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OVERALL VIBRATIONS: HISTORY AND PRESENT DAY USES

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ABSTRACT

The history of overall vibration measurements in North America and Europe goes back to the 1950s. Over the decades, there have been many misunderstandings related to this subject. The sources of the misunderstanding will be described.

Currently, there is a trend to try to use overall vibration measurements for screening vibrations in selected areas, such as reciprocating compressors and piping. One such guideline has been developed and published by the European Forum for Reciprocating Compressors (EFRC). It will soon be an ISO Standard.

A new standard for high speed reciprocating compressors is nearing completion, and will be discussed. It will also provide guidance for using overall vibrations as a screening tool.

La mesure des vibrations en Amérique du Nord et en Europe remonte au début des années 1950. Tout au long de cette période, divers types de mesure ont parfois mené à des interprétations erronées des phénomènes observés. L'origine de ces mauvaises interprétations sera discutée.

Présentement, la tendance est à mesurer des quantités globales et de les utiliser pour solutionner des problèmes de vibration plus spécifiques tels que ceux qu'on retrouve autour des compresseurs à piston et la tuyauterie qui les entoure. Un guide utilisant cette stratégie a été préparé et publié par le Forum européen des compresseurs à piston (EFRC). Ce guide deviendra d'ailleurs sous peu une norme ISO.

Une nouvelle norme applicable aux compresseurs à piston opérant à haut régime est en voie d'être complétée. Celle-ci est aussi présentée dans cet article. Cette nouvelle norme offrira quelques conseils pour mieux utiliser des mesures globales comme outil de résolution des problèmes de vibration plus spécifiques.

1. INTRODUCTION

The concept of simplifying a complex vibration measurement into a single number is attractive. In the early days of vibration analysis, separating different frequencies was difficult, so measuring an overall value was the only available method. However, in the early days, the ability to measure a "true" vibration reading with electronic instruments was not available. Instruments (typically voltmeters) were only able to measure amplitudes accurately over a narrow frequency range – typically around 50 or 60 Hz since electrical engineers tended to be the designers of the equipment.

Then, in the 1950s, the "true RMS circuit" was developed. The advantage of such a circuit was that it could faithfully estimate the root mean square overall (OA) amplitude of complex signals, independent of the range of frequencies in the signal. The first company that seems to have made use of this technological advance was IRD in the 1950s.

Unfortunately, the instrumentation that was developed displayed the overall amplitude with the waveform descriptors "peak", or "peak to peak". This one simple accident has resulted in many arguments and disputes between North America and Europe in the ensuing years regarding the benefits of peak versus RMS measurements of overall vibrations.

The Overall Peak value in the IRD instruments (which was the dominant measurement system for decades in North America) was obtained by multiplying the RMS Overall value by the square root of 2 for velocity (in/sec pPk) and 2 root 2 for displacement (mils pPP). These conversions are mathematically correct for a single frequency, but in general are not correct for complex waves (that is, ones made up of more than one frequency).

As a result of this mathematical inconsistency, people use various terms to refer to this erroneously named peak overall value, such as pseudo peak (pPk OA). This usage has led to the cumbersome term "True Peak OA" when measuring the peak overall correctly, to ensure that there is no misunderstanding.

The Data Trap System, developed by Beta Monitors and Controls, in Calgary, was the first system that offered the user the option of measuring any of the overall types. Since then many (but not all) vibration systems offer this same flexibility.

Over many decades, North American vibration specialists built up a large data base of vibration readings, apparently based on overall peak measurements. When discussions ensued at the international level, the argument was presented that Peak OA was better than RMS OA since Peak is proportional to the stress that causes fatigue failures. Eventually, it was realized that the European historical data base was essentially the same as the North American database, differing only by a constant. Though the argument that fatigue failures are more closely related to peak vibration than RMS is still valid, the instrumentation argument was lost by North America! The standard reading for ISO Standards became RMS.

RMS is proportional to power, and as such is appreciated by electrical engineers, but for most vibration technicians, the power in a vibration signal has no obvious meaning. Nevertheless, RMS Overall had the advantage of being simple to measure after the development of the "true RMS circuit". Nowadays, RMS OA can be derived from a frequency spectrum (sometimes called Spectral RMS OA), which is found to be very nearly the same as an RMS derived from the time waveform, and is easier to calculate over a defined frequency range. RMS measurements are less sensitive to subtle changes in a vibration waveform, than peak measurements (which can be good or bad, depending on the machine being analyzed). Peak overall measurements provide an obvious alternative to RMS OA measurements on dynamic machinery and piping due to the relationship between peak stress and peak vibration, and the potential for fatigue failure. Peak measurements must be derived from time waveforms, rather than from frequency spectra. Peak measurements may be more sensitive to subtle changes in vibrations. RMS and Peak measurements are not related by a constant.

