OpenPulse - Open source code for numerical modelling of low-frequency acoustically induced vibration in gas pipeline systems

Theory Reference A: Acoustic gas pulsation module
V1.0

Diego M. Tuozzo, Olavo M. Silva, Lucas V. Q. Kulakauskas,
Jacson G. Vargas, André Fernandes, José L. Souza and Ana P. Rocha
dmtuozzo@mopt.com.br

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1 Introduction

The acoustic gas pulsation module consists of an interface that allows to simulates 1D-plane wave propagation problems in acoustic fluids for piping. Mathematically, the motor behaviour of the module interface is designed to solve the 1D-wave equation in the plane wave mode frequency range using an analytic solution in the FETM formulation. Physically, an acoustic gas pulsation problem is being solved. The module gives the possibility to do a time harmonic analysis of the acoustic fluid.

The time harmonic analysis enables to solve pressure field inside the piping under time harmonic pressure and volume velocity sources as well as nodal impedances BC's. This is useful to model excitation sources as compressors, pumps and different piping elements as plate orifices, pressure vessels, valves and acoustic filters. The generated post-processing from this analyses is one of the first steps into the acoustic induced vibration analysis and allows to identify critics piping frequencies for gas pulsation phenomena.

2 Acoustic gas pulsation

Reciprocating/positive displacement pumps and compressors generate pressure fluctuations in the process acoustic fluid simply by virtue of the way in which they operate [9].

The gas (acoustic fluid) pressure fluctuation produced by this kind of machine can be intended as an incident pressure wave coming from an external pulsation source that is partially reflected and transmitted at every piping element such as orifice plates, valves, any throttling elements, reducers, expanders, etc [8].

Since these pressure fluctuations can reach amplitudes over 20 times higher than the dynamic pressure in main pipe [8] the structural vibration behavior of pipeline systems can be strongly affected by the response of the acoustic domain represented by the gas being transported through the pipes. These flow-related vibration phenomena are generally known as FIV. When flow-induced noise is present, the term FIVN is used. The term FIV became popular after [7] where was used in his book's title and probably for the first time, FIV phenomena were classified based on the two basics flow types: steady flow induced and unsteady flow related [1].

Particularly, deal with vibrations induced by compressor gas pulsation's is known as AIV. This vibration mechanism occurs in many industrial plants and is considered an important problem in industry because is a commonly cause of failure that obstructs smooth plan operations and in serious cases can lead to significant maintenance and repair costs and costly losses in productivity.

The AIV is a vibration mechanism which responds to an unsteady fluid flow and to a pulsating flow field [1]. Dealing with AIV means that the general random frequency characteristic of the fluid flow in the piping have a particular frequency component (and harmonics if broadband excitation exist) that becomes dominant when the interaction between the acoustic fluid and the compressor (intermittent suction/discharge compressor flow, Figure 1) occurs, generating pressure pulsations (acoustic fluid oscillations).

Reciprocating/positive displacement pumps and compressors can cause these pressure pulsations which can contain many harmonic components of the rotational speed (generally less than 100 Hz). Also centrifugal compressors can generate tonal pressure pulsations at low flow conditions and sub-synchronous tonal pressure component (10 to 80 % of rotor speed) caused by rotating stall. Generally, the pressure pulsation is to weak to cause any problem by it self, but if a coincidence with any pressure field and structural piping natural frequency occurs (Figure 1), the pressure pulsation can be largely amplified [2] and hence shaking forces [9].

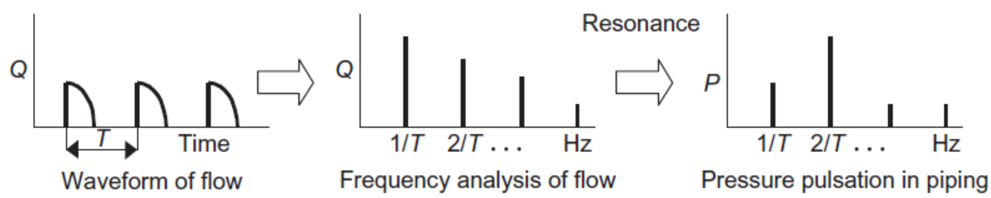


Figure 1: Suction/discharge flow and pressure pulsation in reciprocating compressors. Adapted from [2]

As the AIV phenomena has 3D complexity in nature, over 40 years models of pressure pulsation transmission of piping elements have been developed. The motivation is, in general, have the overall transmission characteristics of an element represented by a simple but accurate enough 1D plane wave mode element model. These models are based on the TMM approach and in the following sections the necessary and essential theoretical background to obtain the TM of a 1D-straight uniform duct element as well as the procedures to model complex piping systems will be described.

3 Basic theoretical background of fluid analysis

For the fluid analysis two principal matrix methods will be analyzed. The first of them, the well known TMM which have typical applications in pipe systems for the study of wave propagation. The other method is the MMM a well known technique which enables to solve more complex pipe systems than the TMM.

The TMM allows to connect the field variables pressure p and volume velocity q from the inlet to the outlet trough the TM with a mixed nodal vector formulation. By contrary the MMM allows to connect the field variables pressure p and volume velocity q from the inlet to the outlet trough the MM with a non-mixed nodal vector formulation which is more suitable to couple with FEM. From the TM is possible to arrive to the MM and vice versa.

The main goal of the acoustic field analysis is to characterize the acoustic pressure for the plane wave frequency band, in all the points of a system under study and carry the information to the FEM structural analysis as and external load under certain coupling conditions.

From the acoustic gas pulsation phenomena view a particular analysis at certain characteristics frequencies generated by the relation between the excitation source, the resultant pressure field and structural response is of great interest .

In the following sections the TM formulation for the 1D hard-walled straight uniform duct element, the MM formulation, it assembly process and BC's insertion for the MM under the name FETM, will be briefly presented.

3.1 Transfer Matrix Method

3.1.1 Introduction

The TMM [12, 23, 4, 2, 8] is an analytical method which has been used to solve a variety of linear and non-linear dynamic or static problems in engineering especially for chain-type and topological systems (i.e. pipes and its related elements).

The TMM is a powerful mathematical technique to build discretized models for performing analytical and numerical studies of the plane wave acoustics in pipe systems. This method is particularly efficient to deal with plane acoustical waves in tubular circuits, because of the following aspects of the formulation [4]:

- Two scalar fields p and q are sufficient to describe the waves.
- Use of exact analytical wave solutions for low order modes propagation (plane waves)
- Easy representation of constant or varying cross-sectional ducts (i.e. horn geometries)
- Only a few types of transfer matrices are necessary to assembly for discretized tubular models.
- The degree of accuracy is independent of the range of wavelengths explored (within the limits of validity of the plane wave approximation)
- Certain implementations and changes in BC's (i.e inner or radiation nodal impedances, position and kind of nodal sources) and extension of the transfer matrix method to dissipative problems can be done maintaining the elementary formulation.

In the following section the TM for the 1D hard-walled straight uniform duct element will be presented.

