AN ALTERNATIVE MULTICHANNEL SYSTEM FOR PRESSURE PULSATION ANALYSIS ON RECIPROCATING COMPRESSORS FOR PREDICTIVE MAINTENANCE

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ABSTRACT: *The need of alternative instrumentation and analysis methods for improving reciprocating compressor monitoring has been motivating an intensive effort in research. The goal here is to find new resources providing increased reliability and availability to such type of equipment. We explore the possibility of developing digital multichannel systems allowing simultaneous measurement of different parameters such as vibration, pressure, position, etc. Synchronous measurement of such parameters is a fundamental resource for diagnosing defects on components of the gas compression end, in addition to providing significant subsides for identifying defects on compressor power end.*

Key Words: Dynamic Pressure , Vibration, Predictive, Monitoring, Compressor.

1. INTRODUCTION

Reciprocating compressors have been put aside in Predictive Maintenance programs, either for lack of knowledge among professionals or for lack of specific instrumentation resources such as multichannel analyzers, sensors, softwares, etc. Due to such deficiency, reciprocating compressors have been primarily maintained by preventive systems that schedule periodic inspections to some components and general overhauls during the maintenance turnarounds. However, currently such strategy does not meet the reliability, availability and cost requirements set by the operation management. That issue encourages technical and managerial professionals to search for cost-effective alternatives to solve this problem.

In regards to reciprocating compressors, the major technical difficulty for performing vibration analysis derives from the overlap of the efforts, originated at the fluid, with those efforts originated when rotational movement is converted into reciprocating movement. Such aspect demands the application of additional analysis parameters, as well as new methodologies for data acquisition and processing.

The popularization of signal digitalization technologies has allowed the development of specific data acquisition and analysis systems, enabling a specific approach to reciprocating compressors according to its unique characteristics.

2. OBJECTIVE

In this study we intended to produce a dynamic pressure measuring system, which simultaneously acquires either vibration signal and crankshaft angular position. Such system allows the association of signals acquired at the different stages of the compressor duty cycle. We expect that the development of such resource will give an important contribution for lowering costs of predictive maintenance devices in Brazil.

3. DEFECTS DIAGNOSIS

We attempted to develop a reciprocating compressor diagnosis methodology based on measurement of vibration and pressure pulsation within the cylinder.

3.1 Diagnosis of Discharge Valve Defects

Schirmer, Fernandes and De Caux (2004) presented a methodology based on the comparison between measured and theoretical P x V (Pressure x Volume) diagrams, which provides us with important information. Table 1 shows the symptoms and justifications for discharge valve defects.

Table 1 – Symptoms of discharge valve defects. (Schirmer, Fernandes and De Caux, 2004)

SYMPTOM	CAUSE
Faster pressure reduction during expansion stage	Gas flows from cylinder to inlet line, where pressure is lower
Slower pressure increasing during compression stage	
Mass balance becomes greater than 1	Volumetric efficiency of inlet increases while volumetric efficiency of discharge diminishes

Symptoms described on Table 1 may be observed on the P x V diagram shown on Figure 1.
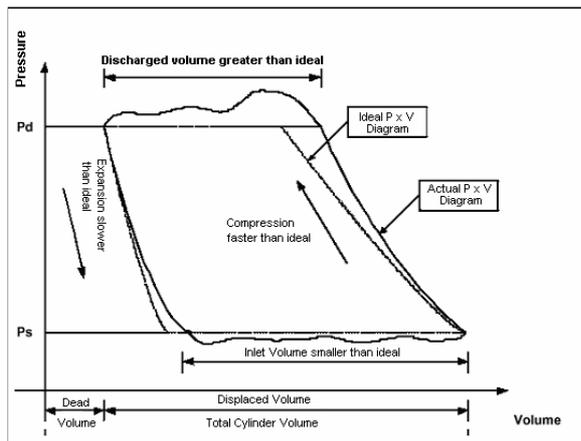
Figure 1 - P x V diagram for a reciprocating compressor leaking through the discharge valve. One may observe significant differences in compression and expansion stages when compared to an ideal cycle. (Schirmer, Fernandes and De Caux, 2004)

