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QUALITATIVE ANALYSIS FOR CHARACTERIZATION OF ABRUPT LEAKS FROM PRESSURE SIGNAL ANALYSIS IN THE FREQUENCY DOMAIN IN STEADY-STATE AND TRANSIENT SINGLE-PHASE (LIQUID) FLOW

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Abstract. *The purpose of these work deals with the development of a system to recognize abrupt leaks (ruptures) in pipelines, on condition of steady-state and transient flow in single phase (liquid) flow, by analyzing the signal acquired from fast response pressure sensor (cutoff frequency over than 250Hz). In this way, analysis in frequency domain is evaluated to extract characteristic information to classify signals with and without leakage, both in steady-state and transient flow. The results were analyzed qualitatively to evaluate possible techniques for signal analysis applied to detection of ruptures. The results show to be promising, since the qualitative analysis of frequency domain shown to be applicable to characterize signs of leakage.*

Keywords: *Leak detection, signal processing, frequency analysis, instrumentation.*

1. INTRODUCTION

The present work deals with the analyze in frequency domain the signal acquired from fast response pressure sensors (cutoff frequency over than 250Hz) from hydraulic transients (abrupt leaks) in pipeline, on condition of steady-state and transient flow in single phase (liquid) flow.

It should be noted that the use of pipelines for the transport of liquids, gases and particulates is present in many industrial processes, due to in many cases the transport pipeline has a higher economic viability when compared to other methods of transportation (Urbanek, Barszcz and Staszewski, 2011).

In this context, the present work aims to study a technique to detect abrupt leaks in pipelines, based on analysis of the dynamic pressure signal (acquired in different positions of the pipeline) evaluating the signal in the frequency (by analyzing the Fourier transform of the signal), to transient or steady-state flow under certain schemes, such as starting and stopping pumps, opening and closing the line lock valve, for single-phase (liquid) flow.

2. LEAK DETECTION IN PIPELINES

Corrosion problems, fatigue, faulty welds, sudden changes in pressure and actions of others can affect the integrity of a pipeline and cause leaks in various proportions and according to the product carried, it represents serious environmental damage, and economic loss.

Many leak detection techniques even show stable in a laboratory environment, but are not yet sufficiently robust for practical application in the field. Thus, several techniques for detecting leaks in pipelines have been proposed and Khomairi (2010) classifies the detection methods into three major types: observational, software based and hardware based methods.

The leak detection systems based on observational methods are simpler to perform leak detection, basically consisting of visual inspection (can use security cameras, aerial inspections, infra-red cameras).

Concerning the software based leak detection systems has a higher cost and require a large processing capacity, and this makes the use prohibitive in short pipelines. Commonly, a Supervisory Control and Data Acquisition (SCADA) is used to capture process data such as pressure, flow, temperature, density, among others, and then the data is analyzed to detect possible leaks in pipelines. Among the methods based on software, include: mass balance; analysis of transient dynamic fluid; inverse analysis of transients; mathematical modeling in real time.

Regarding the hardware based leak detection methods, different electronic devices are used for detection and location of a leak which can be classified according to the detection principle. Noteworthy the method of acoustic leak detection in pipelines.

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2.1. PRESSURE SIGNAL ANALYZE IN THE FREQUENCY DOMAIN APPLIED TO LEAK DETECTION

Since the dawn of human life signals are used for communication and to transfer information. From the five basic senses (sight, hearing, smell, taste and touch), the human body acquired external signals and uses these signals to classify patterns. Boubaker et al. (2012) estimated that there are specific areas of the brain which are responsible for certain types of classification, that is, there are areas trained to respond to stimulus from external signals and classify those signals.

In a mathematical analysis there are several techniques used to analyze a signal in order to identify the characteristic parameters, to be able to sort and group different types or classes of signal. Usually, such techniques can be applied to the signal in the time, frequency or time-frequency domain.

Haykin and Veen (2001) show that a signal (periodic or not) can be reconstituted from a weighted superposition of complex sinusoids, and the frequency analysis of signals look up the weightings of each sinusoid.

Cohen (1995) mentions that there are three great reasons to analyze the signal spectrum (frequency domain analysis). First, because from the spectral analysis, information can be extracted from the generating source of the signal. Second, it is noted that a signal propagating through a medium is dependent on the frequency (or wavelength) of the signal. A practical example is the propagation of light in a glass medium, but this occurs in a middle of aluminum, for example, while the X-ray propagation can occur in the middle of aluminum. It should be highlighted that the signal propagation medium has great effects on the attenuation of frequency components in the signal propagation, and Martins (2011) demonstrated empirically in a study for the attenuation of transient hydraulic pressure to a leak signal in multiphase flow (liquid-gas).

