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TIME-FREQUENCY ANALYSIS BY GABOR TRANSFORM IN A QUALITATIVE ASSESSMENT TO CHARACTERIZE ABRUPT LEAKS 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 time-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

To transport fluid through pipelines is necessary to use high pressure upstream to overcome the pressure drop along the pipe. This high pressure drop, along with other factors, such as corrosion, operational failures, soil movement, natural phenomena and external actions unintended or unauthorized (eg, illegal connections for theft), can cause leaks in the duct, one the most important problems associated with transportation in pipelines.

Several techniques for leak detection in pipelines have been researched in order to avoid and reduce environmental damage and economic losses. As reported by Guo et al. (2012), the occurrence of leaks in pipes is inevitable and academic and engineering development is needed, in order to minimize the damage.

However, there is a quote from Stouffs and Michel (1993): "No method of leak detection is universally applicable and operational requirements dictate which method is most effective for the process. In general, it is best to use more than one independent leak detection system in pipelines important ", even written 20 years ago it is still valid and current.

In this context, present work deals with the analyze in time-frequency domain (Gabor transform) of 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.

2. LEAK DETECTION BASED ON PRESSURE SIGNAL ANALYSIS

In fact, an abrupt leak or a structural failure of a pipeline generates a transient fluid dynamic. Concerning hydrodynamic concepts, the transient fluid dynamic analysis can be defined as a process where there are variations of pressure and flow velocity of the fluid as a function of time, both upstream and downstream flow, which may cause structural failure (Martins and Seleghim, 2010). Any functional change in motion, such as the occurrence of a leak, or the change of a component of the system, such as pumps, turbines or valves, causes the fluid dynamic transients. Thus, after the occurrence of the disorder there is a transient flow and the earlier steady state is changed to a new steady state.

Typically the transient fluid dynamic is propagated both upstream and downstream at the sound velocity on the fluid, and commonly the leak detection method based on analyses the pressure transient generated by a transient fluid dynamic is named acoustic leak detection methods.

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. We emphasize hardware-based methods, which use sensor elements (intrusive or not) for the detection of transient hydrodynamic generated by the occurrence of leakage.

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

It is well known that a signal (periodic or not) can be reconstituted from a weighted superposition of complex sinusoids, so that the purpose of frequency analysis of the signals is to determine the weighting coefficients of each sinusoid (Wang et. al., 2002).

There are several techniques for signal analysis in time domain, such as calculating the signal power, energy, convolution with a pre-determined function, mean, variance, standard deviation, absolute error, relative error, etc. In the frequency domain, there is the Fourier transform, widely used to determine the characteristic frequencies present in a signal. Furthermore, in the time-frequency domain, there are a large number of application of the Gabor wavelet transform and.

Considering the signal analysis theory, the techniques of time-frequency analysis has been widely used for solving scientific and technological problems, particularly for analyzing physical phenomena whose frequency spectrum changes over time.

Thus, it is possible for a clearer representation of the signal, using the temporal representation of the analysis combined with the frequency analysis. In summary, performing just a frequency analysis is possible to visualize the frequencies present in the signal, however, there is no information of the time instant at which each frequency was present. This need is met by a diagram in time-frequency analysis (Cohen, 1995).

Many of these techniques have been used to verify the classification of field signals acquired pipeline (pressure, flow, temperature) for the detection of leaks and obtain regimes of flow. For example, Klein et. al. (2004) had characterized flow patterns for a horizontal air-water flow, analyzing signal from a conductive electrode in intermittent and annular flow.

Also, the work of Selli and Seleghim (2007) studied the development of systems for classification of flow patterns (intermittent and stratified wavy), based on an artificial intelligence classifier using an artificial neural networks, and for learning and classification the neural network used coefficients of time-frequency analysis (Gabor transform) of the dynamic pressure signal. This technique showed satisfactory results being successful classification allocated to time-frequency analysis of the signal.

Within leak detection, this paper aims to analyze the techniques of time-frequency analysis, evaluating the instant of occurrence of each characteristic frequency in the signal acquired. It is desired to evaluate the characteristic frequencies in the pressure signal for each time point for both steady state and transient flow with or without leakage.

