Understanding Discrepancies in Vibration Amplitude Readings Between Different Instruments

Part 2 of 2

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[Editor’s Note: Selected portions of this article were originally published in the March 1994 issue of ORBIT as “Monitoring versus diagnostics — why do peak readings differ?”]
Introduction

In part 1 of this 2-part article, we began an in-depth look at the answer to a question that arises numerous times each year from our customers: “I took a vibration reading with a portable diagnostic instrument, but it does not agree with what I am seeing on my Bently Nevada™ monitor. Why?”

Customers often assume that there must be a problem with the monitor, the diagnostic instrument, or both. However, as explained in part 1 and as repeated here, this is rarely the case. Instead, there are some very straightforward reasons why there are often discrepancies in vibration readings between two instruments — particularly peak-to-peak amplitude readings.

In our previous article (ORBIT Volume 25, Number 2, 2005), we defined four stages of a signal as it travels through a vibration measuring instrument. For convenience, those stages and the corresponding diagram are repeated below as Figure 1.

Figure 1 – By considering the four stages of a signal as it travels through an instrument, it is easier to understand and isolate discrepancies in readings between two devices.
In part 1, we examined stages 1 and 2. Here, we continue by investigating stages 3 and 4. Stage 3 involves the circuits/algorithms used to actually perform the amplitude detection function in a variety of modern vibration instrumentation, and we will explain the differences between these various algorithms. Stage 3 is notable in that it accounts for more discrepancies in readings than any other single factor and is often the aspect least understood by users. As such, we devote a majority of part 2 to educating the reader on this important topic.

We then conclude with a brief discussion of stage 4: calibration/indication issues. Ironically, when customers contact us to report discrepancies in readings between GE’s Bently Nevada™ instruments and those of other manufacturers, they often assume the discrepancies are due to calibration problems or indication malfunctions. However, in our experience, these are actually the least common reasons for discrepancies. Nevertheless, they can affect older analog systems as well as any system that has not been properly configured, and are included in this discussion for completeness.

Measurement Conventions

In part 1, we defined the measurement conventions used for describing a vibration signal’s amplitude in all Bently Nevada™ instrumentation. For ease of reference, we present them once again in Table 1 below and Figure 2 on the next page.

Part 1 also discussed the discrepancies that can occur due to differences in conventions for whether peak readings are defined as pp/2 (as in all Bently Nevada instruments) or as the larger of the waveform’s positive- or negative-going peak. When a waveform is asymmetrical, as in Figure 2B, these differences in conventions will indeed result in discrepancies.

Another facet that we briefly addressed was the convention for determining the RMS amplitude of a signal. There are two primary methods for measuring the RMS amplitude of a generalized waveform. The first is by way of analog circuitry that essentially solves the integral given in Table 1, providing an output proportional to the RMS value of the waveform. This is known as a “true RMS” circuit. However, such a circuit has no way of

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak-to-Peak (pp)</td>
<td>The difference between the maximum positive-going and negative-going peaks in a periodic waveform during one complete cycle.</td>
</tr>
<tr>
<td>Zero-to-Peak (pk)</td>
<td>The pp value of a vibration signal divided by two (pp/2). Also referred to as “true peak.”</td>
</tr>
<tr>
<td>Root Mean Square (RMS)</td>
<td>A measurement of the effective energy content in a signal. Mathematically, the RMS value of a waveform ( f(t) ) is defined as ( A_{RMS} = \sqrt{\frac{1}{T} \int_{t_0}^{t_0+T} f(t)^2 dt} ) where ( T ) is the period (one complete cycle) of the waveform*.</td>
</tr>
</tbody>
</table>

* To accommodate all expected periods in generalized waveform inputs to an instrument, \( T \) is typically chosen for computation purposes to coincide with the lowest frequency measurable by the instrument. Thus, an instrument with a bandwidth down to 0.5 Hz would use \( T = 2 \) seconds.
detecting the period (T) of a single waveform cycle. As such, T becomes the length of the measurement period, rather than a single waveform cycle. T is typically chosen to accommodate the lowest frequency of interest in the instrument’s bandwidth. For example, if the instrument is to handle waveforms with frequency content as low as 0.5 Hz, it will take 2 seconds to compute an accurate RMS value, since the period of a 0.5 Hz wave is 2 seconds. There are also digital emulations of analog RMS circuits, and this is the approach taken in newer Bently Nevada instrumentation.

The other method of RMS detection is digital, but it is not simply a digital emulation of an analog circuit. Instead, it approximates the RMS value of a waveform by quadratically combining the amplitudes of all spectrum lines and then taking the square root. We will examine this digital RMS algorithm in considerably more detail later in this article. For the moment, we will merely point out that it is the basis of digital RMS calculations in many portable data collectors and can vary considerably from the value given by analog RMS circuits, depending on how the user has configured their spectrum sample.

