AcoustoDict

User Guide

GeoDict release 2023

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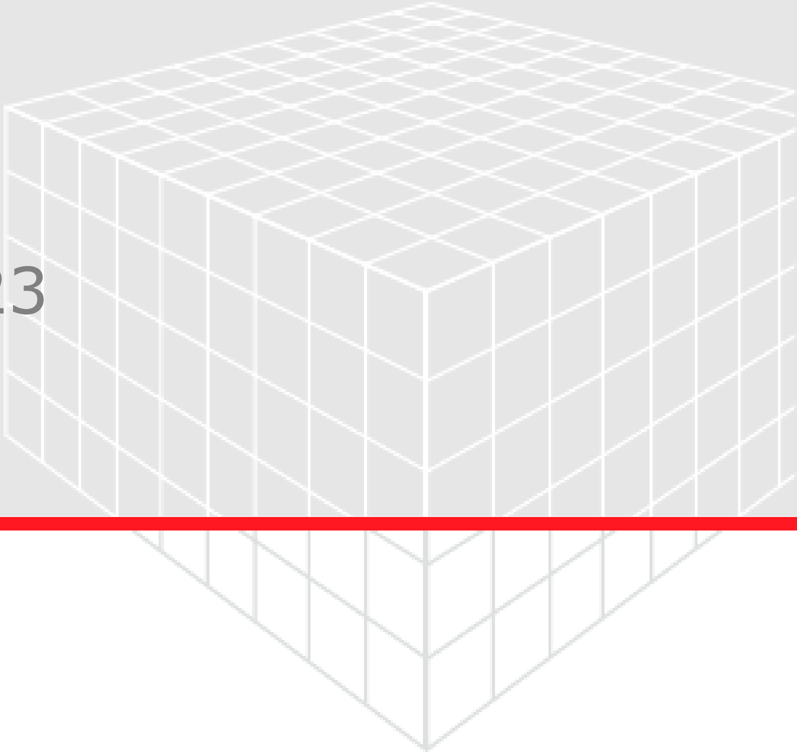

GeoDict

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INTRODUCTION

THE IMPEDANCE TUBE

In an experimental setup, the acoustic properties of porous absorbers are measured using an impedance tube, commonly referred to as Kundt's tube. Within the impedance tube, a plane sound wave is generated and directed towards a sound-absorbing specimen in front of a reverberant termination. The sound pressure resulting from this is measured by two microphones positioned in front of the material sample. By evaluating the incoming and reflected sound energy at the desired sound frequency values, the sound absorption coefficient of the material is determined.

COMPUTATION OF SOUND ABSORPTION

The sound absorption coefficient α is computed as

$$\alpha = 1 - |R|^2, \tag{1}$$

where R is the sound pressure reflection coefficient, given by

$$R = \frac{Z_s - Z_0}{Z_s + Z_0} = \frac{Z_s - \rho_0 c_0}{Z_s + \rho_0 c_0}. \tag{2}$$

Here, Z_s is the acoustic surface impedance, ρ_0 is the density of air, c_0 is the speed of sound in air, and $Z_0 = \rho_0 c_0$ is the characteristic impedance of air. The acoustic surface impedance Z_s is a quantity that depends on the sound frequency f, and therefore, the sound pressure reflection coefficient R and the sound absorption coefficient α are quantities that also depend on the sound frequency f. The objective is to calculate the relationship between the sound absorption coefficient α and frequency f for a given porous medium represented as a 3D pore-scale structure in GeoDict. Refer to Table 2 for a summary of the relevant quantities and their physical units.

The relationship between the acoustic surface impedance Z_s and the properties of the sound-absorbing specimen (porous medium) in the Kundt tube is dependent on whether the porous medium is a single homogeneous layer or if it is composed of multiple layers that are parallel to the sound-reflecting wall.

SINGLE LAYER

For a single layer, the acoustic surface impedance Z_s can be derived by

$$Z_s = -jZ_c \cot(k_c d), \tag{3}$$

where d is the thickness of the medium, Z_c is the characteristic impedance, and k_c is the complex wave number. Those three parameters d, Z_c, k_c describe the acoustic properties of the porous layer.

MULTILAYER

Consider N stacked porous layers with acoustic properties described by i sets of parameters d_i, $Z_{c,i}$, $k_{c,i}$ for $i \in \{1, \dots, N\}$, where the layer adjacent to the wall has the index 1. Then, the acoustic surface impedance $Z_{s,i}$ for the stack consisting of layer 1 to i is given by the impedance transmission theorem [1, Eq. 2.16]:

$$Z_{s,1} = -jZ_{c,1} \cot(k_{c,1} d_1), \tag{4}$$

$$Z_{s,i} = Z_{c,i} \frac{Z_{c,i} - jZ_{s,i-1} \cot(k_{c,i} d_i)}{Z_{c,i-1} - jZ_{s,i} \cot(k_{c,i} d_i)} \quad \text{for } i \in \{2, \dots, N\}, \tag{5}$$

i.e., the acoustic surface impedance for the multilayer is

$$Z_\mathrm{s} = Z_{\mathrm{s},N}. \tag{6}$$

The absorption coefficient α and the reflection coefficient R for the multilayer are then computed by (1) and (2), respectively.

DETERMINATION OF THE CHARACTERISTIC IMPEDANCE

With the considerations above, the sound absorption coefficient α of a sound-absorbing specimen in the Kundt tube can be predicted when the characteristic acoustic properties d, Z_c, k_c of each porous layer are known. The thickness d of the medium is a straightforward quantity, the question then arises regarding how to determine the characteristic impedance and the complex wave number of a porous layer.

These parameters cannot directly be directly obtained through numerical simulation. Instead, different models exist for various types of porous materials that derive these parameters from other more measurable or computable quantities.

For highly porous absorbers, the Delany–Bazley model can be used and for stiff absorbers, the Johnson–Champoux–Allard model is appropriate.

DELANY–BAZLEY MODEL

The **Delany–Bazley Model** [4] is applicable for highly porous materials with porosity close to the maximum of 1. The model expressions for the complex wave number k_c and the characteristic impedance Z_c are functions of frequency [1, Eq 2.28 and 2.29]:

$$k_\mathrm{c} = \frac{\omega}{c_0}(1 + 0.0978 \cdot X^{-0.700} - j\, 0.1890 \cdot X^{-0.595})\,, \tag{7}$$

$$Z_\mathrm{c} = \rho_0 c_0 (1 + 0.0571 \cdot X^{-0.754} - j\, 0.0870 \cdot X^{-0.732}) \tag{8}$$

for $0.01 < X < 1.00$, where the dimensionless parameter X is given by

$$X = \frac{\rho_0 f}{\sigma}. \tag{9}$$

Here, ρ_0 is the air density, c_0 is the sound speed in air, f is the frequency in Hertz, $\omega = 2\pi f$ is the angular frequency, σ is the static air flow resistivity of the porous medium, and j denotes the complex unity. Thus, the only unknown material parameter in this model is the static air flow resistivity σ.

The Delany–Bazley command of AcoustoDict therefore computes the static air flow resistivity σ of porous materials—the only parameter needed to describe the acoustic behavior of highly porous materials. The results predicted by Delany–Bazley are in best agreement with experimental results, even for low frequencies. To achieve continuous dependence of the absorption on the frequency, the correction of Mechel [8,9] is used. This modifies the Delany–Bazley formulas to

$$k_\mathrm{c} = \frac{\omega}{c_0} \cdot \begin{cases} 1 + 0.0978 \cdot X^{-0.693} - j\, 0.1890 \cdot X^{-0.618} & \text{for } X > \dfrac{1}{60}, \\ -\sqrt{1.466 - j\, 0.212 \cdot X^{-1}} & \text{for } X \le \dfrac{1}{60}, \end{cases} \tag{10}$$

$$Z_{\mathrm{c}} = \rho_0 c_0 \cdot \begin{cases} 1 + 0.0489 \cdot X^{-0.754} - j\,0.0870 \cdot X^{-0.731} & \text{for } X > \dfrac{1}{60}, \\ \dfrac{0.159 \cdot X^{-1} + j\,1.403}{\sqrt{-1.466 + j\,0.212 \cdot X^{-1}}} & \text{for } X \leq \dfrac{1}{60}. \end{cases} \tag{11}$$

Reference [15] applies this approach for the acoustic design of nonwoven materials.

JOHNSON–CHAMPOUX–ALLARD MODEL

The **Johnson–Champoux–Allard Model** [2,3] (named Allard–Johnson model in previous versions of AcoustoDict) is applicable to porous materials with a rigid frame and arbitrary pore shapes. The model expressions for the complex wave number k_{c} and the characteristic impedance Z_{c} are

$$k_{\mathrm{c}} = \omega \sqrt{\frac{\rho_{\mathrm{e}}}{K_{\mathrm{e}}}}, \tag{12}$$

$$Z_{\mathrm{c}} = \sqrt{\rho_{\mathrm{e}} K_{\mathrm{e}}}, \tag{13}$$

where ω is the angular frequency, ρ_{e} the complex effective density, and K_{e} the complex dynamic bulk modulus.

The effective density ρ_{e} is expressed by (cf. [2, Eq. 13], [16, Eq. 18], [17, Eq. 1])

$$\rho_{\mathrm{e}} = \alpha_\infty \rho_0 \left(1 - j \frac{\sigma \phi}{\alpha_\infty \rho_0 \omega} \sqrt{1 + j \frac{4 \alpha_\infty^2 \eta_0 \omega \rho_0}{(\Lambda \sigma \phi)^2}} \right) \tag{14}$$

and the dynamic bulk modulus K_{e} by

$$K_{\mathrm{e}} = \gamma_0 P_0 \left(\gamma_0 - (\gamma_0 - 1) \left(1 - j \frac{\sigma \phi}{\alpha_\infty \rho_0} \sqrt{1 + j \frac{4 \alpha_\infty^2 \eta_0 \rho_0 \mathrm{Pr}_0 \omega}{(\Lambda \sigma \phi)^2}} \right)^{-1} \right)^{-1}. \tag{15}$$

In these equations, the constants η_0 (viscosity), ρ_0 (density), γ_0 (specific heat ratio), Pr_0 (Prandtl number) describe the properties of the ambient air and are given as defined in Table 1.

The parameters σ (air flow resistivity), α_∞ (tortuosity), ϕ (porosity), and Λ (viscous characteristic length) describe the properties of the porous material.

DETERMINATION OF MATERIAL PARAMETERS

The Delany–Bazley model and the Johnson–Champoux–Allard model allow to predict the sound absorption of a material if certain material parameters of the porous medium are known.

The only unknown material parameter in the Delany–Bazley model is the static air flow resistivity σ.

The Johnson–Champoux–Allard model additionally requires the porosity ϕ, the tortuosity α_∞, and the viscous characteristic length Λ.

GeoDict can compute these parameters based on a 3D pore-scale structure of the sound absorbing specimen.

STATIC AIR FLOW RESISTIVITY

The static air flow resistivity σ is defined as

$$\sigma = \frac{\eta_0}{\kappa}, \tag{16}$$

where κ is the relative permeability of the porous medium (cf. Table 2). The FlowDict handbook of this User Guide describes in detail how the permeability is computed by solving the Stokes equation.

TORTUOSITY

The high frequency limit of the tortuosity α_∞ (also called the tortuosity factor) is defined as

$$\alpha_\infty = \frac{\phi}{d^*}, \tag{17}$$

where ϕ is the porosity and d^* the relative diffusivity of the porous medium. The DiffuDict handbook of this User Guide describes in detail how diffusivity and tortuosity are computed by solving the Laplace equation.

The low frequency limit of the tortuosity α_0 is not used in the Johnson–Champoux–Allard equations above, but may serve the user as a reference value, if needed:

$$\alpha_0 = \phi \frac{\int_{V_{\mathrm{pore}}} |\boldsymbol{v}|^2 \mathrm{d}x}{\left(\int_{V_{\mathrm{pore}}} v_i \, \mathrm{d}x\right)^2} \tag{18}$$

where $\boldsymbol{v}$ is the air velocity in the pore space V_{pore} and v_i the component of $\boldsymbol{v}$ in through direction.

VISCOUS CHARACTERISTIC LENGTH

The viscous characteristic length Λ is approximated via

$$\Lambda = \sqrt{\frac{8\alpha_0\kappa}{\phi}} \tag{19}$$

with α_0, κ, and ϕ as defined above.

THERMAL CHARACTERISTIC LENGTH

The thermal characteristic length Λ' is the ratio of pore volume to pore surface area:

$$\Lambda' = \frac{2\int_{V_{\mathrm{pore}}} 1}{\int_{\partial V_{\mathrm{pore}}} 1}. \tag{20}$$

The pore volume is computed by counting the pore voxels, the pore surface area using the method of Ohser [11], see the MatDict handbook of this User Guide for details. This value is not used in the Johnson–Champoux–Allard equations above, but may serve the user as a reference value, if needed.

NOTATION

Table 1 gives an outline of physical constants and also of quantities that are constant if the environment has constant pressure and temperature. A comprehensive reference for fundamental constants, data, and nomenclature in the field of chemistry and physics is Quack et al. [14]. Physical quantities used in AcoustoDict are listed in Table 2.

