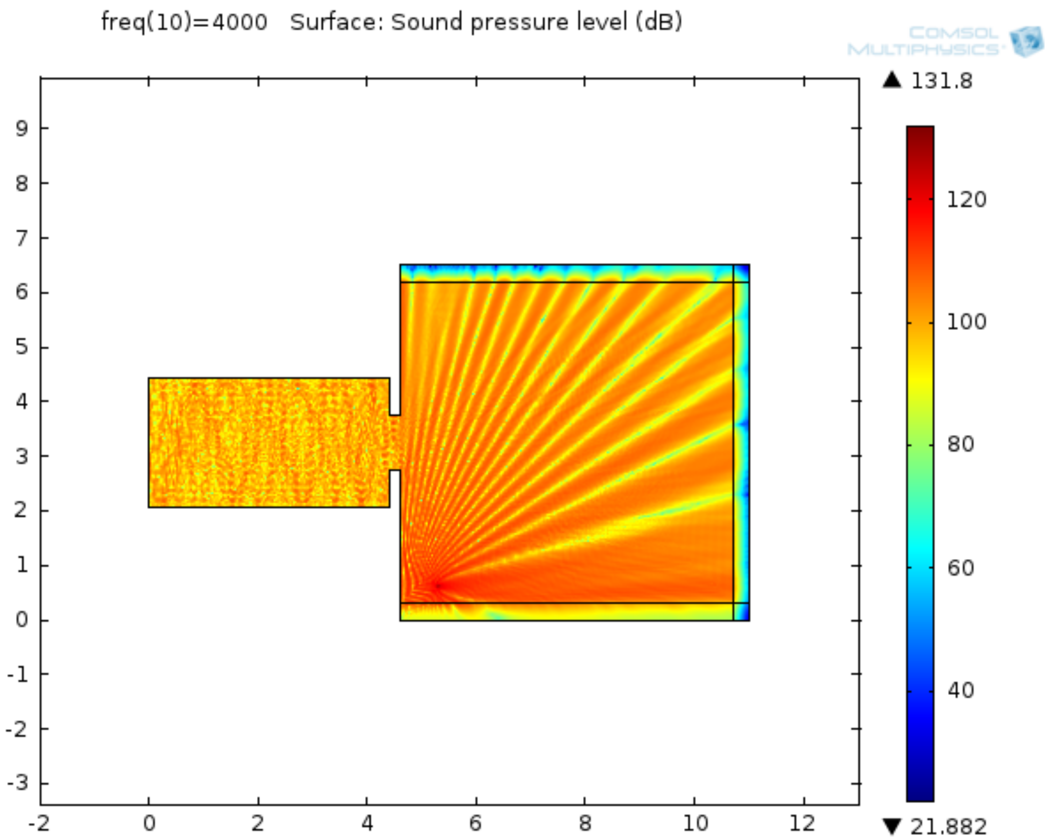

freq(5)=583.26452 Surface: Sound pressure level (dB)
COMSOL MULTIPHYSICS
▲ 126.52
120
110
100
90
80
70
60
50
40
▼ 32.973
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-2
0
2
4
6
8
10
12


freq(6)=857.243983 Surface: Sound pressure level (dB)
COMSOL MULTIPHYSICS
▲ 127.61
120
100
80
60
40
▼ 24.098
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-2
0
2
4
6
8
10
12


freq(7)=1259.92105 Surface: Sound pressure level (dB)
▲ 129.05
▼ 30.856


freq(8)=1851.749425 Surface: Sound pressure level (dB)
▲ 129.42
▼ 22.124


freq(9)=2721.58 Surface: Sound pressure level (dB)
COMSOL MULTIPHYSICS
▲ 130.99
▼ 31.95
130
120
110
100
90
80
70
60
50
40
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-2
0
2
4
6
8
10
12


freq(10)=4000 Surface: Sound pressure level (dB)
COMSOL MULTIPHYSICS
▲ 131.8
▼ 21.882
120
100
80
60
40
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-2
0
2
4
6
8
10
12

APPENDIX 4. DnT (dB) calculation for the numerical model:

- Opening area 0.10m^2 in 0º:

		SOURCE ROOM		RECEIVER ROOM				
	LOUDSPEAKE R L 0º	S1	S2	R1	R2	R3	R4	R5
PT1	x=7,32/y=3,2 5	x= 5,6/y=3,2 5	x=6,6/y=3 ,25	x=3.6/y= 3.25	x=2.6/y= 3.25	x=2,1/y= 2,75	x=1,3/ y=3	x=3,1/y= 3,75
125	123,4	103,2	104,8	87,3	97,7	78,2	96,2	94,5
184	124,6	108,3	109,3	99,6	106,3	79,0	107,5	96,7
270	124,7	103,5	108,7	102,7	100,5	89,3	89,5	101,4
397	126,1	102,8	107,6	106,8	106,4	102,0	97,9	108,2
583	127,1	101,3	108,4	117,4	107,7	104,4	108,8	105,9
857	127,9	107,4	109,9	109,5	108,9	102,8	97,6	95,1
1.2 60	128,9	106,7	108,6	98,7	105,5	96,6	88,8	81,4
1.8 52	129,8	105,2	110,0	109,7	98,3	97,2	105,5	99,5
272 2	130,8	110,5	109,6	99,1	110,4	108,9	93,3	106,6
400 0	131,5	100,1	109,1	104,4	97,5	93,2	97,5	97,5

		bandas de octava							
		SOURCE ROOM		RECEIVER ROOM					
	LOUDSPEAKER L-0º	S1	S2	R1	R2	R3	R4	R5
	x=5,3/y=5,88	x= 4,86/y=4,22	x=5,12/y=5,18	x=3,6/y=3,25	x=2,6/y=3,25	x=2,1/y=2,75	x=1,3/y=3	x=3,1/y=3,75
125	123,4	103,2	104,8	87,3	97,7	78,2	96,2	94,5
250	124,7	105,3	109,0	100,9	102,5	81,6	92,4	98,5
500	126,5	102,0	108,0	109,4	107,0	103,1	100,6	106,9
1000	128,4	107,0	109,2	101,4	106,9	98,6	91,3	84,3
2000	130,3	107,1	109,8	101,7	101,0	99,9	96,1	101,7
4000	131,5	100,1	109,1	104,4	97,5	93,2	97,5	97,5

	LOUDSPEAKER L-0º	SOURCE L2	RECEIVER L1	TR1	TR2	D	DNT1	DNT2
125	123,4	104,1	94,3	0,49	0,75	9,7	9,7	11,5
250	124,7	107,5	98,9	0,28	1,05	8,6	6,1	11,8
500	126,5	105,9	106,4	0,30	1,47	-0,5	-2,6	4,2
1000	128,4	108,2	101,5	0,36	1,49	6,7	5,3	11,4
2000	130,3	108,6	100,5	0,31	1,34	8,1	6,0	12,4
4000	131,5	106,6	99,7	0,28	0,98	7,0	4,4	9,9

- Opening area $0.10m^2$ in +35º:

		SOURCE ROOM		RECEIVER ROOM				
	LOUDSPEAKER L+35º	S1	S2	R1	R2	R3	R4	R5
PT 3	x=6,83/y=1,69	x= 5,42/y=2,68	x=6,24/y=2,1	x=3.6/y=3.25	x=2.6/y=3.25	x=2,1/y=2,75	x=1,3/y=3	x=3,1/y=3,75
125	122,7	91,2	110,2	87,1	97,5	78,5	95,9	94,4
184	123,6	105,7	106,1	99,2	105,9	79,3	107,1	96,2
270	124,4	107,3	100,4	101,8	99,6	92,7	91,4	10,2
397	126,2	106,7	107,8	105,0	104,6	104,9	103,5	103,3
583	126,9	96,6	102,4	113,9	103,0	105,0	99,8	92,1
857	128,1	105,5	111,3	112,0	108,6	104,8	99,6	100,3
1260	128,6	102,8	103,1	87,8	99,8	95,5	108,0	97,3
1852	129,8	109,6	109,5	106,7	97,3	93,6	107,8	107,2
2722	130,5	107,8	112,1	91,7	110,5	100,5	105,8	100,6
4000	131,2	110,7	108,1	105,0	95,6	103,4	101,7	95,3

