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NUMERICAL AND EXPERIMENTAL INVESTIGATION OF THE LEAKAGE VIBRO-ACOUSTIC SIGNAL IN A PLASTIC WATER PIPE

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Abstract. *Currently, according to the National Sanitation Information System (SNIS), water distribution companies in Brazil lose, on average, more than a third of their treated water. Most of this due to real losses, as leaks at the operating units along the supply system. To change this scenario faced by water supply companies, it is necessary not only to explore the detection methods, but also to characterize the vibro-acoustic signal generated by the leak. This work provides a better understanding of the characteristics of the leakage signal, and the natural frequencies of the system and also analyzes the influence of the pressure and the leak diameter on the propagation of the signal. The study was performed experimentally and some results were compared with numerical analysis.*

Keywords: *Leak signal, water distribution pipes, vibrations, acoustic method.*

1. INTRODUCTION

The current scenario faced by the water distribution sector in Brazil should not be ignored. According to the latest research realized by SNIS, the national average of treated water losses reaches 38% (SNIS, 2017). These losses lead to inflation in the final cost and therefore, unnecessary exploration of natural water resources.

Many techniques are being developed and improved in recent years in order to better estimate the location of the leaks. Among them stands out the acoustic methods, which uses the leakage own vibro-acoustic response for its detection and have been shown to be effective and common use in the water industry (Fuchs and Riehle, 1991). Usually, the used techniques are: noise correlator, geophone, and listening stick (Hunaidi, 2000).

The vibration along the pipe is due to the Fluid-Structure Interaction (FSI) between the contained water and the pipe skin. Studies show that energy transmission is dominated by the circumferential modes in which the pipe pulsate, changing their volume and internal fluid pressure (Moore, 2016), and generating axisymmetric waves (Pinnington and Briscoe, 1993).

Structural vibrations of pipelines show a two-dimensional modal pattern, being formed by circumferential modes (n) and associated axial modes (m). In tube-fluid system, each circumferential mode will be associated with an unlimited number of axial modes (Pavic, 1991). Figure 1 shows a schematic representation of these modes.

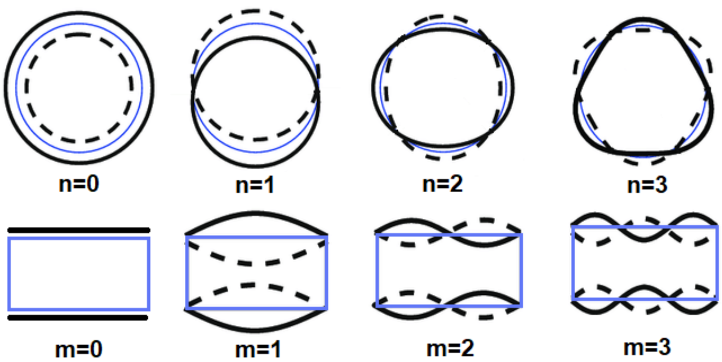


Figure 1. Schematic representation of the first circumferential (n) and axial (m) modes.

The size and the type of leakage also influence the noise characteristics, such as its intensity and its dominant frequencies. It is worth noting that the signal intensity is more related to the water pressure in the pipe than to the size of the leakage, which explains the difficulty in detecting leakage in low-pressure systems (<1 kgf/cm^2) (Hunaidi, 2000).

By means of experimental tests and numerical simulations, the natural frequencies and the relevant modes of vibration were found, which have much of the energy of the measured signal on the system. This paper investigated the influence of the pressure and the leakage diameter on the characteristics of the generated vibro-acoustic signal.

2. NUMERICAL SIMULATION

In this study, a numerical analysis was performed by using Finite Element Method (FEM) to the aim of understanding the behavior of the system. The simulation was done using a general-purpose package in ANSYS Workbench. The complex system approached is built in stages.

Different phenomena might happen when a fluid medium interacts with the internal pipe structure. So, the vibrations occur due to the internal forces resulting from these interactions.