Symbol	Quantity	Value	SI Units	Comment
$\boldsymbol{c_0}$	speed of sound in air	342.2	$\mathrm{m{\cdot}s^{-1}}$	
$\boldsymbol{\eta_0}$	dynamic viscosity of air	1.825e−5	$\mathrm{Pa{\cdot}s}$	$\eta_0 = \rho_0 \nu_0$
$\boldsymbol{P_0}$	air equilibrium pressure	101325	Pa	
Pr_0	Prandtl number of air	0.702	1	
$\boldsymbol{\rho_0}$	air density	1.204	$\mathrm{kg\,m^{-3}}$	
$\boldsymbol{T_0}$	environment temperature	293	K	
$\boldsymbol{\gamma_0}$	specific heat ratio of air	1.4	1	

Table 1: Physical constants used in AcoustoDict.

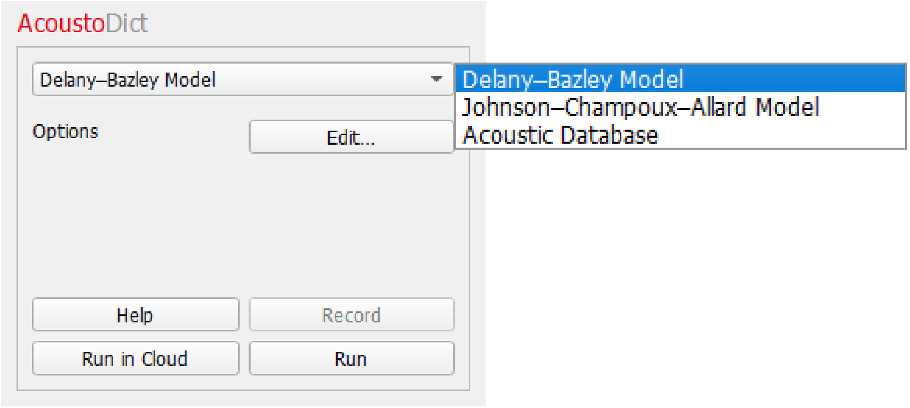
Symbol	Definition	SI Units	Comment
$\boldsymbol{\alpha}$	sound absorption coefficient	1	
$\boldsymbol{\alpha_\infty}$	high frequency limit of tortuosity (tortuosity factor)	1	
$\boldsymbol{d}$	thickness of porous medium	m	
$\boldsymbol{f}$	sound wave frequency	$\mathrm{s^{-1}}$	
$\boldsymbol{K_e}$	dynamic bulk modulus	Pa	complex
$\boldsymbol{k_c}$	complex wave number	$\mathrm{m^{-1}}$	complex
$\boldsymbol{\kappa}$	permeability	$\mathrm{m^2}$	
$\boldsymbol{\Lambda}$	viscous characteristic length	1	
$\boldsymbol{\Lambda'}$	thermal characteristic length	1	
$\boldsymbol{\omega}$	angular frequency	$\mathrm{s^{-1}}$	$\omega = 2\pi f$
$\boldsymbol{\phi}$	open porosity	1	
$\boldsymbol{P}$	upscaled pressure at inlet/outlet	Pa	
$\boldsymbol{\rho_e}$	effective density	$\mathrm{kg\,m^{-3}}$	complex
$\boldsymbol{R}$	sound pressure reflection coefficient	1	complex

$\boldsymbol{\sigma}$	static airflow resistivity	$\mathrm{kg\,m^{-3}\,s^{-1}}$	
$\boldsymbol{X}$	auxiliary variable	1	$X = \frac{\rho_0 f}{\sigma}$
$\boldsymbol{Z}_\mathbf{c}$	characteristic impedance	$\mathrm{kg\,m^{-2}\,s^{-1}}$	complex
$\boldsymbol{Z}_\mathbf{s}$	acoustic surface impedance	$\mathrm{kg\,m^{-3}\,s^{-1}}$	purely imaginary

Table 2: Physical quantities used in AcoustoDict.

ACOUSTODICT COMPUTATIONS

Switch to AcoustoDict by selecting **Predict** → **AcoustoDict** in the Menu bar. In the AcoustoDict section, the pull-down menu lists the two models for which AcoustoDict can compute the media-dependent acoustic parameters, as well as provides access to the AcoustoDict Database.



The **Options** for the selected command from GeoDict can be modified through the **Edit...** button. After entering the **Options**, click **Run** to start the computations. A progress dialog box opens to follow the computations.

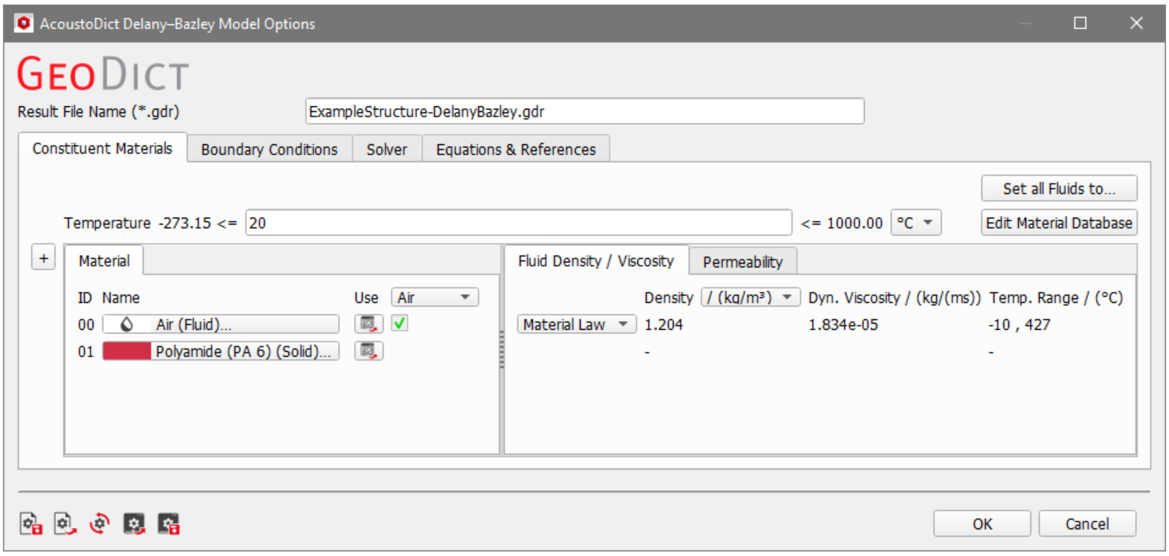
When recording a macro, the **Record** button becomes active and the **Run** button changes to **Run & Record**.

Click **Run in Cloud** to run it in the Kaleidosim cloud, see the [High Performance Computing]() chapter of the GeoDict User Guide for details.

Clicking **Help** gives direct access to this AcoustoDict handbook through our web page.

DELANY–BAZLEY MODEL

The **AcoustoDict Delany–Bazley Model Options** dialog box opens when clicking the **Options' Edit…** button in the **AcoustoDict** section. The parameters necessary to run the solver can be entered under the **Constituent Materials**, **Boundary Conditions**, and **Solver** tabs. The **Equations and References** tab displays further information about the model.



Result File Name (*.gdr) ExampleStructure-DelanyBazley.gdr

Temperature -273.15 <= 20 <= 1000.00 °C

ID	Name	Use Air		Density / (kg/m³)	Dyn. Viscosity / (kg/(ms))	Temp. Range / (°C)
00	Air (Fluid)...	✓	Material Law	1.204	1.834e-05	-10 , 427
01	Polyamide (PA 6) (Solid)...			-		-

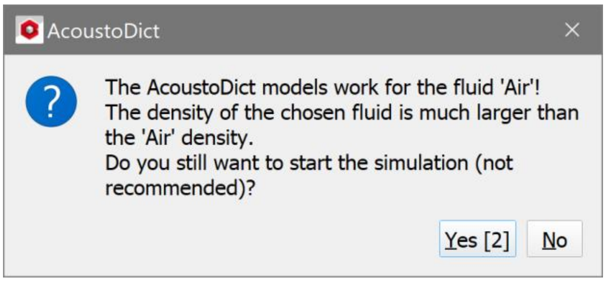
Clicking **OK** confirms the entered solver options, while clicking **Cancel** closes the dialog without modifications.

The **Result File Name (*.gdr)** of the AcoustoDict simulation must be entered in the edit box. Choose a name according to your current project. The results files are saved in the chosen project folder (**File → Choose Project Folder**, in the menu bar).

CONSTITUENT MATERIALS

Under the **Constituent Materials** tab, the constituent materials of the fluid phase and the solid phase in the structure model currently in memory are shown.

The Delany–Bazley model is only valid when the fluid is air and the simulations assume that this is the case. If the constituent material for the fluid occupying the pore space is changed to some other constituent material (which is possible to do), a warning pops up when trying to run the simulation.



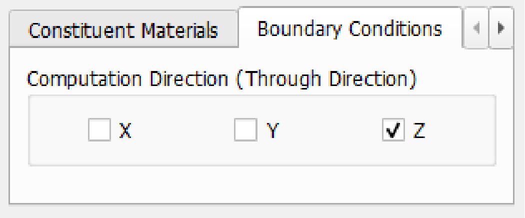
The AcoustoDict models work for the fluid 'Air'!
The density of the chosen fluid is much larger than the 'Air' density.
Do you still want to start the simulation (not recommended)?

Click **No** and go back to the Constituent Materials tab. Click on the button for Material ID 00 to change it to Air through the **Material Selector**.

Under the assumptions made in the Delany–Bazley model, only the air flow resistivity and the porosity of the material are important for the acoustic absorption. Thus, the constituent material(s) chosen for the solid phase does not influence the results.

BOUNDARY CONDITIONS

For the **Boundary Conditions**, in the **Computation Directions** panel, choose the direction orthogonal to the direction of wave propagation (also referred to as through direction). Only one through direction can be active.

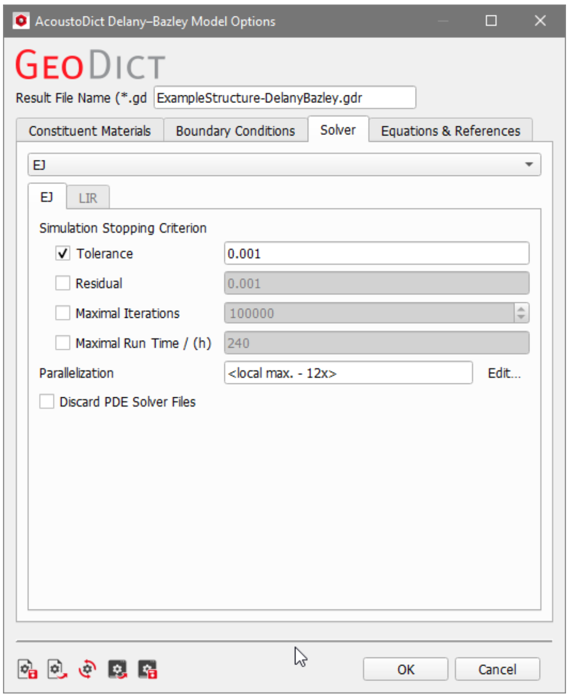


Computation Direction (Through Direction)

☐ X ☐ Y ☑ Z

SOLVER

AcoustoDict solves the Stokes equation to compute the air flow resistivity two solvers, **EJ** and **LIR** can be chosen to solve the Stokes problem.



Result File Name (*.gd: ExampleStructure-DelanyBazley.gdr

EJ

Simulation Stopping Criterion

☑ Tolerance: 0.001

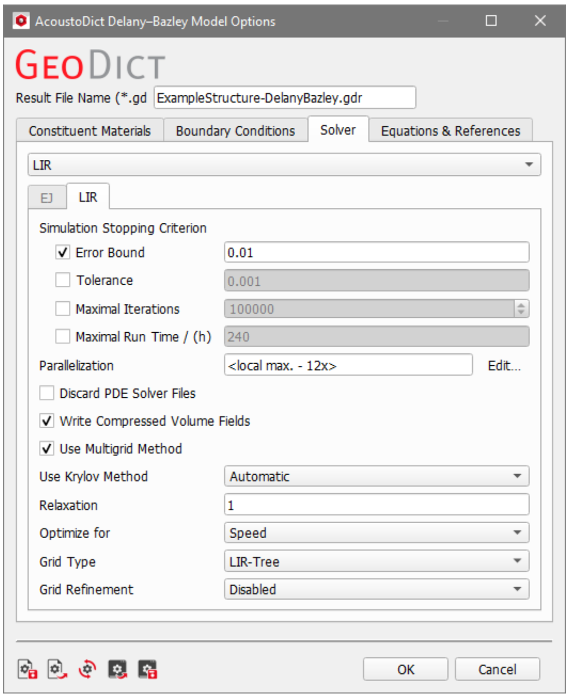
☐ Residual: 0.001

☐ Maximal Iterations: 100000

☐ Maximal Run Time / (h): 240

Parallelization: <local max. - 12x>

☐ Discard PDE Solver Files



Result File Name (*.gd: ExampleStructure-DelanyBazley.gdr

LIR

Simulation Stopping Criterion

☑ Error Bound: 0.01

☐ Tolerance: 0.001

☐ Maximal Iterations: 100000

☐ Maximal Run Time / (h): 240

Parallelization: <local max. - 12x>

☐ Discard PDE Solver Files

☑ Write Compressed Volume Fields

☑ Use Multigrid Method

Use Krylov Method: Automatic

Relaxation: 1

Optimize for: Speed

Grid Type: LIR-Tree

Grid Refinement: Disabled

For highly porous structures, the LIR solver is in general recommended.

