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EXPERIMENTAL STUDY OF THE ACOUSTIC CHARACTERISTICS OF A DIAPHRAGM TUBULAR RESONATOR

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Abstract: Noise reduction, located in a narrow frequency band, is easily achieved by using resonant acoustic systems, such as Helmholtz resonators, dampers or acoustic tubes. However, a major disadvantage arises if there are significant variations in the noise emitted by certain equipment, but in a relatively narrow frequency band. This paper presents an acoustic system whose acoustic characteristics can be easily modified, which can lead, through appropriate automation, to the transformation of a passive acoustic vibration damping system into an active one.
Keywords: noise reduction; Helmholtz resonators; acoustic tubes; acoustic resonance

INTRODUCTION

The analysis of vibrations and noise occurring during the operation of many mechanical systems, agricultural or industrial machines, appliances, vehicles or buildings is an area of great interest to both manufacturers and operators or users. Vibrations and noise are already used to diagnose equipment and monitor the state of health through the effects they produce (*Biriş S.Şt. et al, 2022; Sorică, E. et al, 2017*). Once the sources of vibration and noise are identified (*Randall, R.B., 2009; Yue, Y. et al, 2022; Golgot, C. et al, 2021*), if their level is high, other complementary systems are often required to mitigate the side effects which they produce. Complex vibration isolation systems can be used (*Crocker, M.J., 2007*), dampers (*Mohanty, A.R. et al, 2005*), sound–absorbing panels (*Chen, J–S. et al, 2020*), special sound–absorbing porous materials or in which Helmholtz–type resonators are inserted (*Boutin, C., 2013; Groby, J–P. et al, 2015*), housings for cars and cabins (*Biriş S.Şt. et al, 2022*) simple acoustic resonators (*Alster, M., 1972; Komkin, A.I. et al, 2017*) or in the form of panels (*Gai, X.L. et al, 2016; Pan., J. et al., 2005*). The use of Helmholtz resonators is one of the oldest techniques for improving the acoustics of some premises, but also for reducing unwanted noises (*Tang, P.K. et al, 1973*). Acoustic resonators can be used either as independent, combined acoustic systems or as panels. They can be used for both amplification and attenuation, depending on certain acoustic parameters that can be imposed by a suitable design (*Chanaud, R.C., 1997; Farooqui, M. Et al, 1994; Shi, X., Mak, C.M., 2015*).

MATERIALS AND METHODS

Theoretical aspects

Acoustic resonators are complex acoustic systems, characterized in that they can amplify or reduce only sound waves that have certain frequencies. Like electrical circuits or elastic systems, it can be said that an acoustic resonator consists of an inertial element (ground, electric coil), an elastic element (spring, condenser, gas volume) and a dissipative element (electrical resistance, damper, acoustic resistance), which form an acoustic circuit, which have an acoustic behavior similar to electrical circuits.

Helmholtz resonator

It consists of a partially enclosed acoustic enclosure, of volume, V, a neck connecting to the outside, of length, l, and an area of section, A, Figure 1.

Under the action of an acoustic pressure, p, the air in the resonator's neck oscillates while the air contained in the acoustic enclosure, of volume, V, behaves like an elastic element, being subjected to successive relaxations and compressions.

Like the equivalent mechanical system, a Helmholtz resonator has a unique resonance frequency, the expression of which, in a first approximation, has the expression:

$$f_0 = \frac{c}{2\pi}\sqrt{\frac{A}{l_{ef}V}} = \frac{c}{2\pi}\sqrt{\frac{G}{V}} \qquad (1)$$

where:

–c– is the speed of sound;

–$l_{ef}=l+l_c$ – is the effective calculation length of the neck;

–$G=A/l_{ef}$ – is the conductivity of the opening.

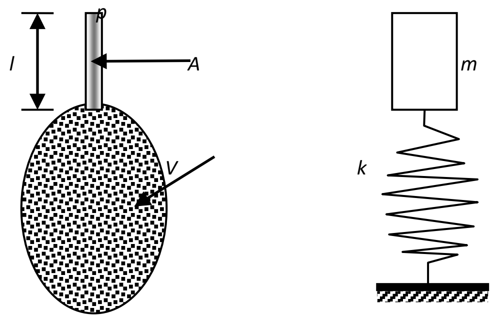

Figure 1 – The Helmholtz resonator and his mechanical correspondent

Relation (1) is similar to that determined in the case of mechanical oscillators with a degree of freedom, where the exact resonance frequency is determined by the expression

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m_{ef}}} = \frac{1}{2\pi}\sqrt{\frac{k}{m + m_c}} \tag{2}$$

Indicating that part of the spring mass is moving, a correction table – m_c – must be inserted. Lord Rayleigh intuited this phenomenon and introduced into the calculation of the resonant frequency of the oscillator an effective calculation length, which takes into account the fact that the air mass entered in oscillation is greater, being entrained air masses located to one side and another of the neck, its length being modified by a correction factor, denoted here by l_c.

