TIME – FREQUENCY ANALYSIS OF ACOUSTIC WAVES IN SINGLE-PHASE FLOW

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Abstract. *The main objective of this paper is to present is to analyze the acoustic propagation in single-phase flow,i.e., the signals provided by pressure sensors in known locations in the test line, by developing techniques for signal analysis. For this case the time - frequency (Gabor transform) method, because the fundamental purpose is to build a joint function dependent on the time and frequency and able to identify the spectral composition of an instantaneous signal. The experimental tests were executed at the pilot pipeline of the Thermal-Fluid Engineering Laboratory of the University of São Paulo, campus of São Carlos-SP. The results show that the time-frequency analysis can efficiently characterize the situations that occur in the simulation of this flow. In particular, Gabor Transform demonstrated a concentration of low frequencies in both the occurrence and the turn off of the leak. It was also possible to observe a large concentration of high frequency throughout the flow, which represents the background noise in this signal.*

***Keywords**: hydraulic transient, time-frequency analysis, signal processing.*

1. INTRODUCTION

The transportation of petrochemical products through pipelines is the most common option, in both industrial applications involving long distances and distribution networks, in which a product must be delivered to a number of processes or customers. In both cases, for a safe and efficient operation of the grid, it is necessary to know the dynamic characteristics of the flow in transient operating conditions, such as alignment of valves, stops and broken pumps. Such a requirement is clear in view of the significant number of accidents that have occurred, usually with economical and environmental consequences.

Intrinsic phenomena can also be extremely harmful to the structural integrity of the pipeline, if generated by inappropriate operations or naturally due to a specific feature of the system. For instance, the appearance of liquid slug flow in pipelines can occur due to their operation at pressures and temperatures by undue operational failure, or due to a geometric feature of the line that biased the accumulation of condensate, blocking the pipeline with consequent ejection of the piston of fluid. In both cases it is possible to detect the formation of the piston and the emergence of a gush through the pressure waves associated with fluid dynamic transients. These waves, which can be used to initiate preventive or palliative actions, propagate at the speed of sound and arrive well in advance at the ends of the pipeline.

From a scientific point of view, a better understanding of these dynamic phenomena in turbulent flows, allowing the proposal of more accurate models to comprehend the mechanisms, among other important contributions, is based on the study and characterization of the acoustic propagation waves caused by such transient operations.

In this context, the main objective of this study is to analyze the acoustic propagation in single-phase flow, i.e., the signals provided by pressure sensors in known locations in the test line, by developing techniques for signal analysis. For this case the time - frequency (Gabor transform) method, because the fundamental purpose is to build a joint function dependent on the time and frequency and able to identify the spectral composition of an instantaneous signal.

According to the literature, Several techniques for leak detection based on transient flow have been presented: "Silva et al. (1996)","Li and Sun (2009)" proposed a leak detection method through the negative pressure waves, based on the fact that at the moment that the spill occurs there is a sudden drop of pressure at the site of the leak, causing a negative pressure waves at the fluid that propagate at the speed of sound towards the upstream and downstream of the leak until it is established a new steady state. These waves propagate over long distances providing early detection, however, it takes a careful filtering of the signal, because a pressure wave may also occur due to closing valves, start and stop of pumps, and other normal procedures of the operation. Already "Lee et. al (2006)"who presented an experimental validation of the frequency response method producing transient signals by the side-discharge solenoid valve. Besides these there are many other methods to be mentioned, however, making use of time-frequency analysis, not so many published works, but there are studies involving flow, which yields good results using the technique of time-frequency analysis, as "Seleghim et. al (1998) who proposed the characterization the different two-phase air-water horizontal flow regimes jointly in time and frequency.

2. TIME-FREQUENCY ANALYSIS

The signal analysis is the study and characterization of the basic properties of signals and was historically developed concurrently with the discovery of the fundamental signals in nature, such as the electric field, sound wave, and electrical currents. A signal is usually a function of many variables; they usually represent space and time. The electric field, for example, varies in both time and space "(Cohen, 1995)".

The time is a fundamental variable, however, sometimes it is more advantageous to study the signal in a different representation, i.e., in terms of frequencies, because beyond the time, the frequency is the most important variable representation. The mathematics of the frequency representation was invented by Fourier, whose main motivation was to find the equation governing the behavior of heat. That way, the signal can be analyzed in three different ways: as a function of the time; in terms of frequency and time-frequency plane, as described in this section.