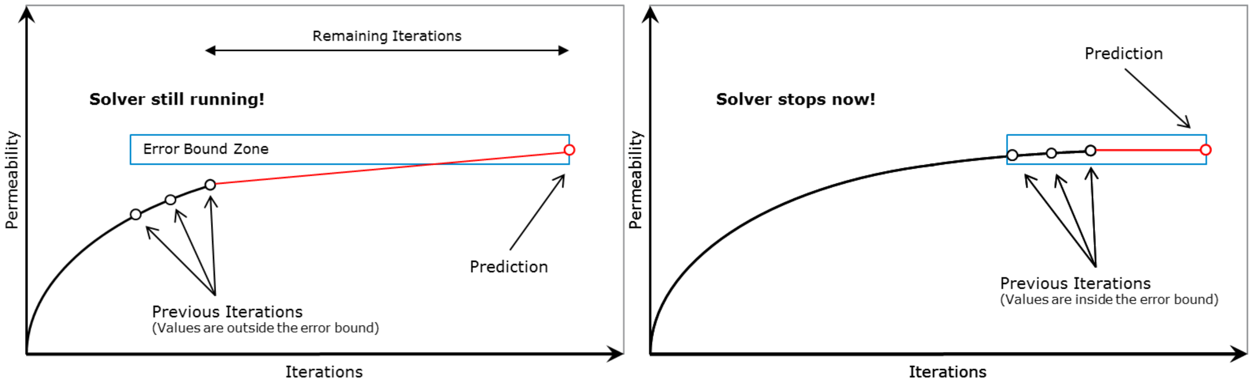
Simulation Stopping Criterion

Both LIR and EJ solve the Stokes equations by an iterative approach. The basic idea of an iterative method is to:

1. Start with some initial guess for the unknown values.
2. Improve the current values in each iterative step.
3. Repeat the iterative process until one of the stopping criteria (**Error Bound**, **Tolerance**, **Residual**, **Maximal Iterations**, or **Maximal Run Time**) is met.

The default stopping criterion of the EJ solver, **Tolerance**, detects if the iterative process becomes stationary. This occurs when the change in the permeability value from iteration to iteration becomes extremely small. If the relative change is smaller than the value entered for **Tolerance**, the iteration is stopped.

The default stopping criterion of the LIR solver, **Error Bound,** uses the result of previous iterations, and predicts the final solution based on linear and quadratic extrapolation. The solver stops if the relative difference regarding the prediction is smaller than the specified error bound. The stopping criterion recognizes oscillations in the convergence behavior and prevents premature stopping at local minima or maxima. A damped convergence curve is fit through the oscillating curve and the solver stops then regarding the damped convergence curve. **Error Bound** is not available for the **EJ** solver.



When the **Residual** stopping criterion is used, the iteration is stopped if the solution satisfies the equation up to the required accuracy.

When the solver stops because the **Maximal Iterations** value or **Maximal Run Time** has been reached, no guarantee on the quality of solution can be given. Following possibilities might help:

- Check the corresponding .log file to see how large the residual values and permeability increase are. If these values are already very close to the desired result, you may decide to use the current result.
- Double check the structure and parameter values. Unphysical parameters or too rough resolution of the structure (leading, e.g., to artificial unconnected components) can cause an iterative solver to fail.

Which stopping criterion has occurred, can be seen in the Result Viewer of the GeoDict result file (*.gdr) under the **Results Map** tab.

Parallelization

Depending on the purchased license, the simulation process can be parallelized.

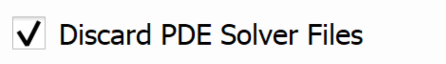

Parallelization <local max. - 4x> Edit ...

The **Parallelization Options** dialog box opens when clicking the **Edit...** button, to choose between **Local, Sequential**, **Local, Parallel**, **Local, Maximum**, and **Cluster** for EJ, and **Local, Sequential**, **Local, Parallel** and **Local, Maximum** for LIR.

For details on how to set up und run parallel computations, consult the High-performance Computing for GeoDict handbook of this User Guide.

Discard PDE Solver Files.

Checking the **Discard PDE Solver Files** box causes the deletion of all intermediate computation files. While having the benefit of saving storage place, discarding solver files has also the side effect of disabling the 3D visualization of the results.



☑ Discard PDE Solver Files

Of course, the contents of the result file (*.gdr) are not discarded even in this case.

Write Compressed Volume Fields (for LIR)

If the option **Write Compressed Volume Fields** is checked for the LIR solver then the adaptive grid structure is used as compression method for writing out .vap files. This option allows to save 80–90% space on hard drive.

☑ Write Compressed Volume Fields

The runtime for writing .vap files is also reduced significantly. If the option **Write Compressed Volume Fields** is not checked then a usual regular grid is used for writing out .vap files.

Use Multigrid Method (for LIR)

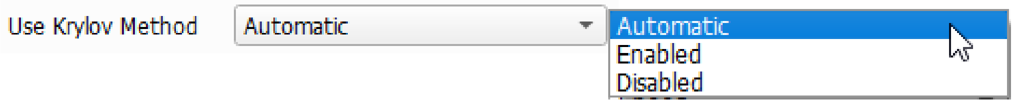
The Multigrid method was introduced to speed-up the computation and reduce the runtime significantly. The main idea of Multigrid is the usage of multiple coarser adaptive grids to speed up convergence behavior but requires only little more memory.

The method is available to solve the Stokes and Stokes–Brinkman equations in FlowDict as well as for solving diffusion, thermal and electrical conduction in DiffuDict and ConductoDict and is enabled by default.

☑ Use Multigrid Method

Use Krylov Method (for LIR)

Depending on the structure and the corresponding material parameters, a significant speedup of the LIR can be achieved by using the BiCGStab method to compute the solution. Using the BiCGStab method approximately doubles the amount of RAM needed for the computation.



Use Krylov Method Automatic

When **Use Krylov Method** is set to **Automatic**, GeoDict decides based on structure, material parameters and boundary condition which method is expected to be faster and uses this method. In case that the Krylov subspace method (BICGStab) is used, the **Relaxation** is also chosen automatically.

Alternatively, the user may also explicitly enable or disable this method.

Relaxation (for LIR)

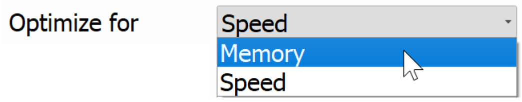
Depending on the material parameters and geometry of the structure, the underlying mathematical problem can vary in complexity, thus influencing the behavior of the solver. The iterative method uses the relaxation number to adjust it from **Stable** (with smaller number chosen, which results in higher number of iterations, slower time stepping, and longer solver run times), to **Fast** with higher number chosen, which makes the solver run less iterations but implies the risk that the solver does not converge.


Relaxation 1.5

For the LIR solver, this balance is managed through the **Relaxation**. The value should be between 0 and 2. For relaxation values smaller than one (<1.0), the simulation is more stable. For relaxation values larger than one (>1.0), the simulation is faster.

Optimize for (for LIR)

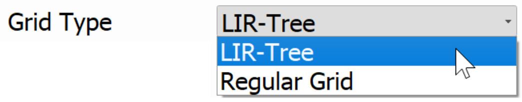
The **LIR** solver can **Optimize for** speed or memory.


Optimize for Speed

If **Speed** is chosen, the solver constructs additional optimization structures. The runtime is decreased by up to 30% but requires up to 50% more memory compared to the other option. If **Memory** is chosen, then the runtime is increased by up to 40% but the solver requires up to 50% less memory.

Grid Type (for LIR)

The **Grid Type** decides what kind of tree structure is used for the simulation.

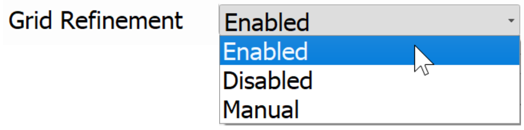

Grid Type LIR-Tree

The default option is **LIR-Tree** and should always be used. The solver uses an adaptive tree structure called LIR-tree and needs up to 10 times less runtime and memory compared the **Regular Grid** option.

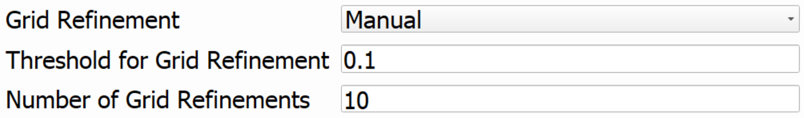
Grid Refinement (for LIR)

The solver can analyze the velocity and pressure field during the computation and improves the adaptive grid in places where more accuracy is needed. The LIR solver splits cells where a high velocity gradient or high pressure gradient occurs. The analysis is enabled if the **Grid Refinement** option is set to **Enabled** or **Manual**.

If the **Grid Refinement** is set to **Enabled**, the solver chooses the **Number of Grid Refinements** and **Threshold for Grid Refinement** automatically.


Grid Refinement Enabled

If the **Grid Refinement** is set to **Manual**, the user can enter the parameters manually.



Grid Refinement: Manual
Threshold for Grid Refinement: 0.1
Number of Grid Refinements: 10

The **Number of Grid Refinement** controls how many velocity-based and pressure-based grid refinements are allowed during the simulation. The value should be between 0 and 10. Velocity-based and pressure-based grid refinements may increase the number of iterations, runtime and memory requirements.

The **Number of Grid Refinement** can be zero in most of the cases and should be greater than zero if a flow simulation is done on a structure with a very long inlet and outlet.

Refinement is done at regions with high-velocity gradient or high-pressure gradient. Cells are split where the current velocity gradient (or pressure gradient) is greater than the **Threshold for Grid Refinements** times the maximal velocity gradient (or pressure gradient). This threshold must be between 0.0 and 1.0. The recommended value range is between 0.05 and 0.1.

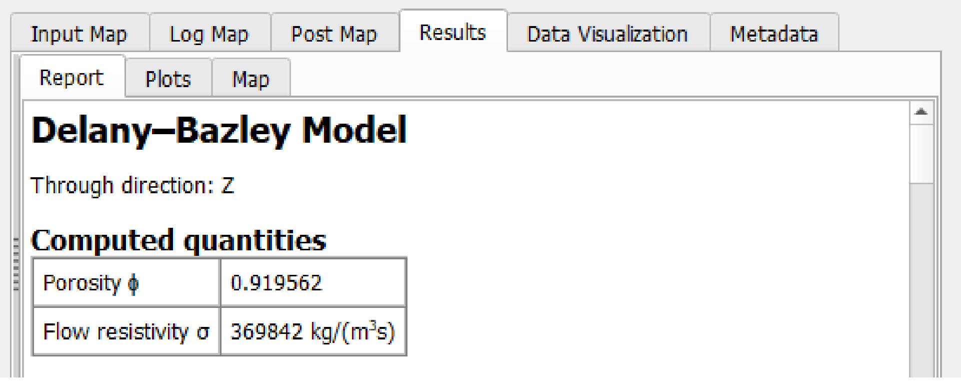
EQUATIONS AND REFERENCES

This tab display formulas and references which are explained in more detail in the introduction of this user guide.

RESULTS

Click **OK** to input the entered parameters, and then click **Run** in the AcoustoDict section to start the command.

The results are immediately shown in the opening Result Viewer after the process is finished, the screenshot below shows the calculated acoustic parameter values for the Delany–Bazley model. The tab shows porosity and flow resistivity calculated in the direction of interest. The porosity value must be close to 1.0 (or over 90%), indicating a highly porous structure and the Delany–Bazley model is (indeed) applicable.



Delany–Bazley Model

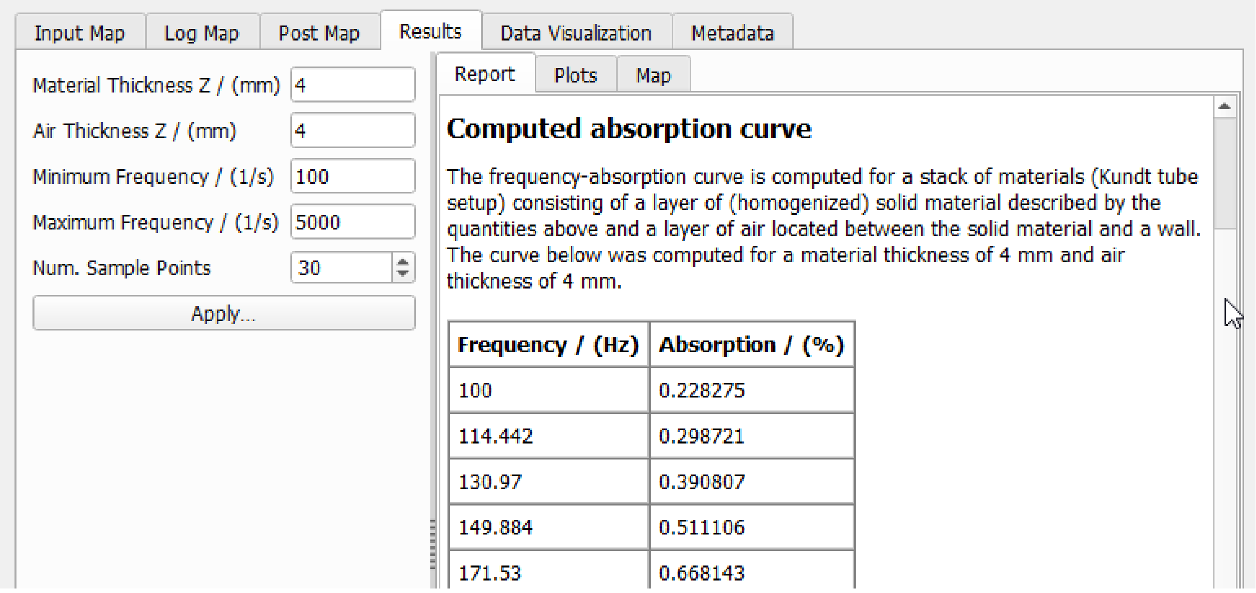
Through direction: Z

Computed quantities

Porosity ϕ	0.919562
Flow resistivity σ	369842 kg/(m^{3}s)

Absorption curve

The frequency–absorption curve is computed for a stack of materials in Kundt tube setup, consisting of a layer of (homogenized) solid material described by the computed flow resistivity and porosity and a layer of air located between the solid material and a wall. The thickness of the material and the air layer can be set in the panel on the left, as **Material Thickness Z** and **Air Thickness Z**. By default, 4 mm are used for both values.



