I. Introduction and Background

There are two standards for the measurement of acoustical properties of materials: ASTM E1050 and ISO 10534-2. Both serve to describe what has come to be known as the “two-microphone” or “transfer-function” method of measuring absorption and impedance of acoustical materials.

In the transfer function method, a sample of the material that is going to be tested is placed inside a straight tube. A rigid plunger is placed behind the sample and serves as a reflecting surface. Then a sound source is connected at the opposite end of the tube to produce a sound in a range of frequencies. A pair of microphones is mounted with the inner wall of the tube and near the sample end of the tube[1]. All of this is shown in Fig. 1.

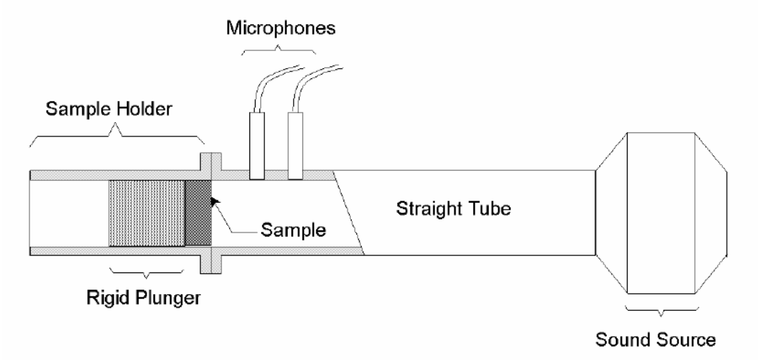

Figure 1 The Transfer-Function method

A multi-channel spectrum analyzer is used to obtain the transfer function H_{12} (frequency vs response function) between the microphones. This transfer function is defined by the complex ratio of the sound pressure measured by microphone 1 and microphone 2. The transfer function is then calculated[2]:

$$H_{12} = \frac{p_1}{p_2} \tag{1}$$

In this measurement, the microphone closer to the source is the referenced as microphone 1. From the transfer function *H12*, the pressure reflection coefficient *R* of the material is determined from the following equation:

$$R = \frac{H_{12} - e^{-jks}}{e^{jks} - H_{12}} e^{j2k(L+s)} \tag{2}$$

, where *L* is the distance from the material being measured to the first microphone and *s* is the distance between the microphones, $k = 2\pi f/c$, *f* is the frequency, and *c* is the speed of sound in the medium. From the reflection coefficient, the absorption coefficient α can be determined by the following equation:

$$\alpha = 1 - |R|^2 \tag{3}$$

For this report a model of an Impedance tube in Actran for the calculation of the absorption coefficient of a material was simulated. The original model was developed by Qiming Guan for a master’s thesis[3]. The purpose of this report is to test the replicability of such model.

II. Preprocessing of Impedance Tube Model in Actran

The first part for the modeling of the Impedance tube in Actran is defining the boundary conditions for the finite element model. The area surrounded of the wall of the tube is the first region of the model and is isolated from the outside environment. Therefore, this area is enclosed by four boundary conditions at the simulation. The dimensions of the impedance tube which was simulated by the original authors has a length LL=2.5ft≈0.762m, inner diameter dd=1.25inch≈0.032m. The first region (grey area in Fig.2) is a cylinder with height LL and diameter dd and filled up by a certain acoustic medium inside. The thickness of the test sample is =1 inch≈0.025m . The second region (green area in Fig.2) is also a cylinder with same diameter dd but it is filled with a porous absorption material.

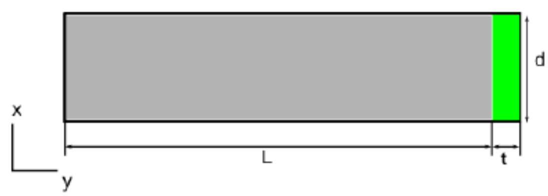

Figure 2 Sketch of the regions analyzed

We can see in Fig.2 the complete model of the kundt tube. These two cylinder will be merged into one cylindrical region which is axisymmetric. Then, the whole 3-D merged region can be simplified to a 2-D region rotated around its axis of symmetry, as shown in Fig.3 In other words, the axis symmetry of the problem allows it to be analyzed as a simplified 2/D region. With this. A 3-D finite element modeling converts into a 2-D finite element modeling.

Figure 3 Sketch of the 2-D simplified Regions

After determining the regions that are going to be analyzed, the next step is creating the mesh for the regions. In the original paper, the two regions are partitioned using quadratic elements. They recommend that at least 4 quadratic elements per wavelength are used so that the fluctuation of the sound wave can be captured in the acoustic region[3]. The first region has the acoustic medium will receive a noise that ranges from 0Hz to 5000Hz generated by a loudspeaker in the physical tube. Thus, the maximum frequency is f_{max} = 5000 Hz. Considering the relationship between wave speed and wavelength:

$$c = \lambda f, \tag{4}$$

where c is the sound speed in acoustic medium, so the minimum wavelength can be obtained as:

$$\lambda_{min} = \frac{c}{f_{max}} \tag{5}$$

Thus, the largest element length in the mesh is:

$$L_{max} = \frac{\lambda_{min}}{4} = \frac{c}{4 \times f_{max}} \tag{6}$$

If we assume that the acoustic medium in the model is air, c=340m/s, which is the sound speed in air, plugging that together with f_{max} = 5000 Hz into the previous equation:

$$L_{max} = 0.017\ m \tag{7}$$

Based on the dimensions of the author's impedance tube, they take $\triangle xx$=$\triangle yy$=0.008m in first region filled by acoustic medium. Similarly based on dimension of the test sample, they take $\triangle xx$=0.008m △y=0.004m, both satisfy L_{max}, hence there are 2×95.25=195.5 elements in first region and 2×6.25=12.5 elements in second region. Taking into account all of these values along with the dimensions of the regions (L≈0.762m, d/2≈0.016m, t≈0.025m), the meshing in ACTRAN Student Edition is shown in Fig.4.

