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VIBROACOUSTIC PREDICTIVE INVESTIGATIONS ON NORMAL OR DEFECTIVE OPERATION OF HYDROSTATIC PUMPS

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Abstract: *In industrial predictive maintenance, as well as in many practical situations, it is necessary to measure the noise and vibrations produced by machines and equipments in order to evaluate their state of functionality or malfunction. In this paper, the results of the experiments of a group of engineers from INOE 2000-IHP Bucharest and from the University Politehnica of Bucharest are presented, which aimed to show the effects of the cavitation phenomenon in hydraulic gear pumps on the frequency spectra resulting from the vibration signals processing.*

Keywords: *Predictive maintenance, noise measurement, vibration analysis, hydrostatic pumps, hydraulic drives*

1. Introduction

In predictive industrial maintenance, but also in many other practical situations, <u>noise measurement</u> is required. A noise is defined by the specific physical parameters, namely: intensity, frequency spectrum or time variation of its level. If the noise refers to a certain source of sound, such as an electric motor, a fan, a textile machine or a pneumatic hammer, then the parameters that characterize the source from an acoustic point of view must be determined, regardless of the environment in which they are working. These are: *acoustic power*, *directivity*, *frequency spectrum* or the *noise variation over time*. In order to obtain appropriate values for each physical parameter mentioned, in addition to a specific measurement technique, a suitable equipment must be used. With regard to noise of the same nature, it can be said that only by observing certain measurement conditions, the resulting data can be accurate and approved for publication. In this way a comparative database from different laboratories can be made.[1]
Also, the maintenance operators determine the proper functioning of a machine, or detect the symptoms of a malfunction appearance within it and by <u>vibration analysis</u>. Two measurements can be made by which the state of a vibrating body can be defined. The first one determines the state of motion of the body by measuring one of the following parameters of vibration: displacement, speed or acceleration, usually the acceleration is measured. The second measurement indicates the state of tension but also of deformation that the body or the surrounding element of construction undergoes as a result of the action of the vibrations that lead to smaller or greater deformations. These can be recorded by *electrical tensometry*, the deformations producing variations of an electrical parameter, such as *resistance*, *capacity or inductance*.[1] This type of method can be used not only for the measurement of vibrations caused by mechanical forces but also for actions of electrical or hydraulic nature. In order to identify the imminently destructive cases of the analyzed equipment, the vibration signal is processed. This results in a signal of the frequency spectrum which is a good indicator by which the cases of faults can be identified between them.[2] As the support technology of the mechanical equipments in the predictive maintenance system and the management of their maintenance advances, it is recommended to measure the mechanical vibrations as an indicator of attention [2,3], and in the large installations, where the danger caused by possible failures can be a major one, a permanent vibrations monitoring and the automatic shutdown of the operation take place if the vibrations level exceeds certain limits.

2. Noises and vibrations in hydraulic installations

In tools and equipments that have moving parts, such as hydraulic equipments, shocks and vibrations occur, which on the one hand are transmitted to the whole system, and have a negative effect on the machine as a whole. On the other hand, vibrations and shocks generate air oscillations, producing unwanted noises. These effects, sometimes fatal, can in many cases be prevented, provided that the involved specialists establish clear relationships between the type of noise and the state of functionality of the equipments [4]. In many cases, *the abnormal noise* is caused by cavitation or by air entering the oil. The noise of the air in the system is given by the compression and decompression of the air, during the movement in the system, together with the working fluid. The aeration results in the foaming of the hydraulic oil that it destroy. Lubrication and sealing are also destroyed, and finally the hydraulic equipments. Sometimes the air enters in system through the suction line of the pump, which may have mechanical defects, or when the oil level in the tank is below of the normal level. The air may also penetrate the pump shaft if its sealing is improper. [4] When the volume of oil required for the hydraulic circuit exceeds the volume received from the pump, the *cavitation* phenomenon occurs. Due to this, there is a drop in pressure in that area of the circuit under the vaporization pressure of the working fluid. As a result, bubbles (cavities) are formed which break down during compression, resulting in a characteristic noise. The consequences in the system may be of the nature of the metal erosions that contaminate the fluid and damage the hydraulic components. Often the defects caused by cavitation are found in the pumps, and for this reason the specialists must take into account that their suction line is free. The introduction of suction filters or valves must be done carefully, with the consent of the designers.[4] Among the processes that strongly influence the occurrence of malfunctions of hydraulic equipments and systems, the vibrations, self-vibrations and shocks caused by the pulsations of pumps, pressure valves and distributors are detached, together with the nonlinearities that appear in dynamic regime .[4]