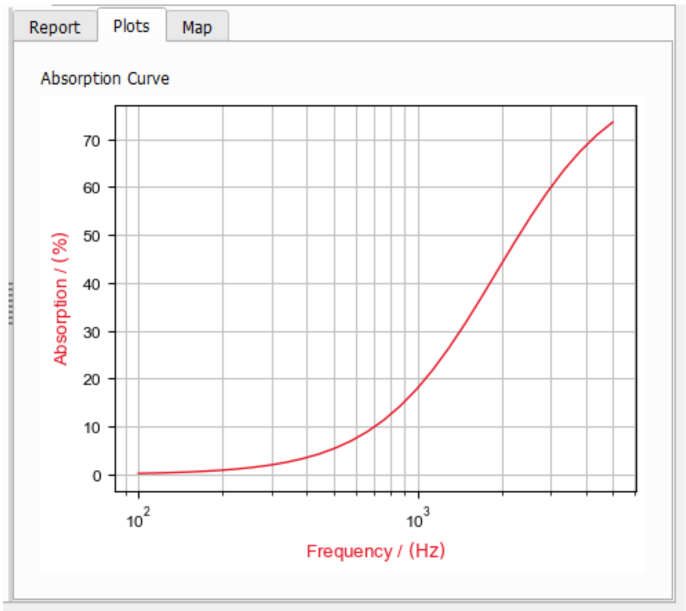
Material Thickness Z / (mm) 4
Air Thickness Z / (mm) 4
Minimum Frequency / (1/s) 100
Maximum Frequency / (1/s) 5000
Num. Sample Points 30

Computed absorption curve

The frequency-absorption curve is computed for a stack of materials (Kundt tube setup) consisting of a layer of (homogenized) solid material described by the quantities above and a layer of air located between the solid material and a wall. The curve below was computed for a material thickness of 4 mm and air thickness of 4 mm.

Frequency / (Hz)	Absorption / (%)
100	0.228275
114.442	0.298721
130.97	0.390807
149.884	0.511106
171.53	0.668143

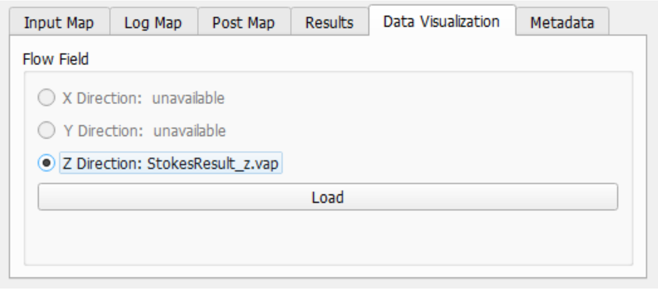
The absorption is computed in a range given by the **Minimum Frequency** and **Maximum Frequency** values, using the given number of **Sample Points**. The curve is shown in the **Results→Plots** subtab.



The **Results Map** subtab gives access to the media-dependent acoustic parameters values computed for the selected acoustic model

DATA VISUALIZATION

The fifth tab contains the setup for the **Data Visualization**. Flow fields that have been calculated to determine the flow resistivity values can be visualized by clicking **Load**.



○ X Direction: unavailable
○ Y Direction: unavailable
● Z Direction: StokesResult_z.vap

The options for the visualization of flow results are explained in detail in the GeoDict Visualization handbook.

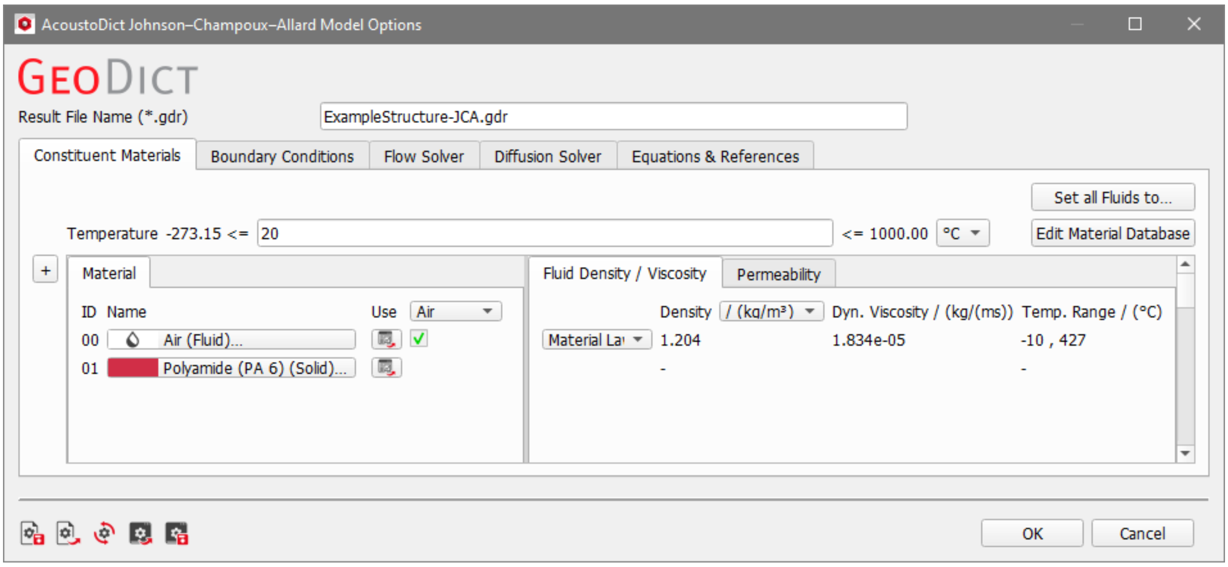
Johnson–Champoux–Allard Model

The **AcoustoDict Johnson–Champoux–Allard Model Options** dialog opens when clicking the **Options**' **Edit…** button in the **AcoustoDict** section.

The options necessary to run the solvers can be entered under the **Constituent Materials**, **Boundary Conditions**, **Flow Solver** and **Diffusion Solver** tabs. The command internally has to solve two partial differential equations:

- Stokes equation to compute the air flow resistivity,
- Laplace equation to determine the tortuosity.

The **Equations and References** tab displays further information about the model.



AcoustoDict Johnson–Champoux–Allard Model Options

Result File Name (*.gdr) ExampleStructure-JCA.gdr

Temperature -273.15 <= 20 <= 1000.00 °C

ID	Name	Use Air
00	Air (Fluid)...	✓
01	Polyamide (PA 6) (Solid)...	

	Density / (kg/m³)	Dyn. Viscosity / (kg/(ms))	Temp. Range / (°C)
Material La	1.204	1.834e-05	-10 , 427
	-		-

Constituent Materials

Under the **Constituent Materials** tab, all parameters are as described for the Delany–Bazley model (page 8). The Allard–Johnson model also assumes that the fluid in the pore space is air and it should be set that way.

Boundary Conditions

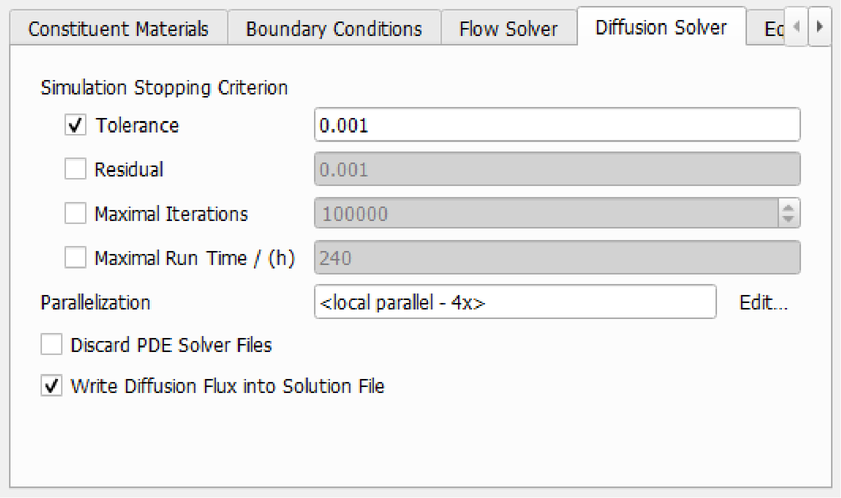
For the **Boundary Conditions**, in the **Computation Directions** panel, choose the direction orthogonal to the direction of wave propagation.

Flow Solver

The parameters entered under the **Flow Solver** tab have the same meaning as described in pages 9f for the Delany–Bazley model.

Diffusion Solver

AcoustoDict solves the Laplace equation to compute tortuosity, diffusivity, and viscous characteristic length.



Simulation Stopping Criterion

☑ Tolerance 0.001

☐ Residual 0.001

☐ Maximal Iterations 100000

☐ Maximal Run Time / (h) 240

Parallelization <local parallel - 4x>

☐ Discard PDE Solver Files

☑ Write Diffusion Flux into Solution File

Simulation Stopping Criterion

The default stopping criterion of the EJ solver, **Tolerance**, detects if the iterative process becomes stationary. This occurs when the change in the diffusivity value from iteration to iteration becomes extremely small. If the relative change is smaller than the value entered for **Tolerance**, the iteration is stopped.

When the **Residual** stopping criterion is used, the iteration is stopped if the solution satisfies the equation up to the required accuracy.

The solver also stops when the **Maximal Iterations** are done or the **Maximal Run Time** has been reached. In these situation, no guarantee on the quality of solution can be given.

Which stopping criterion has occurred, can be seen in the Result Viewer of the GeoDict result file (*.gdr) under the **Results Map** tab.

Parallelization

Depending on the purchased license, the simulation process can be parallelized.

Parallelization <local max. - 4x>

The **Parallelization Options** dialog box opens when clicking the **Edit...** button, to choose between **Local, Sequential**, **Local, Parallel**, **Local, Maximum**, and **Cluster**.

For details on how to set up und run parallel computations, consult the High-performance Computing for GeoDict handbook of this User Guide.

Discard PDE Solver File

Checking the **Discard PDE Solver Files** box causes the deletion of all intermediate computation files. While having the benefit of saving storage place, discarding solver files has also the side effect of disabling the 3D visualization of the results.

Write Diffusion Flux into Solution File

With **Write Diffusion Flux into Solution File**, the flux in the three coordinate directions is saved, allowing a detailed analysis of the flux field. The size of the result files increases when selecting this option.

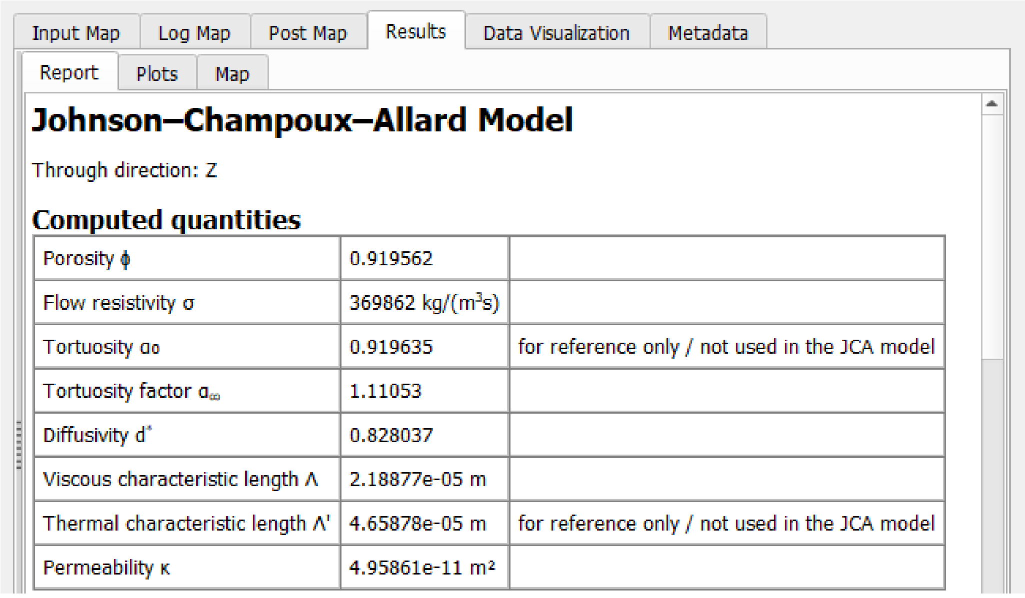
EQUATIONS AND REFERENCES

This tab display formulas and references which are explained in more detail in the introduction of this user guide.