An important and extensive contribution to corrections was made by M. Alster (1972) and Tang (1973).

Sound tubes

Like Helmholtz–type acoustic systems, acoustic tubes are characterized by resonant frequencies, but they are not as unique as they are. It can be said that acoustic tubes have a behavior close to continuous elastic systems, such as wires, bars or plates, which have an infinite number of their own frequencies.

Given that the opening section at the end is small in relation to the total area, about 2%, it is expected that the system will have a closed tube behavior at both ends, figures 2 and 3. Although such an acoustic system is not analyzed separately, precisely because it would be acoustically inactive, it can be said that the acoustic waves that will form inside will be characterized by zero velocities at the ends. This type of system can be compared to an open tube at both ends, where the sound pressures are zero at the ends. The resonant frequencies of an open tube at both ends can be determined by the relationship

$$f_n = n\frac{c}{2L}, n = 1, 2, \ldots \tag{3}$$

PRESENTATION OF THE STUDIED ACOUSTIC SYSTEM

The acoustic system used is a semi–closed sound tube, which, like a Helmholtz resonator, can be considered to consist of a closed volume, *V*–shaped acoustic enclosure and a neck through which the sound tube (enclosure) is connected with the outside, Figures 2, 3.

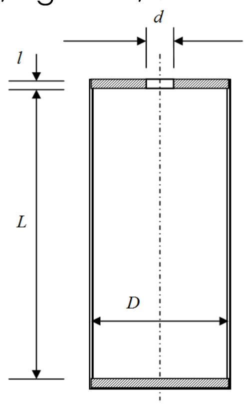

Figure 2 – Acoustic system – dimensions

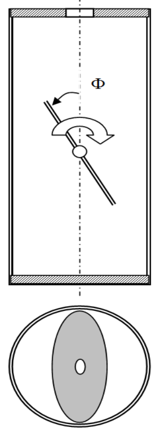

Figure 3 – Position of diphragme in tube

The dimensions of the sound tube are: *L* = 272 [mm], *D* = 80 [mm], *l* = 10 [mm], *d* = 12 [mm].

According to (Alster, M., 1972), for neck of circular section, $l_c = 8d / 3\pi$. So:

$$V = \frac{\pi D^2}{4} L = 0{,}00136722 \quad [m^3] \tag{4}$$

Neck length:

$$l_{ef} = l + l_c = l + \frac{8d}{3\pi} = 0{,}020186 \quad [m] \tag{5}$$

Neck section area:

$$A = \frac{\pi d^2}{4} = 0{,}0001131 \quad [m^2] \tag{6}$$

Opening conductivity:

$$G = \frac{A}{l_{ef}} = 0{,}00560276 \; [m] \tag{7}$$

Helmholtz resonant frequency, for c=440 [m/s]

$$f_0 = \frac{c}{2\pi}\sqrt{\frac{G}{V}} = \frac{344}{2\pi}\sqrt{\frac{0{,}00560276}{0{,}00136722}} = 110{,}8379 [Hz] \tag{8}$$

Own frequencies for an open or closed sound tube at both ends:

$$f_n = n\frac{c}{2L} \rightarrow f_1 = 632{,}35; \quad (9)$$
$$f_2 = 1264{,}7;\ f_3 = 1897{,}06;...$$

