

Reactive Acoustic Filters as a Replacement for Absorbing Material

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O. I. Ilkorur¹, K. Yuksek^{*2}

Abstract-The usefulness of reactive acoustic low pass filters inside transmission line enclosures, instead of absorbing materials, was examined by means of linearity and efficiency. Wave equation was solved numerically in an unbounded domain, and the numerical solution was used to simulate the behaviour of acoustic filters inside transmission line enclosures. The filters inside the transmission line were placed based on the Thiele and Small parameters of the test unit used. A relation between the numerical results and SPL values was found and this relation was used to decide whether a filter is suitable for audio purposes.

I. INTRODUCTION

After the model of transmission line enclosures was introduced in 1965 by Bailey and Radford, the need for controlling the resonance peaks inside the line has gained significant importance. Studies on removing the resonances inside the transmission line loudspeaker enclosures are mainly concentrated on using fibrous stuffing or absorptive linings [1], [2], [3]. In order to achieve the highest possible efficiency with minimal pass band ripple some suggestions have been made. For instance, Augspurger (2000) tested different types of fibrous materials and found these fibrous absorbers had different absorbing characteristics [5]. For simulation purposes, the model of Locanthi's horn equation, with some empirical parameters, which have been received from the real life measurements, were used [4], [5]. Locanthi's analogy includes the mobility model of the loudspeaker, followed by an LC ladder in which series inductors represent air compliance and shunt capacitors represent mass. In the model, each LC section is equivalent to a cylindrical element of specified diameter and length. The accuracy of the model depends on the length of the elements used. The performance of Locanthi's horn equation has been shown to be depended on the material, which can be used inside the line, by adding shunt resistances to model the damping losses. On the other hand, Augspurger (2000) introduced the idea of changing the cross-sectional area of the line abruptly to reduce the cancellation in the troublesome fourth-harmonic region, but no details were given in this work. Resonance problems in pipes with varying cross-sections, such as exhaust systems and HVAC (Heating Ventilating and Air Conditioning) installations, have been investigated in different studies. But, in all those cases, the fluid is not stationary, unlike the condition in loudspeaker enclosures. The cases examined had similar boundary conditions [6], [7], [8], [9]. Although, structure and modelled the low-pass Butterworth filter as 18dB/octave, using electro-acoustic analogy [10], the borders of the sections of the cavity were not drawn clearly. The same cavity was also examined by Leach Jr. (2003) with

electro-acoustic analogy, but, the borders of the cavity were still not defined in detail [11]. Morse also worked on the same problem and generated a solution using conformal transformations under steady-state flow conditions [12]. Munjal (1987) examined sudden area changes by using transfer matrix method [13]. He emphasized the importance of how the resonances inside the transmission line affect the output amplitudes. He also gave information about how resonators, which are placed as a branch on the lines, can affect the transmission loss as they resonate. The transfer matrix method, however, can not be used with sudden area changes, where the discontinuity has negligible thickness. In present work, further studies were carried out to investigate the effect of sudden area changes in the line. In this work, to reach the goal of achieving the highest possible efficiency with minimal pass band ripple, instead of fibrous absorbers or absorptive linings, a third-order low-pass filter was used. Two sudden changes, forming a cavity in the middle, were placed inside the line. The position of the filter was chosen according to the length of the transmission line. A solution was found by solving the wave equation numerically in a time domain with absorbing boundary layers. A test cylinder, which has a length of 1meter and a diameter of 0.16meter, was used for measurements. A suitable loudspeaker was used as the source. Depending on the radial resonances caused by the boundary of the test cylinder, the simulations were limited with 1000Hz. A low-pass filter, which reduces all the resonance peaks between the nominal quarter-wave pipe resonance frequency and 1000Hz, was searched and the filter, satisfying that condition was tested. The positive and negative aspects of the filter were investigated.

II. MATHEMATICAL MODEL

The mathematical model is based on the wave equation in two dimensions using Cartesian co-ordinate system [14].

The diffusion equation, subjected to $u(x,y,t) = 0$ on the boundaries $x=0,1$ and $y=0,1$ is given by;

$$\frac{\partial u}{\partial t} = D \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \quad (1)$$

About¹. Yildiz Technical University, 34349, Istanbul, Turkey

About². Istanbul Kultur University, 34156 Istanbul, Turkey

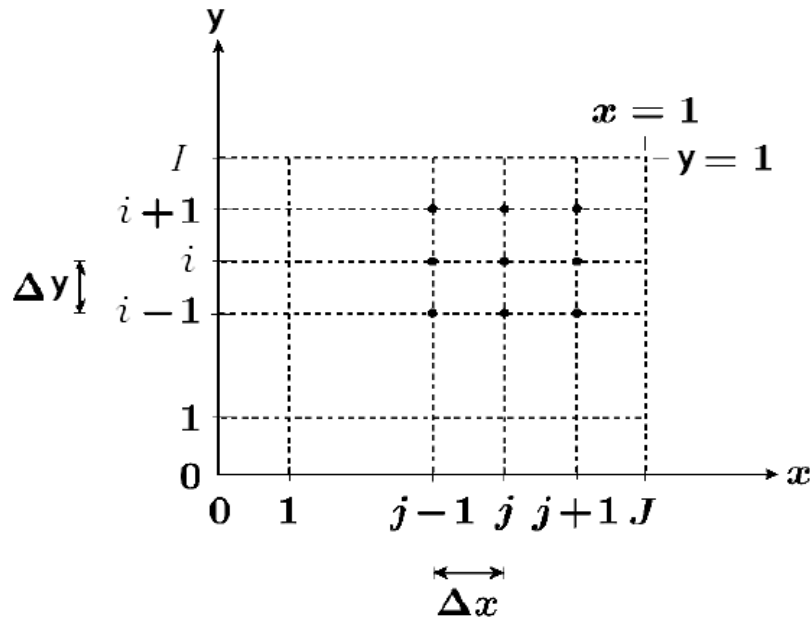


Fig. 1. Numerical Solution Variables

For the boundary conditions given as;

$u(x,y,t=0) = u_0(x,y)$, the solution for $t > 0$ was found.

