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# THEORETICAL AND EXPERIMENTAL STUDY OF A HELMHOLTZ RESONATOR FOR ATTENUATION OF PRESSURE WAVES IN THE PRESENCE OF PULSATING FLOW ORIFICE PLATE

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***Abstract:*** *Several hydraulic installations have pulsating flows; however, in many of them the pressure waves must be damped or even eliminated. When the considerations of a project such as limitations of space and material make the acoustic response degrade the system performance and/or create excessive noise, the solution may be to add a resonator to the system, improving therefore its response. The behavior of the Helmholtz resonator in the hydraulic system in which the flow of oil sent by a pump has opposite direction of propagation of pressure waves has been investigated. An experimental study of pulsating flow in pipes of a hydraulic bench for a resonator was conducted and the results showed that the installation of the resonator significantly affects the response of the system.*

***Keywords:*** *Helmholtz resonator. Pulsating flow. Pressure waves.*

## 1. INTRODUCTION

In some cases there is pulsating flow inside pipes and tubes that should be eliminated or absorbed. Acoustic resonators and filters are widely used for noise control, especially for noise attenuation of discrete frequencies (pure tones) in industrial processes, vehicle exhaust, among others. The acoustic characteristics of reactive silencers are determined only by its geometric shape, being designed in order to pass a fluid, strongly reducing its sound energy (KINSLER, 1982).

The principle of silencing is based on the reflection of waves for the source, in other words, waves when passing through the muffler, find a change in acoustic impedance for a very large value or a very small one. Then, a small

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portion of energy travels through the muffler and most of it is reflected back to the source. These silencers are economical and with low pressure loss of the charged fluid (TANG, 1973; GORIN, 1987; GERGES, 1992).

Helmholtz Resonator is a simple device and ideal for control acoustic systems that can be used in side vents or ducts in the walls indoors and it is used mainly as a neutralizer of sound waves at low frequencies (TANG, 1973; GERGES, 1992; KELA, 2009). An example of application is the admission system of internal combustion engine that is designed so that acoustic response enhances engine performance, increases fuel economy and reduce emissions (ORTWING, 2005; VIERSMA, 1980). Helmholtz Resonators are widely used in pneumatic systems, but there are few studies of its use in hydraulic systems.

Specifically for hydraulic systems, it is common to find installations of resonators in series in the system that substantially reduces problems associated with pressures pulses of high frequency, whether caused by the characteristic pulsatile pump, for quick closing valves or sudden changes in the direction or flow velocity.

The problem is due to design, build and install a device between the top and the bottom pipes of a flow bench used to analyze the pulsating flows output measurement. This flow bench has two orifice plates: the first one at the top pipe for steady flow measurement and the second one in the bottom pipe for pulsating flow measurement. Between these two plates there is a pressure pulse generator. The pressure waves created by the pulse generator propagate in both pipes. In the bottom ducts, the propagation direction of these waves is the same as the propagation direction of the hydraulic oil flow. In the top ducts, the propagation direction of pressure waves is opposite to the direction of hydraulic flow. To reduce or eliminate the pressure waves that propagate in the top orifice plate direction, it was decided to install between the two orifice plates a resonator, considering the efficiency in noise attenuation, the operational simplicity, the easy construction and the low cost of these devices.

The study was based on the resonator physical model, basically consisting of a cavity and a small opening (neck) that will be in contact with the fluid from the hydraulic system.

The Helmholtz resonator has been analyzed and tested in this bench with the objective of evaluating the pressure waves attenuation in the flow bench.

## 2. DEVELOPMENT

### 2.1 Fluid compressibility

All fluids are compressible. For high pressure hydraulic systems, the compressibility of the hydraulic fluid is truly important and should necessarily be considered in system design (ERNEST, 1960).

The hydraulic fluids compressibility is the predominant factor to determinate the resonance frequency of hydraulic systems. In most cases, this involves the limitation of a component response speed to a given input signal, in other words, a limitation of the dynamic behavior (LINSINGEN, 1989).

### 2.2 Speed of sound in liquids

In elastic or compressible environment, the transmission of an impulse is delayed due to the inertia of its elements. A finite time is required for the sound wave to travel a certain distance through a compressible environment (BINDER, 1951). The travel speed of this wave influences compressible flows.

The speed of sound in liquids is obtained by (LINSINGEN, 1989), Eq. 1:

$$c_{liquid} = \sqrt{\frac{\beta}{\rho}} \tag{1}$$

Where ρ is the flow density in a certain temperature and pressure ($kg/m^3$) and $\beta$ compressibility modulus ($N/m^2$).