3.1.2 Transfer matrix of an uniform 1D tube element

Considering an uniform tube length as shown in Figure 2, fluid properties like mean density ρ and speed of sound c are assumed to be uniform inside the tube. The volume velocity and pressure at the inlet of the element are denoted q_1 and p_1, while q_2 and p_2 denote the corresponding quantities at the outlet. Z represents the acoustical impedance of the tube element. The objective is find a matrix equation wich express the volume velocity $q(x,k)$ and the pressure $p(x,k)$ at any point x inside the tube element at the wave number (frequency) $k = \omega/c_f$, in terms of they values at the inlet. Accordingly, the tube element can be represented as a matrix linear system with two inputs and two outputs as follows

$$\begin{bmatrix} p_2 \\ q_2 \end{bmatrix} = \mathbf{T} \begin{bmatrix} p_1 \\ q_1 \end{bmatrix} \tag{1}$$

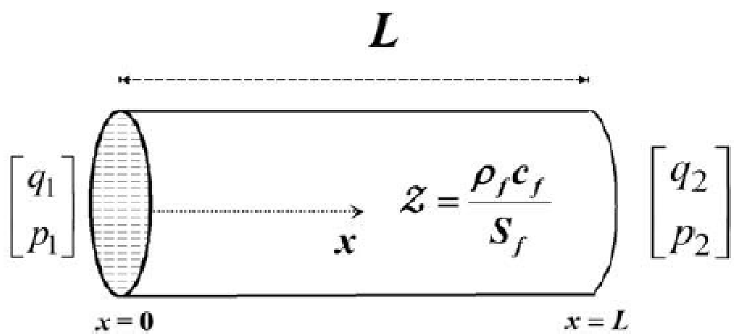


Figure 2: Uniform tube element. [4]

where $\mathbf{T}$ is the transfer matrix for the uniform tube element wich has four elements inside as follows

$$[\mathbf{T}]_{ij} = \begin{bmatrix} T_{11}(x,k) & T_{12}(x,k) \\ T_{21}(x,k) & T_{22}(x,k) \end{bmatrix} \tag{2}$$

where to obtain each of that elements we need to solve the wave equation under the assumption of plane waves. By definition , the volume offered to the fluid in a tube is characterized by one dimension x, which is much larger than the others two (the transverse dimensions). As a consequence, physically, for a fluid oscillation at a given frequency ω the compressibility parameter is much larger in the longitudinal direction than the others. Moreover if ω is small enough the compressibility parameter can be taken in account just in the greater direction. So, the idea is as larger is the wavelength λ, better works the plane wave assumption because the transverse dimensions smaller each time. Then, we can assume constant pressure in the hole tube cross-section and establish a frequency range validity for this assumption as

$$\frac{\lambda}{r_i} = \frac{c_f}{\omega r_i} >> 1 \tag{3}$$

where r_i is the inner duct radius. For this simple case, the homogeneous and non dissipative wave equation is

$$p_{,xx} - \frac{1}{c_f^2} p_{,tt} = 0 \tag{4}$$

then the 1D solution is written in terms of traveling waves for the pressure as

$$p(x,t) = \left(Ae^{-ikx} + Be^{ikx}\right) e^{i\omega t} \tag{5}$$

and with the aid of Euler's equation

$$q(x,t) = \frac{S_f}{\rho_f c_f} \left(A e^{-ikx} - B e^{ikx} \right) e^{i\omega t} \tag{6}$$

where q is the interior nodal volume velocity and is equal to $q_n = S_{element_n} u_n$. From the mathematical standpoint, the two constants of integration A and B appearing in the general solution of the local equation 4 are univocally defined if both the pressure and the volume velocity are specified at the inlet of the tube element.

Evaluating equations 5 and 6 in $x = 0$ and $x = L$ the constants A and B are eliminated and we obtain the components of the transfer matrix as

$$[\mathbf{T}]_{ij} = \begin{bmatrix} cos(kx) & -i\, Z_f\, sin(kx) \\ -\frac{i}{Z_f}\, sin(kx) & cos(kx) \end{bmatrix} \tag{7}$$

and we can complete now the matrix system (presented in equation 1) wich involves the connection between the two-port nodes p and q at the input and at the output of the straight tube element with the transfer matrix $\mathbf{T}$

$$\begin{bmatrix} p_2 \\ q_2 \end{bmatrix} = \begin{bmatrix} cos(kx) & -i\, Z_f\, sin(kx) \\ -\frac{i}{Z_f}\, sin(kx) & cos(kx) \end{bmatrix} \begin{bmatrix} p_1 \\ q_1 \end{bmatrix} \tag{8}$$

where $Z_f = \rho_f c_f / S_f$ is the acoustic fluid impedance. Observing that the matrix 7 is not symmetrical (self-adjoint) cause by the choice made in the definition of the input and output vectors which mix kinematics and stress variables (mixed formulation) [4].

3.2 Finite Element Transfer Matrix Method

3.2.1 Introduction

A combinations of matrix methods generally can be used to improve the computational cost, i.e. of FEM approaches, or for a quickly analysis of complex piping systems. The FETM [23], , sometimes called too SMM [2, 12, 13] or MMM [17] was one of the first methods to reduce the high computational cost from solving large matrix systems with high number of elements and was developed in the early 90s with the [12, 17, 24] and [23] works.

The transfer matrix system presented in equation 8 is based on a mixed formulation [4]. As can be seen in that equation, the nodal input and output vector have two different field variables, p and q (kinematic and stress variables), inside each one . That is, from a mathematical point of view we are dealing with scalar and vector field variables, solution of wave equations originated by fundamental field equations.

To relate the TM with a FEM matrix form a few algebraic operations needs to be done with the objective of arrange the variables of the mixed formulation into one not mixed (the same type of variables in each nodal vector), which is more suitable with the FEM matrixes. In structural mechanics this method is know as the FETM [23].

In the following section the MM for the 1D hard-walled straight uniform duct element it coupling process, characteristics and BC's will be presented.

3.2.2 Mobility Matrix of a uniform hard-walled straight 1D duct

The transformation of the mixed nodal vector TM system into a non-mixed was suggested by different authors [12, 23, 17, 10].

Taking the process suggested by [12] (one of the firsts in applied this proceeding for duct acoustics), directly we can use the TM system of Equation 8 and apply to the TM of Equation 7. Then the elementary $\mathbf{K_{A,e}}$ matrix for a straight tube with $\mathbf{q}$ and $\mathbf{p}$ as nodal variables is

$$\mathbf{K_{A,e}} = \begin{bmatrix} -i\,cot(kx)\,/\,Z_f & i\,/\,Z_f\,sin(kx) \\ i\,/\,Z_f\,sin(kx) & -i\,cot(kx)/\,Z_f \end{bmatrix} \tag{9}$$

where $\mathbf{K_{A,e}}$ is the elemental mobility matrix [17] and is clearly a symmetric matrix. This name probably is the most appropriated based on the mechanical/acoustic analogue force-velocity/pressure-volume velocity. The $\mathbf{K_{A,e}}$ matrix also is called the acoustic stiffness matrix [12] probably using the structural analogy stiffness-displacement-force, the Admittance Matrix too [10, 22] (electroacoustic analogy for the mobility, inverse of the mechanical impedance) and the four-pole matrix [24] due to the 4 node variables involved. In essence, the matrix $\mathbf{K_{A,e}}$ still depends on harmonically functions and on the fluid wave-number k, that it's mean, frequency dependent ($k = \omega/c$).

The combination between the TMM and the FEM can be classified as an hybrid method. This is because from a technique point of view the elementary matrixes are developed using the TMM formulation and then coupled (in the MM formulation) to form the global matrix system using a FEM based assembly process. From a mathematical point of view, the heart of this hybrid method consists in the quadratic or linear finite element form functions substitution by analytic field solutions of wave equation (in this case pressure and velocity inside a 1D straight constant section duct element) [21].

Finally the complete non-mixed TM system with q and p nodal vectors is

$$\begin{bmatrix} -i\,cot(kx)\,/\,Z_f & i\,/\,Z_f\,sin(kx) \\ i\,/\,Z_f\,sin(kx) & -i\,cot(kx)/\,Z_f \end{bmatrix} \begin{bmatrix} p_1 \\ p_2 \end{bmatrix} = \begin{bmatrix} q_1 \\ q_2 \end{bmatrix} \tag{10}$$

In the matrix system presented in Equation 10, the pressure and volume velocity nodal vectors are isolated (non-mixed formulation), this is quite similar to the classical finite element acoustic system according to the equation [21]

$$\left(\mathbf{H} + i\omega\mathbf{D} - \omega^2\,\mathbf{Q}\right)\,\mathbf{p} = \mathbf{q} \tag{11}$$

On LHS of equation 11 the mass $\mathbf{Q}$, stiffness $\mathbf{H}$, and damping $\mathbf{D}$ global matrixes ([15] convention) are condensed into a single matrix as a function of frequency called the mobility matrix $\mathbf{K_A}(\omega)$. In a global sense the system in Equation 10 can be written as

$$\mathbf{K_A}\,\mathbf{p} = \mathbf{q} \tag{12}$$

where $\mathbf{p}$ are the nodal pressures and $\mathbf{q}$ are the inner nodal volume velocities.