Using a square mesh size, $\Delta x = \Delta y = 1/m$, and $D=1$,

the Laplacian operator can be used for approximation

for the internal points $i=1, m-1$ and $j=1, m-1$. On the

boundaries ($i=0, j$), ($i=m, j$), ($i, j=0$) and ($i, j=m$), have

$u_{ij}=0$. The diffusion equation is simplified to

$$\frac{\partial u_{i,j}}{\partial t} \approx (u_{i+1,j} + u_{i-1,j} + u_{i,j+1} + u_{i,j-1} - 4u_{i,j}) / \Delta x^2 \quad (2)$$

If the derivative of equation 2 is taken, it becomes:

$$U'_{i,j}(t) = (U_{i+1,j} + U_{i-1,j} + U_{i,j+1} + U_{i,j-1} - 4U_{i,j}) / \Delta x^2 \quad (3)$$

where the U_{ij} represents our approximation of U at the mesh point x_{ij} . Using the Euler method in which $Y_{n+1} = Y_n + \Delta t \cdot f(Y_n, t_n)$ equation 3 is given by;

$$U_{i,j}^{(n+1)} = U_{i,j}^{(n)} + \mu (U_{i+1,j}^{(n)} + U_{i-1,j}^{(n)} + U_{i,j+1}^{(n)} + U_{i,j-1}^{(n)} - 4U_{i,j}^{(n)}) \quad (4)$$

where the Courant number is $\mu = \Delta t / \Delta x^2$ and where the stability depends on both time and μ [15].

The absorbing boundaries can be added to the solution as a damping function. An imaginary single degree damping function can be defined as;

$$A(x) = c_{slope} \cdot (x - (x_{max} + x_{border})) + c_{offset} \quad (5)$$

where equation A is the damping term, which is depended on the position at which the coordinate it is calculated

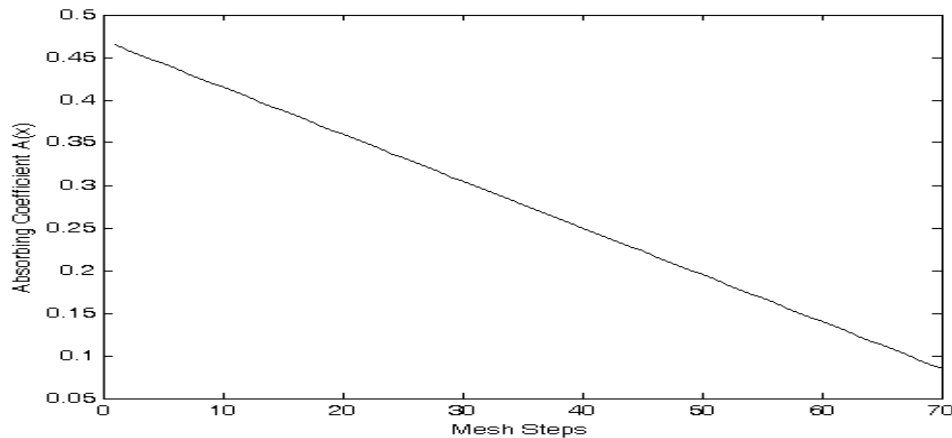


Fig. 2. Absorbing Coefficient with Respect to Mesh Steps

c_{slope} and c_{offset} are the two parameters defining the character of the absorbing function. x_{max} and x_{border} are the two parameters keeping the values of the maximum dimension of the total solution area of the simulation and the width of the absorbing border, respectively. As the wave enters the border, the absorption coefficient reduces from its' maximum to its' minimum to reduce the amplitude of undesired reflected waves. c_{slope} and c_{offset} values were calculated by a simple optimization process. An impulse signal was generated inside the solution area and the amplitude of the reflected wave was measured. The software was set to select the constants which give the minimum amplitude for the reflected wave.

Equation 5 was integrated on the borders of the solution area. The width of the border, surrounding the solution area,

was defined as the half of the wavelength of the lowest frequency used in the simulations [16]. This ensures that the wave has to travel a full of its' wavelength before it leaves the absorbing boundary. The simulation conducted under steady state conditions between the nominal quarter-wave pipe resonance frequency and 1000Hz was found to be stable.

III. TEST ENCLOSURE

The test enclosure is made of a rigid cylinder and a speaker unit, mounted on the one side of the cylinder. The other end of the cylinder is open. The enclosure tuning was checked and the impedance of the speaker, mounted on the empty pipe, was measured. (Figure 3)

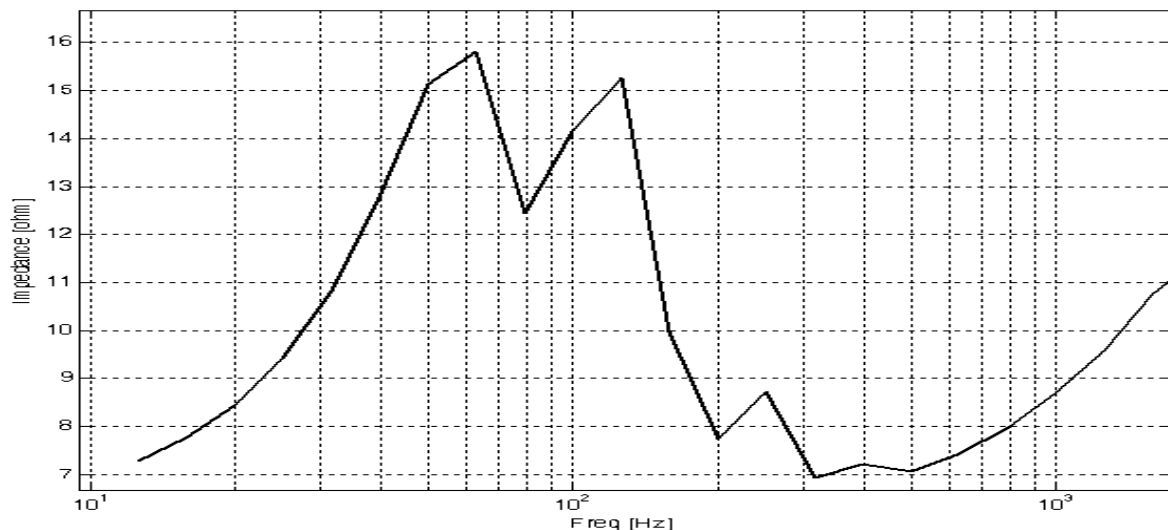


Fig. 3. Impedance Graph of the Speaker at the End of Empty Pipe

The Thiele/Small parameters of the speaker unit are measured and found to be $F_s = 77$ Hz, $R_e = 5.7$ Ohm, $Q_e = 0.54$, $Q_m = 1.73$, $Q_t = 0.4$, $V_{as} = 5.47$ lt and S_d is measured to be 87 cm^2 according to Clio Standard Measurement System [17].

