An Introduction to the Spectral Dynamics Rotating Machinery Analysis (RMA) package For PUMA and COUGAR

Introduction:

The RMA package is a PC-based system which operates with PUMA and COUGAR hardware to offer the best possible acquisition and analysis of vibration and noise data in variable speed measuring applications. At the heart of this system is a dual Tachometer hardware board which runs at a clock speed near 100 MHz and uses double-buffered counters. This permits accurate, real-time measurement of tachometer signals up to 100,000 Hz on each channel. Thus rotors with speeds up to 100,000 RPM and 60 pulses per rev can easily be accommodated.

Real-Time measurements have always been the forte' of Spectral Dynamics and the RMA package only enhances this reputation. Capable of working with from 4 to 30 signal input channels, in addition to the 2 Tacho inputs, RMA offers Real-Time displays of:

- Input Time Waveforms
- Standard Spectrum (vs. frequency)
- Spectrum vs. Orders
- PSD vs. Frequency or Orders
- G^2 vs. Frequency or Orders
- Order Tracking of selected Orders vs. RPM
- Waterfall displays with wide range of Colors and orientations
- Spectral Intensity Diagrams with Hz or Orders vs. RPM
- True Campbell Diagrams of Frequency vs. RPM

These displays can be combined for multiple channels on a single display, or multiple displays per page, or multiple pages, but you get the idea.

Tachometer Signal Processing:

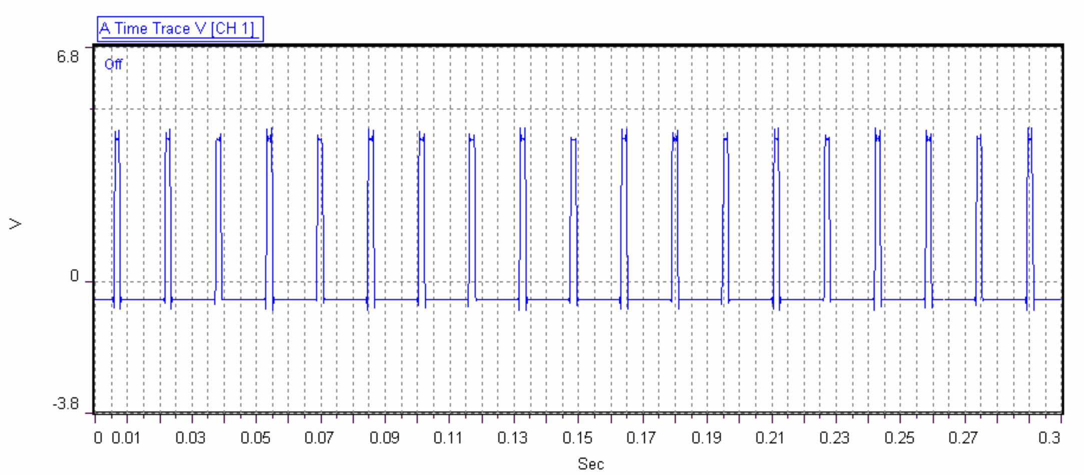


Fig. 1; Time Trace of input Tachometer signal also attached to Channel 1

Figure 1 shows a typical time trace from a fiberoptic tachometer used for variable speed measurements. Tacho processing, as performed by the Rotating machinery application, uses the traditional method for determining the frequency of an input signal. This processing method relies on monitoring the number of fixed time increments observed between a start and stop of a single cycle of the tacho waveform. This assumes that the tacho waveform is of a single periodic nature and that a start/stop event pair can be determined similar to the way triggering is performed on impact waveforms. Once the trigger events (start/stop) have been defined, the number of fixed time increments are counted between the start/stop events of a single tacho cycle. Knowing the frequency (i.e. delta T) of the fixed time increments we can convert the "counts" to a frequency by the simple equation:

Tacho period = Counts/Tacho Clock ; Tacho freq = 1.0 / Tacho period

Ref freq = Tacho freq / Pulses per Rev

There are usually 2 ways that the tacho can be measured:

1) The simplest, but not necessarily the best way, is to use a data channel as a tacho channel ("pulse" option). In this case, the Tacho Clock is actually the sample rate of the data channels. This sample rate usually limits the tacho frequency range since the tacho range is now set by the input data frequency range requirement. In addition, due to the "frame" nature of the input sampling process (i.e. we have to acquire a certain number of data points (1024,2048,4096,...etc.) we are limited to how we acquire the tacho signal. This restriction usually means we get several tacho cycles in every data frame. The result is often an "averaged" value which is okay unless the tacho signal is changing frequency during the data frame event, which is often the case.

2) Another way is to use a special tacho hardware daughter card ("H/W" option) that contains its own Tacho Clock which runs at a much higher speed; typically 100 MHz. This tacho hardware also contains special double buffered counters (i.e. to read "Counts") which maintain a continuous counter reading (from tacho cycle to tacho cycle) to avoid skipping any triggered cycles of the tacho signal. There is also an option to allow these counters to "average" several tacho periods for cases when the input tacho frequency is very high. The advantage here is that we decouple the Tacho Clock from the input data rate. In addition, we double buffer the counters to avoid missing or combining tacho input cycles. This means we can have an extremely high update rate to the tacho frequency as it is based only on the input tacho frequency. This is important when dealing with any tacho source that has a varying input frequency (aka "skew").

ACCURACY

Tacho measurement accuracy, in either of the two measurement methods, basically relies on how accurately we measure the "Counts" value. For a fixed frequency input, the counts are expected to vary depending on the frequency/accuracy of the trigger points and how close the Tacho Clock frequency is to the input tacho frequency. Our internal specification for counting accuracy is 1 count in a 1000. This means that the "Count" value should be at least 1000 in order to ensure a reasonably accurate result.

A) TACHO H/W

For example, the H/W tacho has a clock of 100×10^6 Hz (100 MHz). For Count =1000 we have a tacho frequency of $1.0 / (1000 / 100 \times 10^6) =$ 100,000 Hz. While the tacho H/W can measure still higher input frequencies, the accuracy will begin to degrade.

B) PULSES

For the case of using the data sample clock, take a typical example of a 2000 Hz BW (10240 Hz sample rate if we use 5.12 oversampling ratio).

In this case: 1.0 / (1000 / 10240) == 10 Hz. Obviously, we must relax the accuracy specification for the fixed sample case in order to get a reasonable range. However, assuming that we only measure 5 points per cycle (the best due to the filter cutoff), we find that the absolute max tacho freq will be: 1.0 / (5 / 10240) == 2000 Hz. This measurement of the tacho is sure to have a lot of "bounce"/variability due to the poor counts available to determine the true tacho frequency. This measurement is somewhat improved by using averaging (due to the probably of there being several tacho cycles in the input buffer). Note that at the max freq there will be over 200 cycles in a 1024 point waveform.

The bottom line is that the "pulses" option (i.e. using a data channel) is only usable in a few cases when the tacho frequencies are on the order of the data frequencies. This can be okay when using very low pulses per revolution tachos. Since the tacho frequency being measured must include the pulses/rev effect, the maximum frequency input must still be below the filter cutoff. For our example above, if we had a pulses/rev of 100 (not unusual for flywheel or geared data), then the usable MAX tacho (reference frequency value) would be 2000 / 100 = 20 Hz maximum fundamental frequency. Your only choice in these applications is to try increasing the measurement BW which then increases the sample rate. Unfortunately this also decreases the frequency resolution of the data analysis (Delta F = Sample Rate /Frame Size).

In any event, such a (pulses) tacho source is not a recommended reference source for performing any tracking sampling measurements due to its lower accuracy and inability to track a slewed data set. OFFLINE processing of "pulses" option data may be the only way to perform tracked data sampling since the tacho waveform is completely digitized and tacho frequency estimators can be employed to better estimate the reference frequency values.

We conclude that the special dual Tacho hardware card used with the Spectral Dynamics RMA package offers the most accurate possible approach for performing a wide range of Real-Time and post processing of machinery-related vibration and noise data.

Observing the Time Waveform:

As with most measurements, it is generally a good idea to take a look at the raw time waveform coming from the transducers, before performing a spectrum analysis and trying to draw conclusions. Problems such as signal clipping, which generate many, many harmonics, can often be quickly discovered by simply observing the transducer signal in a "scope" mode.

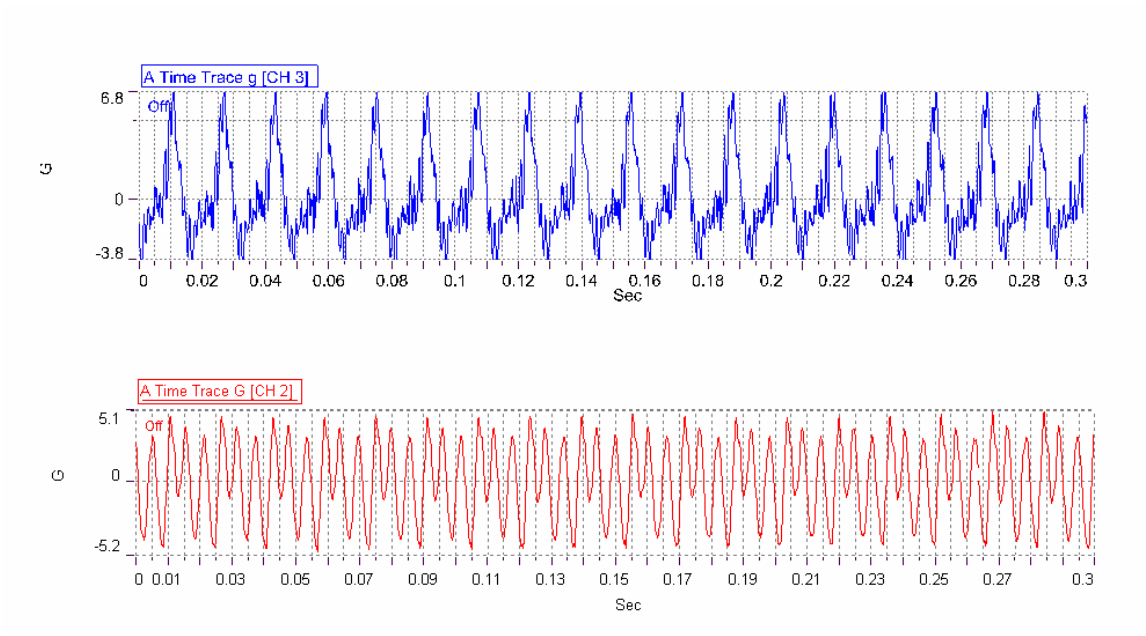


Fig. 2; Example of Time Trace of two bearing-mounted Accelerometer waveforms

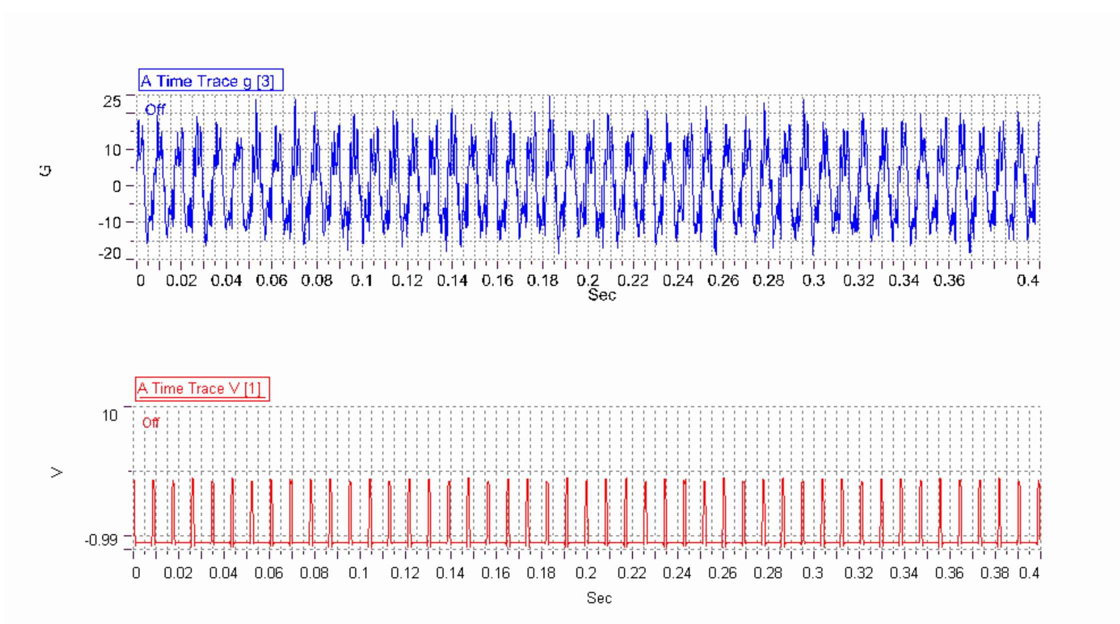


Fig. 3; Channel 3 vibration signal shown with corresponding 1/Rev Tacho

<u>Spectrum Analysis of Vibration/Noise Signals:</u>

There are many ways to process and display spectrum information of Machinery Vibration, especially for a machine which is changing speeds during the measurement interval. In the following sections we will introduce many Analysis/Display techniques, some of which are unique to Spectral Dynamics. We'll begin with Time and frequency.

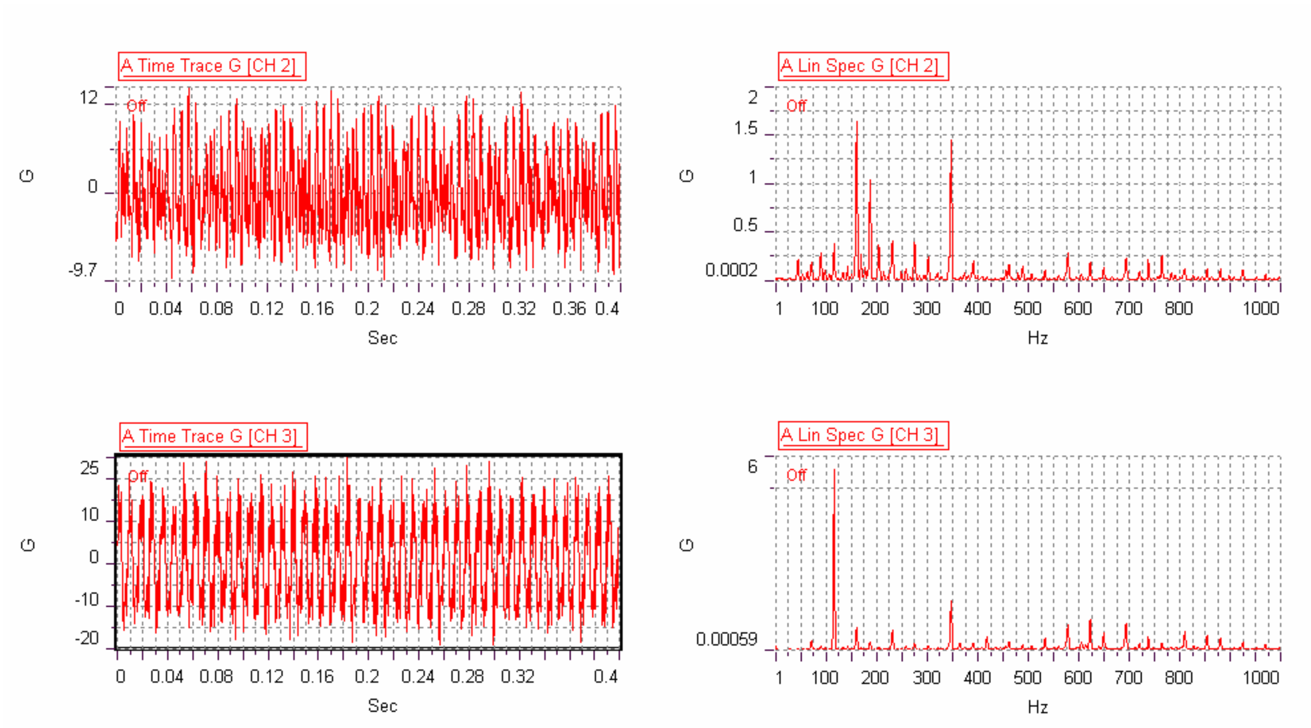


Fig. 4; Time and spectrum for 2 bearing accelerometers at 6900 RPM

Note that for the bearing Accelerometer attached to Channel 2, the level of the 1/rev component is extremely small at 9,600 RPM, whereas that of Channel 3 is over 5.5 g RMS. This will also be obvious later when observing a Tracked Order display.

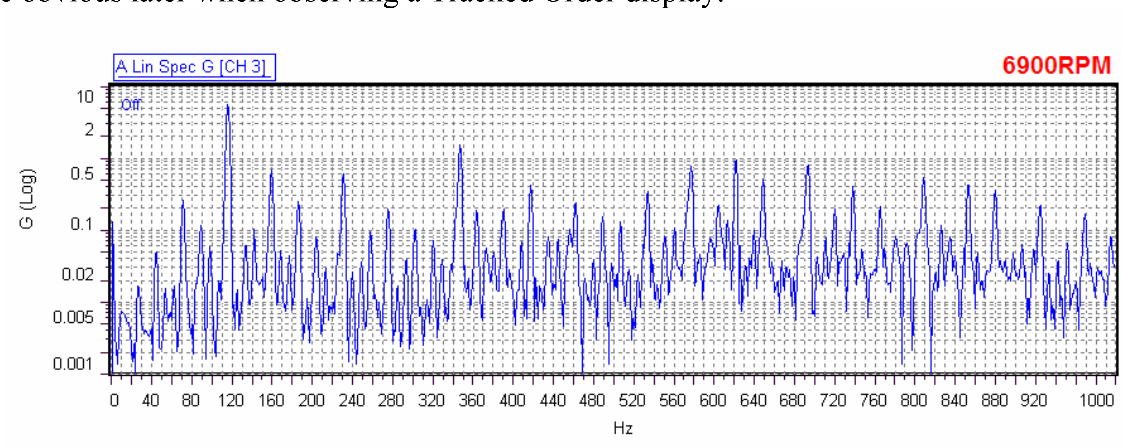


Fig. 5; CH 3 Bearing Acceleration spectrum shown in Log Magnitude format

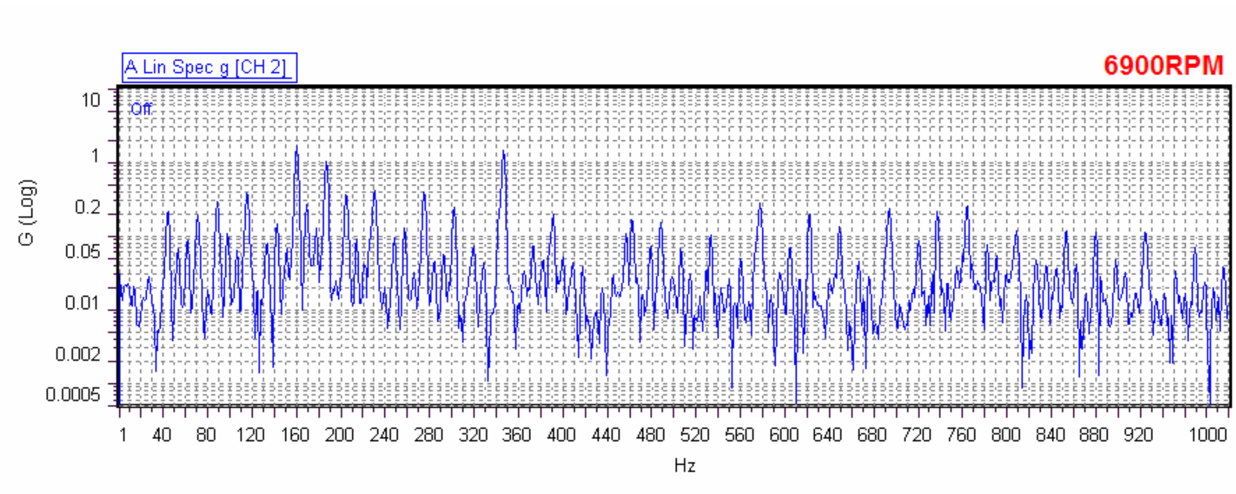


Fig. 6; CH 2 Bearing Acceleration spectrum shown in Log Magnitude format

Figures 5 and 6 show the bearing acceleration spectra in a Linear Frequency, Log Magnitude format. This format shows the existence of many lower level spectrum components which may be interesting but not particularly damaging to the bearings. It also shows a low level for the 1/rev component at 115 Hz but a much higher level at the 3rd order near 345 Hz. These can be seen more clearly if the spectra are presented vs. rotational Order instead of frequency. Next, let's overlay the 2 bearing spectra taken at 6,918.47 RPM.

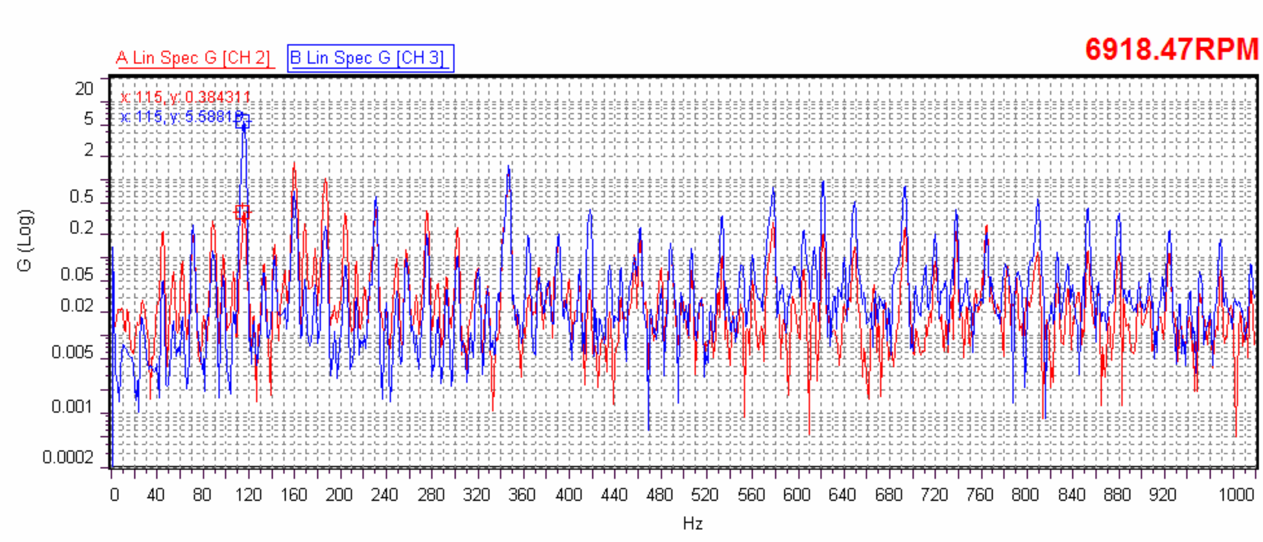


Fig. 7; Spectrum of 2 bearing accelerometers taken at 6,918.47 RPM, shown vs. Frequency

Note that at the running speed, shown here as 115 Hz, the first order component of Channel 3 is 14.5 times higher than that of Channel 2. However, at the third order, near 345 Hz, the 2 levels are virtually the same. If we display the spectra vs. Orders instead of Frequency, this is quite apparent.

Spectrum display vs. Rotational Order:

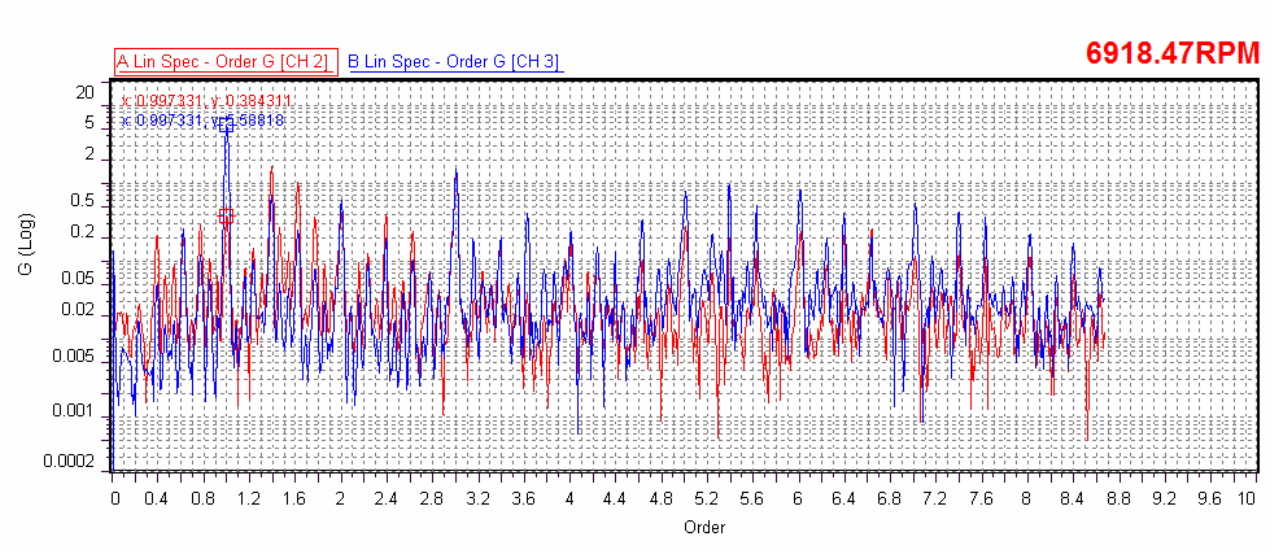


Fig. 8; Spectrum of 2 bearing accelerometers taken at 6,918.47 RPM, shown vs. Order

Figure 8 shows the same bearing vibration spectrum as previously but with the abscissa normalized to Rotational Order, based on the 1/rev Tacho input. This order-related display often makes it much easier to relate vibration components to driven speeds directly. Note that in this case, the highest Order displayed is 8.672. That is because the frequency range selected was 1,000 Hz full scale and the highest rotor speed reached was 6,918.47 RPM. That is the equivalent of 115.308 Hz which produces a full scale Order of [1,000 ÷ 115.308 = 8.672]. If a spectrum snapshot was taken at 6,000 RPM, a full 10 Orders could be displayed. Or if the 2,000 Hz frequency range was selected, we could analyze up to the 17th order. Or on the Acquisition menu page we could select Tracked Sampling, instead of the Fixed Sampling used in this example, and then select the desired number of Orders to be displayed, such as 10 or 20. [See Appendix 1.]

Tracked Order displays:

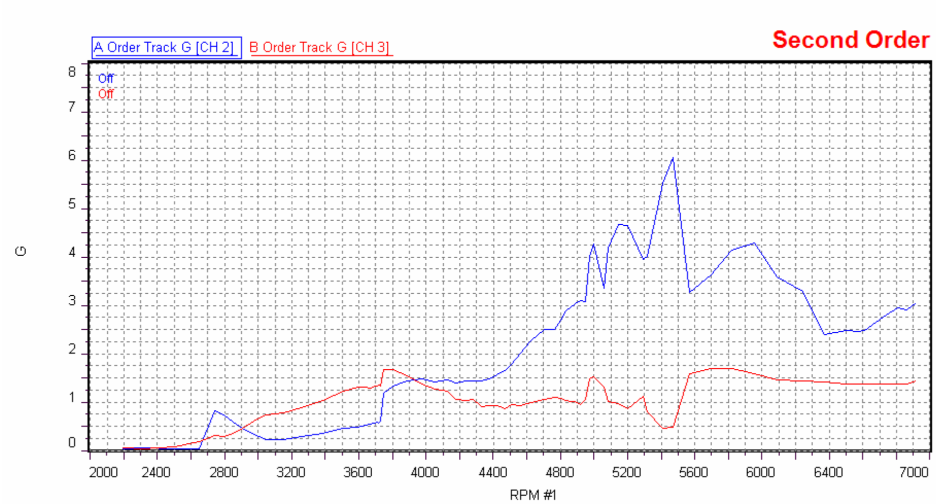


Fig. 9; Track of Second Order (2/rev) vs. rotor speed for 2 bearing accelerometers

An Order Tracking plot can be very useful in determining critical machine speeds over a operational selected speed range. The vibration patterns produced by any of the displays shown here are always showing a combination of motion produced by both the driven rotors, gears and bearings plus machine responses resulting from different Mode Shapes being excited by various machine harmonics. Some presentations, such as Tracked Order displays, try to concentrate on unbalance and other speed driven components to assist in trouble-shooting machinery vibration to help extend the machine's operational life as long as possible. Other presentations, such as 3-D displays and the classic Campbell Diagram, offer information about both driven components and structural resonances which may be excited during machinery operation.

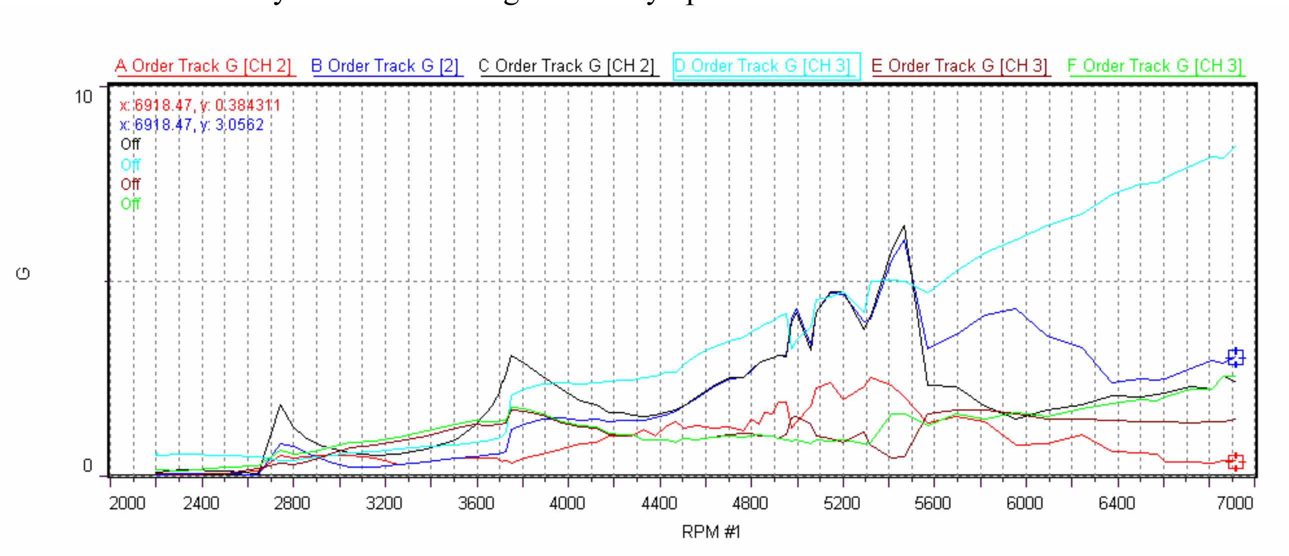


Fig. 10; Order Track of first 3 Orders from both bearing accelerometers

The Order Tracks shown above may be identified as follows:

Channel 2, First Order
Channel 2, Second Order
Channel 2, Third Order
Channel 3, First Order
Channel 3, Second Order
Channel 3, Third Order

Note that the Third Orders of both bearing signals are virtually identical at full speed. Also, as the cursors on the display of Figure 10 show, the second order of Channel 2 is nearly 10 times greater than the first order of Channel 2 at full speed.

The Order Tracking displays shown here can be viewed in Real-Time, as the machine speeds up or coasts down, or can be viewed from stored data in a post-test mode.

3-D Waterfall displays:

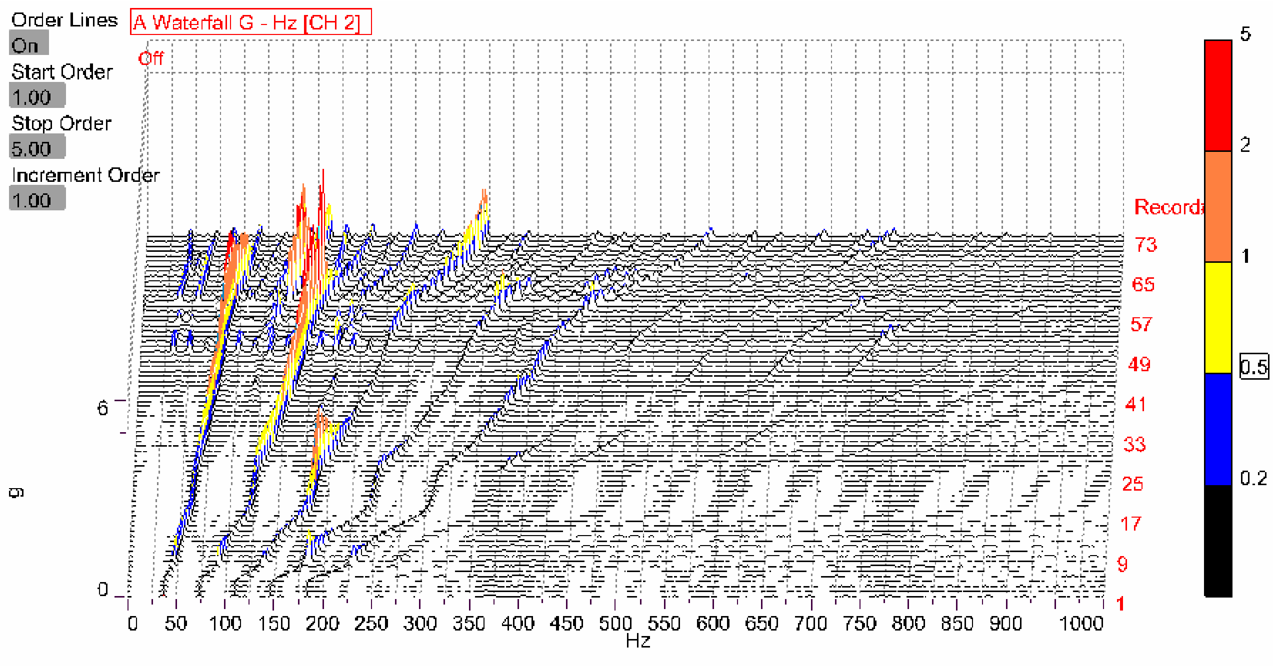


Fig. 11; 3-D display of g vs. frequency vs. Record No. for Channel 2

Note that in Figure 11 there are 5 Order lines superimposed on the display in addition to the vibration spectra. However, the Order lines do not appear straight because the records were not taken at even increments of time or rotor speed. This can be corrected as shown below.

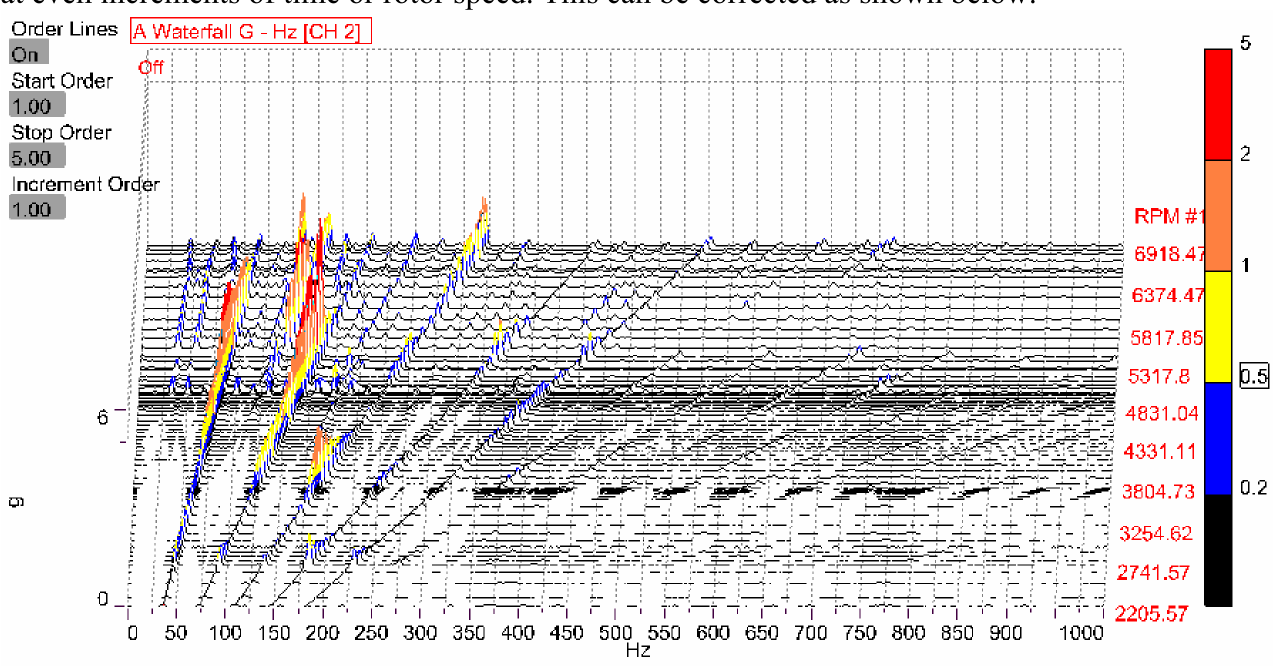


Fig. 12; 3-D display of g vs. frequency vs. RPM for Channel 2

By selecting RPM as the 3rd axis the Order lines automatically line up in a straight line.

Multiple Waterfall displays:

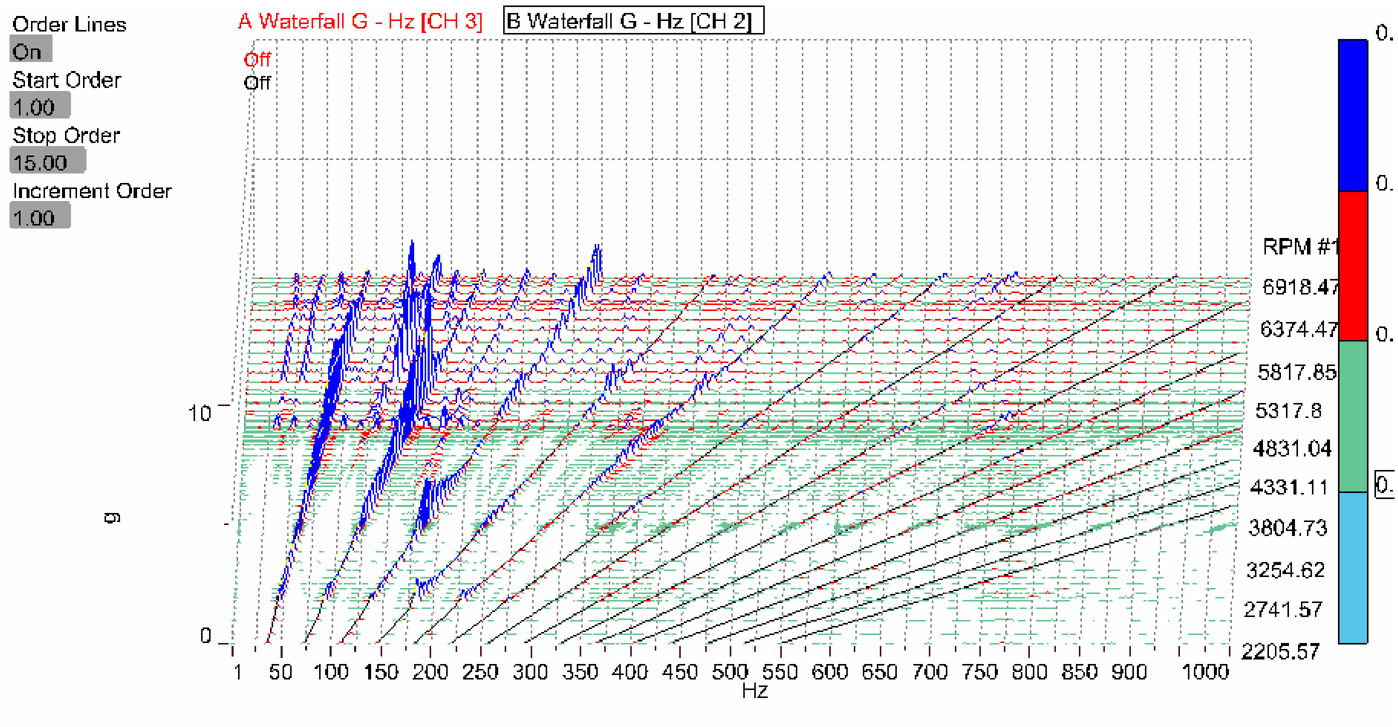


Fig. 13; 3-D Waterfall display with 2 active traces for CH3 and CH2

Multiple channels can be selected for a Waterfall display. But generally, it would be too confusing to observe and analyze Waterfall traces from multiple transducers simultaneously. So once the traces have been selected for display, simply click on the desired trace descriptor to see that trace. In Figure 13, the data for Channel 2 is shown since the descriptor B Waterfall G - Hz [CH 2] has been highlighted. In this way 3, 4 or more Channels can be selected and brought forward with a single click.

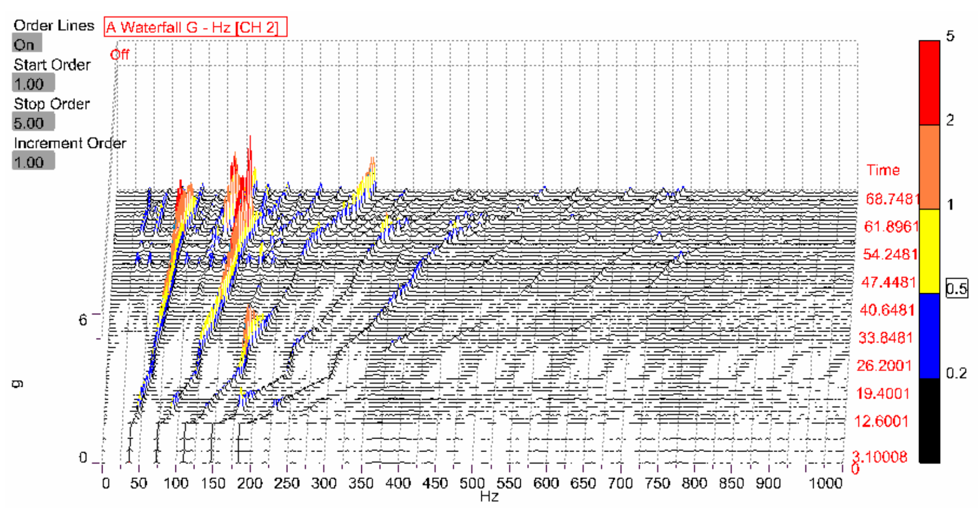


Fig. 14; Channel 2 data displayed as g vs. Frequency vs. Time of Acquisition

Spectral Intensity displays:

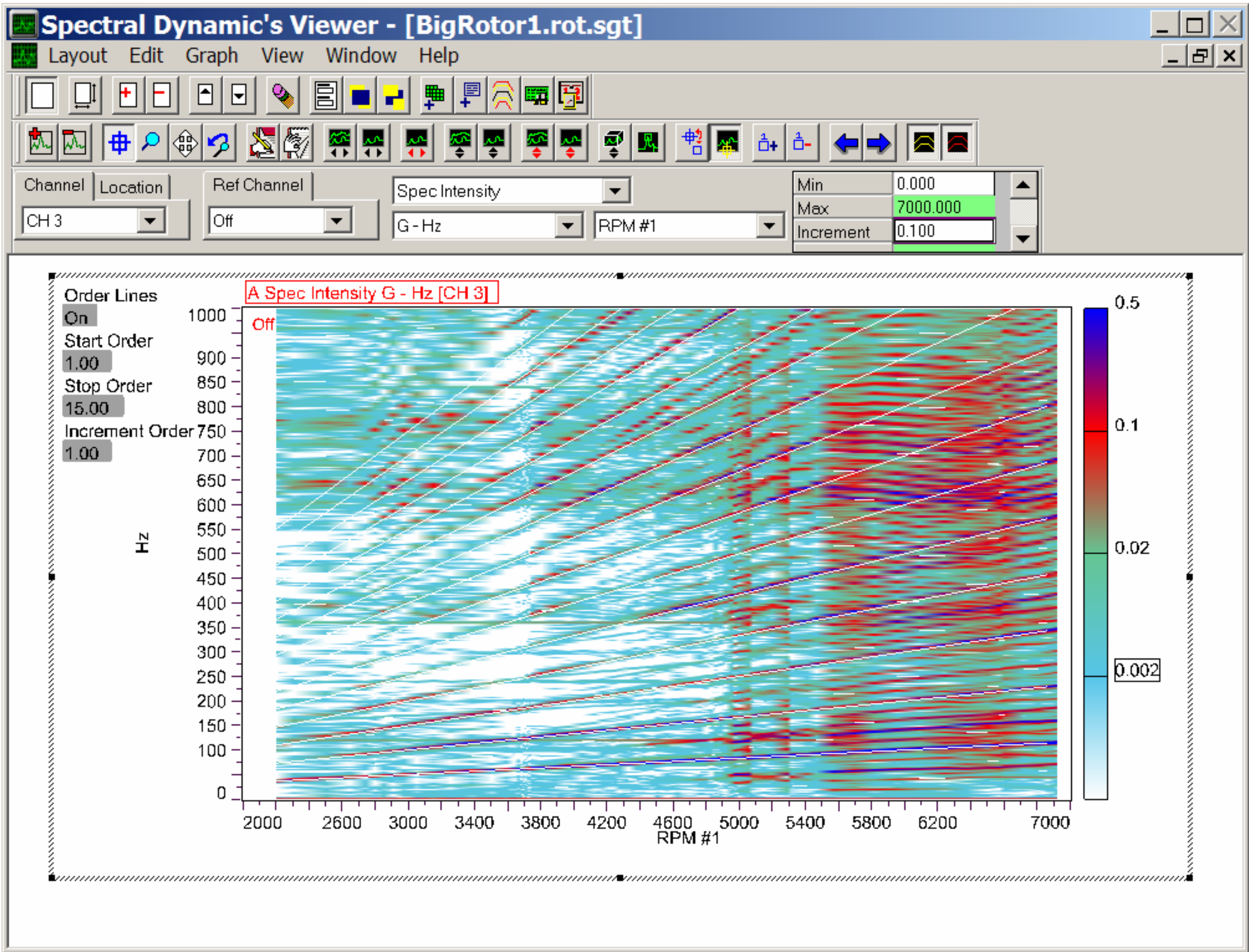
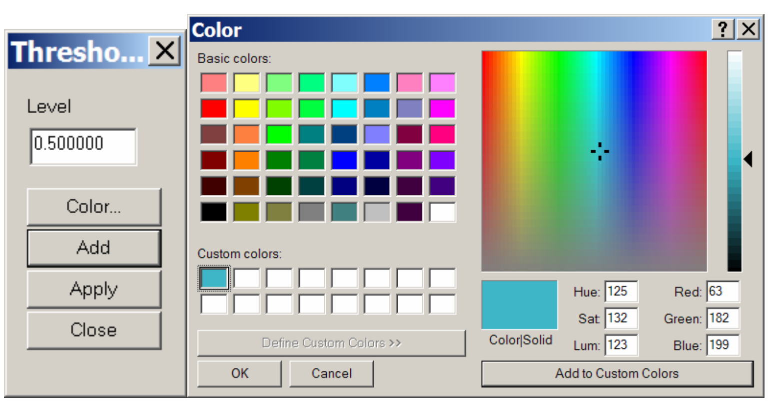


Fig. 15; Spectral Intensity plot of Channel 3 vibration, RPM vs. Frequency

In a Spectral Intensity diagram, the magnitude of the vibration or noise is shown as a color palette. This makes it very simple to set thresholds of critical levels and realize at a glance whether or not these thresholds have been exceeded. The association of a particular color with a specific level of Sound or Vibration can be quickly selected or modified through simple menu selection as shown.