RESULTS

Click **OK** to input the entered parameters, and then click **Run** in the AcoustoDict section to start the command.

The results are immediately shown in the opening Result Viewer after the process is finished, the screenshot below shows the calculated acoustic parameter values for the Johnson–Champoux–Allard model. The **Results→Report** subtab shows porosity, flow resistivity, tortuosity, tortuosity factor, diffusivity, viscous characteristic length, thermal characteristic length, and permeability in the direction of interest.



Johnson–Champoux–Allard Model

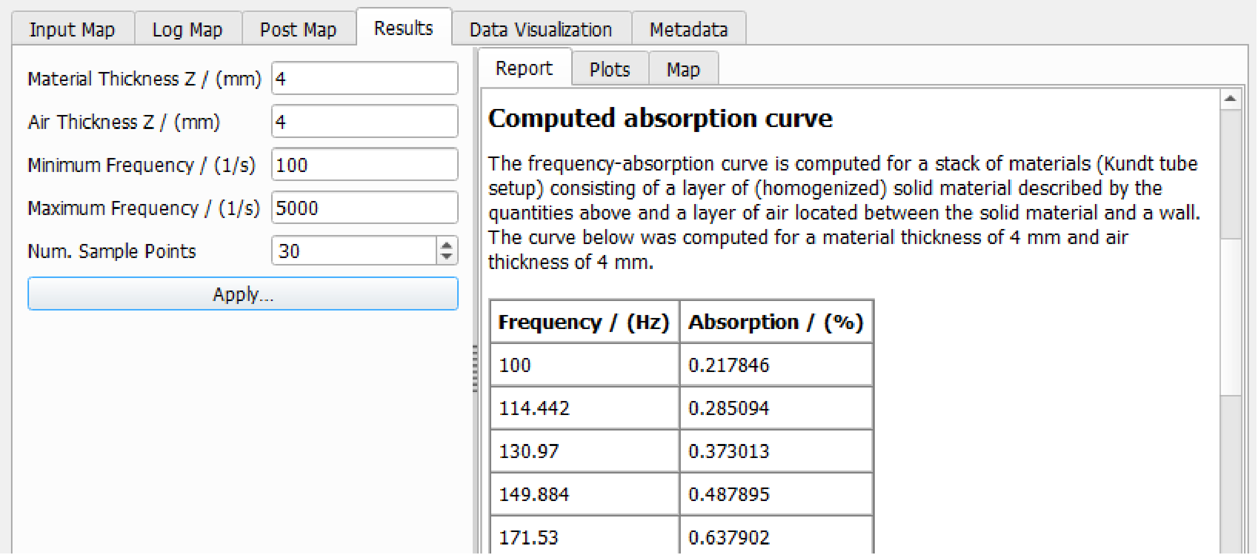
Through direction: Z

Computed quantities

Porosity ϕ	0.919562	
Flow resistivity σ	369862 kg/(m^{3}s)	
Tortuosity α_0	0.919635	for reference only / not used in the JCA model
Tortuosity factor α_∞	1.11053	
Diffusivity d^*	0.828037	
Viscous characteristic length Λ	2.18877e-05 m	
Thermal characteristic length Λ'	4.65878e-05 m	for reference only / not used in the JCA model
Permeability κ	4.95861e-11 m^2	

Absorption curve

The frequency–absorption curve is computed for a stack of materials in Kundt tube setup, consisting of a layer of (homogenized) solid material described by the computed flow resistivity and porosity and a layer of air located between the solid material and a wall. The thickness of the material and the air layer can be set in the panel on the left, as **Material Thickness Z** and **Air Thickness Z**. By default, 4 mm are used for both values.



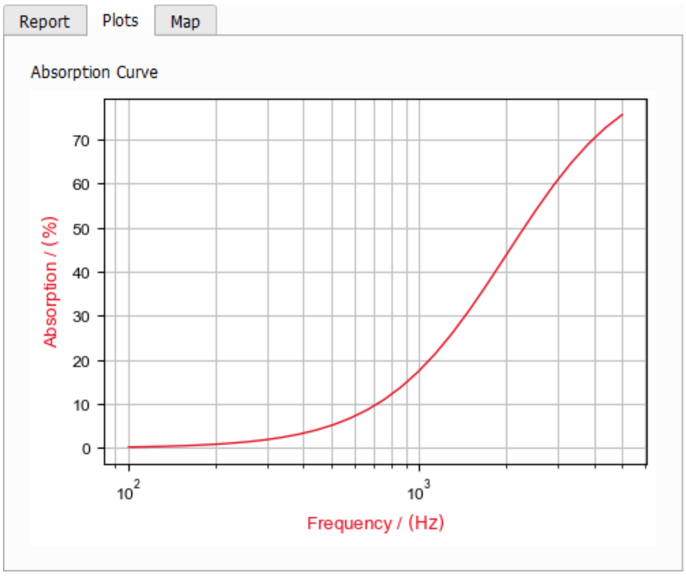
Material Thickness Z / (mm) 4
Air Thickness Z / (mm) 4
Minimum Frequency / (1/s) 100
Maximum Frequency / (1/s) 5000
Num. Sample Points 30

Computed absorption curve

The frequency-absorption curve is computed for a stack of materials (Kundt tube setup) consisting of a layer of (homogenized) solid material described by the quantities above and a layer of air located between the solid material and a wall. The curve below was computed for a material thickness of 4 mm and air thickness of 4 mm.

Frequency / (Hz)	Absorption / (%)
100	0.217846
114.442	0.285094
130.97	0.373013
149.884	0.487895
171.53	0.637902

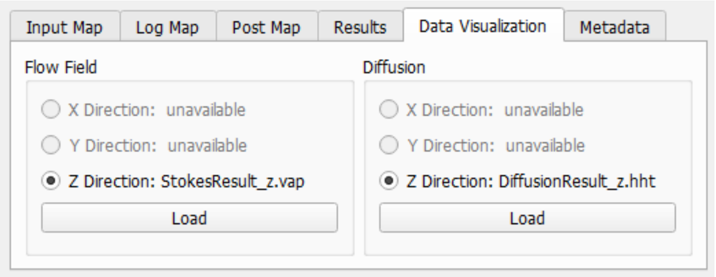
The absorption is computed in a range given by the **Minimum Frequency** and **Maximum Frequency** values, using the given number of **Sample Points**. The curve is shown in the **Results**→ **Plots** subtab.



The **Results**→**Map** subtab gives access to the media-dependent acoustic parameters values computed for the selected acoustic model.

DATA VISUALIZATION

The fifth tab contains the setup for the **Data Visualization**. Flow fields and concentration fields that have been calculated can be visualized by clicking **Load.**



Flow Field
○ X Direction: unavailable
○ Y Direction: unavailable
● Z Direction: StokesResult_z.vap

Diffusion
○ X Direction: unavailable
○ Y Direction: unavailable
● Z Direction: DiffusionResult_z.hht

The options for the visualization of results are explained in detail in the GeoDict Visualization handbook.

ACOUSTIC DATABASE

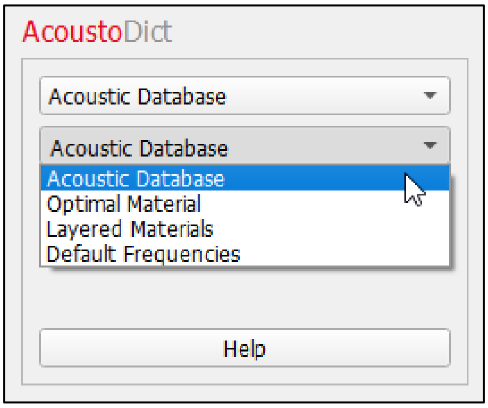
The flow resistivity values calculated with the Delany–Bazley model can be entered into the user's AcoustoDict **Database** to predict the frequency-dependent acoustic absorption of their structure.

A default database is included in the installation and—if the default installation settings have been kept—it is located at:

`C:\Users\`*`username`*`\GeoDict2023\AcoustoDictDataBase`

This editable AcoustoDict database can be used to store own results and later predict the acoustic properties of virtual materials at different degrees of compression.

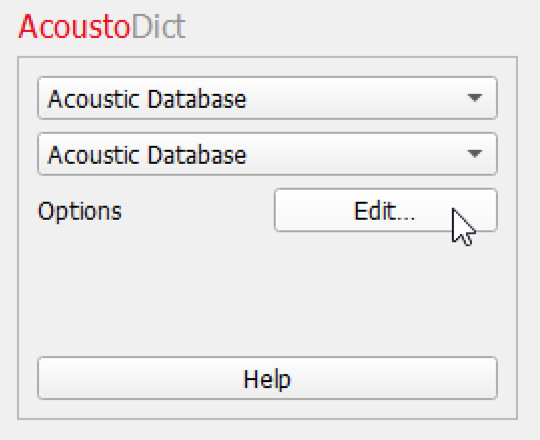
To access the AcoustoDict database, select **Acoustic Database** from the pull-down menu in the AcoustoDict section. Four options are available: **Acoustic Database**, **Optimal Material**, **Layered Materials**, and **Default Frequencies**.



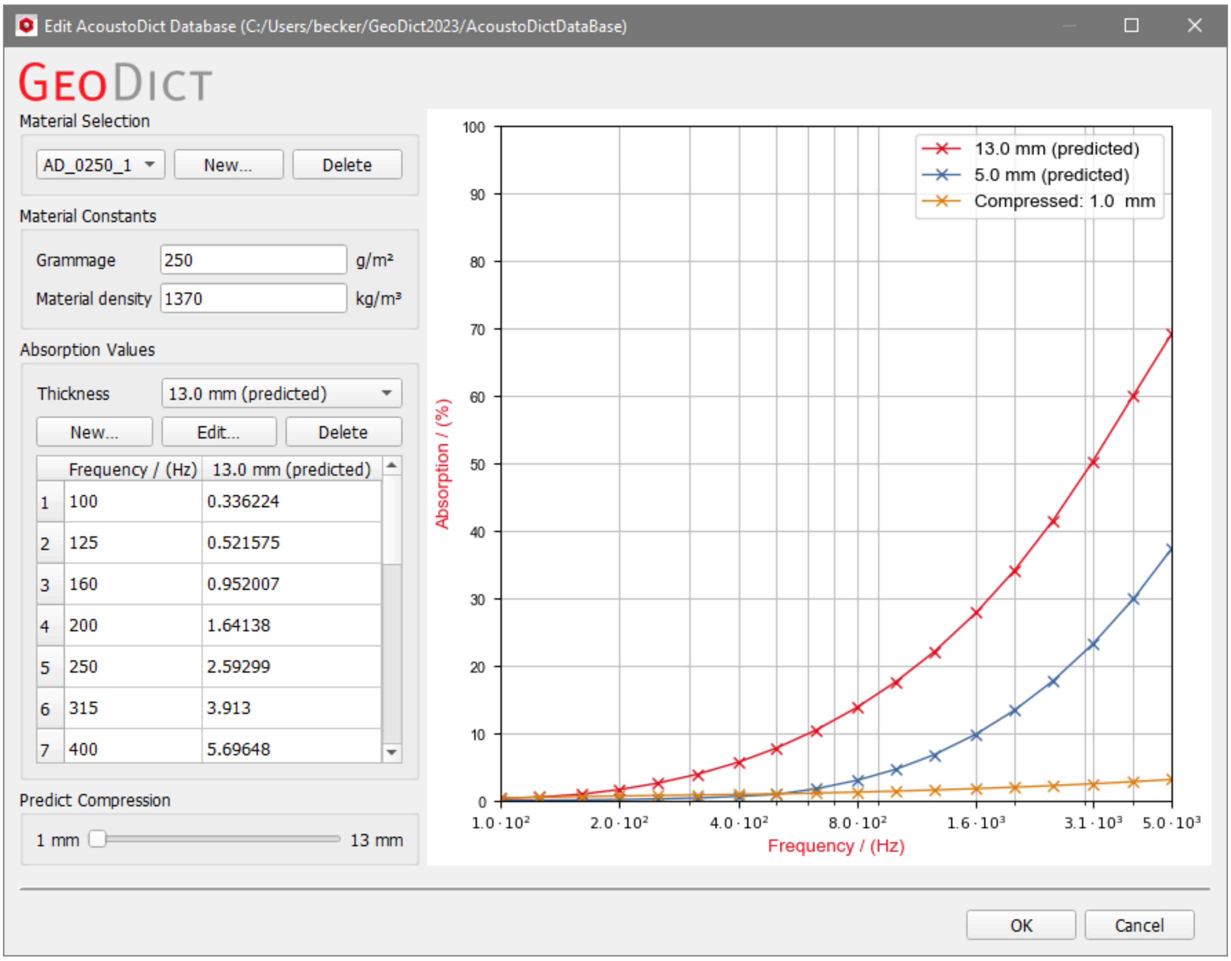
The **Acoustic Database** works differently from a usual GeoDict command, and the **Record** and **Run** buttons disappear from the AcoustoDict section when **Acoustic Database** is selected. When opening a dialog, the whole functionality of modifying and accessing the database takes place inside the dialog widgets. No macro can be stored for those actions and no results files are created during those actions.