3.3 Diagnosis of Mechanical Looseness

Zusman and Palm (2001) proposed a measurement of transient vibration signals using special electronic circuits for detecting peaks – which would not be detected by traditional methods. According to those authors, signals bearing short duration and high amplitude indicate the existence of mechanical looseness. Since measuring isolated pulses could lead to false alarms, Zusman and Palm (2001) propose counting those events, within a given time interval, and comparing this number to a given threshold value.

4. PROPOSED SOLUTION

Currently on a worldwide basis there are researchers dedicated to the development of monitoring and analysis systems for reciprocating compressors. Usually those systems use several channels for simultaneous measurements, and may present different configurations according to application, resources available and solutions adopted by every manufacturer. Some of the main systems are as follows:

- Dedicated data collector;
- Sensors signal conditioning and digitalization system connected to a portable PC;
- Acquisition boards, installed in panels next to the equipment, which send signals to a desktop (supervisory).

Consequently it is possible to use several sensors and systems for data acquisition and analysis. As a consequence, one shall state some characteristics considered as important ones due to the application requirements and the availability of resources: portability; non-complex power supply; high rate signal sampling; single or multichannels data acquisition; non-complex data transfer; specific exploitation software; friendliness in data analysis software; low cost. In order to achieve a maximum compliance with items listed above, the following components were selected to our measurement and diagnosis system:

- Vibration measurement – ICP-type piezoelectric accelerometer;
- Dynamic pressure measurement – ICP-type piezoelectric dynamic pressure sensor;
- Piston position measurement – photo tachometer;
- Gas temperature measurement – thermocouple;
- Static pressure measurement – manometer;
- Data acquisition interface – TR2X12, homemade interface, developed at the Laboratory of Optical Properties at The Federal University of Bahia;
- General configuration – signal conditioning and digitalization system connected to a laptop personal computer;
- Data transmission – PC parallel printer port;
- Data acquisition software – developed using Visual Basic language;
- Analysis software – Origin 7.0.

5. EXPERIMENTAL CONFIGURATION

The experimental configuration was designed to simulate a real system. Its configuration allows the introduction by hand of defects into the experimental compressor. The intent was to subsequently study those defects as a way to validate the developed instrumentation.

5.1 Sensor Description

5.1.1 Dynamic Pressure Sensor

Dynamic pressure measurement was performed with a PCB Piezotronics 111A23 sensor, which is an ICP-type transducer. For powering that sensor we used 20 VDC and a decoupling capacitor provides the voltage output. In addition to signal conditioning that sensor requires a device for mechanical adaptation in order to enable measurement of the cylinder inner pressure. Such adapter (Figure 2) is composed of four pieces:

> Probe attached to valve top;
> Heat exchanger;
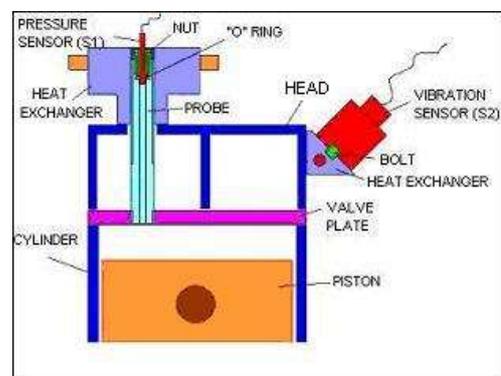> Sensor attaching nut;
> Sensor "O" Ring.

Figure 2 – Configuration for vibration and pressure measurement. On the left hand side there is a probe interconnecting the pressure sensor to the inner part of cylinder, heat exchanger and pressure sensor. On the right hand side a vibration sensor is attached to a heat exchanger.

