Time Waveform Analysis
(In the beginning)

William T. Pryor III
Technical Director
PdM Solutions, Inc.
715 Twining Road, Suite 135
Dresher, PA 19025
bill.pryor@pdmsolutions.com

Abstract: The basic concepts necessary to begin using the time waveform for analysis will be presented. This presentation will be directed toward the analyst who is just beginning to use the time waveform as a diagnostic tool. This paper will present basic waveform terminology, data acquisition considerations, and introduction to diagnostics utilizing the waveform. Diagnostics will include measurement of level, frequency, shape, phase, and comparative measurements. Waveform data will be presented along with spectral data where appropriate.

Key Words: Time Waveform, Phase, Spectrum, Comparative Analysis, Overall level, RMS, Derived Peak, True Peak, Period, Frequency, Harmonic, Periodic

Introduction: How is the time waveform used for analysis? How do I interpret the time waveform? Where can I go to get information on waveform analysis? Are there any courses on time waveform analysis? These questions continue to be some of the most commonly asked in the vibration analysis community and not just from individuals who are new to the field. There are many experienced analysts who do not use the time waveform as part of their day to day analysis and there are those who do not even collect it as part of their PdM program. Some analysts only consider collecting the waveform as part of "advanced troubleshooting". This is especially interesting considering that everything we use for machinery analysis starts with the time waveform.

Overall level, spectrum, and phase are all derived from waveform processing, so why is it that the waveform is not one of our primary diagnostic tools? The most likely answer is that the analyst cannot go directly to a chart, table, cheat sheet, or use some rule of thumb to get an answer in 10 seconds or less. But is the quick answer always right? Do we have all the information we need to fully assess the situation and condition? If we are paying attention, we soon find out that we are not seeing a complete picture if we are only using these tools. As a result it becomes apparent that we need something else to help answer our questions or at least improve on our best guess. In many cases this missing piece of information can be found in time waveform evaluation.

As in every aspect of vibration analysis we find that we cannot use just one tool to measure, analyze, and solve every machinery malfunction. We need to utilize different transducers, different data collection devices, different analysis techniques, and presentations based on the malfunction or condition being evaluated. For this paper we will concentrate on steady state analysis utilizing a hand held data collection device. However the techniques discussed can be applied to other digital collection devices as well.

For steady state analysis the 4 primary diagnostic tools we have using a data collector are:

1) Overall Level
2) Frequency Analysis
3) Waveform Analysis
4) Phase

What happens in many cases is that the beginning analyst gets their initial (sometimes final) vibration analysis training as part of the PdM software and data collector purchase. In most cases this introduction deals with level and frequency of common machinery malfunctions. Phase may be discussed as part of balancing but not discussed as a diagnostic tool. Thus, there is no initial exposure or discussion on the uses and importance of waveform shape analysis and phase as a diagnostic tool. Hopefully, we can provide an initial introduction to these important diagnostic tools.

What we will find is that using the time waveform, while not difficult, requires the analyst to do slightly more evaluation, a little interpretation, use their experience, and maybe even have to perform a couple of calculations. While it may take a little time to develop a comfort level with their use, adding the waveform to the bag of diagnostic tools used on a daily basis can pay big dividends. Maybe we will even become better analysts in the process.

Waveform Data Collection: All instrumentation being developed today is performing digital sampling of the data. As a result we need to understand the digital sampling process in order to obtain the desired result. As with spectral analysis where we have to be concerned with Fmax, Lines of Resolution, and Window Functions to ensure we are making a proper measurement, sampling considerations have to be made to ensure the time waveform is representative of the machine response.

For time waveform sampling our goal is to maximize the number of samples made per shaft revolution (# Samples/Revolution). Using a data collector as our sampling device we can control this by varying # of Lines and the Fmax that we select. We also need to take into account that our final goal will be to produce a waveform which would closely approximate a wave which is completely unfiltered. This means that we have to sample at a high enough frequency to capture all components which are present. Selecting an Fmax which is to low will result in loss of high frequency components above the cut off frequency selected. As a secondary goal we may also want to select a sampling time span which will limit the number of revolutions we capture in order to make our evaluation of the waveform more direct.

Let’s begin this process by looking at the time it takes for 1 revolution of the shaft to occur and make a decision that we would like to display between 5 and 10 revolutions on our final plot. To calculate the time it takes for 1 revolution to occur we will need to perform the following calculation.

$$\frac{Seconds}{Revolution} = \frac{1\ second}{Machine\ speed\ Hz.} = \frac{60\ Seconds}{RPM}$$

So for an 1800 RPM machine we will get the following result:

$$\frac{Seconds}{Revolution} = \frac{1\ second}{30\ Hz.} = \frac{60\ Seconds}{1800\ RPM} = 0.033\ sec/rev$$

So if our end result is to display between 5 and 10 shaft revolutions on our resulting plot we will need to collect between 0.167 seconds and 0.33 seconds of data. The following table shows these calculations for common motor speeds.

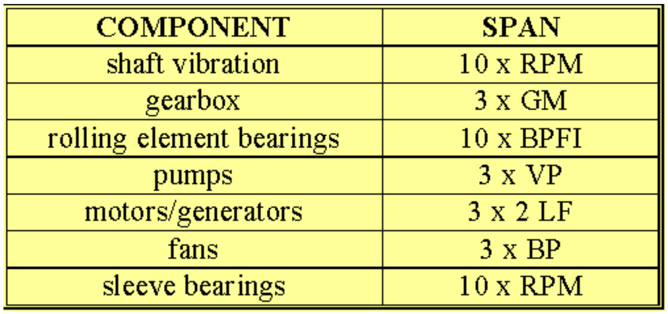
Motor Speed RPM	Seconds/Revolution	5 Revolutions (Seconds)	10 Revolutions (Seconds)
900	0.0667	0.333	0.667
1200	0.05	0.25	0.5
1800	0.0333	0.167	0.333
3600	0.0167	0.0835	0.167

Table 1

Hopefully most of us have learned that sample time for a spectrum is calculated using the following formula:

$$\text{Sample time} = {\#\ of\ Lines}\Big/{Fmax\ (Hz)}$$

Since our data collector probably does not allow us to choose a sampling time for a given Fmax, we will need to use this formula to setup our data collector for time waveform sampling. As we have discussed our goal is to produce a waveform which will closely approximate the raw overall signal coming from the machine casing. This means that we have to sample at a high enough frequency that our Fmax setting will not filter out frequencies which may be present. At this point we need to think about the machine and machine construction to come up with our best educated guess. The following table taken from the Vibration Institute's Basic Machinery Vibration course can serve as a good guide for selecting an appropriate Fmax for waveform sampling.



COMPONENT	SPAN
shaft vibration	10 x RPM
gearbox	3 x GM
rolling element bearings	10 x BPFI
pumps	3 x VP
motors/generators	3 x 2 LF
fans	3 x BP
sleeve bearings	10 x RPM

Table 2: Default Frequency Spans for Data Collectors

From Table 2 we will find that for many of the machines we are testing that the Ball Pass Inner Race will be the controlling factor in determining an Fmax for sampling. So for many components this will result in a desired sample span between 50X and 75X operating speed. Using this as a guide we can now determine the number of lines (samples) we need, to optimize our time waveform sampling. For the time waveform the number of discreet digital samples collected can be determined by multiplying Lines of Resolution by 2.56. This gives us the total number of time domain data points which are collected during a single sample. Table 3 shows the relationship between spectral lines and number of time domain sample points.

