MANUAL FOR WINFLAG, VERSION 2.1

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CONTENTS

1 INTRODUCTION

The program calculates absorption coefficient, impedance and sound reduction index for constructions combined of material layers of different types (porous materials, perforated plates etc.). As an add-on to the program, one may calculate the approximate sound attenuation in dB/m for a rectangular duct lined on two sides with the specified layer construction.

Calculations may be performed at single frequencies or as mean values in one-third-octave bands, in both cases for a free field sound incidence as well as in a diffuse field. The program is modelling the acoustic properties of a combination of such layered materials using the transfer matrix method. Basically, each layer in the combination, assumed to be of infinite extent, is represented by a matrix giving the relationship between a set of physical variables on the input and output side of the layer. These matrices may then be combined to give the relationship between the relevant physical variables for the whole combination. Characteristic data as absorption coefficient, input impedance and transmission loss (sound reduction index) may then be calculated assuming plane wave incidence. The size and complexity of these matrices, however, are totally dependant of the specific material in the actual layer, i.e. how many physical variables one have to use describing the wave motion in the material and then how many material parameters that are necessary to specify the material. In many cases, only two physical variables are sufficient being the sound pressure and the particle velocity. A simple 2 by 2 matrix then describes the relationship between these variables on the input and the output side.

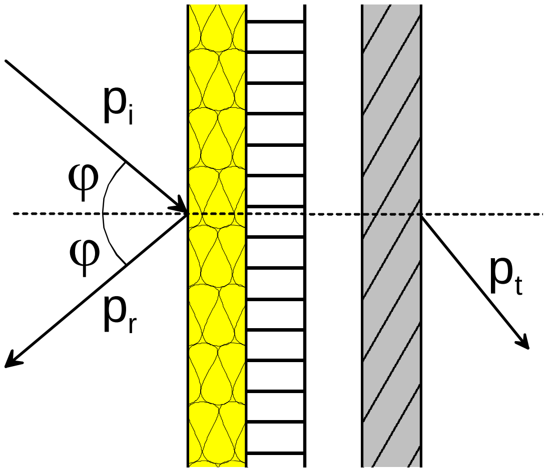


Figure 1-1 Combination of several layers (each of infinite extent)

For the description of layers being thin plates (panels), either perforated or non perforated, two physical variables are always sufficient. The word "thin" here signify that we do not need to worry about the wave motion inside the plate itself; the wavelength being much longer than the thickness of the plate. With thicker elastic materials this simple model is no longer feasible. We shall at least need four physical variables, e.g. the particle velocity and the stress in two directions. Describing the relationship between the input and output we then need a 4 by 4 matrix. It may be shown, however, that if there are fluid layers on both sides of the elastic layer, this 4 by 4 matrix may be reduced to a simple 2 by 2 matrix. This is the procedure utilised in the WinFLAG program to include single elastic layers (thick panels) and also sandwich elements.

Porous materials may also be included in a simple 2 by 2 matrix description if they are modelled as an equivalent fluid. Such a model is applicable to many porous materials, e.g. mineral wool type absorbents. The basic assumptions are that the material is homogeneous and isotropic, having pores filled with air embedded in an infinitely stiff matrix or skeleton. Again, if the elastic properties of this skeleton have to be taken into account a description using two physical variables only is again not feasible. It is therefore not to be expected that the program WinFLAG gives correct results in the latter case, e.g. for many foam materials.

2 OVERVIEW

The program main files are the following:

• WINFLAG 2.1.EXE	This is the main program
• FLAG_V21.DLL	"Dynamic Link Library" - calculation routines
• WINFLAG_HELP_V21.PDF	Help file (this document)

To get help during program execution it is assumed that the help file may be read, the computer must have the program Adobe Acrobat installed, version 4.0 or higher. Please note that there are several cross-references in the document, i.e. when sections and figures are referred to, clicking on the Section or Figure number will bring you to the item.

3 MAIN FEATURES

- Calculates the absorption coefficient for 14 different types of layers, including 4 different models of porous materials. The absorption coefficient may be calculated, with some exceptions, for any combination or any number of these layers limited to a total of 20 layers. A 15th type of layer, the infinitely hard wall, may be included in the case of absorbers placed against a hard wall in a room.
- Absorption coefficients obtained in a standard reverberation room (the commonly used product data after ISO 354) may be estimated, as well as the weighted sound absorption coefficient α_W according to ISO 11654.
- The sound reduction index in dB (sound transmission loss) is simultaneously calculated for all combinations not including the infinitely hard wall. The weighted sound reduction index R_w according to ISO 717 Part 1 is also calculated when applying a diffuse field option and calculating results in one-third-octave band.
- The acoustic impedance is also simultaneously calculated in all cases when an angle of sound incidence is specified.
- All the data mentioned above may be calculated for a given angle of incidence or in a diffuse field.
- Calculations are performed at single frequencies or as mean values in one-third-octave bands. There is also an option for exporting calculated results as mean values in octave bands.
- As an add-on to the program the attenuation of noise in ducts, e.g. air-conditioning ducts, lined with the chosen layer configuration may be calculated.
- A report window in Rich Text Format (.rtf file) is implemented where specifications, tables of results and diagrams may easily be imported.
- Results, together with specifications for the combination of layers, may be exported to a plain text file (ASCII), alternatively to a Microsoft Excel file.
- Results may be exported, via Clipboard, to the program WinRT60 that calculates reverberation time in rooms.
- A chosen combination of layers, a configuration, may be saved to a file and later imported for additional calculations. The same applies to single layers, which enables the user to build up a library of material layers.

Note Please be aware that due to the introduction of new layers having a higher number of parameters the reuse of configuration files from the first version 1.0 is not possible without some minor editing. Information is given in Annex A.

3.1 NEW FEATURES IN VERSION 2.1

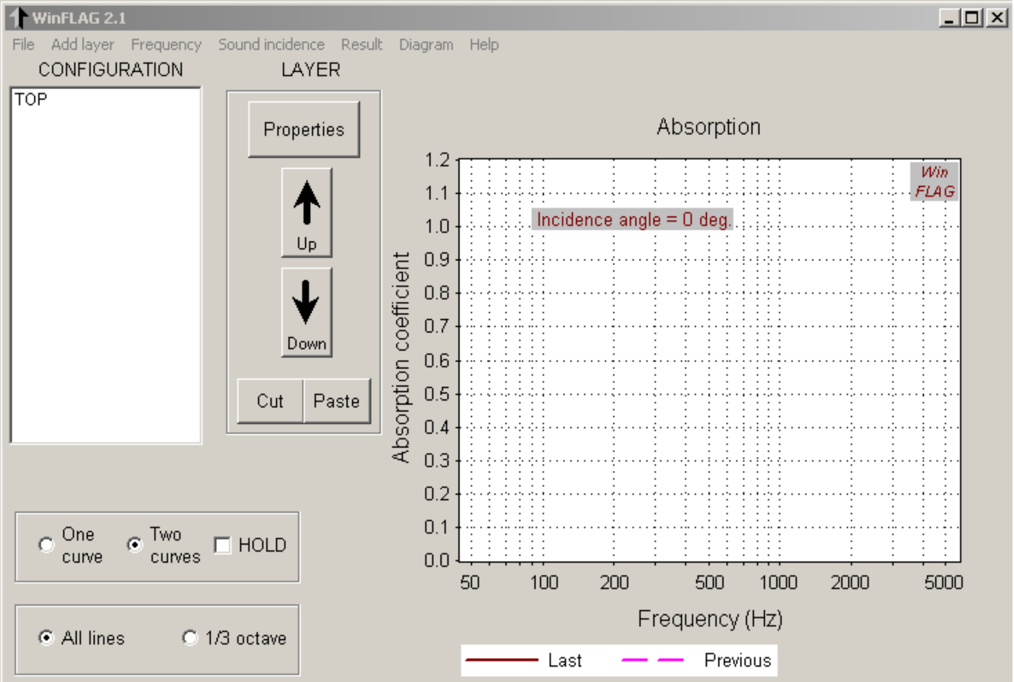
Two new types of layers have been added in version 2.1 as compared with version 2.0. In relatively thick perforated panels, 9 - 10 mm or more, both calculations and measurements show that using conically shaped apertures as opposed to normal holes or slots may greatly enhance the absorption capabilities of resonator panels. In addition to the normal hole-perforated and slotted panels one may now design resonator absorbers having conical apertures. An example is given in Annex D.

Further changes include the following:

- When exporting calculated results, either to a text or Excel-file, the data will be preceded by a list specifying the properties of the layer configuration. Furthermore, calculated results in octave bands may be added to the results calculated in one-third-octave bands. Results may also be exported, via the Clipboard to the program WinRT60 that calculates reverberation time in rooms.
- As the menu **Add layer** have became quite long, submenus have been introduced for porous materials, perforated and slotted panels. The specific layer is no longer automatically added to the end of the list, but may be directed by the user.
- Deleting a layer in the list, using the Delete button, has been replaced with a Cut and Paste button.
- A submenu **Properties of materials** has been added to the **Help** menu, calling up a copy of Annex B in this manual.

4 BRIEF DESCRIPTION OF THE PROGRAM

The program is started from your program menu, alternatively by clicking on the file WINFLAG 2.1.EXE or by making a shortcut to this file and start from the desktop. The following window should then appear, see *Figure 4-1*.



○ One curve ● Two curves ☐ HOLD

● All lines ○ 1/3 octave

Figure 4-1. The main window at start-up time

In the list box to the left (labelled CONFIGURATION and having the word TOP on the first line) one composes the combination of layers for which calculations are desired. The word TOP indicates the side of the incident plane wave in air. As mentioned in the introduction, the layers may be of the type porous materials, perforated panels etc. For a detailed description of the different types of layers, see under the Section 5.2 below. **Please note that except when including the layer HARD WALL, the backside of the last layer will be air (as on the incident side).**

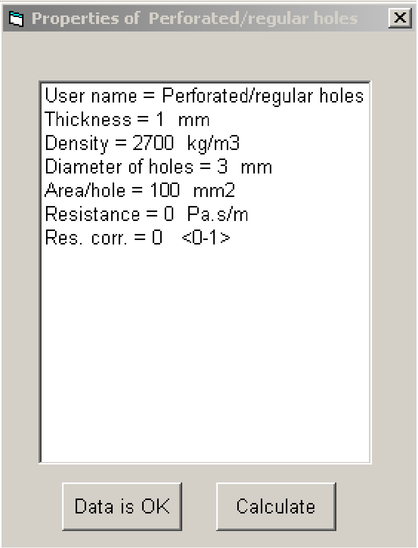
The graphical picture to the right always shows the results of the calculations. In addition, a previous result may be displayed in the same diagram. At start up time a default diagram for the absorption coefficient is shown.

The program has, as listed below, a total of seven menus which is explained in more detail under Section 5. From the last one of these menus: **Help**, this help file may be called.

• **File**	handles the configuration, layer, result and report files. Exits the program.
• **Add layer**	adding a chosen type of layer (NB! no calculations are performed)
• **Frequency**	frequency range of calculations, type of scale (linear, log)
• **Sound incidence**	choice of angle of incidence or diffuse incidence.
• **Result**	choice of calculated result (absorption, impedance, transmission and optionally duct attenuation)
• **Diagram**	choice of axis scale values in the diagram
• **Help**	calling files containing either the full manual or a material property list

To the right of the list box specifying the configuration, one will find a frame labelled LAYER with five command buttons. Clicking on the button P**roperties** (or double-clicking in the list box) will bring up a new window giving the material properties for the layer marked in the list box. An example is shown in *Figure 4-2* where the layer is a perforated plate. Clicking on a parameter value one may change the value listed. In addition, one may exchange the default name of the layer into a chosen user name. As shown, this specification session may be terminated by a calculation. Alternatively, the calculations may be started with the command button **Calculate** that will appear under the configuration list box. This button will appear when changes necessitate a recalculation; see the example given in *Figure 4-3*. A number of changes, however, will automatically start the calculations.

Concerning the command buttons **Up** and **Down**, shown in *Figure 4-1* or *Figure 4-3*, these will move a marked layer up or down in the configuration list box. Below these are the **Cut** and **Paste** buttons for a single layer. The layer is always pasted below a marked layer in the list.