(continued on page 45)

Key Point

The relationship between peak and RMS is commonly denoted as the Crest Factor (CF) where pk = CF x RMS. The CF is not a constant — it is completely dependent upon the shape of the waveform (i.e., frequency and phase content) and will differ between waveform shapes. For example, the CF for a square wave is 1, the CF for a pure sinusoid is 1.414 (i.e., √2), and the CF of the waveform in Figure 2B is 2.06. Do not make the mistake of using a single CF (such as 1.414) to apply to any generalized waveform. Instead, accurate conversion between RMS and pk or pp readings must always use the relationships of Table 1. Many discrepancies in readings can be traced to the erroneous use of a “scaling factor” (such as CF) when converting between pk and RMS. CF must be interpreted in the same way a practitioner would interpret the spectrum of a waveform: it is unique to that waveform.

Figure 2 – Peak-to-peak (pp), zero-to-peak (pk), and RMS are the most commonly used conventions for expressing the amplitude of vibration waveforms. The conversion between RMS and pk is only equal to 0.707 for a pure sine wave (A). For a more complex signal (B), the equation of Table 1 must be used to compute the RMS value. The conversion between pp and pk can differ between manufacturers and becomes apparent if the waveform is asymmetrical (B). When using the Bently Nevada instrumentation convention of pk = pp/2, the pk value may not be equal to either the positive or negative peaks on an asymmetrical waveform.
The origins of RMS as a way of describing a signal’s amplitude lie in electrical engineering, where a method was needed to compare an ac signal’s ability to deliver power with that of a dc signal. Thus, an ac signal with an RMS value of 1 volt will deliver the same power to a resistive load as will a 1 volt dc battery. RMS is so widely used in electrical engineering that ac signals involved in power utilization are almost always denoted in terms of their RMS values. For example, the 110/220 Vac conventions used for residential wiring worldwide are RMS voltages. This corresponds to 156 and 311 Vac pk respectively. In fact, many voltmeters and multi-meters are designed to measure signal amplitude in terms of RMS values, while also providing a peak amplitude setting. When using such meters in conjunction with vibration measurements, it is important to understand if the meter provides true peak and RMS measurements, or if it simply converts between pk and RMS using the factor 1.414. While such conversions are suitable for applications involving pure sinusoids (such as residential wiring with minimal “noise”), they do not hold true for generalized waveforms, or even for conventional 60 or 50 Hz power where appreciable noise is present.

A very common mistake made by practitioners when calibrating or verifying the operation of vibration instruments is to measure the signal amplitude using a voltmeter or other instrument that returns an RMS value, and then erroneously convert to a “peak” amplitude by multiplying this RMS value by 1.414. Unless the signal of interest is a pure sinusoid (such as the vibration signal filtered to only its 1X component), the relationship pk = RMS x 1.414 does not hold true.

A simple test to determine whether your instrument uses a “scaled RMS” or a “true peak” measurement is to input a square wave using a signal generator. This waveform is chosen because it is comprised of complex frequency components and is also the only waveform that has identical pk and RMS values. Adjust the amplitude on the signal generator to 2 volts pp (1 volt pk) as observed on an oscilloscope. Also, be sure to adjust the frequency of the waveform so that it is well within the bandwidth of your instrument (we recommend using a square wave frequency at least 25 times less than the frequency response of your instrument, due to the importance of the higher harmonics in representing a square wave faithfully). Make a note of your instrument’s scale factor and observe the reading. For example, if your instrument has a scale factor of 100 mV/in/sec pk and you input the square wave above, you will observe approximately the following values:

“True Peak” circuit: 1 volt pk ÷ 100 mV/in/sec = 10 in/sec

“Scaled RMS” circuit: (1 volt rms ÷ 100 mV/in/sec) x 1.414 scaling factor = 14.14 in/sec

Do not use a pure sinusoid to conduct such tests, as this waveform will always produce the same results whether your instrument uses a “true peak” circuit or a “derived peak” circuit, as shown below:

“True Peak” circuit: 1 volt pk ÷ 100 mV/in/sec = 10 in/sec

“Scaled RMS” circuit: (0.707 volt rms ÷ 100 mV/in/sec) x 1.414 scaling factor = 10 in/sec
Dissimilar Amplitude Detection Algorithms

We divide our discussion here into two parts: amplitude detection used in GE’s Bently Nevada instrumentation, and amplitude detection used in other instrumentation.

Bently Nevada Peak Detection

All true peak-to-peak (pp) detectors have fundamental performance factors that affect their ability to respond to various input waveforms. These performance factors are the same whether the circuit is analog or digital in nature and regardless of whether the circuit displays pk or pp readings. During the nearly fifty years that we have been producing Bently Nevada instruments, two basic types of pp detectors have been employed in these products to measure vibration. One type of pp detector is reserved for monitor systems such as 3500 and 3300, while the other type is used in diagnostic instruments such as the ADRE® System. These different detectors are used because of the different uses of the instruments (see sidebar at right).

There is no difference in the measurement of peak-to-peak between a Bently Nevada monitor and diagnostic instrument (within the device’s frequency response) when both are measuring “clean” waveforms. The chief differences are exhibited when processing waveforms with transient noise.