# of Lines	100	200	400	800	1600	3200
# of Samples	256	512	1024	2048	4096	8192

Table 3: Number of lines vs. Number of samples

So if we rewrite our formula we should be able to calculate the number of lines required to give us a good time waveform sample.

$$\#\text{ of Lines} = (\text{Sample Time seconds})(\text{Machine Speed Hz})(50\text{ orders})$$

For an 1800 RPM machine this would say that we need a spectrum of 499.5 lines

$$\#\text{ of Lines} = (0.33\text{ Seconds})(30\text{ Hz})(50\text{X}) = 495\text{ Lines}$$

So for our example we will need to determine if we want to use 400 or 800 lines. Using our sample time formula we find that using 400 lines will take 0.27 seconds at an Fmax of 1500 Hz and 0.53 seconds using 800 Lines. If we divide the sample time by the seconds/revolution we find that at 400 lines we get 8 revolutions while at 800 lines we get 16 revolutions of the shaft.

We can also determine the number of data points which will describe 1 revolution. Simply this is the done by dividing the # of sample points by the number of revolutions. Thus for a 400 line sample we get 1024 samples/8 revolutions = 128 samples/revolution. For an 800 lines spectrum we find that at 1500 Hz we have 2048 samples/16 revolutions = 128 samples/revolution. Having 128 samples/revolution will provide us with very high resolution time domain plot. Experience has shown that if we achieve 50 samples/revolution or higher that our time waveform plot will closely approximate that which is present on an Oscilloscope screen.

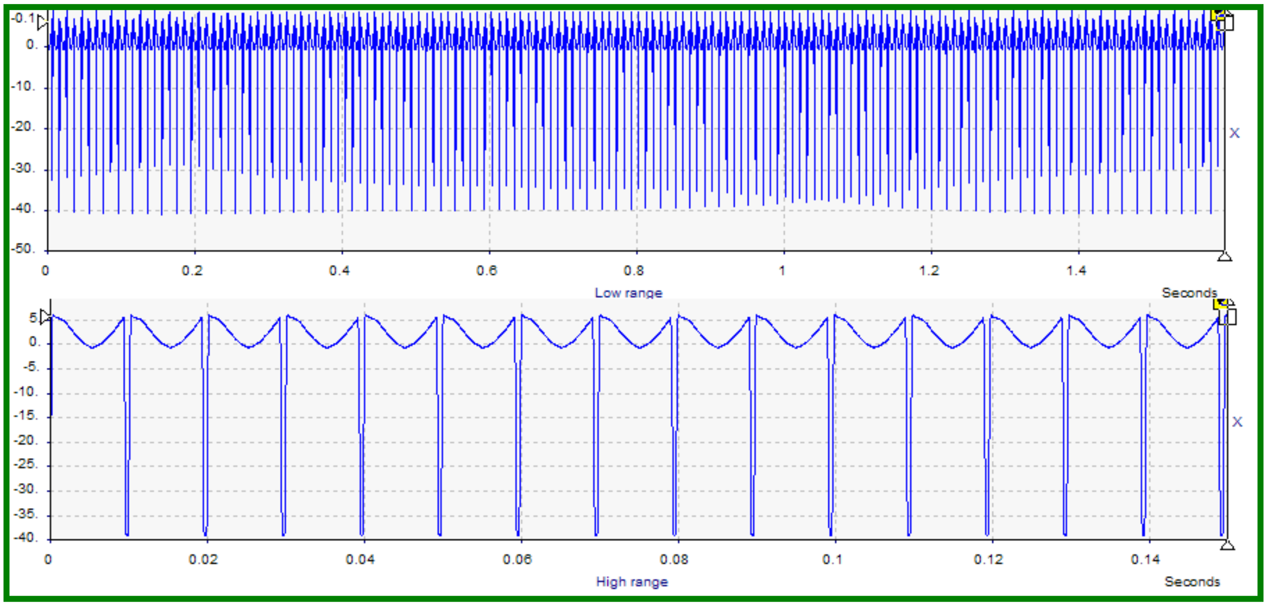
If the fault components present are primarily low frequency having only 20 sample points may yield more than satisfactory results however we need to think about what components may be present under malfunction conditions when we select the Fmax and resolution requirements for both the spectrum and time domain data.

As we were discussing, if the frequency components present are primarily low frequency the resolution required will typically be lower than that required for higher frequency bearing impacts. The following example using a 1/revolution pulse shows the challenge of accurately documenting the response of an impact.

For our example we have a machine which is operating at 6000 RPM (100 Hz). This results in a sample time/revolution of 0.01 sec/rev. The table compares using a 200 line spectrum (512 samples) to that of a 1600 Line (4096 sample) spectrum. What the table shows is that for a given Fmax the number of samples which describe 1 revolution of the shaft is the same independent of the number of lines utilized for the measurement. However, increasing the number of lines increases the sample time resulting in a higher number of shaft revolutions. The only drawback in displaying a larger number of cycles is that the analyst may have to perform a zoom to limit the number of waveforms being evaluated.

Fmax Hz.	200 Lines (512 Samples)			1600 Lines (4096 Samples)		
	Sample Time (sec.)	# of Shaft Revolutions	# of Samples/Rev	Sample Time (sec.)	# of Shaft Revolutions	# of Samples/Rev
500	0.4	40	12.8	3.2	320	12.8
1000	0.2	20	25.6	1.6	160	25.6
2000.	0.1	10	51.2	0.8	80	51.2
5000	0.04	4	128	0.32	32	128
10,000	0.02	2	256	0.16	16	256

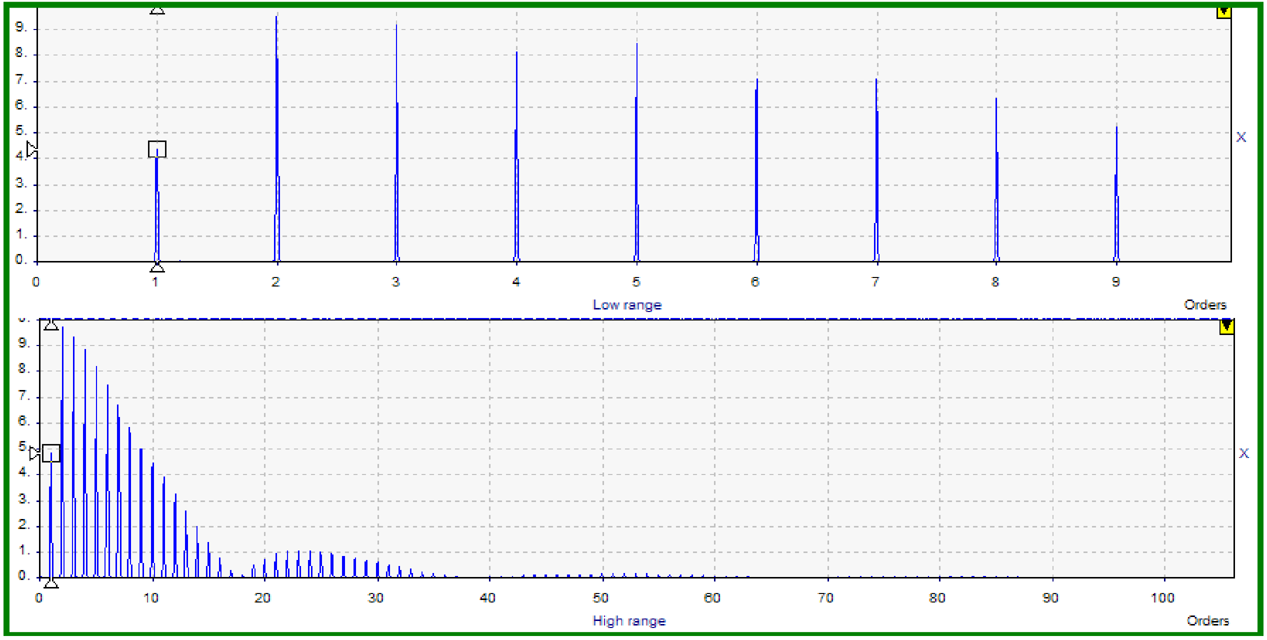
Table 4: Sample times and # of samples/revolution for 100 Hz. machine