The time-frequency transform goal is to analyze the characteristic frequencies present in the signal, in every moment, in a window of analysis (Cohen, 1995). Mathematically, the Gabor transform (P (t, ω)) can be represented as the spectral power at time τ, for a t positions window as shown in Equation (1).

$$P(t,\omega) = \left| \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} e^{-j\omega\tau} s(\tau)\, h(\tau - t)\, d\tau \right| \qquad (2)$$

where h(τ-t) is the window function. For the Gabor transform the window function is a Gaussian normal distribution, as expressed in Equation (2).

$$h(\tau - t) = e^{-\alpha(\tau - t)^2} \qquad (3)$$

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).

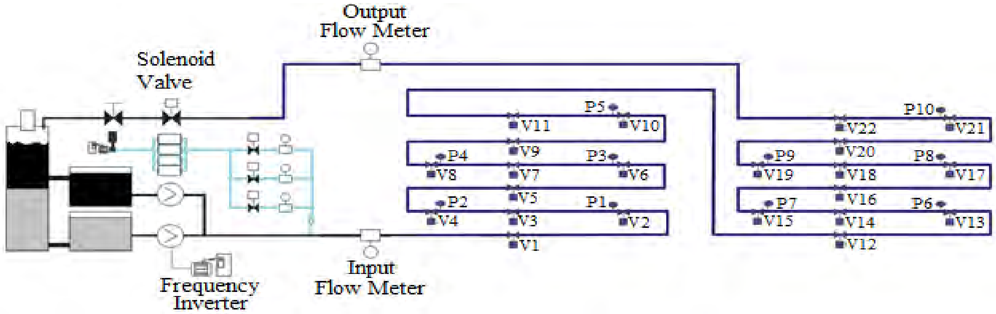

Figure 1. Schematic representation of the experimental loop at the Industrial Multiphase Flow laboratory.

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.

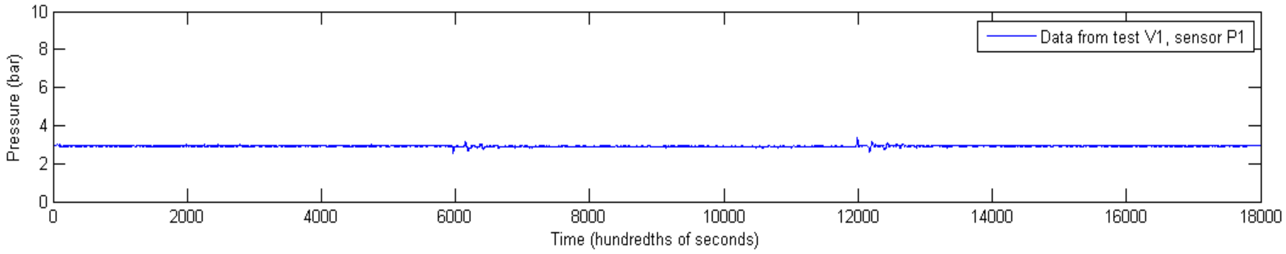

Figure 2. Data from experimental tests acquired from sensor P1 with leak test at valve V1 in steady state flow.

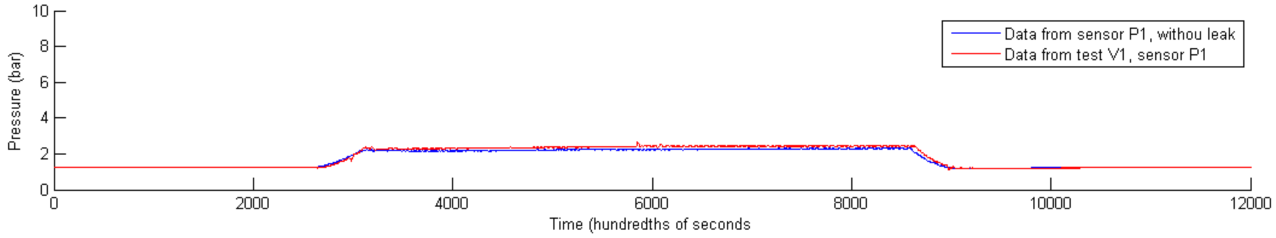

Figure 3. Data from experimental tests acquired from sensor P1 without and with leak test at valve V1 in starting and stopping pump transient flow.