		bandas de octava						
		SOURCE ROOM		RECEIVER ROOM				
	LOUDSPEAKER L+35º	S1	S2	R1	R2	R3	R4	R5
	x=5,3/y=5,88	x= 4,86/y=4,22	x=5,12/y=5,18	x=3,6/y=3,25	x=2,6/y=3,25	x=2,1/y=2,75	x=1,3/y=3	x=3,1/y=3,75
125	122,7	91,2	110,2	87,1	97,5	78,5	95,9	94,4
250	124,0	106,4	102,4	100,3	101,7	82,1	94,3	13,2
500	126,5	99,2	104,3	107,5	103,7	104,9	101,3	94,8
1000	128,3	104,0	105,5	90,8	102,3	98,0	102,0	98,5
2000	130,1	108,6	110,6	94,6	100,1	95,8	106,7	102,7
4000	131,2	110,7	108,1	105,0	95,6	103,4	101,7	95,3

	LOUDSPEAKER L+35º	SOURCE L2	RECEIVER L1	TR1	TR2	D	DNT1	DNT2
125	122,7	107,3	94,1	0,49	0,75	13,2	13,1	14,9
250	124,0	104,9	97,5	0,28	1,05	7,3	4,8	10,5
500	126,5	102,4	104,1	0,30	1,47	-1,6	-3,8	3,1
1000	128,3	104,8	99,8	0,36	1,49	5,0	3,6	9,7
2000	130,1	109,7	102,2	0,31	1,34	7,5	5,5	11,8
4000	131,2	109,6	101,8	0,28	0,98	7,8	5,3	10,8

- Opening area 0.10m^2 in +70º:

		SOURCE ROOM		RECEIVER ROOM				
	LOUDSPEAKER L+70º	S1	S2	R1	R2	R3	R4	R5
PT5	x=5,3/y=0,62	x= 4,86/y=2,28	x=5,12/y =1,32	x=3,6/y= 3,25	x=2,6/y= 3,25	x=2,1/y= 2,75	x=1,3/ y=3	x=3,1/y= 3,75
125	122,0	109,5	109,6	86,8	97,2	78,5	95,6	94,1
184	124,6	109,8	105,7	98,4	105,1	79,1	106,3	95,4
270	125,4	107,8	94,4	100,0	97,8	93,6	91,7	101,2
397	125,9	106,0	110,8	101,2	100,9	104,8	104,3	98,1
583	126,6	106,7	109,8	105,5	89,3	100,2	91,7	97,2
857	127,5	86,6	108,2	112,0	111,4	105,6	90,9	97,1
1.260	129,2	105,0	95,2	71,3	86,2	100,6	99,5	100,8
1.852	129,4	107,3	105,7	87,4	102,4	104,8	90,6	97,6
2722	131,0	94,9	103,9	89,2	92,6	106,6	100,9	80,7
4000	131,9	105,3	109,6	102,3	91,7	100,8	98,1	98,5

		SOURCE ROOM		RECEIVER ROOM				
	LOUDSPEAKER L+70º	S1	S2	R1	R2	R3	R4	R5
	x=5,3/y=5,88	x= 4,86/y=4,22	x=5,12/y=5,18	x=3,6/y=3,25	x=2,6/y=3,25	x=2,1/y=2,75	x=1,3/y=3	x=3,1/y=3,75
125	122,0	109,8	105,7	98,4	105,1	79,1	106,3	95,4
250	125,0	106,8	97,3	100,6	99,1	96,3	94,5	99,3
500	126,2	89,6	108,9	107,6	92,3	102,1	91,3	97,1
1000	128,3	106,0	97,8	74,2	89,1	102,2	93,1	98,9
2000	130,1	97,6	105,9	92,0	92,1	102,8	99,3	83,6
4000	131,9	105,3	109,6	102,3	91,7	100,8	98,1	98,5

	LOUDSPEAKER L+70º	SOURCE L2	RECEIVER L1	TR1	TR2	D	DNT	DNT
125	122,0	108,2	102,3	0,49	0,75	5,9	5,8	7,6
250	125,0	104,2	98,5	0,28	1,05	5,8	3,2	9,0
500	126,2	106,0	102,2	0,30	1,47	3,8	1,6	8,5
1000	128,3	103,6	97,4	0,36	1,49	6,2	4,8	11,0
2000	130,1	103,5	97,9	0,31	1,34	5,6	3,5	9,9
4000	131,9	108,0	99,5	0,28	0,98	8,5	6,0	11,4