User name = Perforated/regular holes
Thickness = 1 mm
Density = 2700 kg/m3
Diameter of holes = 3 mm
Area/hole = 100 mm2
Resistance = 0 Pa.s/m
Res. corr. = 0 <0-1>

Figure 4-2. The window listing the properties of a given layer (example Perforated plate with regular holes)

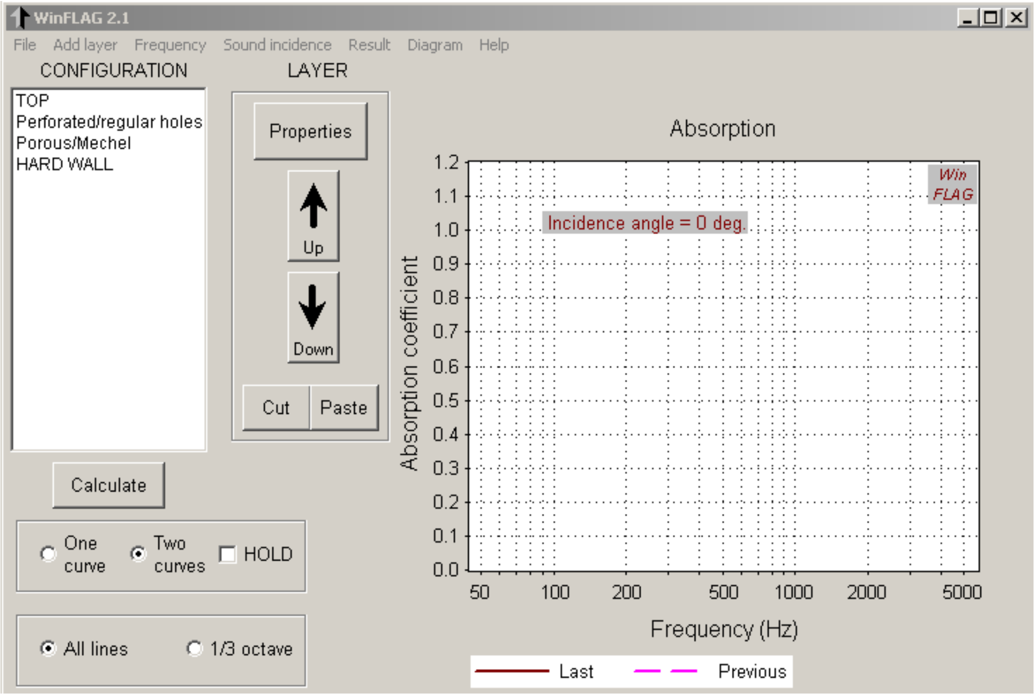
4.1 CALCULATION OPTIONS

Below the configuration list box one will find two frames containing options. The first offers the possibility of having two curves displayed, a previous result together with the last calculated result. This is the default option. Marking of the box **Hold** after a calculation will keep this result for a comparison with a later result. Unmarking the box will continually update the second curve. The exception to this action is when displaying the input impedance. In this case the two curves represent the real and imaginary part of the impedance respectively, and no former results are available.

The last set of options offers the choice between calculating results for all frequency lines or mean values in one-third-octave bands, frequency range 40 Hz to 10 kHz (centre frequencies of bands). In the latter case mean values are based on a minimum of 10 frequency lines inside each one-third-octave band. In this case mean values in full octave bands are calculated as well, data that may be exported, see Note 2 below Section 5.1.

4.2 PROGRAM EXECUTION. SOME EXAMPLES

Starting the program a main calculation window will appear as shown in *Figure 4-1*. The first task for the user is to "compose" the configuration by pulling down the various layers in the configuration list box by clicking on the submenus under the menu **Add Layer**. Having done this, one may change the default parameters for each layer to the desired ones by clicking on the button **Layer properties** or double-clicking on the item in the list box. This opens up the properties window, an example of which is shown in *Figure 4-2*. When the last layer is updated one may start the calculations from this window, alternatively by the command button **Calculate** under the configuration list box, see *Figure 4-3*. A calculation will otherwise start automatically when using the menus **Frequency** or **Sound incidence**. Below are shown examples of results from calculations of absorption coefficients, input impedance, sound reduction index and duct attenuation.



TOP
Perforated/regular holes
Porous/Mechel
HARD WALL

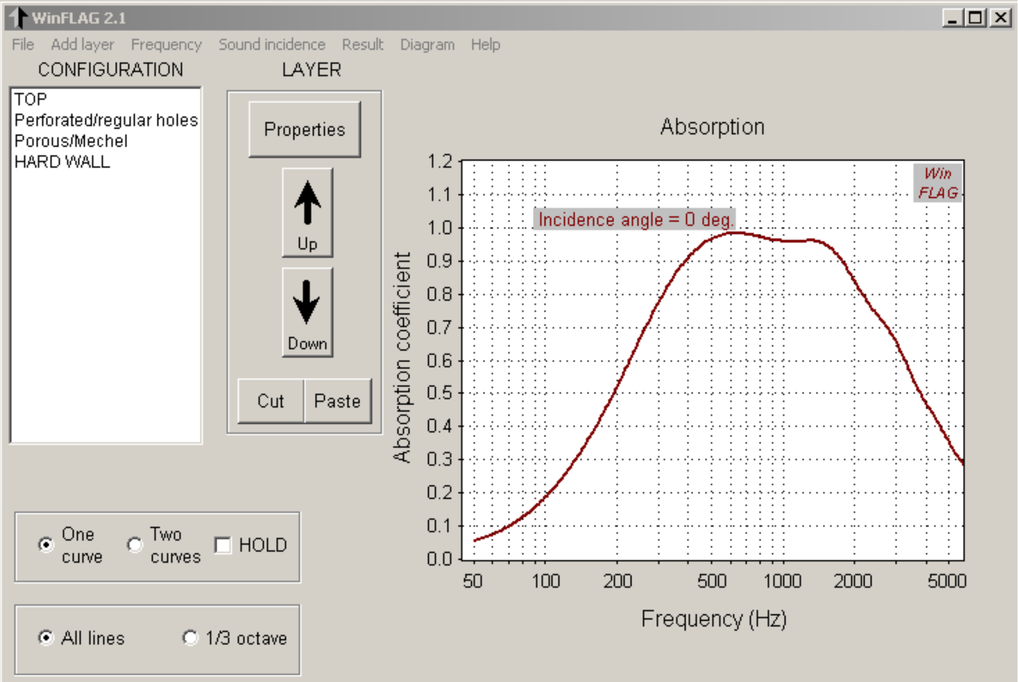
Incidence angle = 0 deg.

○ One curve ● Two curves ☐ HOLD

● All lines ○ 1/3 octave

Figure 4-3. The main calculation window where layers have been entered into the configuration list box (before parameters are updated and any calculations performed)

An example from a calculation of the absorption coefficient is shown in *Figure 4-4*. The resonant absorber is a perforated plate combined with an air space in front of a hard wall (or hard ceiling), the space filled with a porous material described using the model after Mechel. *Figure 4-5* shows the corresponding normalised input impedance for the same configuration. A more detailed description of the various models is given below under the Section 5.2.

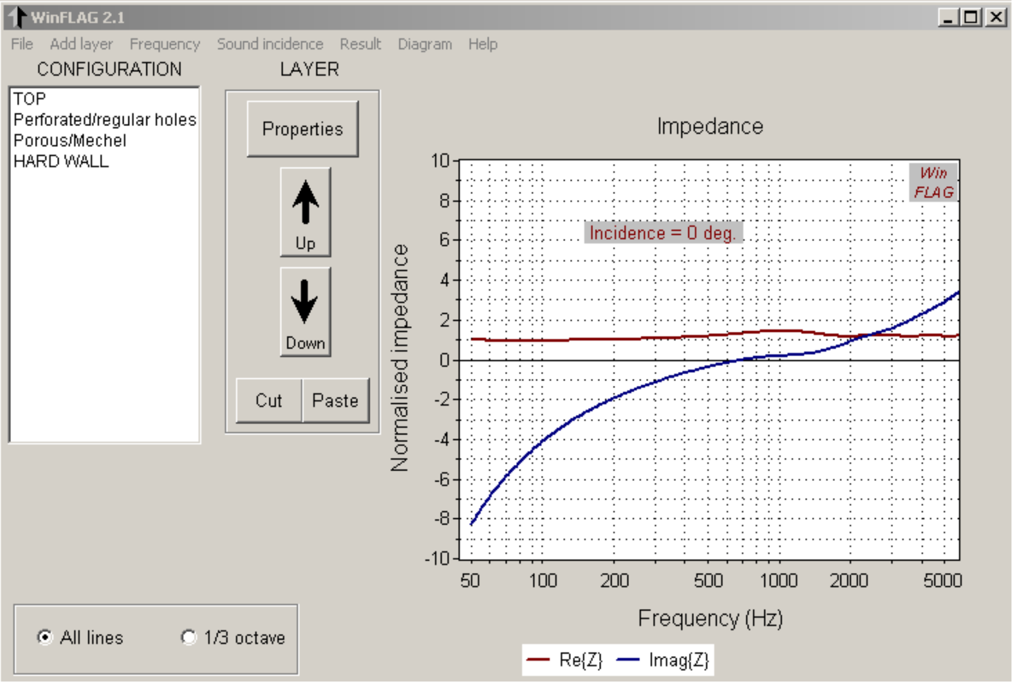


TOP
Perforated/regular holes
Porous/Mechel
HARD WALL

● One curve ○ Two curves ☐ HOLD

● All lines ○ 1/3 octave

Figure 4-4. Example showing the absorption coefficient of a resonant absorber for normal incidence. The parameters for the chosen layers are the default ones except for the thickness of the porous layer (100 mm)

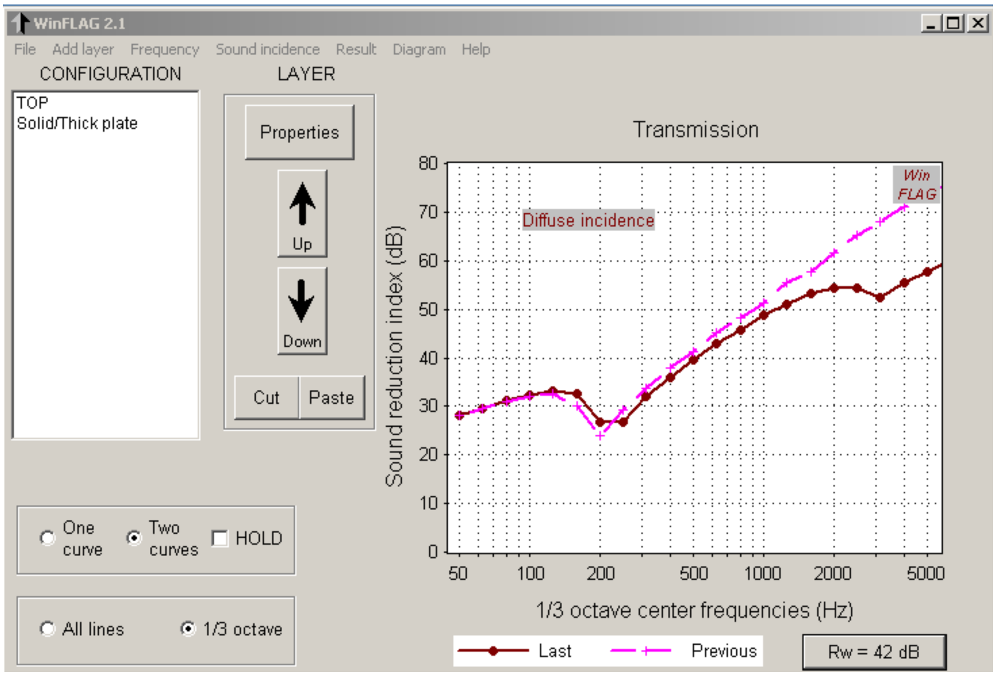


TOP
Perforated/regular holes
Porous/Mechel
HARD WALL

● All lines ○ 1/3 octave

Figure 4-5. The normalised impedance corresponding to the data in Figure 4-4

Figure 4-6 shows an example of calculation of the sound reduction index of a panel or wall in a diffuse sound field. The specimen is a 250 mm aerated concrete calculated respectively as a thin plate (marked "Previous") and as a thick elastic plate (marked "Last"). In contrast to the examples above, mean values in one-third-octave band are calculated.