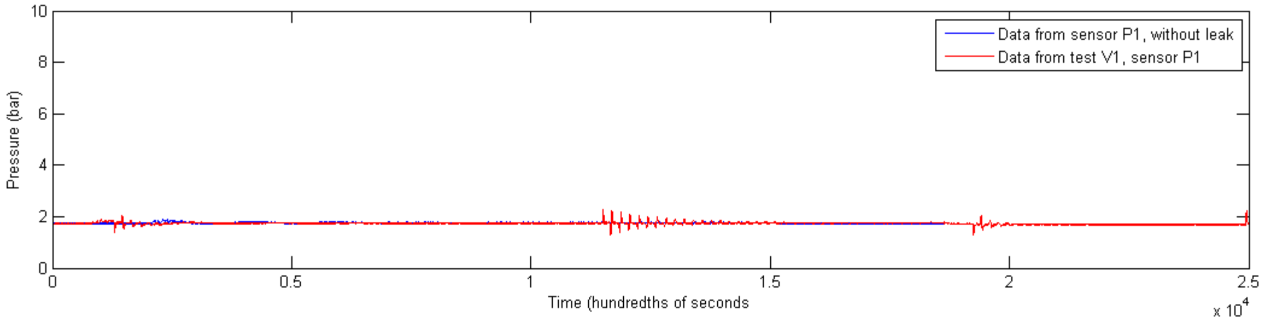

Figure 4. Data from experimental tests acquired from sensor P1 without and with leak test at valve V1 in closing and opening line lock valve transient flow.

4. RESULTS AND DISCUSSION

Analyzing the Gabor transforms for all experimental signals can be observed that the frequencies for the different characteristics tests are below 10Hz. It is possible to differentiate the characteristic frequencies for signals with or without leaks.

Thus, Figure 5 represents the Gabor transform for testing steady state flow with and without occurrence of leaks; Figure 6 represent the Gabor transform for testing starting and stopping the centrifugal pump, without and with leaks at leak valve V1; and finally, Figure 7 represent the Gabor transform for testing closing and opening line lock valve, with and without leakage.

Considering Figures 5, 6 and 7 it is possible to differentiate the characteristic frequencies for signals with or without leaks. Especially, it is possible to visualize characteristic frequencies of leak more pronounced around 0.5, 1.0 and 1.5 Hz.

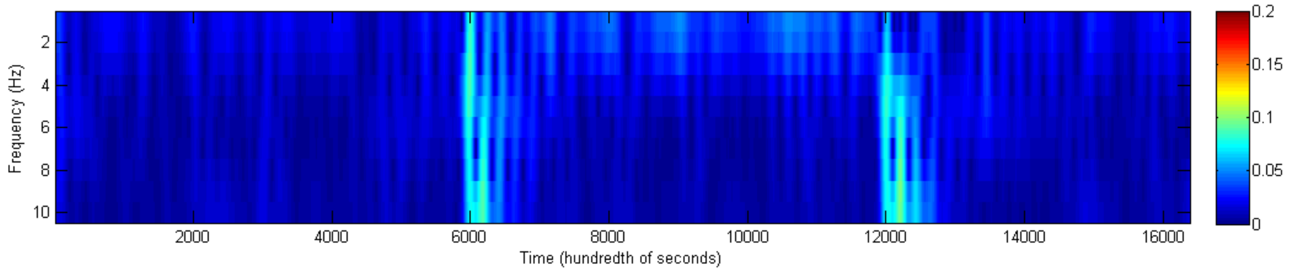

Figure 5: Gabor transform from signal acquired from sensor P1 without and with leak test at valve V1 in steady state flow.