The first step starts with a fluid flow simulation to calculate the pressure fluctuation inside the pipe. These pressure results obtained from ANSYS CFX can be imported as pressure loading and applied to the internal pipe wall in the structural stress analysis. After obtaining the Computational Fluid Dynamics (CFD) results and the structure analysis results, the can be coupled field pipe-water and used in a modal analysis of the whole structure. This simulation is only possible because of the chosen software has the ability to consistently carry the parameters and variables between the different analyzes (Jweeg and Ntayeesh, 2015).

The physical properties of plastic pipe and water, in the analysis, were based on technical catalogs. The filled pipe was pressurized to 1.1 kgf/cm^2, and has a modulus of elasticity E = 2.8 GPa, a Poisson coefficient $\upsilon = 0.38$ and a density $\rho = 1410$ kg/m^3.

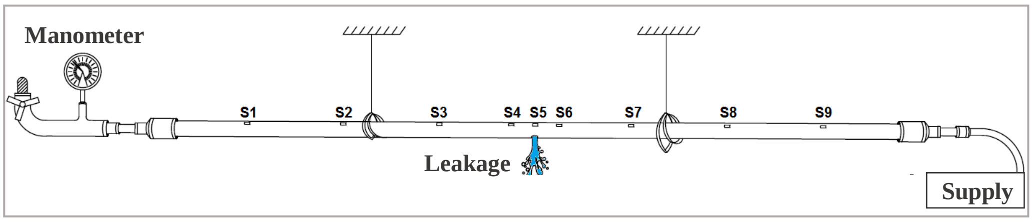
3. EXPERIMENTAL TEST

The experimental tests used polyvinyl chloride (PVC) pipe, which complies with Brazilian Standard NBR 5648 (ABNT, 2018) that specifies the requirements for PVC-U pipes and fittings for water distribution.

The pipeline has 3m length and 50mm diameter and as shows the Fig. 3, it was suspended by elastic latex tubes at both ends to minimize link effects. The leak was simulated in the center of the pipe by a circular hole with 1mm and 2mm diameter. Using the local water network via a water tap, the system was supplied and pressurized with three different pressures 0.5 kgf/cm^2; 1.1 kgf/cm^2 and 2.6 kgf/cm^2. Between the tap and the pipe connector, there is a 30m rubber hose to reduce the effects of turbulence and the network disturbances.

The vibro-acoustic signal of the leak was collected along the pipe during 30s, with nine uniaxial accelerometers fixed therein, and the pressure was measured with a Bourdon manometer installed at one end of the tube. The Siemens LMS ScadaXs acquisition system was used.

Figure 2 shows the schematic representation of the experimental apparatus and the relative position of each sensor and Figure 3 exhibit test bench. It was adopted as zero mark the place where the leakage is located. The signals collected by the nine accelerometers were treated and analyzed in the frequency domain.



Sensors	S1	S2	S3	S4	S5	S6	S7	S8	S9
Position [m]	- 1.2	- 0.8	- 0.4	- 0.1	0	+ 0.1	+ 0.4	+ 0.8	+ 1.2

Figure 2. Schematic representation of the experimental apparatus.

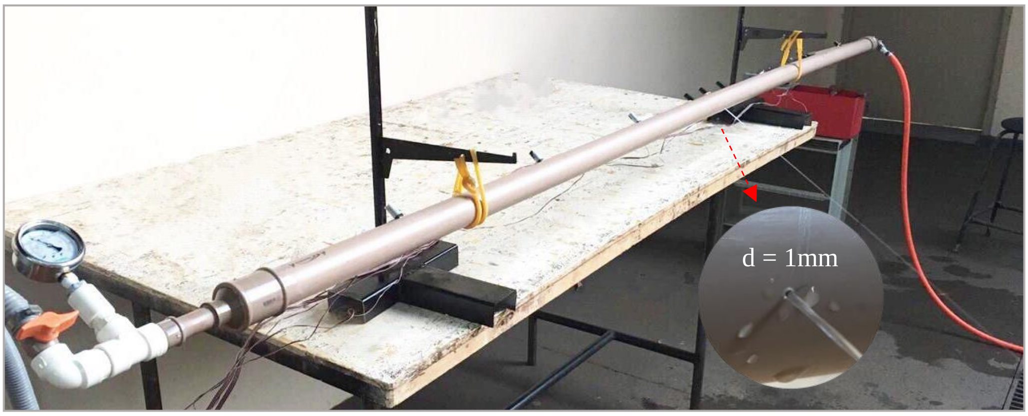


Figure 3. The test bench. Hole diameter d = 1mm.