1. Monitor pp Detection

First, we consider the circuit used in Bently Nevada monitors. These systems have evolved to provide extremely reliable machine monitoring. This relies, in part, on the monitor’s ability to perform the pp detection function while minimizing susceptibility to noise. Originally, this was achieved by using analog circuits consisting of diodes, resistors, and capacitors. The resistor-capacitor (RC) components gave such circuits distinctive charge/discharge time constants. Today’s systems use digital technology; however, they have been intentionally designed to emulate the response of these older analog pp circuits, providing

Monitoring Versus Diagnostics

Depending on the instrument’s primary purpose, different philosophies are employed in GE’s Bently Nevada™ product line regarding signal processing. For purposes of this article, we can divide vibration-measuring instruments into two broad categories: diagnostic instruments and continuous monitoring instruments*.

For diagnostic instruments, the goal is to provide a measurement similar to what would be observed on an oscilloscope, tracking all information in a transducer signal regardless of origin. The objective is to facilitate detailed diagnostics, allowing the engineer to ascertain everything present in the signal, whether it is actual mechanical vibration, electromagnetic interference, scratches on the shaft, or anything else. Diagnostic instruments generally take a limited duration “snapshot” of the signal. The signal during that particular window of time is processed through an analog circuit or, more commonly with modern instruments, a digital algorithm that provides the signal attribute of interest, such as frequency components or waveform amplitude.

In contrast, a continuous monitoring system has a continuous stream of input data and is expected to provide a continuous output, generally an indication of the overall vibration amplitude used for comparison against alarm setpoints to help protect the machine. For continuous monitoring instruments, the goal is to faithfully represent the actual mechanical vibration present, but to incorporate signal processing techniques that improve the system’s immunity to spurious signals — such as transient noise — that would result in false alarms or trips.

To reflect these differences in applications, distinctly different peak-to-peak detection circuits are employed.

* Our Snapshot™ family of portable data collectors actually uses a slightly different algorithm for peak detection than either our monitors or diagnostic instruments. However, it generally emulates the response of our monitoring systems, allowing pk and pp readings from our data collectors to agree closely with that of our monitoring systems for most waveforms.
consistency between various historic and current monitoring systems, and ensuring that a retrofit from an older system to a newer system will produce the same readings.

The response of this type of peak-to-peak detector is shown in Figure 3. This type of detector continually processes the incoming signal. Its output is constantly adjusted based on the instantaneous value of the incoming signal and the circuit’s memory of past peaks. When the input signal exceeds the circuit’s memory of past peaks, the output increases. We describe this as “charging.” When the input signal is less than the current memory of the past peaks, the output decreases. We call this “discharging.”

These charge and discharge cycles work as follows:

— **Monitor Charge Cycle**

Analog pp detector circuits used in older Bently Nevada monitors used a peak capacitor. The rate at which this capacitor could be charged was limited, based on the circuit design, and the detector circuit would respond to a new peak at a rate of approximately 5% of the monitor’s full scale value per millisecond. For example, a monitor with a 10 mil full scale would see a maximum rate of change in its pp detector of approximately 0.5 mils per millisecond. This controlled charge rate has the benefit of reducing the pp detector’s response to transient and high frequency noise. Because of the design’s success, we haven’t changed this characteristic of our pp detection circuits over the years, even though it is technically feasible. Today, of course, the design is realized digitally, rather than with analog components, but the fundamental response of today’s digital monitors was intentionally modeled to replicate these older analog circuits.

A result of this limited charging rate is that frequencies with periods of less than 1 millisecond require multiple cycles to “charge” the detector to the input pp value. For example, the pp detector would require approximately 20 cycles to charge to within 1% of its final value if the input were a 1 kHz sine wave.

CUSTOMERS OFTEN **ASSUME THE DISCREPANCIES ARE DUE TO CALIBRATION PROBLEMS OR INDICATION MALFUNCTIONS. HOWEVER, IN OUR EXPERIENCE, THESE ARE ACTUALLY THE LEAST COMMON REASONS FOR DISCREPANCIES.**
Monitor Discharge Cycle

If the input signal goes to zero, the peak value will discharge to zero after a certain period of time. The time it takes the circuit to discharge to within 37% of its final value is described as the discharge time constant. Monitoring circuits use two different discharge time constants. The first discharge time constant is the most common. It is used on all monitors optioned for use with seismic transducers and on radial vibration monitors with a low-pass frequency response of 240 cpm. This time constant is approximately 1 second. A longer time constant of 4 seconds is used only on radial vibration monitors with a low-pass frequency response of 60 cpm for very low speed machines. This time constant allows the pp detector to “remember” past peaks for a longer time period.