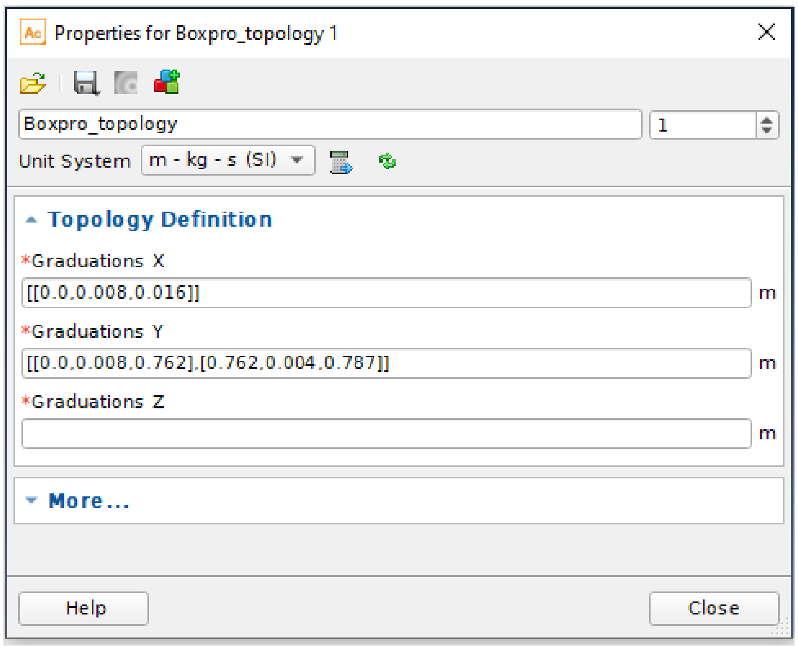

Figure 4 meshing two regions in ACTRAN Student Edition

After finish meshing the regions, we have to add a new domain that represents the air in tube. We can see in Fig.5 the two-dimensional new domain has been named as "Air", whose interpolation has been set as quadratic. Its range in *x* coordinate (vertical) is from 0m to 0.016m, and in *y* coordinate (horizontal) it ranges from 0m to 0.762m. These dimensions are defined in an pop-up window in Actran Student Edition using the button "Edit regions", as shown in Fig.6. The dimensions are according to those of region 1.

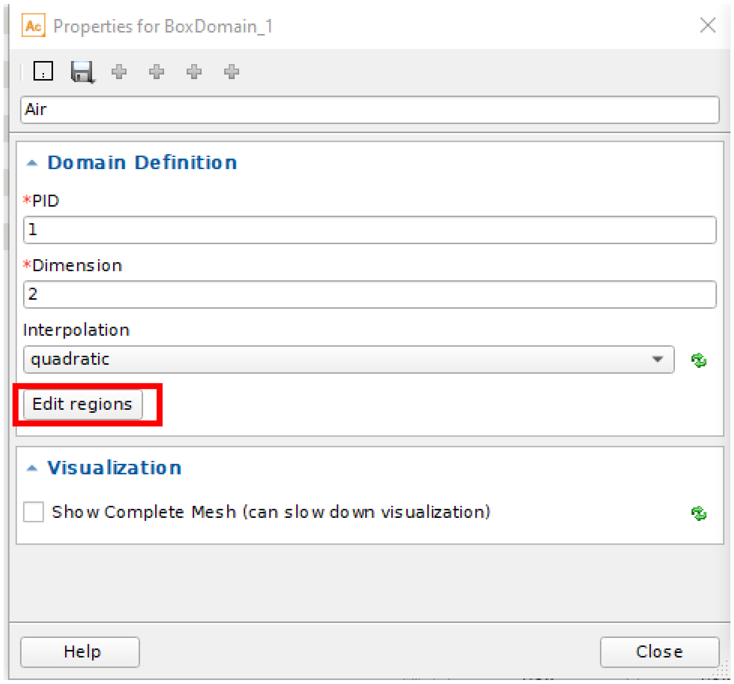

Figure 5 Add and fill the properties of a new domain named "Air" for the air

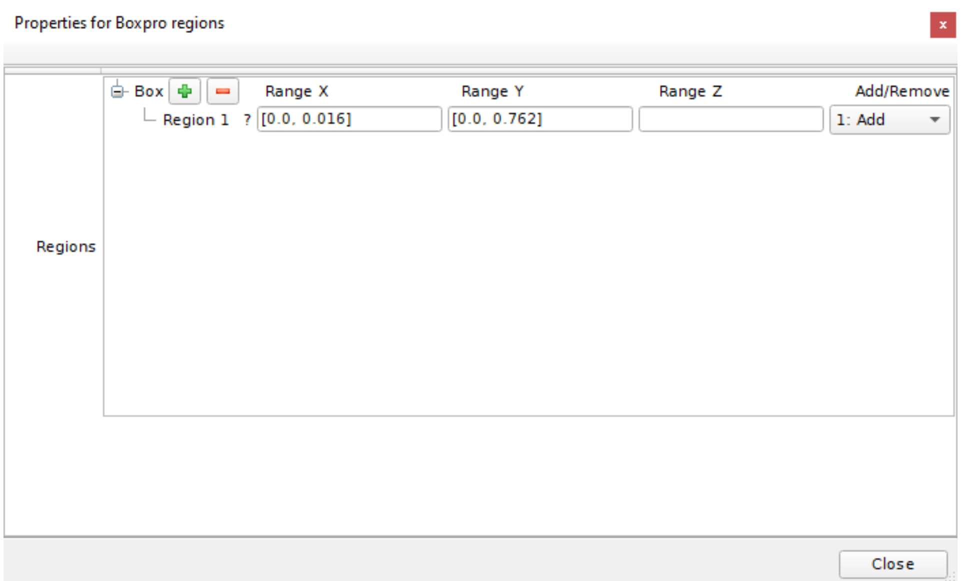

Figure 6 Add and fill the properties of a new domain named "Air"

After adding the air domain, the next step is to add a new domain which will represent the porous absorption material located at one end of tube. In Fig.7 , the two dimensional new domain has been named as "porous absorption material" and its interpolation is also set as quadratic, the range of this domain in *x* coordinate (vertical), which is the same as the air domain, is from 0m to 0.016m, and in *y* coordinate (horizontal) it ranges from 0.762m to 0.787m, as shown in Fig.8.

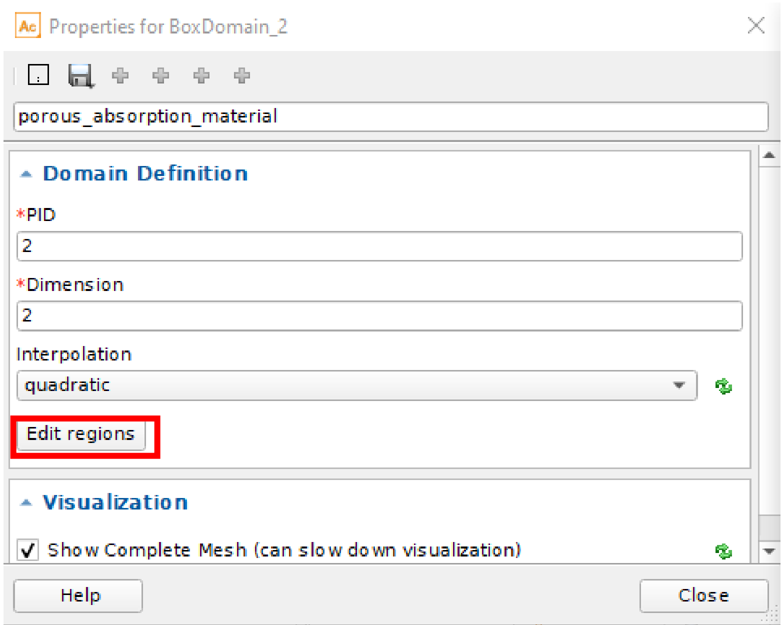

Figure 7 Add and fill the properties of a new domain named "porous absorption material" for the porous absorption material

