Smart Methodologies Of Monitoring Reciprocating Compressors

SMART METHODOLOGIES OF MONITORING RECIPROCATING COMPRESSORS

ABSTRACT

Although trending of overall vibration measurements is an excellent tool for monitoring the health of rotating machinery, it is not generally effective for monitoring reciprocating machinery because common faults present themselves as impacts with little effect on overall vibration level. As a result, abnormalities are not diagnosed until damage has occurred and it is too late to take simple corrective measures. There are several reciprocating machinery faults which do not significantly increase a machine's overall vibration level until damage has reached a severe level, including:

- Loose or broken bolts
- Excessive clearance in connecting pins
- Loose or cracked rod nuts
- Liquid or debris in the cylinder
- Cracked connecting or piston rod
- Scoring in the cylinder
- Excessive crosshead/slipper clearance
- Other broken parts

This paper describes improved shock monitoring methodologies especially suited to effective vibration monitoring of reciprocating machines for fault diagnosis at an early stage. Also, implementation of the same is discussed for an industrial plant.

1.0 INTRODUCTION

Typical vibration monitoring techniques that are routinely used on rotating machinery like in Figure1 have been unsuccessfully applied to reciprocating engines and compressors for many years.

Figure 1(a)– Rotating machine	Figure 1(b)– Reciprocating machine

The reason is that many typical faults on reciprocating machinery are characterized by mechanical looseness, which results in impacting or shock events in the machine. Since impacts generally have little effect on the overall vibration level, these faults are not detected at an early stage. As a result, abnormalities are not diagnosed until damage has occurred and it is too late to take simple corrective measures. Figure 2 shows vibration data taken off of a good and bad compressor. Even though there are significant differences in the peak amplitudes due to the impacts, the overall vibration level does not change enough to detect it.
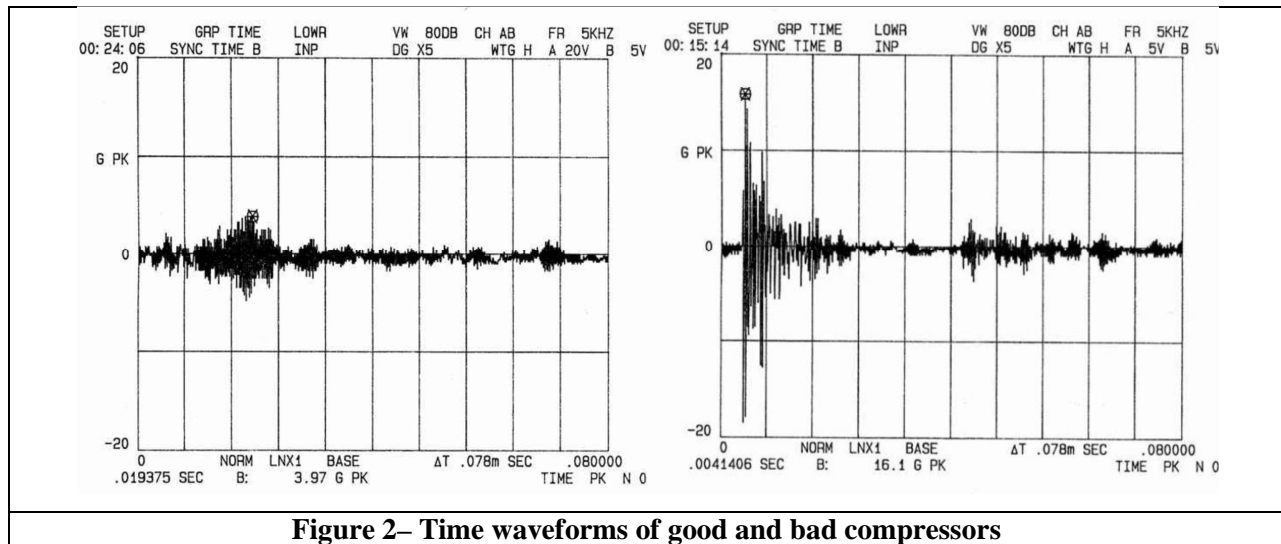