Furthermore, Cohen (1995) reports that the third reason for analyzing the spectrum of the signal is to simplify the understanding of the signal, as detected characteristic frequencies present in the signal, whereas even a disordered signal may comprise a weighted sum of sine wave.

In the literature several works concerning leak detection aims at introducing a transient hydraulic with well known and well established characteristic frequency, and analyze the transient pressure signals acquired along the pipeline. Highlighting the work of Ferrante and Brunone (2003), which applies an impulse input and uses frequency analysis to solve the equations that govern the transient flow (continuity equation and one-dimensional time), in the frequency domain. Wang et al. (2002) also used the technique of applying a hydraulic transient frequency with well known frequency and studied the change of frequency characteristics of amplitude, phase to a pipeline with and without leakage, sensing changes in such features.

The Fourier transform is the most widely used method for studying non-stationary signals in the frequency domain. Through FFT is possible to view the frequencies present in the non-stationary signals. Thus, it is possible to evaluate if the occurrence of leak has frequency characteristics that may coincide with transient events and then evaluate the applicability of this technique to develop a pattern classifier algorithm leaks.

Mathematically, Equation 1 expresses the Fourier Transform S (ω) for a time signal s (τ), around the time τ.

$$S(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} e^{-j\omega\tau} s(\tau)\, d\tau \tag{1}$$

3. EXPERIMENTAL LOOP AND TEST PROCEDURE

Experimental tests were performed at the pilot pipeline of the Industrial Multiphase Flow Laboratory at the University of São Paulo, the campus of São Carlos - SP. A representation of the experimental pilot pipeline is showed in Figure 1. The instrumentation in pipeline is capable of measuring and simulating several flow regimes occurring in representative of oil and gas pipelines and works with compressed with single phase (air, water and oil – mineral oil Shell's vitrea 100) and multiphase flow (air-liquid and liquid-liquid).

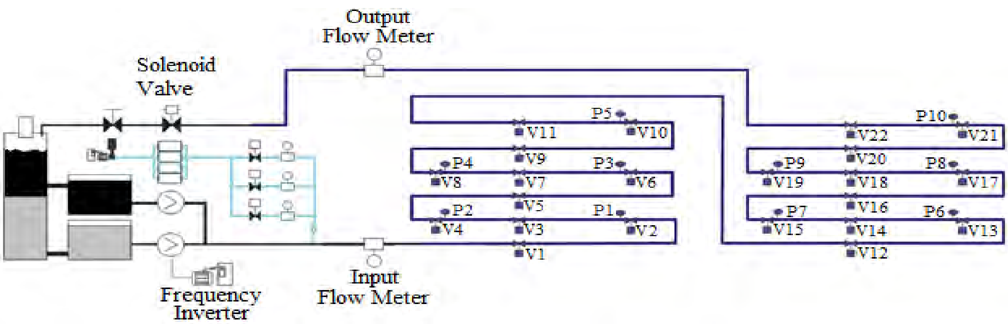

Figure 1. Schematic representation of the experimental loop at the Industrial Multiphase Flow laboratory.

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The test section is constituted by 50.8 mm internal diameter metallic tubes, with wall thickness e=3mm, extending through approximately 1500m between the exit of the water pump and the entrance of the separation reservoir. Water is injected by a centrifugal pump of 15kW and oil is injected by a screw pump of 15kW and both pumps is controlled by frequency inverters. Also air is supplied by a 50kW screw compressor and the flow rate is adjusted by three servo-valves. 22 solenoid valves are used to simulate leaks in well-known position as described at Table 1. A high speed video camera was used to determine the response time of these valves and the average value was 4 ms (Martins and Seleghim, 2010). The leak's diameter was defined with the help of 8 mm orifice plates placed between the solenoid valve and the "T" connection to the pipeline and the valve orifice diameter was adjusted to obtain a flow of 2.1L/min when the pipeline flow rate is 70L/min in steady state flow. Also a line lock valve (globe vale) controlled by a electro-pneumatic on/off actuator is positioned at the outlet of pipeline to produce water hammers.

Table 1. Leak (solenoid) valves relative position.