3.2.3 Assembly process for the Mobility Matrix

The global mobility matrix $\mathbf{K_A}$ is obtained doing the same procedure as proposed in the FEM. Some brief comments about the basics of this process will be done but for a complete understanding about this topic the lecturer is referred to a classic specialized bibliography as [16, 11, 18, 5].

Each acoustic 1D element have two nodes and each node 1 DOF (pressure). Also, the elements can have arbitrary length and cross-sectional area and at each node connection the continuity of the field variables p and q is guaranteed. Briefly, the general steps for the assembly process of the n $\mathbf{K_{A,e}}$ is

- Node indexing in a convenient way (dependant on the bandwidth of $\mathbf{K_A}$)
- Construction of the connectivity table
- Assembly of the n $\mathbf{K_{A,e}}$ according to the connectivity table.

3.2.4 Boundary Conditions

In the global system presented in Equation 12 the pressure field nodal vector $\mathbf{p}$ is presented as an unknown variable and must be solve. Before solve the system inverting the global mobility matrix $\mathbf{K_A}$ as indicated in equation 13 is necessary to apply all the corresponding BC's into the global matrix .

$$\mathbf{p} = \mathbf{K_A}^{-1}\,\mathbf{q} \tag{13}$$

Three general BC's can be applied in the FETM formulation

- Inner nodal volume velocity, q
- Nodal pressure, p
- Nodal acoustic impedance, Z

When one of these BC's is known is common to refer as prescribed BC's. The followings items briefly describe how each BC is applied.

- Volume velocity

  The simplest BC is a prescribed nodal volume velocity source $q_i = S_{e_n}\, u_i$ is prescribed on node $i = j$. If there are any other q volume velocity source at the $N-1$ remain interior nodes [12], the global matrix system for the piping becomes

$$[\mathbf{K_A}]_{ij} \begin{bmatrix} p_j \\ p_{j+1} \\ p_{j+2} \\ \vdots \\ p_{J-1} \\ p_J \end{bmatrix} = \begin{bmatrix} q_j \\ 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix}. \tag{14}$$

  when the value of q_j could be frequency dependant $q_j(\omega)$.

- Pressure

  If a nodal pressure is prescribed the classical process applied in FEM when a prescribed displacement occurs needs to be done as in [14]. The global system equation 12 in its final form becomes

$$\begin{bmatrix} 1 & 0 & \dots & 0 & 0 \\ 0 & K_A^{(i+1)(j+1)} & \dots & K_A^{(i+1)(J-1)} & K_A^{(i+1)J} \\ \vdots & \vdots & \dots & \vdots & \vdots \\ 0 & K_A^{(I-1)(j+1)} & \dots & K_A^{(I-1)(J-1)} & K_A^{(I-1)J} \\ 0 & K_A^{I(j+1)} & \dots & K_A^{I(J-1)} & K_A^{IJ} \end{bmatrix} \begin{bmatrix} \overline{p}_j \\ p_{j+1} \\ \vdots \\ p_{J-1} \\ p_J \end{bmatrix} = \begin{bmatrix} p_j \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix} - \overline{p}_j \begin{bmatrix} 0 \\ K_A^{(i+1)j} \\ \vdots \\ 0 \\ 0 \end{bmatrix} \tag{15}$$

  when the value of p_j could be frequency dependant $p_j(\omega)$.

- Impedance

  For the case when a node is connected to a system that has a known acoustic impedance Z the effect of this are added into appropriate (node) locations of the global mobility matrix

[13] in the acoustic admittance form ($A = 1/Z$). If an acoustic radiation impedance A_{rad} wants to be added in the end of the tube, the matrix system of equation 12 becomes

$$\begin{bmatrix} 1 & 0 & \dots & 0 & 0 \\ 0 & K_A^{(i+1)(j+1)} & \dots & K_A^{(i+1)(J-1)} & K_A^{(i+1)J} \\ \vdots & \vdots & \dots & \vdots & \vdots \\ 0 & K_A^{(I-1)(j+1)} & \dots & K_A^{(I-1)(J-1)} & K_A^{(I-1)J} \\ 0 & K_A^{I(j+1)} & \dots & K_A^{I(J-1)} & K_A^{IJ} + A_{rad} \end{bmatrix} \begin{bmatrix} \overline{p}_j \\ p_{j+1} \\ \vdots \\ p_{J-1} \\ p_J \end{bmatrix} = \begin{bmatrix} q_j \\ q_{j+1} \\ \vdots \\ q_{J-1} \\ 0 \end{bmatrix} \tag{16}$$

where $A_{rad} = 1/Z_{rad}$.

From a user impedance input point of view, just the specific impedance (z) should be inserted in the BC's windows of acoustic gas pulsation module. Then, internally, the software internally makes the z_r transformation to Z_r dividing the value of the specific radiation impedance by the correspondent element area S_n and after an inversion finally the acoustic admittance A_r is obtained. This is done to avoid area and impedance type user's insertion error.

However to avoid insertion errors, all the impedance BC's entry possibilities will have the correspondents dimensional units and a possibility to insert a measured acoustic or specific impedance varying with frequency, i.e with a *.txt* form, will be possible.

To clarify a little more the mean of different impedance types, the definitions proposed by [19] are presented

- Specific impedance = $z = p\,/\,u$ = pressure / normal particle velocity = $[Pa\,s/m]$
- Acoustic impedance = $Z = z\,/\,S = p\,/\,q$ = pressure / normal volume velocity = $[Pa\,s/m^3]$.
- Acoustic radiation impedance = $Z_r = z_r\,/\,S$ = pressure / normal volume velocity = $[Pa\,s/m^3]$
- Mechanical impedance = $Z_m = S\,z = S^2\,Z$ = force / particle velocity = $[N\,s/m]$

where S is the boundary surface or the cross-sectional element area which better represents the node where the impedance BC is applied and pressure and velocity in Z_r are evaluated at the open end of a tube. Volume velocity sometimes is referred as volume flow rate.

The following wave-guide end impedances exclusive for model pipe ends with absence of mean-flow are available in BC section of the Acoustic gas pulsation module

- Specific Anechoic impedance (fluid plane wave impedance) = $z_{end} = \rho_f\,c_f$
- Specific radiation unflanged pipe impedance, circular [3, 6]:

$$z_{unflanged} = \rho_f c_f\;(0,25\,(kr_i)^2 + i\;0,6133kr_i) \quad \left[\tfrac{Pa\,s}{m}\right] \quad ; \quad kr_i < 0,5.$$

- Specific radiation unflanged pipe impedance, circular (normal incidence of plane waves, θ=0) [20]:

$$z_{unflanged} = \rho_f c_f \left(\frac{1+R}{1-R}\right) \qquad \left[\frac{Pa\,s}{m}\right] \qquad ; \qquad kr_i < 3,832. \tag{17}$$

$$R = |R|\,e^{2ikr_i\delta} \tag{18}$$

$$|R| = e^{(-kr_i)^2/2}\left[1 + \frac{(kr_i)^4}{6}\,ln\left((\gamma kr_i)^{-1} + \frac{19}{12}\right)\right] \qquad ; \qquad kr_i < 1. \tag{19}$$

$$|R| = \sqrt{\pi kr_i}\,e^{-kr_i}\left(1 + \frac{3}{32(kr_i)^2}\right) \qquad ; \quad 1 < kr_i < 3,832. \tag{20}$$

$$\tag{21}$$

– Specific radiation flanged pipe impedance, circular [6]

$$z_{flanged} = \rho_f c_f \left(1 - \frac{2J_1(2kr_i)}{2kr_i} + i\,\frac{2H_1(2kr_i)}{2kr_i}\right) \qquad \left[\frac{Pa\,s}{m}\right].$$

where δ is the end correction [20], an interpolation function found by numerical integration, $\gamma = e^{0,5772}$, J_1 is the Bessel function of order 1, H_1 is the Struve function of order 1, the subscript f refers to the word fluid, r_i the inner ratio of the last tube element and k the wave number.

