Reciprocating Machine Protection

Why You Should Be Monitoring the Needle Instead of the Haystack

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The connection between reciprocating equipment's 1X levels and mechanical health, or why 1X monitoring provides the best shutdown protection available today without the added cost of nuisance trips.

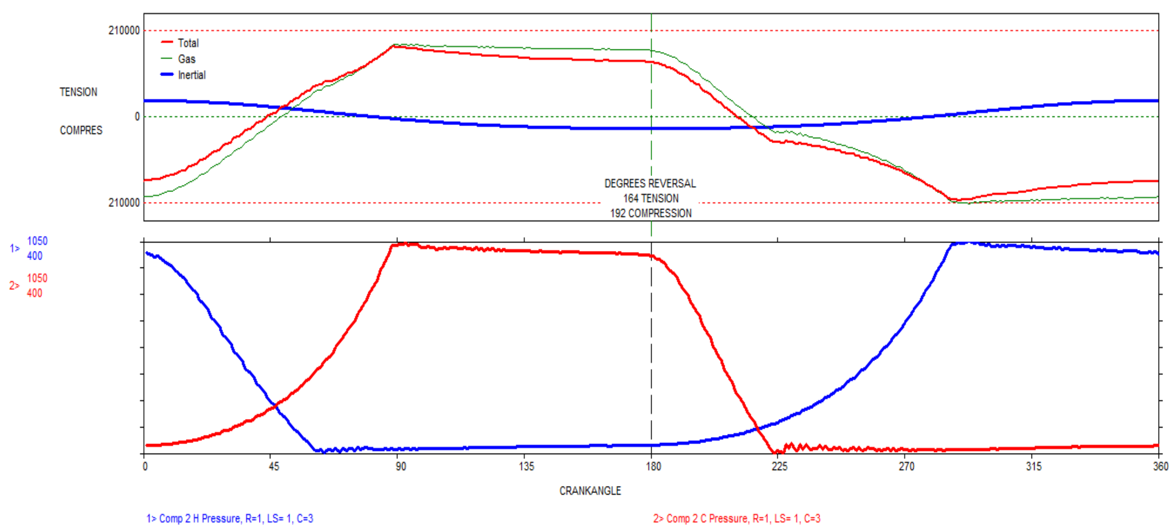
When selecting technology to be used for protecting rotating equipment, the goal of most package designers and operators is to buy something that will avoid or limit damage to monitored equipment, while minimizing nuisance trips that reduce revenue and increase labor expenses. This paper will discuss the relationship of a specific frequency and its association with the various mechanical processes of reciprocating equipment and why this technology, not only increases the protection of an asset, but also minimizes costly nuisance shutdowns. For the first time, this same technology offers operators the opportunity to implement procedures that can catch many different changes in condition before serious damage occurs.

Understanding why 1X vibration and machine health is so integrated

The reason the claims above can be made is that there is one force generated on reciprocating equipment that is tightly coupled to mechanical condition; the vibration force at the 1X frequency. To understand why the 1X is so important, it helps to understand the relationship between the mechanical processes of reciprocating machinery and 1X forces.

When it comes to understanding reciprocating compressor forces, the highest and most limiting force on the machine is **Gas Rod Load.** All the components leading from the crankshaft out to the pistons see forces from 10,000 lbs. up to 210,000 Lbs. (depending on the frame size) and those forces are changing direction from 4 to 30 times per second. Those forces are contained and distributed through the cylinders, cross head guides and frame for the life of the machine. Any changes in how those forces are contained and distributed will affect the amount of energy in the 1X energy component, at every location on the monitored equipment.

When looking at a cylinder pressure/time diagram of a typical compressor and its rod load, based on gas forces, the mechanical changes translating from full compression to full tension occur in 360 degrees.



