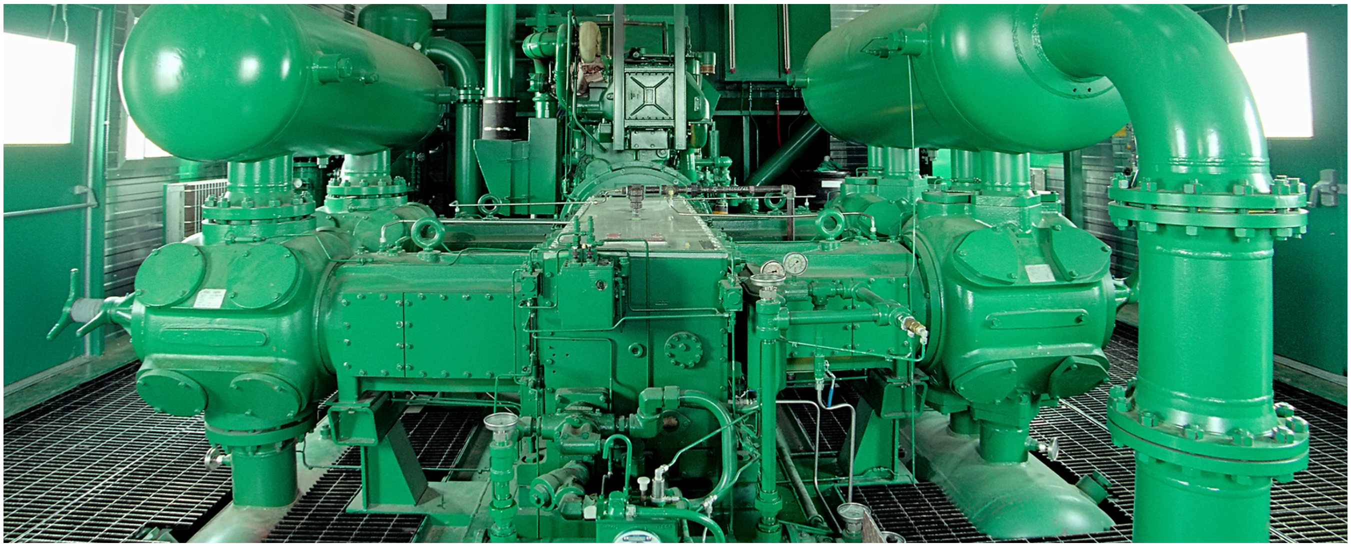

Smart Methodologies of Monitoring Reciprocating Compressors

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ABSTRACT

Traditional vibration monitoring works well for monitoring the health of rotating machinery, but often falls short when applied to reciprocating compressors. That's because many of the faults common in these systems, like mechanical looseness or internal impacts, produce short, high-energy impacts that don't significantly affect overall vibration levels. As a result, common faults can go undetected until severe damage has already occurred.

This paper describes a refined approach to monitoring reciprocating machinery using high-frequency shock detection and weighted peak analysis. By focusing on impact events and calculating a Reciprocating Fault Index (RFI), this method allows for earlier fault detection and more informed maintenance decisions. The result is improved protection, less unplanned downtime, and greater confidence in compressor reliability.

KEYWORDS: Reciprocating Compressors, Reciprocating Machine Protector (RMP), Reciprocating Fault Index (RFI), Shock, Peak Count

1.0 INTRODUCTION

Conventional vibration monitoring is widely used to assess the health of rotating equipment, but its effectiveness drops sharply when applied to reciprocating compressors. The reason is simple: many of the faults that occur in reciprocating machinery—such as looseness, cracked components, or debris in the cylinder—create short, high-amplitude impacts that don't meaningfully change the overall vibration level. These faults often go unnoticed until they cause serious damage.