4 Acoustic gas pulsation module: a user's guide approach

4.1 Running OpenPulse software

Once the OpenPulse's installation is done and the python interpreter is into the OpenPulse's folder location, is possible to initialize it by the following command in the python terminal:

```
C:\"OpenPulse's folder location"\OpenPulse>python pulse.py
```

After this, the OpenPulse's interface will be open as is shown in figure 3

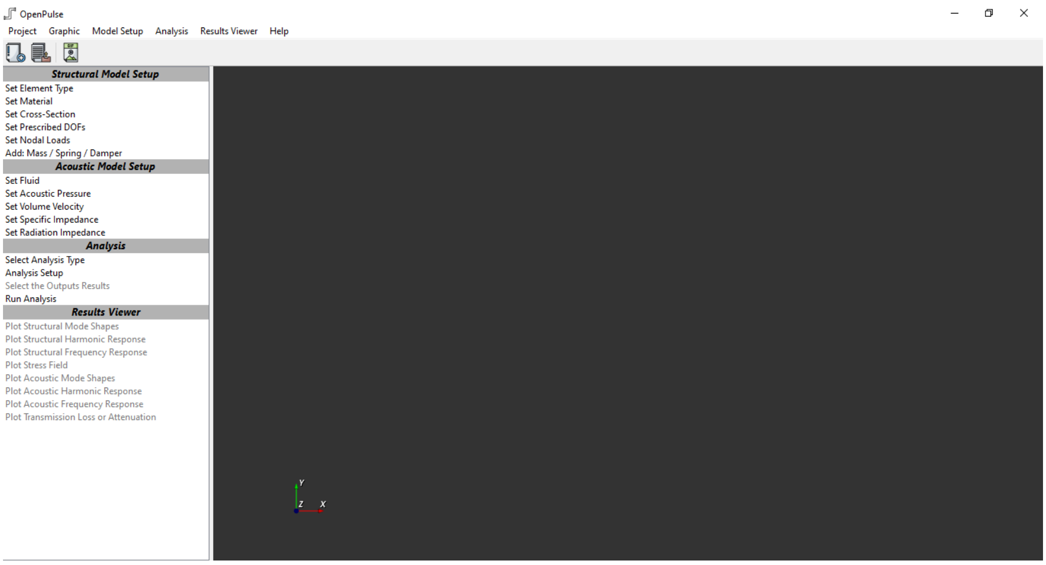


Figure 3: OpenPulses's interface

On the LHS of Openpulse's interface there is a tree of options and in this section just the last three options will be used. These are, Acoustic model setup, Analysis and Result Viewer. On the top of the screen, there are some options related with the project, the geometry and the analysis process, all of these with their correspondents shortcuts.

4.2 Create project and import geometry

To start a new project the shortcut `ctrl+N` will help or clicking on the project option located on the top of the screen (Figure 4). OpenPulse is capable of read `.iges` format files (lines based geometry) or `.dat` format files from commercials FEM programs as *Ansys*.

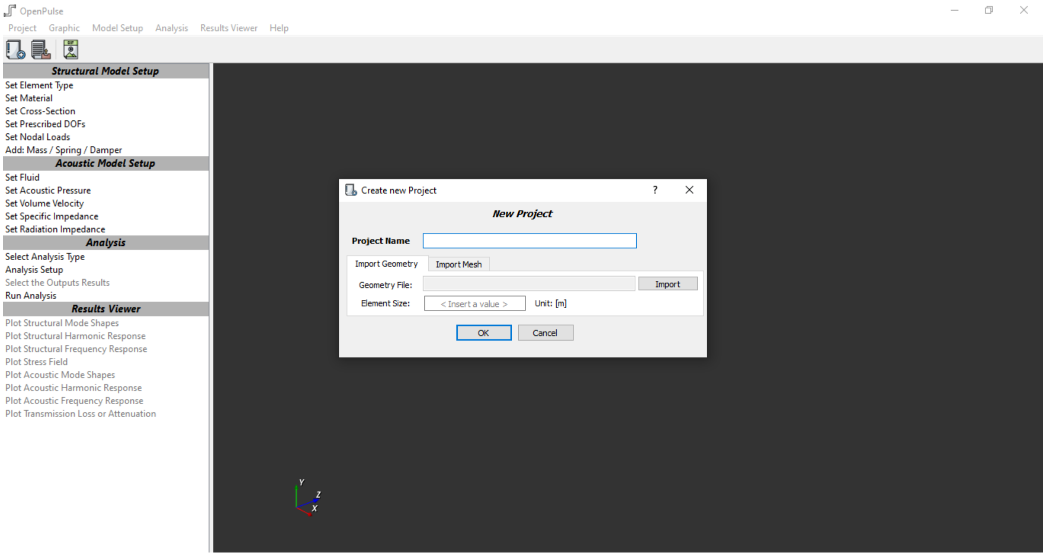


Figure 4: OpenPulses's interface: create project

Once the `.iges` geometry was imported, the element size (in meters) for discretization is required (in this case was used 0.01 m). The new project is created under the name indicated in the first field clicking on the `OK` button. The imported geometry will appear as is shown in Figure 5. Maintaining pressing the right mouse button is possible to rotate the geometry and moving the scroll mouse button up and down is possible to do zoom in and zoom out, respectively. Maintaining pressing the scroll button is possible to move the entire geometry inside the screen.

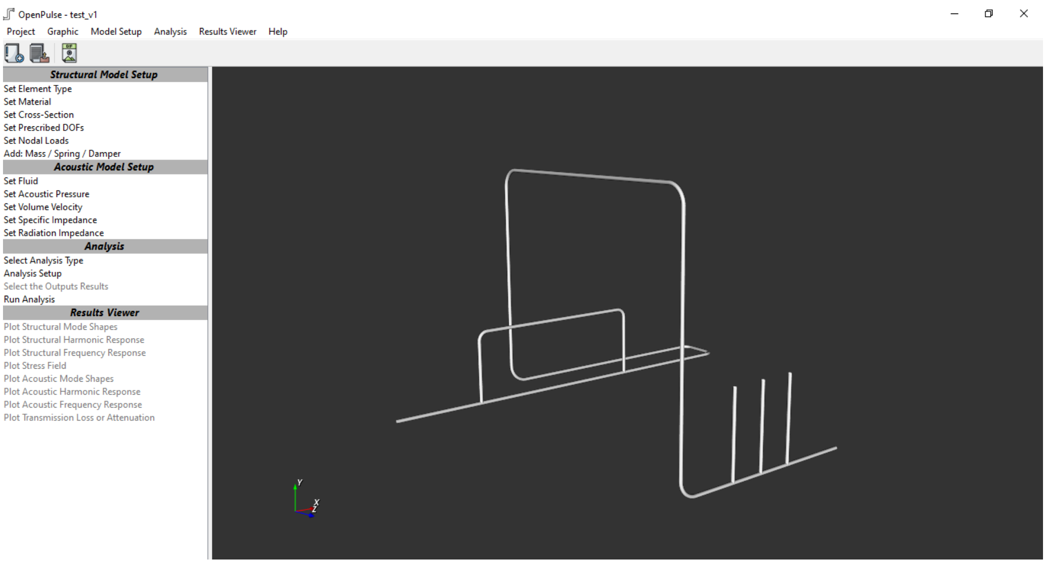


Figure 5: OpenPulses's interface: Imported geometry

4.3 Setting material and cross sections

In this version of OpenPulse the acoustic module is not totally independent of the structural module. For this reason, if the user wants to do only a structural analysis, two options of the

Structural model setup needs to be configured. These are, the material (Figure 6) and cross section options. These have direct influence on the acoustic analysis, the structural material is used to correct the speed of sound of a plane wave in a gas by the presence of rigid walls and the cross section options determine the volume of the acoustic fluid to analise.