### 2.3 Helmholtz Resonator

A Helmholtz resonator is often used to modify the acoustic response of a system. The Helmholtz resonator is basically a hole with a small opening through which the fluid contained therein will come into contact with the fluid system or the environment.

When the dimensions of the cavity of an acoustical system are small, compared to wavelength, the movement through the system is analogous to a mechanical system of one degree of freedom, which has a set of mechanical elements: mass, stiffness and damping. The Helmholtz resonator consists of an enclosure with volume V, communicating with outside through a small opening area S, radius A and length l, Fig.1. (TANG, 1973; GERGES, 1992).

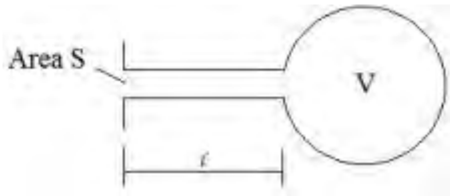


Figure 1. Simple Helmholtz Resonator

The operation of the resonator is based on reflection of waves at the source, that is, when passing through the muffler, find a change of acoustic impedance with a very small value. Then, a small portion of energy propagates through the resonator, and most of the energy is reflected back to the source (TANG, 1973; GERGES, 1992). Impedance is defined as the physical quantity which opposes the movement of the system. Inertia is the tendency not to modify the kinetic state of the system and the impedance is the tendency to eliminate movement (KELA, 2009).

In Fig. 2, when a sound wave with the same resonant frequency of the resonator goes through point C, the impedance at point A will be zero, with no pressure amplitude. So, no sound is transmitted to the output D of the tube (BINDER, 1951).

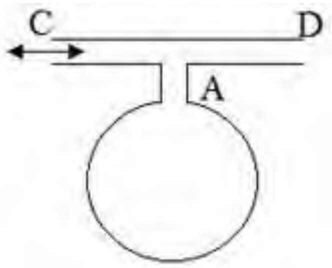


Figure 2. Closed Tube with the Helmholtz resonator in the lateral opening

The Helmholtz resonator can be considered as a system of one degree of freedom acoustic with the following three elements:

Mass element: the opening (neck), it is considered that the fluid moves as a mass element.

Stiffness: the fluid pressure inside the cavity changes when it is alternately compressed and expanded by acoustic excitation of the fluid through the opening. The volume of fluid in the cavity acts similarly to a spring.

Resistance element: resistance of the system is the term responsible for the dissipation of acoustic energy. Two mechanisms are responsible for sound absorption: the acoustic radiation of the air vibrant cylinder fluid in the opening and viscous friction between the air cylinder/fluid and the vibrating surface of the opening (TANG, 1973; GERGES, 1992).

These three elements can easily be perceived as an air jet is perpendicular to the neck cavity, Fig. 3(a). Vibrations of the air force the mass of air contained in the neck when entering in the cavity, compressing the air inside it, Fig. 3(b). The pressure generated in the cavity will now force the air mass in the neck out of the cavity so that the pressure inside it backs to its initial state, however, briefly air mass that comes out of the neck a short distance beyond the initial position, Fig. 3(c). This will make the rarefied air in the cavity and, consequently, the air mass to move back toward the inside of the cavity. This effect is similar to the vibration of a mass attached to a spring, Fig. 3(d).

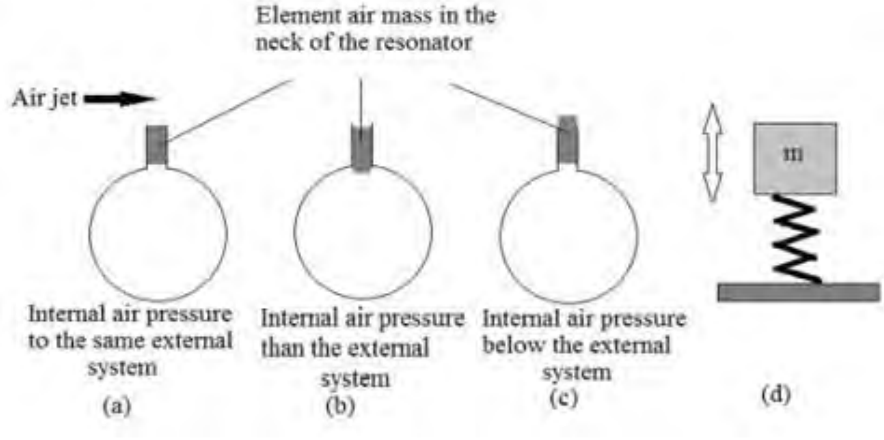


Figure 3. Analogy of the operation of the Helmholtz resonator with a mass spring system