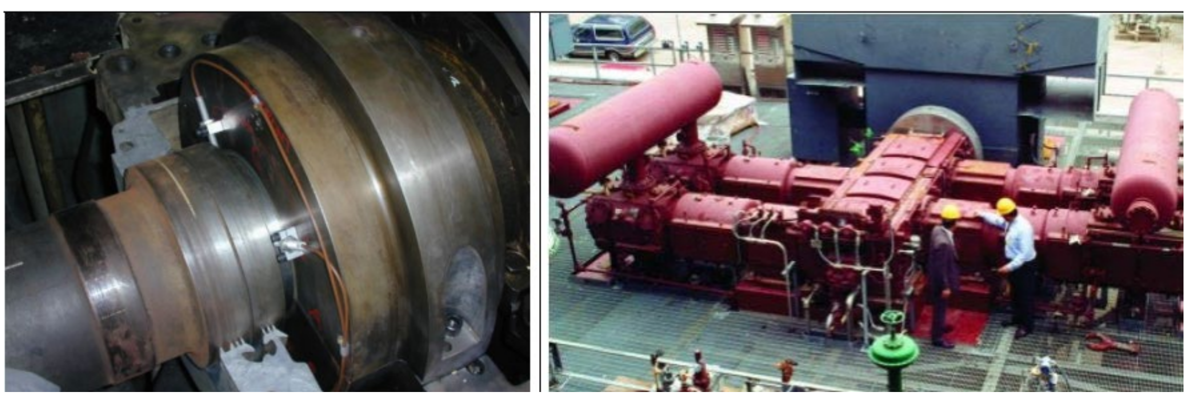

Figure 1(a). Conventional vibration monitoring on a rotating machine. **Figure 1(b).** Vibration monitoring on a reciprocating machine.

This paper presents a more targeted solution: a shock monitoring method designed specifically for reciprocating equipment. The method involves measuring the amplitude of each shock event within a preset sample time, and then comparing the data with two preset shock threshold levels. Based on improved exceedance criteria, a Reciprocating Fault Index (RFI) is calculated. This index is essentially a weighted measure based on the number and severity of shock events, which provides an earlier warning of developing problems than standard vibration methods.

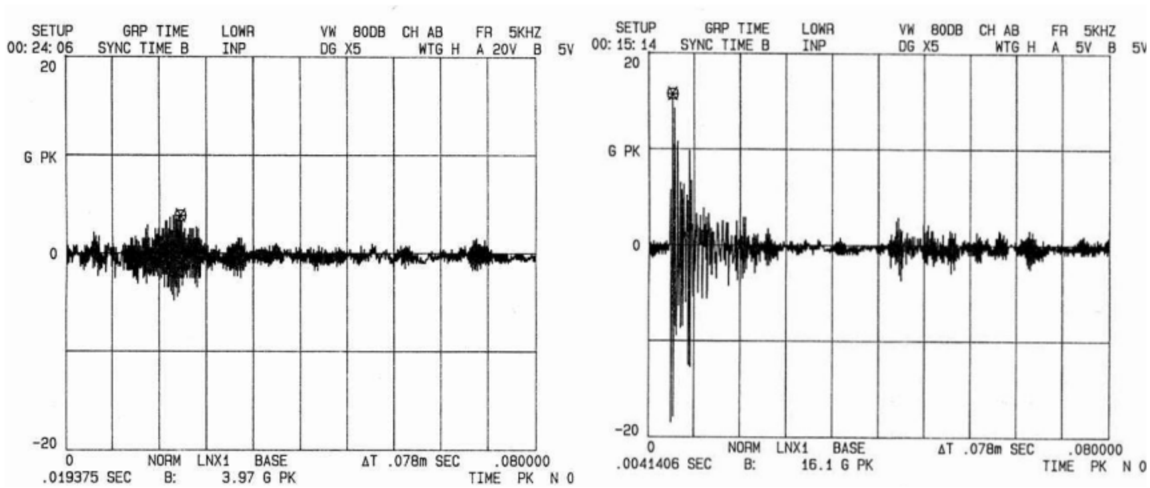

Figure 2. Time waveforms of healthy and faulty compressors. Even though there are significant differences in the peak amplitudes due to the impacts, the overall vibration level does not change enough to detect it.

While shock monitoring doesn't replace the need for compressor performance analysis, an increasing trend in the RFI could signify when deeper analysis is needed. It also supports better maintenance planning and improves the reliability of run/no-run decisions.