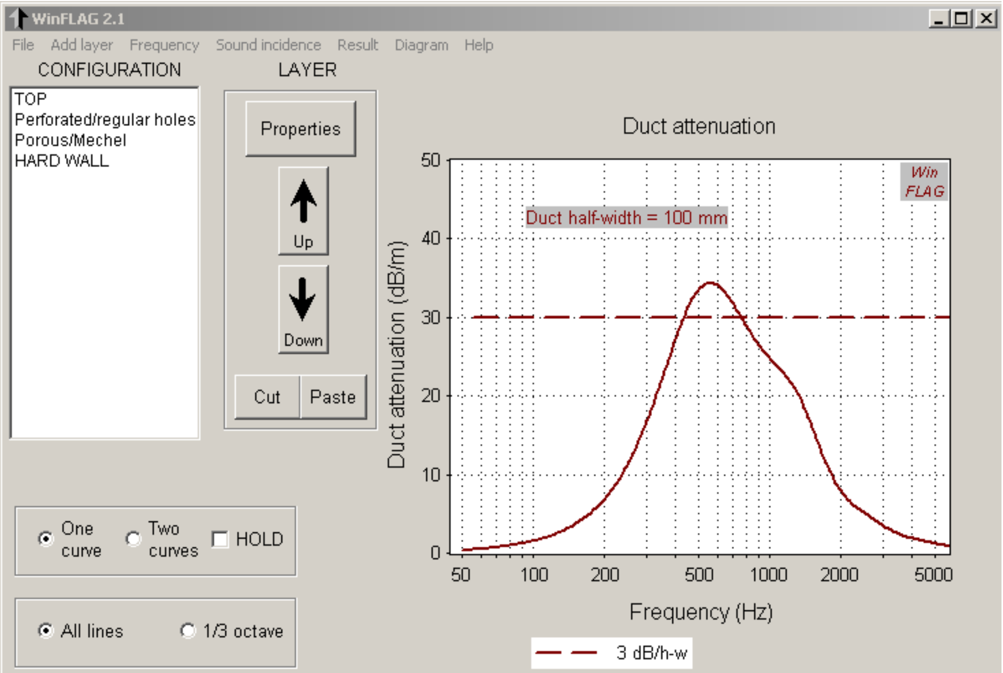


CONFIGURATION
TOP
Solid/Thick plate

○ One curve ● Two curves ☐ HOLD
○ All lines ● 1/3 octave

Rw = 42 dB

Figure 4-6 Example on the sound reduction index for a wall (aerated concrete) using layer types thin and thick plate, respectively. Diffuse sound incidence. Calculation of mean values in one-third-octave bands.



CONFIGURATION
TOP
Perforated/regular holes
Porous/Mechel
HARD WALL

● One curve ○ Two curves ☐ HOLD
● All lines ○ 1/3 octave

Figure 4-7. Attenuation in a rectangular duct lined on two walls with the resonant absorber having the impedance shown in Figure 4-5. The free air space has a total width (or depth) of 200 mm. The dotted line indicates a value of 3 dB per length of duct equal to the half-width.

Finally, *Figure 4-7* shows an example of the calculation of sound attenuation in a rectangular duct lined on two sides with a lining of the same type as used in *Figure 4-4* (and *Figure 4-5*). The duct has a free air space of total width (or depth) 200 mm. For a general description and details concerning the implementation, see Section 6.

5 MENUS

An overview of the main menus and options was given above. Below, the menus are described in more detail with explanations concerning the input data that the user must supply to the program. Specifically, this applies to the input parameters for the different layers.

5.1 THE FILE MENU

The menu contains the following submenus:

- Save configuration
- Open configuration
- Save layer data
- Export results
- Export data to WinRT60
- Make report
- Report window
- EXIT

The first four submenus will open up the Microsoft standard window for saving/opening files. The next item concerns exporting data to the accompanying program WinRT60 (via Clipboard), and the following two items concerns a separate window allowing the user to make a report document in a standard Rich Text Format (.rtf).

Menu		**Shortcut**	**Description**
Save configuration (Example in Annex A)		None	Saves the configuration and all parameters for the layers to a file. The file name is given by the user with the extension ".lag"
Open configuration (Example in Annex A)		None	Opens a file with a formerly saved configuration. Calculations according to the given configuration are performed and results displayed.
Save layer data		None	Saves the user name and all parameters for a single layer to a file. The file name is given by the user with the extension ".alg"
Export results	Plain text	Ctrl T	The last calculated results, together with data for the configuration, are exported to a text file (ASCII) with the extension ".txt". Data that are not relevant in a given configuration, e.g. the sound transmission index when a HARD WALL is included, are set equal to an arbitrary high (negative) number.
	MS Excel	Ctrl E	The last calculated results, together with data for the configuration, are exported to a Microsoft standard Excel-file with the extension ".xls". The option only works if the program Excel™ is installed on the computer.
Export data to WinRT60		None	Copies calculated absorption coefficients in one-third-octave bands to the Clipboard. Intended for exporting data to program WinRT60, calculating reverberation time.

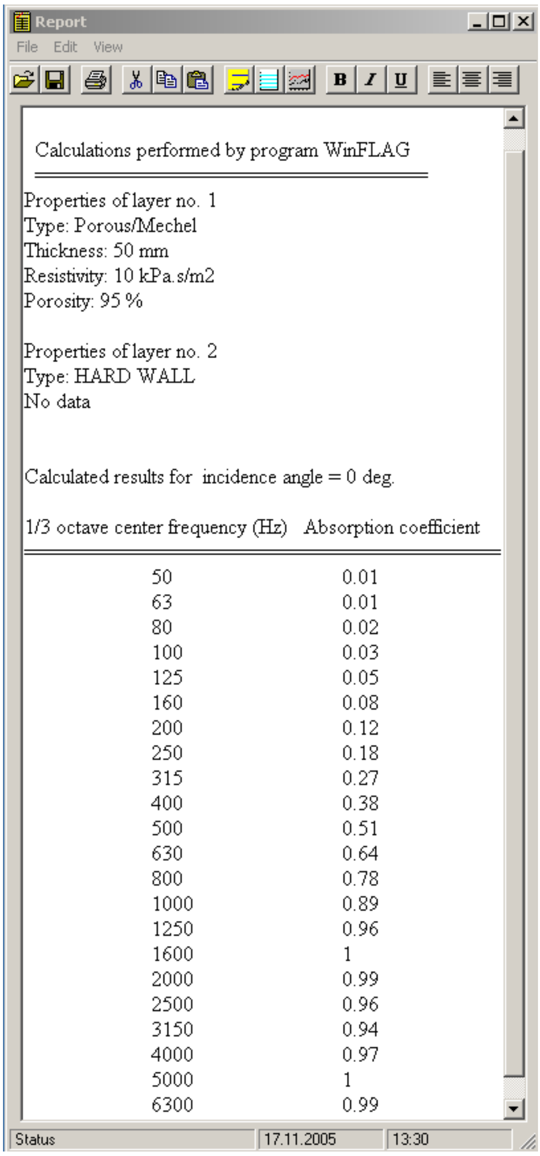
Make report	None	Hides the calculation window and opens up a report window with a text box (.rtf – format) in which the user may import configuration data, results tables and the graphical picture. A description is given below, see Section 5.1.1
Report window	None	Shows the current report window. Hides the calculation window.
EXIT	None	Terminates the program on confirmation.

NOTE 1 A proper saving of the configuration assumes that a calculation has been performed, i.e. the configuration saved is the last one calculated.

NOTE 2 When exporting results calculated in one-third-octave bands one will be offered a choice to add octave-band data to the file.

5.1.1 Making a report

The menu **Make report** opens up a new window, see *Figure 5-1* below, allowing the user to make a report specifying the actual configuration including all parameters for the layers, a copy of the graphical picture and also a table of the results. The latter is limited to one-third-octave band results. If need be, the results for all frequency lines may also be included, a procedure which is outlined below.



Calculations performed by program WinFLAG

Properties of layer no. 1
Type: Porous/Mechel
Thickness: 50 mm
Resistivity: 10 kPa.s/m2
Porosity: 95 %

Properties of layer no. 2
Type: HARD WALL
No data

Calculated results for incidence angle = 0 deg.

1/3 octave center frequency (Hz)	Absorption coefficient
50	0.01
63	0.01
80	0.02
100	0.03
125	0.05
160	0.08
200	0.12
250	0.18
315	0.27
400	0.38
500	0.51
630	0.64
800	0.78
1000	0.89
1250	0.96
1600	1
2000	0.99
2500	0.96
3150	0.94
4000	0.97
5000	1
6300	0.99

Figure 5-1 The report window where the layer properties and one-third-octave results are imported

The report, see *Figure 5-1*, has three menus, **File**, **Edit** and **View** and a toolbar. Most of the submenus are reflected in this toolbar. The **File** menu has the following items

- Open…
- Save as…
- Print
- Calculation window
- Close

The first two submenus will open up the Microsoft standard window for opening/saving files. The first option is included if need be to use a formerly saved report file (or a text file) as the basis for a new report. The save option saves the report as an rtf-file.

The print option opens up a standard print window allowing the user to directly print the report on an attached printer. The user can process the report file in a text-processing program. As a consequence, the toolbar offer only a limited number of processing options; i.e. font type and aligning in addition to the standard cut, copy and paste. The latter items are also found under the **Edit** menu.

Furthermore, the submenu Calculation window will hide the report window and revert to the main calculation window for further calculations, the results of which may be added to the report. The Close option will, after confirmation, close the report window (without saving).

The **Edit** menu has in addition to the common options of editing (undo, cut, copy and paste) three special paste commands:

- Paste layer properties
- Paste diagram
- Paste one-third-octave band results

These commands paste a list of the layer properties, the diagram and the results of a one-third-octave band calculation; the latter only if this option is chosen in the main calculation window. These commands are also called using the toolbar buttons to the right of the paste button. In the upper part of *Figure 5-1* an example of a property list is shown, in the lower part the result of a one-third-octave band calculation.

If need be to paste any of the results calculated for single frequency lines the procedure will be a little more involved. The first step is to export the results either to a text file or directly to a Microsoft Excel file. These options are found in the submenus under **Export results** in the **File** menu in the main calculation window. The text file data may easily be imported into a spreadsheet, e.g. Microsoft Excel or similar, edited and pasted into the report using the general copy and paste procedure. Finally, the **View** menu controls the toolbar and the status line.

5.2 THE ADD LAYER MENU

The submenus offer the choice of adding the following type of layer:

- Air
- Porous layer
    - Delany/Bazley
    - Mechel
    - Attenborough
    - Allard-Johnson
- Slotted plate
    - Regular slots
    - Conical slots
- Perforated plate
    - Regular holes
    - Conical holes
    - Microperforated
- Limp mass
- Solid plate (panel)
    - Thin plate
    - Thick plate (elastic)
    - Sandwich
- HARD WALL
- Add layer from file

Except for the last item, clicking on one of these submenus brings a layer of the specified type into the configuration list box. Using the last item, a formerly saved layer is placed in the list box. **The layer is added below a marked layer. If no layer is marked it will be added at the end of the list.** A short description of each of these layers is given in the table below together with a reference to a Section under which to find a more detailed explanation of the various models used.

Submenu		**Shortcut**	**Description**
Air		None	This layer has its thickness as the main parameter with a default value of 50 mm. There is also the possibility to specify an attenuation coefficient. See details under the Section 5.2.1
Porous layer	Delany/Bazley	None	Porous material described by the empirical model after Delany and Bazley. The model has two parameters, the thickness and the flow resistivity and presupposes porosity near to 100%. On details, see under the Section 5.2.2.1
	Mechel	None	Porous material described by a model after Mechel. Compared to the model after Delany and Bazley it has the porosity as an additional parameter (see Note 1 below table). The model is a combination of a theoretical model for the behaviour at low frequencies and an empirical model for the higher frequencies. See details under the Section 5.2.2.2
	Attenborough	None	Theoretical model after Attenborough using a total of five parameters. Two of these parameters, a factor s_f describing the form of the pores and the flow resistivity r, are input as one parameter $s_f^2 \cdot r$. Details are given under the Section 5.2.2.3.
	Allard-Johnson	None	Theoretical model with a total of six parameters. The shape of the pores and their interconnections are characterised by parameters denoted viscous length and thermal length. Details are given under the Section 5.2.2.4.
Slotted plate	Regular slots	None	Conventional slotted plate constructed from beams of rectangular cross section and having sharp edges, e.g. a wooden slotted panel. See details under the Section 5.2.3.1
	Conical slots	None	Slotted plate as above but constructed from beams of trapezoidal cross section. See details under Section 5.2.3.2
Perforated plate	Regular holes	None	Plate or panel perforated with holes of circular shape; typically metal, gypsum or chipboard panels. See details under the Section 5.2.4.1.
	Conical holes	None	Panel perforated with holes of conical shape; typically relatively thick panels (> 9 – 10 mm) of gypsum, chipboard etc. See details under the Section 5.2.4.2

Perforated plate	Micro-perforated	None	Plate, panel or foil perforated with holes of circular shape but the diameter of the holes are less than 0.5 mm. Details are given under the Section 5.2.4.3
Limp mass		None	A mass layer characterised by its thickness and density only. Represents typically a thin layer of plastics or metal. See details under the Section 5.2.5.
Solid plate (panel)	Thin plate	None	A thin plate or panel characterised by its bending stiffness, mass and loss factor. See details under the Section 5.2.6.1
	Thick plate (elastic)	None	A solid elastic plate characterised by the same material properties as the thin plate but allow for thickness deformation. See details under the Section 5.2.6.2
	Sandwich	None	Sandwich panel construction with three layers, i.e. two identical thin face sheets with a thicker core. All layers are isotropic and homogeneous. See details under the Section 5.2.6.3
HARD WALL		None	An infinitely stiff wall. It is typically used to represent a termination for an absorbent placed against the ceiling or wall in a room. This layer has no parameters.
Add layer from file		Ctrl L	A formerly saved layer with user specified name and parameter data is input from a file (with extension .alg) and placed in the configuration list box.