Graph 1: 100 Hz machine waveform - Fmax of 1000 Hz (top) compared to Fmax of 10,000 Hz (bottom)

Graph 1 shows the time waveform sample of a 1/rev pulse. In both cases a 1600 Line Spectrum (4096 sample point) was utilized. The top plot shows the data collected with an Fmax of 1,000 Hz. compared to an Fmax of 10,000 Hz. in the bottom plot. If we look at the number of samples per revolution we find that at 1,000 Hz we sampled 160 revolutions of the shaft. This gives us a number of sample/revolution (4096 samples/160 revolutions) of 25.6. Sampling with an Fmax of 10,000 Hz. decreases the number of revolutions collected to 16 and improves the number of samples/revolution to 256. Notice that on the bottom high resolution plot the negative going pulse is at a constant amplitude level. However, when we view the plot collected using an Fmax of 1,000 Hz we see that the bottom of the 1/rev pulse appears to be varying in amplitude. This apparent response is the result of insufficient samples/revolution causing the peak vibration amplitude to be missed (peak occurred between samples) and not a modulation or beat. As a result not selecting the appropriate Fmax can result in misleading time waveform information if the analyst has not setup the waveform sampling correctly.

Graph 2:

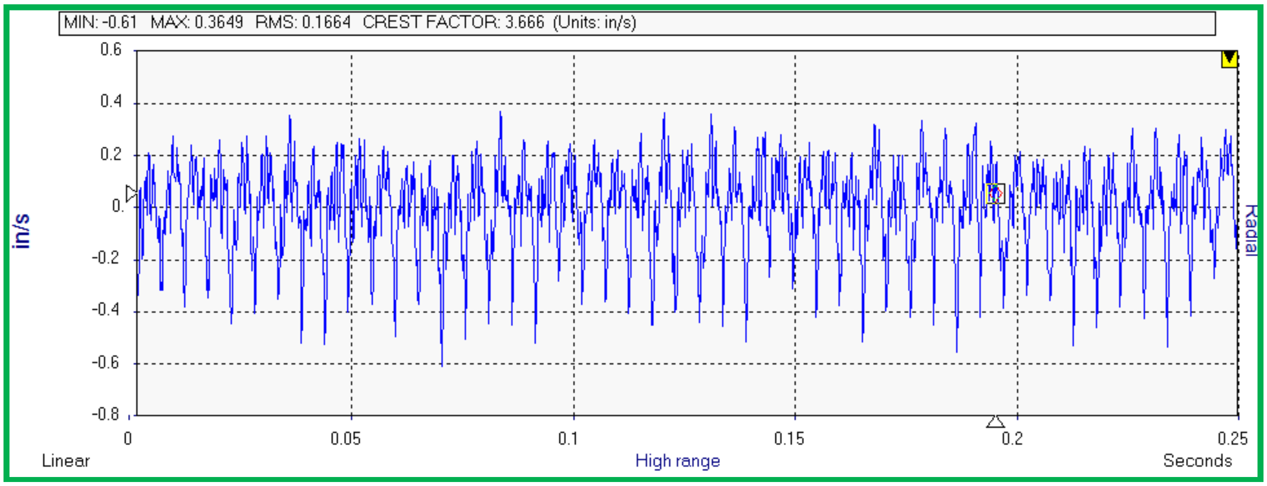


100 Hz machine - 1600 line spectrum - Fmax of 1000 Hz (top) compared to Fmax of 10,000 Hz (bottom)

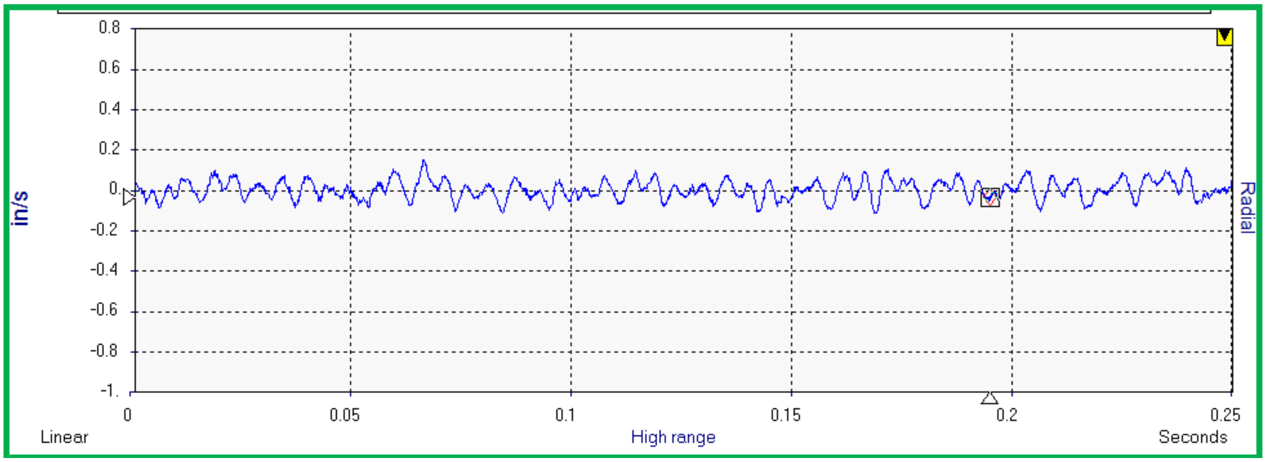
The spectrums displayed in Graph 2 were acquired along with the time waveforms displayed in the previous graph. Note the strong harmonic series which is typical of an impulse going out to approximately 35X operating speed.

Waveform Comparison: Even if we have no experience with time waveform analysis we can use the time waveforms to look for differences in the machine response. By comparing a “baseline reading” to the current survey data we can look for changes. Most of us are already doing this with the spectrum and have developed a pattern recognition in our mind of what is an expected normal response for a given machine group. The same recognition can be developed for the time waveform if we will start to look at them as part of our normal analysis routine.

The following waveforms shown in graphs 3 and 4 were collected on a fan operating at 1250 RPM. Shown are baseline data in Graph 4 and data collected 12 December, 2010 Graph 3.