The time-frequency analysis originated about fifty years and recently has had a major development in the establishment of basic principles and practical applications. Importantly, this field is evolving very rapidly due to the introduction of new ideas.

The signal (time domain) and its spectrum (frequency domain) sometimes are not sufficient alone to describe physically what is happening. Through the spectrum, it is can know what frequencies were present in the signal, but do not know when they existed. For this reason it is need to make the time-frequency signal analysis.

The main objective of the time-frequency analysis is to find a function that describes the energy density of a signal simultaneously in time and frequency, and can be used and manipulated just as any density. In possession of such a function (or distribution), it is can know what fraction of energy existing in a certain age and temporal frequency, and calculate the density of frequencies at a particular time, and global and local moments among others. That way, the time-frequency analysis based on Fourier transform.

The short time Fourier transform is the most widely used method for studying no stationary signals, because it can partition the signal into small time intervals in order to determine which frequencies are in each range, and get a sense of how the spectrum varies in time, but it is important to know that the time intervals cannot be very short. This is because, if the analysis window is very narrow, the spectrum becomes meaningless and no shows any relationship to the total spectrum. To evaluate the properties of the signal for a time t, emphasis is given to the signal at that time and hides it at other times. This is achieved by multiplying the signal by a window function $h(t)$ in order to produce a modified signal of type as Eq.(1):

$$s_t(\tau) = s(\tau)h(\tau - t) \tag{1}$$

The modified signal $s_t(\tau)$ is a function of two times: the fixed time t and the running time τ. The window function h is chosen to leave the signal more or less unaltered around the time t but to suppress the signal for times distant from the time of interest.

The term window comes from the idea that we are seeking to look at only a small piece of the signal as when we look out of a real window and see only a relatively small portion of the scenery.

Since the modified signal emphasizes the signal around the time t, the Fourier transform will reflect the distribution of frequency around that time, as Eq.(2):

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

Replacing the Eq. (1) at the Eq.(2):

$$S_t(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} e^{-j\omega\tau} s(\tau) h(\tau - t)\, d\tau \tag{3}$$

The energy density spectrum $P_{SP}(t,\omega)$ at time t is therefore as Eq.(4):

$$P_{SP}(t,\omega) = \left|S_t(\omega)\right|^2 = \left|\frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} e^{-j\omega\tau} s(\tau) h(\tau - t) d\tau\right|^2 \tag{4}$$

For each different time we get t we get a different spectrum and the totality of these spectra is the time-frequency distribution $P_{SP}(t,\omega)$. Normally, this distribution is call spectrogram.

Short time Fourier transform, Gabor transform, Wavelet transform and Wigner-Ville distribution are way of the to construct the function $P_{SP}(t,\omega)$. What distinguishes each way is the function h used. The Gabor transform (used in this work to construct the time-frequency plane), for example, uses the Gaussian function (normal distribution) as a function $h(\tau - t) = e^{-\alpha(\tau - t)^2}$. "(Cohen, 1995)"

3. THE EXPERIMENTAL CIRCUIT

In this paper, all the experimental tests were executed at the pilot pipeline of the Thermal-Fluid Engineering Laboratory of the University of São Paulo, campus of São Carlos-SP, Brasil. In this section will be describe the pilot pipeline system of instrumentation and data aquisition.

3.1 Pilot Pipeline and Instrumentation

The three-phase pilot pipeline operates with mixtures of gas-liquid-liquid and has sections of tests constructed of galvanized steel with 50.8 mm internal diameter and 1512 m of length. A tank system installed in the downstream sections of the test is responsible for the primary air-liquid separation and, subsequently liquid-liquid separation.

Centrifugal pumps controlled by frequency inverters of 15kW (YASKAWA CIMR-P5U2011) recirculate the liquid phases. This architecture was given to allow larger-scale variations in strategies of flow control. As for the instrumentation of the pipeline, both upstream to downstream are installed flow sensors and transmitters of electromagnetic type (EMERSON ROSEMOUNT 570TM) with full scale of 23.76 m³ / h (396 l / min). The instrumentation also includes pressure transducers for rapid response (WIKA A10) to measure the loss and acquisition of audio signal flow, with full scale of 16 bar.

3.2 System of Control and Date Aquisition

The signals set to be read by a data acquisition system is composed of 10 pressure transducers, 2 flow transducers and 22 solenoid valves distributed along the pipeline to simulate leaks in certain positions. Figure 1 shows a schematic representation of the pilot pipeline.