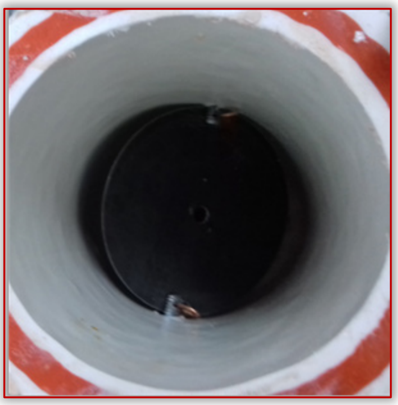

Figure 4 – Position of diphragme in tube, Φ=60°

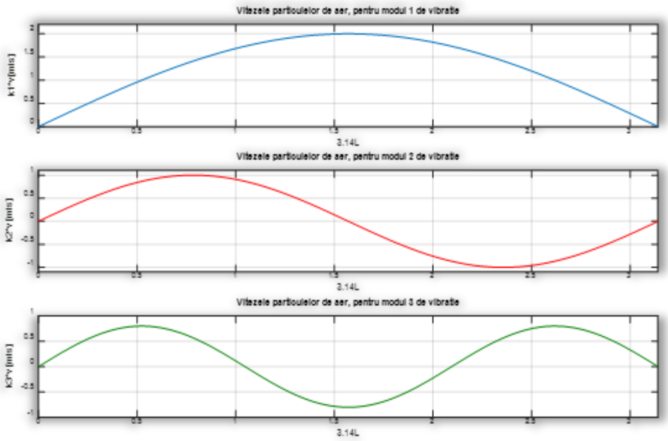

Figure 5 – The first 3 proper forms of vibration in speeds

Figure 5 shows the amplitudes of the oscillation velocities in the longitudinal direction of the air for the first three Eigen modes of vibration.

EQUIPMENT USED

Several sets of acoustic measurements were performed:

- on the initial acoustic system, without diaphragm, Figure 2;
- on the acoustic system with a circular diaphragm, located in the middle of the sound tube, which can be rotated in relation to an axis that is the diameter of the circular section of the tube, in its 6 positions, figures 3 and 4.

The acoustic system was excited with White Noise (W.N.) through a generation chain, consisting of: Sine Random Generator 1027 (B&K) – Power Amplifier Type 2706 (B&K) – Speaker.

The measuring chain consisted of: Bswa Microphone –placed on the upper circular plate, near the resonator's neck – Acquisition Board – N.I. 9233– Dell Latitude D380 Laptop.

SIGNAL PROCESSING

The processing was performed using the dB software – Metravib. The processing of the signals obtained following the excitation of the acoustic system with white noise of different acoustic intensities consisted in obtaining their spectra.

Figure 6 superimposed two distinct images of the same spectrum – of the tube without diaphragm, just to show the values of its resonant frequencies with the help of sliders.

From the spectra of the excited acoustic system with different sound levels, figure 7, several resonant frequencies can be identified, figure 6, both the one corresponding to a closed cavity connected by an outer neck, and the ones corresponding to a "partially closed" tube at both ends.

Figure 8 shows some spectra of the tube with diaphragm in open position Φ = 0, excited with acoustic intensities of different levels, which highlight the first 4 resonant frequencies whose values are slightly different from those previously determined, influence due to the appearance of the diaphragm.

Figure 9 shows the spectra of the same type of excitation for different positions of the diaphragm, being highlighted with the help of the sliders the frequency band f_3 of the tube. It should be noted that all the exact results and values obtained from the measurements are presented in Table 1.

