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SHOCK MONITORING TECHNOLOGY FOR RECIPROCATING MACHINERY

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Abstract

Although vibration is a good tool for condition monitoring the health of rotating machinery, there are certain reciprocating machine health issues that will not affect the overall machine vibration level until damage has progressed beyond critical level. This paper includes the description of shock monitoring technology which is more sensitive to early-stage development of harmful mechanical conditions in reciprocating compressors. Such conditions may include loose rod nuts, loose bolts, worn pins, broken parts, liquid in the process, rubbing and several others.

The monitoring technology is based on detecting mechanical shock events in or near the machinery cylinder assembly. The amplitude of the each shock event is measured during the preset time window and is compared with two preset thresholds. If the amplitude of the shock event does not surpass the low threshold during the time window then the monitoring output presents the normalized maximum amplitude of the shock event in previous time window. If the amplitude of the shock event surpasses one or both thresholds then the monitoring output presents the counted number of above events with the specific wait ratio. Such technology has proven very reliable in practice for identifying conditions such as looseness, cracks and leakage. This paper also describes several case stories as well as a structure of the monitoring sensor which realized the technology.

INTRODUCTION

For years we have applied rotating machinery vibration measurement sensors to reciprocating engines and compressors. The results have been less than satisfactory and even confusing at times. There are certain abnormal operating characteristics that can not be detected at an early stage on reciprocating machinery. As a result,

abnormalities are not seen in the overall vibration level until it is late to make simple adjustments.
The actual machine data reviewed in this paper compares vibration with “shock” or “impact” measurements on a reciprocating gas compressor, and clearly illustrates the difference in these two measurements. Mechanical problems such as looseness, cracked or broken components, liquids in the process, or other causes can be reliably detected by monitoring the impact that occurs due to these mechanical failures. While vibration is still a concern, mechanical looseness is of greater importance due to the significant damage potential.

Shock Monitoring:

Shock monitoring has been successfully used to find mechanical looseness on large reciprocating compressors in recent years utilizing empirically determined criteria. Mechanical shocks produce short duration, high amplitude “spikes” when measured using a piezoelectric accelerometer. These spikes are blurred by traditional vibration monitoring techniques because of signal processing methods and time constants that are used to accurately measure vibration. To measure impact, a special peak detection circuit is required that has a fast rise time and will not blur these signal spikes or impact events.

Figures 1 and 2 show examples of signals measured using an accelerometer on a compressor cylinder. The signals were acquired using the transient capture mode on a spectrum analyzer. In the first case there are no significant impact events. This would be considered a normal time waveform for a compressor cylinder. Short duration and high amplitude spikes are present in the second case which is a direct result of mechanical looseness.

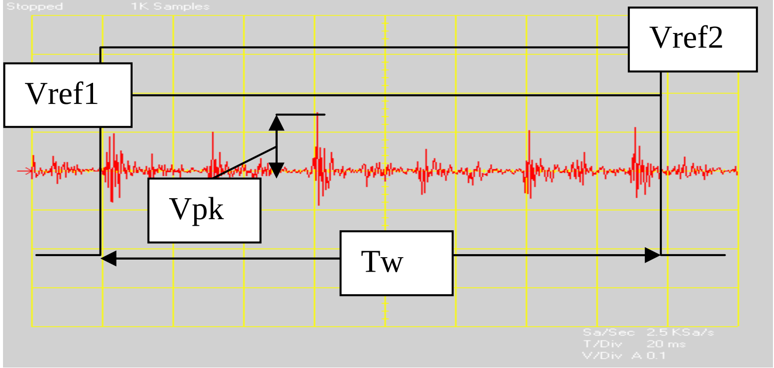

Figure 1- Compressor cylinder time waveform with insignificant impact

There is no correlation to compressor piston position for these captured signals, although looseness more likely occur at points of rod reversal. For compressor protection the impact measurement is not synchronized with crank angle. For compressor analysis it is very important to synchronize the acquired data with rotation.

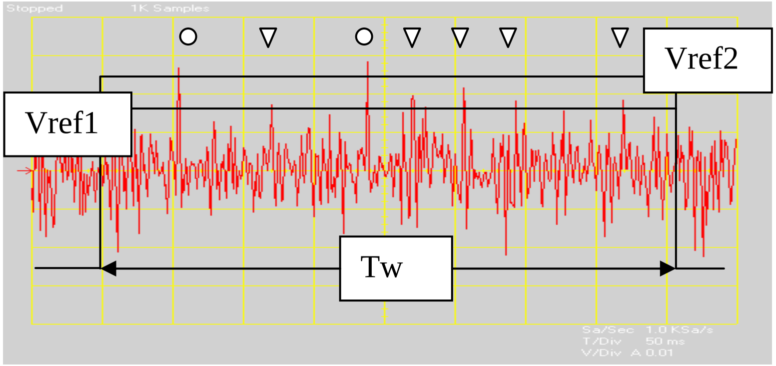

Figure 2-Compressor cylinder time waveform showing significant impact

More on Shock:
It is important to understand more about the methods in which vibration signals are processed to realize why shock measurement works with a high degree of reliability. An industrial accelerometer is always used for impact measurements because it operates over a wide frequency range, and therefore is capable of responding to impact events. The output of an accelerometer is measured in mV/g (g being a gravitational unit).

A conventional vibration monitor would process the acceleration signal in a manner allowing a steady (not jumping around) and accurate measurement of the overall vibration level. The detector circuits for this type of measurement are typically RMS or peak type. The measurement objective is to produce a smooth signal to be displayed on a meter or output (4-20 mA) to a PLC, DCS, or other control system. The smoothing is accomplished by time averaging. Impact signals are not accurately detected in such a circuit, as seen in Figure 2. If filtering or signal integration is applied in order to display the measured signal in velocity vibration units, the signal is further processed and altered; thus making it even more difficult in terms of detecting impact signals. For vibration measurement these circuits produce very accurate results and are recommended for repeatability.

For detecting shock signals from the same type of accelerometer, a special peak responding detector circuit with fast response time is required. The detector circuit must be able to respond to short duration, high amplitude signals. Signal smoothing can not be used! One might ask, at this point; “Doesn’t this produce a nervous responding measurement which can lead to false indications of machine problems?” The answer is, “Yes it can.” So something else must be done to qualify the impact signals. The next part of the impact measurement circuit counts impact events within a specified amount of time referred to as a reset time.

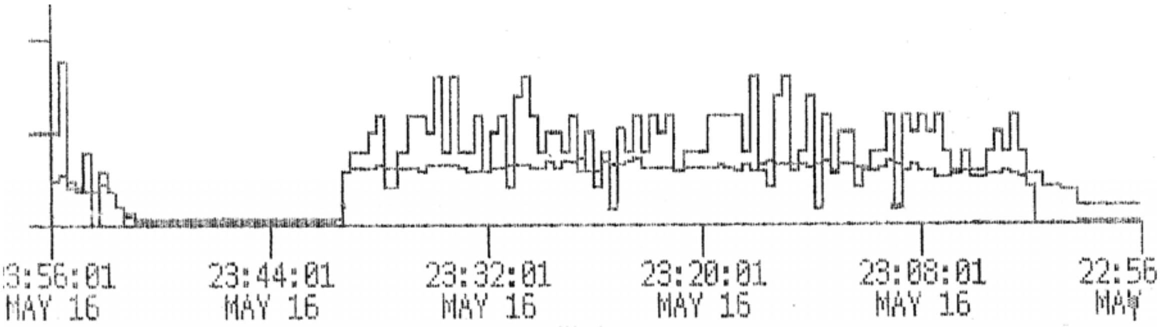

Figure 3- Trend graph of an overall vibration level and impact severity

Additionally, a threshold value is set in g's so that impact events are not counted until the level of the measured signal crosses over that threshold. The impact count is based on the number of impacts that exceed the threshold level within the reset period. This counting method has proven to be very reliable. It separates transient operating characteristics, where impact events appear and go, from developing mechanical looseness, where impact events appear and stay.

The difference between measuring the overall vibration level and measuring impact severity can be seen in Figure 3. This is a trend graph of these two measurements – over a of 60 minutes period. The impact severity trace appears as a "cityscape" while the overall vibration shows little variation. Some level of mechanical looseness is evident and the impact severity trend shows a worsening condition as time progresses. The short interruption is a period where the compressor was stopped and soon restarted. It is important to notice that when the impact severity was at the highest values, the overall level changes were extremely minimal. This proves that overall vibration alone cannot be used as an indicator for mechanical looseness.

Setting Shock Criteria:

It was stated that impact severity is the number of impact events that exceed the threshold level with occur within the reset period. By counting the impact events this way, it is possible to determine the severity of mechanical problems. It should be pointed out that one impact signal might contain more than one impact event. That is, there might be more than one time where the signal crosses through zero and rises again as a result of "ringing". If you look closely at the signal in Figure 2, for example, it may contain 3 or 4 events, depending on where the amplitude threshold level is set, and the timing of the counter circuit. The latter is usually in the order of a few milliseconds.

There are three parameters that are set in the field. These include threshold amplitude, reset time (time window), and response type in terms of alarm or trip. The threshold amplitude is set 3 or 4 times the baseline level in g peak, assuming there are no impacts at the time. When impacts occur the peaks will rise well above the baseline operating level which is why threshold amplitude is set there. False alarms could result if it is set too low.

The next setting is the sampling time window or reset time. This is based on predominant compressor operating speed. A simple formula is used to determine the reset time: Reset Time or T_W = 960/RPM. Alarm (high alarm) or shut down (high high alarm) is based on the impact severity level. On traditional panel mounted monitoring systems, there is usually a separate relay function for the alarm level and shut down level. For example, a smooth running compressor should have the alarm set for 3 or 4 counts, and the shut down for 7 or 8 counts. These could be adjusted after having some running experience. With the apparatus that is described below a similar logic applies, however the PLC or DCS must be programmed to perform the alarm and shut down tasks. Refer to the discussion on the apparatus output in the next section.

Reciprocating Machinery Protection Apparatus:

The apparatus detects impacts that occur during a predetermined window of time. Information specifying the exact time duration is communicated from the external computer to a central processing unit, or a microprocessor, located in the protection apparatus. The central processing unit utilizes that information to generate a periodic time window signal, T_W.

The apparatus utilizes two threshold voltages V_{ref1} and V_{ref2}, as well as information regarding the magnitude of these threshold voltages which is communicated from the external computer to the protection apparatus during initialization. The central processing unit uses this information to establish two reference voltage sources.

In the event that no impacts greater than the lower threshold voltage (V_{ref1}, Fig. 1) are received during a given duration, the apparatus detects and stores a voltage corresponding to the impact with the highest magnitude that is received during that time. This detection may advantageously be effected using a peak detector whose output voltage, V_{peak}, is digitized and then input into a microprocessor. At the end of the window of time, apparatus generates an output current I_{OUT} in accordance with the following formula:

$$I_{OUT} = V_{peak} / V_{ref1} \text{ x } (I_L - 4 \text{ mA}) + 4 \text{ mA} \qquad (1)$$

where I_L is any selected current which is > 4 mA and < 20 mA. The external computer also communicates the value for I_L to the central processing unit in the protection apparatus during initialization. In one embodiment, I_L = 10 mA.

In the event that impacts are received during a given duration that exceed either or both the threshold voltages, the number of impacts exceeding the lower threshold voltage and the number of impacts exceeding the upper threshold voltage during that time are counted . At the end of that duration, the apparatus generates an output current I_{OUT} according to the following formula:

$$I_{OUT} = \alpha_1 N_1 + \alpha_2 N_2 + I_L \qquad (2)$$

where N_1 = the number of impacts in the time window > $V_{ref1,}$
N_2 = the number of impacts in the time window > $V_{ref2,}$
α_1 and α_2 are incremental currents, the values of which were communicated from the external computer to the central processing unit during initialization. In one embodiment, α_1 and α_2 are each 0.5 mA.

The simplified block diagram of the Reciprocating Machinery Protector (RMP) is shown on Fig. 4. RMP includes a sensor (accelerometer) which functions in response to a vibration (impact) to produce a voltage as its output. The output of sensor is fed into a bandpass 500 Hz - 10,000 Hz filter. The output of bandpass filter is coupled through an amplifier to peak detector. RMP also includes a central processing unit (“CPU”). One function of the CPU is to generate a time window signal T_W of a predetermined duration. The duration of T_W is a parameter which the external computer provides to the CPU during initialization. Normally, as mentioned above the duration of T_W is equal to the time required for 12 RPM of the reciprocating machine shaft to occur and the duration of T_W may be between 0.5 and 4 seconds.

The CPU generates the periodic signal T_W at one of its outputs which is coupled to the reset input of a peak detector. During the active state of T_W, peak detector is enabled. The peak detector is reset on the trailing edge of the active state of the signal T_W. The apparatus comprises two threshold voltages, V_{ref1} and V_{ref2}, where V_{ref2} is greater in magnitude than V_{ref1}. The values of V_{ref1} and V_{ref2} are also communicated from the external computer. Reference voltage sources, which are controlled by the CPU, provide voltages at their outputs equal to V_{ref1} and V_{ref2}, respectively. In certain instances, there may be no impacts greater than the lower threshold voltage V_{ref1} which are received during a given time window T_W. This type of occurrence is illustrated in Fig. 1, where each of the impact events is less than the first reference threshold voltage V_{ref1}. In this instance, the peak detector detects the impact event during the time window having the highest voltage i.e. V_{peak} (Fig. 1). An analog-to-digital converter (A/D) digitizes the value of V_{peak} and provides that value to the CPU. At the conclusion of the time window in the situation illustrated in Fig.1, the apparatus causes an output current I_{OUT} to appear at output node according to the formula (1). Impact events may be received during the time window which exceed only the lower threshold voltage V_{ref1} or which exceed both the lower threshold voltage V_{ref1} and the upper threshold voltage V_{ref2}. The latter situation is illustrated in Fig. 2 where seven impact events are shown that exceed the lower threshold voltage V_{ref1} and two impact events illustrated which exceed the higher threshold voltage V_{ref2}. The output of the amplifier is connected to one input of comparator 1 and one input of comparator 2. The second input of comparator 1 is connected to the output of voltage source 1 which produces the first threshold voltage V_{ref1}. The second input to comparator 2 is connected to the output of voltage source 2 which produces the second threshold voltage V_{ref2}. The apparatus counts the number of impact events that exceed the first threshold voltage V_{ref1} during a given time window and the number of impact events that exceed the second threshold voltage V_{ref2} during that time window. In the situation illustrated in Fig. 2, the output current I_{OUT} appears as the output node according to the formula (2).By using RMP, impact events are detected which are lower in magnitude than events detected by traditional impact technology. These lower magnitude events provide extremely useful information with respect to the onset of malfunctions in reciprocating machinery. With this information, potential problems may be detected and fixed before they become major problems.

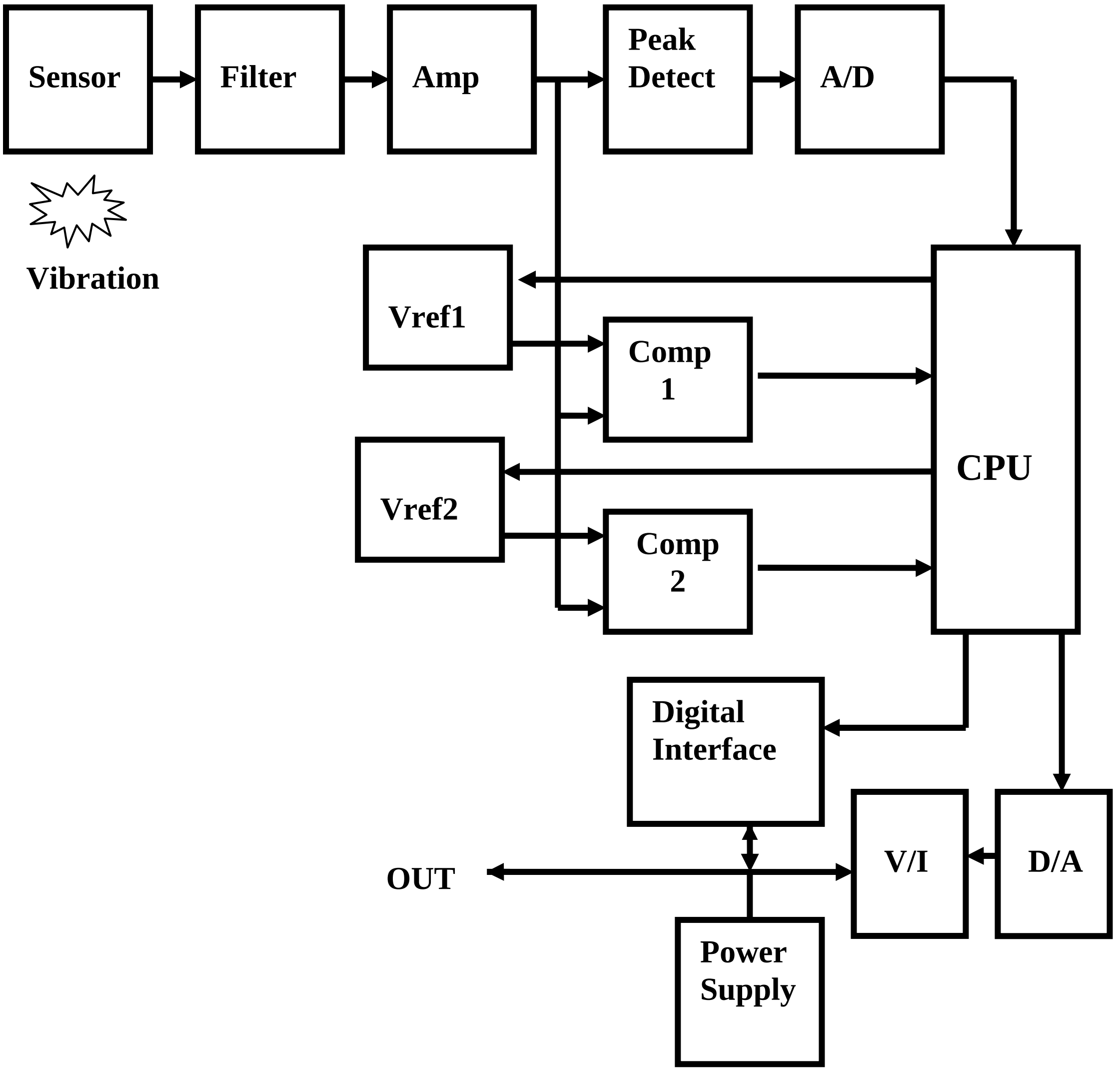

Figure 4-Simplified block diagram of Reciprocating Machinery Protector

Operating experience might provide data supporting some variance from these values. Also, the threshold level that is set will affect the number of impact events that get counted. If it is set low, then the count criteria for alarm should be set higher.

The RMP is designed to detect mechanical looseness, not vibration. Therefore it is mounted to the direction of rod motion, up on top of the crosshead or distance piece, where it will be out of the way of routine inspection or maintenance.

Shock monitoring will not replace the need for compressor performance analysis. An increasing trend in measured impact severity could provide the basis for performing an analysis.

The purpose of any monitoring is to protect machinery by providing operating condition data that operators can use to make run/don't run decisions. This data is also used to maximize operating efficiency. The operating condition data can also be used to help mechanical equipment engineers assess plant equipment availability. Trending these measurement parameters adds another dimension to the running condition data.

Case History:
A rebuilt 6 cylinder compressor was being put into service as part of an expansion project in a gas plant. This compressor is driven with a 3000 HP electric motor running at 300 RPM. This plant had a policy of monitoring and trending velocity vibration on most of their plant equipment, including reciprocating compressors. They decided to install RMP transmitters on each compressor cylinder on this machine.

At startup they were knocked off line by one of the transmitters. Upon an attempt to restart the machine the RMP transmitter knocked them off line again. At this point they investigated and found that the retaining bolts on the high pressure packing case had not been tightened.

As with rotating machinery, many problems are found at startup following an overhaul or other work being done for maintenance. Reciprocating machinery is no different in this regard. Reciprocating machinery can develop mechanical looseness after periods of running. If left alone, looseness only gets worse and can lead to more costly breakage.

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