To obtain the resonant frequency of the Helmholtz resonator, it is initially necessary to assume that the wavelength of vibration is much larger than the linear dimensions of the resonator neck. One must assume, too, that any disturbance of pressure within the cavity propagates in reversible and adiabatic conditions, and that the movement of fluid within the neck of the resonator is lossless (TANG, 1973; GERGES, 1992).

### 2.4 Installation of measuring devices in the hydraulic system pressure

To study the influence of the resonator on the system, it is necessary to compare measurements of pressure in the pipes with and without the resonator. When installing the system without the transducer resonator is required by the pulse generator (TGP), a transducer near the lower orifice plate (TPOI) and another at the entrance of the system without resonator (TES-SR). Fig. 4(a) illustrated the hydraulic bench without the resonator and the arrangement of pressure transducers.

To assemble the Helmholtz resonator installed, the transducer system entry is designated by TES-CR (system input transducer with resonator). Fig. 4(b) illustrates the arrangement of the transducers to the bench with the Helmholtz resonator. It is observed that the resonator was installed in the pipe connecting the pipe below the top, in order to mitigate the pressure waves that propagate toward the upper orifice plate.

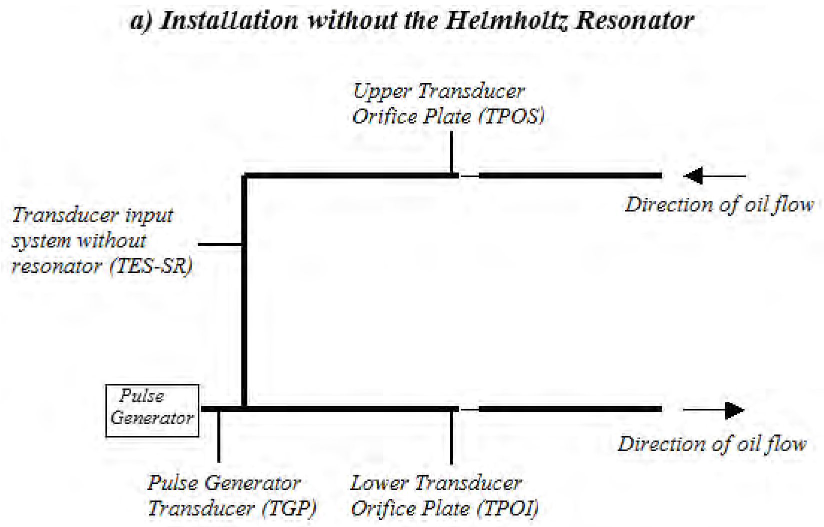


Figure 4a. Installation scheme of the bench with the main hydraulic pressure sensing assembly without the Helmholtz resonator

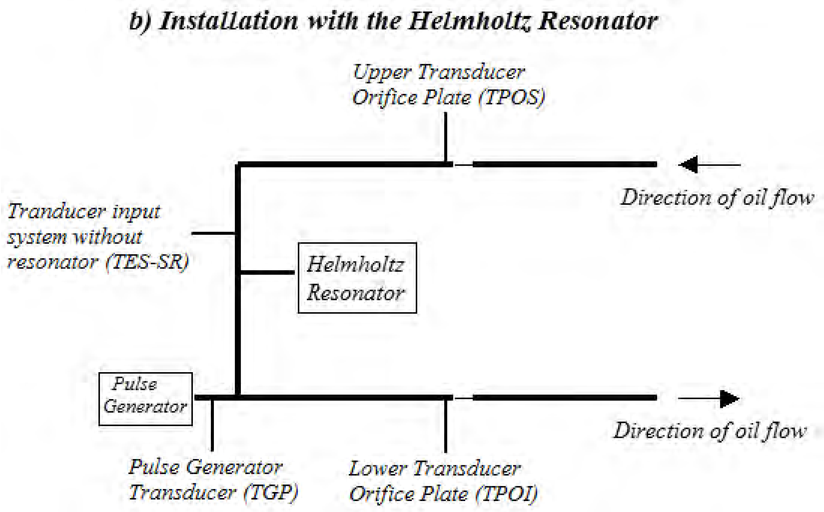


Figure 4b. Installation scheme of the bench with the main hydraulic pressure sensing assembly with the Helmholtz resonator