Valve	Relative Position (m)	Valve	Relative Position (m)
V1	100	V12	835
V2	142	V13	878
V3	185	V14	921
V4	266	V15	1002
V5	344	V16	1080
V6	387	V17	1122
V7	430	V18	1165
V8	511	V19	1246
V9	589	V20	1324
V10	613	V21	1366
V11	674	V22	1410

For acquire data from pilot pipeline there are 10 piezoelectric relative pressure sensors with a range of 0 to 10bar and 2-wire 4-20mA output and cutoff frequency over than 250Hz, installed along the pipeline. Also, 2 electromagnetic flow meters are positioned to measure inlet and outlet pipeline's flow. Table 2 provide the information about positioning of the pressure and flow meters.

Table 2: Pressure sensors relative position.

Valve	Relative Position (m)	Valve	Relative Position (m)
P1	143	P6	879
P2	263	P7	1001
P3	388	P8	1123
P4	508	P9	1243
P5	615	P10	1367

For acquiring all data from sensors (pressure, flow meter and temperatures), as well for generating all commands signal to actuators (frequency inverters for centrifugal pump, solenoid valves for generating leaks and electro-pneumatic valve for generating water hammer), in each test procedure, a National Instruments programmable and automation controller (PAC) is used. It is emphasized that the PAC is a reliable and robust automation hardware which have three main parts: FPGA chassis, real time controller and I/O modules. A FPGA chassis NI9114 is responsible for execute time-critical routine, read and write data from I/O modules and then, transmit data from I/O modules to the real time controller. The real time controller NI9014 execute the main routines running different procedures for tests, transmit data from FPGA to the main supervisory computer and also write the data acquired into a ASCII format file in a flash memory at 100Hz. The experiment driver perform several operations cyclically in order to assure that each test was done precisely the same way. Three different experimental cycles were performed: Steady state flow; Starting and stopping centrifugal pump; and opening and closing line lock valve (water hammer).

The steady state flow tests have the following procedures:

i. Starts data acquisition and storage to flash memory in ASCII files;
ii. Waits for opening the leak valve (60 seconds);
iii. The specific leak valve (solenoid valve) opens;
iv. Waits for closing the solenoid valve (60 seconds);
v. Closes the leak valve;
vi. Waits system get back to steady state flow (60 seconds);
vii. Finalize test and stop data acquisition.

The starting and stopping centrifugal pump tests (transient flow) have the following procedures:

i. Starts data acquisition and storage to flash memory in ASCII files;
ii. Performs the pump start;
iii. Waits a random time (t) for opening the leak valve (0 <t <8s);
iv. The specific leak valve (solenoid valve) is opened;
v. Waits system get back to steady state flow (30 seconds);
vi. The specific leak valve (solenoid valve) is closed;
vii. Waits system get back to steady state flow (30 seconds);
viii. Performs the pump stop;
ix. Waits a random time (t) for opening the leak valve (0 <t <8s);
x. The specific leak valve (solenoid valve) is opened;
xi. Waits system get back to steady state flow (30 seconds);
xii. Finalize test and stop data acquisition.

And also, the opening and closing the line lock valve tests (transient flow) have the following procedures:

i. Starts data acquisition and storage to flash memory in ASCII files;
ii. Performs the line lock valve closes after 10 seconds;
iii. Waits a random time (t) for opening the leak valve (0 <t <8s);
iv. The specific leak valve (solenoid valve) is opened;
v. Waits system get back to steady state flow (120 seconds);
vi. The specific leak valve (solenoid valve) is closed;
vii. Waits system get back to steady state flow (60 seconds);
ii. Performs the line lock valve opens;
ix. Waits a random time (t) for opening the leak valve (0 <t <8s);
x. The specific leak valve (solenoid valve) is opened;
xi. Waits system get back to steady state flow (60 seconds);
xii. Finalize test and stop data acquisition.

Figures 2, 3 and 4 shows the obtained signals from stead state flow, starting and stopping centrifugal pump and line lock valve tests.