Figure 2– Time waveforms of good and bad compressors

The monitoring technology presented in this paper is the technology of detection of mechanical shock events that occur in or near the machine's cylinder assembly. This technology is not new and has been successfully used on reciprocating compressors for many years. However, the techniques presented in this paper are a vast improvement upon the existing methods. The amplitude of each shock event that occurs within a preset time window is measured and is then compared with two preset threshold levels. Based on improved exceedance criteria, a Reciprocating Fault Index (RFI) is calculated that indicates the health of the machine. This index provides a better indication of machine health than is provided by conventional impact transmitters.

The main purpose of any monitoring system is to protect machinery. It also provides critical data that operators and engineers can use to asses equipment condition, determine machinery availability and make informed run/no run decisions. In some cases, this data may also be used to maximize operating efficiency. It should be noted that shock monitoring will not replace the need for compressor performance analysis. An increasing trend in the RFI could provide the basis for performing an analysis.

The techniques presented are very effective in detecting faults involving mechanical looseness or other impact mechanisms at an early stage of their development. These faults include the following.

- Loose or broken bolts
- Loose or cracked rod nuts
- Cracked connecting or piston rod
- Excessive crosshead/slipper clearance

- Excessive clearance in connecting pins
- Liquid or debris in the cylinder
- Scoring in the cylinder
- Other broken parts

It should be noted that while overall vibration level is still a concern, mechanical looseness detected using this method is of greater importance due to the significant damage potential if the faults go undetected. The vibration data reviewed in this paper compares conventional vibration trending with shock or impact measurements made on a reciprocating gas compressor. The results clearly illustrate the advantages of shock monitoring in reciprocating machinery.

2.0 SHOCK MONITORING

The improved vibration monitoring technology is better than the conventional techniques in the following ways:

- The peak amplitude of routine data that does not exceed a threshold level is measured and can be trended.
- Peaks are evaluated relative to two threshold levels rather than one. This allows more flexibility in setting thresholds resulting in earlier warning of faults.
- The peak counts are weighted based on their levels to help better quantify vibration severity.
- A "dead time" is used to eliminate false peak counts due to mechanical ringing of lightly damped structures that are caused by the impacts.
- The monitoring parameters are programmable so the process can be optimized for particular machines.
- The monitor has a higher frequency response than existing units.

Impacts caused by mechanical looseness produce very short duration, high amplitude spikes that can be accurately measured using a piezoelectric accelerometer. These high amplitude spikes, however, are masked by traditional vibration signal processing techniques because they add very little energy to the vibration signal. Thus, the overall vibration amplitude is relatively unaffected and provides little warning of serious faults. To accurately measure impacts, special peak detection circuitry is required that has a very fast response time.
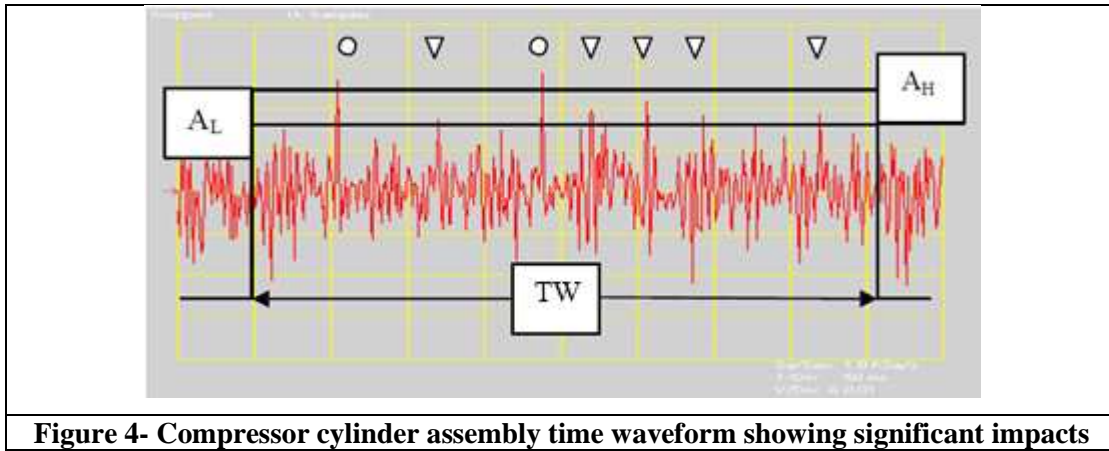