3. Assessment of the hydrostatic pumps behavior using flow charts

In the predictive maintenance, in the last years, the authors of the paper have made numerous attempts to evaluate the behavior of hydrostatic pumps in operation by specific non-invasive methods, of which two main methods are detached: namely, the investigation with the help of infrared thermography or the method of vibration analysis, which have led to interesting results and conclusions published in various articles, such as those indicated in the Bibliography in the positions, [5,6]. Because it is almost impossible to attempt the quickly establish of the cause and to correct any errors that have occurred, even in the simplest hydraulic system, it is advisable to adopt a logical approach of the maintenance in order to locate an occurred fault during in the shortest possible time and in the most precise way (Fig. 1). In the industry, the outcome time of modern machines is very expensive, because an allocated hour for detecting a fault can mean a very large amount of money. In the recent years, hydraulic systems became more and more complex and, accordingly, the control methods of machines became more and more sophisticated. Therefore it is essential that the manufacturer's equipments or service information keep up with the used hardware. In this paragraph are presented procedures for logical approach of the maintenance operations that can be extended to certain machines in all industrial fields. The basis of these procedures, related to the control of excessive noise and vibration in hydraulic installations, find their support in numerous examples and applications in the industry. A flowchart (*Algo 0.3*), proposed by ***EatonVickers (USA)*** for testing hydrostatic pumps, when excessive operating noise appears, is shown in Fig. 2. Similarly, another flowchart for testing hydrostatic pumps at the occurrence of excessive vibrations in operation is shown in Fig. 3. In this case the FAULT, CAUSE, REMEDY (F.C.R) charts can be used to locate the problem area [7].

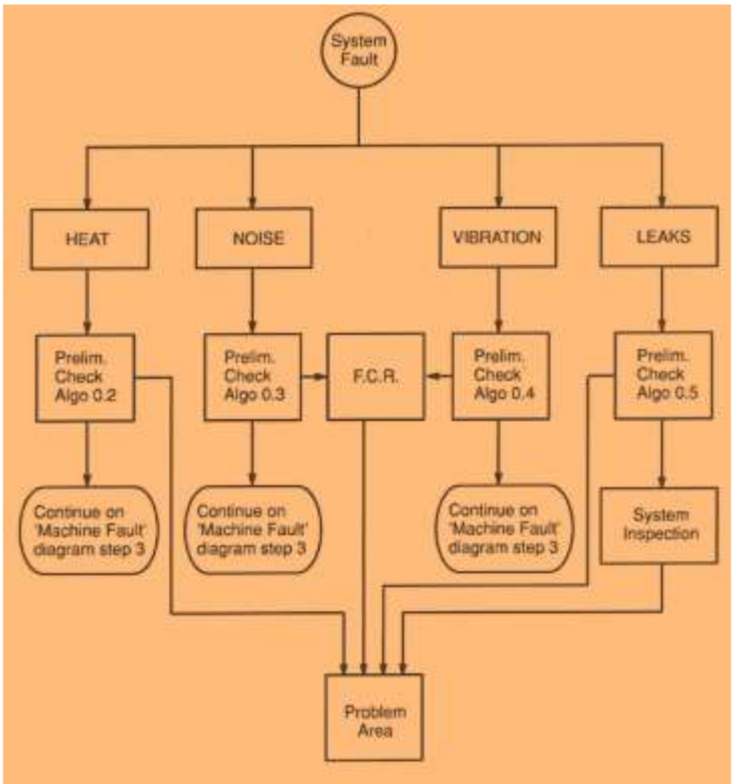
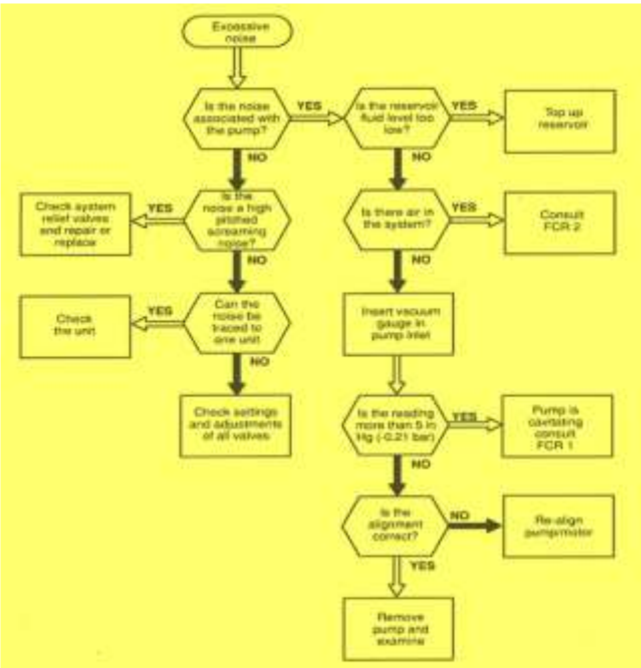