ACOUSTIC DATABASE

To edit the **Acoustic Database**, select **Acoustic Database** from the pull-down menu and click the Options's **Edit…**. button in the **AcoustoDict** section.



The **Edit AcoustoDict Database** dialog box opens, showing the path to the database in the caption.



Material Selection: AD_0250_1

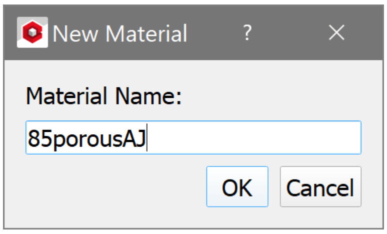
Grammage: 250 g/m²

Material density: 1370 kg/m³

Thickness: 13.0 mm (predicted)

	Frequency / (Hz)	13.0 mm (predicted)
1	100	0.336224
2	125	0.521575
3	160	0.952007
4	200	1.64138
5	250	2.59299
6	315	3.913
7	400	5.69648

In the **Material Selection** panel, the pull-down menu displays the names of the database materials. New materials can be added to the database by clicking **New…** and entering the **Material Name**.



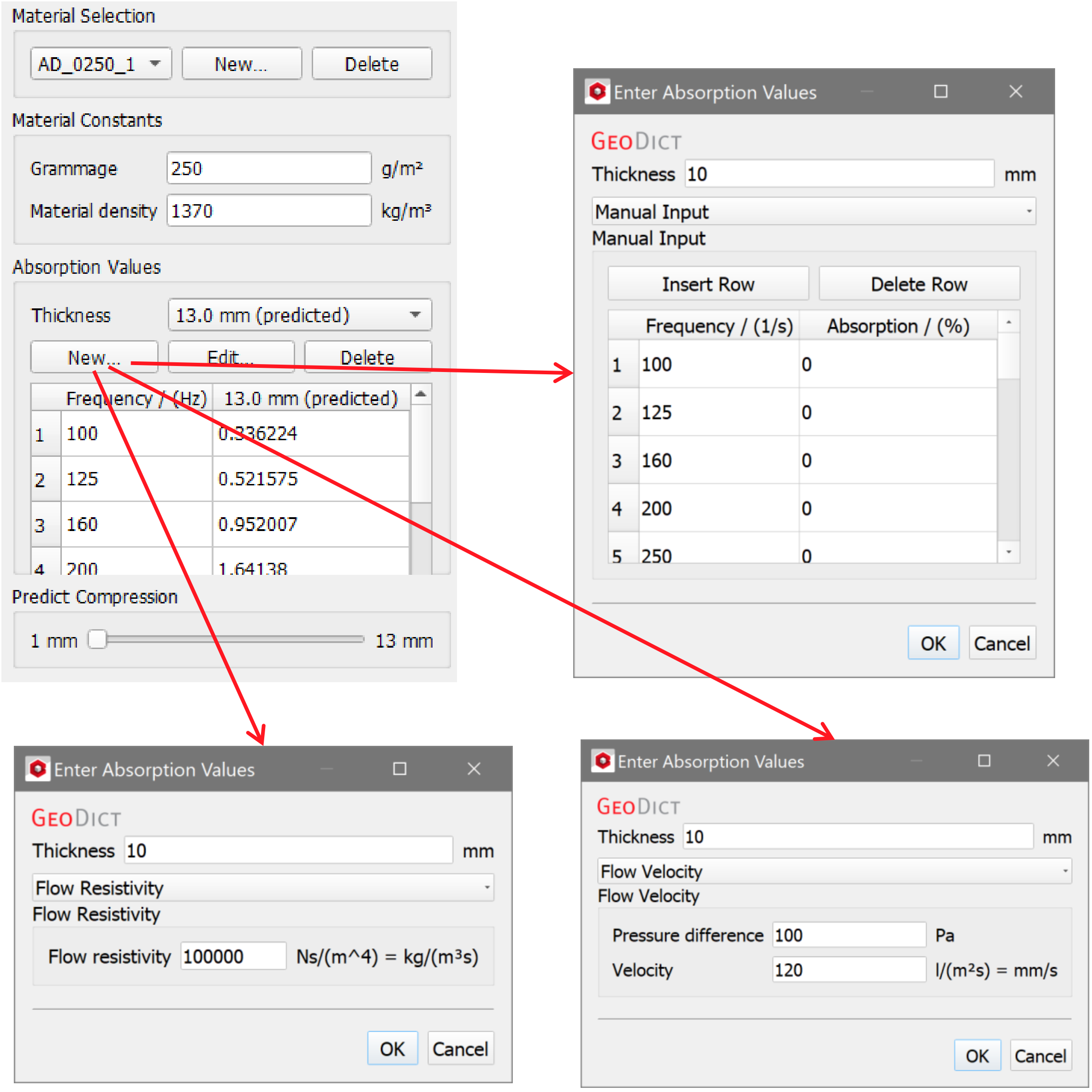
Material Name: 85porousAJ

Materials can be removed from the database by clicking **Delete**. and confirming the deletion.

When a material is selected that is already in the database, its **Grammage** and its **Material Density** are shown (and are editable) in the **Material Constants** panel.

In the **Absorption Values** panel, clicking **New…** opens the **Enter Absorption Values** dialog box.

The default material **Thickness** of 10 mm can be changed and the way of entering the acoustic data (as **Manual Input**, **Flow Velocity**, or **Flow Resistivity**) can be selected by the user from the pull-down menu below.



Material Selection: AD_0250_1

Grammage: 250 g/m^2

Material density: 1370 kg/m^3

Thickness: 13.0 mm (predicted)

	Frequency / (Hz)	13.0 mm (predicted)
1	100	0.336224
2	125	0.521575
3	160	0.952007
4	200	1.64138

Predict Compression: 1 mm – 13 mm

Thickness: 10 mm

Manual Input

	Frequency / (1/s)	Absorption / (%)
1	100	0
2	125	0
3	160	0
4	200	0
5	250	0

Thickness: 10 mm

Flow Resistivity

Flow resistivity: 100000 Ns/(m^4) = kg/(m^{3}s)

Thickness: 10 mm

Flow Velocity

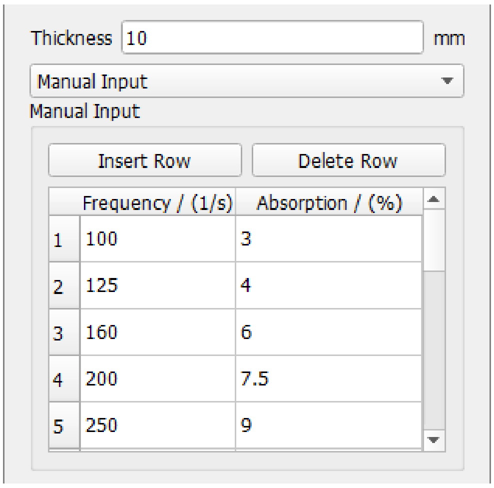
Pressure difference: 100 Pa

Velocity: 120 l/(m^{2}s) = mm/s

The acoustic absorption of real materials, experimentally measured in an impedance tube, can be entered by the user after selecting **Manual Input**. The measured absorption coefficients are entered manually in the table.

Typical fluid flow measurements can also be used to predict acoustic absorption by selecting **Flow Velocity** from the pull-down menu and entering the applied pressure drop and the measured flow velocity for a material. The Delany–Bazley model is then used to compute the frequency dependent absorption values.

After clicking **OK**, the absorption values at varying frequency values predicted for a material at the given thickness fill now the previously empty table in the **Absorption Values** panel and the predicted **Acoustic Absorption Curve** appears on the right.

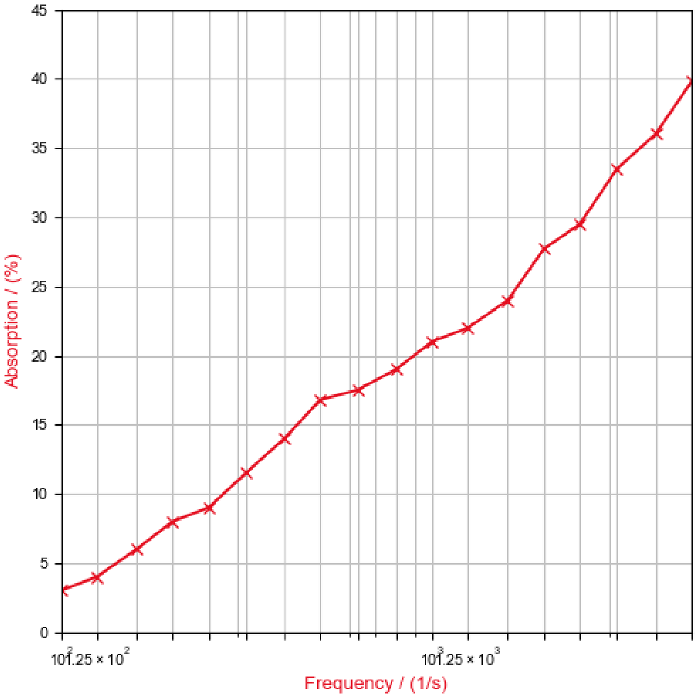


Thickness 10 mm

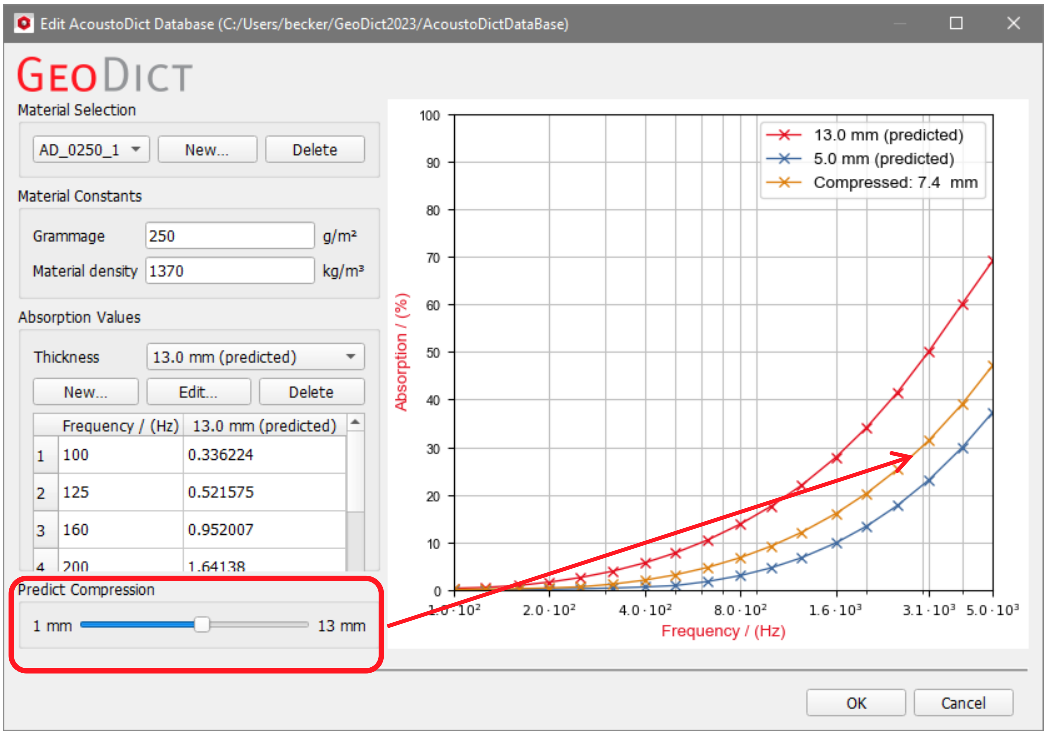
Manual Input

Manual Input

	Frequency / (1/s)	Absorption / (%)
1	100	3
2	125	4
3	160	6
4	200	7.5
5	250	9



When data for the same material at different degrees of compression exists, they can be entered and saved to obtain curves at each material thickness. In this case, the slider in the **Predict Compression** panel at the bottom left corner is activated and the user can obtain the predicted acoustic absorption curves for arbitrary thicknesses.



Edit AcoustoDict Database (C:/Users/becker/GeoDict2023/AcoustoDictDataBase)

Material Selection

AD_0250_1

Material Constants

Grammage 250 g/m²

Material density 1370 kg/m³

Absorption Values

Thickness 13.0 mm (predicted)

	Frequency / (Hz)	13.0 mm (predicted)
1	100	0.336224
2	125	0.521575
3	160	0.952007
4	200	1.64138

Predict Compression

1 mm 13 mm

The prediction relies on the fact that the Delany–Bazley model allows to compute the sound absorption from the viscous flow resistivity of the porous material. This is combined with an approximation for the dependency of the viscous flow resistivity σ of the porous material on the thickness d of the material. We use the Ansatz function

$$\sigma(d) = \alpha\rho(d)^{\beta}, \tag{21}$$

where $\rho(d)$ is the thickness-dependent density of the porous material. Under the assumption of mass conservation, the density $\rho(d)$ can be computed from the **Material density** of the constituent fiber materials, the porosity of the uncompressed layer and the rate of compression. Note that the **Grammage** and the **Material density** of the constituent fiber material need to be entered in the **Material Constants** panel, for this computation to be accurate.