4. RESULTS AND DISCUSSION

The Power Spectral Density (PSD) was calculated for the sensor S5, behind the leakage, for three different water pressures. In order to observe the relationship between the signal amplitude and the working pressure, as well as the attenuation of the signal along the PVC pipe, the RMS values of each sensor were collected for the same worked pressures. The results of the 1mm hole case are shown in Fig. 4 and 5.

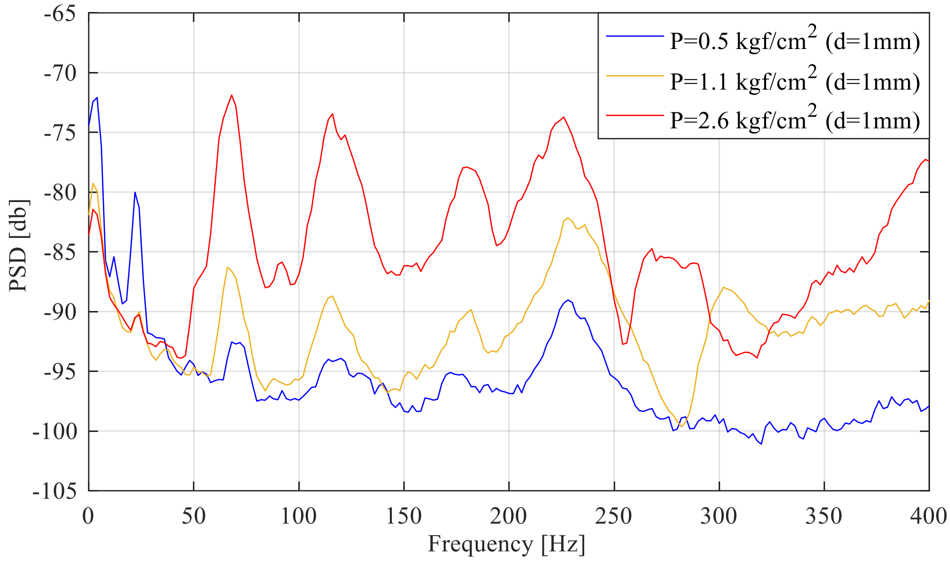


Figure 4. Power Spectral Density of signals collected by the fifth sensor, on three different pressures (Ø=1mm).

The Table 1 compares the numerical results with the experimental ones - PSD. As can be seen, the simulation has achieved good results, providing the natural frequencies and the vibrations modes of the system.

Table 1. Comparison of the numerical and experimental results (frequency peaks on PSD curve) [Hz].

Num	4.2	12.4	21.0	33.2	54.4	84.8	123.3	151.1	169.1	221.9	234.8	280.8	320.6	345.7
Exp	2.0	11.0	24.0	36.0	50.0	66.0	116.0	152.0	160.0	182.0	228.0	302.0	332.0	344.0

In the numerical simulation, it is seen that the third circumferential mode dominates in the range third of 12 - 55 Hz, and the second mode dominates in the range of 56 - 150 Hz. In 151 Hz happen the arrangement (m = 0; n = 0).

As studied by Moore (2016) the circumferential modes in which the pipe pulsate dominate the energy transmission because they change the pipe volume and the internal fluid pressure. Experimentally, for all tests, a large concentration of energy was observed in the 200-300 Hz range, for all nine sensors and there was good coherence between them. As expected, the numerical simulation showed pulsating circumferential modes in this range. This effect can be seen in Fig. 5, which shows the spectral density of sensors S1, far from the leak, and S5, behind the leak.