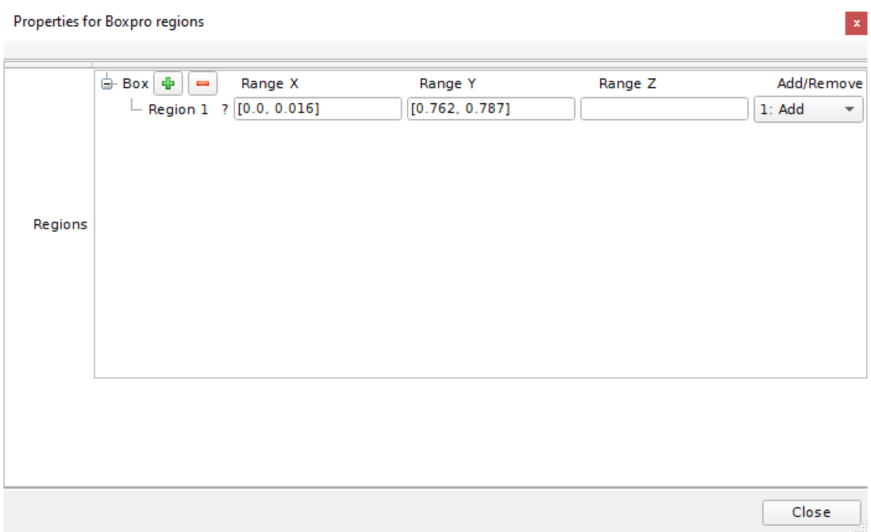

Figure 8 Add and fill the properties of a new domain named "porous absorption material" for the porous absorption material

Finally, we need to add one boundary condition at the other end of tube. Defining a new domain, we will represent represents the velocity boundary excitation applied at the other end of tube. In Fig.9, the one dimensional new domain is named "Boundary Excitation" and its interpolation has also been set as quadratic, the range of this domain in *x* coordinate (vertical), which is the same as the air domain and domain of porous absorption material, is from 0 m to 0.016 m, and in *y* coordinate (horizontal) it locates at 0 m, as shown in Fig.10. Therefore, we set its dimension equal to 1 in the parameters.

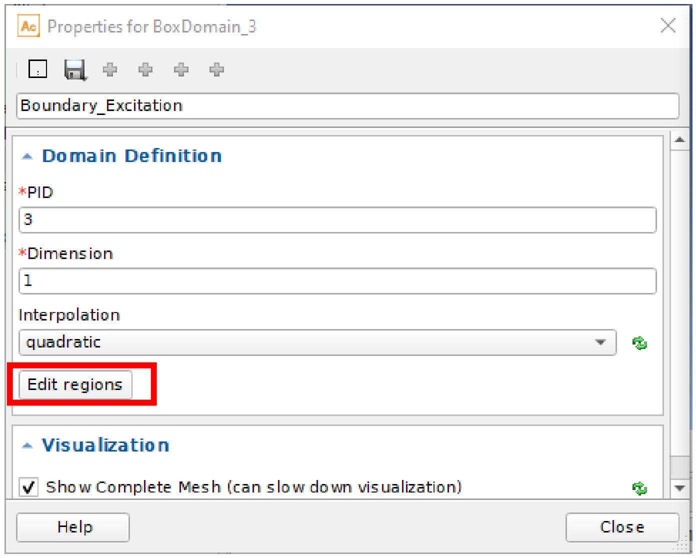

Figure 9 Add and fill the properties of a new domain named "Boundary Excitation" for the boundary excitation

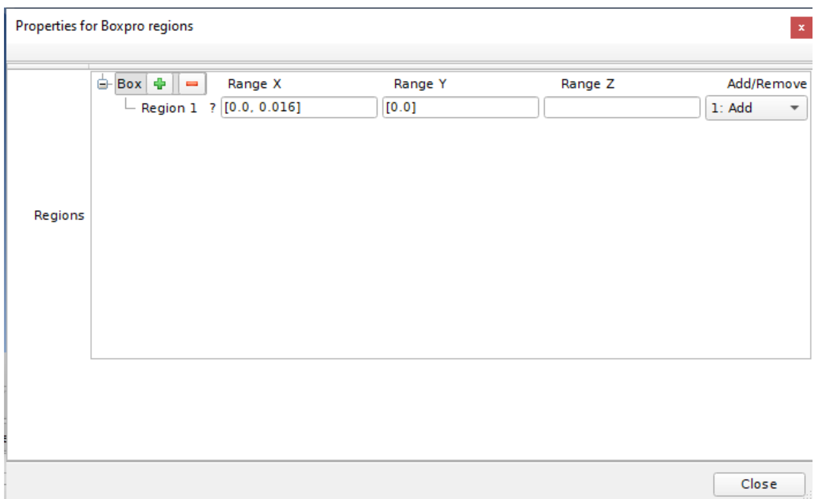

Figure 10 Add and fill the properties of a new domain named "Boundary Excitation" for the boundary excitation

In Fig.11, we can see the different regions already defined for our model.

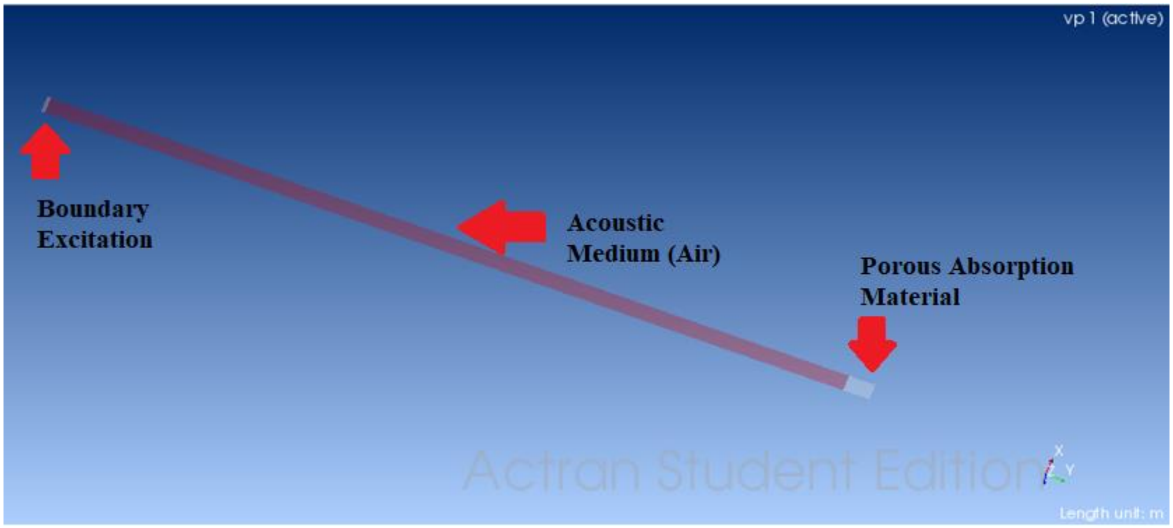

Figure 11 Regions defined for the analysis

To generate plane wave in tube, the original authors of the article state that the highest frequency must satisfy that:

$$f_{max} \approx \frac{101}{r} \tag{8}$$

, where r is the radius of the tube. Considering that the diameter of the tube that is being modeled is d = 1.25 in = 0.031 m, the maximum frequency can be calculated with the previous equation:

$$f_{max} \approx 6516\ Hz \tag{9}$$

However, the loudspeaker of the modeled impedance tube can only reach a frequency of 5000 Hz. Thus, the range of frequency defined in Actran goes from 20 Hz to 5000Hz with 1Hz step[1]. For the reason that ACTRAN model is 2-Dimensional axisymmetric model, the axisymmetry order must be set to 0, which specifies a constant solution with varied azimuthal angle in the tube. All of this is shown in Fig. 12.

[1] In different versions of Actran, sometimes is necessary to define the frequencies to output map results, which in this they will just have to the same values we already defined for the frequency response.

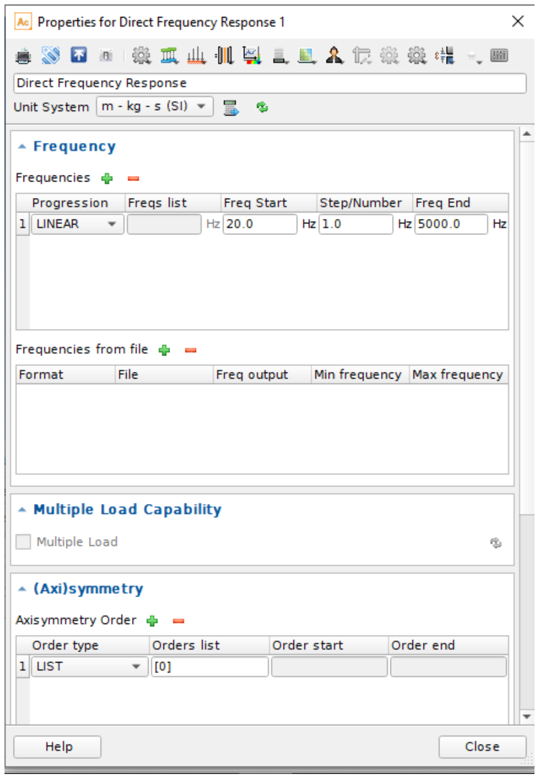

Figure 12 Specify the frequency range and define the axisymmetric order

Next, we add a finite fluid component and name it "Acoustic", which is shown in Fig.13.

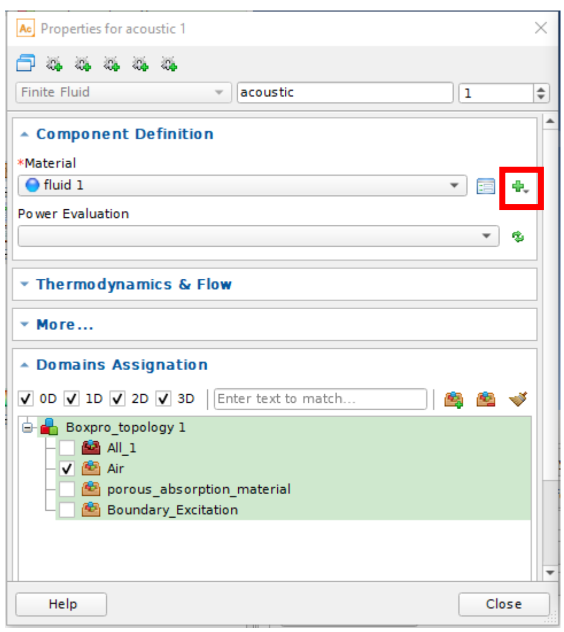

Figure 13 Add a finite fluid component named "Acoustic"

Then we set up the fluid material using the plus button at the right side of the "Material section". We name this fluid "Air", the standard properties of air, which are sound speed and fluid density, need to be specified as 340 m/s and 1.225 kg/$mm3$ respectively. Also, with the scope selector, the Air domain is assigned to the Acoustic component, which is shown in Fig.14.

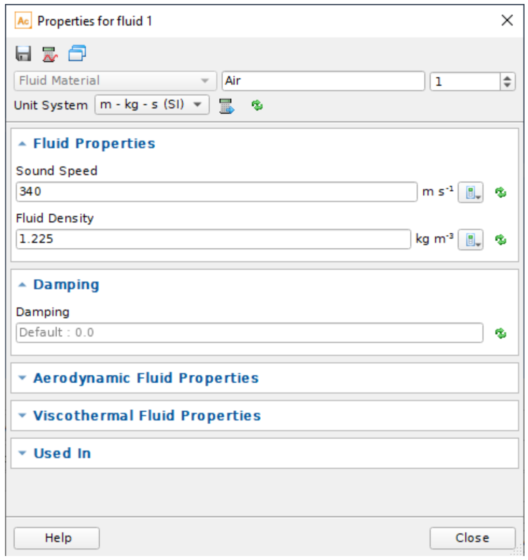

Figure 14 Create a new fluid material named "Air" and specify standard properties of Air

In the next step, we add a porous rigid component and name it "porous material", then we specify the power evaluation to "1" to activate the computation of the dissipated power, which is shown in Fig.15. This power evaluation is not fully explained in the original paper.