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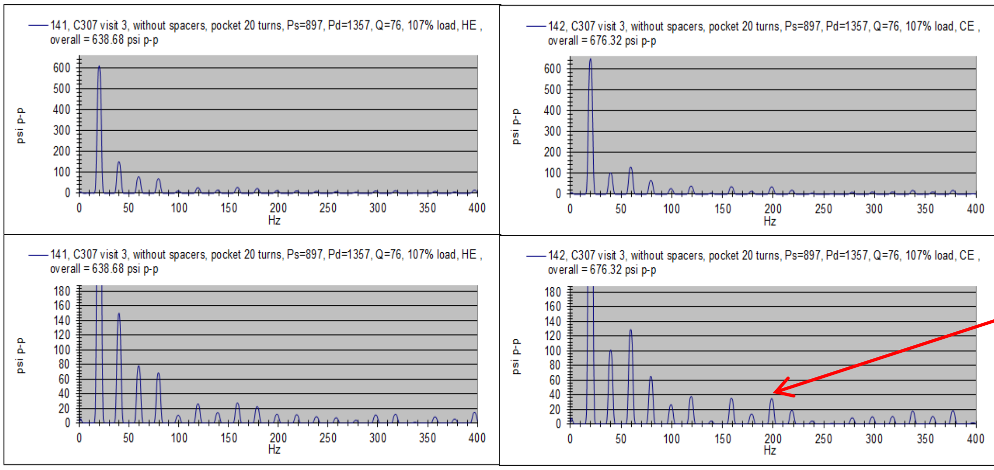
The periodic function of the gas rod load force can be broken down and measured into a frequency based spectrum using a FFT (Fast Fourier Transform) algorithm. When breaking down the pressure/time waveform into a FFT, which shows frequency based data, we can clearly see that there is a predominant frequency component at the 1X run speed, with harmonics at 2X, 3X, 4X… all the way to infinity.



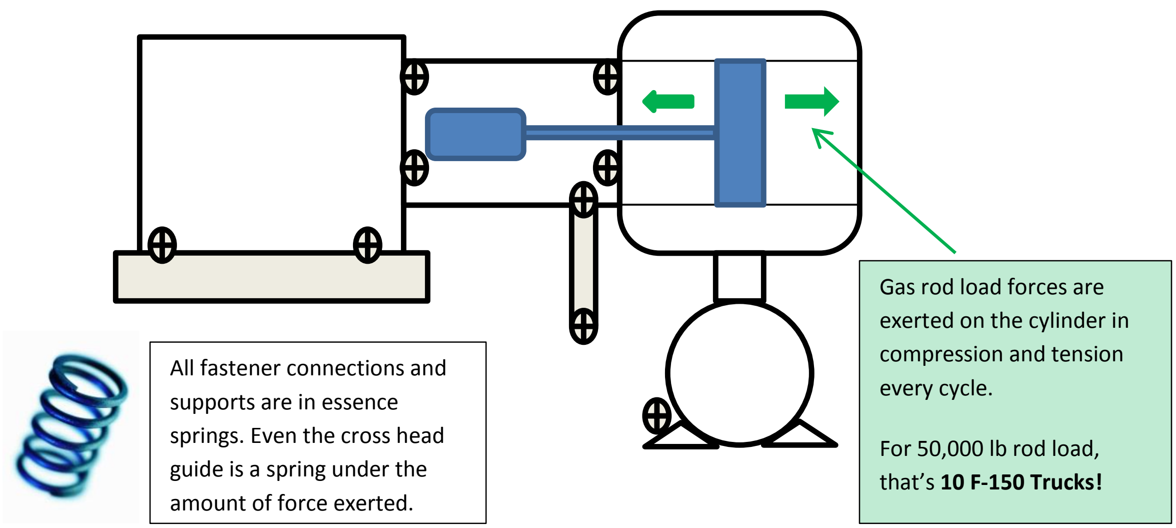
The pressure data here is the spectrum on a 12" cylinder pressure time curve. This cylinder had a very high vibration at 200 Hz. The 30 psi p-p at 200 Hz turns into a force of 3400 pounds exciting the horizontal cylinder MNF.

The equation to find vibration at given frequency:

$$F = k * x$$

F = Force **k**= spring constant (stiffness) **x**= vibration (motion)