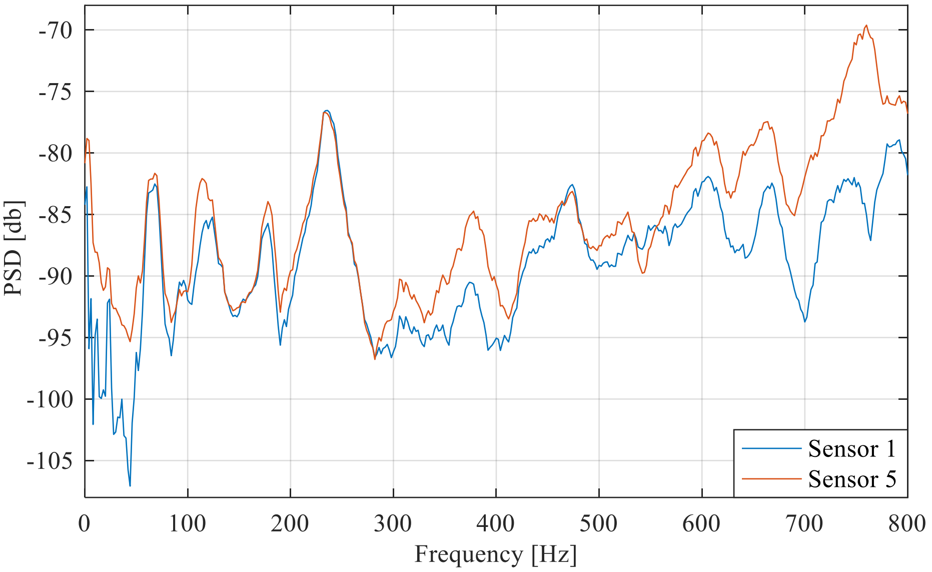


Figure 5. Comparison of the Spectral Density of the signals collected by S1 and S5 (P=0.5 kgf/cm^2).

Figure 6a shows the 3rd circumferential mode associated with the 2nd axial mode (m = 2; n = 3), in 33 Hz, and Fig. 6b shows the 2nd circumferential mode associated with the 5th axial mode (m = 5, n = 2), in 123 Hz. The last two figures show the first and the third circumferential mode n = 0.