The types of faults best detected by this method include:

- 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 or slipper clearance
- 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 potential for significant damage if these 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 shock monitoring method and technologies presented here improves upon conventional techniques in several ways:

- Measures and trends peak amplitude, even when they do not exceed predefined threshold levels.
- Compares peaks against two shock threshold levels rather than one. This allows more flexibility in setting thresholds, resulting in earlier warning of faults.

- Applies weighted scoring to peaks based on their magnitude, offering a more accurate picture of severity.
- Incorporates a “dead time” to eliminate false peak counts caused by ringing in lightly damped structures.
- Offers fully programmable parameters to optimize performance for particular machines.
- Provides a higher frequency response than traditional impact monitoring systems.

Mechanical looseness in reciprocating compressors generates short-duration, high-amplitude impacts (i.e., “spikes”) that are best captured with 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 and are further obscured by RMS, averaging, filtering, or integration. Thus, the overall vibration amplitude is relatively unaffected and provides little warning of serious faults.

To detect these fast transient events accurately, specialized peak detection circuitry with rapid response time is required.

Figures 3 and 4 illustrate this concept:

- **Figure 3** shows a typical waveform for a healthy compressor. No significant peaks exceed the lower (AL) or upper (AH) shock threshold.
- **Figure 4** shows a faulty machine with multiple short-duration, high-amplitude spikes exceeding both AL and AH, indicating mechanical looseness.

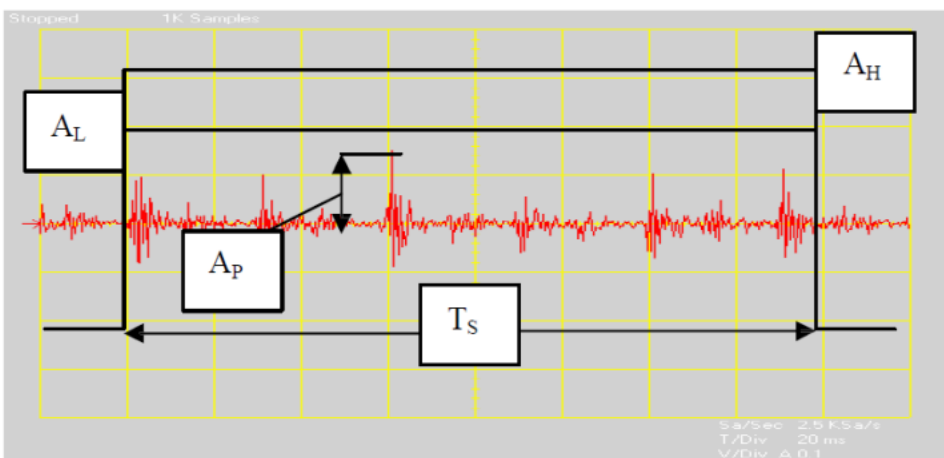

Figure 3. Compressor cylinder assembly time waveform with insignificant impacts.

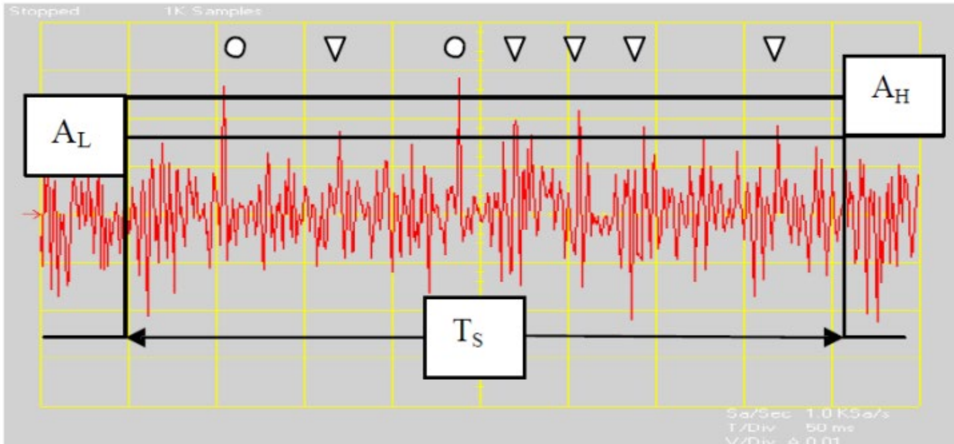

Figure 4. Compressor cylinder assembly time waveform showing significant impacts.