Fig. 1. Flowchart for faults that may occur in a hydraulic system, [7]



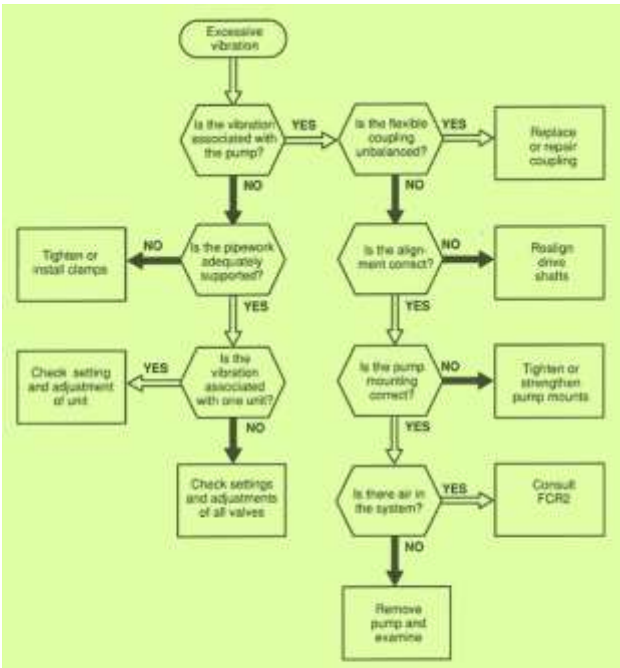


Fig. 2, Fig. 3 (from left to right) Hydrostatic pumps tested for excessive noise and for excessive vibration [7]

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4. Assessment of the measured vibration spectra in operation of certain hydraulic gear pumps in normal and cavitational mode

Inside of Hydraulics Laboratory of INOE 2000-IHP, an experimental stand was created (Fig. 4), on which two hydraulic gear pumps model **Vivoil XV 2P-DC (Italy)** were separately tested in normal and cavitational mode (Fig. 5, Fig. 6), having the displacements of **9 cm^3 /revolution** , respectively **6 cm^3 / revolution.**

Fig. 4. Experimental stand

Fig. 5. Pump with a displacement of 9 cm^3/rev

Fig. 6. Pump with a displacement of 6 cm^3/rev

The hydraulic diagram of the experimental stand and its components are shown in Fig.7 and Fig.8

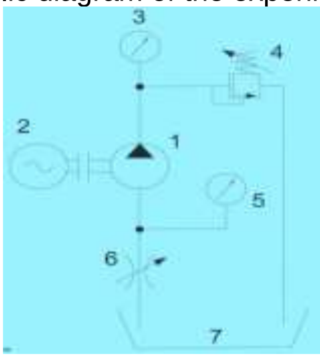

Fig. 7. Hydraulic diagram of the stand

No.	Component	Technical characteristics	Manufacturer
1	Hydraulic gear pump	Tip XV 2P-D/C , V_g = 9 cm^3	Vivoil, Italy
2	Electric motor	Tip D63110, 2,65 kW, 1420 rot/min, 50Hz	AG Motoren GmbH, Rodgau, Germany
3	Gauge with glycerin	P = (0-160) bar, precision class 1,5	Hansaflex, Germany
4	Pressure valve	Tip SPP 6-04, Pmax= 315 bar	Hidrosib, Romania
5	Vacuummeter	P = (0-1) bar, precision class 1,5	Afriso, Germany
6	Throttle valve	FT 257/2-12, 400 bar	F.lli Tognella, Italy
7	Oil basin	V= 79, 3 l	INOE 2000-IHP, Romania

