Reciprocating compressors have a reputation as bad actors among the rotating equipment fleet, showing the highest number of damages while being process critical at the same time.

Although this is a crucial combination, insufficient protection and condition monitoring systems can still be found on reciprocating machinery.

Prognost asked a potential customer’s reliability engineer whether he employed time-based or condition-based maintenance strategies. He was completely caught by surprise and replied, “None of these. We operate on ‘crater maintenance.’ As long as there is no crater visible where once was a recip, no maintenance is needed on the machine.”

His reply was in jest, but it underscores the fact that “cheap” maintenance usually is not cost-effective at all.

Even after numerous catastrophic recip failures, some operators still use inadequate Machinery Protection Systems (MPS). A review into the history of applicable standards offers some insights.

From the first publication of API 670 in 1976 (“Noncontacting Vibration and Axial Position Monitoring System,” which is dedicated to proximity sensor-based machinery monitoring) until its currently valid fourth edition “Machinery Protection Systems,” API 670 largely focused on the technical requirements of centrifugal equipment (gas and steam turbines, centrifugal and axial compressors).

Besides other important factors, API 670 requires monitoring of dynamically changing parameters, such as axial and radial shaft displacement, speed, surge along with bearing, and casing vibration. But none of these (except vibration) deliver effective and reliable machinery protection on a reciprocating compressor.

Until 2007 to ’08, when the API 670 fifth edition task force was formed, reciprocating compressors have not been in focus within API 670. This latest edition, which is expected to be released this year, hopefully will offer valuable information and guidance on how to effectively protect reciprocating compressors (Figure 1).

It would be desirable if the standards include crosshead acceleration as a safety protection parameter, based on practical lessons learned. That topic will be discussed later.

The IEC 61511 provides the official framework for operators of rotating equipment, potentially bearing risk to harm Health, Safety and Environment (HSE). It also offers guidance to the process equipment operator, defining the Safety Integrity Level (SIL) requirements which have to be fulfilled by the machinery protection system to be installed.

The Risk Graph is one way to obtain an overview regarding which SIL is appropriate to mitigate the inherent remaining risk to an acceptable level. Using the four different risk parameters (Occurrence Probability, Extent of Damage, Exposure Time and Hazard Avoidance [once damaging occurs]) the appropriate SIL 1 to SIL 4 will be indicated (with SIL 4 being the most stringent level).

History Of API Standards (American Petroleum Institute)

<table>
<thead>
<tr>
<th>Year</th>
<th>Edition</th>
<th>Description</th>
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<tbody>
<tr>
<td>1986</td>
<td>API 670—Second Edition</td>
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<td>1993</td>
<td>API 670—Third Edition (Extension Of Previous Standards And Incorporation Of API 678)</td>
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<td>2010</td>
<td>(20xx) API 670—Fifth Edition</td>
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Figure 1. API standards are about to be revised again.

Oliver Franz received his chemical engineering diploma in 2000 and held an engineering position with an EPC before starting as an account manager supporting a major German pump and vacuum OEM. In 2007 he joined Prognost Systems as Area Sales Manager responsible for North America and selected countries of South America. He is the responsible product manager and an active member of API 670 fifth edition task force. He wrote about Safety Integrity Levels for rotating equipment in the March 2011 issue of COMPRESSORtech².
Not all machinery protection applications may justify a SIL 1-, SIL 2- or even SIL 3-certified solution. One thing, however, is important when performing an evaluation likely driven by budget constraints: The likelihood of a safety protection system failing on demand can be 10 < 100 times higher if the operator choses a SIL 1 over a SIL 2 solution. If a system meeting SIL 3 requirements over a SIL 1 system is chosen, the likelihood of the systems to fail on demand can be 100 < 1000 times higher.

Guidance in the SIL standards (IEC 61511) regarding machinery protection systems (API 670) can help operators to reduce HSE and economic risks appropriately.

To understand the limitations of the standard approach of monitoring vibrations on reciprocating machinery, it is important to understand the difference between a uniform rotating movement of a turbine shaft in comparison to a oscillating operation mode.