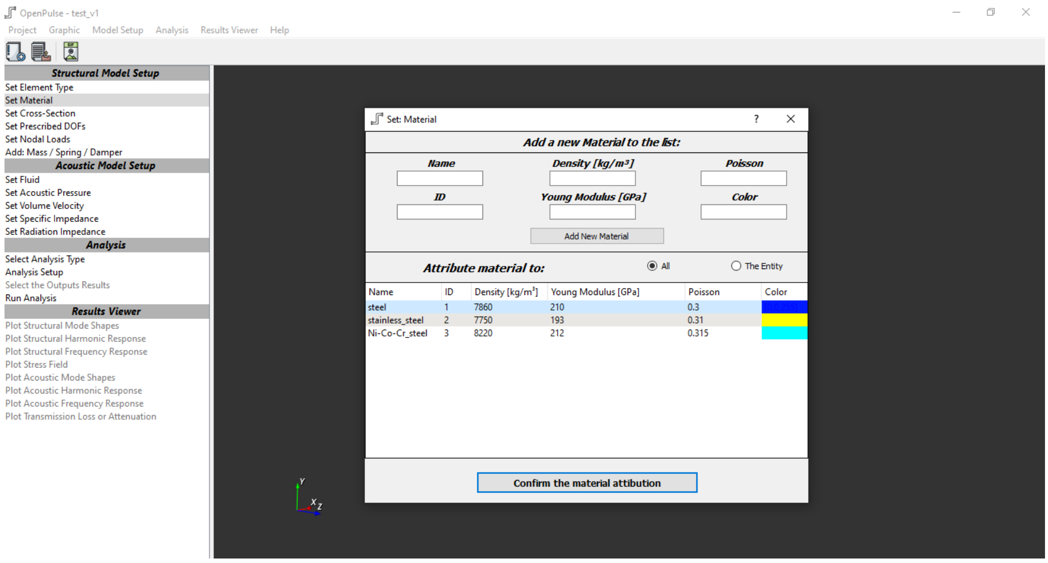


Figure 6: OpenPulses's interface: Configuration of structural material for all geometry elements.

For the example piping geometry an outer duct diameter of 0.05 m was set with a thickness of 0.008 m (Figure 7). It is possible to check if the cross section configuration was done successfully clicking on `Graphic > Entity with Cross-section`. This option allow us to see the elements with the configured cross section. Because this geometry has an expansion chamber, we need to set for this entity a different cross section. This is done clicking on the correspondent identity and setting again the element cross section as is shown in figures 8a and 8b. This process need to be repeated for each element that has a different main duct's cross section. Clicking again on the mouse's left button is possible to disable the selected entity.

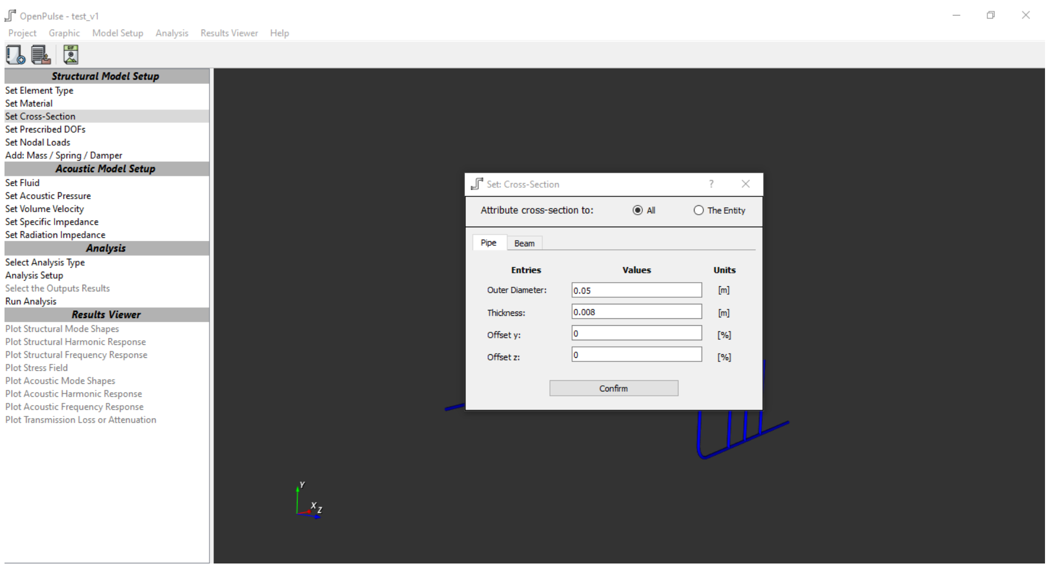
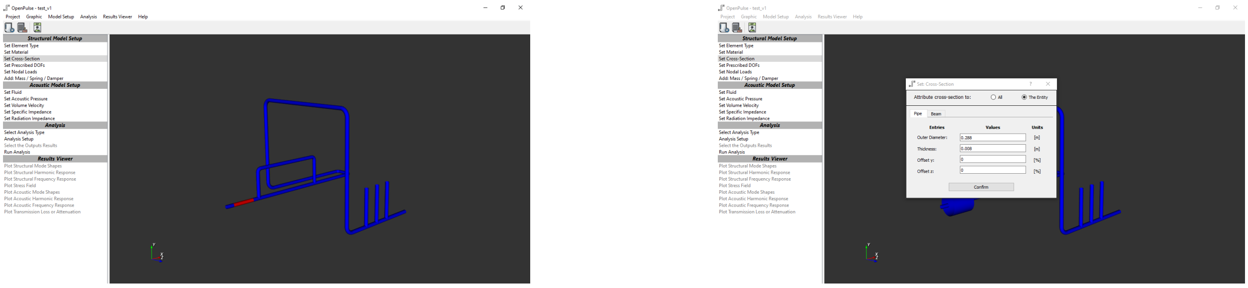


Figure 7: OpenPulses's interface: Cross section settings



(a) (b)

Figure 8: Selection of an entity (8a) and configuration of its cross-section (8b)

4.4 Acoustic Modal Setup

4.4.1 Acoustic fluid

Once the geometry is well defined, is time to set the fluid properties. For this, `Acoustic modal Setup > Set Fluid` as is shown in figure 9. In the Set Fluid windows is possible to select an in build fluid property or create a new one and apply to all the entities or just to one of them.