The need of a heat exchanger emerged from experience acquired during tests, when we noticed measurement alterations related to temperature.

5.1.2 Vibration Sensor

A Wilcoxon 786F sensor was used to measure the vibration, the signal conditioning was carried out in a similar manner, as well as for the dynamic pressure sensor. Settling that sensor is very simple and the heat exchanger was used to ensure constant temperature. The heat exchanger (Figure 2) was fixed to the head with adhesive and to the sensor using a bolt.

5.1.3 Photo Tachometer

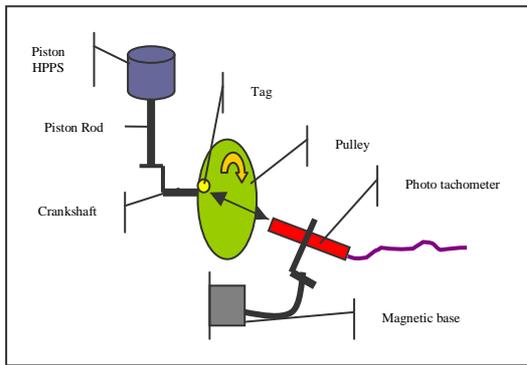A Monarch Instrument ROS-5P photo tachometer was used.

Figure 3 – Configuration for measuring stage. Image shows piston at the Highest Point of Piston Stroke (HPPS), the piston rod, the crankshaft and the pulley equipped with a tag that reflects light emitted by photo tachometer, which is supported by a magnetic base.

That signal does not require any conditioning step since it is a TTL standard digital signal that could be directly connected to the appropriate input on the interface. The sensor (Figure 3) was fixed to the compressor by a magnetic base. The light emitted would hit the reflective tag attached to the compressor pulley generating positive pulses. To achieve the adequate system operation, we fastened the reflective tag on the pulley with the piston at the Highest Point of Piston Stroke (HPPS). This procedure ensures the piston is on the HPPS every time a pulse is emitted by the photo tachometer. Considering that there are 360 degrees between a pulse and the subsequent pulse, it is possible to determine the piston position at any moment by studying the piston kinematics movement in regards to the piston rod, assuming that the crankshaft rotating speed is constant.

5.2 Data Acquisition Software

The software developed for data acquisition uses Visual Basic 6.0 language. It provides the communication between the interface and the PC, controlling the analog to digital conversions of pressure and vibration signals according to the time signal generated by the photo tachometer. Acquired data are stored in a matrix with four columns, along with the value corresponding to the time instant in which the measurement was performed. Hence pressure and vibration are digitalized and the

timing given by the tachometer – corresponding to every single measurement – this information can be saved as a text file for later processing and analysis with specific software. In addition to the text file, a second file (*cycle spreadsheet*) may be generated with pressure data as a function of piston displacement. The piston displacement is calculated by the software, using the tachometer information. For that purpose, the software stores the time instants where a descending transition of tachometer signal took place. After that, the software calculates the difference among those marks, obtaining the average cycle period and consequently the frequency *f*. Considering that there is a periodic relation between time and piston displacement in every cycle, we are able to convert time into unitary displacement using the following expression:

$$D(temp(i)) = \frac{Di}{Dt} = \frac{1}{2}(1 - Cos(2\pi * f * temp(i))) \tag{1}$$

In this case, we represent unitary piston displacement as (*D*), obtained by the ratio between instant piston displacement (*Di*) and total piston displacement (*Dt*).

5.3 Final Processing Software for Analysis

In order to allow required analysis for identifying reciprocating compressors defects, we preferred to use commercial software for final data processing. The software selected was Origin 7.0 SR0 (2002) given its diversity of available resources, such as: mathematical, graphical, and statistical resources, filters, FFT, etc.

6. METHODOLOGY FOR DATA ACQUISITION AND PROCESSING

6.1 Dynamic Pressure

Using the cycle spreadsheet we created a graphic representing all cycles occurring within a given measurement interval (Figure 4).
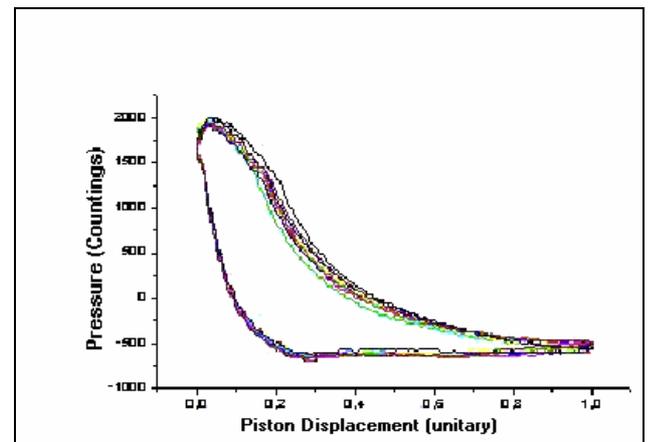

Figure 4 – Pressure for several cycles (Origin 7.0 SR0, 2002)

The graphic presented on Figure 4 enables us to calculate the Pressure x Piston Displacement average curve using the Origin 7.0 SRO (2002) resource Average Multiple Curve, which generates a new spreadsheet. After being adjusted by subtracting the offset and multiplying by a

calibration factor, this average curve results in a Pressure x Volumetric Displacement (unitary) plot (Figure 5). Us we know, the Unitary Piston Displacement is equal to Unitary Volumetric Displacement given that the piston head area is invariable.
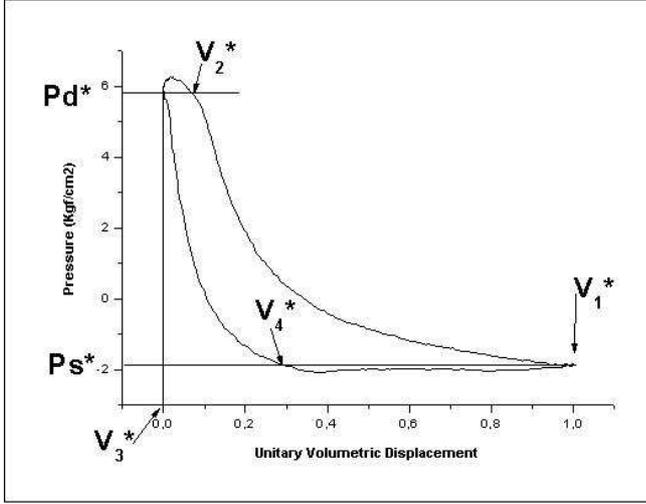

Figure 5 – Non-corrected Pressure x Unitary Volumetric Displacement plot. (Origin 7.0 SR0, 2002).

The curve represented above is not the correct curve yet, since the sensor measures pressure variations around an average pressure. Such error may be confirmed by observing the negative absolute pressures shown on Figure 5. It is necessary to calculate the average pressure around which the pressure varies. For that purpose we used the following calculation process:

To find the average pressure (Pm), we started calculating the compression rate r:

$$r = \frac{P_d}{P_s} = \frac{Pd*+Pm}{Ps*+Pm} \tag{2},$$

where $Pd*$ and $Ps*$ represent non-corrected discharge and inlet pressures, identified on Figure 5.

In order to obtain r, we initially equalized equation (3) – which calculates inlet volumetric efficiency from non-corrected P x V diagram – to equation (4), that calculates inlet volumetric efficiency for a real gas:

$$\eta_{VS} = \frac{Vasp}{V_D} = \frac{(V_1*+V_0)-(V_4*+V_0)}{(V_1*+V_0)-V_0} = \frac{V_1*-V_4*}{V_1*} \tag{3}$$

$$\eta_{VS} = \frac{Vasp}{V_D} = 1 - C\left(r^{1/k}-1\right) - L \tag{4}.$$

Assuming $L = 0.05,$

$$V_0 = V_2 * \left(\frac{V_4*+0.05}{1-(V_2*+V_4*-0.05)}\right) \tag{5}$$

Where V_0 is the dead volume existing within the cylinder when the piston reaches the Highest Point of Piston Stroke.

Yet considering the gas behavior as per the adiabatic hypothesis, as a first order approximation, we are able to calculate the compression rate r using equation (6).

$$r = \left(\frac{V_1*+V_0}{V_2*+V_0}\right)^k \tag{6};$$

where V_1^* and V_2^* may be obtained from the plot on Figure 5.

Adding the pressure values (P) to the average pressure (Pm) we obtained a corrected P x V (Pressure x Unitary Volumetric Displacement) graphic.
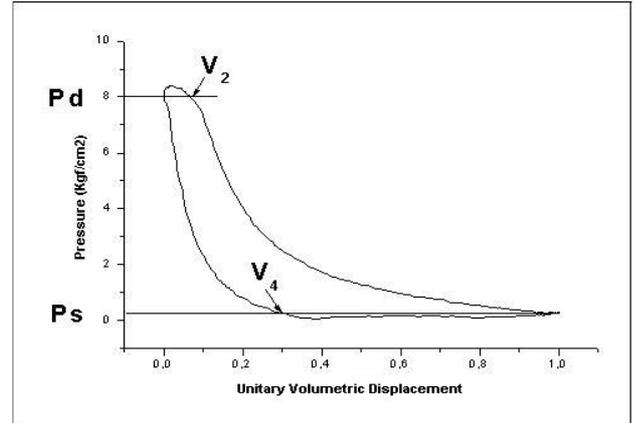

Figure 6 – Corrected Pressure x Unitary Volumetric Displacement plot. (Origin 7.0 SR0, 2002)

6.2 Vibration

For vibration data processing we multiplied the ADC counts by a calibration factor. Afterwards, we calculated the absolute value of the whole data, applied a 1kHz high-pass filter and used a data presentation form, where peak involutes are shown for several shaft spins (see Figure 7).
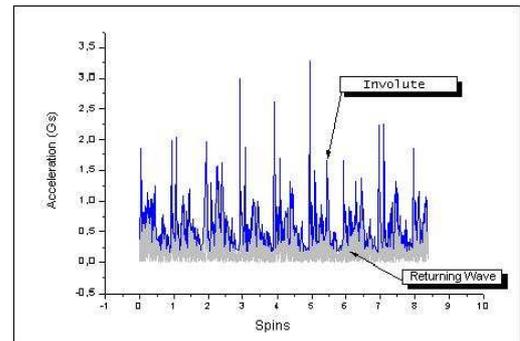

Figure 7 – Pulse involutes for shaft spins. (Origin 7.0 SR0, 2002)

7. TEST RESULTS

7.1 DEFECTS in Discharge Valves

In addition to visual comparison of cycles (Figure 4), some comparison parameters could be calculated from duty cycles analysis information and the P x V diagrams. This process highlights the importance of quality in the information processing stage, ranging from the sensor to the plot of results.

For testing different defects levels in discharge valves, we used three valve types: Valve 0, Valve 1, and Valve 2. The valves were artificially worn out according to pictures on Figure 8.
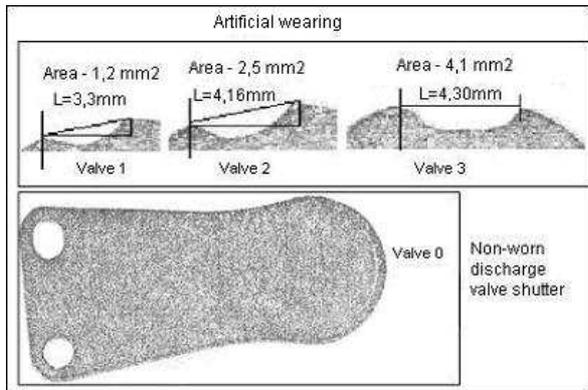

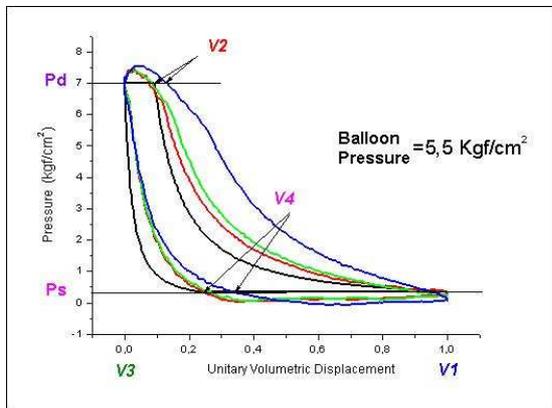**Figure 8 – Discharge valve shutter wearing.**

Figure 9 – P x V curves for different valves: Valve 0 (red), Valve 1 (green), Valve 2 (blue) and theoretical curve (black). It is also possible to identify on the diagram the start of each cycle stage, denominated as V1, V2, V3 as V4. (Origin 7.0 SR0, 2002)

Comparing the curves obtained (Figure 9) with symptoms described by Schirmer, Fernandes and De Caux (2004) we confirmed the behaviors listed below:

- Slower pressure reduction in the expansion stage as we used valves with increased defects, due to gas returning from discharge;
- Faster pressure increase in the compression stage as we used valves with increased defects, also due to gas inlet through discharge valve leakage;
- Increasingly distancing from theoretical curve with increased defects;
- In addition to qualitative evaluations based on the presented graphics, there are quantitative parameters obtainable from information presented on P x V view graphic, which were applied to equations designed for assessment of compressor performance (Table 2).

Table 2 – Parameters for performance evaluation

Valve	Volumetric efficiency at Inlet	Volumetric efficiency at Discharge	Mass Balance	Adiabatic efficiency	Volume Flow at Inlet (m3/min)	Mass Flow at Inlet (Kg/min)	HP Consumption
Ideal	0.77	0.091	1.02	1.00	0.122	0.059	0.338
V0-Good	0.75	0.078	0.97	0.75	0.117	0.040	0.437
V1-Regular	0.71	0.088	0.67	0.69	0.112	0.030	0.449
V2-Poor	0.56	0.132	0.18	0.49	0.087	0.012	0.494

7.2 Piston Rod Defects

To study the mechanical defects in reciprocating compressors, we chose to increase the clearance between the piston rod hole and the crankshaft. The following piston rods clearances were used:

- Piston Rod B0 (GOOD) - 0.26 mm
- Piston Rod B1 (POOR) - 0.41mm
- Piston Rod B2 (VERY POOR) - 0.60 mm

As shown on Figure 10, there are significant differences between the average involutes obtained with piston rods bearing different clearances.
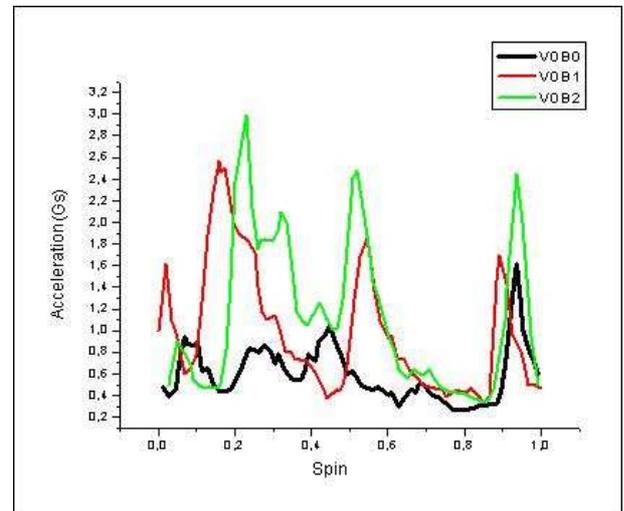

Figure 10 – Involutes representing average vibration above 1 kHz using Valve V0 (GOOD) and piston rods B0, B1 and B2. (Origin 7.0 SR0, 2002)
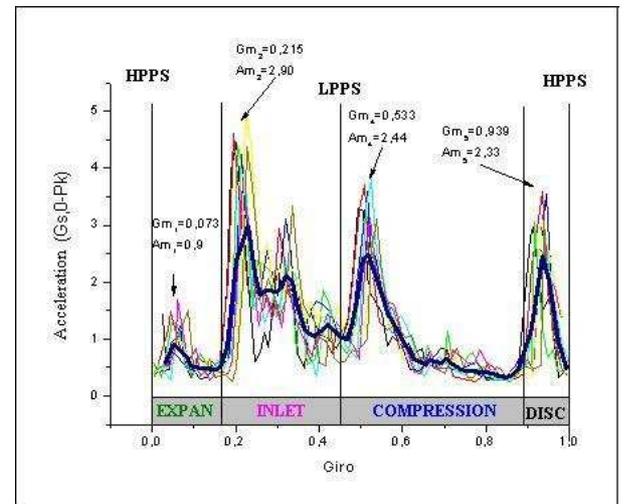

Figure 11 – Vibration involutes above 1kHz using Valve 0 and Piston rod B2. (Origin 7.0 SR0, 2002)

The analysis of involutes on graphic (Figure 11) associated to compression stages cycle (identified by P x V diagram) allowed the identification of phenomena as follows:

- Expansion - pulses at 7% of spin (31°), average amplitude 0.9 Gs 0-pk.
- Inlet – pulses right after opening of inlet valve, average amplitude 2.9 Gs 0-pk.
- Compression – pulses right after Lowest Point of Piston Displacement, average amplitude 2.44 Gs 0-pk.
- Discharge – pulses at 92% of spin (331°), average amplitude 2.33 Gs 0-pk.

8. DISCUSSION

8.1 Dynamic Pressure Study

Consistency of data acquired by the system and methodology used for data processing was tested when we kept the same operational conditions and introduced defective valves. In such case, curve modifications followed the behavior already predicted on the literature (Schirmer, Fernandes and De Caux (2004) and DYNALCO CONTROLS (2003)). Subsequently we confirmed that using view graphic resources and thermodynamic parameters quantification it is possible to build a range of quite effective tools for defects assessment at the fluid end. We should point out that in our study we used discharge valve as a test element for the data acquisition and analysis system; however it is certainly possible to test different components using the same methodology.

8.2 Vibratory Behavior Study

Validation of tool was achieved by studying the vibratory behavior using the data digitalization and processing system developed along this study. Additionally, it is possible to clearly observe the application limits for vibration as a parameter for defects analysis. The present work was also used for developing data processing and result presentation forms more adequate to our goals.
Taking the data collected in the V0B0 test as referential, one may notice that major vibration increments – observed in V0B1 and V0B2 tests – are mostly located at inlet stage and compression start stage. It means that as we used piston rods with increased gaps, impact loads came up in those cycle stages. Pulses occurring on compression start stage behave as described by Zusman and Palm (2001), tending to occur on the inversion points of piston displacement direction.

9. CONCLUSIONS

- The data acquisition and processing system developed for analysis of Reciprocating Compressors has proven to effectively detect defects both at the Fluid and Power ends.

- Periodic measurements and analyses using the tools developed along this work allow assessment of Reciprocating Compressor condition.
- In addition to being useful for diagnosis of defects, the performance data computed based on P x V diagrams allow identification of deviations from design and operation condition.
- Some conditions are required for obtaining the results: measurement of dynamic pressure within the cylinder and sensors temperature control.
- Method used to calculate the average pressure (*Pm*) to correct the P x V diagram is correct.

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