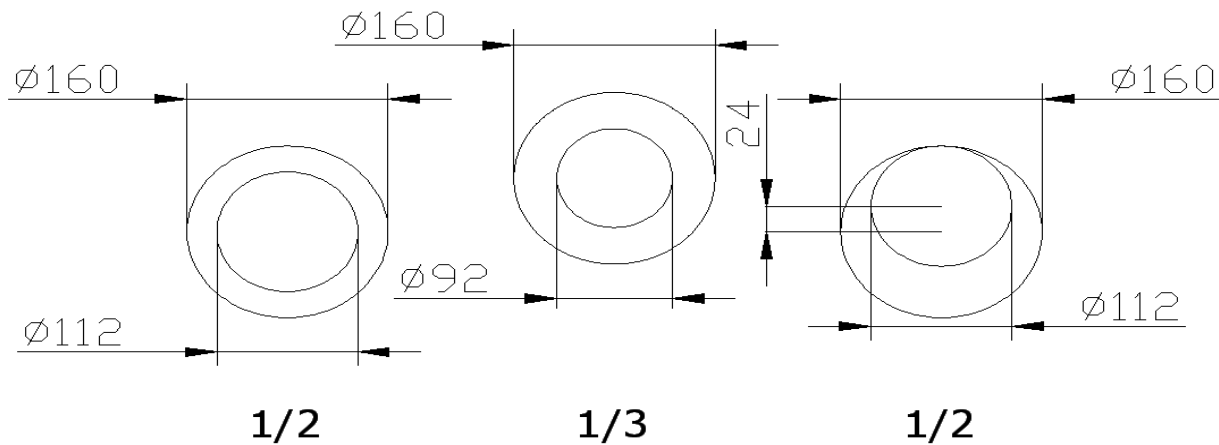


Fig. 4. Filter Parts

Thin aluminium disks with a thickness of 4mm were drilled. Two of the pairs were prepared to have holes at their centres. Two types of holes having an area equal to half of the cross sectional area of the transmission line (S_{TL}) and one third of the S_{TL} were drilled on those disks. A third pair

was prepared where the holes were off the axis. Holes having an area equal to the half of the S_{TL} were drilled. A schematic representation of the system, showing all the possible filter placements used in the study, is given in Figure 5.

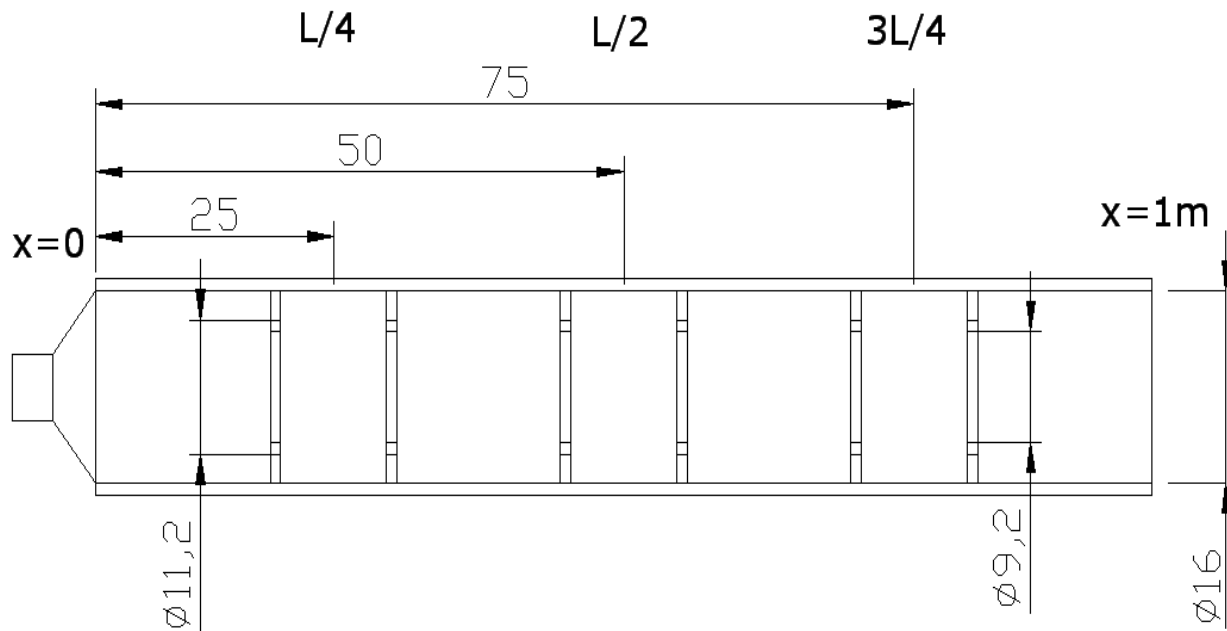


Fig. 5. Placement of Filter Parts

Depending on the length of the transmission line, the pairs were placed inside the test enclosure. The length of the transmission line was divided into three equal parts. The filters were placed inside the transmission line, in such a way that, the mid points between the two filter parts coincided with these three specified points. Only one pair was left in the transmission line during measurement.

IV. SIMULATION RESULTS AND MEASUREMENTS

For the model used in numerical solution, a two-dimensional slice of the test enclosure, dividing it into two equal parts from the symmetry axis, was used. The rigid boundaries of the test enclosure were assigned as purely reflective boundaries in the two-dimensional simulation area. The source was defined as an ideal piston, which was not affected by the reflected waves coming from the obstacles inside the line. A simulation programme was generated to obtain a sine sweep between the nominal quarter-wave pipe resonance frequency and 1000Hz. The transfer function was also generated to identify the resonances inside the test enclosure. During a sine sweep for a particular filter, the RMS pressure of input and RMS pressure of output amplitudes were recorded under steady-state conditions for each frequency. Those values were used to generate a normalized transmission ratio graph. Transmission ratio (TR) is given by;

$$TR = \frac{\text{Output Signal(RMS)}}{\text{Input Signal(RMS)}}$$

In transmission ratio graphs (Figures 6, 8, 10 and 13), higher values indicate lower radiation amplitude and lower values show higher radiation amplitude from the line opening. These graphs are used to detect if any resonances in the selected frequency band occur. The location of the filter parts was decided according to the length of the calculated transmission line. The filters were placed at three different locations with the same cavity volume in between. The volume between the filter parts was determined according to the desired cross-over point. The volume between the filter parts was found to be the only effective parameter on the cross-over frequency. The location of the filter parts inside the transmission line and the cross-sectional area of the holes on the filter parts were found to have no effect on the cross-over frequency. In order to control the resonances over third harmonic, the volume between the filter parts is found to be 0.002m^3 . This value was achieved by running a range of volume values, which are capable of generating cross-over frequencies below and above the third harmonic, to the simulation software. The software generated results for the values within the given range and the volume which resulted in a cross-over point at 500Hz was selected.