NOTE 1. Porous/Mechel layer: Actually, the model for this layer also applies to high porosity materials only, even if the porosity is a parameter. Mechel, see reference under Section 5.2.2.2, recommends setting this parameter to 95%, which he assumes applies to most commercial fibre materials.

NOTE 2. Thick plate and Sandwich layer: Please note that these “layers” may only be directly coupled to the fluid layers, i.e. either the air layer or the porous ones.

5.2.1 The air layer

The layer is specified by its thickness in mm and characterised by the specific impedance (characteristic impedance) $\rho_0 \cdot c_0$ of air, where ρ_0 is the density and c_0 is the speed of sound. These quantities are given the values applicable for a temperature of 20 °C, i.e. ρ_0 and c_0 take on the values 1.21 kg/m^3 and 343 m/s. The characteristic impedance is then approximately 415 Pa·s/m. There is also an option to introduce attenuation in the layer by a power attenuation coefficient m (km^{-1}), i.e. the wave intensity is reduced by the factor exp($-mx$), where x the distance in km. The corresponding intensity level is reduced by approximately $4.343 \cdot m$ (dB/km). Please note that this input parameter is a constant value (frequency independent). General data for the coefficient $\alpha = 4.343 \cdot m$ (dB/km) as a function of frequency, air temperature and humidity is tabled in ISO standard 9613 – 1.

5.2.2 Porous layer

The program offers a choice of using four different models for describing a porous layer. These models use one or more material parameters to calculate the acoustical properties. However, as also pointed out in the introduction, the material is in all models treated as an equivalent fluid, i.e. the elastic properties are not taken into account and may not properly describe foam materials.

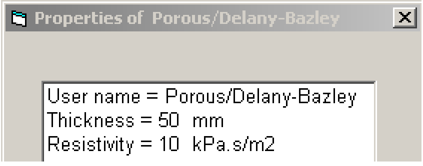
5.2.2.1 *Model by Delany and Bazley*

The model presented by Delany and Bazley, see reference below, is an empirical one based on a large number of measurement on materials having a porosity approximately equal to one (or 100% as used in this program). Using the frequency and the flow resistivity of the material as the only variables they arrived at empirical equations for the complex propagation coefficient Γ and the complex characteristic impedance Z_k of the material which may be written:

$$Z_\mathrm{k} = \rho_0 c_0 \left[1 + 0.0571 \cdot E^{-0.754} - \mathrm{j} \cdot 0.087 \cdot E^{-0.732}\right]$$

and $$\Gamma = \mathrm{j}\frac{\omega}{c_0}\left[1 + 0.0978 \cdot E^{-0.700} - \mathrm{j} \cdot 0.189 \cdot E^{-0.595}\right] \qquad \text{where } E = \frac{\rho_0 f}{r}.$$

The quantity r is the flow resistivity in Pa·s/m^2; f is the frequency in Hz and ω is the angular frequency in radians/s. The window specifying the material parameters for a layer using this model may be seen from the *Figure 5-2.*



User name = Porous/Delany-Bazley
Thickness = 50 mm
Resistivity = 10 kPa.s/m2

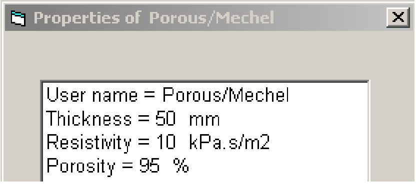
Figure 5-2. The property window for a porous layer using the Delany-Bazley model

Reference: M.E. Delany and E.N. Bazley (1970) Acoustical properties of fibrous materials. *Applied Acoustics* **3**, 105.

5.2.2.2 *Model by Mechel*

Mechel presents an extension of the Delany-Bazley model where he gives different equations depending on frequency. The model uses a theoretical expression for the behaviour at low frequencies combined with a curve fitting procedure to experimental data to predict the behaviour in the middle and the high frequency ranges. The model has the porosity as an additional parameter as compared with the Delany-Bazley model. Actually, the model for this layer also applies to high porosity materials only, even if the porosity is a parameter. The porosity parameter will only affect the low frequency part. Mechel, see the second reference below, recommends setting this parameter to 95%, which he assumes applies to most commercial fibre materials.

We omit the presentation of the equations here, which can be found from the references below. The window specifying the material parameters for a layer using this model may be seen from *Figure 5-3.*



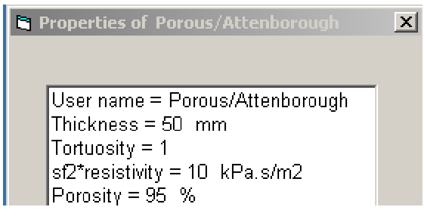
User name = Porous/Mechel
Thickness = 50 mm
Resistivity = 10 kPa.s/m2
Porosity = 95 %

Figure 5-3. The property window for a porous layer using the Mechel model

References:
1. F.P. Mechel (1976) Ausweitung der Absorberformel von Delany und Bazley zu tiefen Frequenzen. *Acustica* **35**, 210 - 213.
2. F.P. Mechel (1988) Design charts for sound absorber layers. *J. Acoust. Soc. Am.* **83**, 1002 - 1013.

5.2.2.3 *Model by Attenborough*

The work of Attenborough is primarily directed towards modelling ground impedance for the purpose of predicting outdoor sound propagation. He introduces a parameter s_f, the pore shape factor, to account for the shape of the pores in the material. One is not, however, able to measure this parameter separately and it must then be estimated by other means. In the program it is input in combination with the flow resistivity as a product $s_f^2 \cdot r$. An additional parameter to describe the pore orientation in the material, the *sinuosity* or more commonly termed the *tortuosity*, is also introduced. The window specifying the material parameters for this model may be seen from *Figure 5-4*. More details concerning this model may be found in the reference below. Please note that Attenborough uses the symbol q^2 for tortuosity.


Properties of Porous/Attenborough

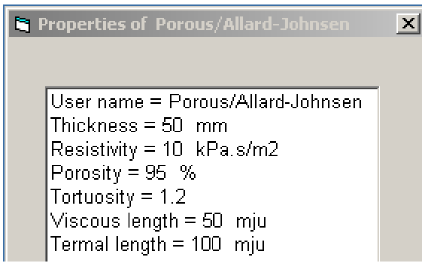
User name = Porous/Attenborough
Thickness = 50 mm
Tortuosity = 1
sf2*resistivity = 10 kPa.s/m2
Porosity = 95 %

Figure 5-4. The property window for a porous layer using the Attenborough model

Reference:
Attenborough, K. (1985) Acoustical impedance models for outdoor ground surfaces, *J. Sound Vib.* **99**(4), 521 - 544.

5.2.2.4 *Model by Allard and Johnson*

This model, which is thoroughly explained in the book by Allard, see the reference below, introduces two parameters to characterise the shape of the pores in the material. These parameters are termed characteristic *viscous length* Λ and characteristic *thermal length* Λ'. The advantage of this description is that, using high frequency sound (some hundred kHz), one may by measurements determine each of these parameters separately. As an indication of the magnitude of Λ and Λ' will, for foam materials, be in the range of some tenths of μm to some hundred μm.


Properties of Porous/Allard-Johnsen

User name = Porous/Allard-Johnsen
Thickness = 50 mm
Resistivity = 10 kPa.s/m2
Porosity = 95 %
Tortuosity = 1.2
Viscous length = 50 mju
Termal length = 100 mju

Figure 5-5. The property window for a porous layer using the Allard-Johnson model

The relationship between these two parameters also gives an indication of the pore shape. For a material with pores resembling straight tubes the two parameters will be of the same magnitude. In contrast, if the pores are interconnected by narrow tubes giving high resistance for flow, we will have $\Lambda << \Lambda'$.

The window for specification of the parameters for this model is shown in *Figure 5-5*. Please note, as stated in the introduction, that in most cases materials of the type of plastic foam need additional parameters for a complete description of the acoustical behaviour. The program will only give correct results when the elastic properties of the frame material may be neglected. As a rule of thumb, for foams layers 25 - 100 mm thickness, the elastic properties may strongly influence the acoustic data below 500 - 1000 Hz.

References:

1. J.F. Allard (1993) *Propagation of sound in porous media*. Modelling sound absorbing materials. Elsevier Applied Science, London and New York.
2. Ph. Leclaire, L. Kelders, W. Lauriks, M. Melon, N. Brown, B. Castanede (1996) Determination of the viscous and thermal characteristic length of plastic foams by ultrasonic measurements in helium and air. *J. Appl. Physics* **80**, 2009 - 2012.

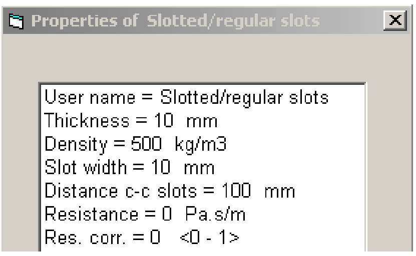
5.2.3 Slotted plate (Slatted panel)

These types of layers are intended to be included in a resonance absorber composed of a slotted plate placed at a distance from a ceiling or a wall, i.e. a common absorber system is the plate, an airspace with or without a porous layer and a hard backing wall. In the normal case the slotted plate could typically be an assemblage of parallel sharp edged beams (slats) of rectangular cross section with a specified thickness and width. This is commonly denoted a slatted panel. However, the calculation procedure also applies to thin, e.g. metal panels so the common name “slotted plate” is used in the menu. These cases are chosen using the submenu “Regular slots”. Using the submenu “Conical slots” the cross section of the beams (slats) will be trapezoidal.

5.2.3.1 *Regular slots*

The distance between the beams is characterised by the *slot width*, see the window for the specification of parameters shown in *Figure 5-6*, and the width of the beams goes into the parameter *centre-to-centre distance* between slots. The density of the material is also part of the specification going into the calculation of the equivalent mass impedance of the plate. Normally, the influence of the latter impedance will be very small.

To obtain a high absorption coefficient for a resonance absorber the panel must be combined with a porous layer or a fabric placed close to the slots, this to give the necessary resistance component. (An exception to this rule is by using the so-called microperforated plate or panel, se below). If a fabric is used, the total resistance (in Pa·s/m) must be specified.



User name = Slotted/regular slots
Thickness = 10 mm
Density = 500 kg/m3
Slot width = 10 mm
Distance c-c slots = 100 mm
Resistance = 0 Pa.s/m
Res. corr. = 0 <0 - 1>

Figure 5-6. The property window for a regular slotted plate

In case one is using a porous layer in the air space directly behind the slotted plate there is also the possibility to add an extra *resistance correction* to the data. This is a parameter that should take on values between zero and one. This indicates that one is adding a resistance component equal to the total resistance of the porous layer having a maximum thickness of one *end correction* for the slots. The rationale behind this option is that the acoustical properties of the panel are not independent of the following porous layer. Further explanation is given in the next section. The default value of this parameter is zero and it should only be changed if warranted by user experience.

Important notice! For wide slots combined with a very high percentage open area, say above 30 – 40 %, this model may give unreliable results for frequencies above the fundamental resonance frequency. Information on the percent open area will be given when updating the relevant parameters.

Reference:
U.R. Kristiansen, T.E. Vigran (1994) On the design of resonant absorbers using a slotted plate. *Appl. Acoustics* **43**, 39 - 48.
(Please note that there is a misprint in equation (6) in the article. The matrix element a_{12} should be $W \cdot \sinh(D)$)

5.2.3.2 *Conical (wedge-shaped) slots*

Instead of using a panel being an assemblage of beams (slats) of rectangular cross section one may use beams having a trapezoidal cross section, i.e. the slots will have a conical shape, see *Figure 5-7*. As shown in the reference below this will, for relatively thick panels, give resonance absorbers acting over a broader frequency range as compared with the regular ones. Due to the shape of the slots the window for specifying the parameters, see *Figure 5-8*, will contain data for *slot width* on the entrance side as well as on the exit side. The same apply to an added resistance layer. This could be placed on either side of the panel.

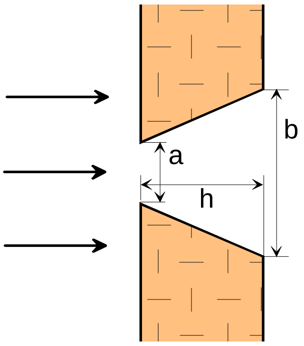
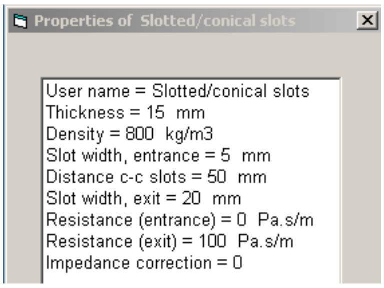


Figure 5-7 Conically shaped slot in a panel of thickness h. The width on the entrance and exit side are a and b, respectively.