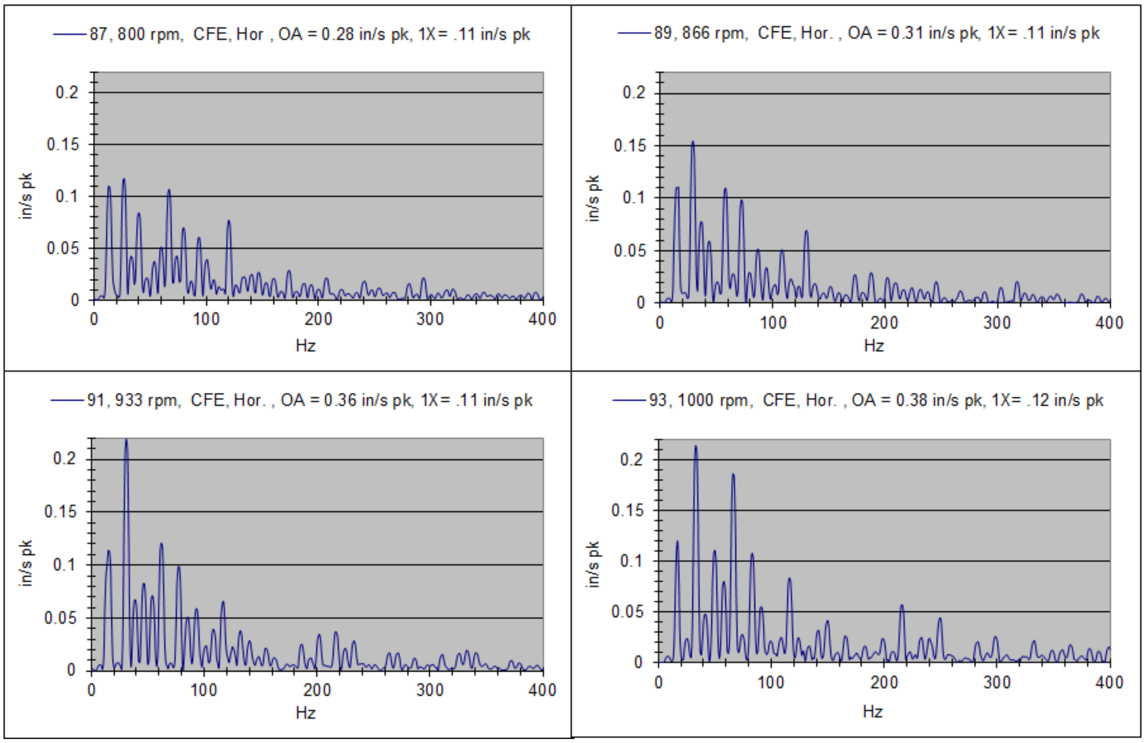
For the given force of the gas on the cylinder ends, acting through the cross head guide supports, the frame and all the support fasteners; if the stiffness remains constant, then so should the vibration amplitude. **Any reduction in the stiffness value through a loosening or failing fastener connection would increase the vibration amplitude**.



The stiffness of the frame, cylinders, cross head guides, supports, bottles, as well as the bearings in the compressor, all play a part in creating the overall k, or stiffness, of the machine which gives a resultant vibration. **If the force (F) and stiffness (k) remain constant, then vibration (x) will also remain constant.**

Comparing the stability and importance of 1X energy to overall RMS energy

As the graphs below show, measurement of the 1X frequency level, the one measurement associated with most of the mechanical operations of reciprocating equipment, has much less variance as speed changes.



Graphs 1-4: Variance in the harmonic frequencies with variance in speed

The table below summarizes the data captured above through the different speed steps on a compressor frame free end (oil pump end) in the horizontal.