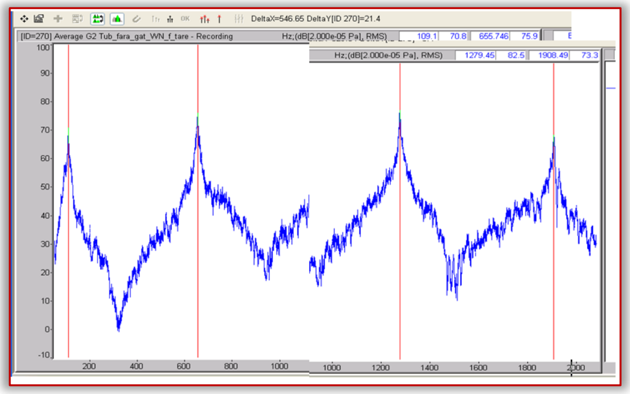

Figure 6 – Spectra of tube whitout diaphragm

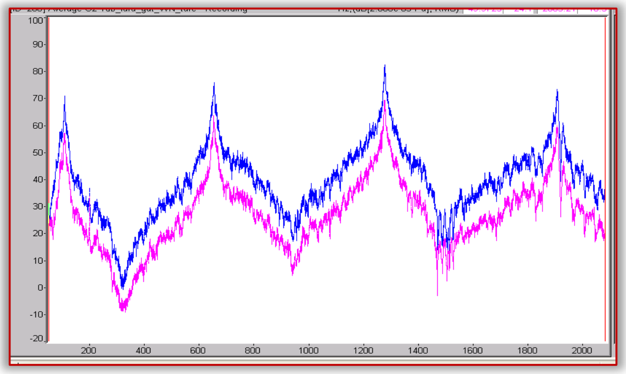

Figure 7 – Spectra of the excited acoustic system with different sound levels

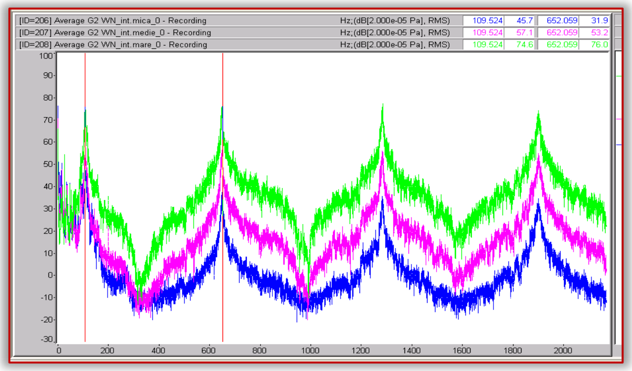

Figure 8 – Diaphragm tube spectrum, Φ=0º

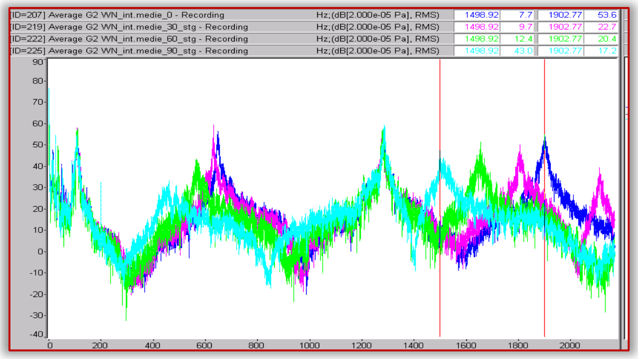

Figure 9 – Spectra of the acoustic system determined for different positions of the diaphragm

RESULTS

The processing of the signals obtained following the excitation of the acoustic system with white noise of different acoustic intensities consisted in obtaining their spectra. Table 1 shows the numerical values of the natural frequencies of the acoustic system, obtained from the realized spectra, and their comparison with those determined theoretically. Table 2 also shows the numerical values of the Eigen frequencies in cases where the diaphragm occupies different positions. As can be seen, only the frequencies f_1 and f_3 are influenced.

Table 1. Comparison of theoretical and measured frequency values

Frequency, [Hz]	f_1	f_2	f_3	f_4
Theoretical, f_T	110,84	632,35	1264,7	1897,06
Measured, f_m	109,10	655,75	1279,45	1908,49
Error [Hz], $f_m - f_T$	–1,74	23,4	14,75	11,43
Relative error, % $\left\|\frac{f_m - f_T}{f_T}\right\| \cdot 100$	1,57	3,7	1,16	0,6

Table 2. The influence of the diaphragm on its own frequencies

f, [Hz]	f_1	f_2 /ε_2%	f_4 / ε_4%
f_T	110,84	632,35	1897,06
f_{m0} – 0°	109,02	650,36	1900,23
f_{m1} – 15°	109,02	649,01/–0,2	1872,59/–1,45
f_{m2} – 30°	109,02	636,80/–2,1	1825,46/–3,93
f_{m3} – 45°	109,02	620,02/–4,7	1767,65/–6,98
f_{m4} – 60°	109,02	563,2/–13,4	1656,09/–12,85
f_{m5} – 75°	109,02	487,94/–25	1545,88/–18,65
f_{m6} – 90°	109,02	463,02/–28,8	1531,30/–19,42

The comparative analysis of the results shows that the acoustic system behaves like a Helmholtz resonator with a tube cavity, but at the same time it has a closed tube behavior at both ends, Table 1.

A first observation: there is a very good correlation between theoretically calculated and experimental values.

It can be seen that the fundamental frequency of the resonant cavity changes insignificantly with the position of the diaphragm, which leads to the idea that: does not change the elastic behavior of the air volume, nor the effective calculation length of the neck, if the diaphragm is located far enough from the neck.

Changing the position of the diaphragm affects only frequencies 1 and 3, but also other higher frequencies (not analyzed in this study) and does not change the frequency 2.

Why? The immediate answer can be given by Figure 5, in which the acoustic flows for the first natural frequencies of the tube are presented, a situation in which stationary waves appear in the tube. From the analysis of the flows it can be seen that, in the middle section of the tube, the sound wave of frequency f_2 has no acoustic flow, more precisely – the particles of the gaseous medium do not oscillate, reason for which these waves are in no way influenced by the position of the diaphragm.

The frequency f1 decreases by almost 30% with the change of the position of the diaphragm, and the frequency f3 decreases by almost 20% with this change, in relation to the position “0”.