- Opening area 0.20m^2 in 0º:

		SOURCE ROOM		RECEIVER ROOM				
	LOUDSPEAKER L 0º	S1	S2	R1	R2	R3	R4	R5
PT1	x=7,32/y=3,25	x= 5,6/y=3,25	x=6,6/y= 3,25	x=3.6/y= 3.25	x=2.6/y= 3.25	x=2,1/y= 2,75	x=1,3/ y=3	x=3,1/y= 3,75
125	123,3	102,2	106,7	85	104	84	103	101
184	124,7	108,1	108,9	101	106	66	108	96
270	124,7	106,2	107,7	105	103	94	96	104
397	126,2	102,2	108,0	109	109	104	100	110
583	127,3	109,4	108,0	98	110	108	94	101
857	128,0	108,3	110,1	107	101	98	85	87
1.260	128,7	110,3	109,7	102	108	98	94	98
1.852	130,3	101,3	112,2	107	108	99	105	109
2722	130,9	109,3	92,2	102	107	111	87	109
4000	131,6	103,2	98,9	99	98	102	107	95

		SOURCE ROOM		RECEIVER ROOM				
	LOUDSPEAKER L 0º	S1	S2	R1	R2	R3	R4	R5
	x=5,3/y=5,88	x= 4,86/y=4,22	x=5,12/y=5,18	x=3,6/y=3,25	x=2,6/y=3,25	x=2,1/y=2,75	x=1,3/y=3	x=3,1/y=3,75
125	123,3	102,2	106,7	85,2	103,9	84,2	102,9	100,8
250	124,7	107,0	108,2	102,7	104,6	68,7	99,1	98,3
500	126,7	104,5	108,0	101,1	109,8	105,6	96,3	103,1
1000	128,4	109,2	109,9	103,9	102,8	97,9	87,1	89,6
2000	130,6	103,7	95,2	103,7	107,5	101,8	89,5	108,7
4000	131,6	103,2	98,9	99,0	97,6	101,5	106,7	95,4

	LOUDSPEAKER L 0º	SOURCE L2	RECEIVER L1	TR1	TR2	D	DNT1	DNT2
125	123,3	105,0	100,5	0,49	0,75	4,5	4,4	6,2
250	124,7	107,7	100,9	0,28	1,05	6,7	4,2	10,0
500	126,7	106,6	105,3	0,30	1,47	1,3	-0,9	5,9
1000	128,4	109,6	100,1	0,36	1,49	9,4	8,0	14,2
2000	130,6	101,3	105,3	0,31	1,34	-4,0	-6,1	0,2
4000	131,6	101,5	101,9	0,28	0,98	-0,4	-2,9	2,5

- Opening area 0.20m^2 in +35º:

		SOURCE ROOM		RECEIVER ROOM				
	LOUDSPEAKER L +35º	S1	S2	R1	R2	R3	R4	R5
PT 3	x=6,83/y=1,69	x= 5,42/y=2,68	x=6,24/y=2,1	x=3.6/y=3.25	x=2.6/y=3.25	x=2,1/y=2,75	x=1,3/y=3	x=3,1/y=3,75
125	122,4	97,1	110,8	101,9	86,4	103,1	100,6	84,7
184	123,5	105,2	105,5	106,5	81,7	104,8	93,4	99,6
270	124,2	105,8	102,7	102,9	105,3	100,2	109,3	102,0
397	126,0	100,4	106,6	106,4	108,3	106,9	110,2	107,1
583	126,8	95,4	102,5	99,9	104,1	97,7	98,2	105,7
857	127,9	107,0	112,0	98,9	95,9	91,4	87,2	90,8
1260	128,6	98,8	105,4	104,3	104,7	94,3	104,7	94,1
1852	130,0	107,9	111,6	107,2	104,8	101,6	107,4	93,2
2722	130,4	106,8	111,8	105,3	108,6	116,1	111,3	103,5
4000	131,8	109,3	106,7	105,2	84,9	110,2	103,0	97,8