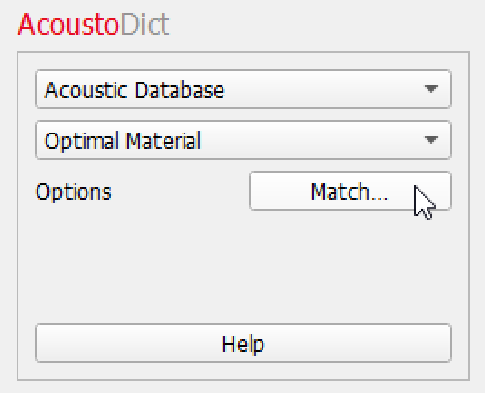
When the user has entered values for at least two different thicknesses (i.e. at least two pairs σ_i, d_i are known), the Ansatz function can be solved for α and β. After α and β are determined, the viscous flow resistivity σ can be estimated for any material thickness, and thus a prediction of the sound absorption with the Delany–Bazley model becomes possible.

The entered values can be edited at any time by clicking the **Edit...** button. This reopens the **Edit Absorption Values** dialog box. Finally, click **OK** in the **Edit AcoustoDict Database** dialog box to save the newly entered or the edited materials in the AcoustoDict Database.

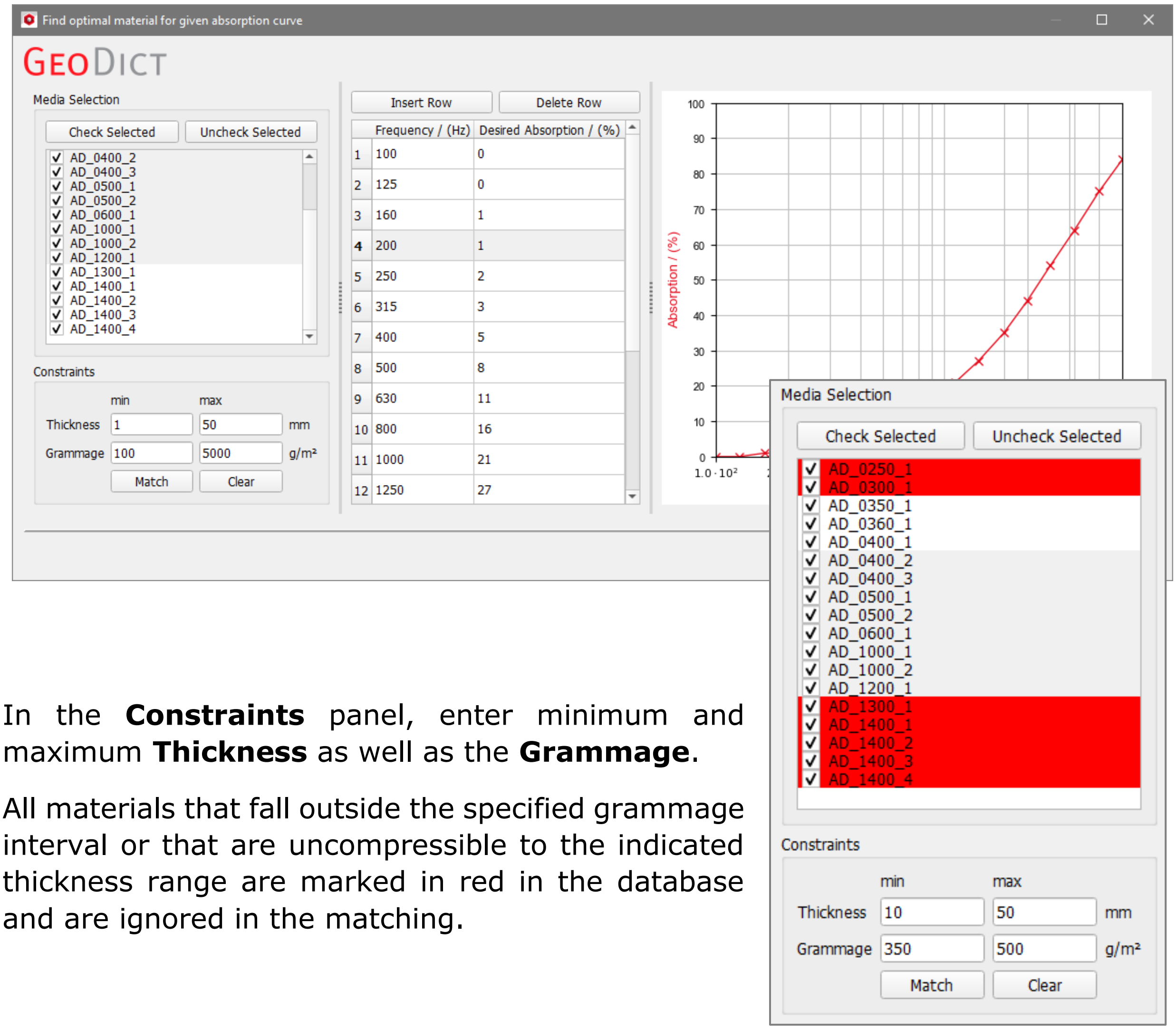
OPTIMAL MATERIAL

Once the AcoustoDict database has been populated, selecting **Optimal Material** and clicking **Match…** allows finding a combination of material and thickness that best matches a desired absorption curve.

In the opening dialog box, in the **Media Selection** panel, select the database materials to be considered for the optimization. As default, all materials are selected.



To deselect one material, click on the name to highlight it and then click **Uncheck Selected** or just uncheck the box. To deselect multiple materials, it is faster to press Shift+Left mouse button while moving the mouse over a range of materials and then, click **Uncheck Selected**. The selection of unselected materials is done in the same way but clicking **Check Selected** instead.



	Frequency / (Hz)	Desired Absorption / (%)
1	100	0
2	125	0
3	160	1
4	200	1
5	250	2
6	315	3
7	400	5
8	500	8
9	630	11
10	800	16
11	1000	21
12	1250	27

	min	max	
Thickness	1	50	mm
Grammage	100	5000	g/m²

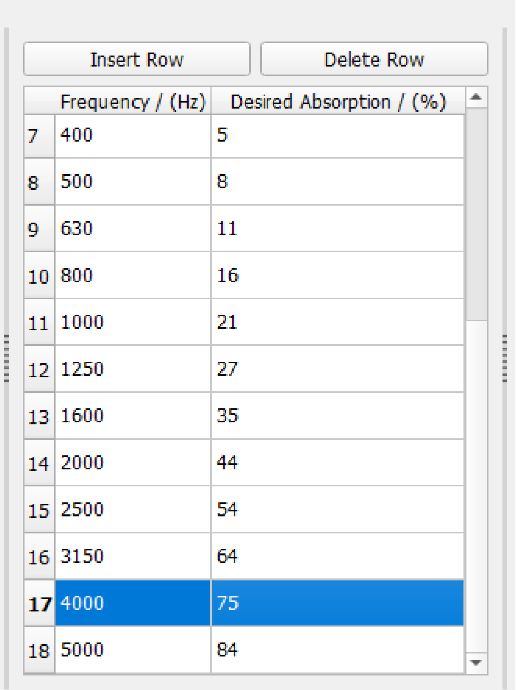
	min	max	
Thickness	10	50	mm
Grammage	350	500	g/m²

In the **Constraints** panel, enter minimum and maximum **Thickness** as well as the **Grammage**.

All materials that fall outside the specified grammage interval or that are uncompressible to the indicated thickness range are marked in red in the database and are ignored in the matching.

The user enters the values for the desired absorption curve in the table, which consists of **Frequency** and corresponding **Desired Absorption** coefficient pairs. Select one of the rows and use **Insert Row** or **Delete Row** to add or eliminate pairs of values.

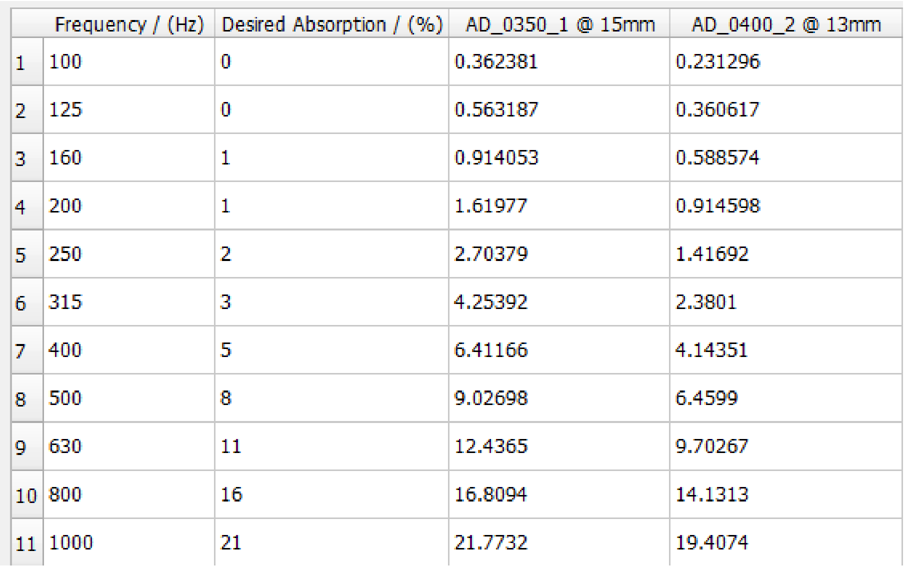
The curve of these frequency/absorption values is displayed on the right while the user enters the values.



	Frequency / (Hz)	Desired Absorption / (%)
7	400	5
8	500	8
9	630	11
10	800	16
11	1000	21
12	1250	27
13	1600	35
14	2000	44
15	2500	54
16	3150	64
17	4000	75
18	5000	84

When clicking **Match** in the **Constraints** panel, AcoustoDict considers the materials fulfilling the given thickness and grammage constraints and computes the absorption curve at different thicknesses within the given interval.

A graph with the five materials that best match the desired absorption characteristics is displayed on the right with the name of the materials in the legend. The table now includes new columns with the absorption values at the given frequencies for these five materials.

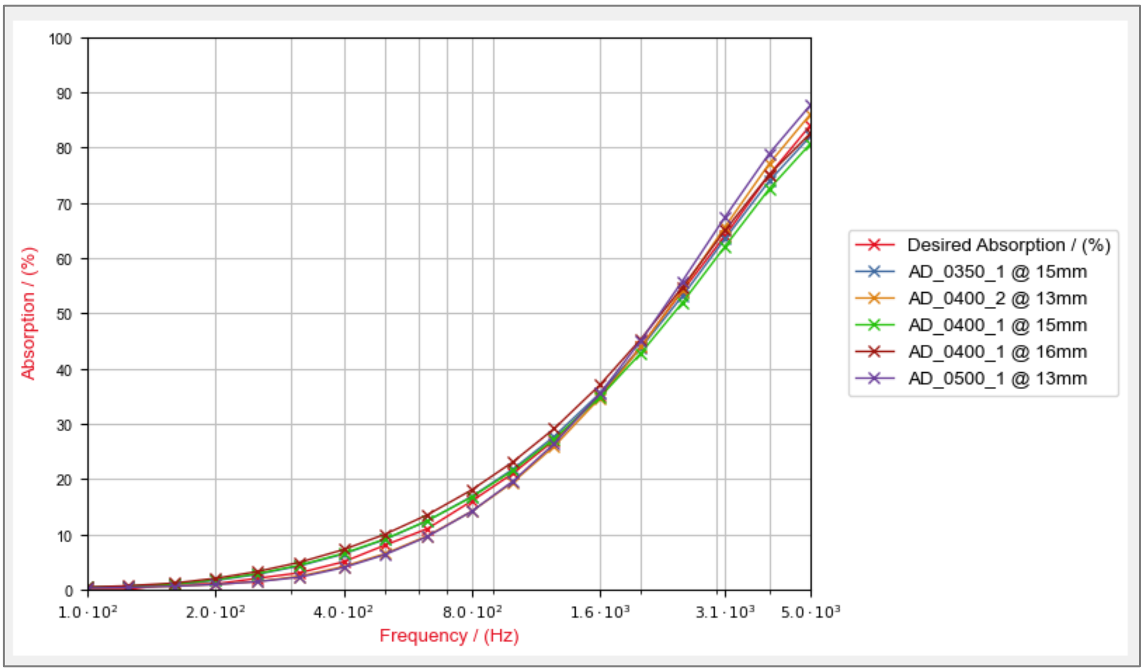


	Frequency / (Hz)	Desired Absorption / (%)	AD_0350_1 @ 15mm	AD_0400_2 @ 13mm
1	100	0	0.362381	0.231296
2	125	0	0.563187	0.360617
3	160	1	0.914053	0.588574
4	200	1	1.61977	0.914598
5	250	2	2.70379	1.41692
6	315	3	4.25392	2.3801
7	400	5	6.41166	4.14351
8	500	8	9.02698	6.4599
9	630	11	12.4365	9.70267
10	800	16	16.8094	14.1313
11	1000	21	21.7732	19.4074

Notice that the thickness of the database materials is also taken into account and, therefore, the name of the materials indicates at which thickness of that material the best match occurs.