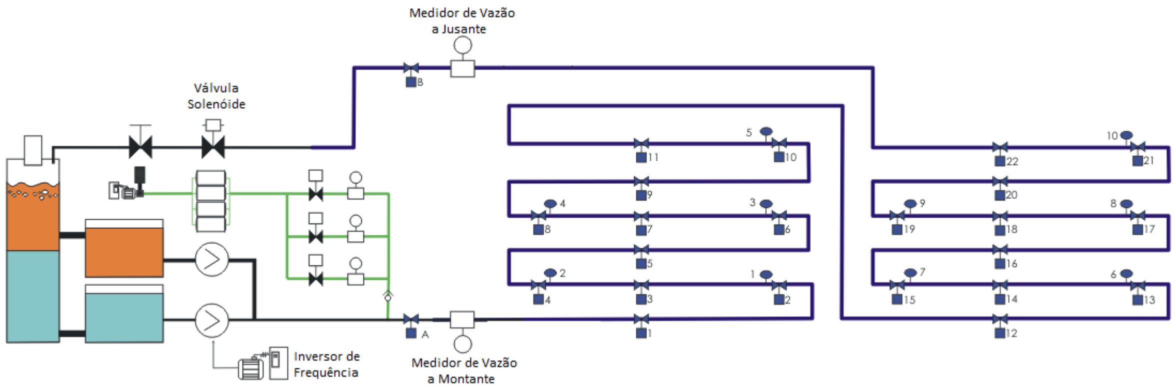

Figure 1. Schematic representation of the pilot pipeline at the NETeF/USP.

The control system and data acquisition is maneged by a Programmable Automation Controller (PAC), which is an electronic hardware from National Instruments ® (NI), called CompactRIO, this being a system of low cost, high performance and reliability. Aplications for CompactRIO used three separate processors: a PC with Windows operating system, a controller with real-time operating system (RTOS) and a field programmable gate array (FPGA).

For acquisition and storage of the experimental data was developed a software for interface with user, where the parameters are configured for the tests. A software on the controller in real time performs the filter of the data from the Butterworth low pass filter with cutoff frequency of 55Hz and data storage in devices of high-capacity type PenDrive.

Finally,for the FPGA performs the acquisition and control data, the sampling frequency was set to 100 Hz. For the tests was used a water single-phase flow, and for to do automatically of the tests, the software performs cyclically the following operations:

i. set water pump frequency;
ii. set the leakage simulation solenoid valve;
iii. wait for 10 seconds;
iv. start store data (9 pressure transducters (
v. Table 1) at the *PenDrive* in ASCII files separate for tab;
vi. wait for 60 seconds to open leakage simulation solenoid valve;
vii. open leakage simulation solenoid valve ;
viii. wait for 60 seconds for to close leakage simulation solenoid valve ;
ix. close leakage simulation solenoid valve;
x. stop acquisition of test signals.

Table 1 – Relative position of the transducters to water pump.

Sensors	Relative position (m)
FMI – Flow Meter Input	15
P1 – pressure transducer 1	143
P2 – pressure transducer 2	263
P3 – pressure transducer 3	387
P4 – pressure transducer 4	508
P5 – pressure transducer 5	632
P6 – pressure transducer 6	878
P7 – pressure transducer 7	1000
P8 – pressure transducer 8	1123
P9 – pressure transducer 9	1243
P10 – pressure transducer 10	1367
FMO – Flow Meter Output	1492

Four pump frequencies were refereed (30, 40, 50 e 60 Hz). Due to maintenance on the pipeline pilot, only 10 of the 22 leakage simulation valves (Table 2) are operating (V2, V4, V6, V8, V10, V13, V15, V17, V19 and V21). Still, the pressure sensor P1 isn`t also operating .This way, in total were constituted 40 cycles of experimental tests, with the duration of each cycle corresponded to 180 seconds, in total, were acquired 360 leakage simulation signals. The average flow of each experiment for the pump frequencies of 30, 40, 50 and 60 Hz are respectively 73.7, 100.4, 125.4 and 146.6 l / min. The opening of the valves used to leakage simulate were calibrated to provide a flow rate of approximately 7 liters by minute with variable frequency drive pump to 30Hz.

Table 2 – Relative Position of the Solenoid Valves (Leakages).