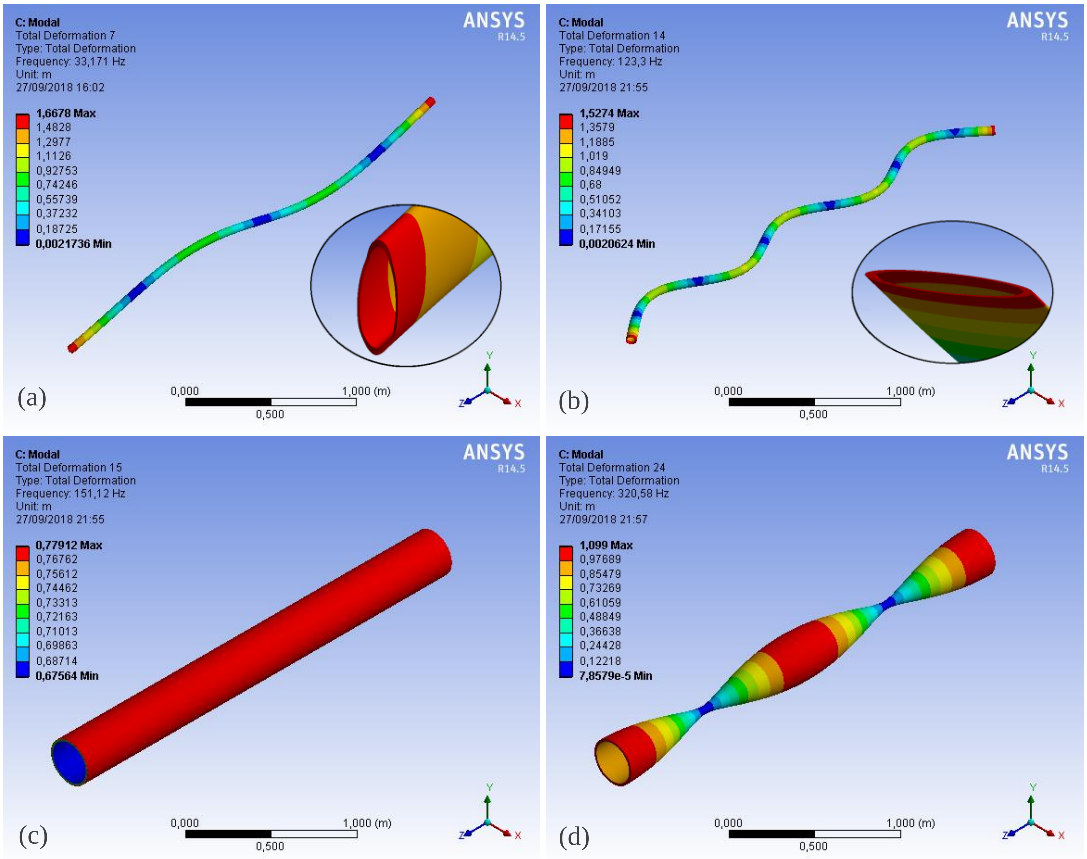


Figure 6. Post-processing of numerical simulation.

After 151 Hz to 1026 Hz when the n = 4 domain starts, it was noticed in the simulation that the pipe pulsation ceases to be axisymmetric, which explains the observed delay in this range between the signals in the experimental analysis. This effect can be easily noticed in the phase of the nine signals.

Regarding the damping effect, the plastic in which the pipe is made rapidly attenuates waves along the length of the PVC pipe (Almeida et al, 2015), and it also behaves as a filter, attenuates high frequencies more efficiently than low frequencies. In this way, the further away the sensor is from the excitation generated by the leak, smaller will be the received frequency content. In the Fig. 7 it is seen that the RMS values of acceleration measured at 0.1m (S4/S6) and 0.8m (S2/S8) away from the leak is, on average, 26% and 76% lower than the one measured at 0m (S5), respectively.

Reducing the pressure from 2.6 kgf/cm^2 to 1.1 kgf/cm^2 there was a 36% change in the RMS value of the acceleration, and the reduction from 1.1 kgf/cm^2 to 0.5 kgf/cm^2, 25%.

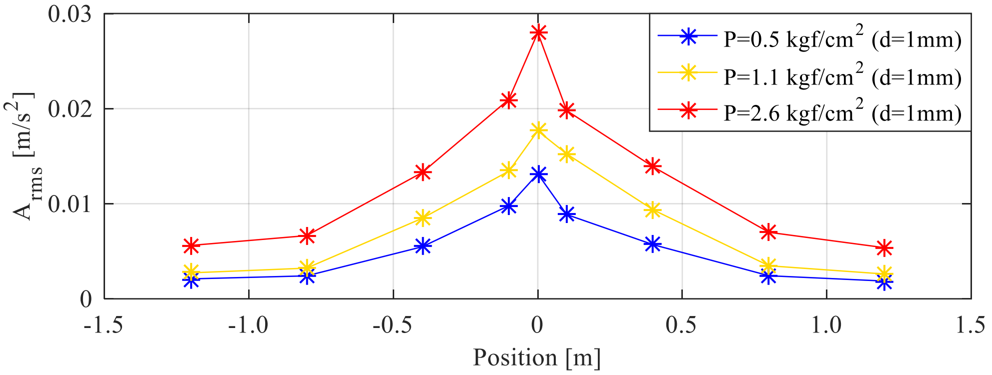


Figure 7. RMS value of the acceleration of each sensor, on the three performed tests (1mm diameter hole).

After increasing the diameter of the circular hole to 2 mm, making the leakage area 4x larger, the results were compared. There was, on average, an increase of 67% in the effective values measured at 0m (S5). In the other positions, the increase was without much expressiveness. Then these results are consistent with the observations made by Hunaidi (2000), who shows that the signal intensity is more influenced by the change of water pressure in the pipe, than with the size of the leakage.

In Figure 8 it is possible to note the comparison of the results found in the two arrangements. The significant energy increase in the last situation - ∅ = 2mm; P=2.4 kgf/cm^2 - will be further investigated in the future.