The conical angle one may use is restricted upwards to approximately 30 degrees. The slot width on the exit may not be equal (or smaller) than the entrance width but calculations may be performed with only a fractional difference, i.e. in the order of 1/10 % so one may well apply this model to regular slotted panels.

The model used is also more advanced than the one used for regular panels where the air in the slot is treated as a concentrated mass of air. This implies that now the real wave movements in the slots are calculated which may show effects at higher frequencies due to thickness resonances.



User name = Slotted/conical slots
Thickness = 15 mm
Density = 800 kg/m3
Slot width, entrance = 5 mm
Distance c-c slots = 50 mm
Slot width, exit = 20 mm
Resistance (entrance) = 0 Pa.s/m
Resistance (exit) = 100 Pa.s/m
Impedance correction = 0

Figure 5-8 The property window for the slotted plate with conical slots.

A correction for the effect of a porous layer behind the panel is included using the parameter *Impedance correction*. This will take effect setting this parameter different from zero. The reason for this name is that the routine calculates the so-called radiation impedance of the slot looking into the porous layer instead of treating this layer as plain air. Experience; see e.g. the paper by Kirby and Cummings in the reference below, shows that using such corrections easily overestimates the effect of the porous layer. The correction used here is therefore empirically set to use the mean value of the impedance in the two cases, air and porous medium.

References:
Vigran, T. E. (2004) Conical apertures in panels; Sound transmission and enhanced absorption in resonator systems. *Acta Acustica united with Acustica*, **90**, 1170 – 1177.
Kirby, R and Cummings, A. (1998) The impedance of perforated plates subjected to grazing flow and backed by porous media. *Journal of Sound and Vibration*, **217**, 619 – 636.

5.2.4 Perforated plate

As for the slotted plate, the perforated plate is intended for use in a resonance absorber. The program offers the choice of three types of plates: regular cylindrical holes, holes of conical shape and micro perforation. The latter means than the diameter of the holes are less than 0.5 mm.

5.2.4.1 *Regular holes*

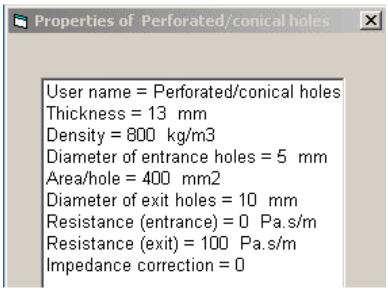
The plate in this case is typically a thin metal plate perforated by holes. The program assumes that the shape of the holes is cylindrical. The model may also be used for thicker plates of other materials, e.g. gypsum, chipboard or similar. The window for specifying the parameters has already been presented; see *Figure 4-2*. Obviously, the parameters resemble the ones for the regular slotted plate. Please note that the notice above concerning the percentage open area also applies to this model of a perforated plate.

It is assumed that the perforation is regular so that a certain area of the plate can be attributed to each hole. One may find patterns having a triangular, a square or a diagonal pitch. For the two latter ones the parameter *area/hole* will be the centre-to-centre distance CC squared, i.e. $(CC)^2$. For the triangular ones this parameter will be $(3^{1/2}/2)\cdot CC^2 \approx 0.87\cdot CC^2$. Alternatively, one may use the producer's data for the percentage perforation (percent open area) of the plate to calculate an equivalent value for this parameter. Information on the percent open area is given when clicking on each of the two parameters *diameter of holes* and the *area/hole*.

5.2.4.2 *Conical holes*

Analogous to the slotted plate with conical slots this layer represents plates perforated with conical holes, i.e. the holes have a shape which may be illustrated by *Figure 5-7* but now the dimensions *a* an *b* are the diameters of the hole at the entrance and exit side, respectively. The window for specifying the parameters, see *Figure 5-9*, is therefore quite similar to the one for a slotted panel with conical slots.

Again, the conical angle one may use is restricted upwards to approximately 30 degrees but calculations may be performed with only a fractional difference between the diameters of the holes on the entrance and exit side.


Properties of Perforated/conical holes

User name = Perforated/conical holes
Thickness = 13 mm
Density = 800 kg/m3
Diameter of entrance holes = 5 mm
Area/hole = 400 mm2
Diameter of exit holes = 10 mm
Resistance (entrance) = 0 Pa.s/m
Resistance (exit) = 100 Pa.s/m
Impedance correction = 0

Figure 5-9 The property window for the perforated plate with conically shaped holes.

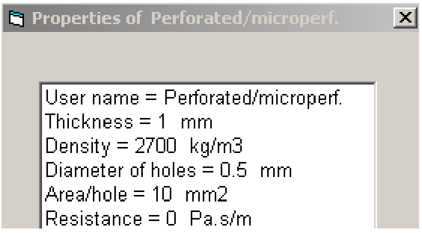
The parameter *Impedance correction* works in the same way as for conical slots; the radiation impedance seen from hole into a porous layer is modified. Annex D gives an example on measurements and calculations on resonator panels comparing panels using conically shaped holes and regular cylindrical ones.

5.2.4.3 *Microperforated*

This plate is in principle equal to an ordinary perforated plate described above in Section 5.2.4.1 but with an important exception: the diameter of the holes should typically be less than 0.5 mm. A porous layer or a fabric is then superfluous to get a necessary resistance component for such a plate used in a resonance absorber. As shown in *Figure 5-10*, the window for specifying the parameters has never the less the option for adding a fabric with a given flow resistance. The density of the material is also part of the specification going into the calculation of the equivalent mass impedance of the plate. Normally, the influence of the latter impedance will be very small using metal plates. However, due to the advent of microperforated plastic sheets acting as membranes this may be an important parameter. For an example, see Annex C.

An analytical expression to calculate the impedance of the holes in such a plate has been known for nearly hundred years but the idea to exploit the principle to make a practical acoustical absorber was put forward by Maa in 1987. The reference given below is a later article by the same author that also has a number of references to other papers on the subject.

It should be pointed out that the present program does not use the approximate formulas for the impedance given by Maa but the calculations are based on the full analytical solution which include Bessel functions with complex argument. This does not imply, however, that the accuracy is very much better than when using the approximate formulas.



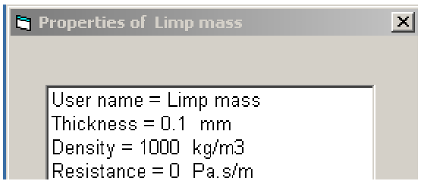
User name = Perforated/microperf.
Thickness = 1 mm
Density = 2700 kg/m3
Diameter of holes = 0.5 mm
Area/hole = 10 mm2
Resistance = 0 Pa.s/m

Figure 5-10. The property window for a microperforated plate.

Reference:
Maa, D. Y. (1998) Potential of microperforated panel absorber. *J. Acoust. Soc. Am*, **104**(5), 2861 - 2866.

5.2.5 Limp mass

The layer is primarily intended to represent a thin, impermeable sheet (plastic, metal etc.) or a very thin plate or panel where the bending stiffness is negligible. It may then be used to calculate the absorption of membrane absorbers, i.e. when this layer is combined with an air space in front of a hard backing wall. However, the normal use will be to calculate the effect of covering a porous material with an impermeable thin layer. In the specification of the input parameters, see *Figure 5-11*, there is also the opportunity to specify a resistance component added to the mass. The size of this component must wholly depend on user experience.



User name = Limp mass
Thickness = 0.1 mm
Density = 1000 kg/m3
Resistance = 0 Pa.s/m

Figure 5-11. The property window for a mass layer (limp mass)

5.2.6 Solid plate (panel)

The program offers calculations with three different types of panel. The first two models a single solid plate using so-called thin plate and thick plate theory, respectively. The first implies that the wavelength for bending waves is larger than approximately six times the thickness of the plate, whereas the second allow for thickness deformation of the plate. This may result in dilatational resonances reducing the sound reduction index of the panel.

The third submenu choice is a sandwich panel. In relation to this program the sandwich panel is a special case. The layer is actually a combination of three separate layers, a core with two face sheets; see sketch in *Figure 5-13*.

5.2.6.1 *Thin plate*

As stated above is the model used for the this layer based on thin plate theory, which implies that the wavelength for bending waves in the plate is larger than approximately six times the thickness of the plate. The so-called wall impedance Z_W of a plate, i.e. the difference in sound pressure across the plate divided by the velocity of the plate, may then be written

$$Z_{\mathrm{W}} = \mathrm{j}\omega m\left[1-\left(\frac{f}{f_{\mathrm{g}}}\right)^2\cdot(1+\mathrm{j}\eta)\sin^4\varphi\right],$$

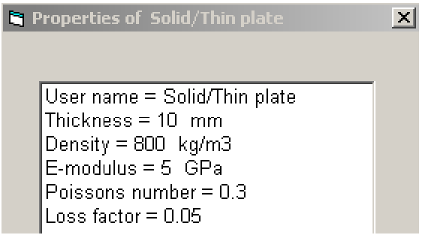
where m, η and f_g are the mass pr unit area, the loss factor and the coincidence frequency respectively. φ is the angle of the incident plane wave and f and ω symbolise the frequency in Hz and the angular frequency in radians pr second. The coincidence frequency is given by

$$f_{\mathrm{g}} = \frac{c_0^2}{2\pi}\sqrt{\frac{m}{B}},$$

where the mass pr unit area m and the bending stiffness B may be calculated from the density of the material ρ and the plate thickness h, respectively from the elastic modulus (Young's modulus) E, Poisson's ratio υ and the thickness using the equations

$$m = \rho\cdot h \qquad \text{and} \qquad B = \frac{E}{1-\upsilon^2}\cdot I = \frac{E}{1-\upsilon^2}\cdot\frac{h^3}{12}.$$

Here the I is symbolising the area moment of inertia pr unit width. The window for specification of the necessary input parameters is shown in *Figure 5-12*.



User name = Solid/Thin plate
Thickness = 10 mm
Density = 800 kg/m3
E-modulus = 5 GPa
Poissons number = 0.3
Loss factor = 0.05

Figure 5-12. The property window for a thin solid plate (panel)

5.2.6.2 *Thick plate (elastic)*

As stated in the introduction we shall need four physical variables, e.g. the particle velocity and the stress in two directions to describe the relationship between the input and output for a thick (homogeneous and isotropic) elastic plate or wall. In another words, we have to use a 4 by 4 matrix instead of the simple 2 by 2 matrices generally implemented in WinFLAG.

However, as stated above, the 4 by 4 matrix may be reduced to a 2 by 2 matrix if there are fluid layers on both sides of the elastic layer.

Explicit analytical expressions for the sound reduction index (transmission loss) of single thick plates (walls) may be found in the reference below, Ljunggren (1991). However, to include the calculations in the general layout of the program an approach based on the general theory of layered elastic media is used, see the reference Folds and Loggins (1977). The latter article give expressions for all 16 elements of the matrix that describe the relationship between the input and output particle velocity and stresses in two directions for a single layer. With the assumption that there are fluid layers or equivalent fluid layers (porous materials) on both sides it may be shown that an effective wall impedance Z_W, see the description on thin panels above, may be expressed using only four of these elements (a_{31}, a_{32}, a_{41} and a_{42}).

The property window for the thick plate is, apart from the default values, identical to the property window for the thin plate or panel.

When calculating the sound reduction index of configurations involving plates it is advisable to compare results using both models. Normally, the differences should be small for most building materials but one should use the thick plate option if the results diverge significantly in an important frequency range. An example on such comparison was presented under Section 4.2; see *Figure 4-6*.

References:

1. Ljunggren, S. (1991) Airborne sound insulation of thick walls. *J. Acoust. Soc. Am.* **89**, 2338 - 2345.
2. Folds, D.L. and Loggins, C. D. (1977) Transmission and reflection of ultrasonic waves in layered media. *J. Acoust. Soc. Am.* **62**, 1102 - 1109.

5.2.6.3 *Sandwich*

As stated above the sandwich is a special case. The “layer” is actually a combination of three separate layers, a core with two face sheets; see sketch in *Figure 5-13*. The core is an elastic layer described by a 4 by 4 matrix discussed above; see Section 5.2.6.2. We may, however, include the sandwich panel as one single layer if we are able to find the equivalent wall impedance Z_W for the total element in the same way as for the single plates. Knowing the wall impedance, the transmission loss may be calculated. Again, there should only be fluid layers directly in contact with this element.