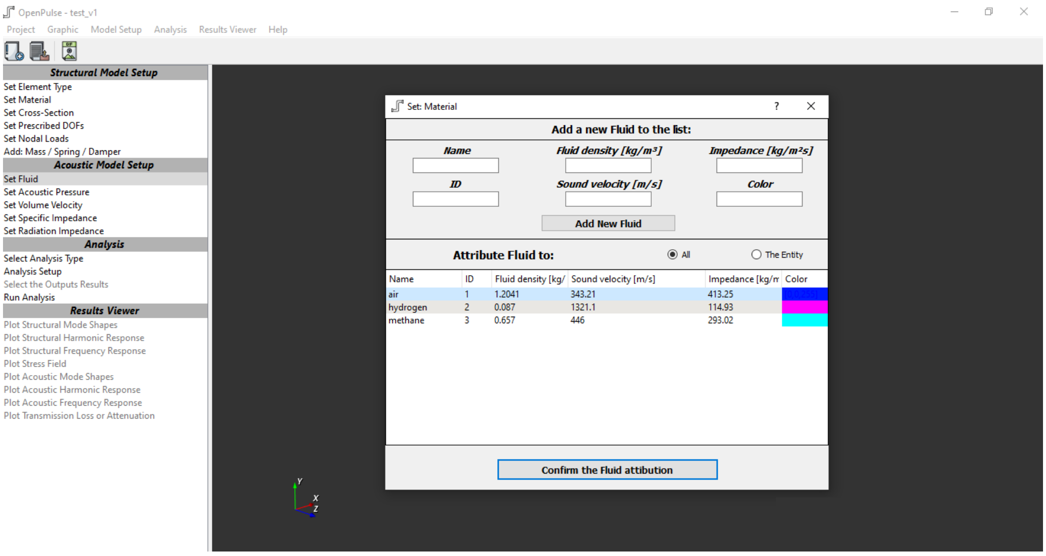


Figure 9: OpenPulses's interface: Set fluid

4.4.2 Boundary Conditions

In this version of Openpulse the available BC's are: pressure, volume velocity, specific impedance and specific radiation impedance. In the pressure boundary condition is possible to insert a table with a frequency dependant pressure excitation. In a near future this function will be available for the others BC's. As is shown in figure 11, the first element (Node ID: 10) was selected to set a constant 1 Pa pressure wave excitation. To select a desired element and also knows which is its `Node ID` value, is recommended to set the geometry's view as points `Graphics > Points` because the `Node ID` value will be displayed on the screen. As was done for the cross section of a particular entity, to set a pressure in a particular element first click on the point (element) desired an then click on the option `Set Acoustic Pressure` on the RHS tree option.

The same process needs to be done for the other BC's. In this example an anechoic impedance was set for the piping's out (Node ID: 1047) clicking on the `Set Specific Impedance` tree option. The default value for the air is 413 $kg/m^2\,s$. For more details on BC's see the Acoustic's module theory reference.

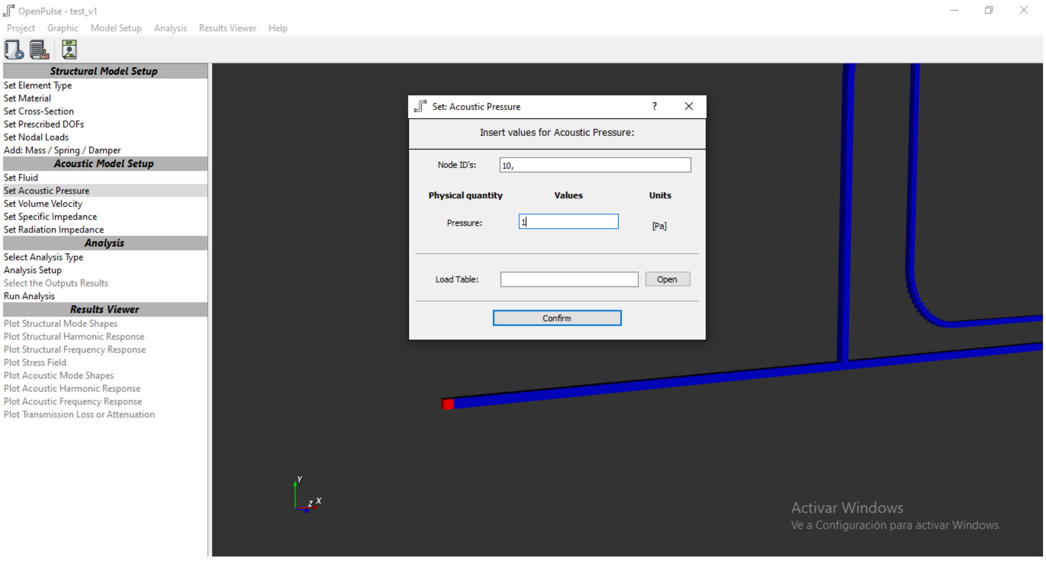


Figure 10: OpenPulses's interface: Set Acoustic Pressure

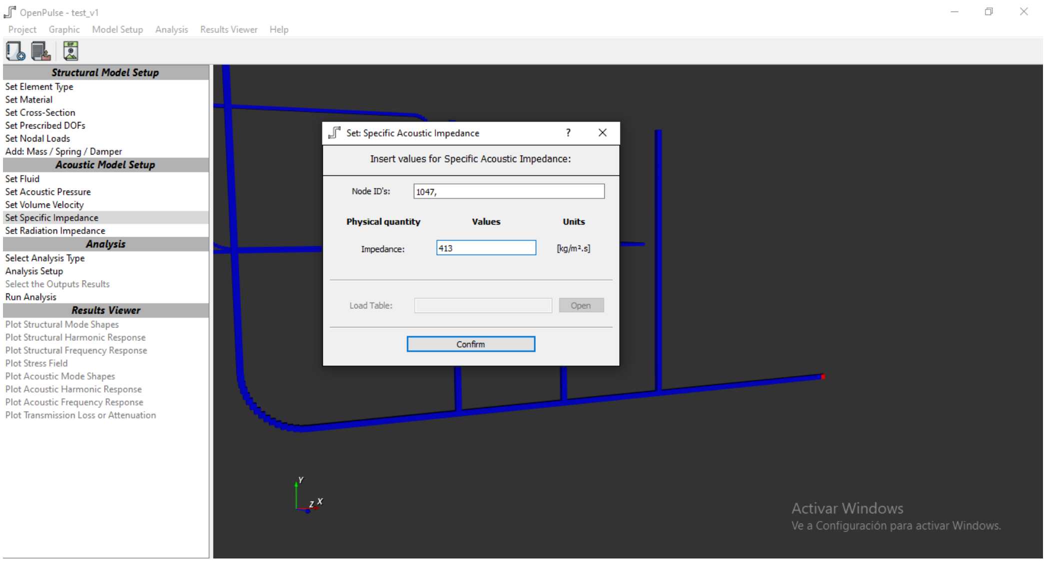


Figure 11: OpenPulses's interface: Set Specific Impedance

4.5 Analysis

After define the geometry and the BC's, the last step before see the results of the time-harmonic acoustic analysis, an analysis setup needs to be done. On the RHS `Analysis` tree option , the `Analysis Type > Harmonic Analysis - Acoustic > Analysis Type > Direct Method` was choice because FETM is conveniently solved, by nature, with a direct method (Figure 12).

After confirm the direct method as a preferred solution method, clicking on `Go to analysis setup` the user is lead automatically to the `Frequency setup`. The frequency range analysis for the current example was from 1 Hz to 250 Hz in steps of 1 Hz as shown in Figure 13.

After confirm the `Frequency setup`, got to `Run analysis` to finally solve the time-harmonic acoustic analysis. A solution finished advice will be displayed after certain time.

4.6 Results Viewer

The `Result Viewer` is enable after solve the analysis. The first of the three available plots is the `Acoustic Harmonic Response` which plots the pressure field distribution for a selected frequency as is shown in figure 14.

