# Field Assessment of Overall RMS Vibration Guidelines for Reciprocating Compressors

**by:**

**Brian Howes**

**Chief Engineer, Beta Machinery Analysis**

**Calgary, Canada**

**bhowes@betamachinery.com**

**and**

**Tom Stephens**

**Senior Equipment Specialist, Ariel Corporation**

**Mt. Vernon, USA**

**tstephens@arielcorp.com**

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**Abstract:**

The EFRC has prepared an overall RMS vibration guideline for reciprocating compressors. The intent is to have this guideline approved as an ISO standard. To assess the accuracy and robustness of this guideline, the authors have completed field studies on a range of compressor installations. These field tests compare the proposed guideline to other vibration parameters and measurement approaches. This paper will present the findings from these field assessments and conclusions regarding the proposed standard.

## 1. Introduction

A new vibration guideline has been proposed for the monitoring of reciprocating compressors, and associated piping. It was first published in 2008 at the 6th EFRC Conference in Dusseldorf. Efforts are currently ongoing to incorporate the EFRC limit into ISO standard 10816-8.

The EFRC Guideline makes use of root mean square overall (RMS OA) vibration measurements in terms of acceleration, velocity and displacement. Zones of vibration are defined in terms of subjective ratings of the integrity of parts of the compressor.

The user of a vibration guideline is likely to be attracted to a method that is easy to use and interpret. The proposed RMS Guideline meets this need because simple handheld instruments can be used to collect the data.

One paper has been published since the introduction of the new guideline at the 7th EFRC Conference. The conclusion of the paper was that most measured vibrations were in acceptable zones. This result was consistent with the long-term satisfactory operation of the machines measured. The purpose of this paper is to evaluate the guideline with more field data, including compressors with problem vibrations. Comparisons of RMS measurements to spectral measurements will be shown.

Author Howes has used a guideline based on individual frequency components – a spectral guideline that has been used globally for the past 40 years by compressor manufacturers and compressor users. Assessments of integrity of the new RMS OA Guideline and the older Spectral Guideline will be compared.

In most cases the two approaches provide similar results and this tends to validate the usefulness of the EFRC Guideline.

Data from five different compressors are included in the analysis. Refer to Table 1 below for a brief description of the units. Also, comments based on decades of experience analyzing reciprocating compressors by the authors will be provided.

The evaluation highlighted the challenges in applying RMS data. This paper illustrates how different vibration instrumentation can result in significantly different RMS Overall data. Accounting for these differences is very important when investigating vibration problems.

*Table 1: Compressors from Field*

| Example Number | Model | Speed (rpm) | Driver | Maximum Frequency (Hz) |
|---|---|---|---|---|
| 1 | JGA4 | 1200 | Engine | 250 |
| 2 | JGK2 | 1000 - 600 | Electric | 500 |
| 3 | JGC6 | 1000 - 800 | Engine | 200 |
| 4 | JGU6 | 745 | Electric | 1000 |
| 5 | JGD4 | 1000 - 600 | Electric | 1000 |

Another important topic addressed in the paper is Crest Factor (CF). This parameter is useful to supplement the RMS result in order to identify problems, especially when the EFRC screening guideline produces marginal or high vibrations. Field data is used to illustrate how CF will vary for the same RMS value.

Certain areas important to all reciprocating compressor systems, such as, pressure relief valves and small bore connections, are not included in the guideline.

The EFRC Guideline requires that spectral data be used for further analysis in the event that vibrations exceed the RMS Guideline. Recommendations are provided for spectral analysis since no details are provided in the guideline.

## 2. Definition of Vibration Measurement Terms

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

- **RMS Overall** can be obtained from two sources and the results will be different:
  - i. Time waveforms, or from simple handheld data collectors.
  - ii. Spectral data (frequency based results) obtained from more complex spectrum analyzers
- **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 the EFRC Guideline.
- **Crest Factor (CF)** (Peak Overall divided by RMS). This parameter characterizes the vibration waveform. For the same RMS, a large CF is an indication that the likelihood of fatigue failures will be higher than if the CF is low.
- **Peak Overall**. This measure of the highest vibration is related to fatigue failure. Peak data is obtained from time waveforms, 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 the data where this is not true is discussed.