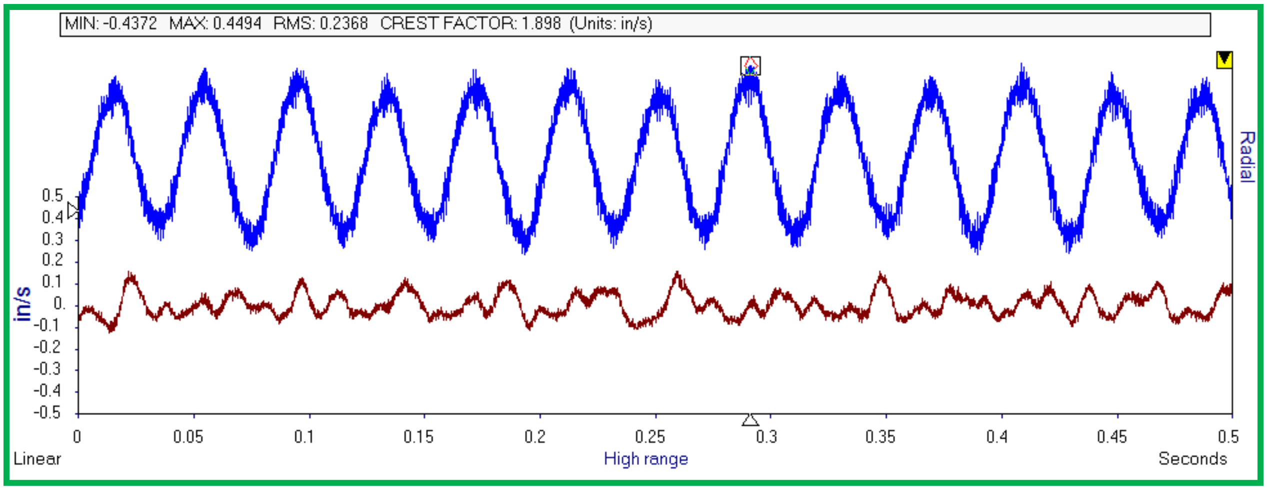


Graph 3: Data collected 12 December



Graph 4: Baseline

Just based on comparison it is clear that the amplitude has increased from approximately 0.1 IPS 0-Pk to over 0.4 IPS 0-Pk with peak amplitudes noted of 0.6 IPS. If we look at the shape of the 12 December wave we might describe it as having higher frequency impacts compared to the baseline. We may also note that the impacts are higher in the negative direction and that the peaks are varying (modulating) in amplitude. It is clear that there has been a significant change in machine response. We may even ask ourselves what malfunction would cause an increase in amplitude due to impacting. So without any training in using the time waveform we are gaining insight into machine condition by looking at amplitude and shape.



Graph 5: Baseline response (bottom) to data collected February, 2011 (top)

Graph 5 shows a comparison of time waveforms. The baseline data is presented on the bottom vs. data collected in February, 2011. An amplitude increase of 3 to 4 times baseline levels is noted. We see that the increase is due to a single frequency as indicated by the sinusoidal waveform and that the component is relatively low frequency. In this instance we are going to look for a single frequency in the spectrum with an amplitude of approximately 0.3 IPS 0-Pk. Again just by comparison of the amplitudes and waveform shape we are able to gain insight into the potential issues which could be present. For a motor/belt drive/ supported fan what malfunction would result in low frequency sinusoidal motion. At this point we could easily perform a calculation find the frequency of the sine wave and compare it to know fault frequencies for this fan.

Notice that in the previous 2 examples we have performed no calculation and have only applied our observations and experience with the machine to gain insight into the change. So let's move a couple of steps further in our evaluation by learning how to determine frequency directly from the waveform.

Time Waveform Measurement - Frequency: The time waveform is the raw unprocessed data sensed by the transducer mounted to the machine casing or observing the rotating shaft. For casing measurements it is this authors experience that having the time waveform and the spectrum available in the same units greatly adds to the ability to directly evaluate and compare waveform to spectral results. Since the waveform is what is acquired directly from the machine all of the other diagnostic presentations are derived from it. So it would make sense that an analyst would be able to evaluate the waveform directly and extract diagnostic information. With a little practice what we find is that as long as the waveform is not overly complex this is a relatively simple task to determine key frequencies and amplitudes. We also find that the shape of the waveform gives us significant insight into many malfunctions which the spectrum cannot provide.

One of the first things that we might want to do is determine the frequency present in the time waveform. Figure 1 shows a simple harmonic waveform. A wave is said to be harmonic when there is only 1 frequency present and the wave repeats itself at a given time interval. This interval between peaks or zero axis crossings represents 1 cycle of motion as shown in Figure 1. The time interval for 1 cycle to occur is referred to as its period. The period of the wave is measured in seconds. In Figure 1, T represents 1 cycle of motion

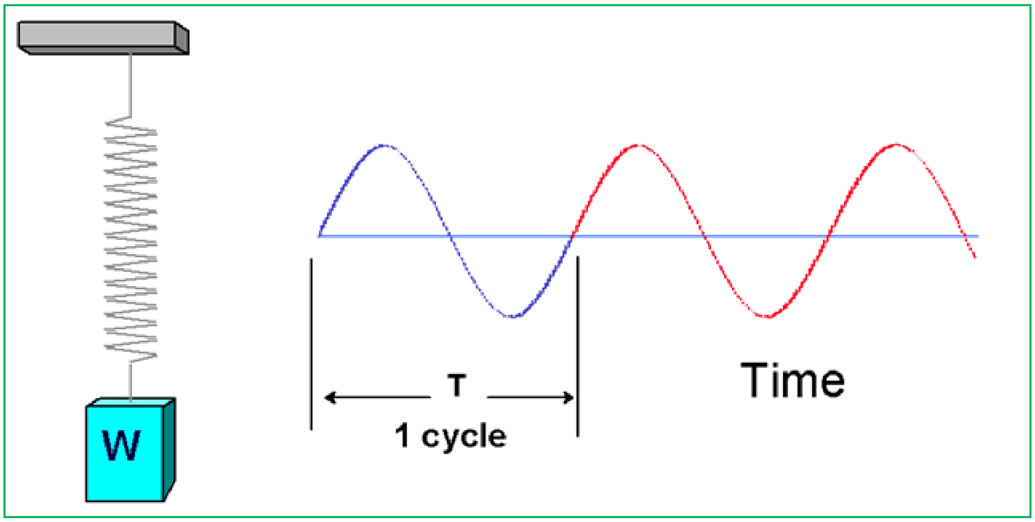


Figure 1

Once we have the time it takes for 1 cycle to occur we can calculate the frequency.