Valves	Relative Position (m)
V1– Solenoid Valve 1	100
V2 – Solenoid Valve 2	142
V3 – Solenoid Valve 3	185
V4 – Solenoid Valve 4	266
V5 – Solenoid Valve 5	344
V6 – Solenoid Valve 6	387
V7 – Solenoid Valve 7	430
V8 – Solenoid Valve 8	511
V9 – Solenoid Valve 9	589
V10 – Solenoid Valve 10	631

V11 – Solenoid Valve 11	674
V12 – Solenoid Valve 12	835
V13 – Solenoid Valve 13	878
V14 – Solenoid Valve 14	921
V15 – Solenoid Valve 15	1002
V16 – Solenoid Valve 16	1080
V17 – Solenoid Valve 17	1122
V18 – Solenoid Valve 18	1165
V19 – Solenoid Valve 19	1246
V20 – Solenoid Valve 20	1324
V21 – Solenoid Valve 21	1366
V22 – Solenoid Valve 22	1410

4. SIGNAL ANALYSIS

The signals processing were evaluated through software developed in Matlab based on time-frequency analysis, as described above. For the case studied in this paper, the experimental tests to leakage simulate were executed in 10 different valves and in 4 different rotations of the pump, and each experiment was recorded in 9 pressure sensors for rapid response. It is emphasized that each experimental signal is composed of two components: 1) DC component, which expresses the value in steady state, 2) AC component, which expresses the transient signal.

The difference of altitude elevation in pressure sensors resulted in a difference at the static pressure in each sensor installed at the pilot pipeline (see Figure 1). So, was extracted the DC component of the signal by subtracting the signal average, for to centralize all the signals and then perform the analysis on the AC component of the signal. The Fig.3 illustrates the AC component extracted from the experimental signal shown in Fig.2. Equations (5) and (6) express mathematically the algorithm for obtaining the experimental AC signal and of the experimental signal acquired.

$$MEDIA\_Pl(i) = \frac{1}{N}\sum_{i=1}^{n} Pl(i) \quad (5)$$

$$Pl\_AC(i) = Pl(i) - MEDIA\_Pl \quad (6)$$

Where Pl the discrete vector of the signal pressure is acquired at the experiment; N is the number of the sample experiment; Pl_AC is the AC component of the signal pressure vector.

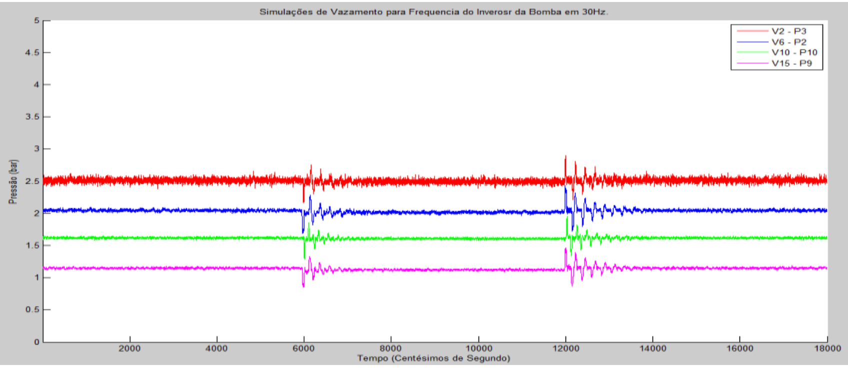

Figure 2. Experimental signal of leakage simulation.

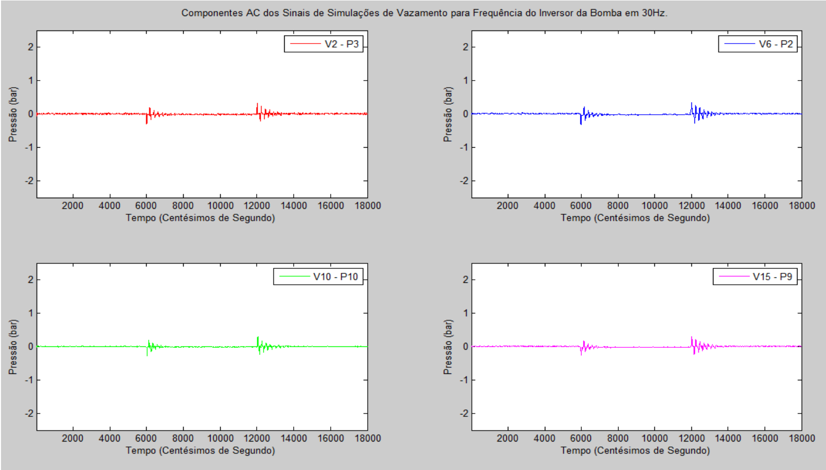

Figure 3. AC Component of the experimental signal of leakage simulation shown in Fig 2.