## 3. RMS Data Analysis – Reconciling Two Methods

At the beginning of the analysis of the data, it was assumed that the process 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, rather than the 2 Hz specified in the EFRC Guideline – a limitation of the analyzer.

During the evaluation, it was determined that RMS OA value from a time waveform or a spectrum was not always the same. See Figure 1 below for data from four selected test points. The blue line compares the ratio of the two approaches (RMS T/RMS F):

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

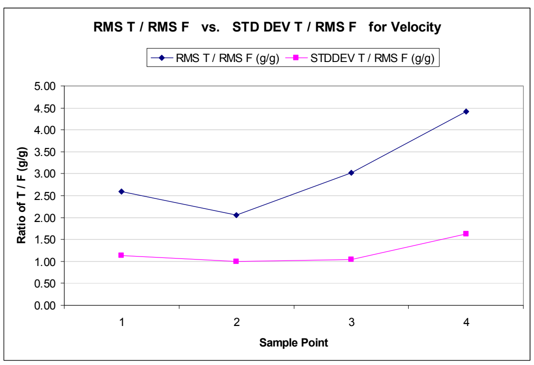


*Figure 1: Ratios of Time vs. Frequency Domain RMS Calculations.*

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

- Velometers vs. accelerometers can produce differences: 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 ERFC defined procedure, then the data will likely need to be corrected.

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

$RMS^2 = mean^2 + standard\ deviation^2$

The RMS OA mentioned in the EFRC Guideline document is expected to have a mean value of the time waveform approaching zero. Usually, high pass filtering the data above 2 Hz will achieve that goal (which is captured in the frequency range of 2-1000 Hz in the proposed standard).

If data are not filtered then using the standard deviation will correct the problem (see red line in Figure 1).

## 4. Spectral Vibration Guideline Used to Compare with EFRC RMS Guideline

The purpose of a vibration guideline is to provide a screening tool for identifying "areas of concern". Generally, these guidelines are derived empirically, although vibration guidelines can also be derived from finite element models of specific geometries. A vibration guideline should always be slightly conservative.

Spectral guidelines are available and in common use for reciprocating compressors. One such guideline has been used by author Howes' company for about 45 years (covering all parts covered by the EFRC Guideline). Over the years, it has been adopted by compressor manufacturers and compressor users around the world.

This Spectral Guideline can be summarized for piping and dampers as the lesser of 10 mils pp (.09 mm RMS) or 1 ips peak (18 mm/sec RMS) at any frequency up to 500 Hz. The limits are multiplied by constants for different parts of the compressor: 0.7 for cylinders and 0.5 for frames. Foundations, considered a special case, are assessed based on limits of 0.05 ips peak (.9 mm/s RMS) for vertical and 0.1 (1.8) for horizontal plane vibrations[1] A special case of the Spectral Guideline is for frequencies above 125 Hz on relief valves (and other parts that are sensitive to internal fretting or vibratory loosening, such as gate valves). An acceleration limit is defined as 2 g peak (14 $ms^{-2}$ RMS). Allowing increased severity over 2 g peak is not recommended.

For the subjective analysis of vibration severity used in this paper, we have added zones to permit comparison with the RMS OA Guideline, as shown in Table 2. No distinction is made between cylinder directions. Foundation zone boundaries are 50%, 100% and 150% of the limits mentioned above.

Note that the frequency below which displacement becomes the defining measurement is 100/PI Hz (about 31 Hz, compared to 10 Hz for the RMS).