In this paper, the following types of vibration measurement will be included in the discussions:
- RMS Overall from time waveforms
- RMS Overall from spectra
- Peak Overall from time waveforms
- Crest Factor (Peak OA divided by RMS OA)
- Amplitudes of individual frequencies in spectra

The user of a vibration guideline is likely to be attracted to a screening method that is easy to use and interpret. Basing a guideline on single numbers at predefined test points makes it easy to pre-screen vibrations on machinery and piping. If overall vibrations are found to be over guideline, then more sophisticated analysis methods can be used to verify the presence of a problem.

Since analysts can be asked to assess a wide variety of machinery, there will be many situations where overall vibration readings are simply not adequate, even for pre-screening. An obvious example would be the assessment of rolling element bearings, where the energy from other sources dominates the energy from the defect in the bearing.

Vibrations generated by reciprocating compressors and pumps are a special case of waveform compared to "simple" rotating machinery. The waveforms are made up of a fundamental sinusoid, and many harmonics. The pattern of vibration is deterministic, meaning that it is steady, as opposed to random (stochastic). The time waveforms generally are repeated from cycle to cycle of the crankshaft. An exception can occur when 2 or more compressors are operated at nearly the same speed. Then a beat can occur, which makes measurement of a single value of vibration more problematic.

2. DEFINITION OF VIBRATION MEASUREMENT TERMS

In this paper, the following types of vibration measurement will be discussed:

1) **RMS Overall:** These readings can be obtained from three sources, and the results may be different:
   a) Time waveforms,
   b) From simple handheld data collectors, or
   c) Spectral data (frequency based results) obtained from more complex spectrum analyzers

2) **Amplitudes of individual frequencies:** These data are obtained from spectral analysis, which is the required approach when analyzing vibration data for troubleshooting, or when vibration exceeds an overall screening guideline.

3) **Crest Factor (CF = Peak Overall divided by RMS OA)**: This parameter characterizes the vibration waveform. For the same RMS OA, a large CF is an indication that the likelihood of fatigue failures will be higher than if the CF is low.

4) **Peak Overall** (meaning true peak): This is a measure of the highest instantaneous vibration and is related to fatigue failure. Peak data is obtained from time waveforms, or analog circuits, using two methods – ISO and non-ISO.

In theory, the time and spectral methods of calculating RMS OA should give the same result. An example from real data where this equivalence is not true is discussed.

3. RMS OVERALL DATA ANALYSIS – RECONCILING TWO METHODS

When we started to assess overall vibration methods in preparation for writing Reference 1, it was assumed that the task would be simple. In fact, pitfalls were discovered.

A spectrum analyzer was used to collect the vibration data. Various maximum frequencies were used. In all cases, the minimum analyzer frequency was zero for time domain collection, rather than the 2 Hz specified by ISO – a limitation of the analyzer without extra post processing analysis steps.

During the evaluation, it was determined that RMS OA values from a time waveform or a spectrum of the same data were not always the same, even though theoretically they should have been. See Figure 1 below for data from 4 selected test points. The blue line compares the ratio (RMS T/RMS F) of the two approaches:

- RMS T = RMS calculated from time waveform data.
- RMS F = RMS based on spectral (frequency) data.

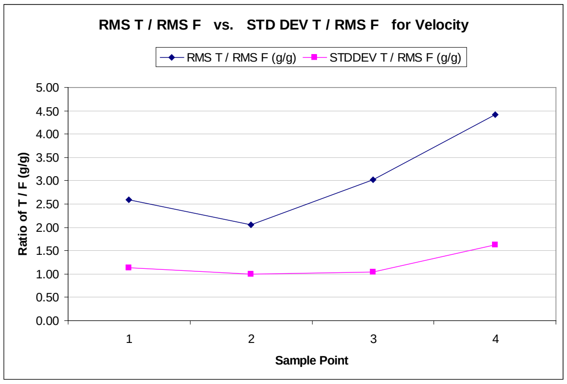

Figure 1: Ratios of Time vs. Frequency Domain RMS Calculations

The difference varies between 200% and 400%. Different analyzer measuring devices account for these differences, due to these reasons:

- Velometers vs accelerometers can produce differences: in this case, accelerometers required digital time domain integration to create vibration results compared to velometers.
- Filtering low frequency data (or not) will produce large differences. Some hardware does not filter low frequencies (below 2 Hz).

This illustrates that methods and test equipment can produce large differences.

Correcting RMS Data

If a different method is used compared to the ISO defined procedure, then the data will likely need to be corrected. Generally the difference of most concern is the corner frequency of the high pass filter – 2 Hz for ISO.

Correction of the problem shown in Figure 1 was achieved by using the standard deviation of the time waveform instead of the RMS, based on the definition below:

$$\text{RMS}^2 = \text{mean}^2 + \text{standard deviation}^2$$

The RMS OA mentioned in ISO documents is expected to be determined from a time waveform with a mean value approaching zero. Usually, high pass filtering the data above 2 Hz will achieve that goal.