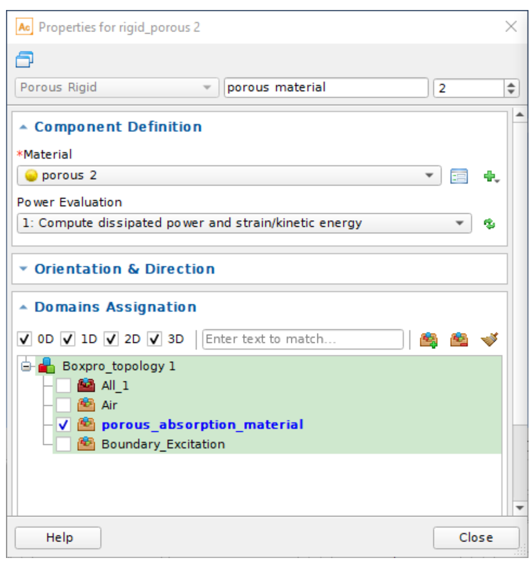

Figure 15 Add a porous rigid component named "porous material"

Then we set up the porous material and name it "Foam", the properties of foam, which are porosity, flow resistivity, tortuosity, viscous length and thermal length, are specified as 0.94, 10000 N.s/$mm4$, 1.06, 3e−5 m and 8e−5 m respectively, which is shown in Fig.16. Since the focus of this report is not the corroboration of this Actran model, but the simple replication of it, the values assigned for the foam are not explained in this report.

In Fig.16, with the scope selector, the porous absorption material domain is assigned to the porous material component.

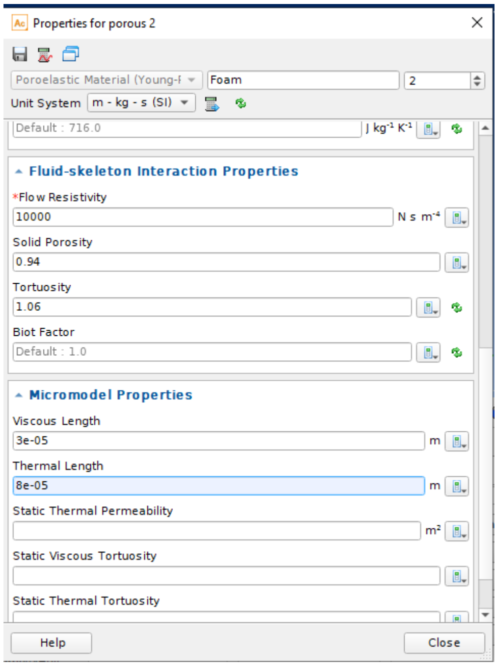

Figure 16 Create a new porous material named "Foam" and specify acoustic parameters of Foam

Next, we create a new velocity boundary condition and name it "Velocity", which is also called boundary excitation. The value of this boundary condition can be specified as 1m/s and the direction is along the Y direction, which is shown in Fig.17 and with the scope selector, the porous absorption material domain is assigned to the Velocity component.

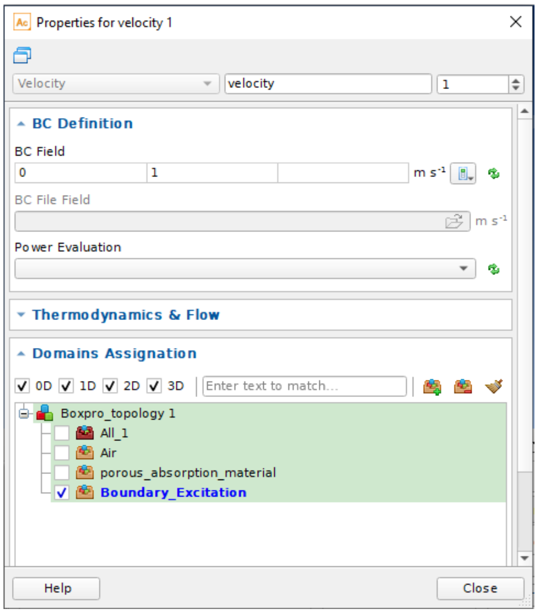

Figure 17 Specify the value of the boundary condition and assign the velocity boundary condition to "Boundary Excitation" domain

The next step is to define the solver of the analysis, the Mumps is selected as the solver, which is shown in Fig.18.

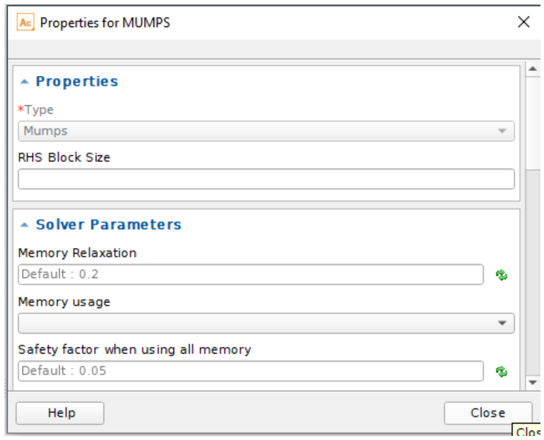

Figure 18 Define the solver of the analysis as MUMPS solver

Once the solver is specified, we need to create the field points in finite element model which represent the microphones in real impedance tube, the positions of three microphones in the air domain which is shown in Fig.19. . It is important to mention that the three microphones are only to use to completely model the impedance tube of the original authors. However, a two-microphone impedance tube can also be modeled since the transfer function will be modeled using the sound pressure of two microphones at the same time.

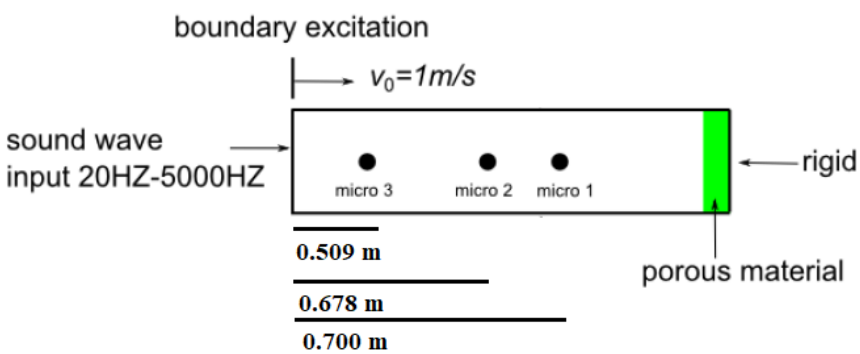

Figure 19 Sketch of positions of three field points which represent three microphones in real impedance tube.

By transferring inch into meter, the coordinates of microphone 1, 2, 3 can be determined and entered as[0.008,0.700,0],[0.008,0.678,0], [0.008,0.509,0] respectively, which is shown in Fig.20, the three red points indicate three microphones.