*Table 2: Spectral Guideline Zone Boundaries*

| Zone Boundary | Frame | Cylinder | Damper or Pipe |
|---|---|---|---|
| | Velocity from 31 to 500 Hz in/sec peak (mm/s RMS) | | |
| A/B | .25 (4.5) | .35 (6) | .5 (9) |
| B/C | .5 (9) | .7 (13) | 1 (18) |
| C/D | .75 (14) | 1.05 (19) | 1.5 (27) |
| | Displacement below 31 Hz Mils pp (mm RMS) | | |
| A/B | 2.5 (.02) | .35 (.03) | 5 (.045) |
| B/C | 5 (.045) | 7 (.06) | 10 (.9) |
| C/D | 7.5 (.07) | 11 (.1) | 15 (.14) |

## 5. Field Data Compared to both EFRC and Spectral Guidelines

Using the comparison boundary zones defined in Table 2, a limit comparison study has been completed. Figures 2 to 5 compare the two methods for many data points collected from the compressor examples. The data is velocity readings (inches per second, IPS).

The shaded boxes represent data points that show similar results between the two guidelines. Data outside these shaded boxes represent areas where the guidelines produce different recommendations.

In most cases, the two methods produce similar results and confirm that the EFRC Guideline is effective in screening for condition.

There are relatively small differences between the methods, as highlighted by the black circles. In all cases the EFRC Guideline results in a slightly more conservative assessment than the Spectral Guideline – a good result.