Fig. 8. Hydraulic components

4.1 - Vibration analysis of a hydraulic gear pump with a displacement of 9 cm^3/revolution in normal and cavitational mode operating

In order to produce the **cavitation** phenomenon, on the suction hose of the pump, with a nominal diameter Dn = 40 mm, an adjustable way throttle was installed, through which several vacuum steps were generated, in a range from -0.2 bar (first measurement) to -0.7 bar (last measurement). Simultaneous, all performed measurements were made by generating through an adjustable valve of three pressure steps, respectively: 50 bar, 75 bar and 100 bar. Recording of the system vibrations under normal operating conditions and under cavitational mode was made using three **Bruel & Kjaer (Denmark)** type accelerometers, **model 4507 B** (Fig. 9), fixed in three different points of the test stand, respectively: on the pump housing. , on the electric motor and on the oil tank (Fig.10,11,12).

Fig. 9. Accelerometers

Fig.10. Accelerometer mounted on pump

Fig.11. Accelerometer mounted on motor

Fig. 12. Accelerometer mounted on oil tank

Accelerometer signal processing was performed using a **National Instruments** data acquisition plate model **NI 9233**, (**USA**), connected to a laptop.(Fig. 13, Fig. 14).

Fig. 13. Data acquisition plate

Fig. 14. Laptop

Note: Due to the installation of the pump on the stand, but also of the dimensions of the hydraulic hoses, at the start of the electric motor, without throttling, the pump has in suction a vacuum of -0.2 bar, registered by the vacuum meter. In the experiment, it was agreed that this value should be considered as a reference for the normal operating mode of the pump, while all measurements corresponding to the throttling steps starting from -0.3 bar to -0.7 bar will be associated of its cavitational operating mode.

4.1.1. Obtained results

As a result of the measurements, **90 vibration signals** resulted. By means of **Matlab** software, all vibration signals were then converted into frequency spectra. For the paper, of a special interest are the vibration signals generated spectra, taken by the accelerometer **A1** mounted on the pump, at different pressures measured respectively by the manometer and the vacuum meter (Table 1).

Table 1: Vibrations signals

Accelerometer signal A1 - pump	Pressure [bar]	
	at vacuummeter	at gauge
01 dB_wave_114.mat	-0,20	100
01 dB_wave_159.mat	-0,50	100
01 dB_wave_177.mat	-0,60	100
01 dB_wave_195.mat	-0,70	100

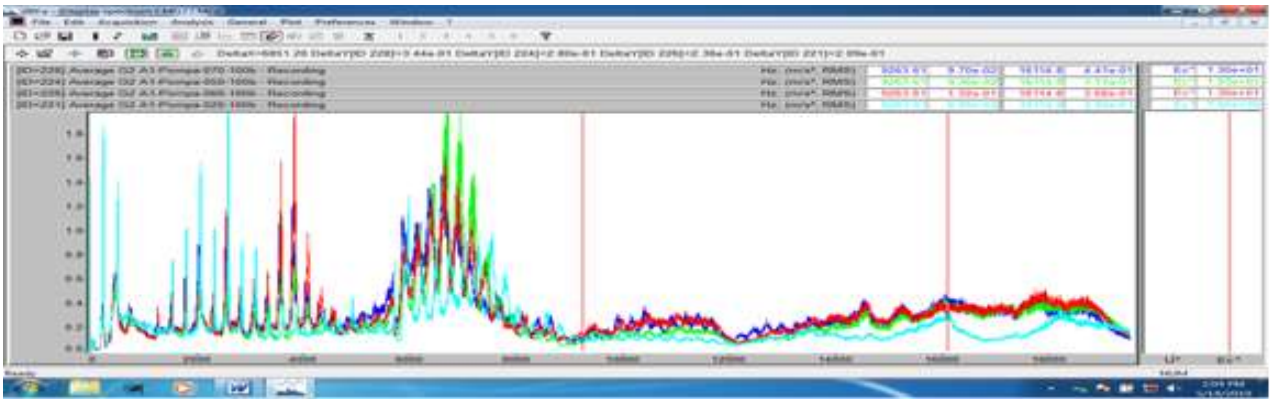

Fig. 15. The overlayed spectra analysis

4.1.2. Discussions

It can be seen from Fig. 15 on the overlayed spectra that in the high frequency band, **9000-16000 Hz**, the acceleration level is higher at big cavities (-0.7 bar; -0.6 bar) and lower at small values (-0.2 bar and -0.5 bar)