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### 2.4. 1 Effective Length

The mass effect of the flow on the opening equals to ρSl′ where ρ is the density of the flow, S is the area of the transverse section of the opening and l' is the effective length. The main reason of use the effective length is the effect of jet during the pulsations. A part of the air around the resonator's mouth also vibrates, which translates in a virtual increase on the length of the pipes that composes the resonator's mouth. Lord Rayleight (1981) studied the problem in details and came to a sense that the air around the resonator's mouth give the bottleneck an "acoustic" length, that does not match with the geometric length of the tube. The acoustic length is, then, the same as the geometric length plus a correction that depends on the radius of the bottleneck (DICKEY, 1996; KELA, 2009).

For a short bottleneck ($l \cong a$), the effective length (KELA, 2009)

$$l' = l + \frac{\pi a}{2} \tag{2}$$

And for ($l \approx a$):

$$l' = l \tag{3}$$

And in the case of (l = 0), it must introduce only the extremes corrections and then:

$$l' = \frac{\pi a}{2} \tag{4}$$

Where: S is the area of the transverse section of the opening ($m^2$); l' is the effective length (m) and $\rho$ is the flow density ($kg/m^3$).

### 2.4.2 Stiffness of the System

To determinate the stiffness k of the system that is caused by the flow pressure inside the cavity (mass-spring effect *F=k.ξ)*, it is necessary to calculate the force acting F on the area S when the flow on the opening is dislocate of $\xi$. So, the volume change of the flow $dV = \xi S$ and the increase of the pressure p is given by (GERGES, 1992):

$$p = \rho c^2 \frac{dV}{V} = \frac{\rho c^2 S \xi}{V} \tag{5}$$

Where: c is the speed of sound (m/s)

The stiffness strength that acts on the opening is (GERGES, 1992):

$$F = pS = \frac{\rho c^2 S^2 \xi}{V} \tag{6}$$

Therefore, the effective stiffness of the system will be:

$$k = \frac{F}{\xi} = \frac{\rho c^2 S^2}{V} \tag{7}$$

### 2.5 Resonant frequency of the resonator

Considering the resonator as an acoustic freedom degree, by the Newton's Second Law, is obtained the following motion equation for the system:

$$\sum F = M\ddot{x}$$
$$M\ddot{x} + kx = 0 \tag{8}$$

Where M represents the flow mass element contained on the resonator's neck, calculated by: (GERGES, 1992):

$$M = \rho l' S \tag{9}$$

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The resonant frequency for the not damping system is given by (ALSTER, 1972; GERGES, 1992):

$$\omega_0 = \sqrt{\frac{k}{M}} = c\sqrt{\frac{S}{l'V}} \quad (10)$$

Where $\omega_0$ results in a value in radians for time unit. For resonant frequency in cycle values for time unit (Hertz) is given:

$$f_0 = \frac{c}{2\pi}\sqrt{\frac{S}{l'V}} \quad (11)$$

This frequency equals to the damping resonant frequency, once the damping caused by the sound radiation and viscosity is really small (ALSTER, 1972; GERGES, 1992).

The pressure waves damping in systems with the Helmholtz Resonator is given by the frequency around the resonant frequency of the resonator $f_0$, characterizing it as a Band Stop filtering Fig 5. The response of a resonant frequency wave form of the Helmholtz Resonator on it resonant range is established by the quality factor Q, defined by (GERGES, 1992):

$$Q = 2\pi\sqrt{V\frac{l'^3}{S}} \quad (12)$$

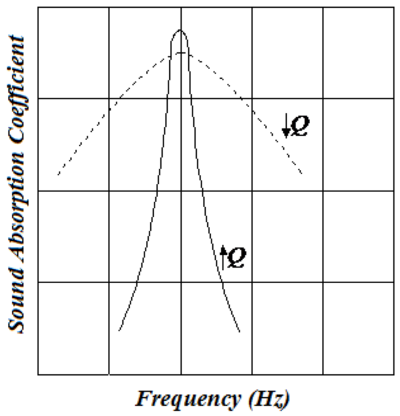


Figure 5. Sound absorption for different quality factor's Resonators Q

The flow bench is under study for the analysis of flow measurement in pulsating flows and has two orifice plates: one at the top piping for flow measurement in steady state and the other in the bottom piping for measuring pulsating flow. Between these two boards is a generator of pressure pulses, Fig. 6.