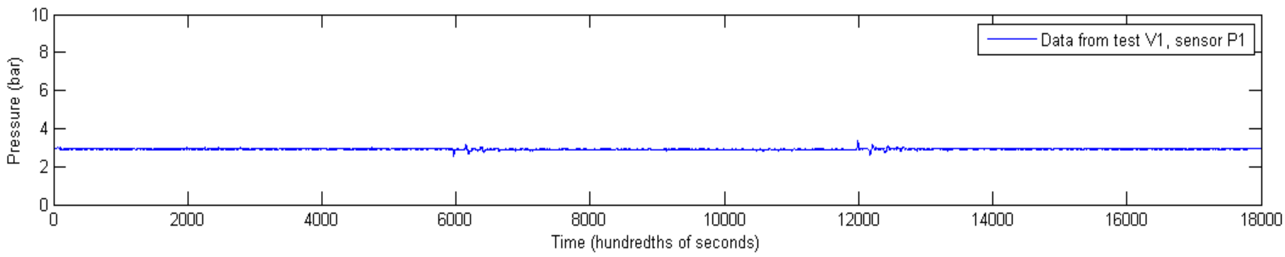

Figure 2. Data from experimental tests acquired from sensor P1 with leak test at valve V1 in steady state flow.

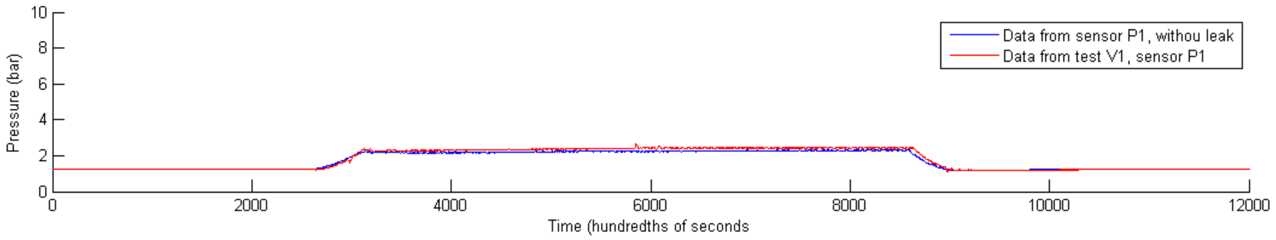

Figure 3. Data from experimental tests acquired from sensor P1 without and with leak test at valve V1 in starting and stopping pump transient flow.

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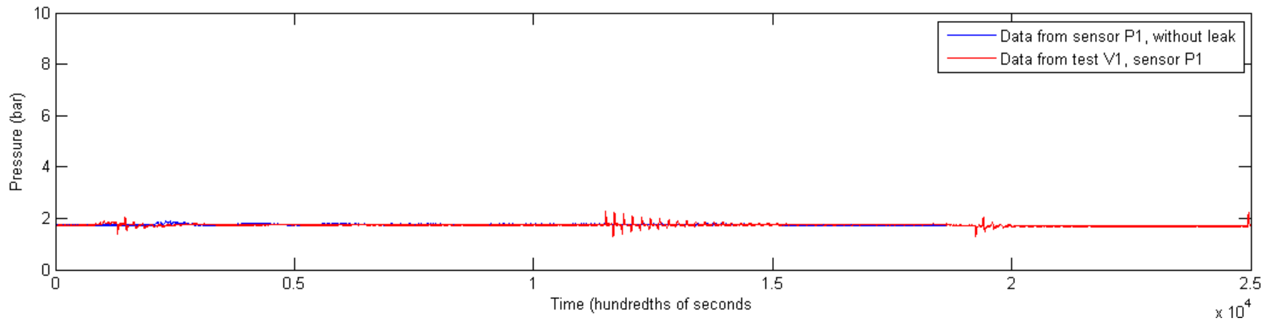

Figure 4. Data from experimental tests acquired from sensor P1 without and with leak test at valve V1 in closing and opening line lock valve transient flow.

4. RESULTS AND DISCUSSION

Analyzing the Fourier transforms for all experimental signals can be observed that the frequencies for the different characteristics tests are below 10Hz.

The comparison between signals from tests with or without leaks shows some characteristics frequencies introduced by leaks, more pronounced around 0.5, 1.0 and 1.5Hz, both on steady-state an transient flow tests.

As an illustration of this result, in a particular case from leak test at V1 valve and pressure signal acquired from P1 sensor, Figure 5 represents the Fourier transform for testing steady state flow with and without occurrence of leaks, Figures 6 and 7 represent the Fourier transform for testing starting and stopping the centrifugal pump, respectively without and with leakage, and finally, Figures 8 and 9 represent the Fourier transform for testing closing and opening line lock valve, respectively with and without leakage.

Considering Figures 5, 6 7, 8 and 9, it is possible to visualize the characteristic frequencies for signals with or without leaks, especially the mentioned more pronounced characteristic frequencies around 0.5, 1.0 and 1.5 Hz.