Analyzing the graph of Figure 2, i.e. the AC component, we can highlight 5 steps in the experiment of simulation leakage.

- i. Between 0 and 6000 hundredth of second: Wait the open leakage simulation solenoid valve;
- ii. At the moment 6000 hundredth of second: Moment of open leakage simulation solenoid valve;
- iii. Between 6000 and 12000 hundredth of second: Accommodation of the leakage signal;
- iv. At the moment 12000 hundredth of second: Moment of close leakage simulation solenoid valve;
- v. Between 12000 and 18000 hundredth of second: Accommodation of the close leakage signal.

After to centralize all signals, spectral analysis of the signal was made through the Fourier transform, which is consisting of the signal decomposition in terms of sines and cosines of different characteristic frequencies, as shown in Fig. 4 and Fig. 5 shows the absolute value of the Fourier transform of the Fig.4.

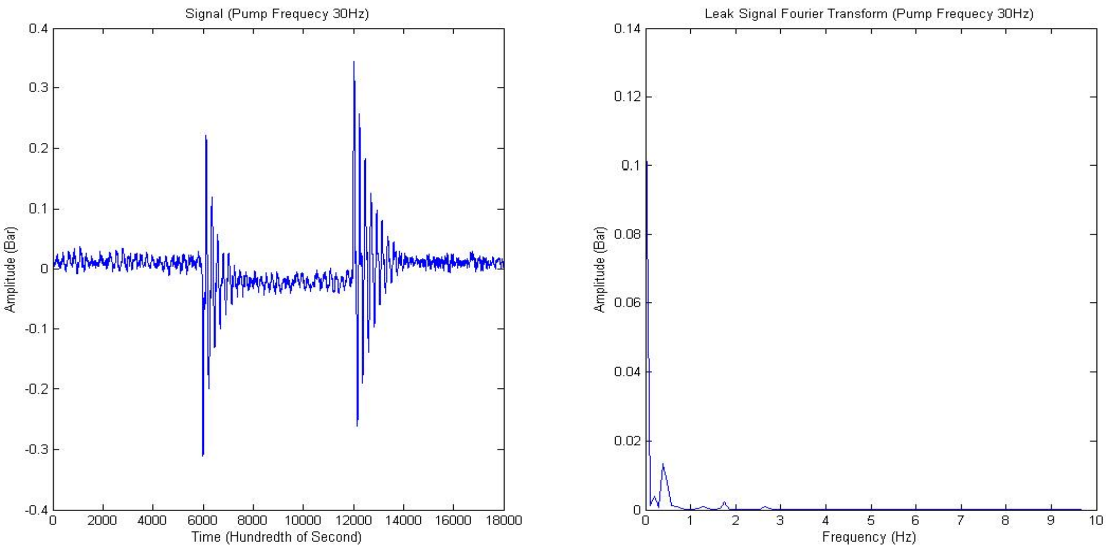

Figure 4. Signal representation at the time domain and frequency domain (Fourier transform).

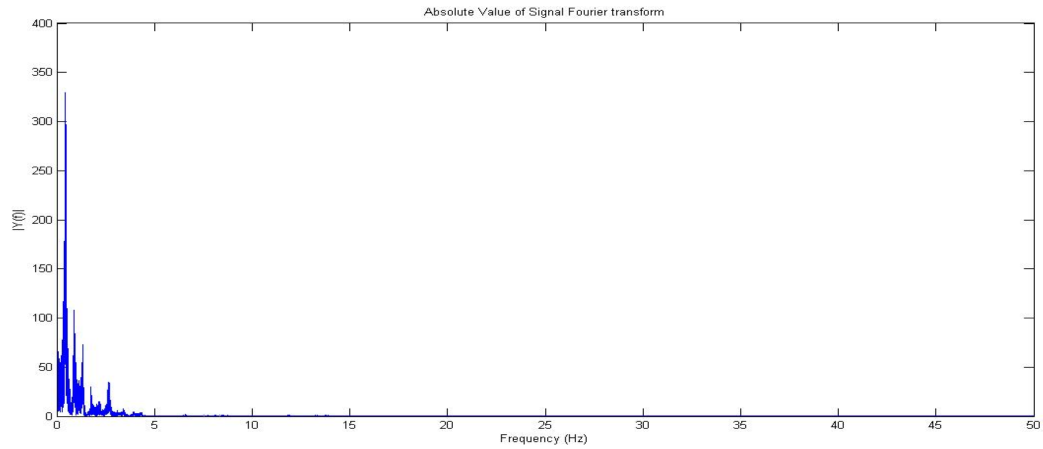

Figure 5. Absolute value of signal Fourier transform.