If data are not high pass filtered, then using the standard deviation will mostly correct the error (see red line in Figure 1).

There is an advantage to using spectra for calculating overall RMS values. The frequency range that is included in the OA can be adjusted with a spectral display more easily than for a time waveform in most spectrum analysers.

4. WAVEFORM DESCRIPTORS (OR MEASUREMENT UNIT QUALIFIERS)

The purpose of a Waveform Descriptor is to allow a single number to be related to a waveform shape (a time waveform, in general).

Consider a sine wave (single frequency waveform). In order to create a picture of a sine wave given a single number (for example, 1 mm/sec), additional information regarding the waveform shape has to be attached. So, if 1 mm/sec becomes 1 mm/sec RMS, or 1 mm/sec Peak, there is sufficient information for the reader to describe the sinusoidal movement.

Complex waveforms (which contain more than one frequency) similarly require a waveform descriptor attached to a single number in order to describe a vibration. A reported vibration of 1 mm/sec overall (OA) does not supply enough information to the reader to understand the severity of the vibration.

Reporting 1 mm/sec RMS OA, or 1 mm/sec Peak OA improves the understanding. Still, the waveform from which the single number was derived is not totally understood from one of these numbers.

In order to improve the understanding of the waveform from which an RMS OA amplitude is derived, the overall peak, or Crest Factor (CF) can be informative. CF is the ratio of Peak to RMS for the complex, or overall wave. Before calculating CF, the peak overall amplitude of the time waveform must be determined. Two subtly different methods of calculating the peak amplitude of a complex waveform are commonly used:

- Absolute value of the mean to maximum or minimum of the time waveform (ISO definition), or
- Peak to peak from a time waveform divided by 2.

It has been observed that Crest Factor decreases as the range of frequencies included (bandwidth) in the overall numbers is reduced.

5. DISPLACEMENT MEASUREMENTS

Displacement measurements of vibration are a special case. Early measurements of vibration amplitude at low frequency were accomplished with mechanical instruments such as dial indicators (below 7 to 10 Hz, typically). As such, a visual estimate of the peak-to-peak vibration amplitude was easily accomplished. There was no way to estimate an RMS quantity. Furthermore, shaft motion relative to a journal bearing is measured as peak-to-peak overall since the key concern is contact between the journal and the bearing Babbitt metal. An RMS OA estimate of shaft relative vibration would seem to have little value.

6. PEAK MEASUREMENTS

Peak measurements can be derived from an oscilloscope display. Oscilloscopes were available before spectrum analyzers. As a result of this ease of measurement, and due to the correlation between peak motion and metal fatigue, peak measurements have been used for many years for machinery and piping integrity assessment.

Peak Stress is directly related to fatigue failures. Refer to a paper by Howes published in the Canadian Machinery Vibration Association proceedings from 1996 (Reference 2). In this paper, a piping failure associated with a plunger pump is described in which the overall peak amplitude was very high, while the peaks at orders of pump speed in the spectrum of the vibrations (and by extension the RMS OA amplitude) were low. In other words, the Crest Factor was high. The Spectral Guideline used by Beta failed to detect this problem. An RMS OA guideline would also have failed to predict a problem in this case. (Fortunately, the problem was detected, mainly due to the analyst knowing that failures had occurred at the location. The simplified analysis of individual peaks was clearly misleading, which lead to the inspection of the true peak vibration. The time waveform made the problem clear.)

If the vibration guideline used to assess machine condition is directly derived from stress calculations, it would seem that a Peak OA measurement would be a better choice than RMS OA. This idea will be discussed more in below in the context of reviewing data from operating compressors.

Note that in the example above, the source of energy causing the vibrations was a plunger pump. A reciprocating pump typically has different vibration characteristics compared to a reciprocating compressor.

7. OVERALL VIBRATION GUIDELINES FOR RECIPROCATING COMPRESSORS

The EFRC (European Forum for Reciprocating Compressors) document Vibration Guidelines for Reciprocating Compressor Systems (Reference 3) is the basis for ISO 10816-8: Mechanical vibration — Evaluation of machine vibration by measurements on non-rotating parts — Part 8: Reciprocating Compressor Systems (Reference 4). ISO 10816-8 has recently been approved and is planned for publication in 2014. These guidelines are utilized by reciprocating manufacturers, engineering contractors and users in Europe. They are applicable to rigidly mounted compressors (i.e., block mounted). If the compressor and driver are mounted on a skid, the skid should be appropriately stiff and mounted directly to a concrete foundation. These guidelines are not intended for isolated mount foundations (e.g., concrete block on springs or skids on anti-vibration mounts). Such mounting configurations are rarely encountered in packages used for natural gas transmission and storage applications.