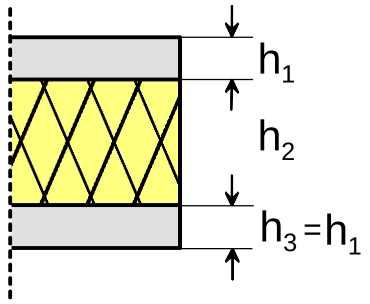
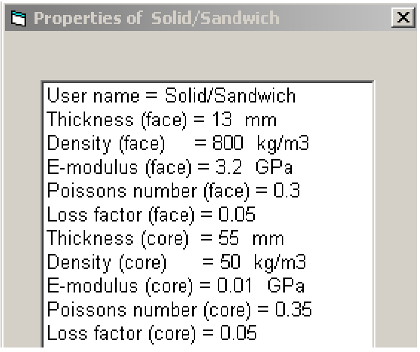


Figure 5-13 Sandwich panel with core and identical face sheets.

The calculation routine is based on a paper by Moore and Lyon, see the reference below, who describe the wave motion of a panel construction with thin face sheets and a thicker and lighter core. The core may be orthotropic but this option is not implemented here. The program presupposes that the core as well as the face sheets is homogeneous and isotropic.

Furthermore the face sheets are considered to be identical. The sandwich panel may in the same way as an elastic layer have symmetric as well as antisymmetric propagating modes, i.e. there may be thickness deformation of the core (dilatational modes) as well as deformation of the panel without changes in thickness. Both types of modes give rise to coincidence phenomena with normally result in increased sound transmission.



User name = Solid/Sandwich
Thickness (face) = 13 mm
Density (face) = 800 kg/m3
E-modulus (face) = 3.2 GPa
Poissons number (face) = 0.3
Loss factor (face) = 0.05
Thickness (core) = 55 mm
Density (core) = 50 kg/m3
E-modulus (core) = 0.01 GPa
Poissons number (core) = 0.35
Loss factor (core) = 0.05

Figure 5-14. The properties window for a sandwich panel with identical face sheets.

Figure 5-14 shows the window for specifying the parameters of the sandwich panel. The uppermost five lines, indicated with (face), give the parameters for the identical face sheets. The corresponding data for the core are indicated by (core).

Reference:
Moore, J. A. and Lyon, R. H. (1991) Sound transmission loss characteristics of sandwich panel constructions. *J. Acoust. Soc. Am.* **89**(2), 777 - 791.

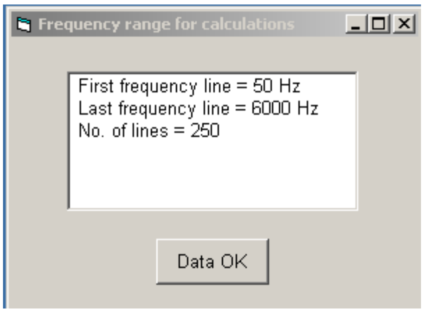
5.3 THE FREQUENCY MENU

The submenus have the following items:

- Frequency range
- Linear scale
- Logarithmic scale

Clicking on any of these items starts a new calculation.

Submenu	Shortcut	Description
Frequency range	Ctrl F	Opens up a new window to specify the frequency range of the calculations including the number (max. 500) of frequency lines used, see *Figure 5-15*.
Linear scale	None	The frequency is incremented linearly
Logarithmic scale	None	The frequency is incremented logarithmically. This option is automatically chosen when calculating mean values in one-third-octave bands, see calculation options under Section 4.1.



First frequency line = 50 Hz
Last frequency line = 6000 Hz
No. of lines = 250

Figure 5-15 Window for setting the frequency range and number of lines used in the calculations

The frequency range being used in the calculations are always specified by the first and the last frequency line in addition to the total number of lines inside this range. When calculating mean values in one-third-octave bands one should preferably set the first frequency line equal to or lower than the lower cut-off frequency of the first frequency band of interest. Conversely, the last frequency line should be equal to or higher than the upper cut-off frequency of the last band of interest.

5.4 THE SOUND INCIDENCE MENU

The submenus have the following items:

- Angle
- Diffuse
- Reverberation room

Clicking on any of these items starts a new calculation.

Submenu	Shortcut	Description
Angle	Ctrl V	Opens up a window for specification of the plane wave angle of incidence (between 0 and 90 degrees). Zero degrees signify normal incidence.
Diffuse	Ctrl D	Calculates a mean value for all angles of incidence. More details concerning this calculation are given below.
Reverberation room	Ctrl K	Calculates an estimate of the absorption coefficient measured for the actual absorbent configuration in a standardised reverberation room test. An option to estimate the weighted coefficient α_W is included; see the description under Section 5.4.2. The specimen is assumed to have a square shape and choosing this option brings up a window for input of the length of the side of the square. The default value is 3.162 meter giving approximately an area of 10 m^2.

When choosing "Diffuse", mean values for the absorption coefficient and the sound reduction index are calculated, the latter one only if relevant. Mean values are not calculated for the impedance. Furthermore, the reverberation room option only applies to the case of absorption coefficients. Some details concerning the calculation of these mean values are given under the Section 5.4.1.

5.4.1 Statistical absorption and transmission coefficients

Choosing the item "Diffuse" a statistical absorption coefficient α_{stat} is calculated using the expression

$$\alpha_{\text{stat}} = 2\int_0^{\pi/2} \alpha(\varphi)\sin\varphi\cos\varphi\,\mathrm{d}\varphi\,,$$

where α (φ) is the absorption coefficient with the incident angle φ. If relevant for the actual configuration, i.e. the layer HARD WALL is not included, a mean transmission coefficient τ_{stat} is calculated in the same way and the mean sound reduction index R in dB is displayed. In this case, however, the upper limit in the integration is set to approximately 80 degrees which is the usual simple way to get a better fit between measured and calculated results. In each case the integral is solved numerically using a Gaussian routine.

With the menu item "Reverberation room" integration over the angle of incidence is also performed. In this case, however, the limited size of the absorbent is taken into account. Due to diffraction effects the effective "acoustical size" may become larger than the actual geometrical size of the absorber. As a result of this so-called edge effect the absorption coefficient may become larger than 1.0.

Thomasson, see the reference below, have shown that we may write

$$\alpha_{\mathrm{stat}} = \frac{4\,\mathrm{Re}\{Z_{\mathrm{n}}\}}{\pi} \int_{0}^{\pi/2} \int_{0}^{2\pi} \frac{\sin\varphi}{\left|Z_{\mathrm{n}} + Z_{\mathrm{f}}\right|^{2}} \mathrm{d}\varphi \mathrm{d}\theta \ ,$$

where Z_{n} is the normalised input impedance of the absorber (normalised to $\rho_0 \cdot c_0$). The impedance Z_{f} is by Thomasson denoted "field impedance" which is dependent on the shape and dimensions of the absorber and also on frequency and the angle of incidence. In general the sound incidence must be specified by the angle of incidence φ referred to the normal and to the azimuth angle θ as well.

The calculations in the program presuppose a square specimen. Please note that the formula above concerns *locally reacting* materials. In the case of mineral wool type of porous materials the calculations have shown to be fairly accurate. Applied to bulk reacting absorbers as resonance absorbers where the airspace is not subdivided (into cassettes) the accuracy is not asserted. Probably the edge effect is a little overestimated.

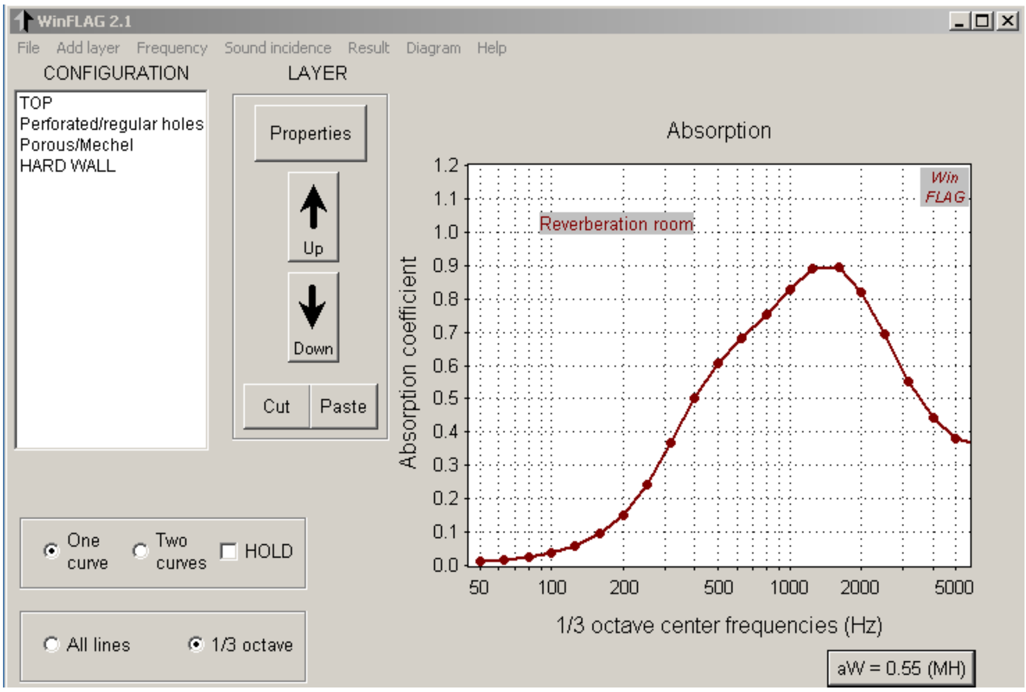
Reference:
S.-I. Thomasson (1980), On the absorption coefficient, *Acustica* **44**, 265 - 273.

5.4.2 Weighted sound absorption coefficient

The weighted sound absorption coefficient α_{W} according to ISO 11654 may be estimated, see the reference below. This applies when using the menu item "Reverberation room" and the option one-third-octave band is set. A button with the caption "Alpha W" will then appear at the bottom right of the graphical picture. Clicking the button will run a calculation and the caption will show the estimated value α_{W} together with the proper shape indicators L, M or H. This calculation presuppose that the side length of the absorber is in the range 3.16 – 3.46 meter, i.e. the area is between 10 and 12 m^2 as given in the measurement test procedure in ISO 354, see below. The default value of this side length is 3.162 meter.

Calculation of α_{W} is based on standard reverberation room measurement results of the sound absorption coefficient in one-third-octave bands. The measurement procedure is described in the standard ISO 354; a reference is given below. From these results practical sound absorption coefficients α_{pi} in the octave bands 250, 500, 1000, 2000 and 4000 Hz are calculated according to certain rounding rules. These data are then compared with a reference curve having the following values in the octave bands listed above: 0.8, 1.0, 1.0, 1.0 and 0.9. This reference curve is shifted in steps of 0.05 until the sum of the unfavourable deviations are less than or equal to 0.1. An unfavourable deviation occurs when at any octave band the measured value is less than the reference value. Only deviations in the unfavourable direction are counted. Finally, the weighted sound absorption coefficient is defined as the value of the shifted reference curve at 500 Hz.

Shape indicators shall be added to α_W (in parentheses) if the practical sound absorption coefficient exceeds the shifted reference curve by more than 0.25, using the letter L if excess absorption occurs at 250 Hz, M if it occurs at 500 or 1000 Hz and H if it occurs at 2000 or 4000 Hz.
An example on a calculation is shown in *Figure 5-16* where the button "Alpha W" has been clicked on, see lower right corner.



TOP
Perforated/regular holes
Porous/Mechel
HARD WALL

● One curve ○ Two curves ☐ HOLD

○ All lines ● 1/3 octave

aW = 0.55 (MH)

Figure 5-16 The main window showing a calculated weighted sound absorption coefficient α_W and shape indicators. The parameters are the same as used in Figure 4-4, except for the thickness of the porous material being reduced to 25 mm.

Reference:
ISO 11654: 1997 Acoustics -- Sound absorbers for use in buildings. Rating of sound absorption.
ISO 354:2003 Acoustics -- Measurement of sound absorption in a reverberation room

5.4.3 Weighted sound reduction index

The weighted sound reduction index R_w according to ISO 717-1 may be estimated, see the reference below. This applies when using the menu item "Diffuse" and the option one-third-octave band is set. A button with the caption "R-weighted" will then appear at the bottom right of the graphical picture (In the same position as the button for α_W; see *Figure 5-16*). Clicking on the button a calculation will run and the caption will show the estimated value provided the frequency range is sufficiently large, see *Figure 4-6*.

Calculation of R_w is normally based on laboratory measurement of the sound reduction index *R* in one-third-octave bands from 100 Hz to 3150 Hz. The measurement procedure is described in the standard ISO 140 part 3; a reference is given below. The measured data are rounded to one decimal and compared to a reference curve. This reference curve is shifted in steps of 1 dB until the sum of the unfavourable deviations are less than or equal to 32 dB. An unfavourable deviation occurs when at any one-third-octave band the measured value is less than the reference value. Only deviations in the unfavourable direction are counted. Finally, the weighted sound reduction index is defined as the value of the shifted reference curve at 500 Hz.