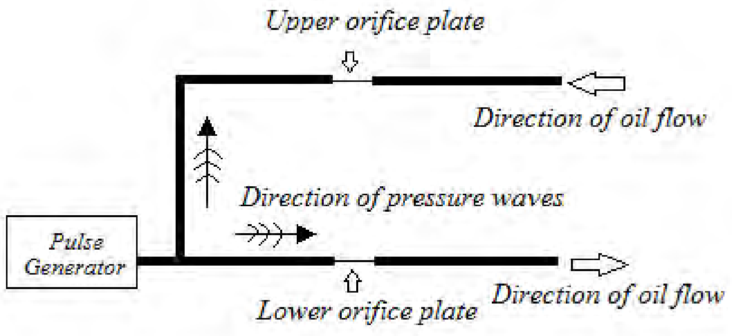


Figure 6. Installation diagram of the hydraulic flow bench

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In Fig. 6 it is noted that the pressure waves created by the pulse generator are propagated in ducts below on the same direction of propagation of flow of the hydraulic oil. Already in the pipeline above, the meaning of such propagation is opposite to the direction of oil flow.

The problem is, therefore, to create a device between the upper and lower pipes that reduce or eliminate the pressure waves that propagate in the direction of top orifice plate, maintaining a constant pressure in this measurement system. For this, we chose to install a resonator in the system between the two orifice plates considering the efficiency of noise attenuation, the operational simplicity and the ease and low cost of construction of these devices.

The study will therefore be based on the physical model of the resonator, basically consisting of a cavity and a small opening (neck) that will be in contact with the fluid from the hydraulic system. The resonator in series will be examined and tested on the bench in order to attenuate the pressure waves to flow bench in question.

To perform experimental tests, it is recommended to do it in a large frequency range. To do so, using the largest possible volume of the cavity, the neck length can alternate from 0.2 m to 2.0 m (obeying the physical limitations of the experimental setup). The internal diameter of the neck should preferably be equal measures of tubes found in general commerce.

With these values, it is possible to work with resonance frequencies of the resonator in the frequency range of 11.62 Hz to 80.50 Hz.

Analyzing the results obtained experimentally, it is observed that to have greater mobility of the frequency applied during the tests, the most suitable dimensions for the construction of the Helmholtz resonator are values near to:

| | |
|---|---|
| Volume of Cavity: | $V = 0{,}03\ m^3 = 30\ l$ |
| Diameter of Neck: | $d = 0{,}015$ m |
| Length of Neck: | $l = 0{,}25$ m a 2,00 m |

## 3. INSTALLATION OF THE PRESSURE MEASURING DEVICES ON THE HYDRAULIC SYSTEM.

Some strategic points for the installation of pressure transducers were defined, but they may change according to the position on the hydraulic system.

To study the influence of the resonator on the experimental bench, it is necessary to compare the system pressure measurements with and without the resonator. Thereunto, the system without the resonator requires a transducer near the pulse generator (SGPT), one close to the bottom orifice plate (TPOI) and the other at the entrance of the system without resonator (TES-SR). Figure 4(a) illustrates the hydraulic bench without the resonator and arrangement of the pressure transducers.

For the Helmholtz resonator installation, the transducer system of the entry is designated by TES-CR (transducer system of the input with resonator). Figure 4(b) illustrates the arrangement of the transducers for the bench with the Helmholtz resonator. It is observed that the resonator was installed in the pipe connecting the pipe below to the top tube, aimed an attenuation of the pressure waves that propagate toward the top orifice plate, because the direction of propagation of pressure waves is the opposite to the flow of hydraulic oil in the system.

Unlike the bench with the Helmholtz resonator, it is observed that the resonator is installed in series in the system. The input (TER) and output signals (TSR) of the resonator will be different at least due to the pressure drop caused by the passing fluid in the resonator.

## 4. HELMHOLTZ RESONATOR ANALYSIS

The Helmholtz resonator is a device commonly used for the attenuation of acoustic waves in gaseous environment, but there are few studies of its application in liquid environment. It is important to remember that the direction of the pressure wave's propagation direction in the present study is contrary to the hydraulic oil flow direction. The operation of the hydraulic system without the resonator will be presented for, posteriorly, compares the results with those obtained after the installation in the hydraulic bench. From this comparison, the absorption coefficient of pressure waves in the system with the Helmholtz resonator will be obtained.