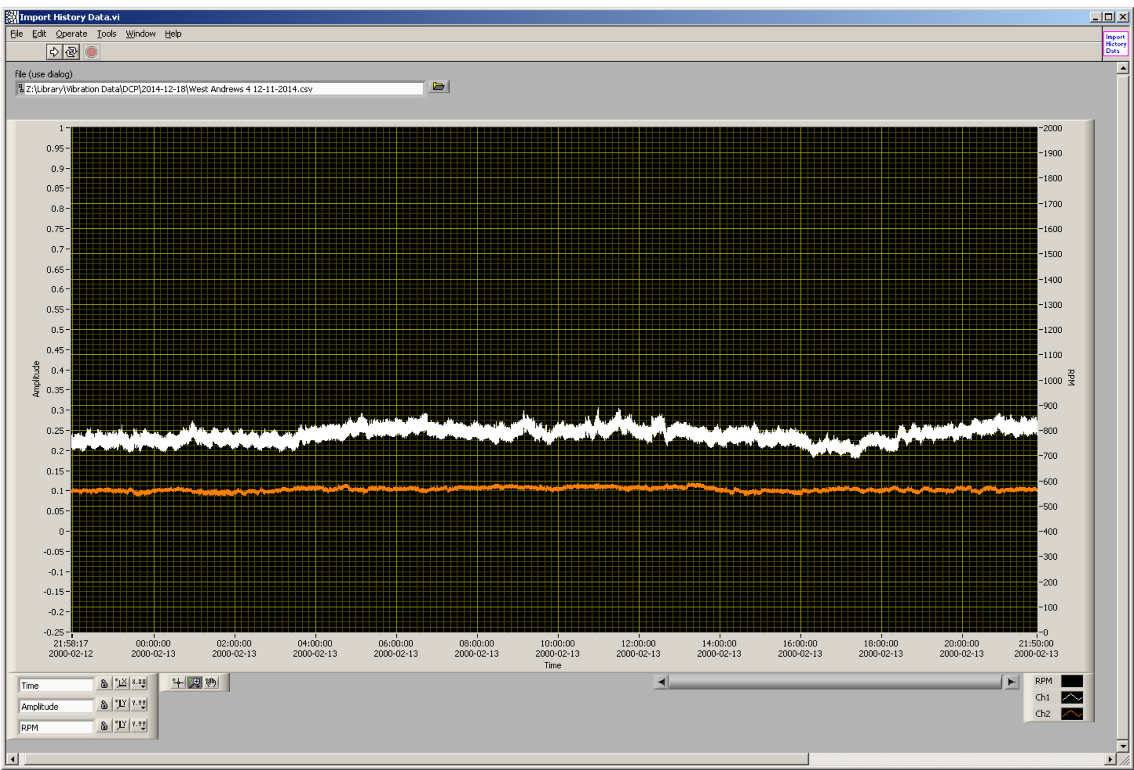
Speed Step	Overall Vibration Level IPS-PK	1 X vibration Peak IPS-PK
800 Rpm	0.28	0.11
866 Rpm	0.31	0.11
933 Rpm	0.36	0.11
1000 Rpm	0.38	0.12
Total change in %	36%	9%

Chart 1: Comparison of variance in vibration levels between Overall and 1X, based on speed variance

Technology that measures overall vibration levels will end up including frequencies that most likely will have no bearing on the health of the unit. Resonances at higher frequencies can cause readings to increase substantially without significant change at frequencies concerning unit health. Overall levels in this case increase by 36% from low to high speed while the 1X frequency component changed 9%. (The reason the higher speed 1X vibration should be higher is explained later.) The ability to closely monitor and set meaningful alarm limits, not only makes it the best tool for safety shutdowns, but also allows it to be used as a great condition monitoring tool.

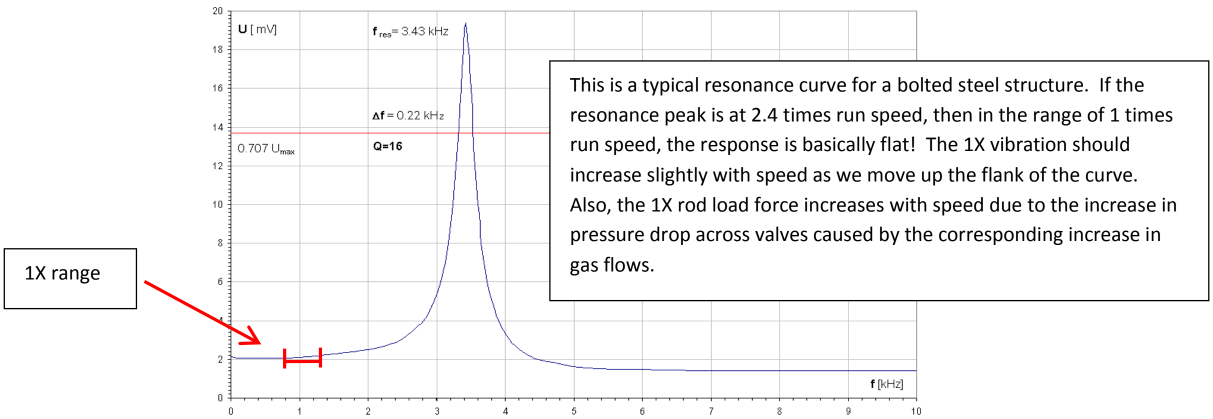
Showing the Effect of Removing Harmonics on Signal Stability

One of the key complaints of overall RMS electronic sensors, while giving better protection than mechanical switches, is nuisance trips. The harmonics included in RMS sensors contribute a large portion to signal instability. Without harmonics, as shown below in the 1X graphs of both an engine and compressor, the engine data in orange varies around 6% while the compressor varies around 12%, mainly due to variance in inlet and outlet pressures.