It should be noted that the uncertainty of data for R_w based on calculated data, rather than measured ones, could be large. As the calculations in this case are on infinite size samples and that any possible mechanical connections between layers are neglected, comparison with “real world” sound-insulating walls will bring out some differences. However, it is the sound insulation in the lower frequency range that normally determines the R_w value, and here the coupling mechanisms simulated in WinFLAG will dominate.

Reference:

ISO 717-1: 1996 Acoustics -- Rating of sound insulation in buildings and of building elements. Part 1: Airborne sound insulation
ISO 140-3:1995 Acoustics -- Measurement of sound insulation in buildings and of building elements. Part 3: Laboratory measurements of airborne sound insulation of building elements.

5.5 THE RESULT MENU

The menu gives the choice on which calculated result should be displayed, i.e.

- Absorption coefficient
- Input impedance
- Sound reduction index
- Duct attenuation

None of these choices calls up the calculation procedure because all relevant data are calculated simultaneously. For the duct attenuation two sub-items are available, Show (results) and Calculate. The latter recalculates if certain conditions are met, see the table below. More details on duct attenuation are given under the Section 6.

Submenu		**Shortcut**	**Description**
Absorption coefficient		Ctrl A	Display the chosen values for the absorption coefficient, i.e. the coefficient for a given angle of incidence, a mean value in a diffuse field or an estimate from a reverberation room.
Impedance		Ctrl I	Display the real and imaginary part of the normalised input impedance for a given angle of incidence.
Sound reduction index		Ctrl R	Display the chosen values for the sound reduction index, either for a given angle of incidence or a mean value in a diffuse field. In the latter case the upper limit of integration is 80 degrees.
Duct attenuation	Show	Ctrl W	Display the result for the duct attenuation in dB/m if the following conditions are set for the layer configuration • At least one porous layer is present • The HARD WALL is included • The incidence angle is set to zero degrees
	Calculate	Ctrl C	Provided the above conditions are fulfilled this choice brings up a window to input the half-width *h* of the air duct, see *Figure 6-1*, the default value being 100 mm. Performs a recalculation and displays the result. *

---

* A maximum obtainable attenuation of 3dB pr length of duct equal to the half-width *h* is often used as a “rule of thumb” in the design of silencers. This limit will be indicated by a dotted line in the graph.

5.6 THE DIAGRAM MENU

The menu offers the choice of changing the values on the axes of the diagram. No new calculations are performed. The choices are the following:

- First frequency
- Last frequency
- Y minimum
- Y maximum

Submenu	Shortcut	Description
First frequency	None	Opens up a window to specify the first frequency marking on the abscissa. The default value is 45 Hz.
Last frequency	None	Opens up a window to specify the last frequency marking on the abscissa. The default value is 5700 Hz.
Y minimum	None	Opens up a window to specify the minimum value for the ordinate. The default value is zero except when displaying the impedance where the value is -10.
Y maximum	None	Opens up a window to specify the maximum value for the ordinate. The default values are 1.2, 10.0 and 50.0 for the absorption coefficient, the impedance and the sound reduction index, respectively. The last value also applies to the duct attenuation.

5.7 THE HELP MENU

The choices are:

- Opening the full manual (pdf-file)
- Opening a material property list (pdf-file)
- Information on WinFLAG

Submenu	**Shortcut**	**Description**
Manual (pdf-file)	Ctrl H	Opens up this help file in pdf-format. The program to read this file, Adobe Acrobat, must be installed.
Properties of materials	Ctrl M	Opens up separately Annex B in this help file.
About WinFLAG	None	Displays an information window on WinFLAG

6 ATTENUATION IN DUCTS (SILENCERS)

Calculation of the attenuation of silencers is not a part of the general transfer matrix scheme used in WinFLAG. Knowing the input impedance of a certain configuration of layers one may estimate the attenuation applying such a lining to a duct wall. The literature on the subject is extensive and procedures exist to calculate the attenuation of silencers of almost any cross section and also being of finite length. The latter implies a complex mode matching technique to match the modal pattern in both the input and output duct to the modal pattern in the lined part of the duct. For a calculation and a review of procedures for handling finite length silencers see e.g. a paper by Kirby (2001), see the full reference below.

The implementation in the program, however, is restricted to the calculation on rectangular symmetrical silencers of infinite length as depicted in *Figure 6-1.* A procedure given by Frommhold and Mechel (1990), see the reference below, is used. Furthermore, only the formulas dealing with locally reacting linings are implemented; i.e. we assume that there is no sound propagation along the duct inside the lining itself. In practice this means that in case of a porous lining material the flow resistivity must be high enough or there must be hard partitions (cassettes) to prevent the sound propagation. The same restriction applies of course to a resonant lining, i.e. a Helmholtz resonator type of lining.

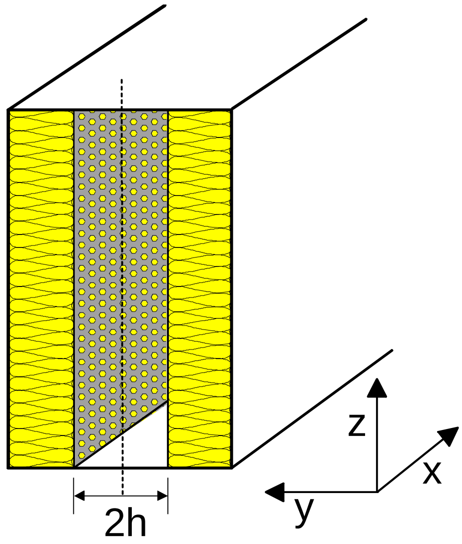


Figure 6-1. Rectangular silencer duct

The attenuation in dB per meter of lined duct is calculated by an approximate solution of the wave equation for the sound field in the air duct, se details below. Partly because the approximations will be poor in the neighbourhood of critical branch points, restrictions are imposed in the program. No calculations are performed if the following conditions are not met:

- At least one porous layer must be present in the lining
- The HARD WALL must be present (simulates the duct outer wall)
- The sound incidence angle must be set to zero degrees

Also please observe that the attenuation always applies to the least attenuated mode, which means that the estimate generally is a conservative one. However, one may experience quite large attenuation rates in smaller frequency ranges, may be 8 – 10 dB pr length of duct equal to the half-width *h*. However, in practice there will always be other sound transmission mechanisms coming into play when the primary sound transmission path is sufficiently attenuated. Such mechanisms may be vibration transmission along the duct walls whereas another is the so-called “break-out” phenomenon, i.e. sound transmission directly out through the duct walls and into the surroundings. This sound energy may subsequently have the possibility to re-enter (“break-in”) in another part of the duct. Flexible connections in the ductwork are certainly a weak point in this respect. Designing a single silencer having a total attenuation in excess of say 40 - 50 dB is then very difficult. Other “rules of thumb” concerning the maximum attainable attenuation are also in existence. One of these is to set 3dB/half-width as a maximum attenuation limit. This limit is therefore indicated when performing these calculations; see under Section 5.5.

A square duct with linings on all walls or the equivalent circular duct (diameter $2 \cdot h$ inside the lining) will approximately give twice the attenuation. For the latter case Frommhold and Mechel also give a quadratic approximate formula, similar to the one cited below. This is, however, taken from an earlier paper and one should note that there is a difference from the original one.

6.1 RECTANGULAR DUCT WITH LINING ON TWO WALLS

With the assumptions given above and furthermore that the sound field in any cross section is the same in the z-direction, the equation for the complex wave number k_y in the crosswise direction may be written

$$(k_y \cdot h) \cdot \mathrm{tg}(k_y \cdot h) = \mathrm{j}\frac{k_0 \cdot h}{Z_{\mathrm{n}0}},$$

where $2 \cdot h$ is the width (or depth) of the air channel and $Z_{\mathrm{n}0}$ is the normalised input impedance of the lining at normal incidence (zero degree incidence angle). Solving this equation for k_y we may from the total wave number k_0 find the complex wave number k_x in the direction of flow. For the latter, which will give us the attenuation, we may write

$$k_x = \mathrm{Re}\{k_x\} + \mathrm{j} \cdot \mathrm{Im}\{k_x\} = \sqrt{k_0^2 - k_y^2}\ ,$$

where Re{} and Im{} signify the real and imaginary part of the wave number. The attenuation for a length ℓ of duct is then given by

$$\Delta L = 20\lg(e) \cdot \mathrm{Im}\{k_x\} \cdot \ell \qquad (\mathrm{dB})\ .$$

(Using the complex propagation coefficient Γ instead of the complex wave number k the real part of Γ must be used in the last equation).

Frommhold and Mechel (1990) express the equation to be solved for k_y as

$$\sqrt{E} \cdot \mathrm{tg}(\sqrt{E}) = \mathrm{j} \cdot U\ ,$$

and they use an expansion of the left-hand side by a so-called method of continued fractions to arrive at polynomial approximations of the equation of various orders. We shall use the quadratic approximation given in the equation (42) and (43) in the paper, which is

$$E_{1,2} = \frac{(78.94 - \mathrm{j} \cdot 5.43) + \mathrm{j}U(34.47 - \mathrm{j} \cdot 2.2) \pm \sqrt{}}{(16.1 - \mathrm{j} \cdot 1.11) + 2\mathrm{j}U},$$

where

$$\sqrt{} = \sqrt{(6203 - \mathrm{j} \cdot 857) + \mathrm{j}U(2887.3 - \mathrm{j} \cdot 372) + (\mathrm{j}U)^2(867.4 - \mathrm{j} \cdot 130)}\ .$$

The calculation in the program always uses the solution giving the least attenuation.

References:

Frommhold, W. and Mechel, F.P. (1990) Simplified methods to calculate the attenuation of silencers, *J. Sound Vib.* **141**(1), 103 - 125.

Kirby, R. (2001) Simplified techniques for predicting the transmission loss of a circular dissipative silencer, *J. Sound Vib.* **243**(3), 403 – 426.

7 WINFLAG LICENSE TRANSFER

Once you have registered the software, you may transfer the license from one computer to another. For this to work, the software has to be registered on the user's computer. Once the transfer is complete, the original program will become unregistered and expire immediately (so it is not possible to run the software on two computer simultaneously).

To transfer the license, the user will need the registration number from the new computer. You must install and run the software on this computer to obtain the registration number. Then click the **Start** button on the source computer and open the command line prompt (select **All programs→Accesories→Command Prompt**).

Then use the command line to transfer the license. The first part is the full path of the executable (your path may not be the same as shown below). XXXX-XXXX is the registration number from the other machine.

```
“c:\Program Files\WinFlag_v21\WinFlag_2.1.exe” /TRANSFER XXXX-XXXX-FL
```

ANNEX A. CONFIGURATION FILE

The configuration file will contain the complete user set-up, i.e. the layer configuration together with the relevant parameters, either specified by the user or the default ones. The file name is given by the user but the file gets the extension ".lag". One line of heading text is also asked for before the file is saved; see the first line in the example below.

The file is, however, a plain text-file (ASCII) that may easily be edited by the user in an ordinary text editor, e.g. Microsoft Notepad or similar. *Such an editing will be necessary if one wants to use a configuration file from the first version of WinFLAG.* New types of layers introduced in WinFLAG Version 2.0 onwards necessitate a use of a total of ten parameters whereas the former version had eight only. The following lines give an example of a configuration file where the print in red colour has to be added to the old configuration files. Only the numbers are important for reading the file into the program, the text between the quotation marks is just for explanation and could be an empty string.

Example:

```
"4-layer test configuration"
50,"First frequency"
6000,"Last frequency"
250,"No. of lines"
1,"Identifier for the scale"
1," Identifier for one-third-octave"
0,"Angle"
0,"Identifier for incidence"
3.25,"Side length"
100,"Duct half-width"
4,"No. of layers"
9,"Limp mass"
4,"Porous/Attenborough"
1,"Air"
11,"HARD WALL"
.1,1000,0,0,0,0,0,0,0,0
50,1,10,95,0,0,0,0,0,0
50,0,0,0,0,0,0,0,0,0
0,0,0,0,0,0,0,0,0,0
```

ANNEX B. PROPERTIES OF MATERIALS

The table, together with the graph below, is intended to give an estimate of some important material data in case data for the product is not available from the producer. The data has been collected from various sources and the conditions for the measurements are not always clear. As for the table, the modulus of elasticity (Young's modulus) should for acoustic purposes be tested under dynamic conditions. Most of the data given here is believed to apply under such conditions, but there may be exceptions where it has been tested under static conditions only. Furthermore, the loss factor only concerns the internal loss in the material and the data should only be considered as a rough estimate. One should be aware that the total loss factor of a specimen is not only very sensitive to the mounting conditions but may also vary with frequency.