### 4.1 Hydraulic system without the resonator analysis.

The analysis of the hydraulic system without the resonator allows us to observe the behavior of pressure waves moving through the pipe.

From several measurements, the amplitude value of the pressure wave at the entrance of the system without resonator is calculated for each frequency (TES-SR). Figure 7 illustrates, for three levels of system pressure, curves of the amplitude variation of waves on the frequency domain.

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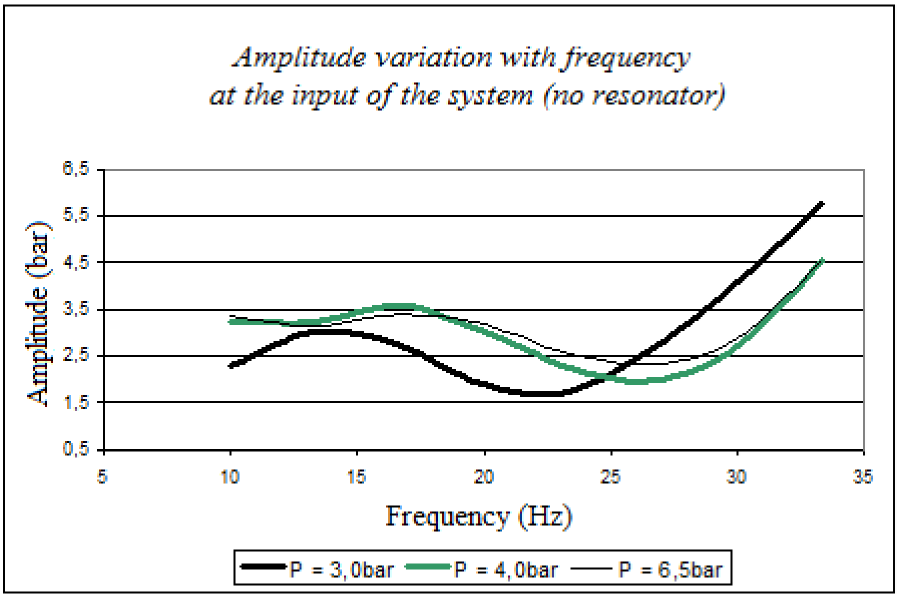


Figure 7. Variation of wave amplitude at the input of the system without resonator (TES-SR) with frequency, for different pressure levels of the hydraulic pump

Whatever the level of pressure in the system may be, the Fig. 7 shows that the curve shape of the amplitude versus frequency, despite moving position, is maintained.

### 4.2 Helmholtz Resonator influence on the hydraulic system analysis

This analysis is based on experimental data obtained in the pulse generator sensor (TGP) and the transducer at the entrance of the resonator system (TES-CR). A comparison between these data and the data on the system without the resonator shows the influence of the resonator system.

From the measurements, is drawn the curve of the pressure waves amplitude variation in the system entrance (TES-CR) on the frequency domain. Figure (8) shows that the curve superimposed on the curve of the pressure waves amplitude variation on the input system without the resonator (TES-SR) to a level of 6.5 bar pressure and neck length of 1.0 meter.

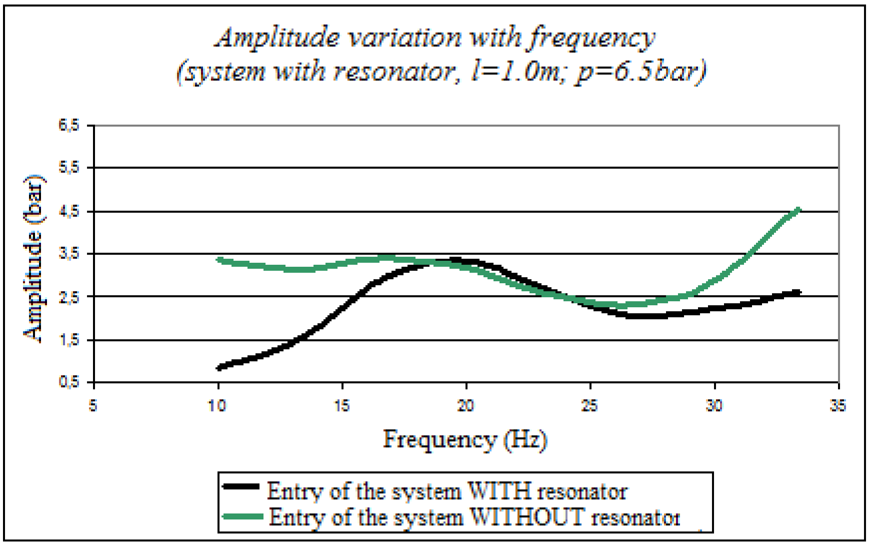


Figure 8. Variation of pressure amplitude at the input of the system with and without the Helmholtz resonator in the frequency domain, w / pressure level of 6.5 bar and 1.0 m length of the neck