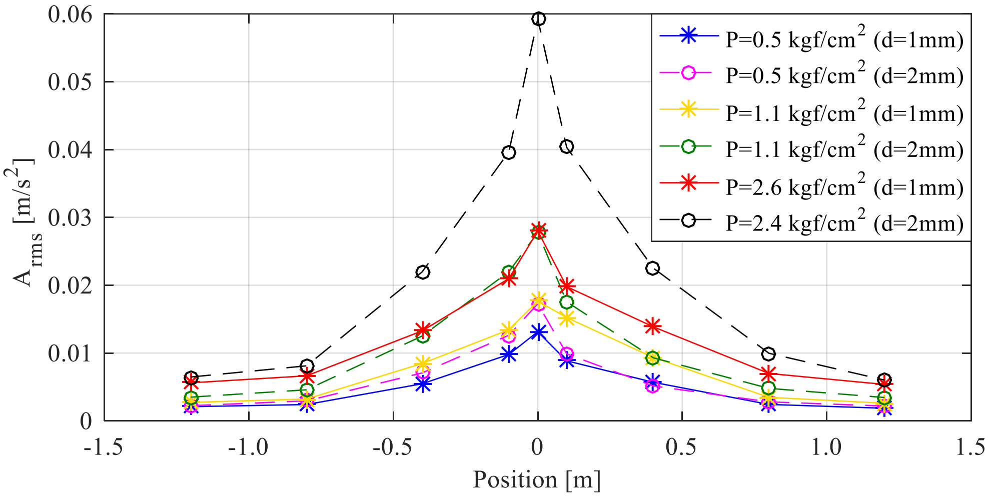


Figure 8. Comparison of RMS value of the acceleration of each sensor
for the two leakage diameters on the three pressures practiced.

In this second event, with the reduction of the pressure from 2.4 kgf/cm^2 to 1.1 kgf/cm^2, occurred a 53% increase in the effective value of the acceleration at 0m (S5), and, with a reduction from 1.1 kgf/cm^2 to 0.5 kgf /cm^2, 38%. With increased hole of the leak, the system became more sensitive to pressure change.

Again the acceleration rapidly decayed along the pipe; maintaining almost the same levels of reduction. The RMS acceleration value of the signal collected by the sensor located at 0.1m (S4 / S6) and 0.8m (S2 / S8) of the leakage is, on average, 32% and 83% lower than the signal collected on the opposite face of the leak (S5).

In Figure 9 it is possible to compare the energy content of the two events approached. As can be seen, the size of the hole did not imply such a significant change in signal energy. However, it is possible to see that the 1mm hole, in general, excited the lower frequencies better, than the 2mm hole.