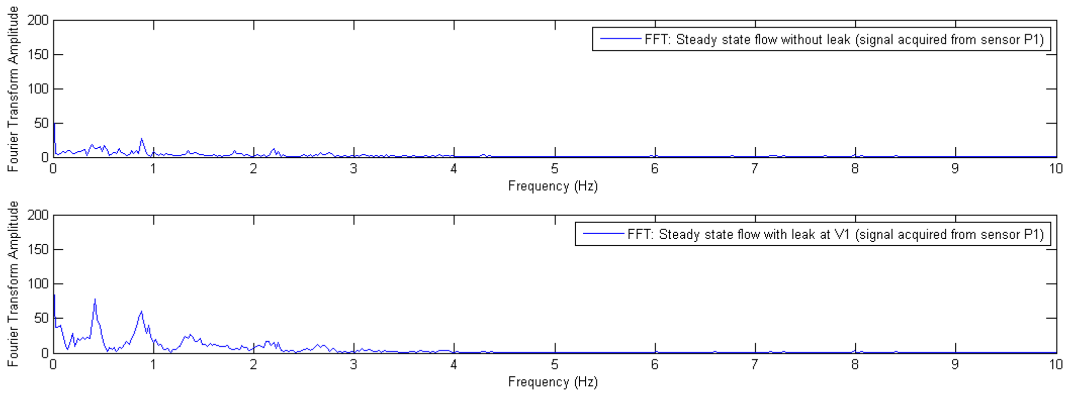

Figure 5: Fourier transform from signal acquired from sensor P1 without and with leak test at valve V1 in steady state flow.

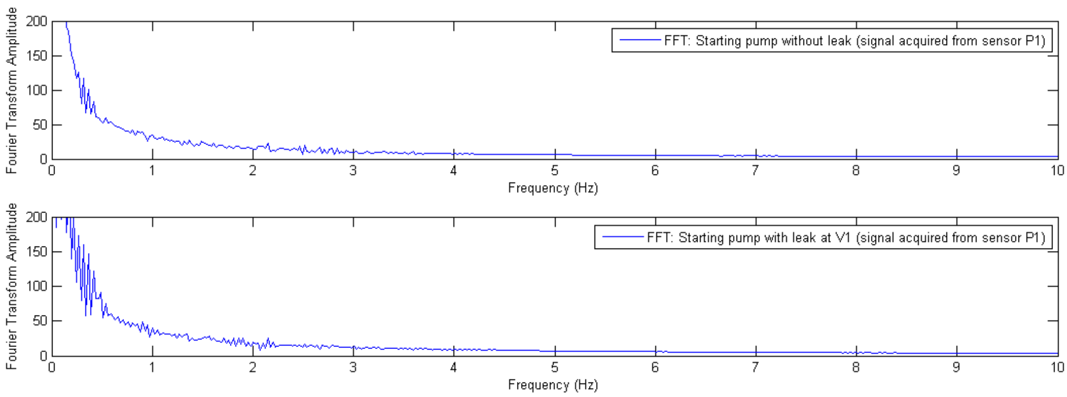

Figure 6. Fourier transform from signal acquired from sensor P1 without and with leak test at valve V1 in starting pump transient flow.

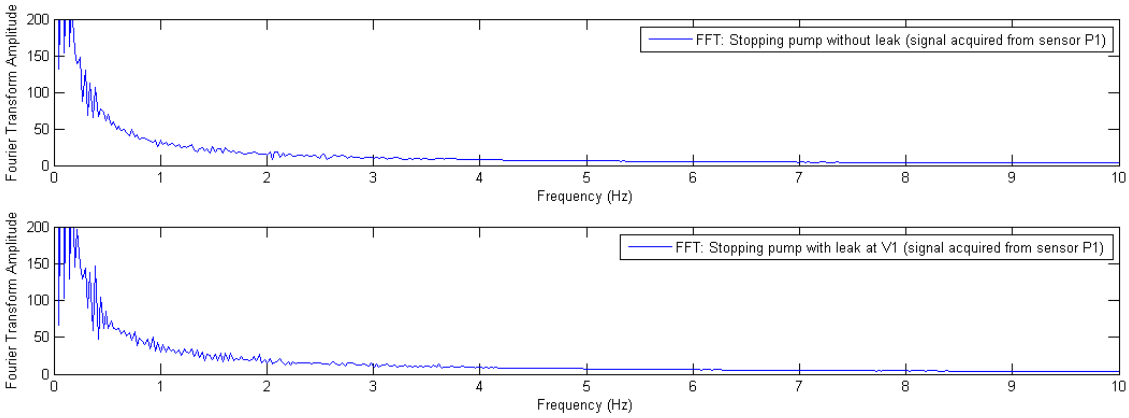

Figure 7. Fourier transform from signal acquired from sensor P1 without and with leak test at valve V1 in stopping pump transient flow.