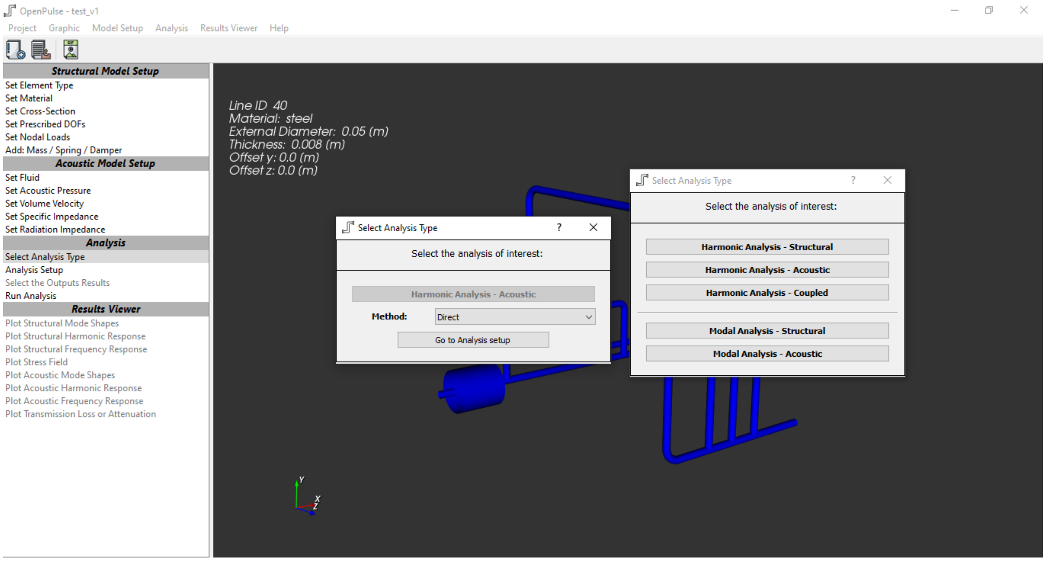


Figure 12: OpenPulses's interface: Select Analysis Type

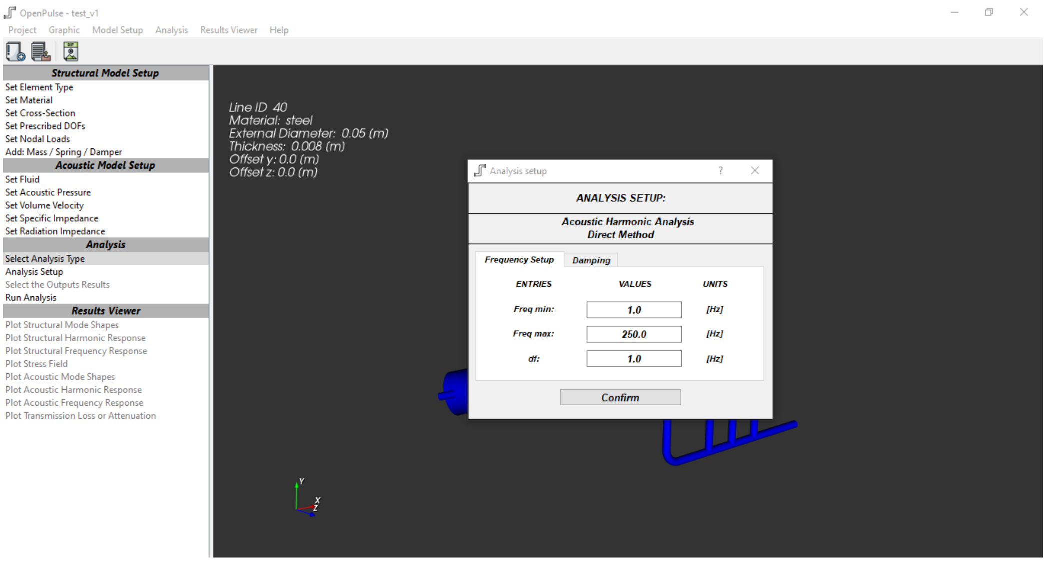


Figure 13: OpenPulses's interface: Select Analysis Type

The second available plot is the `Acoustic Frequency Response` which plots the value of pressure field for an specific location in the geometry (Node). The magnitude, real and imaginary part of pressure can be plotted introducing the desired `Node ID` as is shown in figure 15.

Also can be exported/imported the absolute or real and imaginary parts of the pressure field results for a certain Node `Node ID`. The import data needs to have an specific file pattern to import data successfully. This is, the columns needs to be separated with coma and the order of the data in the columns from left to right should be: frequency, real part of pressure, imaginary part of pressure and absolute value of pressure as is shown in figure 16a.

The pressure magnitude value showed in figure 16b is calculated as

$$SPL_Z = 20\, log_{10}(p_{RMS,node1047}/p_{ref}) \tag{22}$$

where $p_{RMS} = abs(p)/\sqrt{2}$ and $p_{ref} = 20 \times 10{-}6$.

The last available plot is the `Transmission Loss or Attenuation`, where both are intended for account the effects of acoustic filters but with a little difference in their conception. `Transmission Loss` is intended for acoustic filter which have the same input and output cross-section and its value is considered negative by default. On the other hand `Attenuation` is

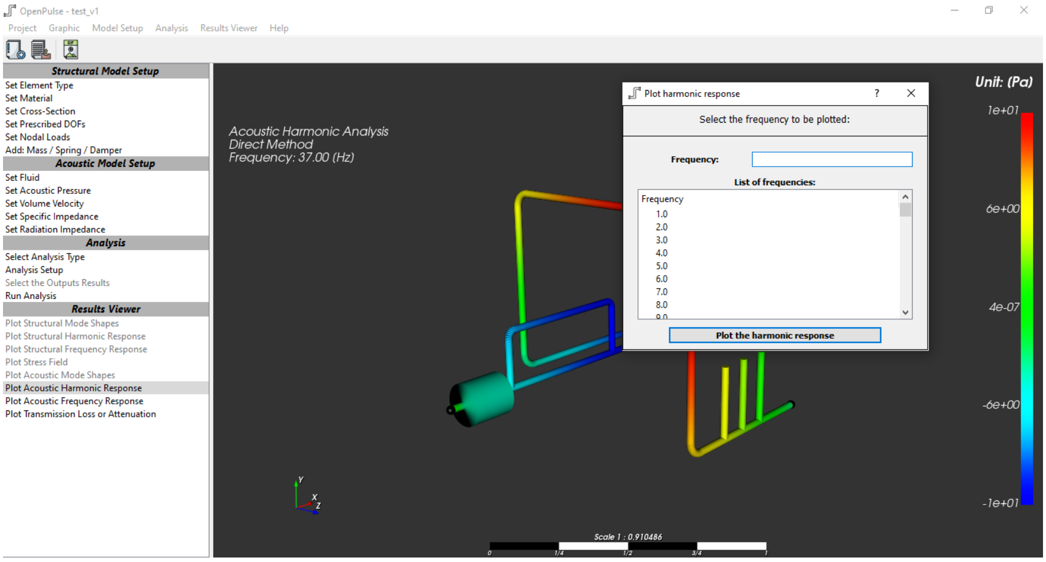


Figure 14: OpenPulses's interface: Plot Acoustic Harmonic Response

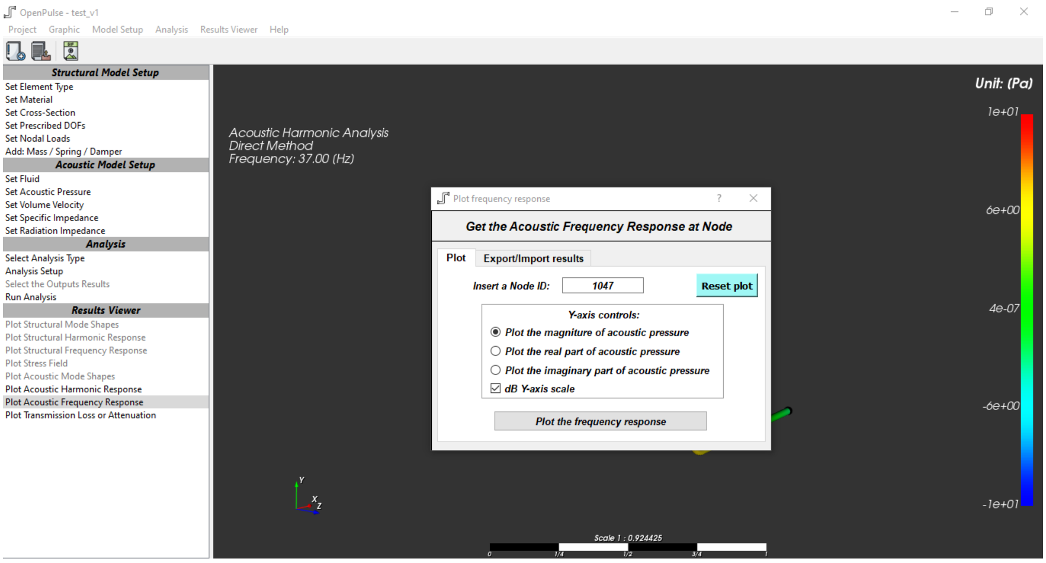


Figure 15: OpenPulses's interface: Plot Acoustic Frequency Response

intended for acoustic filters which have different input and output cross-section and its value is considered positive by default.