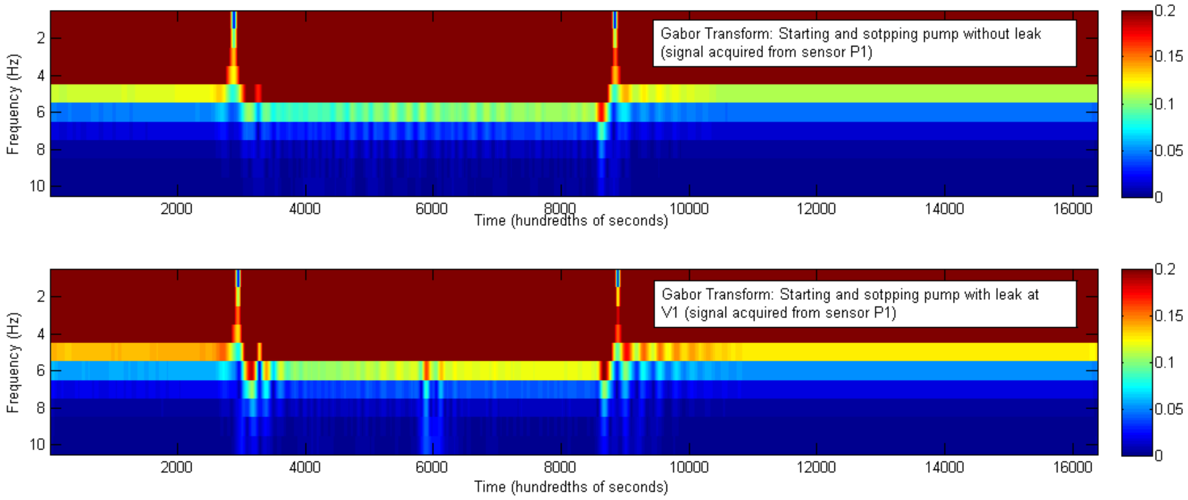

Figure 6. Gabor transform from signal acquired from sensor P1 without and with leak test at valve V1 in starting and stopping pump transient flow.

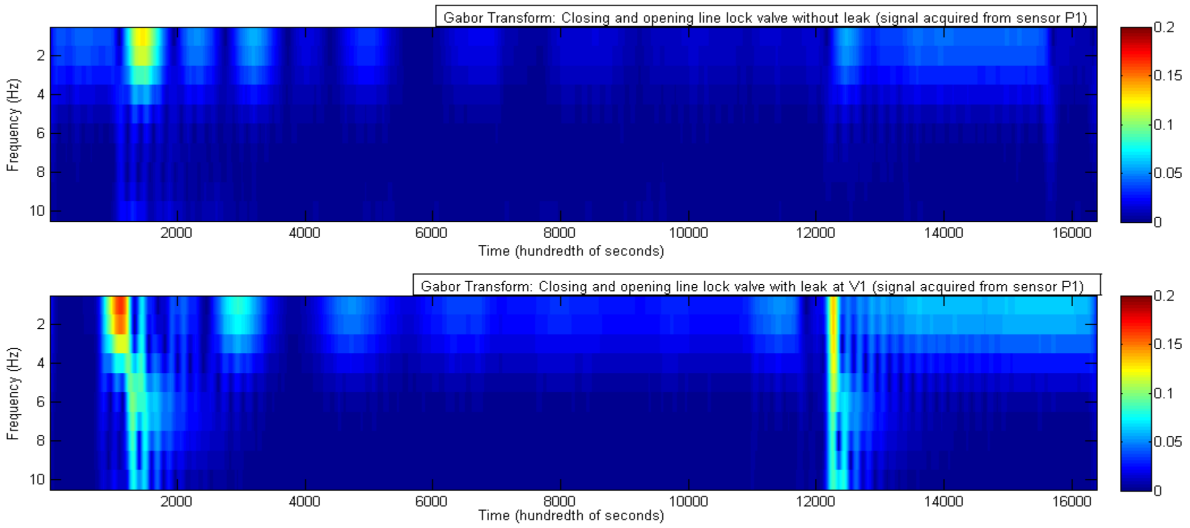

Figure 7. Gabor transform from signal acquired from sensor P1 without and with leak test at valve V1 closing and opening line lock valve transient flow.

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 (starting and stopping of the pump and opening and closing line lock valve).

6. ACKNOWLEDGEMENTS

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