The decrease of the values of the own frequencies 1 and 3 is mainly due to the fact that the wave fronts are deviated by the presence of the diaphragm, the waves being forced to travel a longer way in the tube, so their wavelength increases and, implicitly, decreases the frequency.

Due to the circular shapes of the tube and diaphragm section, it is difficult to find a simple theoretical model, especially since the diaphragm has a small hole in the center so as not to produce a tube rupture effect if Φ = 90°.

Because the theoretical modeling, sometimes necessary to be able to simulate the acoustic behavior of such a system, is difficult to perform on the system on which the measurements were made, empirical expressions were sought that could approximate, as a continuous function, as well as possible. this acoustic behavior of the system.

We consider that the following expressions meet these conditions

$$\varepsilon_1(\varphi) = \varepsilon_1(90) \cdot \sin^5(\Phi) \tag{10}$$

$$\varepsilon_3(\varphi) = \varepsilon_3(90) \cdot \sin^3(\Phi) \tag{11}$$

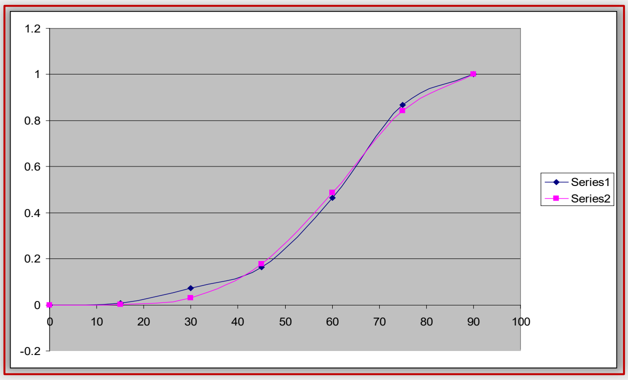

Figure 10 – Relative error ratio from frequency f_1 – series 1 and curve $\sin^5(x)$ – series 2

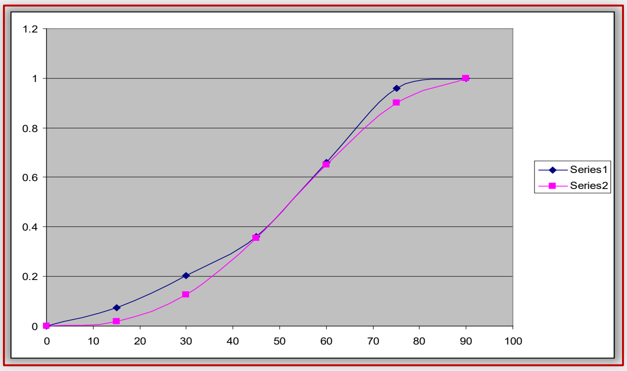

Figure 11 – Relative error ratio from frequency f_3 – series 1 and curve $\sin^3(x)$ – series 2

Figures 10 and 11 show the curves of the relative errors and those obtained by representing the empirical approximation relations, for the two own frequencies of the acoustic system.

CONCLUSIONS

The theoretical approach and experimental measurements have shown that, in the case of a closed tube acoustic system, unlike Helmhotz resonators, they have several resonant frequencies, in addition to the resonant frequency there are a large number of resonant frequencies of the tube, which overlap with the Helmholtz type. From an acoustic point of view, the resonant behavior of this system is completely different: the Helmholtz resonator produces the resonance of the vibration of the air mass located in the throat and in its immediate vicinity, while the resonance in the tube produces standing waves in it, with nodes and belly.

Of great importance in this study is the clear and satisfyingly precise link between the theoretical values of resonances and those measured experimentally. The relative errors are small, with a maximum of 3.7% in the case of the first resonant frequency of the tube, the accuracy being better and better for the next ones, reaching 0.6% in the third!

By using a diaphragm, located in the middle plane of the tube, with the change of its angle in relation to the longitudinal axis of the tube are also modified some of the resonant frequencies corresponding to the tube, more precisely the frequencies at which in the middle plane of the diaphragm the corresponding standing waves they have a knot. It can be seen that the Helmholtz frequency and the second resonant frequency of the tube are not altered by the position of the diffraction.

The Helmholtz frequency does not change because the volume of the cavity does not change (the diaphragm having a hole about 16 mm in diameter in the center), and the second resonant frequency of the tube remains unchanged because in the diaphragm area the particles do not oscillate, being a node in this plane. .

Because resonant acoustic systems can be used as both amplifiers and acoustic absorbers, by their quick and easy modification, from a functional point of view, the acoustic characteristics can be extended to their wide use as adaptive absorbing systems.

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