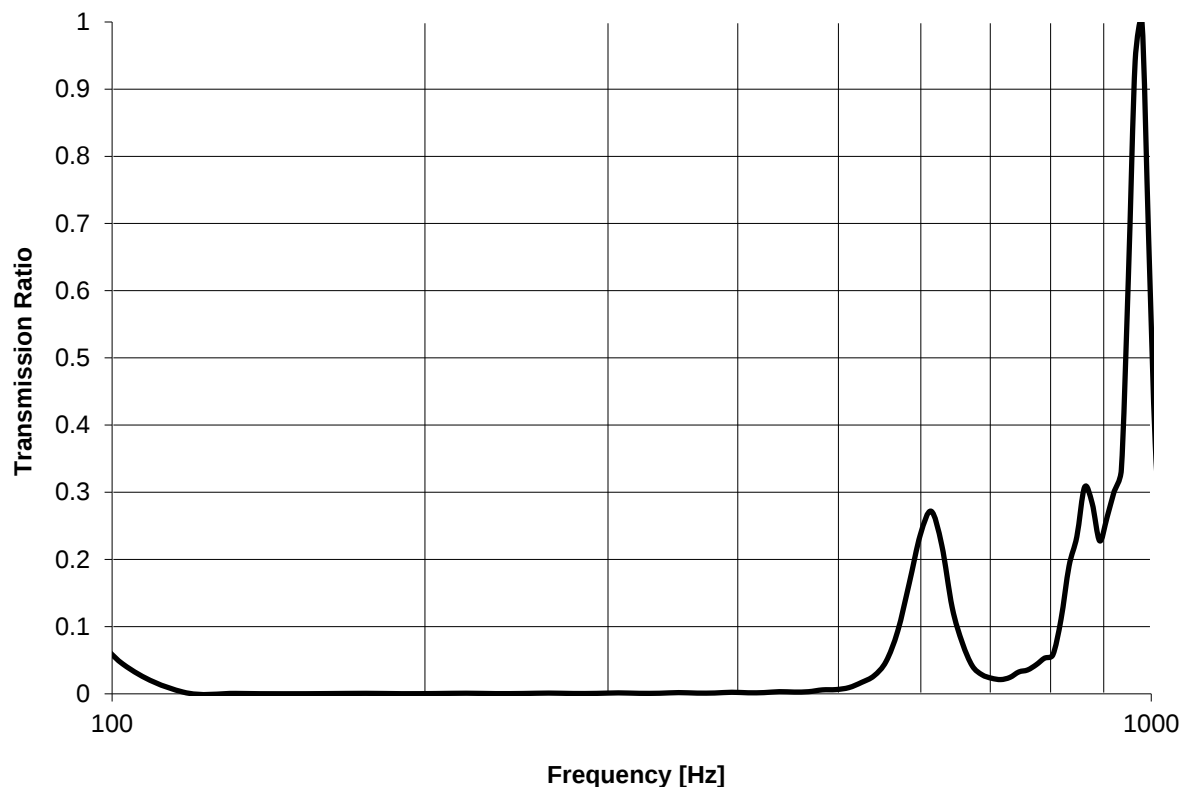


Fig. 6. Response for 20cm - 30cm Placement

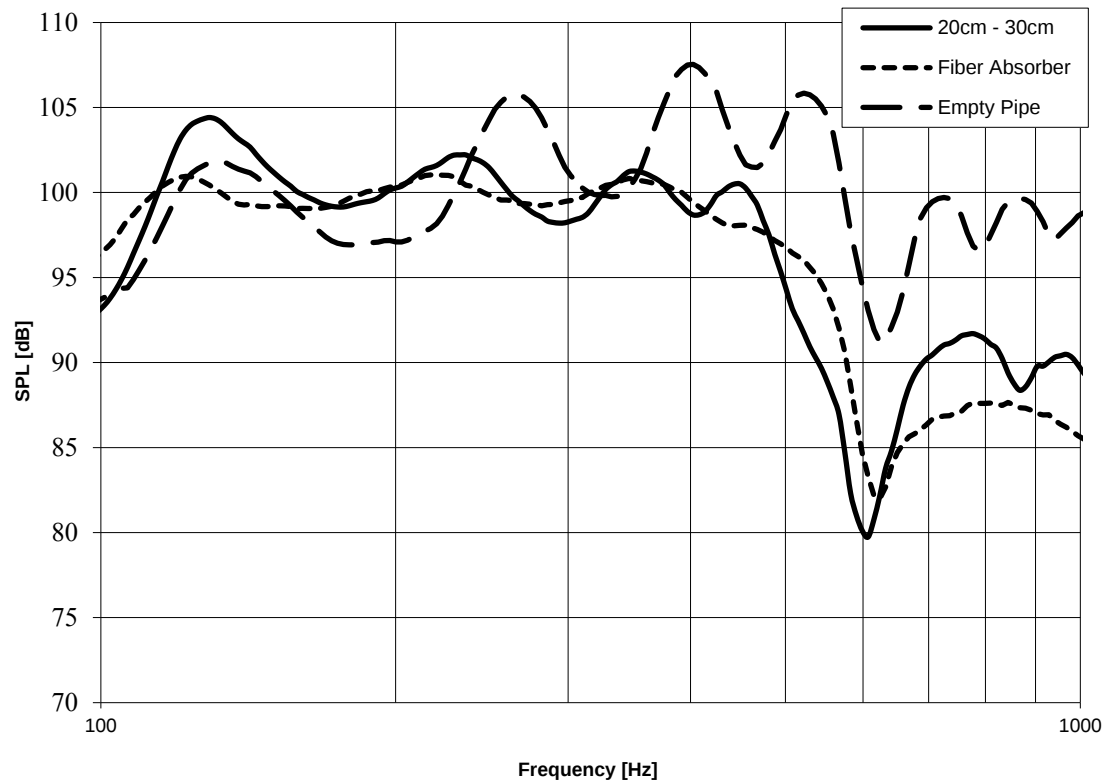


Fig. 7. Frequency Response for 20cm-30cm Placement

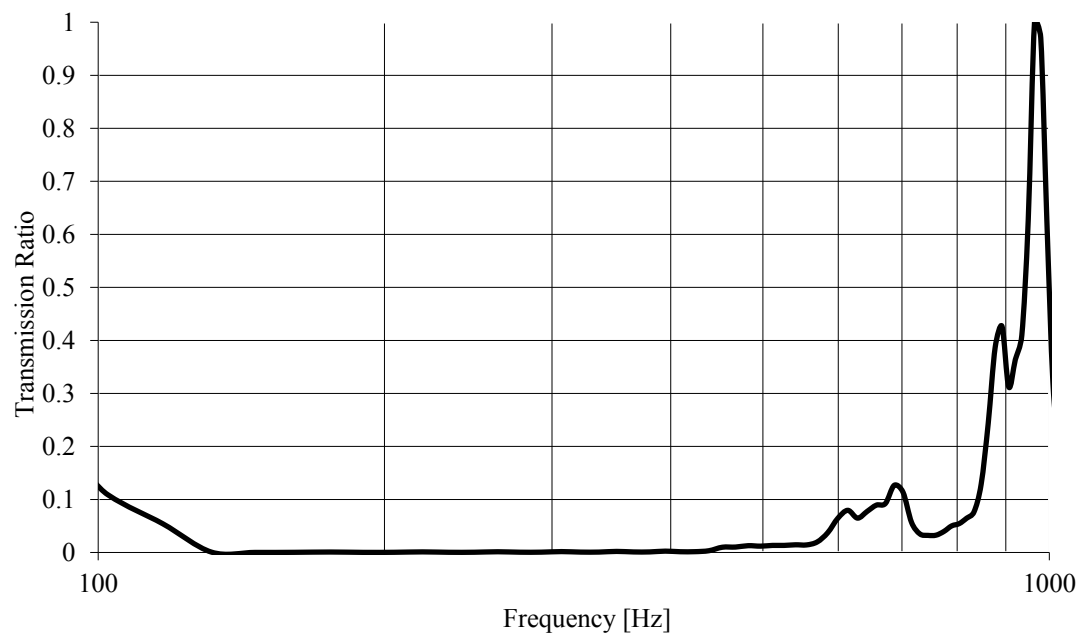