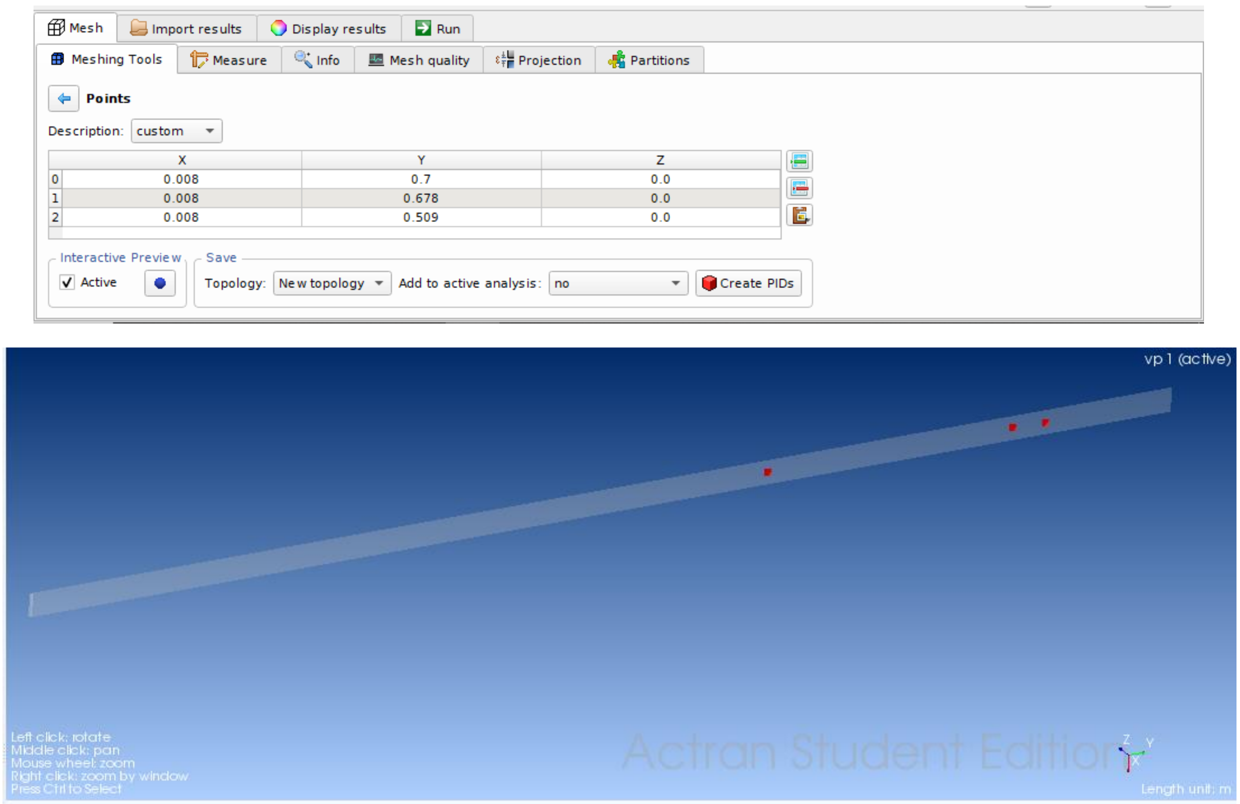

Figure 20 Create three field points in air domain of finite element model.

After finishing the pre-processing, the next step is to export the analysis file and launch the computation in ACTRAN.

The analysis is exported in the EDAT Actran input file. We have to right click on the *Direct Frequency Response*, and choose *Export analysis (EDAT format)*.

The topology was created with BOXPRO. However, the analysis may be exported in two different formats: the first one is the *BOXPRO* format, in which the mesh is written in the EDAT file the same way as in the topology definition. Nodes coordinates and elements are created at the beginning of the analysis. On the other hand, we have the *ACTRAN* format, in which the mesh is written in the EDAT file. For this instance, we select the BOXPRO as the output format.

To finish the preprocessing part, we need to launch the computation. First, we open the FFT Launcher by right clicking on the EDAT input file and select Launch with ACTRAN. Then, we click in on the green arrow to run the computation as shown in Fig.21. After finishing the computation, a PLT file will be generated in the assigned location.

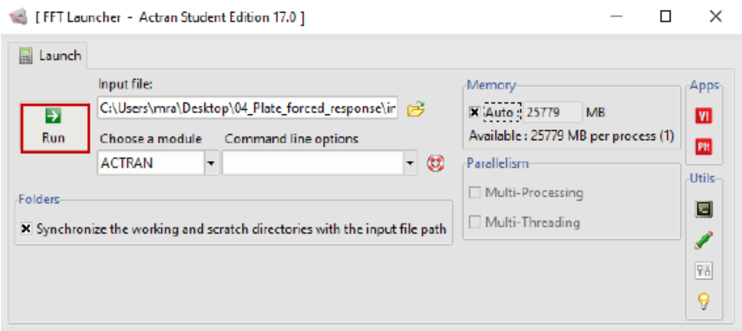

Figure 21 Run the EDAT input file in the Actran Launcher.

III. Postprocessing of Impedance Tube Model in Actran

In the post-processing section, the primary purpose is to obtain the sound pressure values detected by three field points. These three field points represent the three microphones in real impedance tube. To achive this, we first need to import the previously generated PLT file to the PLTviewer. PLTViewer is the dedicated post-processing utility to visualize FRF's from Actran (stored in the PLT file) or from measurements. Then we can plot the graphs of sound pressure values of three microphones (dB) vs. frequencies from 20 Hz to 5000Hz, as shown in Fig.22.

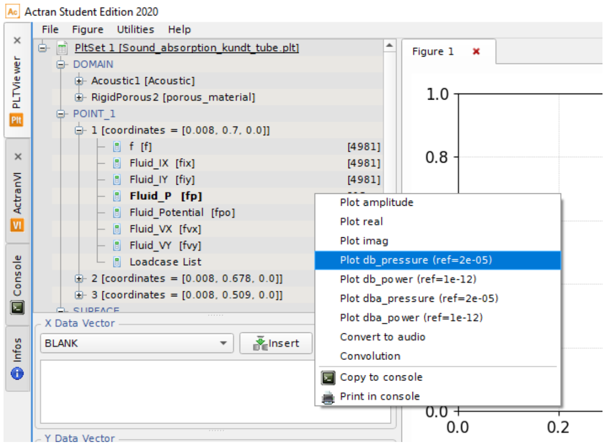

Figure 22 Plotting dB pressure of Microphone 1

The pressure values that we plot in the Figure window at PLTviewer can be exported as a txt format using the *Export Tool*, as shown in Fig.23.