Material	**Density kg/m^3**	**Modulus of elasticity 10^9 Pa**	**Poisson's ratio**	**Loss factor (internal) 10^{-3}**
Metal, glass etc.				
Aluminium	2700	66 - 72	0.33 - 034	~ 0.1
Copper	8900	110 - 120	0.35 - 0.36	~ 0.2
Magnesium	1750	42 - 45	~ 0.35	
Steel	7700 - 7800	190 - 210	0.28 - 0.31	~ 0.1
Glass	2300 - 2600	50 - 65	-	0.6 - 2.0
Plexiglas	1150	3.8		2 - 4
Concrete	2300	32 - 40	0.15 - 0.2	4 - 8
Concrete (reinforced)	2400	33 - 45	0.15 – 0.2	10 - 50
Concrete (lightweight aggregate)	1300	3.8	~ 0.2	10 - 20
Concrete (autoclaved aerated)	400 - 600	1.0 - 2.5	~ 0.2	10 - 20
Panel materials				
Plywood (fir, spruce)	500 - 600	8 - 10		10 - 30
Plywood (birch)	650 - 700	9 -10		10 - 30
Fibre board (pressed, 5 – 10 mm)	700 - 950	2 - 4		10 - 30
Gypsum board (9 – 13 mm)	800 - 900	4.1	~ 0.3	10 - 15
Wooden chipboard	650 - 800	3.8	~ 0.2	10 - 30
Mineral wool				
Rock wool 1)	110 - 135	0.00025 – 0.00030 2)		
Glass wool 1)	~ 125	0.00011 – 0.00013 2)		
Plastic materials:				
PVC (hard)	1380 - 1550	2 - 3		20 - 40
Polystyrene	980 - 1110	1.5 – 3.9		
Polystyrene (expanded)	10 - 20	0.0003 – 0.003		
Polyurethane (foam)	33 - 72	0.007 – 0.019	~ 0.4	

1) High density types intended for vibration isolation, sandwich element etc. 2) At 2 kPa static load

A graph is presented below giving mean values for the flow resistivity of two common types of mineral wool, rock wool and glass wool, indicated on the curves with the letter R and G. Again; the data from the producer should be used if available.

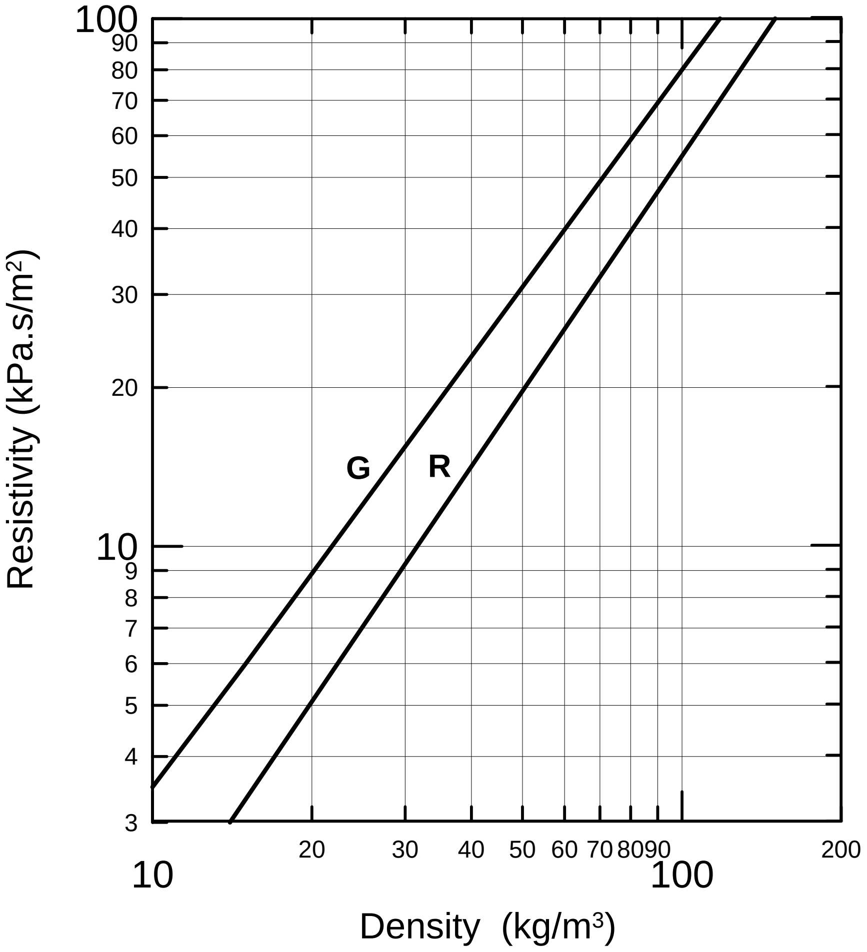


Figure B-1 Flow resistivity for mineral wool of type rock wool and glass wool, curves marked R and G. (typical data for products used in Norway)

Note The flow resistivity of fibrous absorbents is highly dependent on the diameter of the fibres. Empirical relationship between the resistivity, fibre diameter and the density may be found in the reference below.

Reference

Beranek, L.L and Vér, I.L (Editors) (1992) Noise and Vibration Control Engineering, Chapter 8: Sound-absorbing Materials and Sound Absorbers. John Wiley & Sons, Inc., New York.

ANNEX C. MEASUREMENT AND CALCULATION ON A MICROPERFORATED MEMBRANE

In WinFLAG version 1.0 the density of the microperforated layer was listed as a property but actually not used. From version 2.0 onwards the mass impedance is included in the calculation. This is due to the use of thin microperforated plastic foils or membranes where the mass will be of much greater importance than for microperforated metal plates. An example on measurement and calculations on such membranes is shown in *Figure C-1* below. The data is reproduced from the reference cited below and plotted together with calculated results using WinFLAG 2.0.

According to the reference the thickness of the foil is 0.11 mm and have a weight 0.14 kg/m^2. The diameter of the holes is 0.2 mm and the percentage perforation is 0.79 %. The foil is mounted against a rigid wall at a distance (airspace) of 100 mm.

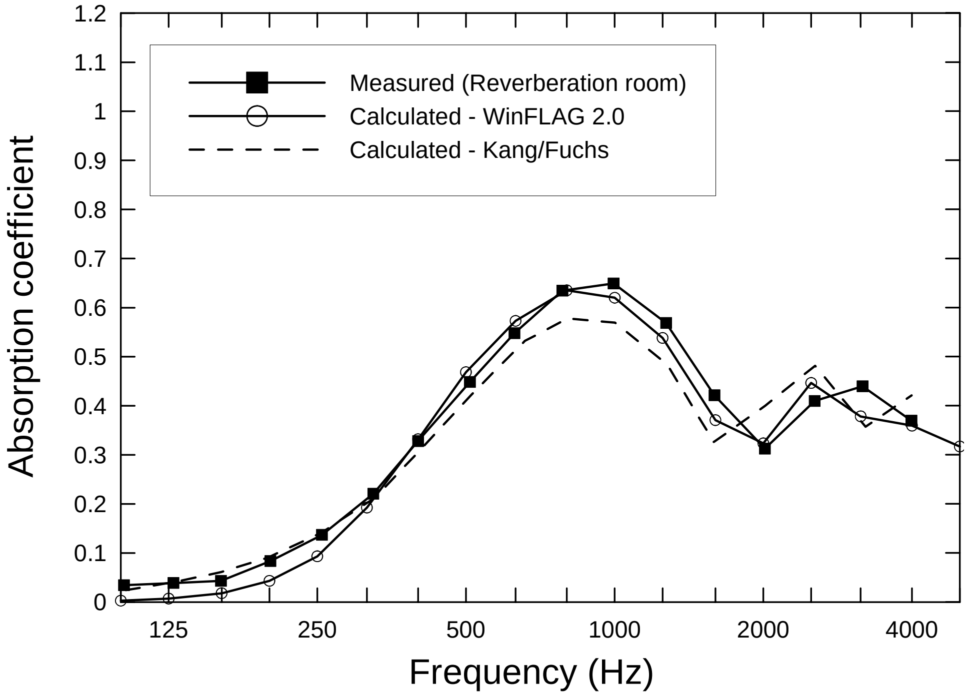


Figure C-1. Absorption coefficient for a microperforated foil (membrane) mounted against a rigid wall at a distance of 100 mm. Measurement data and calculated results by Kang & Fuchs are reproduced from figure 12 in the reference below.

Reference:
Kang, J. & Fuchs, H.V. (1999) Predicting the absorption of open weave textile and micro-perforated membranes backed by air. *J. Sound and Vibration,* **220**, 905 – 920.

ANNEX D. MEASUREMENTS AND CALCULATIONS ON A RESONATOR PANEL USING PERFORATONS WITH CONICALLY SHAPED HOLES

Designing resonator absorbents using conically shaped apertures in the panels may greatly enhance the absorption capability as compared with using regular shaped holes or slits. An example is shown below; see *Figure D-2*, comparing results when using a panel with regular 8 mm diameter cylindrical holes as opposed to holes having the shape depicted in *Figure D-1*. As seen the shape has not the ideal conical shape as shown in *Figure 5-7* and presupposed in the calculations. As seen from *Figure D-1*, however, the fit between measured and calculated data is quite good. The data for the regular case is calculated setting the exit diameter of the holes slightly larger than 8 mm (≈ 0.5 % larger). In both cases the impedance correction is used.

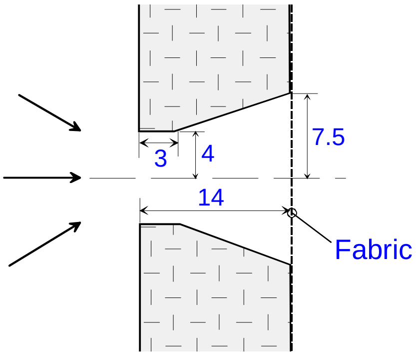


Figure D-1. Holes in the panel having a conical part. The fabric has a flow resistance of 190 Pa.s/m.

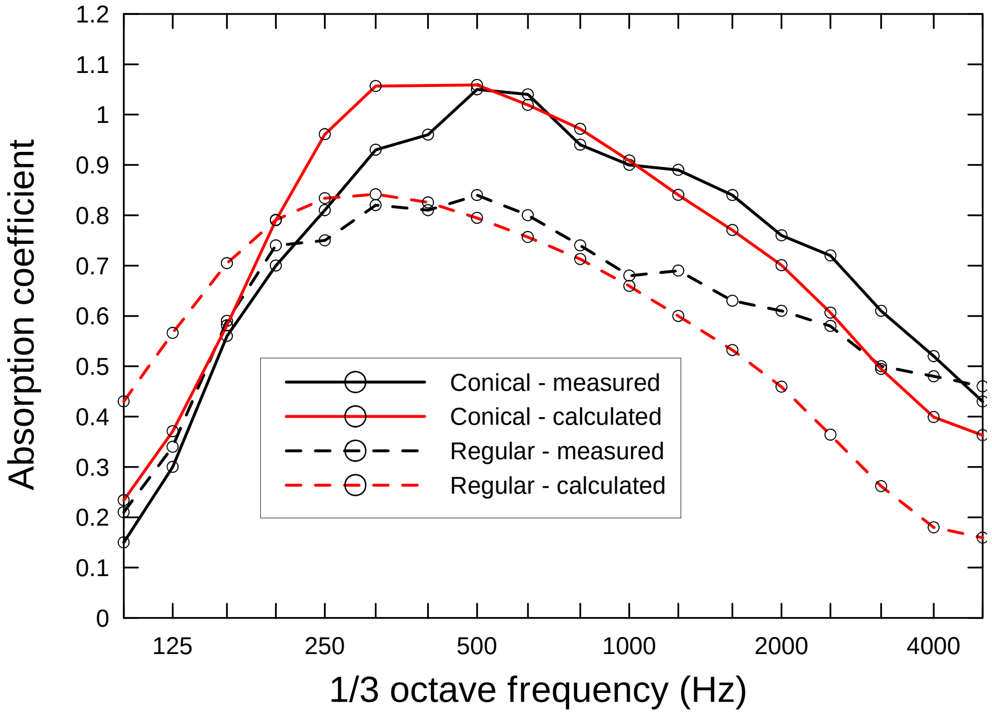


Figure D-2. Measured and calculated absorption coefficients in a reverberation room. Resonator absorbent of 14 mm perforated panel, perforation 12.5%, with a layer of fabric and mounted with airspace of 50 mm filled with mineral wool, flow resistivity 30 kPa.s/m^2. Measurements data taken from Figure 14 in the reference below. The shape of the conical apertures is shown in Figure D-1 above.

Reference:

Vigran, T. E. (2004) Conical apertures in panels; Sound transmission and enhanced absorption in resonator systems. *Acta Acustica united with Acustica*, **90**, 1170 – 1177.