	LOUDSPEAKER L+35º	SOURCE ROOM		RECEIVER ROOM				
		S1	S2	R1	R2	R3	R4	R5
	x=5,3/y=5,88	x= 4,86/y=4,22	x=5,12/y=5,18	x=3,6/y=3,25	x=2,6/y=3,25	x=2,1/y=2,75	x=1,3/y=3	x=3,1/y=3,75
125	122,4	97,1	110,8	101,9	86,4	103,1	100,6	84,7
250	123,9	105,5	103,8	104,3	84,6	101,9	96,3	100,6
500	126,4	97,2	104,0	102,0	105,7	100,2	100,9	106,4
1000	128,2	101,2	107,6	100,8	98,4	92,6	90,2	92,1
2000	130,2	107,3	111,7	106,2	106,3	104,5	108,9	95,8
4000	131,8	109,3	106,7	105,2	84,9	110,2	103,0	97,8

	LOUDSPEAKER L+35º	SOURCE L2	RECEIVER L1	TR1	TR2	D	DNT1	DNT2
125	122,4	108,0	99,8	0,49	0,75	8,2	8,1	9,9
250	123,9	104,7	100,7	0,28	1,05	4,1	1,5	7,3
500	126,4	101,8	103,8	0,30	1,47	-1,9	-4,1	2,7
1000	128,2	105,5	96,7	0,36	1,49	8,8	7,4	13,5
2000	130,2	110,0	105,9	0,31	1,34	4,1	2,1	8,4
4000	131,8	108,2	105,2	0,28	0,98	3,1	0,5	6,0

- Opening area 0.20m^2 in +70º:

		SOURCE ROOM		RECEIVER ROOM				
	LOUDSPEAKER L+70º	S1	S2	R1	R2	R3	R4	R5
PT5	x=5,3/y=0,62	x= 4,86/y=2,28	x=5,12/y=1,32	x=3,6/y=3,25	x=2,6/y=3,25	x=2,1/y=2,75	x=1,3/y=3	x=3,1/y=3,75
125	121,9	110,4	109,3	100,2	87,2	101,6	99,5	83,7
184	124,6	110,2	106,0	103,4	85,0	102,0	90,7	96,3
270	125,5	105,6	100,7	101,3	104,7	91,6	107,5	93,9
397	125,9	107,5	110,1	101,6	103,4	107,0	108,5	105,4
583	126,5	102,8	111,4	95,6	98,5	99,5	92,6	102,3
857	127,6	97,2	107,3	91,6	110,3	113,9	89,1	99,5
1.260	129,1	107,7	97,4	104,9	103,7	99,2	101,5	93,5
1.852	129,4	108,7	108,0	99,3	89,9	100,1	102,1	74,6
2722	131,0	98,1	103,5	102,2	106,9	97,3	91,6	98,2
4000	131,8	104,6	110,3	92,1	91,3	101,4	103,3	102,7

		SOURCE ROOM		RECEIVER ROOM				
	LOUDSPEAKER L+70º	S1	S2	R1	R2	R3	R4	R5
	x=5,3/y=0,62	x= 4,86/y=4, 22	x=5,12/y= 5,18	x=3,6/y= 3,25	x=2,6/y= 3,25	x=2,1/y= 2,75	x=1,3/ y=3	x=3,1/y= 3,75
12 5	121,9	110,2	106,0	103,4	85,0	102,0	90,7	96,3
25 0	125,0	106,4	103,2	101,5	104,0	94,5	108,0	96,6
50 0	126,2	99,1	108,8	93,2	101,2	102,3	90,5	100,7
10 00	128,3	108,1	100,1	101,2	92,7	99,6	101,8	77,5
20 00	130,1	100,3	105,7	94,7	94,2	98,9	94,3	99,9
40 00	131,8	104,6	110,3	92,1	91,3	101,4	103,3	102,7

	LOUDSPEAKER L+70º	SOURCE L2	RECEIVER L1	TR1	TR2	D	DNT	DNT
12 5	121,9	108,6	99,4	0,49	0,75	9,2	9,2	11,0
25 0	125,0	105,1	103,4	0,28	1,05	1,7	-0,8	4,9
50 0	126,2	106,3	99,6	0,30	1,47	6,7	4,5	11,4
10 00	128,3	105,8	99,0	0,36	1,49	6,8	5,4	11,5
20 00	130,1	103,8	97,1	0,31	1,34	6,7	4,6	10,9
40 00	131,8	108,3	100,5	0,28	0,98	7,8	5,3	10,7