Figure 3 – The response of the peak-to-peak detection circuit as used in all Bently Nevada monitors (with exception of selected eccentricity and low-frequency monitors). Note the circuit’s slow response to the highest amplitude spikes in the input waveform, indicative of transient noise.
2. Diagnostic pp Detection

The pp detectors used in Bently Nevada diagnostic instruments are designed to calculate peak-to-peak with results equal to what would be seen on an oscilloscope. The goal is to track all information in a transducer signal, regardless of its origin. This type of detector’s performance has continually improved over time based on available technology, providing faster and more accurate results. For example, the newly introduced ADRE system (see page 60 in ORBIT Volume 25 Number 2, 2005) features the most sophisticated pp detection circuit we have ever been able to offer.

Bently Nevada diagnostic instruments sample the input for a specific duration or for a set number of shaft rotations. They take a “snapshot” of the signal during this time period, in contrast to a monitor which is constantly providing a value proportional to the current input based on the past inputs. Thus, the diagnostic instrument works very differently during its “charge” and “discharge” cycles, and its response is shown in Figure 4.

These charge and discharge cycles work as follows:

— Diagnostic Charge Cycle

During its charge cycle, the diagnostic instrument’s pp detector charges much faster than the monitor’s.
detector. In fact, while a monitor’s circuit is intentionally designed to have a finite charge rate that helps reject spurious signal content, the goal of a diagnostic instrument is to have an infinitely fast charge rate, allowing it to capture any part of a signal, no matter how fast it is changing. Typically, our diagnostic instruments have a pp detector that charges at a rate 20 times faster than a monitor’s pp detection circuit. This makes the diagnostic instrument very responsive to most signals.

— Diagnostic Discharge Cycle

During the discharge cycle, diagnostic instruments completely discharge their pp detectors at a set interval or based on a Keyphasor® pulse. The pp value from such a circuit discharges instantly, prior to each new “snapshot” of the input signal.

By comparing Figures 3 and 4, the differences between the pp detection circuit of a monitor (such as 3500) and of a diagnostic instrument (such as ADRE) are readily apparent.

As a final note, recall that the convention used for peak detection in all Bently Nevada instruments is simply the pp value divided by two. Thus, even those monitors that do not provide a pp display option (such as from velocity or acceleration transducers) use the same fundamental peak-to-peak detection circuitry as described above. The peak reading is simply returned as one-half the pp value.

Next, we turn to the question of amplitude detection algorithms used in instruments made by other manufacturers.
Peak Detection in Other Instruments

Earlier, we explained that a true RMS reading must emulate the integral shown in Table 1 if it is to be valid for all waveform types. Also, even if the RMS detection itself is quite accurate, it is not appropriate to simply multiply the RMS value by 1.414 to obtain a true peak value, as this relationship only holds true for a pure sine wave.

Nevertheless, early portable data collection instruments often provided a peak reading that was simply the RMS value x 1.414. Later, more options for waveform amplitude determination were added, but by then, many analysts had become accustomed to this so-called “derived peak” reading and had large databases of historical trends that they did not want to abandon. Thus, the measurement was retained and is present in many data collectors and other instruments under various names. Our purpose here is not to argue for or against the use of this measurement as a trending tool. It is merely to point out that it will bear little or no resemblance to the true peak value of a waveform as observed in a timebase display, on an oscilloscope, or from a Bently Nevada monitor.

Recognizing this, many manufacturers began providing multiple amplitude detection options. For example, the CSI® 2120 and 2120-2 machinery analyzers provide options summarized in Table 2.

Table 3 provides a similar summary, showing nomenclature used by selected instruments in Rockwell Automation’s Entek® and Entek IRD® product lines.

Table 2 – OVERALL WAVEFORM AMPLITUDE DETECTION OPTIONS FOR CSI® 2120 MACHINERY ANALYZERS

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Description</th>
<th>Comparison to Bently Nevada Instrumentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digital Overall</td>
<td>The RMS value as calculated by quadratically adding spectral lines, encompassing only the frequency span selected for the spectrum.</td>
<td>Will not agree with pk or pp readings from a Bently Nevada monitor, even if a scaling factor of 1.414 or 2.828 is used. May not generally agree with RMS readings from a Bently Nevada monitor unless bandwidth of both instruments is set equally.</td>
</tr>
<tr>
<td>Analog Overall</td>
<td>The RMS value as measured by an analog RMS-to-DC circuit, encompassing the full bandwidth of the instrument.</td>
<td>Will not agree with pk or pp readings from a Bently Nevada monitor, even if scaling factor of 1.414 or 2.828 is used. May agree reasonably closely with RMS readings from a Bently Nevada monitor, depending on bandwidth settings.</td>
</tr>
<tr>
<td>True Peak Overall</td>
<td>The maximum positive-going or negative-going peak within the time waveform for the specified sample duration.</td>
<td>May not agree with the pk reading from a Bently Nevada monitor, as this type of algorithm more closely resembles those used in Bently Nevada diagnostic instruments. Also, differs from the Bently Nevada convention of pk = pp/2 which will create discrepancies if the waveform is asymmetrical.</td>
</tr>
<tr>
<td>Average Peak Overall</td>
<td>The average of the “true peak overall” calculated by the data collector for a specified number of sample blocks.</td>
<td>May agree more closely with the pk reading from a Bently Nevada monitor, since the algorithm is less responsive to “spikes” in the waveform through its averaging operation. However, the algorithm does not emulate the charge/discharge algorithms used in Bently Nevada monitors (figure 3) and discrepancies may still exist.</td>
</tr>
</tbody>
</table>