5. RESULTS

After the signal Fourier transform were applied the time-frequency analysis (in this case Gabor transform), for analyze the different frequencies in each moment. As show in Fig. 6 was possible to notice a concentration of low frequencies in both the occurrence and the turn off of the leak, i.e. around of 2 Hz in 6000 and 12000 hundredth of second. The large concentration of high frequency throughout the flow represents the background noise in this signal.

This time-frequency analysis agrees with results showed in time domain and frequency domain analysis (Fig.4). Figure 7 show the results completed about the Gabor transform (Fig.6) in three-dimensions.

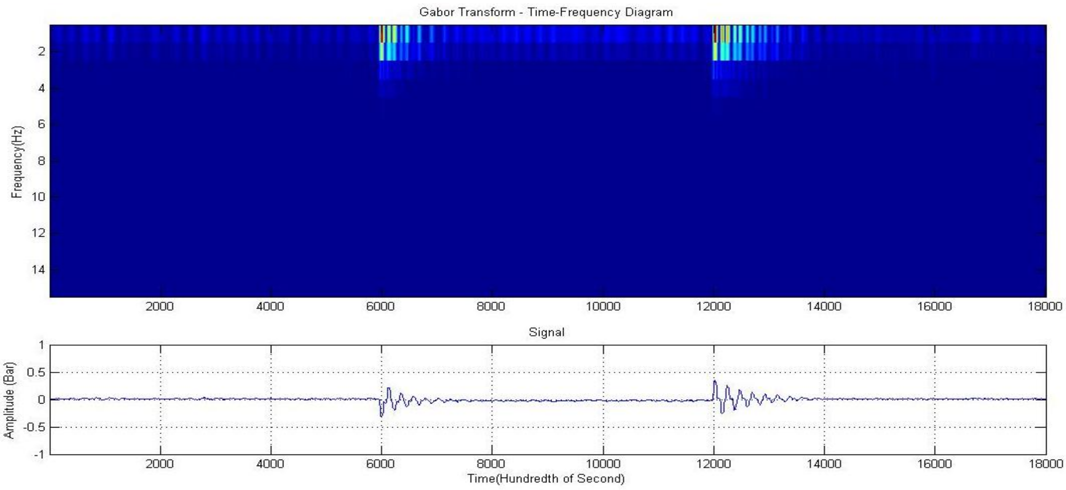

Figure 6. Gabor transform (time-frequency representation)

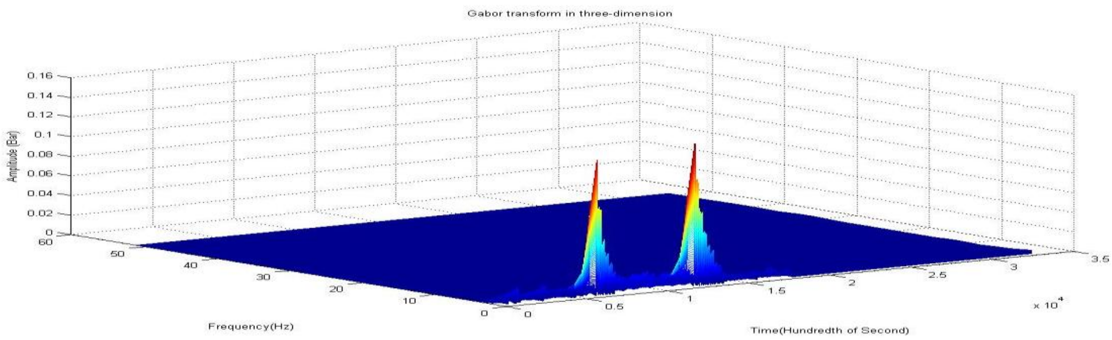

Figure 7. Gabor transform (time-frequency representation 3D)

6. CONCLUSIONS

The results show that the time-frequency analysis can efficiently characterize the situations that occur in the simulation of this flow. In particular, Gabor Transform demonstrated a concentration of low frequencies in both the occurrence and the turn off of the leak. It was also possible to observe a large concentration of high frequency throughout the flow, which represents the background noise in this signal.

7. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE