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Diagnostic Process by Using Vibrational Sensors for Monitoring Cavitation Phenomena in a Getoror Pump Used for Automotive Applications

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Abstract

A full experimental investigation on a Gerotor pump used for the lubrication of engines is described in this paper. These pumps, as well known, are widely used on engines for all hydraulic circuits and, for this reason, often they work in some conditions (such as at high speeds and pressure value) which are very challenging.
In this paper one of the most unwanted phenomena that often occurs during the pump operation has been investigated: the cavitation.
The cavitation can be triggered by many multiple factors such as the sloshing in the tank (translational and rotational motions), high percentage of gas dissolved in the fluid and pressure too low at the pump suction port. Therefore, the characterization of a Gerotor pump in cavitation condition is really interesting.
In order to replay the cavitating conditions a pump has been installed on a dedicated test bench of the Department of Industrial Engineering of the university of Naples “Federico II”. The pump has been forced to cavitate by placing calibrated orifices on the suction side of the pump. Many decreasing diameters have been located in an aluminum connection block, to measure all the working parameters like the flow-rate, pressure (at the suction and delivery ports), pump speeds and pressure ripple. Cavitating and no-cavitating conditions have been investigated by using an accelerometer sensor in proximity of the pump suction chamber with the aim of monitoring the phenomena in terms of vibration amplitude.
As afore mentioned, the pump under investigation has been studied in all operative conditions with and without cavitation phenomena by using a non-intrusive sensor like accelerometer in order to monitoring if cavitation is present.
More precisely, the accelerometer sensor has been located close to the pump suction chamber and the vibrations have been acquired contemporarily with pressure signals (intake and outgoing discharge) and properly triggered with tachometer signal by using a multichannel acquisition system (Siemens™). A spectral vibration analysis has been used as diagnostic tool for

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accurately detecting pump degradation. The results coming from the analysis have shown that in presence of cavitation phenomena the non-intrusive monitoring technique represent a good diagnostic method for assessing pump operability.

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Keywords: Gerotor pumps, Cavitation detection, FFT, Vibration.

Nomenclature			
		$f_{van\ Passes}$	Frequency originated on the inner rotor teeth
p	Pressure	$N_{inner\ teeth}$	Number of inner rotor teeth
p_v	Saturated vapour pressure	$F_{outer\ teeth}$	Frequency originated on the outer rotor teeth
f_0	frequency		
ω_{RPM}	Pump shaft rotation	$N_{outer\ teeth}$	Number of outer rotor teeth

1. Introduction

Mechanical systems that interact with liquids, such as pumps or propellers, may present an unwanted phenomenon called cavitation. The cavitation, as well know, depends by pressure In fact, when a liquid at a constant temperature is subject to a decreasing pressure, p, which falls below the saturated vapor pressure p_v cavitation may occurs [8-11]. Therefore, the process of rupturing a liquid by decrease in pressure at roughly constant liquid temperature is often called cavitation. Issues related to the cavitation are essentially the noise and the material damages that can be caused by the high velocities, pressures and temperatures. In fact, when exposed to high pressure, those voids tend to collapse, releasing a great amount of energy, usually in form of an acoustic shockwave, or even as visible light.

Those acoustic shockwaves can be easily detected by using a sensor such as an accelerometer positioned near the cavitation zone. One of the methods to detect the presence of cavitation, is by processing the time history signal of this sensor and performing a FFT (Fast Fourier transform) analysis, which will give an insightful point of view of the cavitation process. As will be discussed later, when cavitation is present, a lot of the energy of the sound spectrum tends to shift towards a higher frequency band, making possible to identify the presence of this problem. One disadvantage of this method, is that in practical situations, the accelerometer is subjected to secondary sources of vibration, making the diagnose of the cavitation problem very complex [2].

In the case of this article, an experiment to detect cavitation was conducted in a Gerotor Pump, used for automotive applications. The pump in question is an oil pump, which were subjected to rotation speeds of 1000 to 6000 RPM in 1000 RPM steps, with three different sizes of orifice on the inlet side of the pump of 18mm, 5mm and 3mm, to induce the cavitation phenomena [2]. An accelerometer was fixed on the pump, near the cavitation zone, and two instantaneous pressure transducers were used to measure the inlet and delivery pressure of the pump, inside the chamber, near the rotor. The pump rotation was also measured. The present work will be a discussion about the detection and identification of the cavitation problem on this Gerotor pump.

2. Reference pump and experimental setup

The pump under investigation is an internal gear pump used for the lubrication system of internal combustion engines. The pump consists of an outer rotor with15 teeth and an inner with 14 teeth.

The pump works in a rotation speed range of [1000 ÷ 7000] rpm and a pressure range of [0 ÷ 6] bar. A relief valve is included in the pump with an opening pressure of 4.5bar.

As already said, the pump has been tested on a test bench of Department of Industrial Engineering of University of Naples "Federico II". In figure 1a the test bench layout is shown. The bench can drive the pump in the real operation condition reaching a maximum shaft rotational speed of 8000 rpm. A hydraulic axial piston motor of 12 cm^3/rev powers the pump, (see figure 1a). The variable displacement axial piston motor is driven by a Power Unit that consists of an oil tank with a nominal capacity of 100 l, an axial piston pump with theoretical displacement of 71 cm^3/rev, a three phase electric motor with 4 poles, capable of delivering a maximum power of 18.5 kW and a heat exchanger air – oil. The pump shaft rotation speed has been varied, during the tests, through an electro-hydraulic regulator handled by a dedicated card. A potentiometer gives the input signal to the card managing the displacement of the axial piston pump of the Power Unit [3-7].

Looking at figure 1a, it is possible to locate all the transducers installed on the test bench. These sensors can monitor and acquire the Gerotor operating parameters. In particular there is a flow-mater to measure the oil flow-rate, two instantaneous pressure transducers (P_1) (P_2) located in the suction and delivery chamber volumes, a mean pressure transducer (P_3) on the pump delivery and a torque meter. The thermostatic tank, with an oil volume capacity of 13 dm^3, is enable to heat oil up to a temperature of 150°C. In the tank has been also installed a separation baffle (figure 1c) to separate suction and delivery ports of the pump.

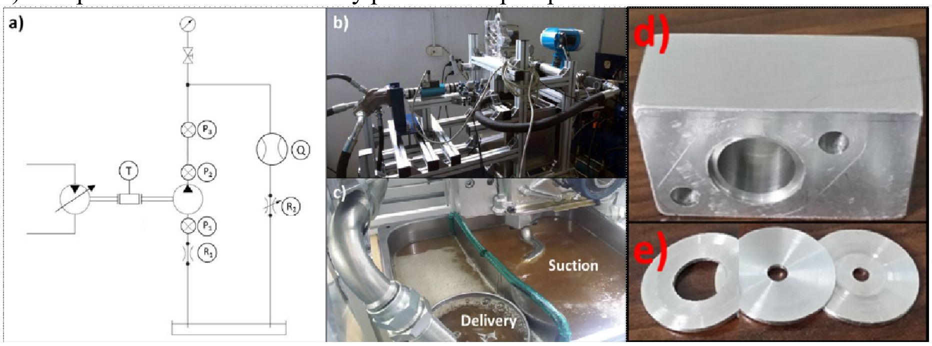

Fig. 1. (a) Test bench layout; (b) Test bench; (c) Suction and delivery view of the pump, (d) and (e) Calibrated orefices.

As already mentioned, three pressure transducers (P_1, P_2, P_3) are installed in the hydraulic circuit. (P_1) and (P_2) are both instantaneous. These sensors are located inside two chambers (respectively suction and delivery chambers) close to the rotors. Both of them are type AVL LP11D, in particular the measuring ranges are [0 ÷ 10] bar for P_1 and [0 ÷ 30] bar for P_2. Thanks to the clock signal of an incremental optical encoder installed on the pump shaft, these sensors can measure the pressure ripples in a pump shaft rotation. Both sensors have a frequency response of > 50 kHz. (P_3) is a mean pressure transducer. It is located at the outlet side of the pump. It is a type Burkert 8314 with a measuring range of [0 ÷ 10] bar and is based on ceramic technology measurement principle. The lamination valve (R_2) regulates the pressure at the delivery side of the pump. The valve is located at the delivery port of the pump after the flow meter (Q). The flow meter (Q) works with a functional principle based on the controlled generation of Coriolis forces. It is able to measure also the temperature and density of the oil. Different signals are acquired by the hardware system NI PCI16-E1-MIO (12-bit ADC converter resolution). All the signals are routed to the board NI PCI-MIO 16-E1 through a 68-pin shielded desktop connector block NI SCB-68. A finite - machine study, developed with National Instruments LabVIEW® 2015 software, thus to control, manage and capture data.

As said, the goal of this analysis is the study of a Gerotor pump forced to cavitate. Cavitating conditions have been achieved reducing the diameter of the suction port with three calibrated orifices (R_1). These orifices are shown in figures 1d and 1e, where the first one (18mm) corresponds to the regular diameter of the inlet port of the pump. The second orifice has a diameter of 5 mm, while the last one is of 3mm. By reducing the diameter of the suction port the performance of the pump changes as well.

The described test bench is able to perform three acquisition methodologies:

- Low sampling rate for main bench parameters (flow-rate, mean pressure, rpm);
- External clock variable sampling rate (instantaneous suction and delivery pressure);
- Time dependent sampling frequency (10 kHz) with a fixed time window (1 ÷ 10 s).

The experimentation has been done in all the pump operating condition with oil: PETRONAS SYNTIUM 7000 0W-20. In particular the pump has been tested varying the delivery pressure in the range [0 ÷ 6] bar and with an oil temperature of 30°C, 60°C and 90°C.

In figure 2 experimental data are shown. In particular, figure 2a shows the pump characterization with no restriction. Figure 2b presents the delivery varying the pump speed by changing the suction diameter with orifices of 18, 5 and 3mm. By the end, in figure 2c the measured pressure ripples are shown, the four spikes are due to geometry of these four teeth.

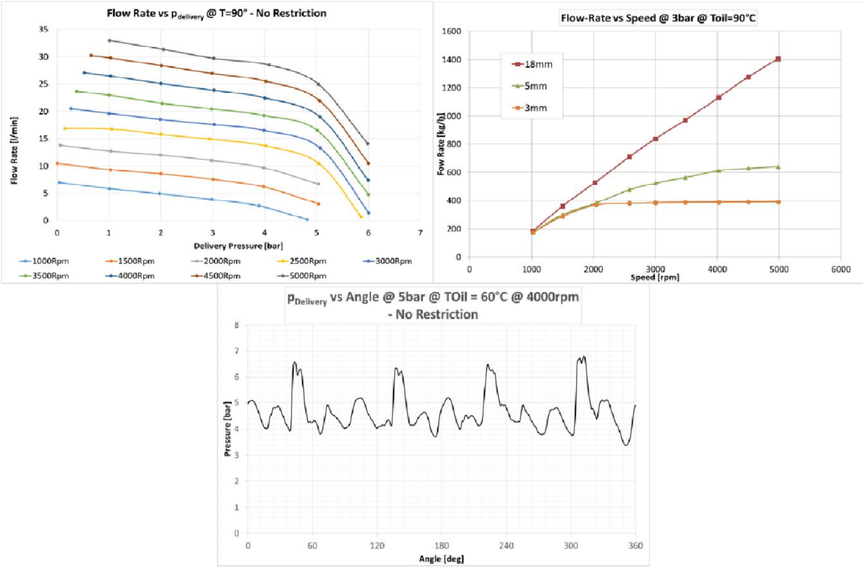

Fig. 2. Experimental data: (a) Pump caracterization, (b) Infuelce of restriction on the pump performance, (c) Pressure ripples.

3. Experimental vibration analysis setup

As discussed before, the experiments were realized on a Gerotor automotive oil pump, settled on a custom test bench. The pump was powered by an axial piston motor powered by an axial piston pump which was finally powered by a three phase electric motor, capable of delivering 18.5 kW of power.

The Gerotor pump was equipped with two instantaneous pressure transducers inside the inlet and delivery regions of the chamber, directly on the oil flow. The transducers used were the type AVL LP11DA, with the inlet one being capable of measuring pressures in the range of [0 - 10] bar and the delivery one on the range of [0 - 30] bar. The transducer accuracy is in the order of < 0.1% FSO, and it is capable of performing measurements at rate of 50 KHz.

A ceramic shear ICP® accelerometer PCB Piezotronics, 10 mV/g, 5 to 60 kHz, model 352A60 was placed outside of the pump near the cavitation zone, as indicated on figure 3. Its sensitivity is low at very low and very high frequencies, with a reasonably flat response (±3 dB variations) over the frequency range 5 Hz to 60 kHz.

Also, on the pump shaft was installed an incremental optical encoder, to measure the shaft speed rotation.

All signals were acquired by using an LMS SCADAS XS 12 channels scope, with the sampling frequency of 52.2 KHz for each channel. The complete experimental array used, is shown on the figure 3 below.

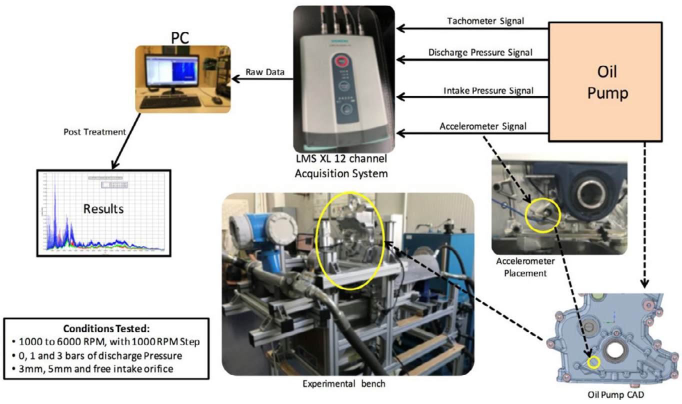

Fig. 3. Experimental Layout.

All the experiments were performed with a constant oil temperature of 40 ºC, for which 54 different conditions with and without cavitation were tested, by mixing the following states:

- 1000 to 6000 RPM with 1000 RPM steps
- 0, 1 and 3 bar of delivery pressure
- 18, 5 and 3 mm of diameter of the intake orifice

Those tests generated 216 data streams in total, composed by, tachometer, accelerometer, pressure-in and pressure-out data. All of this data was post processed on the Siemens LMS.Lab Signal Acquisition software, mainly by applying a FFT to obtain their FRF's (Frequency response functions).

4. Results and Discussion

The results obtained by the experimental setup described in last section will be exposed here. They will be classified in two classes: no cavitation and developed cavitation. One clue to identify if cavitation is present, is that it will tend to shift most of the energy in the frequency spectrum into higher frequency bands, between 7 KHz and 14 KHz, when compared to low frequencies. On the low band of the frequency spectra, some important regions that usually contains a lot of energy are located around the fundamental frequency - eq 1, that originates from the shaft rotation, the van passes frequency – eq 2, that originates from the inner teeth's of the rotor and the outer teeth frequency – eq3, which, as the name implies, is originated on the outer teeth's of the rotor. The theoretical value of those frequencies can be calculated from the equations below.

$$f_0 = {}^{\omega_{RPM}}/_{60} \tag{1}$$

$$f_{van\ Passes} = f_0 * N_{inner\ teeth} \tag{2}$$

$$f_{outer\ teeth} = f_0 * N_{outer\ teeth} \tag{3}$$

On the following figure 4, is possible to see the spectrum the response frequency of the accelerometer, for a first essay realized at 2000 RPM, with an orifice size of 5mm, and various delivery pressures (0, 1 and 3 bar).

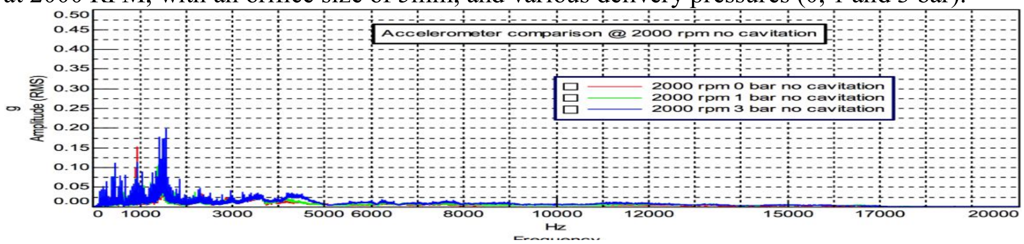

Fig. 4. Accelerometer response at 2000 RPM.

In this spectrum is noticeable that no cavitation is present, because of the lack of any important activity on the high frequencies bands. Most of the energy is located on the lower end of the spectrum, meaning the system is being mainly excited by conventional mechanic sources of vibration, such as misalignments and manufacturing defects, which does not tend to present high frequency responses.

In next figure, the spectrum shows the frequency response of the accelerometer for a pump rotation of 3000 RPM, an orifice size of 5mm, and the same three delivery pressures from last case.

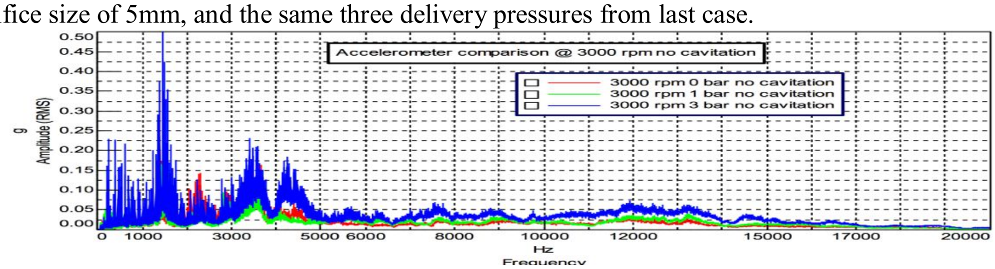

Fig. 5. Accelerometer response at 3000 RPM.

It is evident that, when the delivery pressure reaches around 3bar, an important amount of energy gets concentrate on the frequency band between 7 KHz and 14 KHz, meaning the cavitation phenomena is starting to develop. It is not possible to confirm surely that it is really present, because the lower frequency band also contains a lot of energy, mainly around 1400 Hz, which represent two times the van passes frequency at 3000 RPM, and on 3500 Hz and 4500 Hz, which are caused by the fluid recirculation inside the pump chamber.

In next figure, the spectrum shows the response of the accelerometer for a pump rotation of 4000 RPM, an orifice size of 5mm, and two delivery pressures (1 and 3 bar). The delivery pressure of 0 bar cannot be achieved at 4000 RPM.

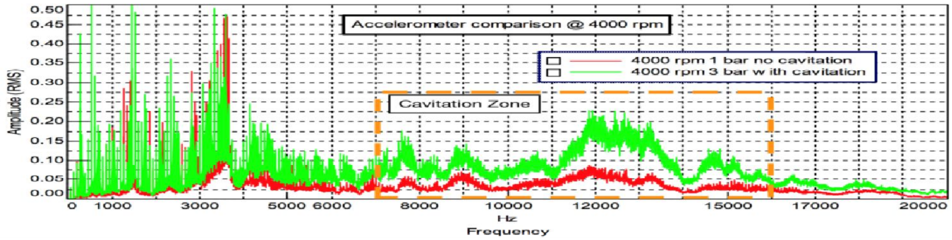

Fig. 6. Accelerometer response at 4000RPM.

Now it is possible to confirm that cavitation fully developed with 3bar of delivery pressure. It is explained, mainly because the energy density of the spectrum, between 7 KHz and 14 KHz is much greater than the lower end of the spectrum, which is usually excited by conventional mechanical sources. The peek of vibration amplitude of around 3500Hz is caused by recirculation inside the pump chamber. In this case, the FRF method to detect cavitation is perfectly suited.

In next figure, the spectrum shows the response of the accelerometer for a pump rotation of 5000 RPM, an orifice size of 5mm, and various delivery pressures (1 and 3 bar). The delivery pressure of 0 bar cannot be achieved at 5000 RPM.

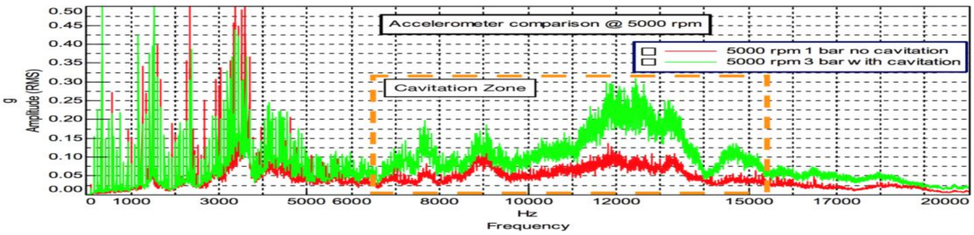

Fig. 7. Accelerometer response at 5000RPM.

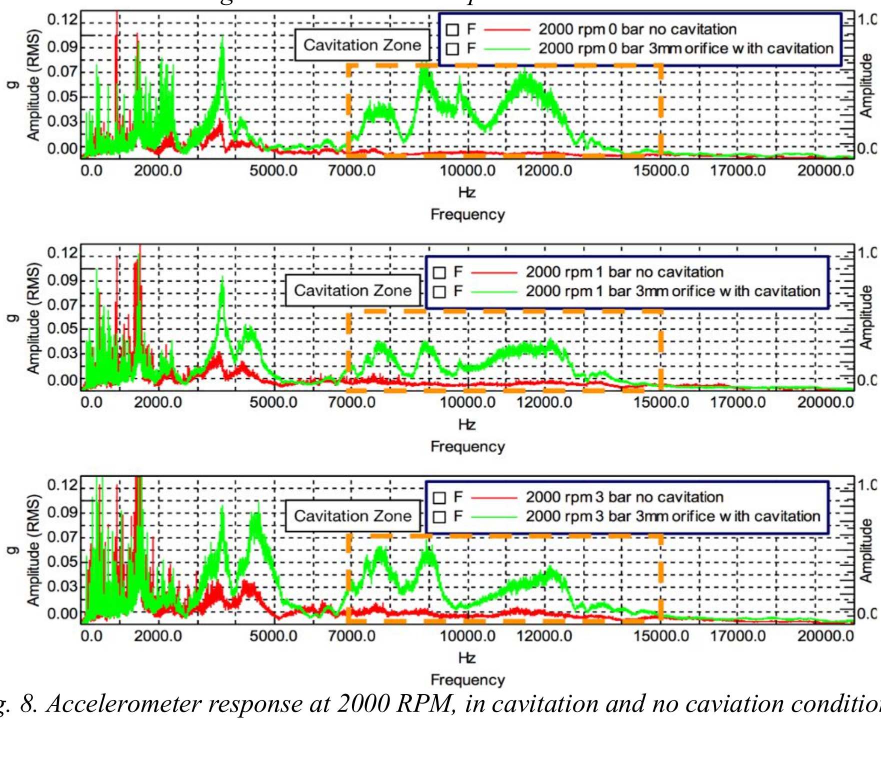

Fig. 8. Accelerometer response at 2000 RPM, in cavitation and no caviation conditions.

Notice that the main behaviour of this scenario at 5000 RPM is very similar to the scenario earlier described at 4000 RPM. The main differences that can be spotted are related to the overall amplitude of vibration in the frequency bands around 3500 Hz and the cavitation zone between 7 kHz and 14 kHz. At 5000 RPM, those amplitudes are much higher than at 4000 RPM, and one more time, as expected, cavitation is present.

In case in figure 9, the three spectres show the Gerotor pump at 2000 RPM in different discharge pressures (0.1 and 3 bar), in cavitation and no cavitation conditions. Cavitation is induced by installing a 3mm orifice on the oil inlet, as oppose to the no cavitation condition, in which the pump is operating normally, with it's default 18mm inlet orifice.

In all three spectrums, it is visible that there is a lot of energy on the lower band of the frequency spectrum. Which is explained again by ordinary mechanical excitations, the van passes frequency and some recirculation, mainly when the lamination valve is open at 0 bar. In all cases also, when cavitation is present, for the green curve, the overall behavior is the same. The main variation that occurs from case to case is related to the overall amplitude of the response of the accelerometer on the cavitation zone, which is bigger on the lower discharge pressure.

In the next case (figure 9), the two spectres show the Gerotor pump at 5000 RPM in different discharge pressures (1 and 3 bar), in cavitation and no cavitation conditions. As on last case, cavitation is induced by installing a 3mm orifice on the oil inlet. The pressure value of 0 bar on the pump discharge cannot be achieved at 5000 RPM, for this reason this test was performed only in 1 and 3 bar of pressure.