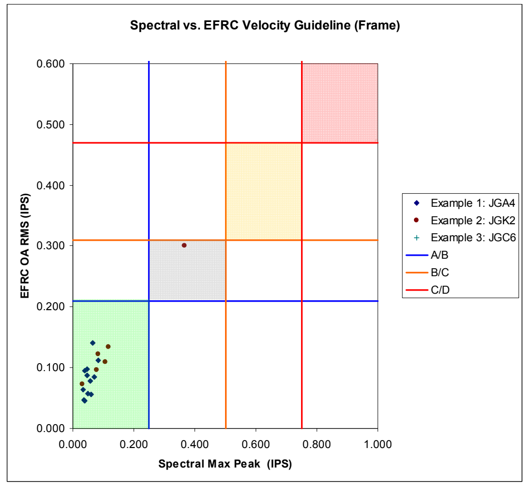


*Figure 2: Compressor Frame*

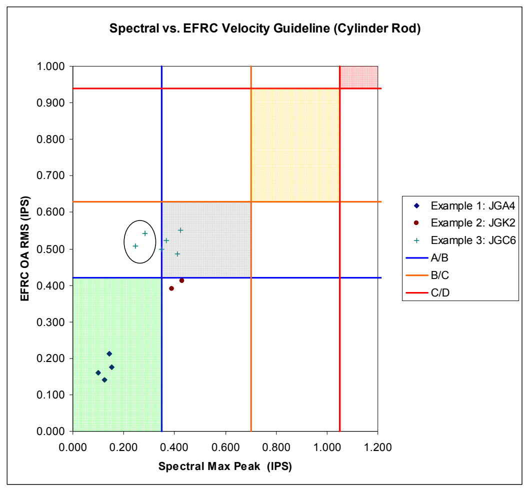


*Figure 3: Cylinder Rod*

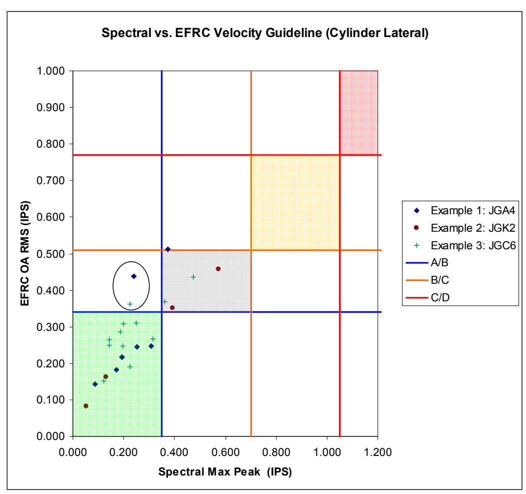


*Figure 4: Cylinder Lateral*

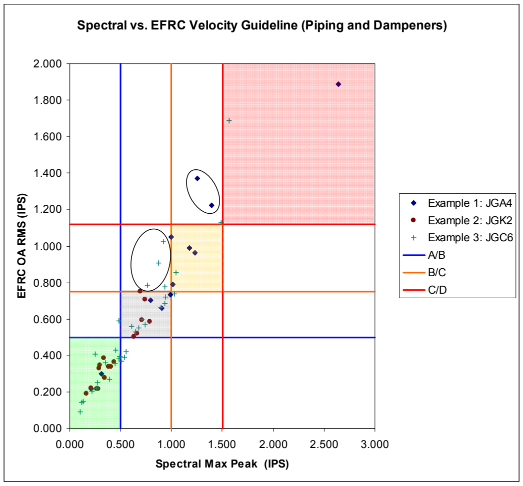


*Figure 5: Piping and Dampers (Pulsation Bottles)*

## 6. Comments on Velocity, Acceleration, Displacement

The evaluation in this paper presents velocity data which is the most common approach for reciprocating compressors.

Displacement data is used for low frequency measurements (below 30 Hz). This would apply to pipe & pulsation vessels (dampers) on slow speed compressors. This paper did not compare the two guidelines in this region. Table 3 shows a comparison of displacement guideline boundaries. Our experience shows that the EFRC displacement limits could result in unacceptably high stresses in damper to cylinder nozzles. More information must be reviewed to confirm this concern.

*Table 3 – Comparison of Displacement Levels*

| Location | Description | Units | Horizontal compressors | | |
|---|---|---|---|---|---|
| | | | A/B | B/C | C/D |
| Foundation | EFRC | mm RMS | 0.032 | 0.048 | 0.072 |
| | EFRC (Converted) | mil p(P-P) | 3.56 | 5.35 | 8.02 |
| Frame (top) | EFRC | mm/s RMS | 0.084 | 0.127 | 0.191 |
| | EFRC (Converted) | in/s pPk | 9.35 | 14.14 | 21.27 |
| | Spectral Guideline | in/s Pk | | 5 | |
| Cylinder | EFRC (Lateral) | mm/s RMS | 0.139 | 0.207 | 0.31 |
| | EFRC (Rod) | mm/s RMS | 0.17 | 0.255 | 0.382 |
| | EFRC (Lateral - Converted) | in/s pPk | 15.48 | 23.05 | 34.52 |
| | EFRC (Rod - Converted) | in/s pPk | 18.93 | 28.40 | 42.54 |
| | Spectral Guideline | in/s Pk | | 7 | |
| Dampers/Piping | EFRC | mm/s RMS | 0.202 | 0.302 | 0.454 |
| | EFRC (Converted) | in/s pPk | 22.49 | 33.63 | 50.56 |
| | Spectral Guideline | in/s Pk | | 10 | |
| EFRC Guidelines are for Overall RMS values from 2-1000 Hz | | | | | |
| EFRC (Converted) values are mils P-P from pseudo-peak (RMS * sqrt(2)) | | | | | |
| Spectral Guidelines are for any discrete frequency <31 Hz | | | | | |

Acceleration data is applicable for higher frequency applications such as relief valves (above 125 Hz). In this region, the EFRC Guideline could be overly conservative for other parts of the compressor system.

Based of 10 years of field analysis, Author Howes evaluated acceleration spectral guidelines. The guideline was 2 g peak acceleration for all parts of the compressor and piping. Howes discovered that too many problem areas were erroneously flagged by this guideline. The conclusion was that for reciprocating compressors, velocities below 1 ips peak above 125 Hz are not a problem, and acceleration should only be used when evaluating relief valves and other components that are sensitive to fretting damage.

## 7. OEM vs. EFRC Guidelines

In practice, the user should also follow guidelines provided by compressor manufacturers.

Author Stephens represents a major OEM who currently employs a frequency bandwidth limited (10-250 Hz) overall peak limit covering the foundation, frame and cylinders. Different levels are provided for frames of varying load capacity. The EFRC Guidelines are less conservative for the smaller frames, and slightly more conservative for the larger frames. In general, the velocity guideline levels are comparable to the EFRC Guidelines. See Table 4 for details. Given that these particular compressors typically operate above 10 Hz, the displacement measure is not employed (nor recommended). Acceleration measures are also not used nor recommended.