Figure 3- Compressor cylinder assembly time waveform with insignificant impacts
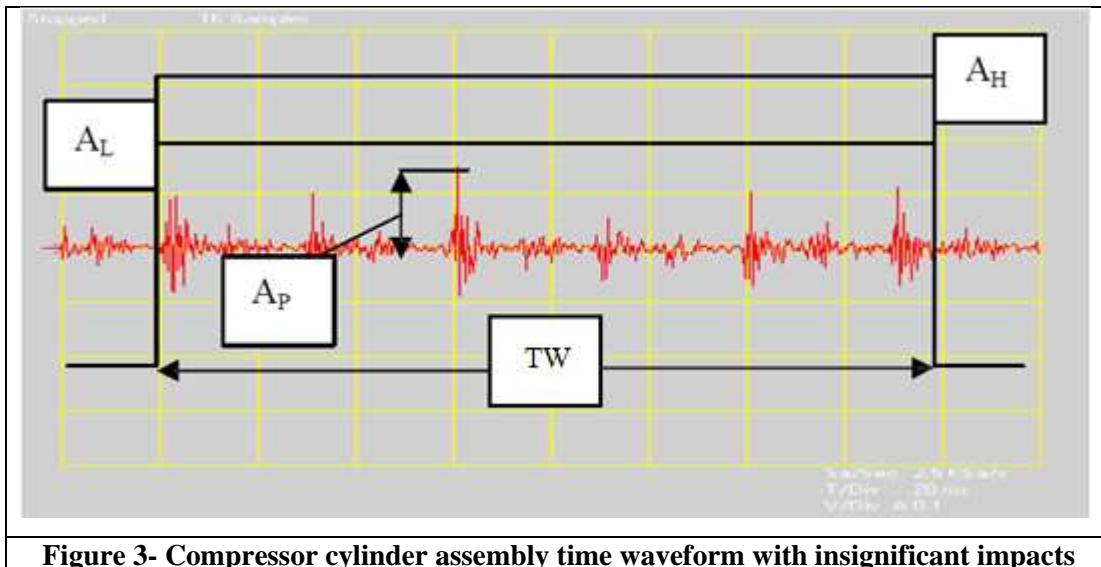
Figure 4- Compressor cylinder assembly time waveform showing significant impacts

Figures 3 and 4 show examples of vibration signals measured using an accelerometer on a compressor cylinder assembly. To illustrate the problem, the signals were acquired using the transient capture mode on a spectrum analyzer. The time window (TW) is typically selected to include several cycles of machine operation to get a representative data sample.

In Figure 3, there are no significant impact events that exceed either threshold level 1 (A_L) or threshold level 2 (A_H) indicating a normal time waveform for a compressor. As a result, vibration is being measured in peak acceleration (A_P) during this time period. However, in case of Figure 4, several short duration, high amplitude spikes exceeding both threshold level 1 or threshold level 2 are observed, which are a direct result of mechanical looseness. The circles on the plot mark peaks that exceed the threshold level 2 and the triangles those that exceed the threshold level 1. The technique used puts greater weight on the peaks that exceed threshold level 2. By using two threshold levels, impact events are detected that 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, minor problems may be detected and fixed before they become major problems or catastrophic failures. One must take care, however, not to set it too low so that it starts counting normal pulses.