Due to the large effort put into the dynamic rotor balancing of centrifugal machinery, they show minimal shaft deflection, resulting in low casing vibration levels.

In contrast, a reciprocating compressor shows a very different behavior: Massive pistons are driven back and forth by crosshead-type drive trains, involving reversal of piston-rod forces from tension into compression, making the entire frame with all its components shake and bend to a good degree. Additionally, multiple groups of suction and discharge valves create opening and closing impacts, within every single revolution leaving distinct vibration events — and we call this a “normal operating condition.”

When comparing the working principles of a recip with a centrifugal machine, it becomes apparent that a recip requires a more dedicated monitoring system designed to handle the specific challenges.

Due to its working principal, the crosshead and its crosshead pin clearly are the focal points of reciprocating machines. Here, the rotating movement of the crankshaft is transformed into a reciprocating (linear) movement of the piston rod. It is the central component where all main forces are transferred via the crosshead pin/wrist pin to the piston rod.

To facilitate movement of these forces in the right direction, a solid crosshead guide is an integral part of each recip. The crosshead guide offers the closest connection of the moving parts within the drive train and is the best position to effectively pick up abnormalities in the vibration signature by the means of acceleration sensors.

As illustrated in the lower left side of a five-month, three-waterfall trend plot in Figure 2, reciprocating machinery typically shows very smooth crosshead acceleration characteristics except two distinct impacts during each revolution around the two rod-load reversal points (approximately 40° CA past TDC and BDC). Changes of the acceleration signature and amplitude indicate different mechanical machine behavior.

This example illustrates a piston nut progressively getting looser over a four-month period. The operator has chosen to maintain his stable process conditions while running the equipment at up to critical 4.5 g crosshead acceleration (45.3 m/s² RMS, 36 segmented per revolution) and stayed in control of the situation at all times.

The operator knew that for days the vibration level had reached a critical, but stable, plateau while having “insurance” on board that in the event things got worse, the automatic shutdown continued on page 20
function of his machinery protection system would reliably save the asset.

In this example an unscheduled lengthy shutdown has been prevented, and when it was time for the scheduled catalyst exchange, the recip was repaired. In the right part of the 3-D image in Figure 2 one can see how smooth that same crosshead operated after the piston nut problem was solved. (The gray area indicates shutdown and maintenance.)

If the machine design allows access to these locations, it is recommended that sensors be installed perpendicularly near the loaded crosshead shoe. For example, when facing the machine axially from the drive end, the best sensitivity on a clockwise rotating reciprocating compressor will be achieved when applying acceleration sensors on top for up-running crosshead shoes (all crossheads to the left) and on the bottom side for down-running crosshead shoes (clockwise for all crossheads to the right). This ensures alignment with the effective direction of forces transmitted to the crosshead (Figure 3).

Frame vibration (velocity) offers some value, and piston rod displacement (piston rod vibration) provides excellent value, in a machinery protection system when the data is applied and evaluated correctly (Figure 4).

Early “rod drop systems” earned a long-lasting reputation for delivering unreliable and misleading results, often leading to nuisance alarms. This was a consequence of using systems originally designed for shaft position measurements on centrifugal machines, involving the same hardware and the same signal analysis logic.

Obviously a piston rod does not rotate, but pushes and pulls the piston — which leads to significant bending of the rod, especially when operating under varying load conditions. These effects are not known from monitoring centrifugal machinery to this degree. Despite the unsatisfying experience of the past, the dynamic component of the piston rod displacement signal serves as a reliable machinery protection parameter many users rely on.

Figure 5 illustrates the significant change of the rod vibration signature during a developing piston rod crack. Legacy machinery protection systems do not offer the ability to detect this severe failure mode leading to one the worst case scenarios of recip operators — loss of containment typically accompanied by significant machinery damage and lengthy downtime. Modern
machinery protection systems can prevent this severe scenario by monitoring the piston rod dynamics in every revolution. Piston rod failures are one of the few failure modes that vibration analysis alone cannot detect timely enough.