*Table 4: Comparison of Velocity Guidelines*

| Location | Description | Units | Horizontal compressors | | |
|---|---|---|---|---|---|
| | | | A/B | B/C | C/D |
| Foundation | EFRC | mm/s RMS | 2 | 3 | 4.5 |
| | EFRC (Converted) | in/s pPk | 0.11 | 0.17 | 0.25 |
| | Spectral Guideline | in/s Pk | | 0.1 | |
| | OEM Guideline (Medium) | in/s Pk | | 0.15 | |
| | OEM Guideline (Large) | in/s Pk | | 0.2 | |
| Frame (top) | EFRC | mm/s RMS | 5.3 | 8 | 12 |
| | EFRC (Converted) | in/s pPk | 0.3 | 0.45 | 0.67 |
| | Spectral Guideline | in/s Pk | | 0.5 | |
| | OEM Guideline (Medium) | in/s Pk | | 0.4 | |
| | OEM Guideline (Large) | in/s Pk | | 0.5 | |
| Cylinder | EFRC (Lateral) | mm/s RMS | 8.7 | 13 | 19.5 |
| | EFRC (Rod) | mm/s RMS | 10.7 | 16 | 24 |
| | EFRC (Lateral - Converted) | in/s pPk | 0.48 | 0.72 | 1.09 |
| | EFRC (Rod - Converted) | in/s pPk | 0.6 | 0.89 | 1.34 |
| | Spectral Guideline | in/s Pk | | 0.7 | |
| | OEM Guideline (Medium) | in/s Pk | | 0.8 | |
| | OEM Guideline (Large) | in/s Pk | | 1 | |
| Dampers/Piping | EFRC | mm/s RMS | 12.7 | 19 | 28.5 |
| | EFRC (Converted) | in/s pPk | 0.71 | 1.06 | 1.59 |
| | Spectral Guideline | in/s Pk | | 1 | |
| EFRC Guidelines are for Overall RMS values from 2-1000 Hz | | | | | |
| EFRC (Converted) values are in/s pseudo-peak (RMS * sqrt(2)) | | | | | |
| Spectral Guidelines are for any discrete frequency from 31-500 Hz | | | | | |
| OEM Guidelines are for Overall Peak values from 10-250 Hz | | | | | |

As earlier discussed, problems due to high vibration are usually a result of motions in the 10-250 Hz frequency range. Higher frequencies are usually a result of impacting and can result in very high true peak measurements, so the band limiting was employed to focus on the frequencies of interest and make the response information less sensitive to impulsive responses. Often, this provides similar effects as an RMS measure, and it is common for people to employ these OEM limits with pseudo-peak measurements or devices.

## 8. Crest Factor (CF) as a Tool to Assist Vibration Analysis

One challenge with using RMS measurements is that RMS value does not indicate the vibration profile. The vibration profile can be important in analyzing reciprocating compressor issues.

Here are two examples which could have the **same RMS** value:

i. A vibration signature containing many harmonics, all having low amplitudes. For a reciprocating compressor this may not represent a risk of fatigue failure. This example would have a low CF.

ii. A vibration signature containing impulsive responses or two or more large amplitude peaks. Due to the process of averaging the entire spectrum, the resulting RMS value would be the same as (i). This signature, however, could pose a much higher risk of fatigue failure. This situation would have a higher CF.

While the EFRC will provide an effective screening tool, it could be enhanced by using CF data – especially if the screening results are in the marginal or high zones.

CF is the ratio of Peak Overall to RMS. CF for a sinusoid is always 1.414. CF is 1.0 for a square wave.

Figure 6 illustrates how CF can vary while RMS OA remains constant. The chart plots increasing numbers of frequency components (peak single frequencies). If the peak amplitude of the individual spectral components are added arithmetically as peak values, then a worst case Peak OA curve results.

The CF starts out at 1.414 for a single frequency peak and climbs to over 4 with 9 peaks combined. In reality, it is unlikely that this worst case situation will occur.