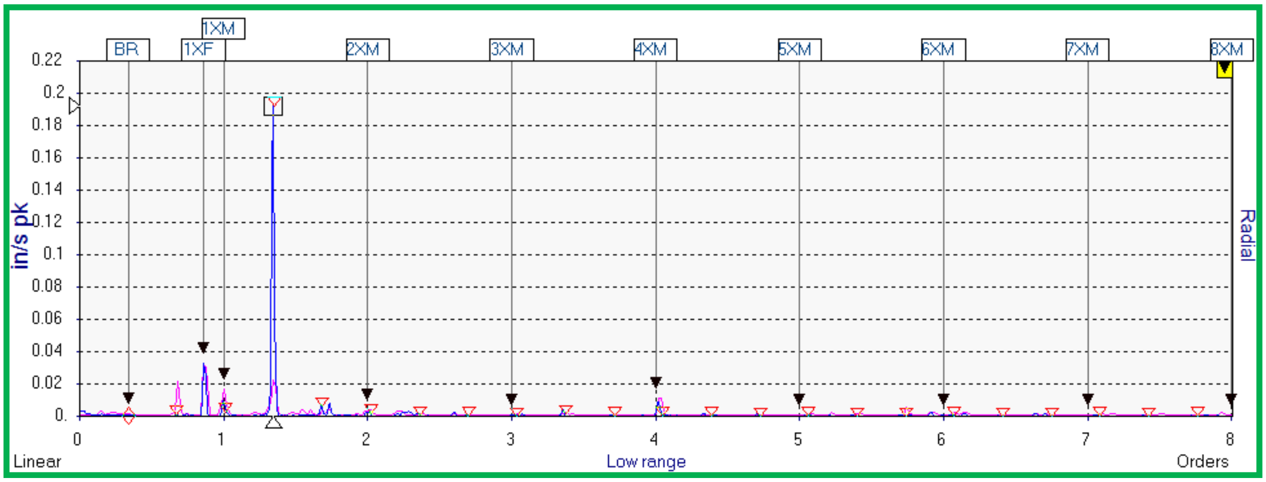
Frequency of wave (f) = $^{1\ cycle}/_{T\ period\ in\ seconds}$

Using our example in graph 5 we see that there are slightly less than 13 cycles which occur in 0.5 second period. From this we can calculate the period and the frequency.

T = 1 cycle of motion = 0.5 seconds/ 12.75 cycles = 0.0392 seconds

Frequency of wave (f) = $^{1\ cycle}/_{0.0392\ seconds}$ = 25.5 Hz. = 1530 CPM

At this point we need to apply our knowledge of the machine in order to determine the root cause of the vibration. The unit operates off a VFD and the resulting motor speed is measured at 1142 RPM and the fan was measured to operate at 991 RPM. Neither operating speed corresponds to the measured vibration which occurs at 1530 CPM. The measured belt rate for this unit occurs at 0.3375X of the motor or 385.4 CPM. Dividing 1530 CPM by the belt rate of 385.4 CPM we get 3.98X belt rate. Rounding this to 4X belt rate is a safe bet. Graph 6 shows the spectrum plot which was acquired along with the waveform plot displayed in graph 5. Using harmonic markers we are able to confirm that the increase in amplitude is due to an increase in the 4X belt rate component.



Graph 6: Spectrum plot for time waveform shown in graph 5

Time Waveform Measurement – Amplitude: In our industry the amplitude of the vibration signal is measured and presented in several ways. There is no agreed upon standard. As a result the method by which the overall level is measured or calculated can vary from 1 data collector vendor to the next or can even vary from 1 analyst to the next. This can make it difficult to talk about an overall level which is meaningful to all of us. This becomes even worse when the analyst does not know how it is being expressed for their system as many of the data collector/PdM software suppliers allow for this value to be expressed in many ways.

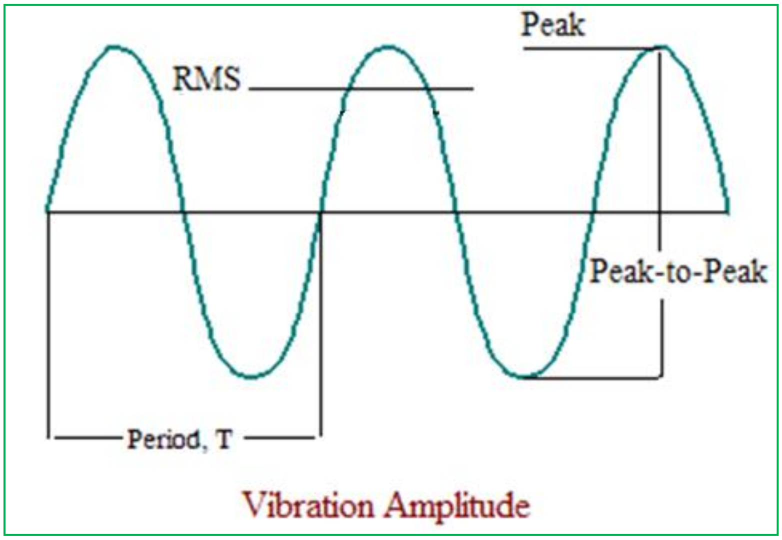


Figure 2

However, all methods of expression are based on RMS, 0-Peak, or Peak-to-Peak measurement as shown in Figure 2.

1. Amplitude is the level of vibration in a data sample.

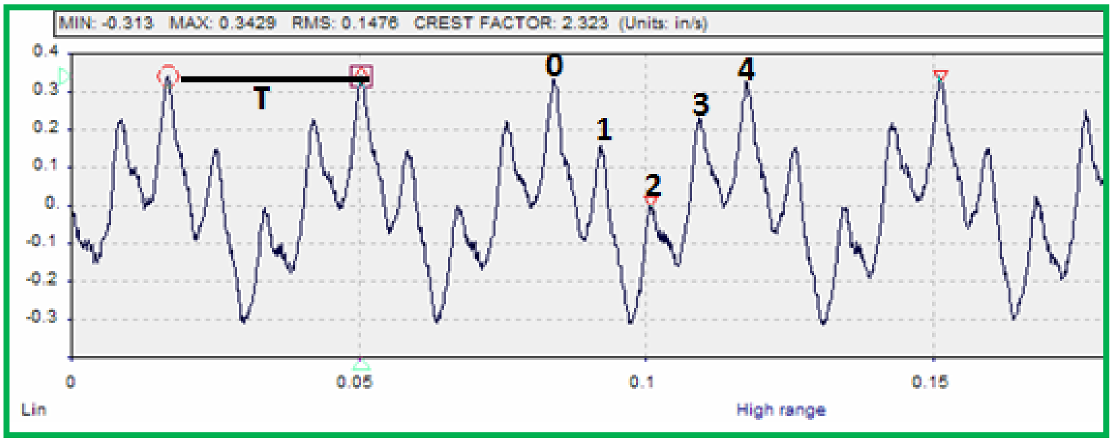
2. Peak amplitude is the largest value taken from the time waveform, plus or minus, in a data sample. This is sometimes referred to as True Peak
3. Peak to peak amplitude is the maximum excursion of a vibration cycle measured on adjacent positive and negative peaks in the time waveform.
4. RMS = root mean square - total energy RMS is measured using a RMS measurement chip built into the data collector or by calculation from the spectrum using the following equation:

$$\text{RMS} = .707\sqrt{V_1^2+V_2^2+V_3^2+...V_n^2} \quad V = \text{spectral peaks}$$