Into the `Plot Transmission Loss or Attenuation` tree option, was set as the `Input Node ID` the node 10 and as the `Output Node ID` the node 1047 (Figure 17).

The plot of the `Transmission Loss` for the current example (`Node ID`: 1047) is shown in figure 18b and is calculated as

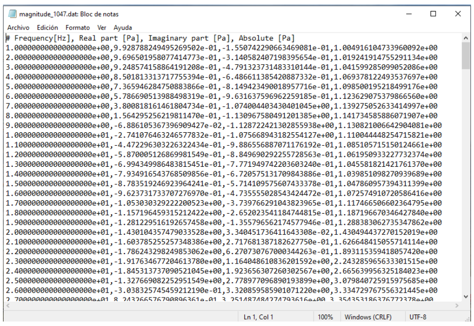
$$SPL_Z = -20\, log_{10}(p_{RMS,out} z_{f,in} / p_{RMS,in} z_{f,out}) \tag{23}$$

where $z_{f,in}$ and $z_{f,out}$ are the fluid specific impedances at the considered acoustic filter's input and output, respectively. On the other hand the `Attenuation` is calculated as

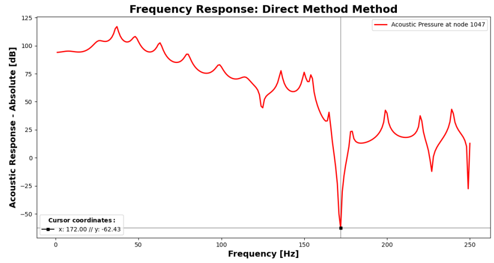
$$SPL_Z = 10\, log_{10}(W_{RMS,out} / W_{RMS,in}) \tag{24}$$

where $W_{RMS,out}$ and $W_{RMS,in}$ are the transmitted RMS power at the considered output of the filter and the incident RMS power at the considered input of the acoustic filter, respectively.

The TL/Attenuation plot also has the export/import option of the plotted data. As was described in the `Acoustic Frequency Response` plot the import data needs to have an specific



(a)



(b)

Figure 16: OpenPulses's interface: view of a .dat file generated by the export function in OpenPulse (16a) and the magnitude frequency response plot at Node ID 1047 (16b)

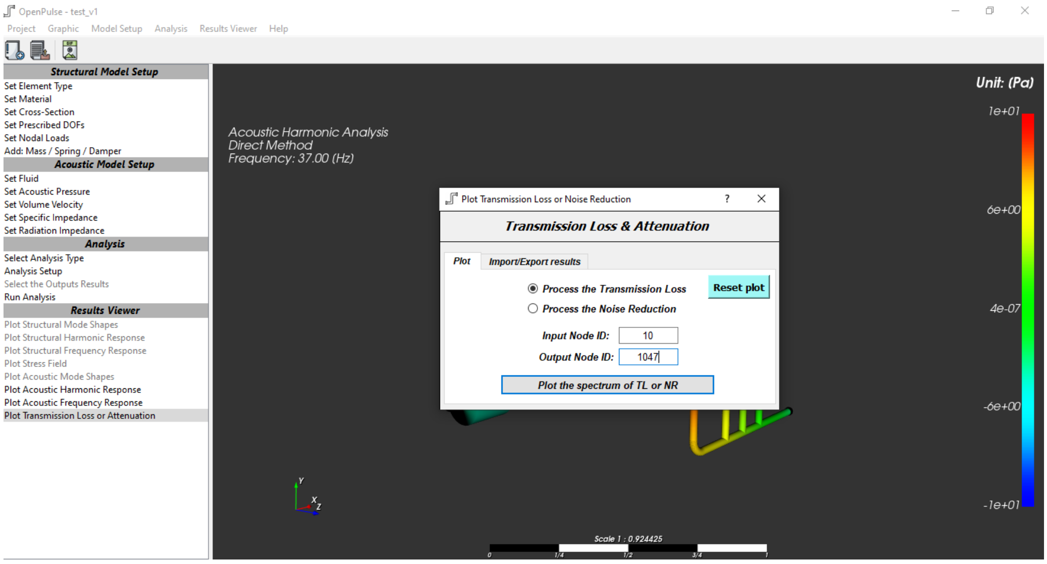
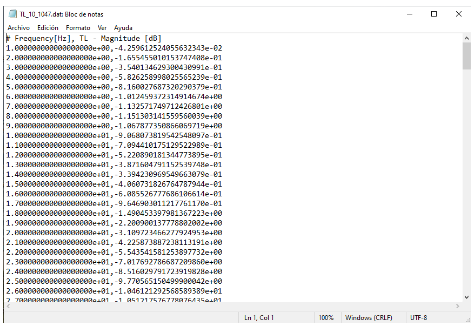
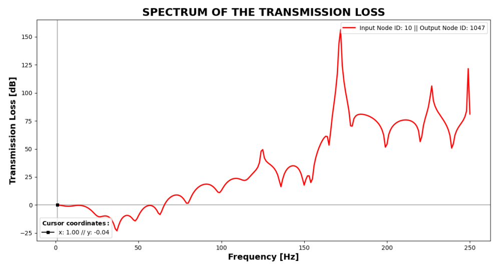


Figure 17: OpenPulses's interface: TL/Attenuation Plot



(a)



(b)

Figure 18: OpenPulses's interface: view of a .dat file generated by the export function in OpenPulse (18a) and the TL plot at Node ID Output 1047 and input 10 (18b)

file pattern to import data successfully. This is, the columns needs to be separated with coma and the order of the data in the columns from left to right should be: frequency and TL/attenuation data as is shown in figure 18a.

5 Nomenclature

- TMM = Transfer matrix method
- MMM = Mobility matrix method
- SMM = Stifness matrix method
- TM = Transfer matrix
- MM = Mobility matrix
- SM = Stiffness matrix
- BC = Boundary condition
- TL = Transmission loss
- BC's = Boundary conditions
- FEM = Finite element method
- FETM = Finite element transfer method
- AIV = Acoustic-induced vibration
- FIV = Flow-induced vibration
- FIVN = Flow-induced noise and vibration
- LHS = Left hand side
- RHS = right hand side
- DOF = degree of freedom
- DOF's = degrees of freedom
- 1D = one-dimensional
- 2D = two-dimensional
- 3D = three-dimensional
- J_0 = first kind Bessel function of order 0
- J_1 = first kind Bessel function of order 1
- H_1 = Struve function of order 1
- p = nodal pressure, Pa
- q = inner nodal volume velocity, m^3/s
- u = particle velocity , m/s
- c = speed of sound, m/s
- $f = \omega/2\pi$ = frequency, Hz

- S = internal area of the pipe's cross section, m^2
- r = pipe radius, m
- z = specific acoustic impedance, Pas/m
- z_r = specific acoustic radiation impedance, Pas/m
- Z = acoustic impedance, Pas/m^3
- Z_r = acoustic radiation impedance, Pas/m^3
- Z_m = mechanical impedance, Ns/m

5.1 Greek Symbols

- ρ = density, kg/m^3
- ω = rotational frequency, rad/s
- δ = end correction function, dimensionless

5.2 Subscripts

- A = related to acoustic
- 0 = related to air medium properties
- e = related to elemental
- f = related to fluid
- i = related to inner
- o = related to outer
- n= related to index of elements ($n = 1, 2, \ldots, N$)
- j= related to index of nodes ($j = 1, 2, \ldots, J$)
- ij= related to matrix entries index ($i, j = 1, 2, \ldots, I, J$)

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