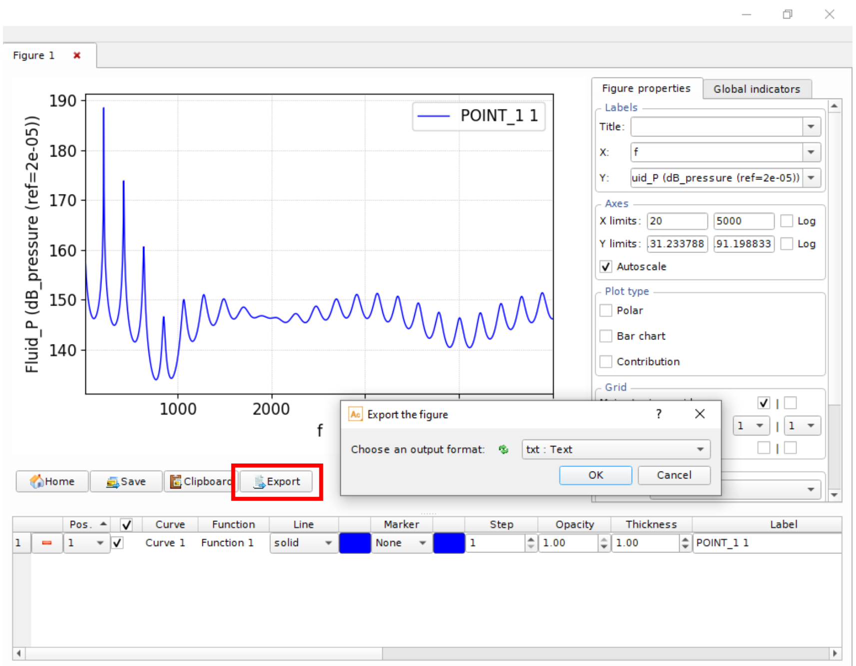

Figure 23 Exporting dB pressure as a txt file

We first export the dB pressure of each field point so that they can be plotted using Matlab. The code that we use for plotting dB pressure vs. frequency is in Appendix A. The sound pressure values of the three microphones (dB) vs. frequencies from 20 Hz to 5000Hz are shown in Fig.24, Fig.25 and Fig.26 , respectively.

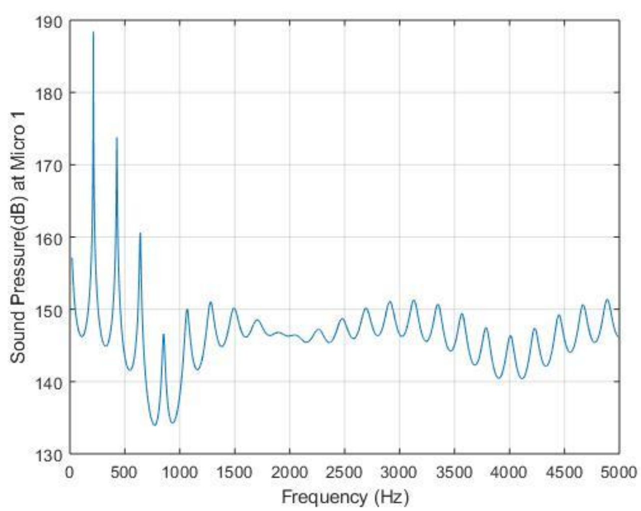

Figure 24 Sound Pressure (dB) vs. Frequencies (20 Hz to 5000Hz) measured at Micro 1 (reference pressure is 2e-05Pa)

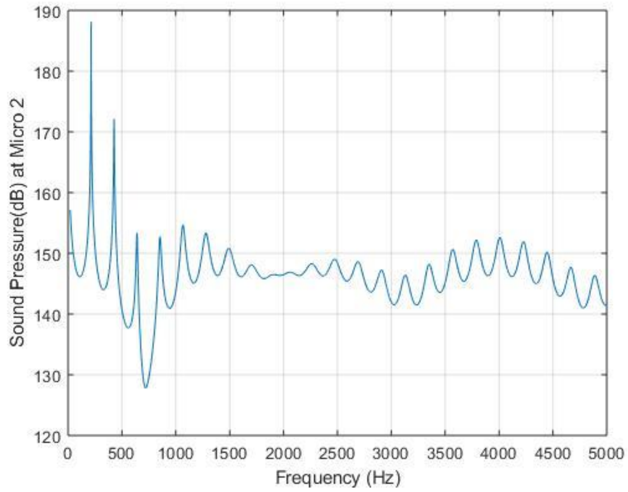

Figure 25 Sound Pressure (dB) vs. Frequencies (20 Hz to 5000Hz) measured at Micro 2 (reference pressure is 2e-05Pa)

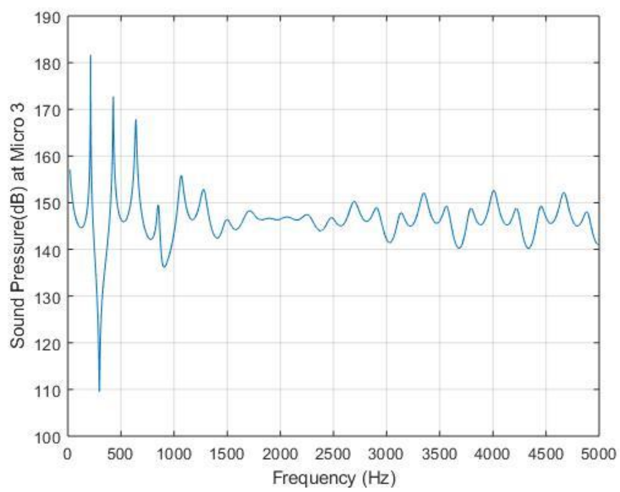

Figure 26 Sound Pressure (dB) vs. Frequencies (20 Hz to 5000Hz) measured at Micro 3 (reference pressure is 2e-05Pa)

In order to calculate the Transfer Function and thereby the absorption coefficient of the material, we need the values of the real and imaginary part of sound pressure (Pa) vs. frequencies (Hz) of each microphone, which can also be obtained and exported as a txt format. Fig.27 shows how the real and imaginary part of a single field point is plotted and then exported as txt file.