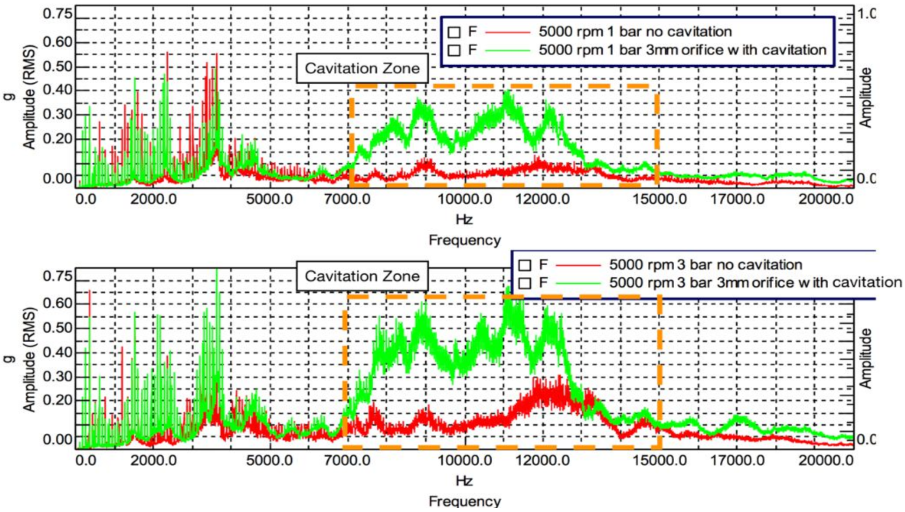

Fig. 9. Accelerometer response at 5000RPM, in cavitation and no caviation conditions.

Notice that in all two spectrums when cavitation is present (green curve), the overall behavior is the same. It is important to notice that the cavitation amplitude at 5000 RPM is much higher than at 2000RPM, at least 5 times as high. In addition, it is noticeable, on the second spectrum, at a discharge pressure of 3bar that the pump starts to cavitate even on the normal working condition, as can be seen on the red curve, on the frequency range between 7 KHz and 14 KHz.

5. Conclusion

In this paper a typical Gerotor pump used for the lubrication of Internal Combustion Engine has been studied in cavitation conditions. The pump has been tested on a test bench installed in the Department of Industrial Engineering of the University of Naples Federico II.

Cavitation has been forced by reducing the suction port of the pump with calibrated orifices with diameters of 18mm, 5mm and 3mm. For each diameters, the Gerotor has been characterized measuring the delivered flow-rate, pressure in the suction and delivery chambers, the mean pressure at the delivery port the absorbed torque and noise with an accelerometer. The detected cavitation is stronger with lower diameters and higher pressure. As discussed earlier, there are some secondary sources of vibration and noise, other than the cavitation itself, like radial misalignments, impeller pressure variations, manufacturing defects of seals, bearings and impellers, and even hydraulic sources of noise, such as transient and unstationary flow causes. All of those secondary vibration sources add to the final measurement captured by the accelerometer, and their identification is important to the quality of the final analysis of the pump. As the identification of some noise sources may be very difficult, such as the hydraulic sources, the fault identification by using only the FRF of the accelerometer is not always obvious.

The main difficulty of implementing a method to detect fault (in this case cavitation) by using the FRF method relies on the threshold that must be set to differentiate cavitation from normal operation. As can be seen on the results section, mainly on figure 5 (3000 RPM-5mm orifice), is not always obvious when the cavitation problem is present or not, and it gets even more difficult to make conclusions, because the response induced on the accelerometer by cavitation, in g amplitude varies for each shaft rotation speed.

Future developments could regard in implementing an effective method to predict failure, some other approaches may be used, mainly the ones that permit to set a constant threshold to determine if cavitation is present or not. One possible approach is the use of the *ARMA* (Auto Regressive Moving Average), [12-14] mathematical model that applies directly on the time history of the accelerometer signal, and permits to set a constant threshold, or even the use of an ANN (*Artificial neural network)*.

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