Fig. 8. Response for 45cm - 55cm Placement

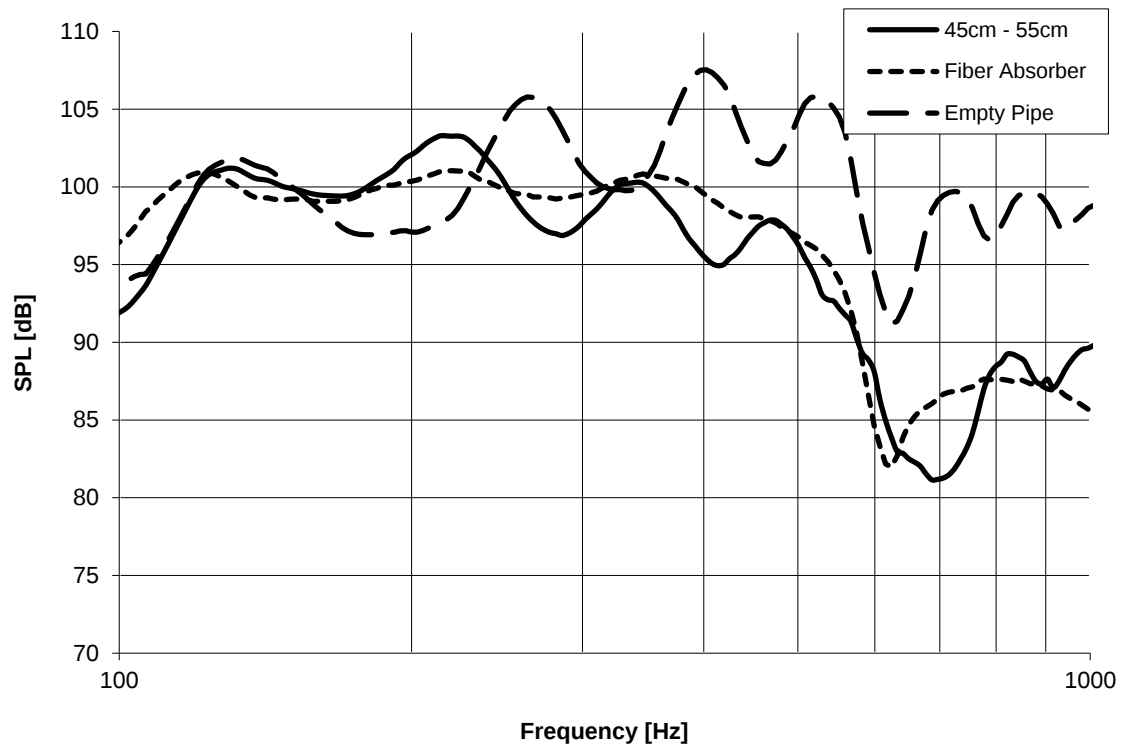


Fig. 9. Frequency Response for 45cm-55cm Placemen

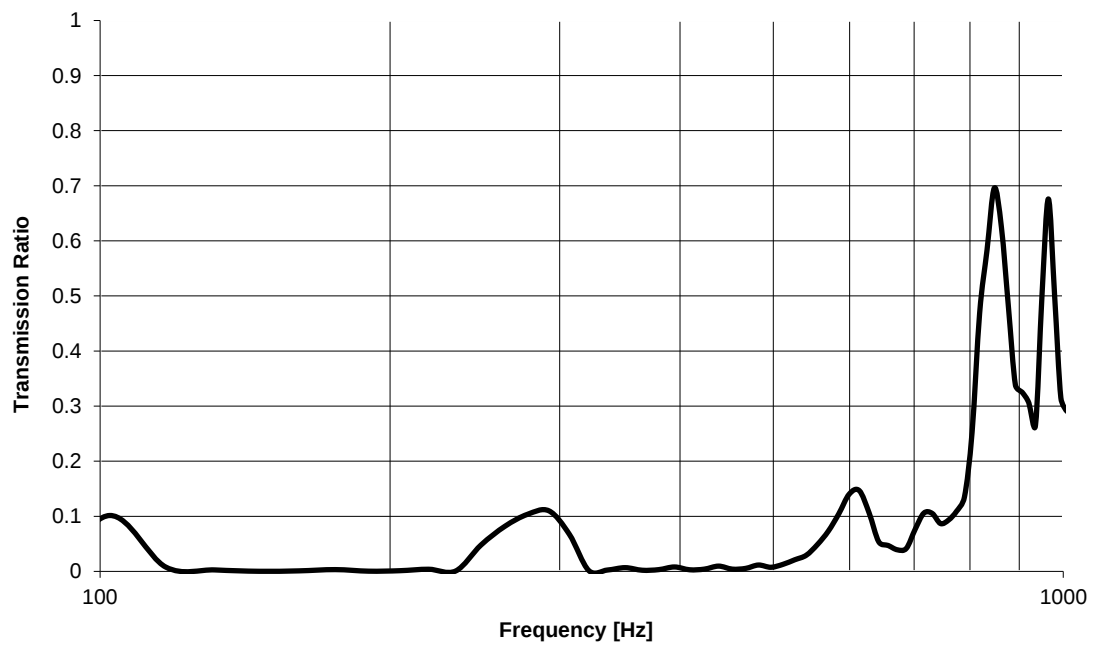


Fig. 10. Response for 70cm-80cm Placement