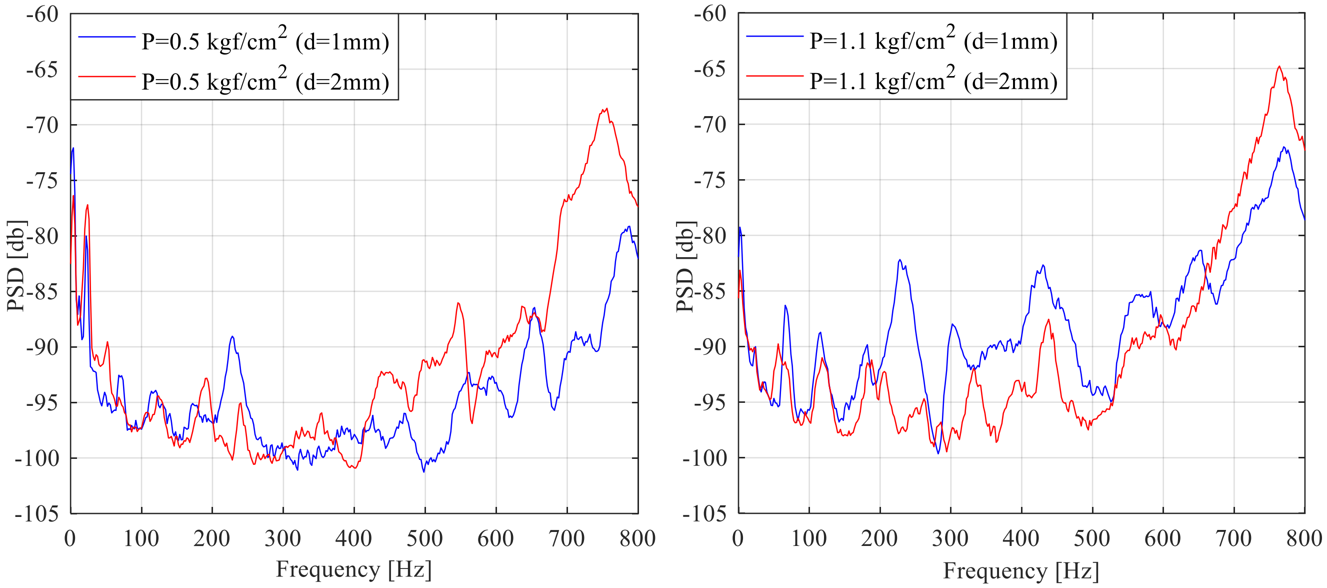


Figure 9. Comparison of the Power Spectral Density of signals collected by the fifth sensor on two different pressures (2mm diameter hole).

The relationship between the pressure and the signal intensity is shown in Fig. 10 and the increase of the leakage area provided a change in the relation of parameters. For the first case, the ratio can be linearly adjusted, while for the larger diameter hole the ratio best fit a second-degree equation. It is also interesting highlight that the increased leakage hole has made the system more sensitive to pressure change.

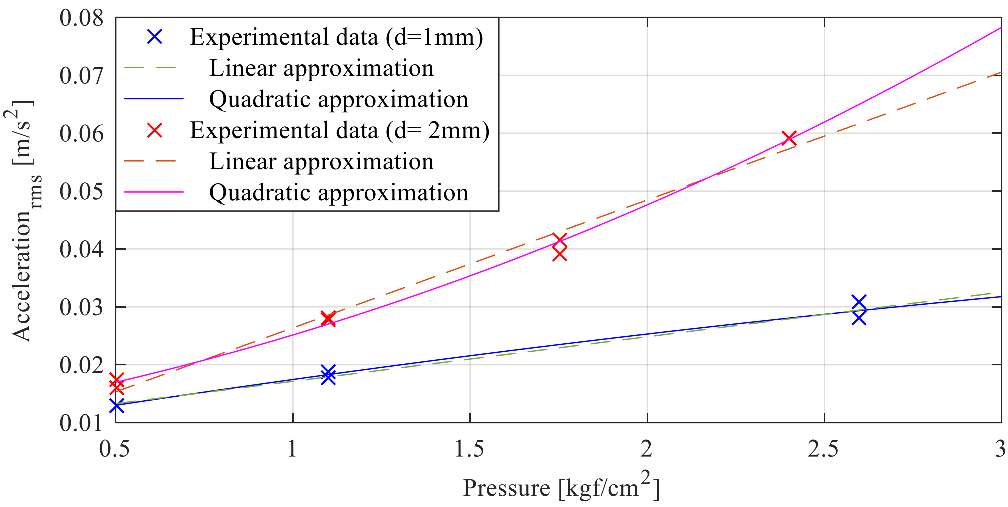


Figure 10. Pressure vs. acceleration (RMS) value for the two setups of the hole.

5. CONCLUSION

By means of the experimental tests and the numerical simulations done, the natural frequencies and the relevant modes of vibration of the system were found. The energy transmission is dominated by the pulsating circumferential modes. Three of these modes are found in the frequency range 150-320 Hz.

The simulation results were coherent with the literature and it could be validated experimentally, becoming a viable tool to understand the behavior of the pipe-water system and the excitation itself.

This paper also investigated the influence of the pressure and the leakage diameter on the characteristics of the generated vibro-acoustic signal. As already mentioned by Hunaidi (2000), the signal intensity was more influenced by the change of water pressure in the pipe than by the size of the leak. However, it was observed that the system became more sensitive to pressure change, with the larger diameter hole.

Due to the absorption effect of the plastic material, the high frequencies are effectively more damped than the low frequencies, thus, in frequency content collected by the sensors far from the leakage, predominates the low frequencies.

It should be emphasized that the vibro-acoustic signal generated by the leakage in submerged pipelines is not only due to the pipe vibration itself (FSI), but also due to the sound of water impact on the ground, water flow sound and the friction sound of the fluid against the pipe (Fuji Tecom, 2018), which should be taken into account and will be studied in future works.

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