Sources:
Reference Manual for CSI 2120 and Model 2120-2 Machinery Analyzers, CSI part number 970047, Rev. 5.
Overall Calculation Computation by the CSI 2100-2120 Data Collectors, Technical Note 95-00314, Emerson Process Management.
While space does not permit us to provide similar summaries for all of the numerous data collectors and other vibration measuring instruments in use today, the reader will generally be able to extrapolate similar comparisons using the information in this article and by consulting the documentation supplied with their instrumentation.

**Computing RMS from Spectral Component Amplitudes**

Although not used in Bently Nevada instrumentation, many portable data collection instruments employ a method for computing RMS by quadratically adding spectral line amplitudes (i.e., adding the squares and taking the square root of the sum). This is shown mathematically in equation 1

\[ A_{RMS} = \sqrt{\sum_{n=1}^{k} A_n^2} \]  \[1\]

where \(A_{RMS}\) is the RMS amplitude of the composite waveform resulting from the spectral components, \(k\) is the number of lines in the spectrum, and \(A_n\) is the RMS amplitude of each spectral line. Indeed, this is precisely the algorithm used by the CSI® 2120 for computing “Digital Overall” and by selected Entek®/Entek IRD® instruments for computing “FFT Overall.”

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**Table 3 – OVERALL WAVEFORM AMPLITUDE DETECTION OPTIONS FOR SELECTED ENTEK® AND ENTEK IRD® INSTRUMENTS**

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Description</th>
<th>Comparison to Bently Nevada Instrumentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFT Overall</td>
<td>RMS x 1.414 where the RMS value is calculated by quadratically adding spectral lines, encompassing only the frequency span selected for the spectrum.</td>
<td>Will not agree with pk or pp readings from a Bently Nevada monitor, since it is a “derived peak” measurement.</td>
</tr>
<tr>
<td>RMS Overall</td>
<td>The RMS value calculated using all sampled points in the timebase waveform. Gives results closer to that of an analog RMS circuit.</td>
<td>Will not agree with pk or pp readings from a Bently Nevada monitor, even if scaling factor of 1.414 or 2.828 is used. May agree reasonably closely with RMS readings from a Bently Nevada monitor, depending on bandwidth settings.</td>
</tr>
<tr>
<td>Peak Overall</td>
<td>RMS Overall x 1.414</td>
<td>Will not agree with pk readings from a Bently Nevada monitor. Peak Overall ÷ 1.414 may agree reasonably closely with RMS readings from a Bently Nevada monitor, depending on bandwidth settings.</td>
</tr>
<tr>
<td>Peak-to-Peak Overall</td>
<td>The difference between the maximum positive-going and negative-going peaks within the time waveform for the specified sample duration.</td>
<td>May not agree with the pp reading from a Bently Nevada monitor depending on high-frequency content of signal, as this type of algorithm more closely resembles those used in Bently Nevada diagnostic instruments.</td>
</tr>
</tbody>
</table>

**Sources:**

APPLICATIONS

To illustrate the use of equation (1), consider the waveform of Figure 5. The mathematical representation of this waveform given by

\[ f(t) = \sin(\omega t) + \sin(2\omega t + \frac{\pi}{2}) + \sin(5\omega t + \frac{\pi}{4}) \]  

where \( \omega \) is 200\(\pi \) radians per second and \( t \) is in seconds.

The RMS value of this waveform can be computed using the "true RMS" method, which employs the integral of Table 1.

\[ A_{RMS} = \sqrt{\frac{1}{T} \int_{0}^{T} (f(t))^2 \, dt} = \sqrt{\frac{1}{T} \int_{0}^{T} \left( \sin(\omega t) + \sin(2\omega t + \frac{\pi}{2}) + \sin(5\omega t + \frac{\pi}{4}) \right)^2 \, dt} \]  

However, since this waveform consists of only three sinusoids, it can be fully characterized by the simple 3-line spectrum shown in Figure 5. This means that equation (1) can be easily used.