In this monitoring method, impacts that exceed the upper threshold are given greater weight in the fault index calculation. Using two shock threshold levels enables detection of lower-magnitude events that traditional impact technology may miss—offering valuable early insight into developing issues. However, thresholds must be configured carefully to avoid false positives from normal machine pulses.

3.0 DATA COLLECTION & SIGNAL PROCESSING

In this method, shock data is collected over several cycles of operation, eliminating the need for a synchronization pulse. For protective monitoring, only amplitude of the shock events is required; phase information (e.g., piston position or crank angle) it is not necessary to know unless detailed diagnostics are being performed.

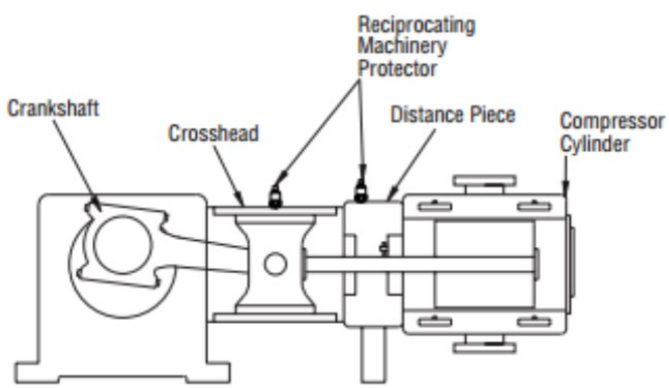

Figure 5. Reciprocating machinery protector mounted on the crosshead.

In conventional vibration monitoring, data is typically collected during steady-state operating conditions (constant speed and load). RMS-based analyzers average the signal data to produce a stable trend, which is suitable for rotating machinery. However, this type of averaging masks short-duration, high-energy events, making it ineffective for reciprocating compressors.

Impact signals, like those in **Figure 4**, are not accurately captured by RMS detectors. Further filtering or integration (often used to convert signals to velocity units) smooths the waveform even further, reducing sensitivity to transient shocks.

To accurately capture high-amplitude, short-duration impacts, the system uses a fast-response peak detector. Since individual impact amplitudes can vary widely, relying on a single alarm threshold would lead to unreliable results. Instead, the method counts the number of peaks exceeding two defined thresholds over a sample window, applies weighting factors based on amplitude, and sums them to calculate an RFI that reflects machine health.

Figure 6 shows a comparison between RFI and overall vibration data trending over a 60-minute period (note: time flows from right to left). The RFI trend (visible as a "cityscape" pattern) clearly shows an increase in impact activity over time, while the overall vibration signal remains relatively flat and fails to trigger any alarms. A brief data gap indicates a stop and restart of the machine.

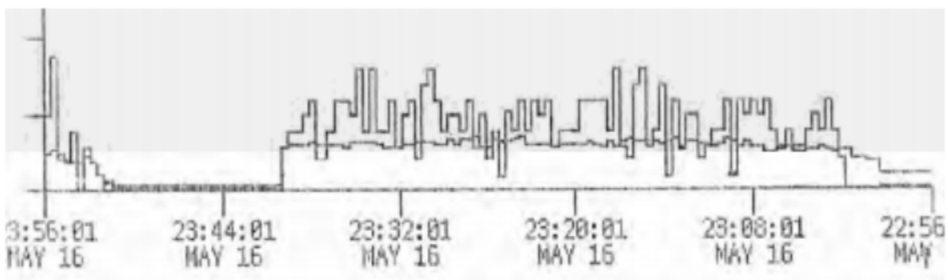

Figure 6. Reciprocating fault index (RFI) vs. overall vibration.

This side-by-side comparison demonstrates that overall vibration monitoring alone is insufficient for detecting mechanical looseness. The RFI provides much earlier and more meaningful insight into deteriorating conditions.