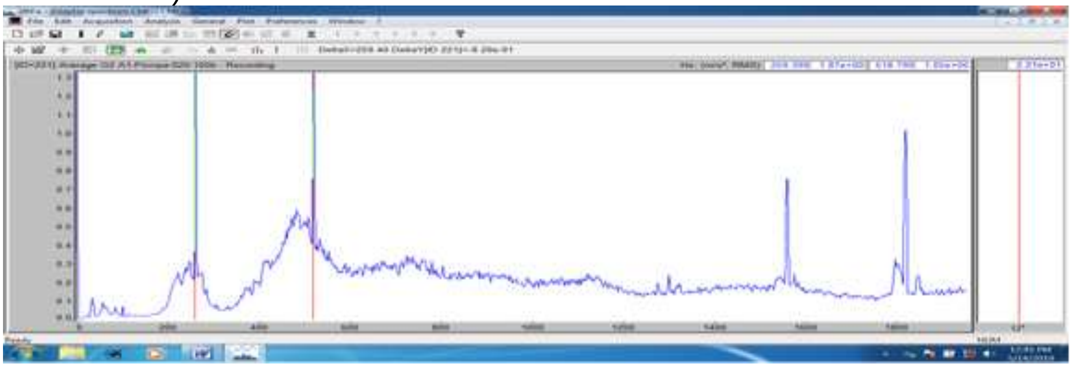

Fig. 16a. Spectrum analysis for Pv = -0.20 bar; Pm = 100 bar

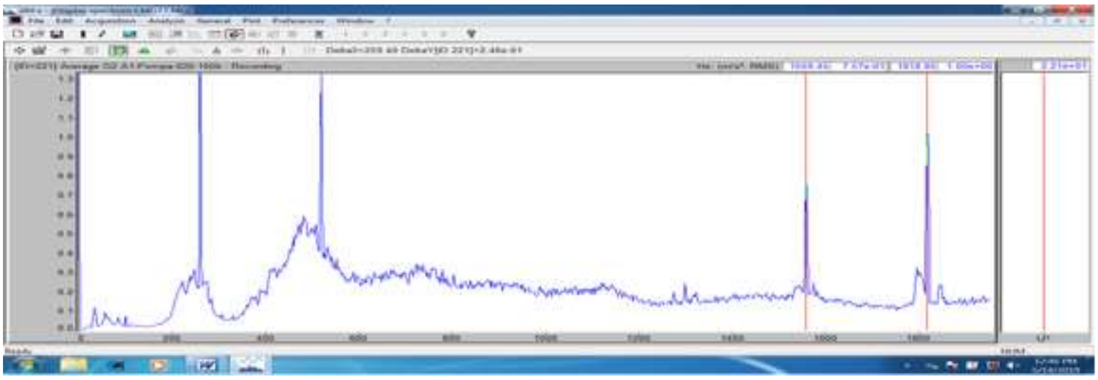

Fig. 16b. Spectrum analysis for Pv = -0.20 bar; Pm = 100 bar

In the spectrum of Fig.16a it is observed that a frequency of about **259.4 Hz** appears, having a harmonic of **518.8 Hz**, and in the spectrum of Fig. 16b it is observed that this frequency is then repeated with higher harmonics of **1559 Hz (6x 258.4 Hz)**, then of **1818 Hz**, etc. (Pv = vacuum meter measured pressures; Pm = manometer measured pressures).

4.2 - Vibration analysis of a hydraulic gear pump with a displacement of 6 cm^3/revolution in normal and cavitational mode operating

For the resulting vibrations analysis following the 6 cm^3/revolution displacement pump testing in the normal and cavitational mode, the same working scenario was followed as in the case of the pump with displacement of 9 cm^3/rev. In contrast to the experiments described above, in this case, for vibration recording, accelerometers were mounted at three different points of the pump(Fig. 17). Thus, the vertical, horizontal and axial vibrations are recorded respectively by the accelerometers **A1**, **A2** and **A3**.

Fig. 17. Positioning of the accelerometers on the pump

4.2.1. Obtained results

Following measurements, **90 vibration signals** resulted. By means of **Matlab** software, all vibration signals were converted into frequency spectra. Two of these are shown in (Fig.18-19). P are the pressures and C are the cavities.