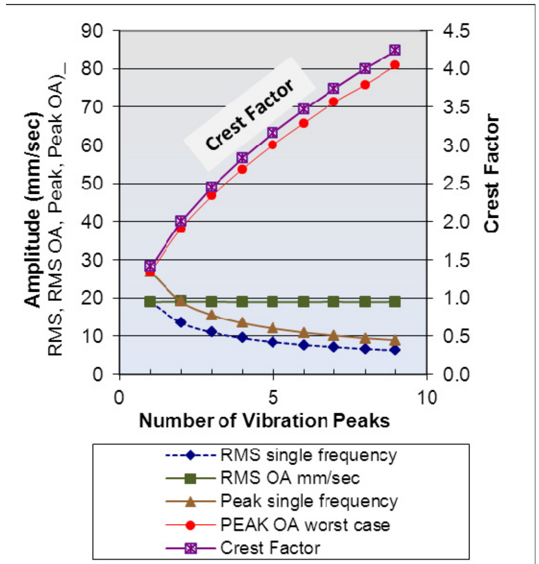


*Figure 6: Crest Factor vs. RMS OA for Complex Spectra*

Our observations of the variability of CFs from measurements of vibrations (see Figure 7) are that typical CFs are in the order of 2 to 3.5 (occasionally, as high as 4 have been seen). This maximum CF of 3.5 from the test data seems to be consistent with the "worst case" calculations above.

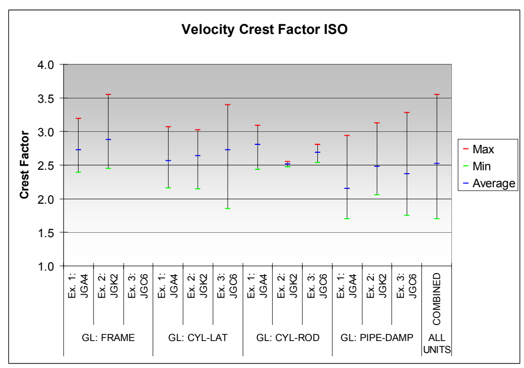


*Figure 7: Crest Factors from Measured Data*

The two methods of calculating peak amplitude of a complex time waveform are:

- Absolute value of the mean to maximum or minimum (ISO definition), or
- Peak to peak divided by 2. This is a commonly provided measurement by spectrum analyzers.

Figure 8 compares the two methods. A ratio of 1.0 would mean the methods were the same. Ratios as high as 1.3 can be seen in the figure.

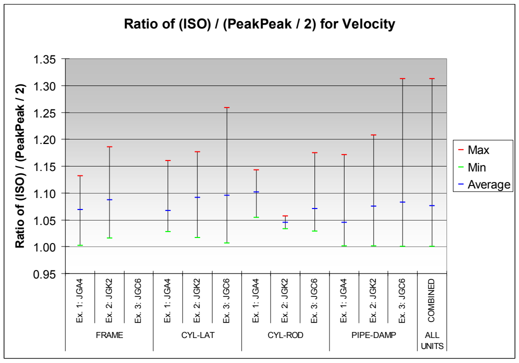


*Figure 8: Comparison of Peak Measurements by Calculation Method*

This observation caused us to calculate all CFs using the ISO definition of peak for this paper. It should be noted that this method will be conservative compared to a PP/2, especially if it is used to calculate a P-P value for fatigue analysis.

## 9. Justification for Crest Factor

Fatigue failures can occur on machinery and piping components. Peak stress is used to predict fatigue-inducing stresses. As a result of this relationship between peak stress and fatigue, peak vibrations (and CF) are valuable for evaluating vibration.

In a previous published paper[2] by Howes, 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 CF was high. The Spectral Guideline used by Howes' company failed to detect this problem. An RMS OA guideline, we assert, would also have failed to predict a problem in this case.

Based on this example, it would seem prudent to consider peak amplitudes as well as either RMS or Spectral measurements when the guideline assessment is at a point in the Marginal Zone.
CF is a convenient way to do this if normal ranges of CF for reciprocating compressor vibrations are known.