A new standard for design and monitoring of high speed reciprocating compressors is nearing completion (Reference 5, soon to be published). One section discusses vibration screening. EFRC and ISO references present screening vibration displacement, velocity and acceleration guidelines.
The majority consensus of the committee that developed the new GMRC Design Guideline for High Speed Reciprocating Compressors is that only the EFRC/ISO velocity screening limits should be considered for large, high-speed compressor packages for natural gas transmission and storage applications.

EFRC screening guidelines have been categorized for the following “key zone” situations:

Zone	Level	Description	Notes
A	<A/B Boundary	Acceptable	Normally acceptable for long-term operation
B	>A/B to <B/C	Acceptable	Normally acceptable for long-term operation
C	>B/C to <C/D	Marginal	Analysis & possible correction
D	>C/D Boundary	Unacceptable	Urgent correction or shutdown to be considered

It is important to note that there are different screening guidelines for different elements (e.g., piping, cylinder, frame, etc.) of the compressor package or system. Reference 1 provides a more in-depth discussion of these guidelines, including comparisons with field test data, and suggestions for improvements.

8. CREST FACTOR AS A TOOL TO ASSIST VIBRATION ANALYSIS

One challenge with using RMS measurements is that an RMS value does not capture the maximum vibration seen in a waveform. This concept is mentioned in Reference 3, but in most cases, analysts ignore CF.

Our observations of the variability of CFs from measurements of vibrations on reciprocating compressor systems (Reference 1) are that typical CFs are in the order of 2 to 3.5 (occasionally as high as 4 have been seen).

It would seem prudent to consider Peak amplitudes (in other words Crest Factor) as well as either RMS or Spectral measurements when the guideline assessment is in the Marginal Zone.

Note that CF for other machines other than reciprocating compressor, such as reciprocating pumps and screw compressors tend to be higher (as high as 10 on screw compressors).

9. CAUTION: "PSEUDO-PEAK", "CALCULATED PEAK", "DERIVED PEAK" ARE CONFUSING TERMS

Over 50 years ago, a major manufacturer of vibration instrumentation created confusion by calculating a Pseudo-Peak Overall measurements (RMS OA times the square root of 2) rather than "true" Peak Overall. Instrumentation is available for purchase today that perpetuates this confusion. Pseudo-Peak Overall measurements provide no additional information compared to RMS measurements.

Caution is urged, therefore, when using guidelines based on Peak readings. Make sure that the type of "peak" reading that was used in the historical data collection is understood.

Manufacturers may use different nomenclature, such as calculated peak, derived peak, overall peak, and other terms. In many cases, there is no indication of the type of peak measurement. Vibration analysts are advised to check their instrumentation closely to determine what conventions are used. Discovering that the overall peak being measured by an instrument is really just RMS OA times a constant opens up a range of new standards that can be used to compare with measured data.

10. CONCLUSION

- Understanding the historical differences between North American and European vibration measurement experience is helpful.
- Pseudo-Peak Overall measurements are equivalent to RMS OA measurements (subject to the frequency bandwidth being the same). As a result, it would seem that use of Pseudo-Peak OA should be discontinued.
- The term “RMS times Square root of 2” may be better than pPeak, since it eliminates the misleading use of the word peak.
- Trending both RMA OA and Peak OA (or Crest Factor) adds value to a vibration screening system.
- Changes in Crest Factor when RMA OA does not change can indicate changes in machinery or piping condition.
- Overdependence on spectral measurements is as bad as an overdependence on RMS OA measurements.
- Understanding how specific instrumentation measures overall vibrations is important for analysts comparing their readings to standards based on historical data.
- Comparison of RMS OA and Standard Deviation for waveforms helps to evaluate the quality of RMS measurements derived from time waveforms.

11. REFERENCES:

[1] *Field Assessment of Overall RMS Vibration Guidelines for Reciprocating Compressors*, presented by Brian C. Howes and Tom Stephens at the 8th Conference of the EFRC, September 27-28, 2012, Dusseldorf, Germany

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[3] *Guidelines for Vibrations in Reciprocating Compressor Systems*, European Forum Reciprocating Compressors, originally presented in 2009

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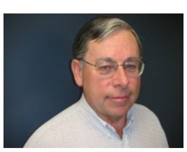
BIOGRAPHIES



Brian has worked with Beta Machinery Analysis since 1972. In his present position as Chief Engineer for Beta, he has performed troubleshooting services all over the world.

Brian has many technical papers to his credit. The range of machinery problems they cover includes all manner of reciprocating and rotating machinery and piping systems, balancing and alignment of machines, finite element analysis, modelling of pressure pulsation, torsional vibration testing and modelling, flow induced pulsation troubleshooting and design, pulp and paper equipment such as pulp refiners, etc. He has also worked on hundreds of reciprocating compressor installations.