4.0 ACCURATE PEAK COUNTS

As noted earlier, this monitoring method relies on counting mechanical shock events that exceed defined threshold levels. To ensure reliability, it's critical that each impact is counted only once. However, a single impact can excite a machine's structural resonances, producing a ringing response that may last several milliseconds. In lightly damped steel structures, this can result in multiple peaks following one shock event—peaks that could be mistakenly interpreted as additional impacts.

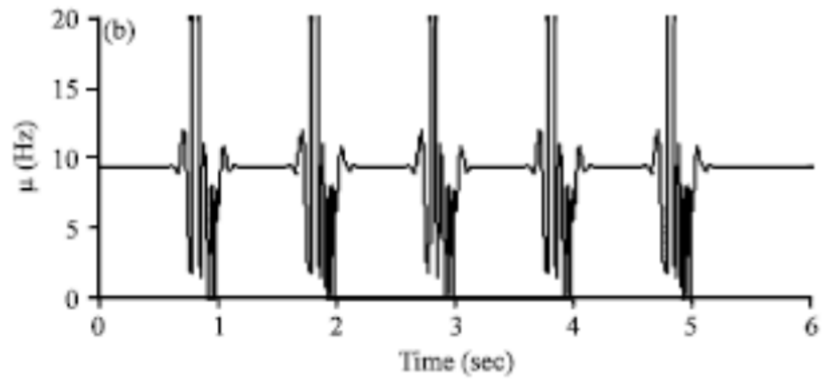

Figure 7. Expanded view of vibration time waveform showing ringing as a result of the impact.

To prevent false counts, the Reciprocating Machine Protector (RMP) includes a programmable dead time (TD) immediately following the initial shock. During this brief window, additional peaks are ignored, even if they exceed the shock thresholds. This allows time for the structural ringing to decay and ensures that each actual impact is counted only once.

By eliminating duplicate counts caused by post-impact ringing, the system improves the accuracy and reliability of the calculated Reciprocating Fault Index (RFI).

5.0 MEASUREMENT PARAMETERS

The Reciprocating Machine Protector (RMP) uses seven parameters to configure the monitoring process. These values are primarily based on the compressor's rotational speed and are refined through empirical testing.

The parameters include:

- Sample time (TS)
- Two shock threshold levels (A_L and A_H)
- Two weighting factors (WF_L and WF_H)
- Two alarm levels (warning and critical)

The sample time is typically set to cover 12 to 16 machine cycles to ensure a representative data set. It is calculated using the following equation, where *N* is the machine RPM and *NC* is number of cycles:

TS = (960 x NC)/N seconds (for NC = 16)

The lower shock threshold (A_L) is usually set to 2–4 times the machine's baseline peak acceleration (in g), assuming no impacts are present during initial setup. If set too low, false alarms may occur.

The upper shock threshold (A_H) is typically set to 1.5 to 1.6 times the lower threshold. When faults occur, shock amplitudes often exceed both A_L and A_H.

Weighting factors determine how much influence each threshold exceedance has on the RFI. Events that exceed A_H are given more weight than those that exceed only A_L. These values can be adjusted over time as failure patterns become better understood.

The RMP can be shipped with factory defaults or programmed in the field. If using default settings, only the machine's RPM is required. However, users can fine-tune all parameters to optimize fault detection or replicate legacy system behavior.

The following equations define the default parameter values used by the RMP:

Table 1. RMP default parameters.

Parameter Description	Equation
Sample Time	$Ts = \frac{960}{N} \sec(for\ N_C = 16)$
Lower Shock Threshold Level	$A_L = \frac{N}{80} g$
Upper Shock Threshold Level	$A_H = \frac{N}{50} g$
Weighing Factor Increment	$\Delta WF = \frac{100}{N} mA$
Weighing Factor Lower	$WF_L = 0.1 + \Delta WF\ mA$
Weighing Factor Upper	$WF_H = 0.9 + \Delta WF\ mA$
Maximum Peak Trending Current	$I_L = 8.0 + 6\Delta WF\ mA$

These parameters allow the system to detect faults early and provide meaningful, repeatable measurements that correlate directly to machine health.

6.0 THEORY OF OPERATION

The operating principle behind the RMP is straightforward. It detects and counts acceleration peaks that exceed defined shock thresholds within a specified time window, then calculates a Reciprocating Fault Index (RFI) based on the quantity and severity of those events.