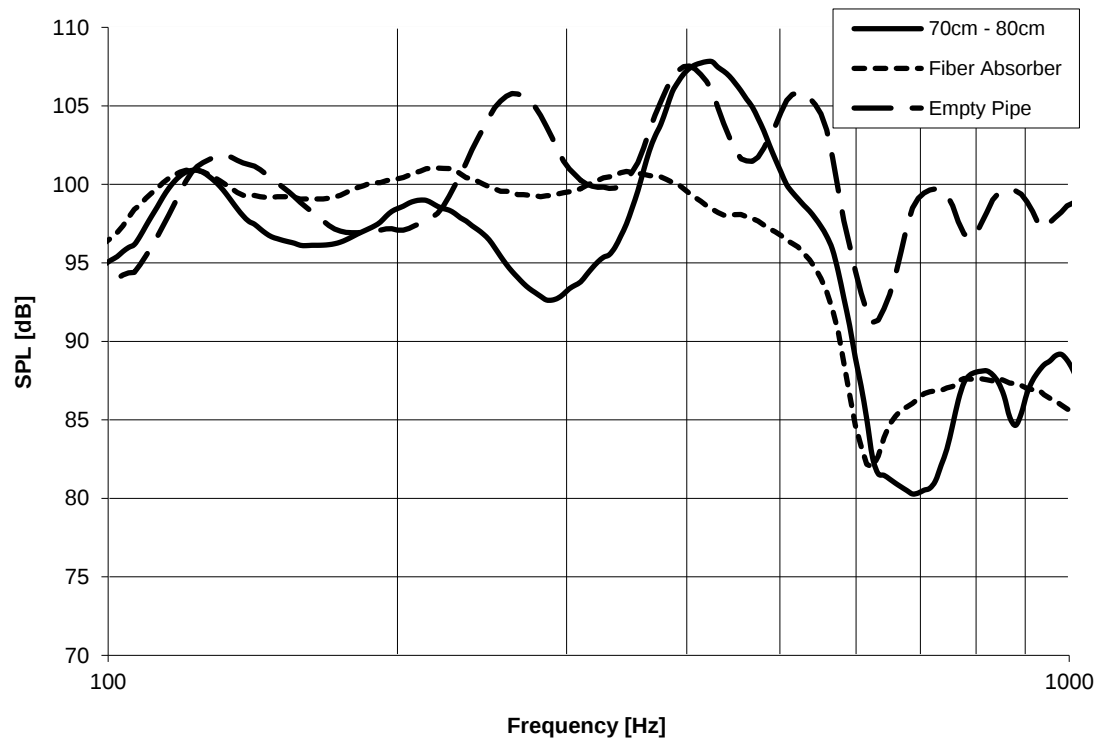


Fig. 11. Frequency Response for 70cm-80cm Placement

In order to have a flat response in the 100 – 1000Hz frequency band, asymmetrical placement of the discs at 45cm and 55cm, was studied also.