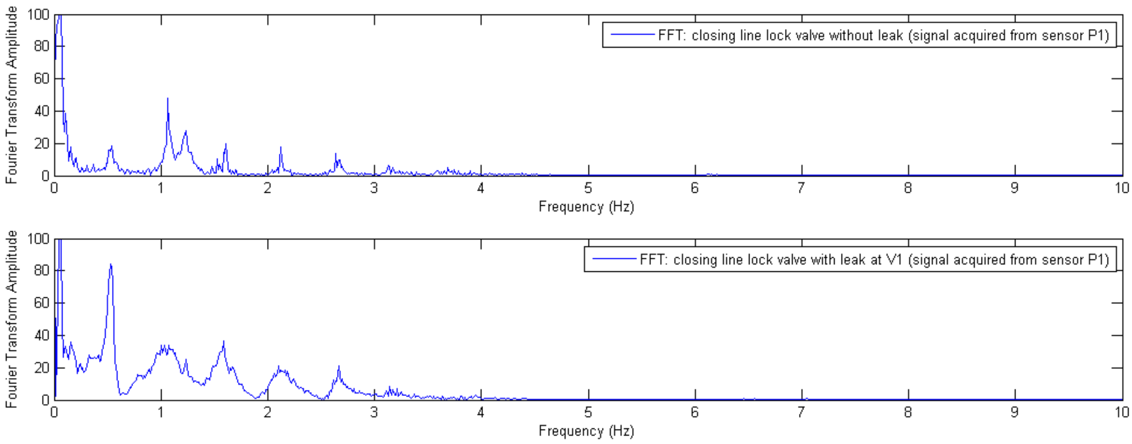

Fig. 8: FFT transform from signal acquired from sensor P1 without and with leak test at valve V1, in closing line lock valve transient flow.

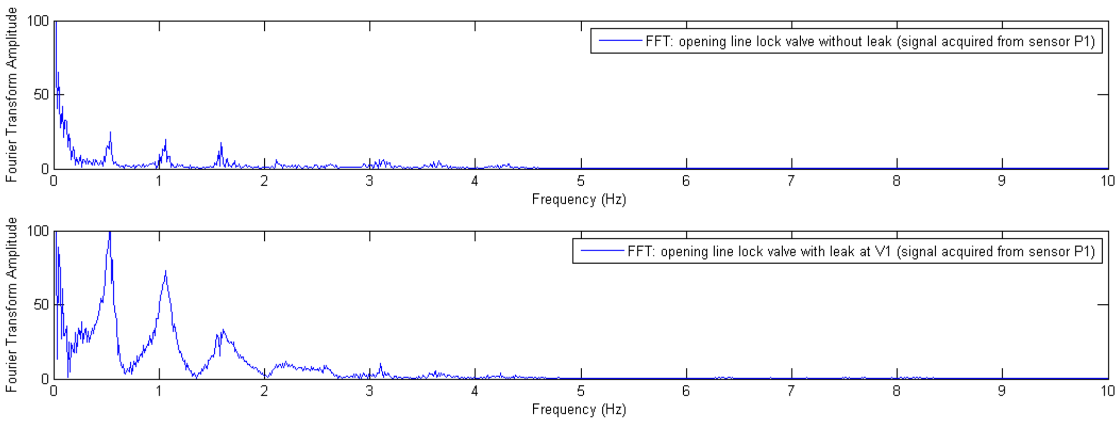

Figure 9. Fourier transform from signal acquired from sensor P1 without and with leak test at valve V1, in opening line lock valve transient flow.

5. CONCLUSION

Analyzing the results qualitatively is possible to discern the occurrence of leakage in both steady state and in different transients flows such as starting and stopping of the pump, as well as opening and closing the line lock valve.

The analysis in the frequency domain shows that the characteristic frequencies of leak occurrences are unmatched in value and amplitude from that characteristic frequencies of steady state and transient flows evaluated in this work

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(starting and stopping of the pump and opening and closing line lock valve). In this way, it should be promissory to use classification algorithms, such as artificial neural network, k-means algorithm and others, to identify the occurrence of leakage both in steady state and transient flows by evaluating the Fourier transform of the pressure signals acquired from pipeline.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE

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