Key definitions:

- A(t) = acceleration time waveform [acceleration signal (g) over time (sec)]
- A_{PK} = highest peak acceleration (g) during the sample time window (T_S)
- A_L = lower shock threshold level (g)
- A_H = upper shock threshold level (g)
- N_L = number of peaks exceeding A_L (includes those also exceeding A_H)
- N_H = number of acceleration peaks exceeding A_H
- RFI = Reciprocating Fault Index
- T_S = sample time or window
- ΔWF = weighting factor increment
- WF_L = weighting factor for AL exceedances
- WF_H = weighting factor for AH exceedances

RFI Calculation:

- If $A_{PK} \le A_L$, then:

  $$RFI = A_{PK}$$

- If $A_{PK} > A_L$, then:

  $$RFI = (N_L \times WF_L + N_H \times WF_H) + A_{PK}$$

This calculation reflects both the intensity and frequency of shock events within the sample period.

Alarm Evaluation Criteria:

- If RFI < LW (Warning Alarm Level): the machine is considered healthy, and values may be trended.
- If LW ≤ RFI < LC (Critical Alarm Level): the machine shows signs of developing faults and should be monitored more closely.
- If RFI ≥ LC: the machine has likely experienced serious mechanical failure and should be shut down for inspection or repair.

This tiered structure allows for proactive maintenance decisions based on fault progression and severity.

7.0 PRACTICAL APPLICATION

In practical application, the Reciprocating Machine Protector (RMP) processes acceleration data and converts it into a 4–20 mA current output signal that represents the Reciprocating Fault Index (RFI). While the concepts remain consistent with Section 6, this section presents the signal flow using real-world voltages and currents.

Key definitions in electrical terms:

- $V(t)$ = analog voltage signal from the accelerometer
- V_{PK} = highest peak voltage during sample time (T_S)
- V_L = lower threshold reference voltage
- V_H = upper threshold reference voltage
- N_L = number of voltage peaks exceeding V_L (includes V_H exceedances)
- N_H = number of voltage peaks exceeding V_H
- WF_L= weighting factor for V_L exceedances
- WF_H= weighting factor for V_H exceedances
- I_W = warning alarm current (mA)
- I_C = critical alarm current (mA)
- I_{OUT} = output current (4–20 mA) proportional to the RFI
- I_L = maximum peak trending current (mA) is an arbitrary maximum current for trending peak acceleration A_{PK}

Figure 8. Reciprocating Machine Protector (RMP).

The RMP is a two-wire, loop-powered device (24VDC) loop power and has a 4-20 mA output signal that is proportion to the RFI. 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.

8.0 INSTRUMENTATION

The RMP includes an embedded piezoelectric accelerometer. Its output—a voltage signal proportional to the shock and vibration sensed on the machine—through a bandpass filter (50 Hz to 10 kHz) and coupled through an amplifier to a high-speed peak detector and both comparators.