An eight-segmented signal analysis (segmenting the 360° crank angle into portions of e.g. 45°), e.g., for determining safety critical piston rod bending effects, has proven to be highly reliable to detect loose connections in the motion works such as piston rod crosshead and piston rod cylinder connections as well as impending piston rod cracks before the rod completely fails. As described before, the piston rod typically moves and bends even during normal operation, but in case of developing mechanical damages and cracks, the behavior of the piston rod changes significantly. These changes in rod vibration can reliably be detected using an eight-segmented analysis based on the dynamic rod position signal in Figure 6.

Frame velocity can reveal slowly developing foundation issues as well as failure modes involving a high number of impacts. The high-energy agitating the equipment in its natural frequency range can develop a dangerous rate of mechanical movement.

The installation of frame vibration transducers often involves choices (e.g. two out of three) to reduce nuisance trips with two groups of three velocity transducers typically mounted on the drive- and nondrive end of the frame.

Some customers also choose to install velocity transducers on the compressor frame horizontally opposed each cylinder to monitor imbalances. The solid recip construction including the heavy foundation requires significant kinetic energy over multiple strong impacts to reach critical velocity limits.

Velocity transducers are typically installed far from likely failing components, finally making frame velocity an overall protection parameter, which should be considered as a second layer of protection only.

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Modern monitoring systems are capable of mathematically integrating the acceleration signal over time, delivering a velocity analysis per acceleration sensor location. This finally reduces the value of adding frame velocity transducers to a monitoring sensor scope.

A reliable and cost-effective tool for suction or discharge valve monitoring is available through cylinder accelerometers. A well-adjusted expert system can pinpoint the affected, failing valve group, by employing for example a 36-segmented (segmenting the 360° crank angle into portions of 10°) vibration analysis in combination with an automated diagnostic system.

Common valves problems are sticky valves (delayed opening impact) and lost valve springs (earlier opening impacts). Operators also use Fast Fourier Transmission analysis to monitor banded frequency ranges — each band having dedicated thresholds.

Specifically, the higher frequency ranges (5 to 10 kHz) offer a valuable tool detecting suction/discharge valve leakage flow and packing blow by, both leading to a higher frequency whistling.

Another type of vibration analysis applied on reciprocating machinery is torsional crankshaft vibration. Undetected torsional vibration can result into loosening counterweights, failing couplings, shearing crankshafts and loosening flywheels.

Machines with greatly varying load conditions — for example, those controlled by stepless unloader systems — greatly benefit from this technology using a strain type, online torque sensing unit attached to the rotating crankshaft or motor shaft. The signal is sent through wireless communication to the nearby receiver and analysed for its dynamic (peak-to-peak) and average torque data.

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In most cases, stepless unloader systems are controlled by a process pressure to be maintained at a constant level. In the event of a developing leakage, the unloader system would simply increase load and cover up the failure, potentially disguising it until the recip runs at 100% load, while still not delivering sufficient throughput.

Summary
The once state-of-the-art monitoring approach used on centrifugal machines was adopted and applied to reciprocating machinery. At that time, frame vibration monitoring and rod position monitoring made their way into the monitoring standards of recips.
However, experience has shown that the former standards did not deliver the desired effect in monitoring reciprocating machinery and eventually led to the development of today’s modern monitoring approach.
One of the main objectives is to make use of the working principle of a recip and focus on the crosshead guide in order to detect developing failures early and reliably. Prognost has experience with about 700 critical machines and has developed adequate machinery protection systems tailor-made for recips.
Prognost recommends employing crosshead slide acceleration as the prime protection parameter. In addition, it recommends using dynamic piston rod position measurement as a reliable second layer of protection.
Frame vibration measurement usually is too far from the main functional components and the velocity type measurement often leads to undetected detects.
There is a trend in industry toward fewer and sometimes less experienced rotating equipment operators, so many companies also are investing in modern machinery protection systems to help them when machines do not run normally.
With such data, severe failures can be prevented in a timely manner and equipment operators are not caught in a “doom loop” of repeated mistakes.