The user can drag the corners and expand the dialog box to better observe the graph and the table columns.

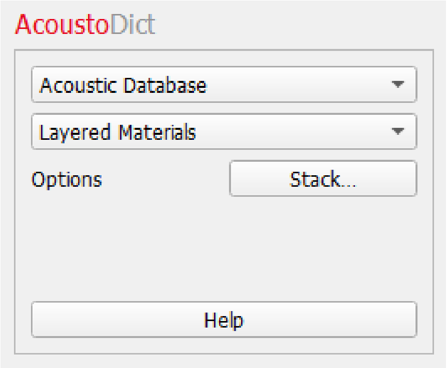
Right-click inside the graph to change the graph settings or right-click inside the table to save it as a .txt file.



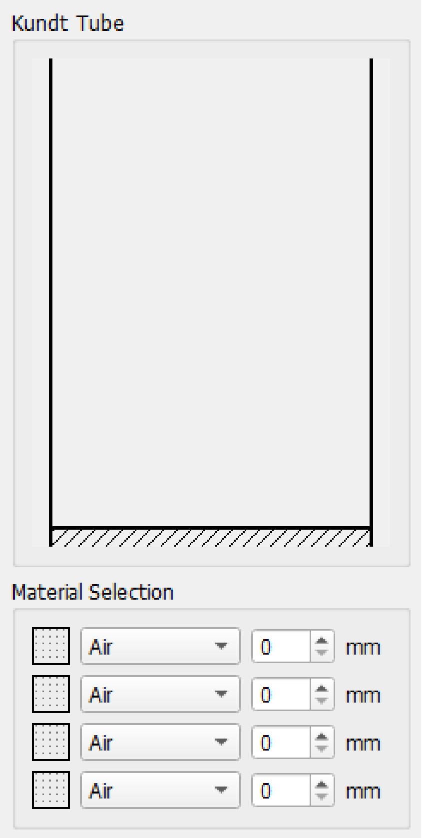
Clicking **Clear** in the **Constraints** panel, makes the values of the matched materials in the table and their curves in the graph disappear. The user can start over trying to match other materials in the database.

LAYERED MATERIALS

Layered Materials is designed to simulate the acoustic absorption of a stack of material layers chosen by the user.

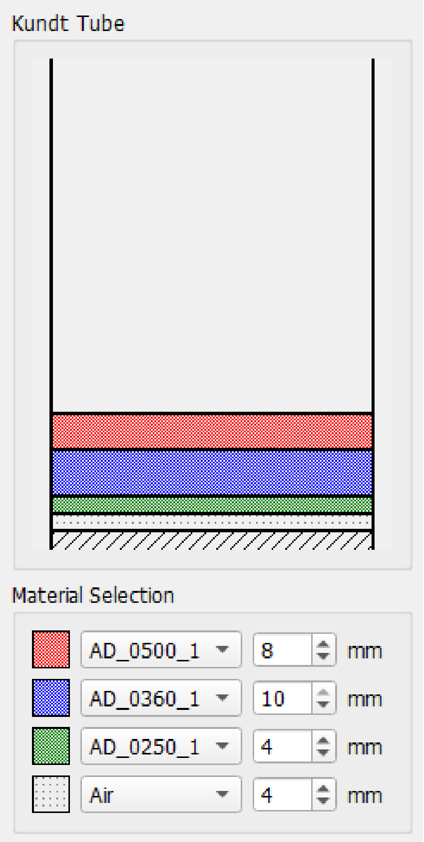


Click **Stack...** to open the dialog box. On the left, the **Kundt tube** panel shows a cross-section schematic drawing of a virtual impedance tube for the measurement of the absorption coefficient of materials. The heavy backing plate is shown at the bottom as a block of slanted stripes.



Air 0 mm
Air 0 mm
Air 0 mm
Air 0 mm

Under the **Material selection** panel, select materials from the AcoustoDict database using the pull-down menus. Stacks of up to four different materials can be constructed. All materials in the database are available, as well as **Air** to allow for air gaps in the stacked multilayer construction.



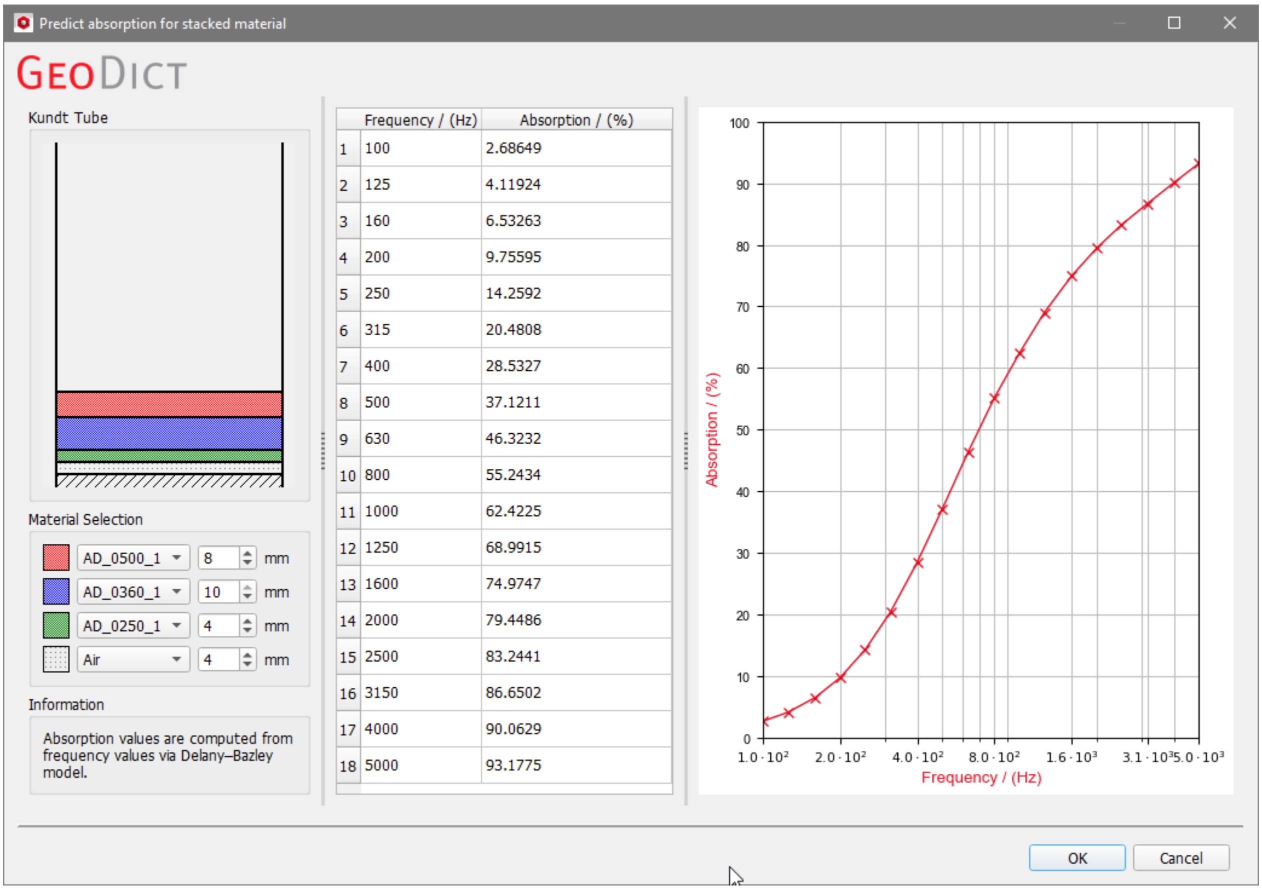
AD_0500_1 8 mm
AD_0360_1 10 mm
AD_0250_1 4 mm
Air 4 mm

A color is assigned to every material (or air) layer and the thickness of the layer can be directly entered or selected through the up-down arrows.

If the multilayer construction should have less than four layers, unused layers can be set to **Air** and **0 mm**.

While the layers are being stacked, the predicted acoustic absorption values of the multilayer stack at various frequencies are already listed in the table and the frequency/absorption curve for the complete multilayer construction is displayed on the right.

Countless variations of the multilayer construction can be built in real time.



Material Selection

🟥 AD_0500_1 8 mm
🟦 AD_0360_1 10 mm
🟩 AD_0250_1 4 mm
Air 4 mm

Information

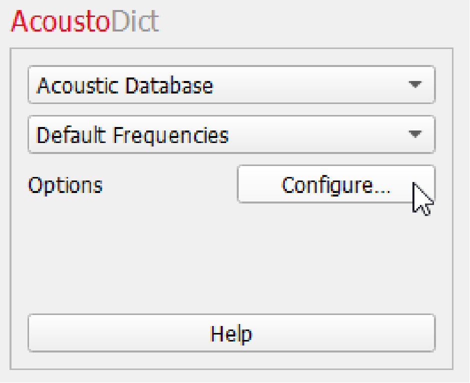
Absorption values are computed from frequency values via Delany–Bazley model.

	Frequency / (Hz)	Absorption / (%)
1	100	2.68649
2	125	4.11924
3	160	6.53263
4	200	9.75595
5	250	14.2592
6	315	20.4808
7	400	28.5327
8	500	37.1211
9	630	46.3232
10	800	55.2434
11	1000	62.4225
12	1250	68.9915
13	1600	74.9747
14	2000	79.4486
15	2500	83.2441
16	3150	86.6502
17	4000	90.0629
18	5000	93.1775

The computation of the acoustic surface impedance Z_s follows Equations (4)–(6).

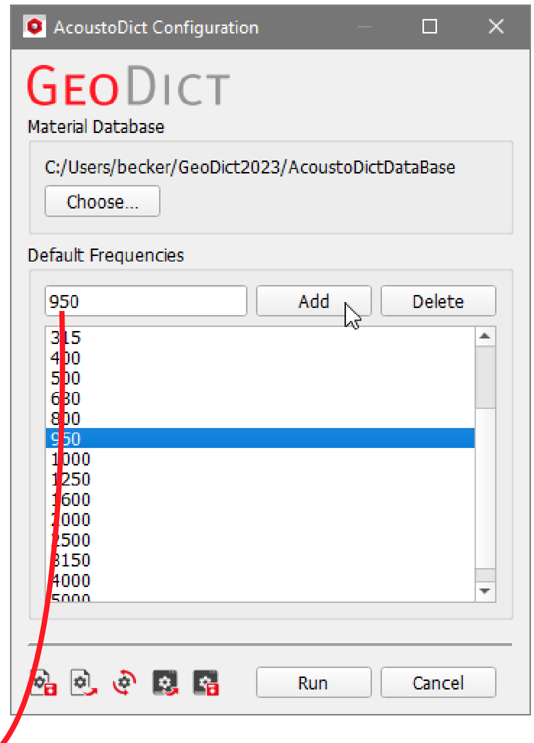
DEFAULT FREQUENCIES

Selecting Default Frequencies and Clicking **Configure…** opens the **AcoustoDict Configuration** dialog box, where the path to the AcoustoDict database can be changed at will.



Each material in the AcoustoDict database is stored in a single file within this folder and can be individually copied, exchanged, or shared with other users of GeoDict.

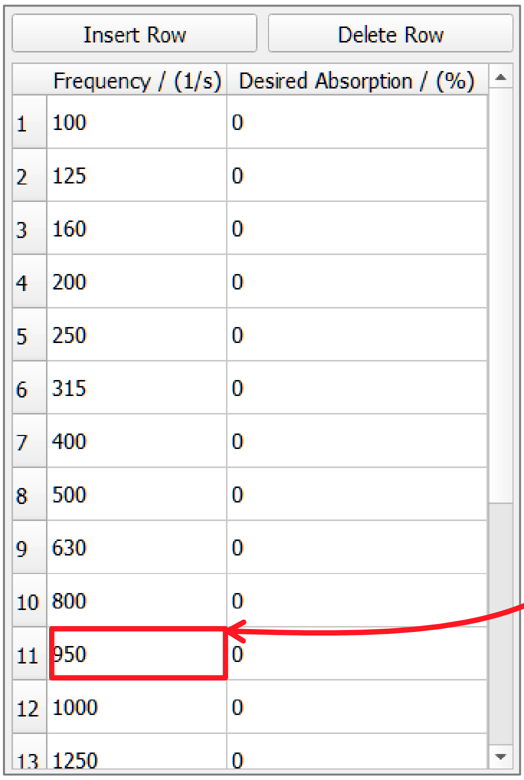
Additionally, the user can define a set of **Default Frequencies**, which is useful when measuring real samples in an impedance tube.



C:/Users/becker/GeoDict2023/AcoustoDictDataBase

950

315
400
500
630
800
950
1000
1250
1600
2000
2500
3150
4000
5000



	Frequency / (1/s)	Desired Absorption / (%)
1	100	0
2	125	0
3	160	0
4	200	0
5	250	0
6	315	0
7	400	0
8	500	0
9	630	0
10	800	0
11	950	0
12	1000	0
13	1250	0

By predefining the frequencies to match those routinely registered by the user's instrument during measurement, only the **Desired Absorption [%]** values have to be manually entered in the table when real measurements are transferred to AcoustoDict.

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