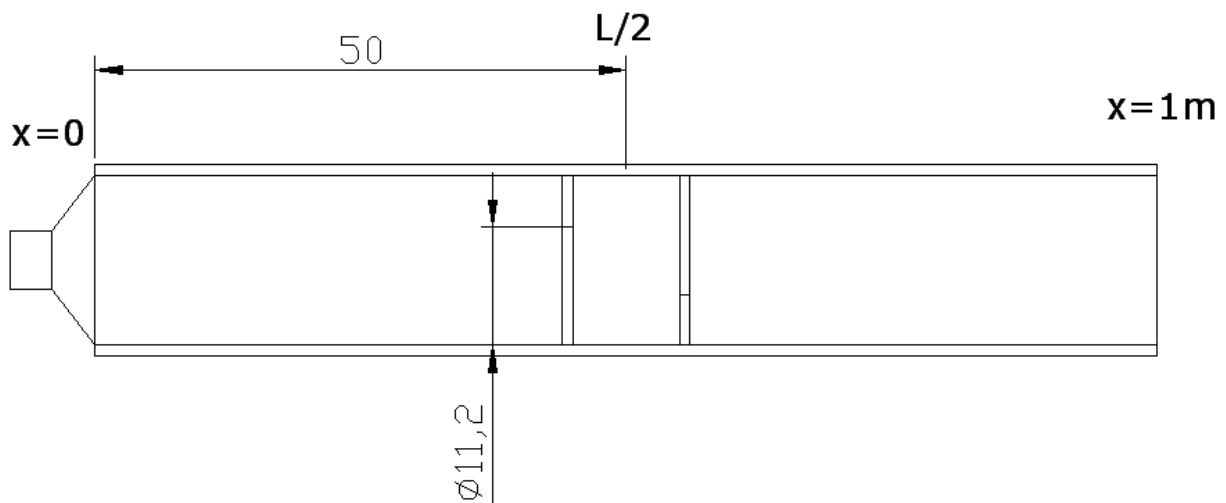


Fig. 12. 45cm - 55cm Asymmetrical Placement

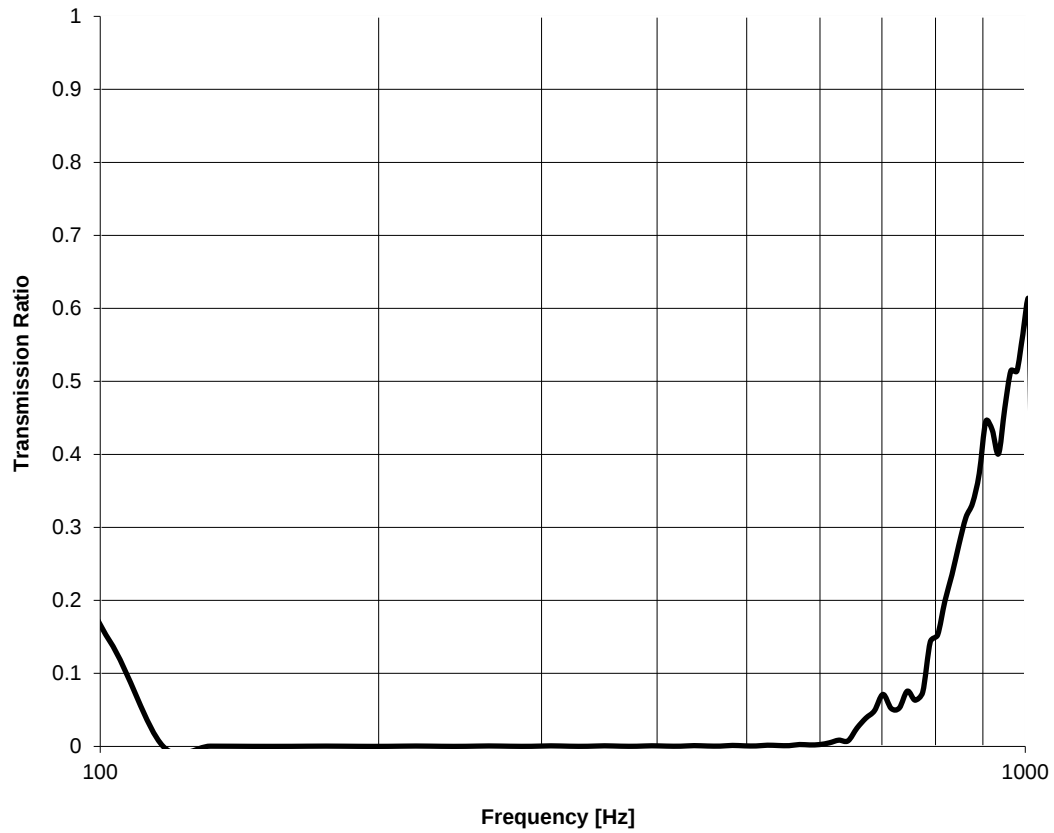


Fig. 13. Response for 45cm - 55cm Asymmetrical Placement

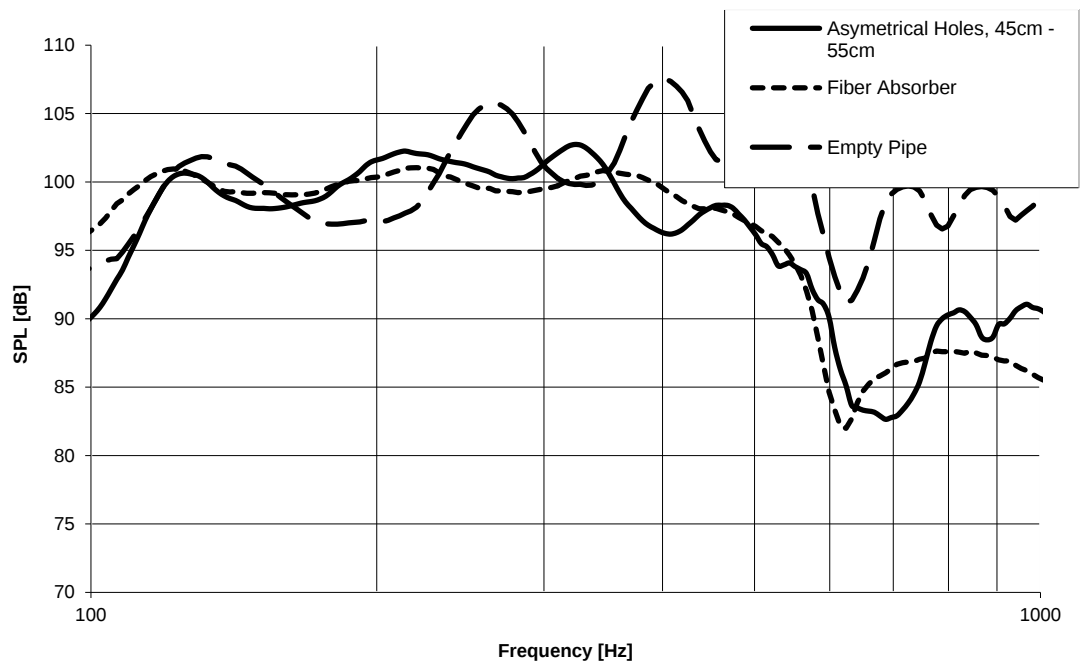


Fig. 14. Frequency Response for 45cm - 55cm Asymmetrical Placemen

The filter parts had openings which were equal to the half of the cross sectional area of the transmission line. The openings had an offset of one radius from the centre and were placed with 180° angle (Figure 12). As it can be seen from Figure 12, no resonances in the selected frequency band were found. Based on the results obtained from the simulations, comparative measurements between the absorber filled, acoustical filter placed and empty transmission line, were performed. The comparison of SPL values for the asymmetrical filter, the filter with the $1/3 S_{TL}$ and the absorber are shown in Figures 7, 9, 11 and 14. Responses in the desired frequency range were similar in

Figures 9 and 14. Therefore, results suggested that asymmetrically placed filters and filters having openings equal to the $1/2 S_{TL}$ and 45cm – 55cm placement can be used for audio purposes. The frequency responses of other filters, which have smaller openings were also measured (Figure 15). The frequency responses were measured based on the absorber response which taken as the reference. Because the frequency responses of these filters were not in the range of ± 3 dB or the SPL values are not as high as absorber response, they were found not to be appropriate for audiopurposes.