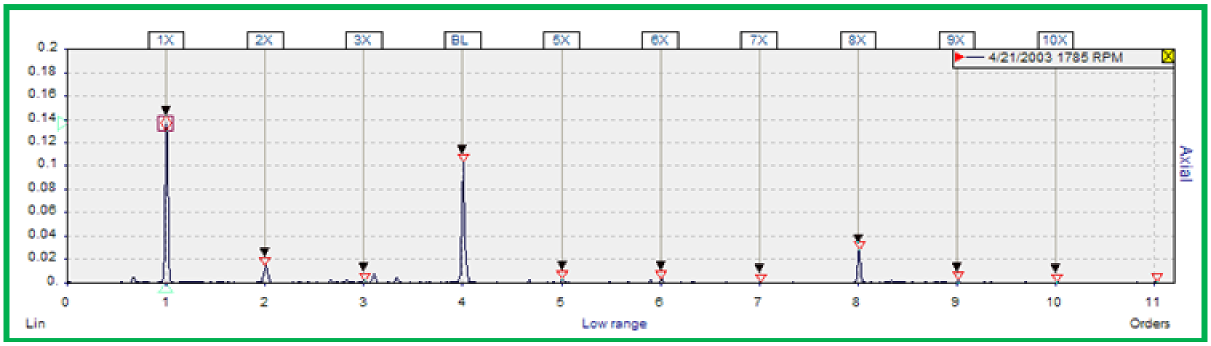
5. For many measurement systems the peak level is calculated by using RMS X 1.414. This level should be more accurately termed Derived Peak as this level has no true relationship to the measured peak value in the waveform.
6. Crest Factor is a method used to express the relationship between the true peak level and the RMS value. Crest factor is the ratio of the True Peak level to the RMS value. Hence if the waveform was a pure sine wave the Crest Factor would be 1.414 and the crest factor value will increase as the waveform become less sinusoidal. Typical crest factor values are found to range between 2 and 3 for problem free machines

For all of our evaluations using the time waveform the Peak and Peak-to-Peak levels are measured directly from the graph. This will greatly assist in relating the amplitude response measured in the time domain to that presented in the spectrum.

Periodic Measurements: Waveforms are called periodic when multiple frequencies are present and the waveform repeats itself in a given time interval. The majority of the machinery we test are periodic and not harmonic waveforms. The waveform shown in Graph 7 was acquired on a screw air compressor. The operating speed of the machine is represented by period T. From the plot we see that this period is approximately 0.033 seconds which represents an operating speed of 30 Hz. We also see that for each cycle of motion there are 4 peaks which are superimposed onto the running speed waveform. This indicates that along with the 1X running speed component there is a 4X running speed component present. This determination makes sense considering the male screw has 4 lobes. Graph 8 is the companion spectrum to this data.



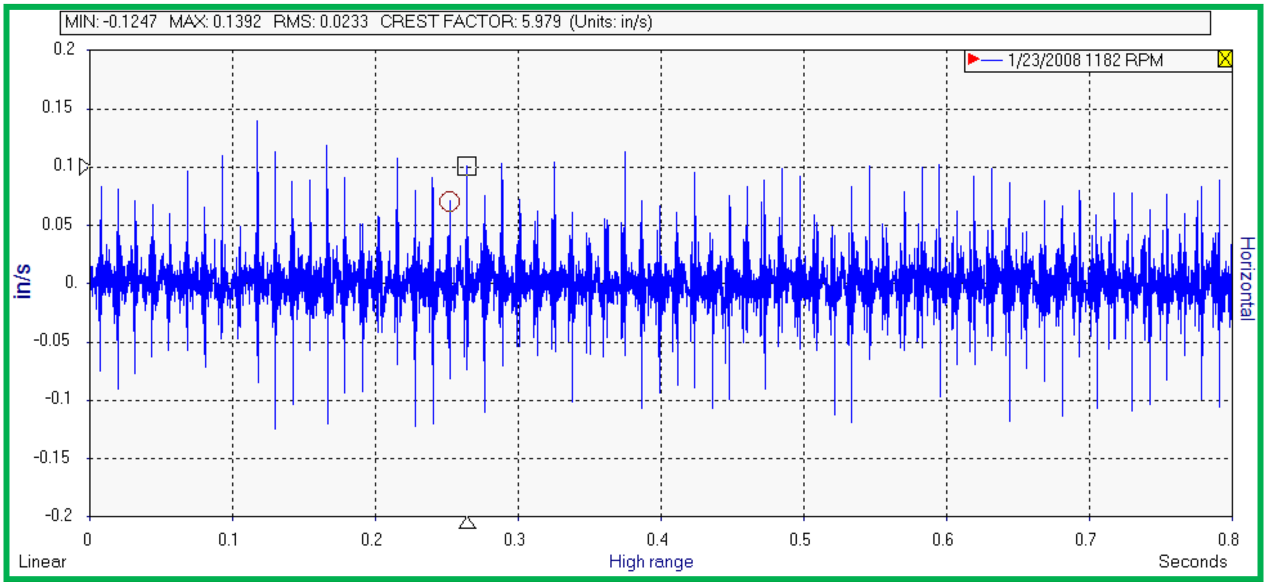
Graph 7: Periodic Waveform



Graph 8: Spectrum showing strong 1X and 4X running speed component present

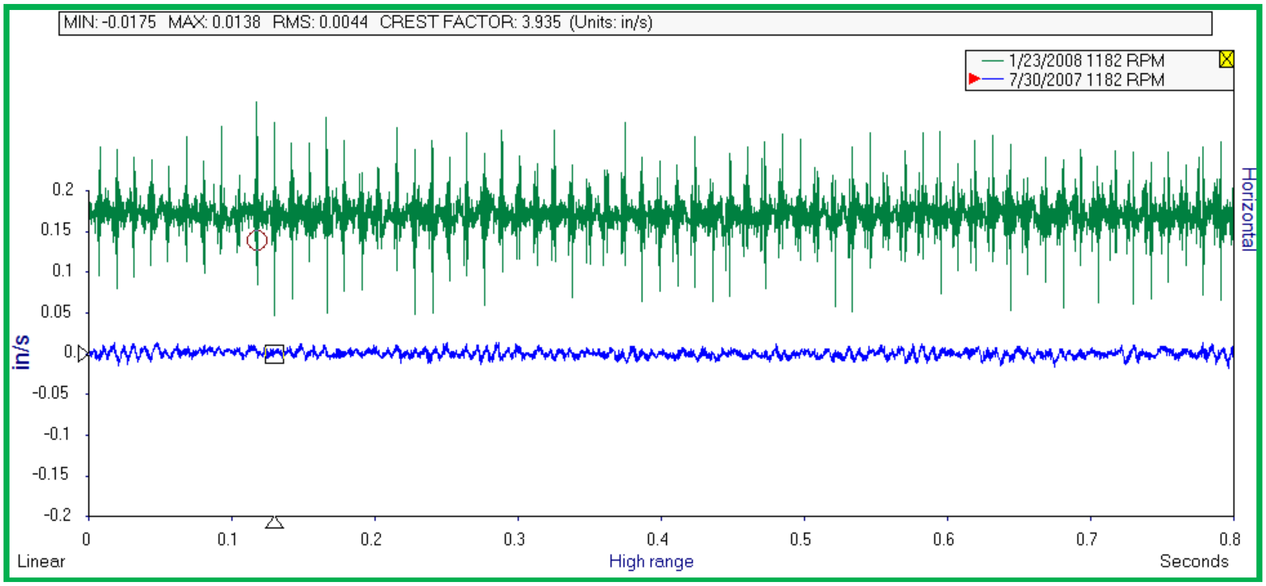
Evaluation of the spectrum indeed shows a 1X and 4X component which is dominant. This confirms our evaluated response based on the time waveform.

Graph 9 shows a time waveform acquired on a pump thrust bearing during normal operation. Speed of the motor is 1181 RPM (0.05 sec/rev).



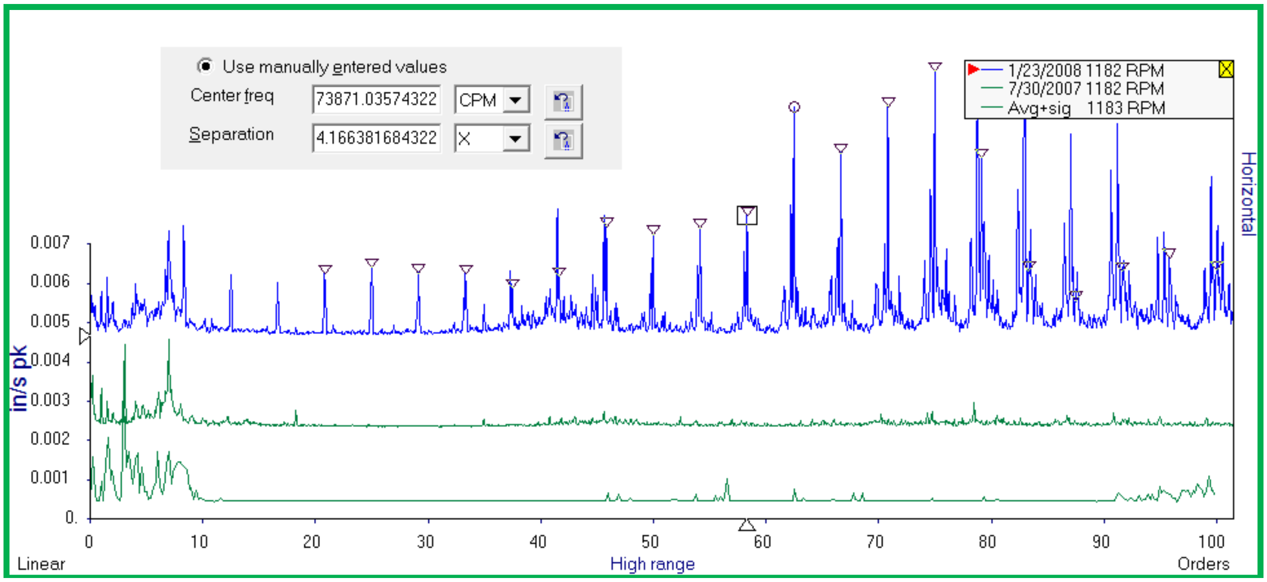
Graph 9: Pump non drive end horizontal location

Impacting is noted to occur at periodic intervals of approximately 0.012 second or 83.3 Hz. This clearly is not the running speed of the unit or an even order harmonic. The data shows that this impulse is asynchronous occurring at 4.16X running speed. Peak amplitudes are measured at 0.13 IPS. The time waveform also shows that modulation is occurring as indicated by the varying level of the peaks. Note that the RMS level is measured to be 0.023 IPS which if viewed by itself would indicate a smooth running machine. The crest factor for this waveform is calculated to be 5.98. Crest factors above 4 indicate a waveform with strong impulses. Based on our review a serious bearing fault is present. This serious condition is further confirmed when the current data is compared to the baseline levels. Graph 10 shows this comparison.



Graph 10: Pump non drive end bearing waveform comparison baseline (bottom) to current (top)

Comparison of the data shows that peak amplitudes increased from 0.017 IPS to 0.13 IPS. Note that baseline waveform shows no indication of impacting.



● Use manually entered values

Center freq 73871.03574322 CPM

Separation 4.166381684322 X

Graph 11: Spectral comparison of current data (top), baseline response (middle), Average response (bottom)

Spectral data confirms 4.16X spacing of bearing fault components. While the maximum amplitude level of the spectral components is low the presence of the spectral series and increase from baseline is significant. The spectral data also shows sidebands to be present spaced at the cage rotational frequency. Cage rate sidebands help to confirm the serious condition of the bearing fault.

Phase: To measure phase the analyst needs to have 2 transducers which are sampled simultaneously. These can both be vibration measurement transducers or a measurement transducer combined with a transducer which provides a 1/revolution timing pulse. The 1/revolution timing pulse is created by using a discontinuity on the shaft such as a key or keyway or by installing a piece of reflective tape if an optical sensor is used. Phase is typically not a trended parameter for most of our PdM work with the exception of online machinery protection systems using proximity probes where a permanently installed 1/rev transducer is typically available.

Simply enough a phase measurement is performed by holding 1 transducer as a fixed reference (does not move) and moving to other transducer to 1 or more measurement locations. Phase is measured by measuring the angular distance between the peaks. The following example shows the measurement of phase using 2 measurement transducers.

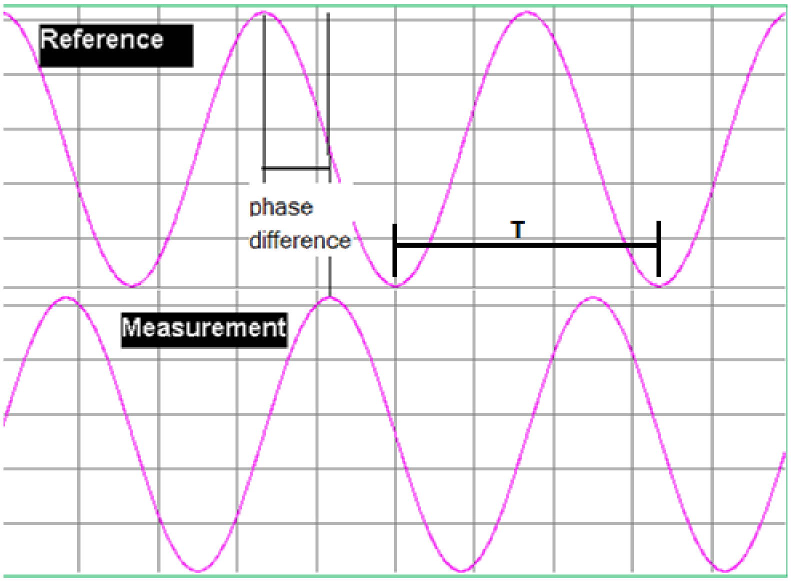


Figure 3: Phase between measurement transducers

In this example we have our 2 measurement transducers and have called 1 a reference (fixed) transducer. We now compare a 2nd transducer to the reference by measuring from the peak of the reference transducer to the peak of the measurement transducer. We find that in our example that the peaks are separated by about 90 degrees. To get the phase we can look at the 2 waveforms and estimate the angle between them or we can calculate the angle by measuring the period of the reference (T) and then measuring the time difference between reference and measurement peak

$$\text{Phase between transducers} = \frac{Time\ between\ peaks\ in\ seconds}{T\ Period\ in\ seconds} \text{ X } 360^0$$

The analyst will find that using 2 measurement transducers to measure phase has many uses including measuring across the coupling to look for misalignment, bent/bowed shaft detection, phase from X to Y measurements at a bearing, phase between any 2 bearings or measurement points, and operating deflection shape measures.

Phase can also be measured in exactly the same way using a 1/revolution timing pulse as a reference and comparing a measurement transducer to it. Figure 4 shows an example of this time waveform relationship.

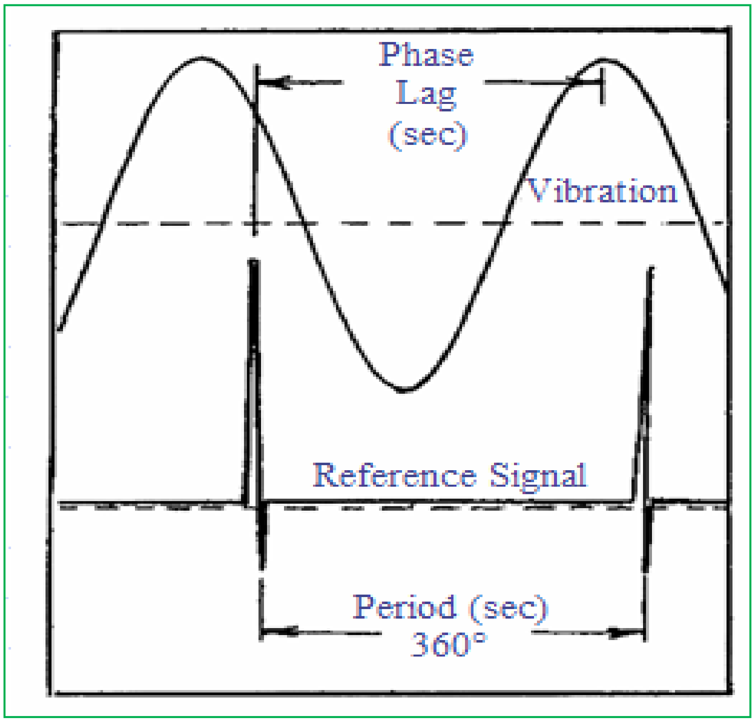


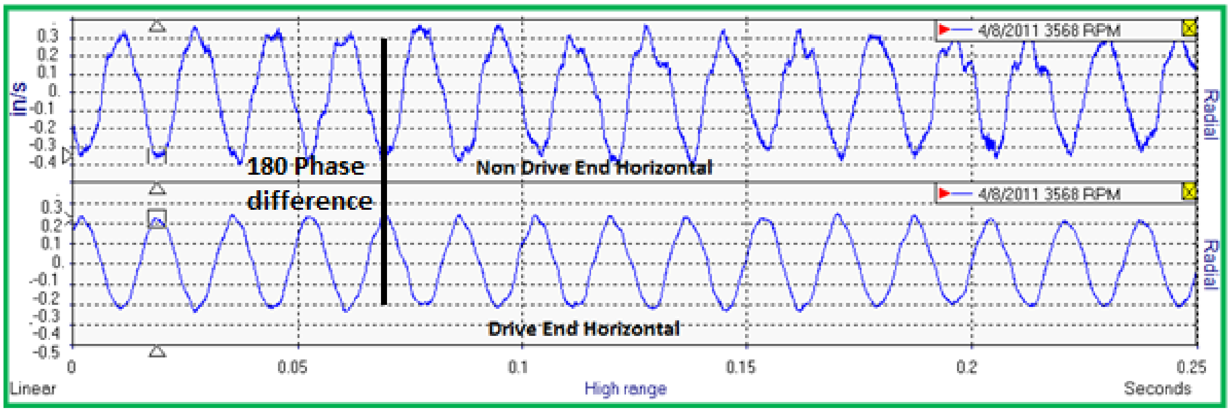
Figure 4: Phase using a fixed 1/rev reference

The angle between the transducers is measured in exactly the same way as we did for 2 measurement transducer example above. The main difference is that when we stop the machine we can locate the point where the shaft discontinuity/reflective tape is located and then rotate the shaft until the peak of the vibration signal is under the measurement transducer. This form of phase measurement can be used for troubleshooting as noted above but is also the type of phase measurement required to perform trim balancing of a rotor.

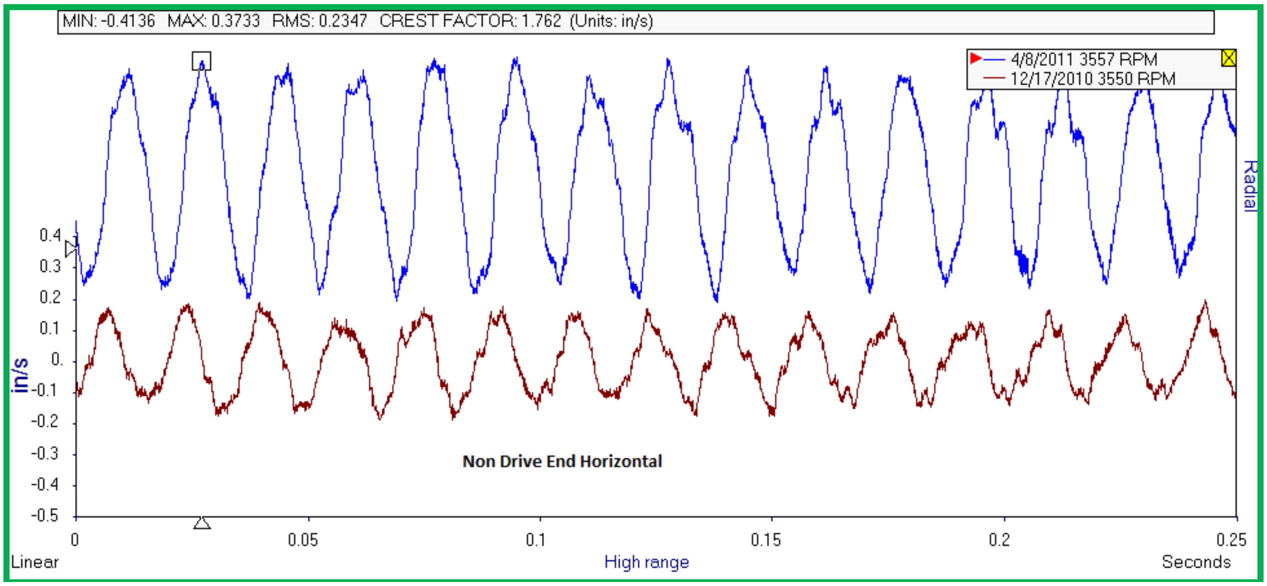
Let's look at a couple of examples where we will measure phase between sensors. In the first example (Graph 11) we are evaluating the response of a pump between drive end and non drive end locations. The speed of the unit is 3,560 RPM. Evaluating the period of the vibration signal we see that there are approximately 3 waveforms for every 0.05 seconds. This gives a period of 0.01667 seconds or 59.99 Hz (3600 RPM). From this we know that the waveform is principally showing the running speed motion of the unit. We also note that the amplitude at the drive end is about 0.25 IPS 0-Pk and while the non drive end bearing is approaching 0.4 IPS 0-Pk. Elevated 1X may indicate some sort of unbalance response. When compared to previous data (Graph 12) it is noted that levels have increased. Overall peak levels increased from 0.2 IPS to 0.4 IPS. Change in rotor condition is indicated.

We also note that at the non drive end bearing (graph 11) the waveform is beginning to show the peaks are becoming truncated (clipped). This is in indicator of distress and may indicate that a clearance issue is beginning to develop. Finally we find that the peaks of the waveforms are

180^0 out of phase between bearings in the horizontal direction. This tells us that the pump casing is rocking in the horizontal plane during operation. This indicates that unbalance may not be the only contributor to the response. Based on observation, a weak mounting base is suspected to be contributing to this response. Further evaluation and inspection has not been performed.



Graph 11: Phase between measurement sensors



Graph 12: Increase in level December, 2010 to April, 2011

In this example we have learned a great deal about the pump response using only the time waveform. This data would typically be combined with the spectrum as part of our review. The spectrum would give us essentially the same information with the exception of phase. However when the waveform data is combined with frequency and amplitude the analyst gets a clearer picture of machinery operation.

References

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4. Timothy Dunton “Introduction to Time Waveform Analysis” 2002