Signal Stability and Speed

In understanding why speed has so little effect on change in the 1X signal, it also helps to understand **resonance**. Every component or piece of equipment has its own resonant frequency. Whenever that component or piece of equipment is stimulated with a frequency approaching resonance, the vibrational amplitude or movement will begin increasing exponentially, even if the amplitude of the stimulating force remains constant. Compressor systems today, designed to the API 618 Guideline, have specifications indicating that all the components related to the compressor must have a resonant frequency above 2.4 times run speed.



The graph above shows the vibration response equivalence of one component, a typical reciprocating compressor with hundreds of components, will have the same type of response shown above. That overall similarity is designed to be greater than 2.4 times run speed. This is why, when the speed of the compressor represented by the graphs shown on page 3 varies, the overall vibrations including all the resonating components also vary, **while the one times component stays relatively flat.** (The 1X increases only slightly with speed.)

The key benefit of monitoring the 1X is that, if anything starts to come loose, the entire system stiffness 'k' decreases, causing the one times vibration 'x' to increase.

Comparing 1X monitoring to other technologies

Monitoring the 1X has significant advantages when compared to the three most popular monitoring technologies (mechanical switches, overall sensor and knock sensors.)

- **Mechanical switches**: One and the oldest and cheapest technologies available have been shown to be either too sensitive or non-protective. These devices give no indications that something is starting to go bad, only that it already has. While maintenance personnel may like the convenience of adjusting protection levels with a screwdriver and a hammer, validating a switch with a hammer only represents that the machine will stop **after** a catastrophic failure has occurred. Plus, because they are measuring overall vibration, which can cause false trips when adjusted sensitive enough to protect, they are usually "de-tuned" to the point that they are ineffectual.

- **Overall RMS Sensors:** RMS Sensors are a vast improvement over mechanical switches because of their ability to indicate changes in vibration levels, giving operators the opportunity of shutting down their asset early in the failure cycle. Unfortunately, sometimes too much protection is just as bad as too little. With nuisance trips, assets can spend too much time idle while waiting on operators to come out and determine whether or not to restart the asset.

The term overall is misleading, in that this technology usually only measures a limited range of frequencies. But, while limited, that limited band of frequencies may include 10 to over 100 harmonic frequency bands which may or may not include the most important 1X. Many times this technology is implemented with filters that remove the 1X frequency, which even if included, would only contribute 1/10 to 1/100 of the RMS total, which makes up the indicated output signal. As explained in this paper, the variance in all these other harmonics, as speed changes, can lead to nuisance trips while hiding real changes in machine health.

Some operators like overall RMS technology because they feel that monitoring many frequencies will protect against various specific mechanical failures that indicate at frequencies other than the 1X. But unless a FFT is performed on the raw signal to measure that specific 'fault' frequency, its contribution will be lost in the overall RMS which combines all the other frequencies. The 1X frequency, while maybe not indicating early changes in every mechanical process, is the frequency that most failures will indicate on. And even failures that might not start out at the 1X frequency will usually end up affecting other processes that will.

- **Knock Sensors:** Knock sensors are a sophisticated technology that monitors for impacting caused by reciprocating parts that are broken or so loose that they are impacting. This technology claims to be able to shut down within a small number of impact events, thereby limiting damage. Because of the many different parts of a reciprocating machine, it is hard to adjust for the different signatures caused by parts that might be damaged to the point of knocking.

Energy at the 1X frequency is comparatively stable, affected minimally, and only by increases in speed or loading. Generally speaking, 1X energy is so stable that changes as little as 10% would indicate a change worth investigating, while a change of 20% would indicate a shutdown event. Setting 1X warning and shutdown levels are easy. Just add the 10% for warning and 20% for shutdown to the baseline 1X vibration levels established during commissioning procedures.

In summary, the 1X run speed component accounts for the largest majority of vibration forces involved in the mechanical processes of the typical reciprocating machine. For the similar cost of other monitoring technologies, measurement of the 1X vibration level which has a direct relationship to overall machine operations, can be relied on to sense and report **meaningful** changes in mechanical health.

Technology that monitors the 1X not only offers better shutdown protection and a reduction of nuisance trips; but also provides the added opportunity, with proper training, of implementing repair procedures before serious damage occurs.

Steady and reliable 1X monitoring provides trustworthy shutdown protection which leads to increases in production and reductions in operating costs, better than any shutdown technology available today.