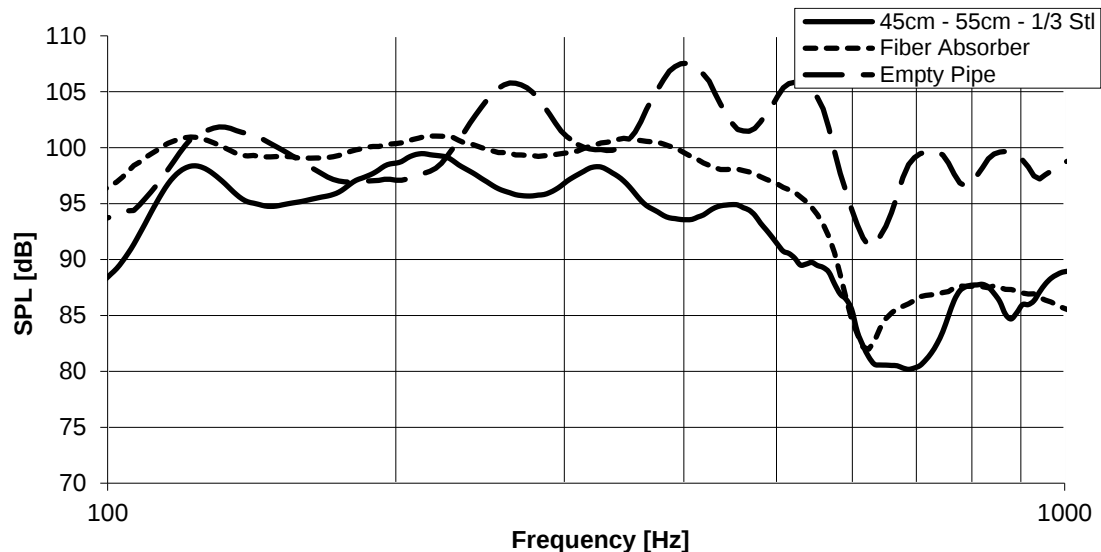


Fig. 15. Frequency Response for 45cm - 55cm with $1/3 S_{TL}$

V. RESULTS AND CONCLUSIONS

A study to investigate the effectiveness of using reactive acoustical filters inside the transmission line enclosures instead of absorbers was carried out. In order to filter the frequencies over third harmonic, the volume, between the filter parts, was determined. The filter parts were placed inside the transmission line depending on the length of the line. Wave equation was solved numerically to investigate the behaviour of the acoustic low-pass filters inside the transmission line. The numeric solution was used to determine the resonances in the frequency band where planar standing waves could occur. Several simulations were carried out to find a flat response. Results of the simulations showed that two filters satisfied the condition of flatness. Comparisons within the desired frequency limits were made to compare the performance of the filters. No plane wave resonance within the desired frequency range (Figures 9 and 14) was observed. The filters, with some resonances exhibited undesirable frequency characteristics (Figures 7 and 11). The simulations showed that when there were less resonance peaks in the desired frequency range,

the frequency response of that filter moved closer to the character of a damped transmission line.

The filter with an opening equal to the $1/2 S_{TL}$ and placed asymmetrically, and the filter with an opening of $1/2 S_{TL}$ and placed in the middle of the transmission line had similar frequency responses. The frequency responses of both filters were very close to that of the absorber response, but, the slopes were sharper than the slope of the absorber below the 100 Hz.

Results suggested that acoustical low pass filters, built by making sudden area changes can be used as a replacement for absorbers in the transmission lines.

VI. REFERENCES

- [1] B. Onley, —A Method of Eliminating Cavity Resonance, Extending Low Frequency Response and Increasing Acoustic Damping in Cabinet Type Loudspeakers”, J. Acoust. Soc. Am., vol 8 (Oct. 1936)
- [2] A. R. Bailey, —NonResonant Loudspeaker Enclosure”, Wireless World (Oct. 1965)
- [3] L. J. S. Bradbury, —The Use of Fibrous Materials in Loudspeaker Enclosures”, J. Audio Eng. Soc., vol. 24, pp 162-170, (April 1976)

- [4] B. N. Locanthi, "Application of Electric Circuit Analogies to Loudspeaker Design Problems", IRE National Convention, vol. PGA-6, (March 1952)
- [5] G. L. Augspurger, "Loudspeakers on Damped Pipes", J. Audio Eng. Soc. Vol 48, pp 424-436, (May 2000)
- [6] B. L. Simith, G. W. Swift, "Power dissipation and time-averaged pressure in oscillating flow through a sudden area change", J. Acoust. Soc. Am. vol 113, (May 2003)
- [7] A. M. G. Gentemann, A. Fischer, S. Evesque, W. Polifke, "Acoustic Transfer Matrix Reconstruction and Analysis for Ducts with Sudden Change of Area", 9th AIAA/CEAS Aeroacoustics Conference and Exhibit 12-14 (May 2003)
- [8] I. D. J. Dupere, A. P. Dowling, "Absorption of Sound near Abrupt Area Expansions", AIAA Journal, vol. 38, No. 2, (Feb. 2000)
- [9] K. J. Baumeister, W. Eversman, R. J. Astley, J. W. White, "Acoustics in Variable Area Duct: Finite Element and Finite Difference Comparisons to Experiment", AIAA Journal, vol 21, no 2, (Feb 1983)
- [10] L. L. Beranek, Acoustics (McGraw-Hill, New York, 1996), p. 136
- [11] W. M. Leach Jr., Introduction to Electroacoustics and Audio Amplifier Design Kendall/Hunt Publishing Co., p.42 (2003)
- [12] P. M. Morse, K. U. Ingard, Theoretical Acoustics, Princeton University Press, Princeton, New Jersey, p. 490 (1968)
- [13] M. L. Munjal, Acoustics of Ducts and Mufflers with Application to Exhaust and Ventilation Systems (John Willey & Sons, Canada, 1987), p. 68
- [14] D. D. McCracken, W. S. Dorn, Numerical Methods and Fortran Programming (John Wiley & Sons, New York, 1964), p. 337
- [15] L. Lapidus, G. F. Pinder, Numerical Solution of Partial Differential Equations in Science and Engineering, (John Wiley & Sons, New York, 1982), p. 486
- [16] G. C. Cohen, Higher-Order Numerical Methods for Transient Wave Equations (Springer, 2006), p.
- [17] Clio Electro-Acoustic Measurement System Manual, Audiomatica, Italy, 2005