Thus, noting that the pk amplitude of each spectral line is 1 and because each spectral line is a pure sinusoid with RMS amplitude pk/\( \sqrt{2} \), we use Equation 1 as follows:

\[ A_{RMS} = \sqrt{\sum_{n=0}^{3} A_n^2} = \sqrt{\sum_{n=1}^{3} A_n^2} = \sqrt{\left( \frac{A_1}{\sqrt{2}} \right)^2 + \left( \frac{A_2}{\sqrt{2}} \right)^2 + \left( \frac{A_3}{\sqrt{2}} \right)^2} = \sqrt{\left( \frac{1.0}{\sqrt{2}} \right)^2 + \left( \frac{1.0}{\sqrt{2}} \right)^2 + \left( \frac{1.0}{\sqrt{2}} \right)^2} = \sqrt{3} = 1.2247 \]  

This simple example was chosen because it allows the reader to better understand the inner workings of the digital algorithm. In this instance, the values computed by equation 1 and a "true RMS" circuit would be the same — equation 1 introduces no discrepancies since it uses a spectrum containing all frequencies present in the original waveform. However, in practice such situations are rare and users will generally see different results between "true RMS" and so-called "digital RMS" because the digital computation of equation [1] introduces inaccuracies in two primary ways:

A. Anti-alias filtering and/or frequency span settings may remove some high-frequency signal content. Thus, the spectrum does not faithfully represent the original waveform.

B. The spectral resolution, if too low, can "blend" discrete frequencies together.

In general, the higher the spectral resolution and the wider the spectrum bandwidth, the more accurate the digital RMS algorithm of equation [1] will be.

We have devoted a considerable portion of this article to a discussion of this "digital RMS" algorithm because it forms the basis of numerous amplitude detection options in portable data collectors. For example, consider a user of selected Entek® portable data collectors who has set their instrument to return an "FFT Overall" (see Table 3) value. The algorithm would first compute the RMS value as shown in equation [4] above. Then, it would multiply this result by 1.414 to obtain an "FFT Overall" amplitude of 1.2247 \( \times \) 1.414 = 1.73. For comparison, the actual 0-pk value of the waveform in Figure 5 is 2.52, once again underscoring the complete absence of any relationship between "true peak" and "scaled RMS" readings for waveforms with more than a single sinusoid.
We often see inquiries from users that assume the term “overall” is a type of peak reading — particularly when a factor of 1.414 is used in the computation. As pointed out earlier, this results in much confusion. Such readings are simply “scaled RMS” amplitudes and bear no relationship to actual peak readings. It does not matter how accurate (or inaccurate) the underlying RMS measurement may be — it is simply not possible to scale an RMS reading into a peak reading except in the very special case of an input signal that is a pure sinusoid.

Figure 5 – Because this waveform consists of only 3 sinusoids, a spectrum with 3 lines is all that is necessary to fully characterize the wave. However, both amplitude and phase spectra are essential to properly characterize the time domain waveform. As was shown in Part 1 of this article, identical amplitude spectra can yield very different time domain waveforms if the phase relationships differ.
Table 4 summarizes the amplitudes that would be returned by various portable data collectors for the asymmetric waveform of Figure 5. It assumes the data collector frequency span fully encompasses the frequency content of the original waveform (100 Hz – 500 Hz).

As is evident from Table 4, significant discrepancies exist, even for this simple waveform consisting of only three frequencies. Users can expect a similar level of disagreement between readings when using real-world vibration signals. Also, unlike our example here, the digital and analog RMS values will rarely agree with one for the reasons previously detailed.

**Case History**

A user of a Bently Nevada™ 1900/27 monitor contacted us recently, complaining that the monitor did not agree with their CSI® 2120 data collector. The customer was connecting the data collector to the buffered output on the 1900/27 monitor, so the same transducer input was being used in both instruments. However, the readings were still vastly different.

**Table 4 –**

<table>
<thead>
<tr>
<th>Detection Algorithm</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bently Nevada monitor pk detector (pp/2)</td>
<td>5.05/2 = 2.525</td>
</tr>
<tr>
<td>Bently Nevada monitor RMS detector</td>
<td>1.2247</td>
</tr>
<tr>
<td>CSI digital overall</td>
<td>1.2247</td>
</tr>
<tr>
<td>CSI analog overall</td>
<td>1.2247</td>
</tr>
<tr>
<td>CSI true peak overall</td>
<td>3.00 (negative peak &gt; positive peak)</td>
</tr>
<tr>
<td>CSI average peak overall</td>
<td>3.00 (negative peak &gt; positive peak)</td>
</tr>
<tr>
<td>Entek FFT overall</td>
<td>1.73 (spectral RMS x √2)</td>
</tr>
<tr>
<td>Entek RMS overall</td>
<td>1.2247</td>
</tr>
<tr>
<td>Entek peak overall</td>
<td>1.73 (RMS overall x √2)</td>
</tr>
<tr>
<td>Entek peak-to-peak overall</td>
<td>5.05</td>
</tr>
</tbody>
</table>

**Table 5 –**

<table>
<thead>
<tr>
<th>Options</th>
<th>Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor type</td>
<td>Bently Nevada™ 200150 Accelerometer</td>
</tr>
<tr>
<td>Integration</td>
<td>Accel – to – Velocity</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>500 mV/in/sec (19.7 mV/mm/sec)</td>
</tr>
<tr>
<td>Display</td>
<td>Velocity – Peak (mm/sec)</td>
</tr>
<tr>
<td>Full-Scale Range</td>
<td>50.8 mm/sec</td>
</tr>
<tr>
<td>Buffered Output Signal</td>
<td>Raw Velocity 500 mV/mm/sec (19.7 mV/mm/sec)</td>
</tr>
<tr>
<td>Buffered Output Impedance</td>
<td>500 Ω</td>
</tr>
<tr>
<td>Passband</td>
<td>8 Hz – 4kHz</td>
</tr>
</tbody>
</table>
To help resolve the discrepancy, we asked the customer to send us the complete configuration settings for their data collector (Table 6), allowing us to compare with the configuration settings for the 1900/27 (Table 5).

Comparing the two tables, the following discrepancies are apparent:

- The 1900/27 monitor accepts an acceleration signal and integrates this to a velocity signal. The buffered output on the 1900/27 provides this unfiltered velocity signal — NOT an acceleration signal. The CSI® data collector was incorrectly set to receive an acceleration signal and integrate this signal to velocity units. It should have been set for a velocity input without integration.

- The buffered output sensitivity of the 1900/27 was 500 mV/in/sec (or 19.7 mV/mm/sec). The data collector was correctly set for metric engineering units of mm/sec, but it incorrectly assumed an input of 0.5 V (500 mV) per engineering unit. This should have instead been 0.0197 V (19.7 mV) per engineering unit.

- The data collector was set to return a value in peak units, using the digital algorithm. It should have instead been set to return a value in peak units, using the “average peak” algorithm.

This case history is typical of many such inquiries we receive each year in that the discrepancy in readings is often due to multiple issues. In this case, and referring back to Figure 1, the issues fell into three of our four categories:

- **Category 1 — Input Discrepancies**
  The input transducer sensitivity was not set consistently across both instruments, even though the same transducer was used.

- **Category 2 — Signal Processing Discrepancies**
  The data collector was adding an additional integration stage to the signal, resulting in integrated velocity, rather than just velocity.

### Table 6 –
**CSI® 2120 CONFIGURATION SETTINGS**

<table>
<thead>
<tr>
<th>Options</th>
<th>Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration:</td>
<td>pk-pk, Average, DB, RMS, Peak:</td>
</tr>
<tr>
<td></td>
<td>Digital, True Peak, Average Peak</td>
</tr>
<tr>
<td>Peak: Digital</td>
<td></td>
</tr>
<tr>
<td>Velocity:</td>
<td>pk-pk, Average, DB, RMS, Peak:</td>
</tr>
<tr>
<td></td>
<td>Digital, True Peak, Average Peak</td>
</tr>
<tr>
<td>Peak: Digital</td>
<td></td>
</tr>
<tr>
<td>Displacement:</td>
<td>pk-pk, Average, DB, RMS, Peak:</td>
</tr>
<tr>
<td></td>
<td>Digital, True Peak, Average Peak</td>
</tr>
<tr>
<td>Avg: Digital</td>
<td></td>
</tr>
<tr>
<td>Nonstandard:</td>
<td>pk-pk, Average, DB, RMS, Peak:</td>
</tr>
<tr>
<td></td>
<td>Digital, True Peak, Average Peak</td>
</tr>
<tr>
<td>Avg: Digital</td>
<td></td>
</tr>
<tr>
<td>Units Mode:</td>
<td>Metric, English: CPM, Hz</td>
</tr>
<tr>
<td></td>
<td>Metric: CPM</td>
</tr>
<tr>
<td>Sensor Type:</td>
<td>Accel, Vel, Displ, Michphn, Currnt, Flix lf, Nonstd</td>
</tr>
<tr>
<td>Convert to:</td>
<td>----, Accel, Veloc, Displ</td>
</tr>
<tr>
<td>Sensitivity (Sensor, V/EU):</td>
<td>Users Option</td>
</tr>
<tr>
<td>Units:</td>
<td>Standard</td>
</tr>
<tr>
<td></td>
<td>Standard</td>
</tr>
<tr>
<td>Window:</td>
<td>Hanning or Uniform</td>
</tr>
<tr>
<td>Integration Mode:</td>
<td>Analog or Digital</td>
</tr>
<tr>
<td>Average Mode:</td>
<td>Normal or (pk Hold, Synchronous, Order-Track, Neg-VE Avrg)</td>
</tr>
<tr>
<td>Trig Mode:</td>
<td>Off or (Normal, Tach, Pre-Trig, Pre-Tach)</td>
</tr>
<tr>
<td>Triax Ctrl:</td>
<td>Off or (Select Ch)</td>
</tr>
<tr>
<td>Input Impedance:</td>
<td>&gt; 125 kΩ</td>
</tr>
</tbody>
</table>
Oscilloscopes Don’t Lie

One of the easiest and fastest ways to settle a dispute when someone insists that one instrument is “right” and another instrument is “wrong” is to use an oscilloscope. Typically, oscilloscopes have a frequency response much higher than the signals encountered in machinery vibration analysis — sometimes into the GHz range. Likewise, they are able to measure very low frequencies accurately — all the way down to DC. This extremely broad and flat frequency response makes the oscilloscope much less prone to errors than portable vibration analyzers/collectors, which are subject to numerous configuration settings. Thus, do not make the mistake of using a portable data collector/analyzer as a substitute for an oscilloscope when conducting the steps below.

• **Step 1**
  Connect the oscilloscope to the buffered output of the monitoring system.

• **Step 2**
  Set the scope to the appropriate input sensitivity. For example, if the transducer used with the Bently Nevada monitoring system is a proximity probe, the buffered output sensitivity will typically be 200 mV/mil. Thus, setting the scope to .2V/div corresponds to 1 mil per division.

• **Step 3**
  Adjust the time scale appropriately (generally to see 3-4 complete cycles of the waveform on the screen).

• **Step 4**
  Observe the maximum positive-going and negative-going peaks. The pp value is simply the difference between the positive and negative peaks, and should agree closely with the amplitude displayed on the monitor (assuming it is a radial vibration monitor for a proximity probe, which measures pp amplitude). If the monitor has a seismic transducer as an input and is measuring pk (rather than pp) amplitude, this is simply one-half the pp value observed on the scope.

If the monitor and scope do not agree, then one of four things is usually wrong:

1. The monitor is filtering and/or integrating the signal, and this is not reflected at the buffered output.

2. The sensitivity of the buffered output (mV per engineering units) does not match the assumptions made on the scope settings. If necessary, check the transducer itself for the output sensitivity. This is generally printed on the label for seismic transducers, and on the Proximitor® sensor for Bently Nevada proximity probe systems.

3. The monitor is out of calibration.

4. The monitor is configured incorrectly.

If the monitor and scope do agree, then you can either disconnect the scope, or — if a t-connector is available — you can simultaneously connect the scope and a portable data collector/analyzer to the buffered output. If your data collector does not match the pp (or pk) amplitude displayed on the scope, then you know that your data collector is either configured incorrectly, out of calibration, or both. Remember: scopes don’t lie.

As a final note, be sure to use either a real vibration signal (preferred) or a complex waveform (such as a triangle wave from a function generator) when conducting such tests. A common mistake is to introduce a pure sine wave into the monitor and data collector as the “reference signal.” A pure sine wave is a special case of most of the amplitude detection algorithms and they will generally all agree closely when such an input is used. Use of a pure sinusoid is an exercise in frustration because it will often give very good agreement between instruments during the “test,” but wide discrepancies will return once a “real” vibration signal is introduced. This is because a pure sinusoid is almost never representative of real-world vibration.
• **Category 3 — Amplitude Detection Algorithm Discrepancies**

The data collector was using a peak detection algorithm that was not designed to emulate that of a Bently Nevada monitor. It should have instead used “Peak: Average Peak.”

Not surprisingly, the plant was observing readings between their data collector and 1900/27 monitor that bore absolutely no resemblance to one another. After conferring with us and adjusting their data collector configuration settings, the two devices agreed much more closely with one another.

**Calibration/Indication Issues**

For reasons the authors have never fully understood, users seem much more inclined to believe that their permanent monitoring system is faulty than to doubt the veracity of their portable data collector. Perhaps this is because they are using their data collectors on an almost daily basis, and the monitoring panel is consulted only occasionally. However, it is not necessary to pit one device against the other. It is very rare that discrepancies are due to a fault in the instrumentation. Instead, it is frequently the case that inputs, signal processing, and amplitude algorithms are not consistent between the two instruments.

There are occasions when calibration will drift over time, leading to erroneous measurements. This was a larger problem on older analog instrumentation, particularly on those that used electro-mechanical meter movements. It is less of a problem on digital instrumentation, but can still arise — typically not because of calibration drifts, but because of incorrect configuration settings, as was shown in the case history above.

**Summary**

In this 2-part article we have shown that a systematic method exists for comparing the signal amplitude computed by two instruments and understanding why the readings may not agree with one another. This is most conveniently done by breaking down the analysis into the following four categories:

- Consistency of inputs
- Consistency of signal processing
- Consistency of amplitude detection algorithms
- Calibration/Indication

Differences in any one of these will lead to discrepancies in readings, and many field cases in which users have complained of disagreement between two instruments have involved inconsistencies in multiple categories. For example, the case history used in this article had discrepancies in three of the four categories. Only when these were resolved did the instruments give close agreement in readings.

One of the most common problems seen in the field is the use of amplitude detection algorithms that do not properly emulate the algorithms used in GE’s Bently Nevada™ family of products. In particular, many data collectors are capable of returning values that are either scaled or un-scaled variations of RMS (Root Mean Square) amplitude measurements. This article has shown that such measurements have no correlation to the peak values typically returned by Bently Nevada monitors, except in the very special case of a pure sinusoid (which is almost never indicative of real-world vibration). In situations where RMS values are returned by the monitor, discrepancies can still exist due to differences in algorithms; however, they are often less dramatic than when users try to compare pk or pp values between instruments.

By understanding and applying the principles outlined in this article, users will be able to identify, isolate, and rectify the vast majority of discrepancies in readings between permanent monitoring systems and portable instruments.