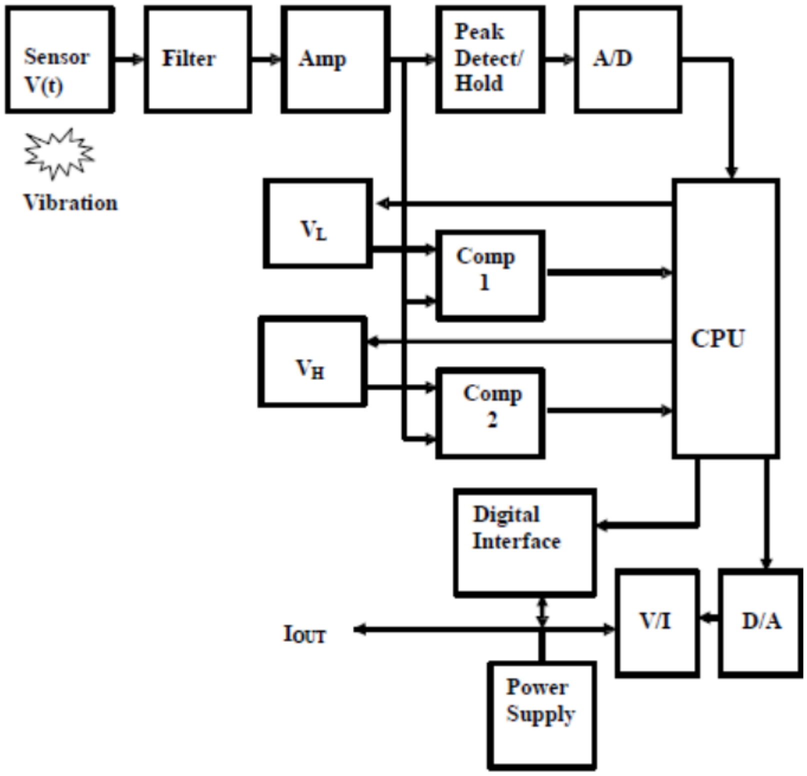

Figure 9. Simplified block diagram of the RMP operation.

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, then the peak value, V_{PK}, is passed through the analog-to-digital converter (A/D) to the CPU (see Figure 9). 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 4-20 mA current that is proportional to the RFI and given by following equation:

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

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 shock 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 TTL 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 DAC and then to the V/I converter. In this case, the system output, I_{OUT}, is given by following equation:

$$I_{OUT} = (WF_L X N_L + WF_H X N_H) + I_L$$

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

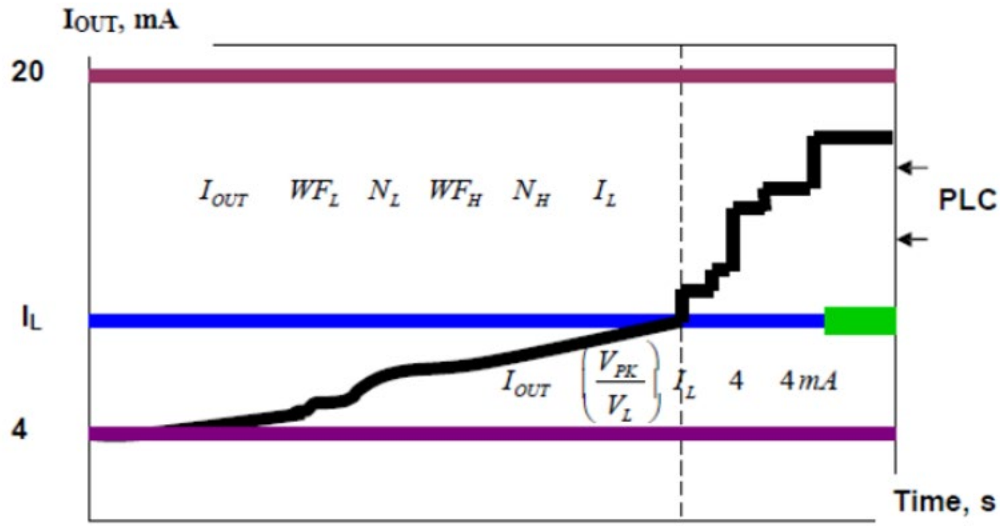

Figure 10. Time trend example of RMP output.

The resulting current output reflects the number and severity of mechanical impacts over time, enabling trend analysis, real-time monitoring, and automatic protection through alarms or shutdown triggers.

9.0 CASE STUDY

A rebuilt six-cylinder compressor was commissioned at a gas plant as part of an expansion project. The compressor, driven by a 3,000 HP electric motor and running at 300 RPM, was instrumented with an RMP on each cylinder.

During startup, the RMP immediately detected abnormal shock activity and triggered a shutdown. A second restart attempt was also interrupted by the RMP. Upon investigation, plant personnel discovered that the retaining bolts on the high-pressure packing case had not been tightened.

Without the RMP, this fault would likely have progressed unnoticed until it caused serious mechanical failure. Instead, the system prevented damage and unplanned downtime by identifying the issue at startup.

10.0 CONCLUSION

This paper has demonstrated the application of the Reciprocating Machinery Protector (RMP), a state-of-the-art 4–20 mA impact transmitter for reciprocating machines. Traditional vibration monitoring fails to reliably detect mechanical looseness. The RMP allows for timely maintenance decisions and improved reliability.

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