3.0 DATA COLLECTION & SIGNAL PROCESSING

Since data is collected over several cycles of operation, no synchronization pulse is required. For compressor protection, it is only necessary to know the amplitude of the shock pulses; it is not necessary to know their phase relative to piston position or crankshaft angle. In order to do more detailed diagnostic analysis, however, it would be necessary to synchronize the data with machine position.
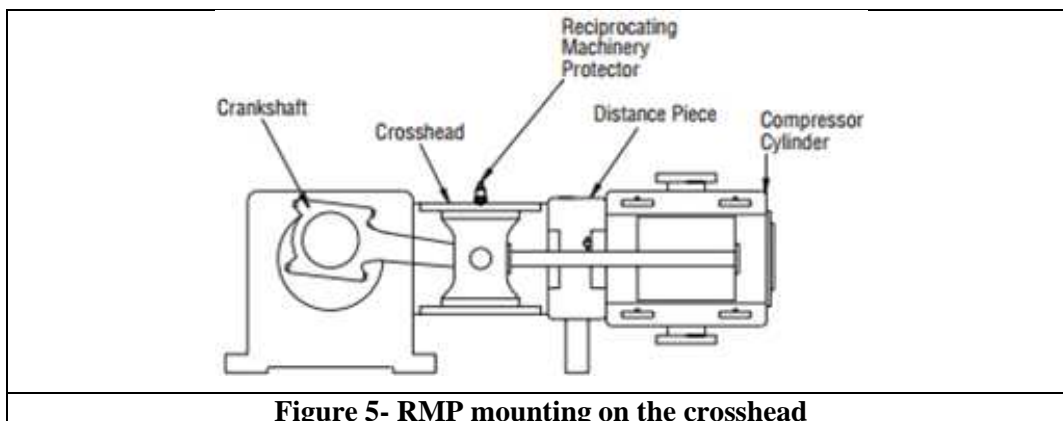

Figure 5- RMP mounting on the crosshead

In conventional vibration monitoring, data is collected with the machine in a consistent steady state condition (constant speed and load) whenever possible. The analyzer averages the data to produce a repeatable overall vibration level that is suitable for trending. The circuits used for this type of measurement are typically true RMS detectors and therefore average the signal. The measurement objective is to produce a consistent, non-time varying signal to be trended, displayed on a meter or to output (4-20 mA) to a PLC, DCS, or other control system. Impact signals, like those in Figure 4, are not accurately detected in such a circuit. If the data is further altered by filtering or integration (ie. to get velocity units) then additional "smoothing" of the data occurs and it becomes even more difficult to detect impact signals. For rotating machinery monitoring applications, average vibration measurements work well but they are ineffective for reciprocating machinery.

In order to accurately measure short duration, high amplitude shock signals, a special peak detector circuit with a fast response time is required. Due to the variability of individual shock pulse amplitudes, a simple comparison of amplitude against an alarm would not be reliable. Since signal smoothing cannot be used, another method must be employed to assure repeatable results and avoid false indications of machine problems. This is accomplished by sampling the data over many machine cycles, counting the peaks that exceed the preset shock threshold levels, applying weighting factors based on amplitude and summing them up to determine an RFI that relates directly to machine health. This process assures consistency and reliability of the data.

The difference between monitoring overall vibration level and RFI is shown in Figure 6. This is a trend graph, over a sixty minute period, showing both measurements on the same compressor. The RFI trace appears as a "cityscape" and shows a significant increase in amplitude over the one hour period. The overall vibration trend, on the other hand, shows little change in amplitude and, in this case, did not trip an alarm. Some level of mechanical looseness is evident and the RFI trend shows a worsening condition as time progresses. The short interruption in the data is a period where the compressor was stopped and then restarted. It is important to notice that when the RFI was at the highest values, the overall vibration level changes were extremely minimal. This clearly shows that overall vibration level alone cannot be reliably used as an indicator for mechanical looseness.
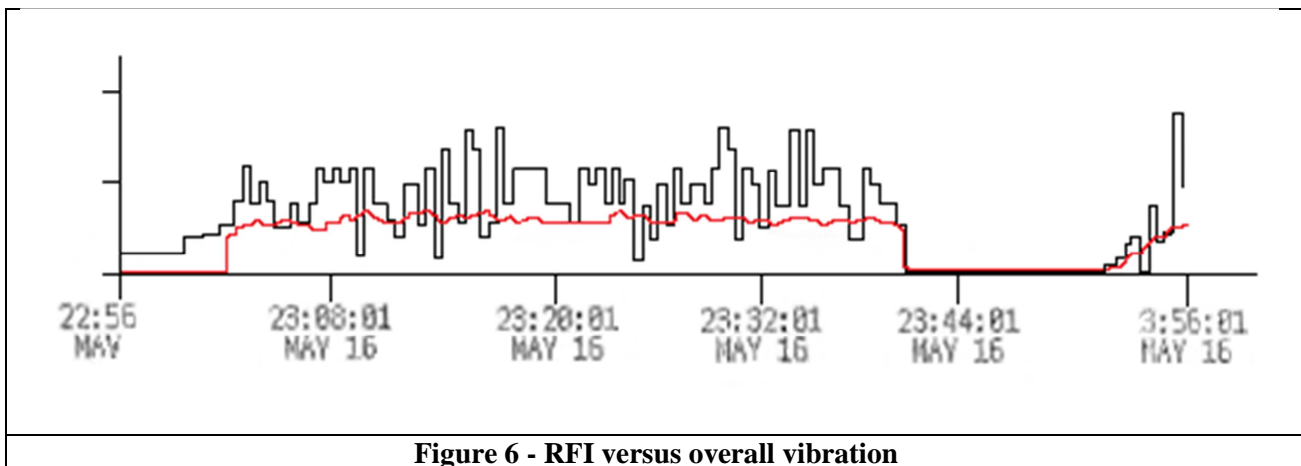

Figure 6 - RFI versus overall vibration

4.0 ACCURATE PEAK COUNTS

As stated earlier, the basis of the analysis is to detect and count mechanical shock events that exceed the shock threshold levels. Thus, it is extremely important to get accurate counts. Unfortunately, a single impact can generate a response signal that appears to contain more than one impact event. This happens because an impact imparts a broadband force into the machine structure which causes a response at its natural frequencies. If the structure is lightly damped (as are most steel structures) the resultant vibration does not die out quickly and "rings" like a bell.

**Figure 7 – Expanded view of vibration time waveform
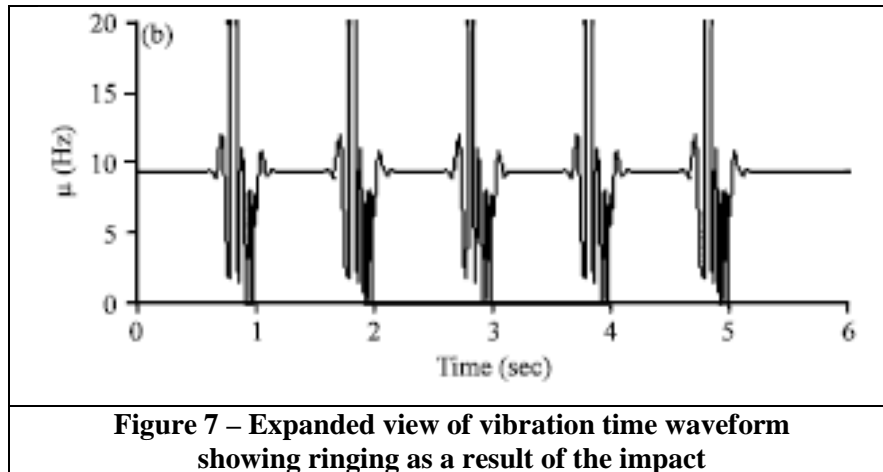showing ringing as a result of the impact**

Figure 7 shows an expanded view of the data in Figure 6. Due to the low damping, the response acceleration takes several milliseconds to die down. If something is not done to exclude the peaks of the response signal that exceed the shock threshold levels, the detector circuit will incorrectly count these as multiple impacts. To combat this problem, the RMP incorporates a dead time for several milliseconds after the initial impact where it does not count peaks that exceed the shock threshold levels. This allows time for the response to die down and thus not produce false counts.

5.0 MEASUREMENT PARAMETERS

There are six key parameters that must be set when installing the RMP on a machine. Their values are based primarily on empirically determined criteria. The parameters are the time window, two threshold levels, two weightings and trending range.

- Time Window: The time window (TW) is typically set between 12 and 16 machine cycles in duration to allow sufficient data collection.
- Threshold Levels: Threshold level 1 (A_L) is typically set to 2 to 4 times the baseline acceleration level measured in g's peak. This is based on empirical results. This assumes a normally operating machine with no impacts at the time of setup. Care should be taken not to set this level too low or false alarms could occur. Threshold level 2 (A_H) is generally set to 1.5 to 1.6 times the lower shock threshold level. When impacts occur in the machine, the peak acceleration will rise well above the baseline.
- Weightings: The weightings (W_L and W_H) are used to determine the emphasis to be placed on peaks that exceed the threshold level 1 and 2. Obviously, higher peaks should be of more concern than lower ones and thus have a higher weighting factor. As the fault characteristics and failure modes of the particular machinery being monitored are better understood, the combination of shock threshold levels and weighting factors can be adjusted.

Proper selection of these parameters will lead to earlier warning of developing faults and better protection of the machine.

- Trending Range: The trending range (I_L) reflects the maximum amount of current output that will be dedicated to peak acceleration monitoring of vibration that is below both thresholds.

Users can either utilize the parameter values pre-calculated by the factory (dependent mode) or can manually adjust the parameters in the field (independent mode). If the pre-calculated settings are desired, the user only needs to use the dependent mode and enter machine RPM into the program. If operating experience provides data supporting a variance from the default values, the user needs to select independent mode and manually enter their own parameters. Through proper selection of the parameters, the unit can be set to optimally protect the compressor or mimic most existing impact monitors currently on the market. The program uses the following equations (Table 1) to compute the default parameters associated with dependent mode.

Table 1: RMP Default Parameters	
Parameter	**Equation**
Time Window (sec)	$TW = (60 / RPM) \times 16$
Threshold Level 1 (g)	$A_L = RPM / 80$
Threshold Level 2 (g)	$A_H = RPM / 50$
Weighting 1 (mA)	$W_L = 0.1 + (100 / RPM)$
Weighting 2 (mA)	$W_H = 0.9 - (100 / RPM)$
Trending Range (mA)	$I_L = 8 + (6 \times (100 / RPM))$

6.0 THEORY OF OPERATION

The basic theory of operation is straightforward to understand. The system looks for and counts peaks that exceed shock threshold levels within a sample window and assesses the condition of the machine based on those results.

Table 2: RMP Definitions	
Parameter	**Definition**
RFI	Reciprocating Fault Index
A_{PK}	Highest peak acceleration (g) occurring in the time window TW
I_L	Maximum portion of current output dedicated to trending in peak acceleration
A_L	Threshold Level 1 (g)
A_H	Threshold Level 2 (g)
N_L	Number of acceleration peaks that exceed A_L
N_H	Number of acceleration peaks that exceed A_H (includes those that also exceed A_L)
W_L	Weighting for peaks exceeding A_L
W_H	Weighting for peaks exceeding A_H

When the peak acceleration occurring in the time window is less than the lower shock threshold level, then the RFI is simply equal to the peak acceleration.

If $A_{PK} < A_L$,   then $4 < RFI < I_L$ based on A_{PK}

When the peak acceleration occurring in the time window is greater than the lower shock threshold level but less than upper shock threshold level, then the RFI is determined by the following equation.

If $A_L > A_{PK} > A_H$,   then $RFI = I_L + (W_L \times N_L)$

When the peak acceleration occurring in the time window is greater than the lower or upper shock threshold level, then the RFI is determined by the following equation.

If $A_{PK} > A_H$,   then $RFI = I_L + (W_L \times N_L + W_H \times N_H)$

7.0   ACTUAL OPERATION

The RMP is a two-wire device that operates off of standard 24V loop power and has a 4-20 mA output signal that is proportion to the RFI. (See Figure 8.) Its output can be connected to a PLC, DCS, or SCADA system as well as many other standard instruments that accept a 4-20 mA signal. The system used should have either dual relays or display functions and is set to provide notification when the RFI exceeds either the warning or critical alarm level. It may also be set to shut the machine down when the critical alarm level if reached.

Figure 8 – Reciprocating Machine Protector

8.0   INSTRUMENTATION

The RMP includes an embedded accelerometer (sensor) that generates a voltage output that is proportional to the shock and vibration sensed on the machine. The output of the sensor is passed through a bandpass filter (50 Hz to 10 kHz) and coupled through an amplifier to a high speed peak detector and both comparators.

Figure 9 – Simplified block diagram of RMP operation
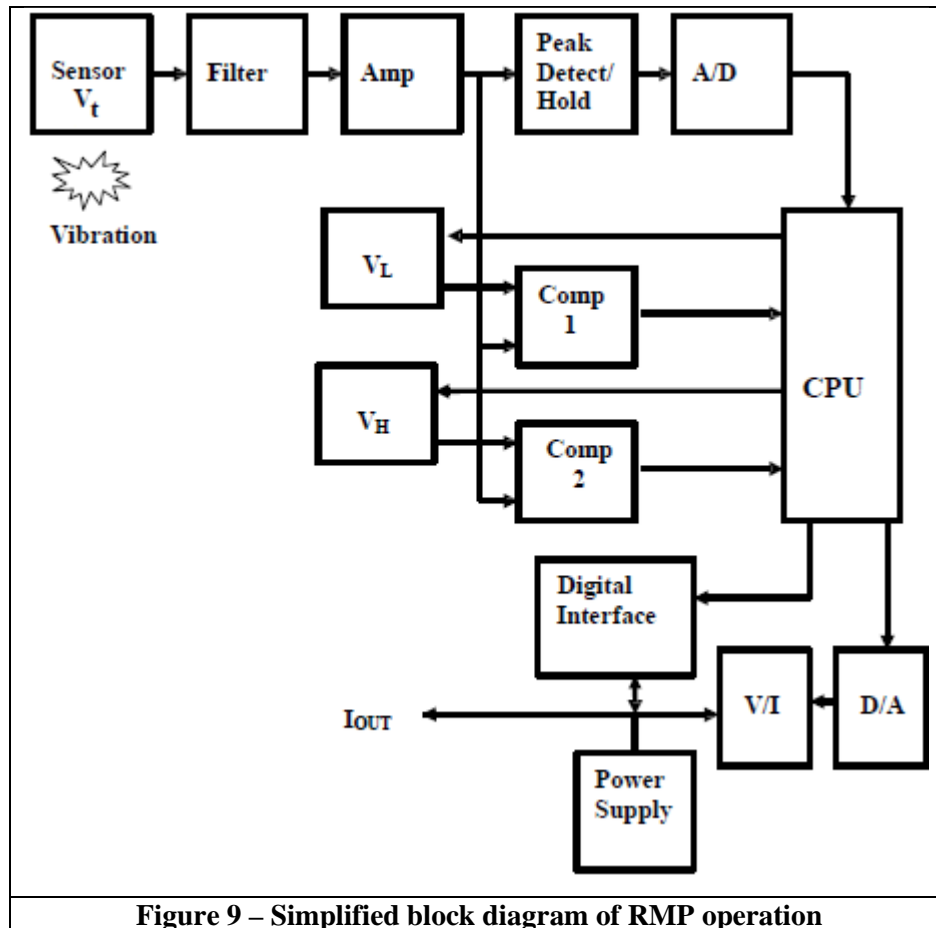
The peak detector monitors the continuous vibration signal and holds the highest amplitude seen within the sample window. If there are no impacts that are greater than either shock threshold level during this sample time (please refer Figure 9) then the peak value is passed through the analog-to-digital converter (A/D) to the central processing unit (CPU). The CPU computes the RFI and then outputs the value to the digital-to-analog converter (D/A) and then to the voltage-to-current converter (V/I). The system output, I_{OUT}, is a 4 to 20 mA current that is proportional to the RFI and given by following equation

$$I_{OUT} = \left(\frac{V_{PK}}{V_L}\right)(I_L - 4) + 4$$

At the end of this process, a reset signal is sent to the peak detector to start over. The comparators are used when there are impact events that exceed either shock threshold level. Each comparator has two inputs, the continuous vibration signal, (V_t) and a threshold reference voltage $(V_L$ or $V_H)$. The output of a comparator is zero if the amplitude of V_t is less than the reference voltage and total level if it is above. The CPU counts the number of times each comparator output goes positive

during the sample window (less any peaks that occur within the dead time). The CPU computes the RFI and then outputs the value to the D/A and then to the V/I. In this case, the system output, I_{OUT}, is given by following equation.

$$I_{OUT} = I_L + (W_L \text{ x } N_L + W_H \text{ x } N_H)$$

Figure 10 shows a time trend example of RMP output based on the above equations.
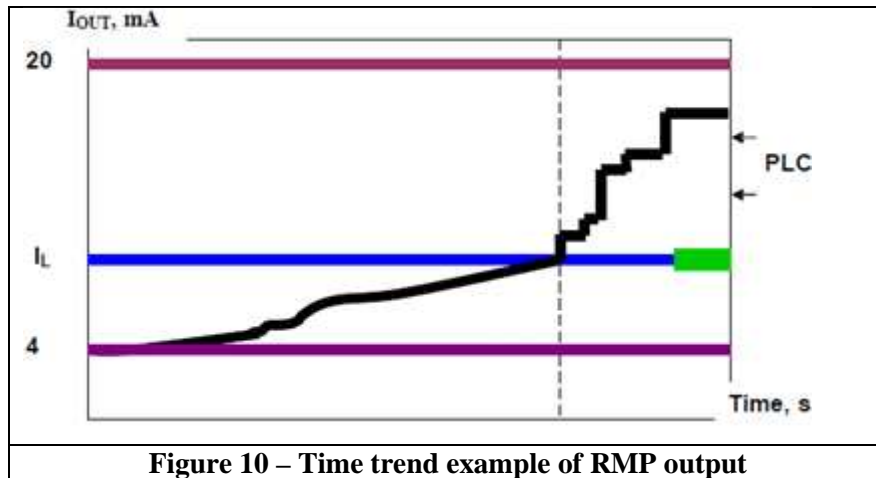

Figure 10 – Time trend example of RMP output

9.0   CASE HISTORY

A rebuilt six cylinder compressor was put into service as part of an expansion project in a gas plant. This compressor is driven with a 3000 HP electric motor and RMS at 300 RPM. This plant routinely monitored and trended velocity vibration measurements on most of their equipment, including reciprocating compressors. They decided to install an RMP on each compressor cylinder on this machine.

At start-up, the RMP's alarm relay tripped and took the compressor off line. While attempting to restart the machine, the RMP again tripped and took them off line. Upon investigation, it was found that the retaining bolts on the high pressure packing case had not been tightened. If not caught, the looseness would have gotten worse and probably lead to catastrophic failure of the compressor.

10.0   CONCLUSION

This paper has successfully demonstrated the application of Reciprocating Machinery Protector (RMP), the state-of-the-art, smart 4-20mA impact transmitter technology especially useful to reciprocating machines for which conventional vibration monitoring has not proved reliable in protection & fault diagnosis. The RMP indicates the distress of the reciprocating machines thereby helping plant professionals take timely decision for running or shutting down the reciprocating machine for required maintenance actions and plan much in advance. The relevant theory and system of operation has been discussed and application to a real-life plant application has been included.

11.0 REFERENCES

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