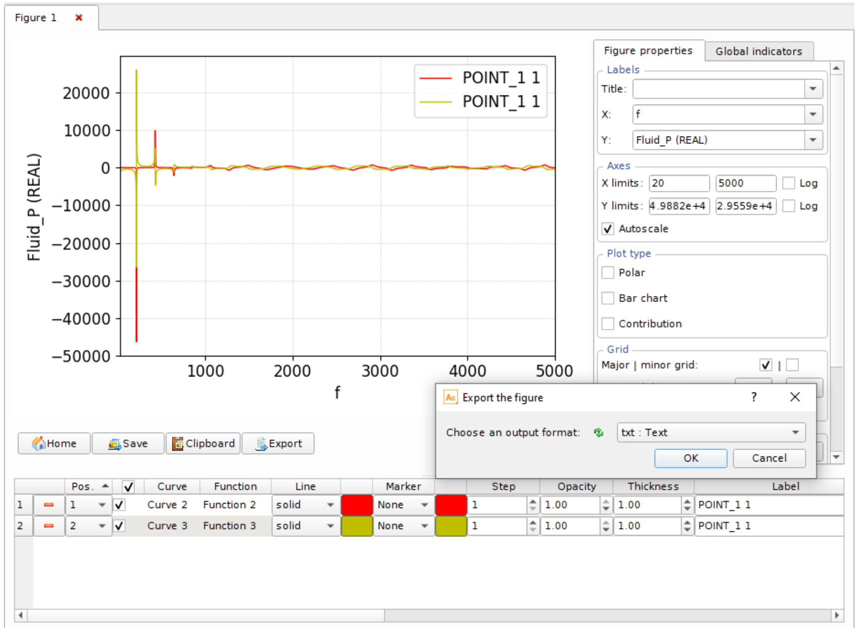

Figure 27 Exporting complex dB pressure as a txt file

Fig.28 is an example of data files obtained, which is the real and imaginary part of sound pressure vs. frequencies (Hz) measured by microphone 1. Similarly, the real and imaginary part of sound pressure (Pa) vs. frequencies (Hz) at Micro 2 and Micro 3 can be obtained in the same way. The data file are imported into MATLAB to do the further calculation and analysis.

# "freq"	"POINT_1 1"	"POINT_1 1"
2.0000000000000e+01	2.3189237960507e-01	-1.4374528359503e+03
2.1000000000000e+01	2.3181018393592e-01	-1.3709477118322e+03
2.2000000000000e+01	2.3172231805505e-01	-1.3105831552397e+03
2.3000000000000e+01	2.3162853468296e-01	-1.2555587927472e+03
2.4000000000000e+01	2.3152857175927e-01	-1.2052076750240e+03
2.5000000000000e+01	2.3142215456878e-01	-1.1589695918919e+03
2.6000000000000e+01	2.3130899106739e-01	-1.1163705466567e+03
2.7000000000000e+01	2.3118877618567e-01	-1.0770067903748e+03
2.8000000000000e+01	2.3106118839507e-01	-1.0405322782497e+03
2.9000000000000e+01	2.3092588998453e-01	-1.0066487212348e+03
3.0000000000000e+01	2.3078252725738e-01	-9.7509762693309e+02
3.1000000000000e+01	2.3063072903580e-01	-9.4565388139169e+02
3.2000000000000e+01	2.3047010690126e-01	-9.1812053398367e+02
3.3000000000000e+01	2.3030025374600e-01	-8.9232453075565e+02
3.4000000000000e+01	2.3012074482915e-01	-8.6811320070616e+02
3.5000000000000e+01	2.2993113473019e-01	-8.4535134431226e+02
3.6000000000000e+01	2.2973095948673e-01	-8.2391880739615e+02
3.7000000000000e+01	2.2951973320508e-01	-8.0370844853731e+02
3.8000000000000e+01	2.2929694931435e-01	-7.8462442718752e+02
3.9000000000000e+01	2.2906207893361e-01	-7.6658075545699e+02
4.0000000000000e+01	2.2881457033687e-01	-7.4950006696520e+02
4.1000000000000e+01	2.2855384759265e-01	-7.3331256592817e+02
4.2000000000000e+01	2.2827931056451e-01	-7.1795512644547e+02
4.3000000000000e+01	2.2799033346260e-01	-7.0337051739402e+02
4.4000000000000e+01	2.2768626385358e-01	-6.8950673319697e+02
4.5000000000000e+01	2.2736642172822e-01	-6.7631641359117e+02

Figure 28 real and imaginary part of sound pressure (Pa) vs. frequencies (Hz) at Micro 1

In this section the computed results for the absorption coefficient are plotted as a function of frequency (Hz) for the Transfer-Function Method. As mentioned in the background and theory, in order to calculate the absorption coefficient, we first need to calculate the absorption coefficient (), using the complex ratio of the sound pressure of the microphones. For this calculation, we use the txt exported files and import them to Matlab:

```
freq_press_mic_1 = [dlmread('Microphone_1_sound_pressure.txt')];

freq_press_mic_2 = [dlmread('Microphone_2_sound_pressure.txt')];

freq_press_mic_3 = [dlmread('Microphone_3_sound_pressure.txt')];
```

After importing the values of frequency and the complex sound pressure, we have to calculate the transfer function. This can be calculated using the following equation in Matlab:

```
h_12 = (freq_press_mic_1(:,2) + i*freq_press_mic_1(:,3)) ./ (freq_press_mic_2(:,2) + i*freq_press_mic_2(:,3));
```

For this example, we are using microphone 1 and microphone. Therefore, we need to define the parameters L and s. Again, L is the distance from the sample to the first microphone and s is the distance between the microphones. These values are equal to L = 0.06233316 m and s = 0.0216154 m. Then, these values are used to calculate reflection coefficient (equation 2) and thus absorption coefficient. The complete Matlab example is shown in Appendix A.

The frequency vs. absorption coefficient that was calculated using the sound pressure of microphone 1 and microphone 2 was calculated and plotted, as shown in Fig.29.

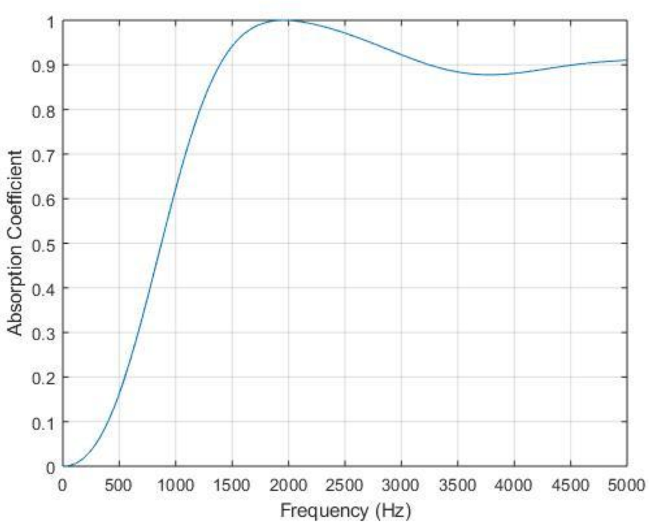

Figure 29 Absorption coefficient vs. Frequencies (Hz) obtained from Transfer-Function Method using Micro 1 and Micro 2.

Reference

[1]Seybert, A. F., Notes on Absorption and Impedance Measurements.

[2] Qiming, G., Analysis of acoustic damping in duct terminated by porous absorption materials based on analytical models and finite element simulations, 2015.

[3] ISO, ISO 10534-1, Acoustics---Determination of sound absorption coefficient and impedance in impedance tubes---Part 1: Method using standing wave ratio. International Standards Organisation. 1996.

[4]Software, F. M., Kundt's Tube-Rigid Termination *Actran Student Edition Tutorial*.