## 10. Caution: Pseudo-Peak is a Confusing Term

Over 50 years ago, a major manufacturer of vibration instrumentation created confusion by calculating 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. Vibration analysts are recommended to check their instrumentation to determine if peak or pseudo-peak data is provided.

## 11. Collecting RMS and Spectral Data

For the purpose of measuring overall vibration data on a reciprocating compressor and its associated piping to conform to the EFRC Guideline, the following settings are suggested on a spectrum analyzer:

- Maximum frequency: 1000 Hz (to conform to EFRC Guideline)
- Minimum frequency: 2 Hz (or, if 0, use Standard Deviation instead of RMS OA when using time waveforms to determine RMS OA)
- Flat-top Window (for amplitude accuracy)
- Bins between orders of run speed: at least 6 (to prevent leakage between orders during Spectral RMS calculations)

In our experience, vibration data of interest on reciprocating compressors is usually limited to a maximum frequency of between 200 and 500 Hz. An advantage of using 1000 Hz as a maximum frequency is that the sample period is lower, allowing for faster updates of measurements as compressor speed is varied.

The time period of the sample, based on the recommended settings above, will be significantly greater than one revolution of a reciprocating compressor crankshaft.

Averaging could be used to eliminate some of the low frequency and random components that can be present in real data.

## 12. Conclusion

- The analysis of field data confirms that the EFRC Guidelines based on RMS OA compares favorably to Spectral Guidelines in the velocity region. Either guideline could be used as a screening tool.

- The EFRC Guideline does not currently address small bore piping. A new guideline for small bore piping should be added to the standard. The current pipe guideline should be used for small bore attachments until a formal level is defined. Small bore attachments have the greatest propensity to fail due to fatigue. Typically, these components tend to have CFs at the lower end of the range mentioned above.

This makes the use of RMS OA for small bore piping assessment attractive (simple and reasonably conservative).

- Use of the EFRC displacement limits on dampers (also referred to as bottles) for low speed (below 600 rpm) compressors should be checked against guidelines derived from stress estimates to avoid damper-to-cylinder nozzle failures. Our experience suggests the RMS displacement limits for this special case are too high. More field data analysis is required.

- Use of the EFRC acceleration limits may result in overly conservative assessments of compressor parts.

- The EFRC Guideline currently does not apply to relief valves and other components sensitive to acceleration. In our opinion, another "part" guideline is required, since relief valves are an integral part of all reciprocating compressor installations. We recommend an acceleration guideline for relief valves, etc. as shown in Table 5 below. The velocity guideline should be the same as for piping.

*Table 5: Suggested Relief Valve Guideline*

| Horizontal compressors m/s$^2$ | | | Vertical compressors m/s$^2$ | | |
|---|---|---|---|---|---|
| Key zones | | | Key zones | | |
| A/B | B/C | C/D | A/B | B/C | C/D |
| 8 | 12 | 18 | 8 | 12 | 18 |
| 1.15 g pk | 1.73 g pk | 2.6 g pk | 1.15 g pk | 1.73 g pk | 2.6 g pk |

- CFs for reciprocating compressors and the attached piping tend to be in the range of 2 to 3.5, with an average less than 2.5, typically. RMS OA values near zone boundaries can be assessed further by examining the corresponding CF.

- Limiting overall vibration readings to a frequency band tends to lower the measured CFs.

- Spectral RMS OA values from spectrum analyzers are more accurate (consistent) than time waveform RMS OA values (without filtering or DC removal). RMS data that has not been filtered (below 2 Hz), will likely have mean values in the time waveform that are not zero. Thus, the data should be corrected by using Standard Deviation instead of RMS OA.

- Peak measurements using the ISO and the peak-to-peak/2 methods can give significantly different results. The ISO method will always give higher peak values.

- Instrumentation users should be careful to understand how RMS and peak measurements are calculated. Caution should be exercised when using pseudo-peak overall data (RMS times 1.414).

- Users of spectrum analyzers should test how their instruments calculate RMS OA and peak values against the methods defined in the EFRC Guideline.

## 13. Acknowledgements

The authors wish to thank Michal Gaca, Scott Lylander, and Russ Barss for their assistance preparing this paper.

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