It is observed in Figure (8) that the shape of the amplitude variation of the pressure curve at the input of the system without the Helmholtz resonator (TES-SR) has changed considerably in relation to the system input curve with the

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resonator (TES-CR) at frequencies below 20 Hz. It can be seen that the Helmholtz resonator changes the system response.

Changing the pressure level in hydraulic bench and the length of the neck of the Helmholtz resonator, the system behavior is similar to the one that is shown in Figure (8).

The absorption coefficient of the Helmholtz resonator in the hydraulic system varies with frequency. For this case, the coefficient is obtained from the following relation:

$$Absorption\ Coefficient = (1 - \frac{Wave\ amplitude\ on\ the\ system\ input\ with\ the\ resonator}{Wave\ amplitude\ on\ the\ system\ input\ without\ the\ resonator})x100$$

Figures 9 and 10 illustrate the Helmholtz resonator absorption coefficient curves, which varies with the frequency for different levels of pressure and length of the neck, respectively.

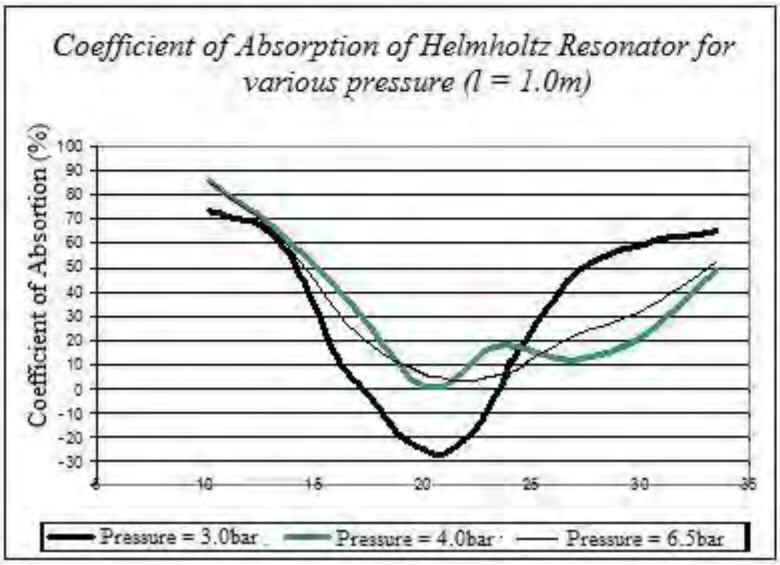


Figure 9. Absorption Coefficient of Helmholtz resonators with varying frequency, for various pressure levels and neck length set at 1.0 m

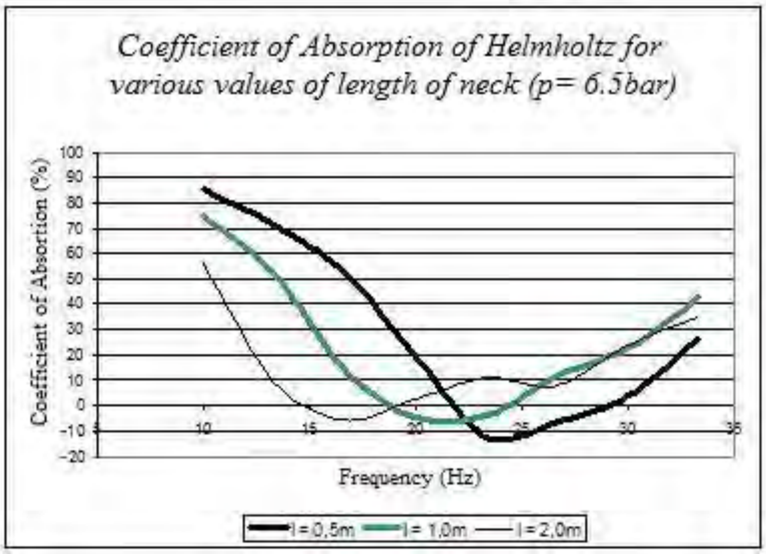


Figure 10. Absorption Coefficient of Helmholtz resonators with varying frequency, for various values of neck length and level of pressure in the system fixed at 6.5 bar

In the analysis of the Fig.9 and 10 it can be observed that the installation of the Helmholtz resonator changes the response of the hydraulic bench. However, the range of frequencies that the Helmholtz resonator absorbs waves of pressure in the system is small, and its installation on the system unworkable.