Fig. 18. A1-vertical /P=100bar C=(-0.40;-0.45; -0.50)bar

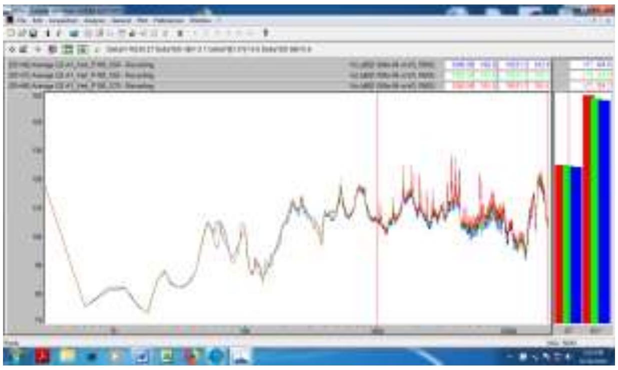

Fig. 19. A1-vertical /P=100bar C=(-0.60;-0.65; -0.70)bar

4.2.2. Discussions

From the vibration spectra analysis indicated in Fig. 18 and Fig.19 it is observed that in the 3000-6000 Hz band, the vibrations are increasing as the cavitation increases (Fig. 20 and Fig. 21).

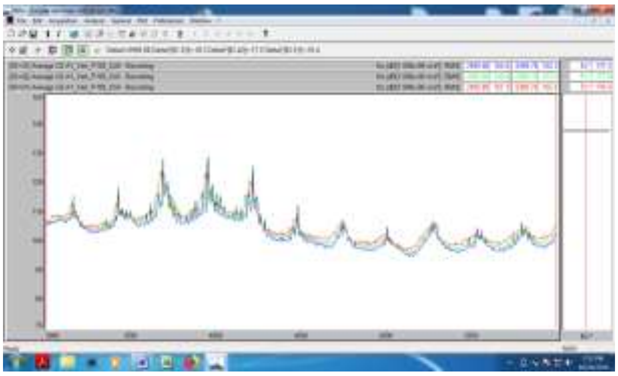

Fig. 20. A1-vertical /P=100bar C=(-0.40;-0.45; -0.50)bar

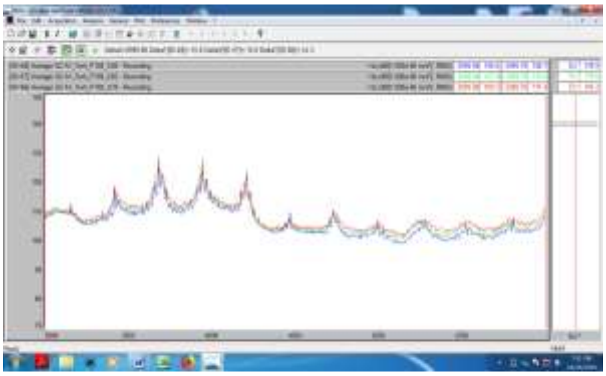

Fig. 21. A1-vertical/P=100barC=(-0.60;-0.65; -0.70)bar

-As the pressure increases on the pump discharge, the amplitude of the vibrations decreases and in some areas, it is greatly reduced.
-The more vacuum on the pump suction is more pronounced, the amplitude of the vibration increases.

5. Conclusions

- By pump testing with displacement of **9 cm^3/rev** the following conclusions could be detached:
  - Although the cavitation phenomenon should have been detected at high frequencies, this thing has been obstructed due to the occurrence of certain higher harmonics of very large amplitudes which are more important especially at low pressures.
  - Clearer determination of how the cavitation is reflected in the frequency spectra could be makes it simpler in the event that these defects would not manifest themselves so obviously.

- By the method of vibration analysis, although surprising results have been obtained, they indicate a state of abnormal operation of the tested pump on the stand, explained by the internal losses suffered of this as a result of the grinding.
- Because the authors wished to obtain more conclusive results, another one Vivolil hydraulic gear pump, with a displacement of **6 cm^3/rev** was subsequently tested, action which resulted in the following conclusions:
- The experiments must focus on signals analyzing at narrower frequency intervals, in order to accurately identify the area where the cavitation is found in the signal.
- By comparing with the normal operating spectrum of the pump, the degree of its wear because of cavitation can be estimated. This will trigger a predictive maintenance alert by re-evaluating /repairing of the suction circuit, or even installing the pump on a checking stand an/or sending it into service in repair procedure. If necessary, the pump will be replaced.

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