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### 4.3 Final Thoughts on the Helmholtz resonator

For the experimental setup in question, however, the installation of the Helmholtz resonator in a hydraulic system has not achieved its goals, as one would expect an attenuation of pressure waves in at least 85% in the frequency range analyzed.

Among the models and the different configurations of resonators studied, only the resonator in series installation with neck at the entrance of pressure waves, Fig. 11, met the objectives of the present work. This resonator is able to absorb the pressure waves that pass through it without, however, create large changes in the response of the system downstream of it. The layout of your installation on the flow bench is represented by Fig. 11.

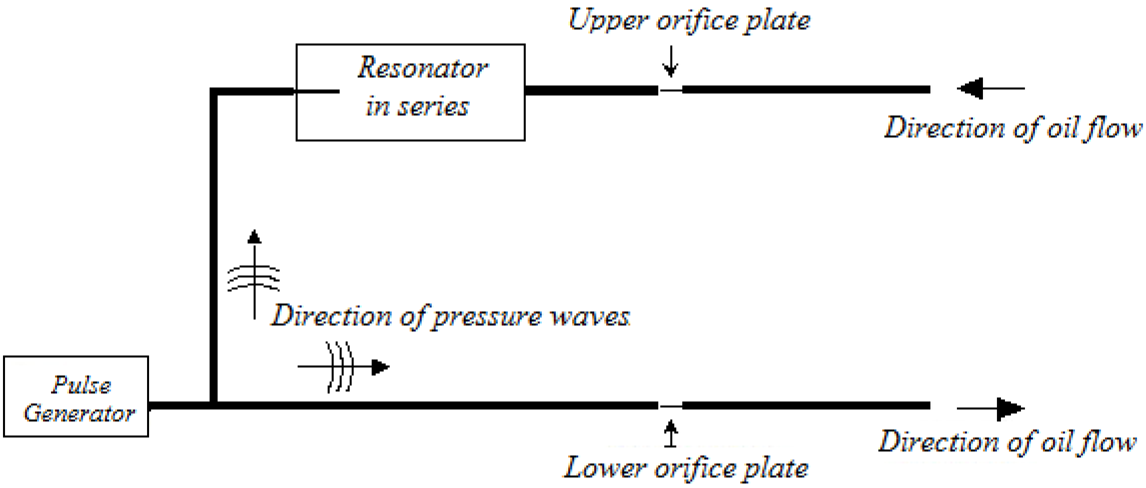


Figure 11. Schematic draw of the flow bench with the resonator in series, with the neck at the entrance of pressure waves

## 5. RESULTS

After several tests and adaptations in resonators, a result was obtained that satisfies the prerequisites the flow bench functioning study: steady flow in top pipe and pulsating flow inside lower tube. Thus, the pressure waves from the pulse generator must not be altered or, at most, have small changes in order to maintain the characteristics of the pulsating flow. Downstream, the pressure waves should be mostly damped in order that the top pipe flow must be on steady-state or, at least, as close to that.

The best results according to the characteristics described above were obtained by the resonator in series on the hydraulic system, with the neck / restriction at the entrance of pressure waves. The main dimensions of the analyzed resonator are: Volume = 30 l; Inner diameter of the neck: 0.015 m; Length of the Neck: 0.83 m.

The analysis is made downstream from the resonator comparing results obtained in the inlet and outlet of the resonator. With these comparisons, it was checked whether or not if the resonator was absorbing the pressure waves passing through it.

## 6. CONCLUSION

A study of the Helmholtz resonator influence in a hydraulic system where the oil flow direction is the opposite of the pressure waves propagation direction was presented.

The Helmholtz resonator affects the hydraulic bench, however, the pressure waves frequency band absorbed by it is small. For the experimental bench in question, the installation of the Helmholtz resonator has not achieved the goal, because it was expected pressure waves attenuation in at least 85% in the analyzed frequency range.

The Helmholtz resonator installation in hydraulic bench changes the system response. Thus, according to the objectives of the present work, the installation on the system is impracticable.

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