Campbell Diagrams:

More than 50 years ago, Dr. Joseph Campbell working in the Rotor Dynamics Laboratory of the General Electric Steam Turbine facility in Schenectady, New York, was looking for a way to present information about turbine blade resonances during critical startups of large steam turbines. He needed to evaluate the performance of a rotating turbine blade (or bucket) during runup or coast down since the reliability of these blades is critical to successful turbine operation. A turbine blade for use in steam or gas turbines is one of the few structures in Engineering which is purposely designed to have extremely low damping. These blades experience fluctuating forces when they pass through non-uniform fluid flow from stationary vanes (or nozzles). The result can be a series of modal excitations including forward and backward whirl modes, gyroscopic effects and structural resonances. Depending on the type and location of transducers during runup, many different responses can be seen. Dr. Campbell determined that a display of response frequency vs. excitation RPM would be optimum and decided on the use of circles whose diameter would give a direct indication of the level of strain, vibration or other measured parameters.

Spectral Dynamics (SD) produced our first Campbell Diagram system in 1969, based on the SD301 Real Time Analyzer, and were very pleased to sell one of these systems to GE in Schenectady. Since that time SD has continued to provide “true” Campbell Diagram displays as well as “modified” Campbell Diagrams.

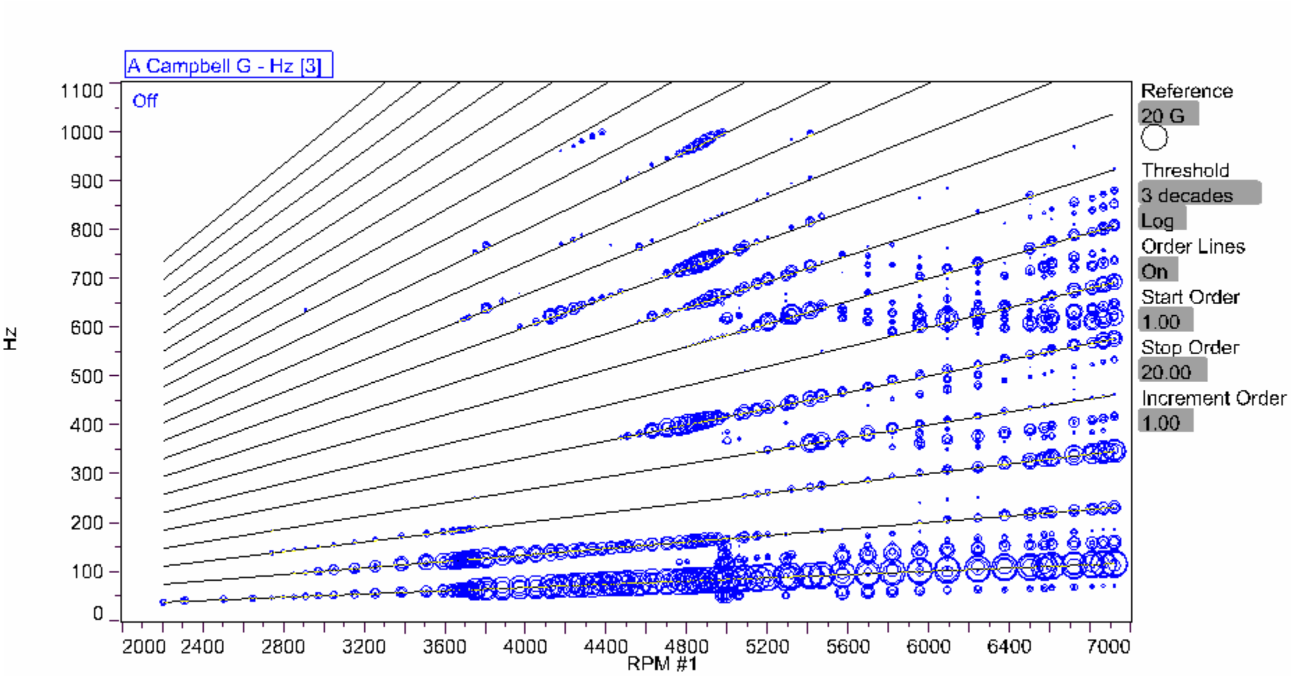


Fig. 16; Channel 3 acceleration shown as True Campbell Diagram

Figure 16 shows a classical Campbell Diagram of bearing vibration. In addition to vibration at integer Orders, the display shows non-integer Order speed related vibration and some fixed frequency responses near 600 Hz.

The next figure shows a modified Campbell Diagram in which the ordinate has been changed from frequency to Order Number.

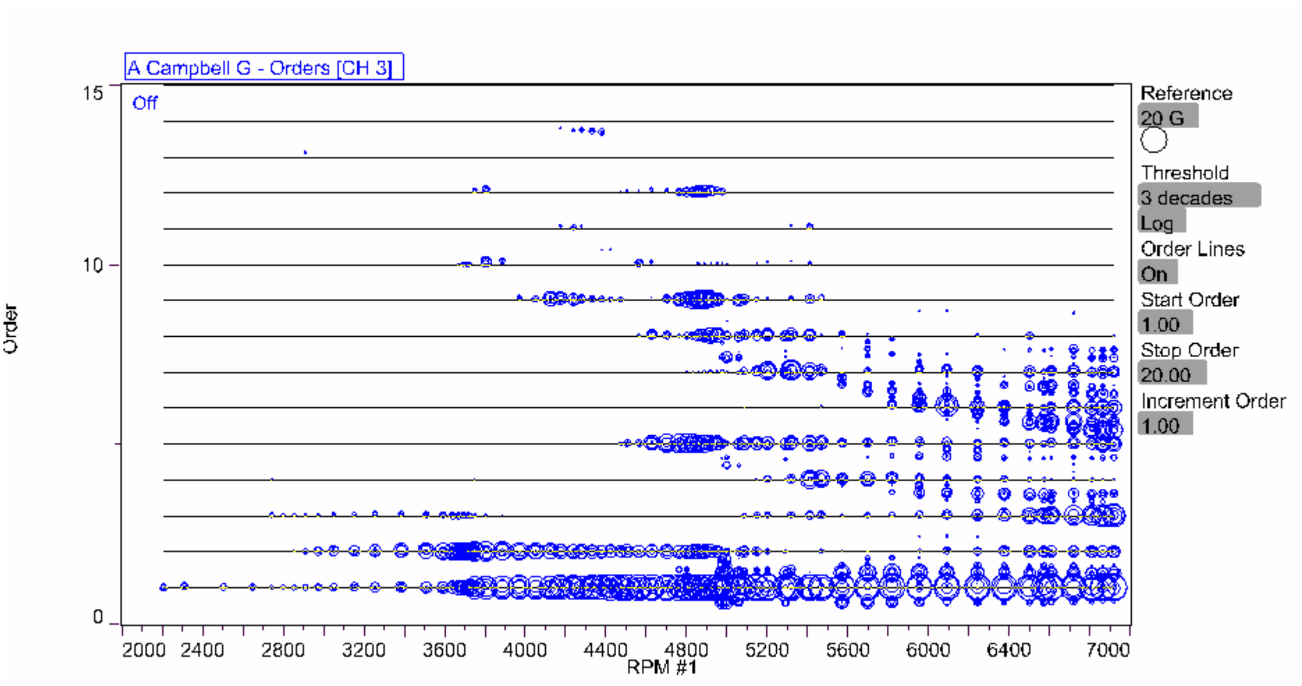


Fig. 17; Modified Campbell Diagram of Order Number vs. RPM

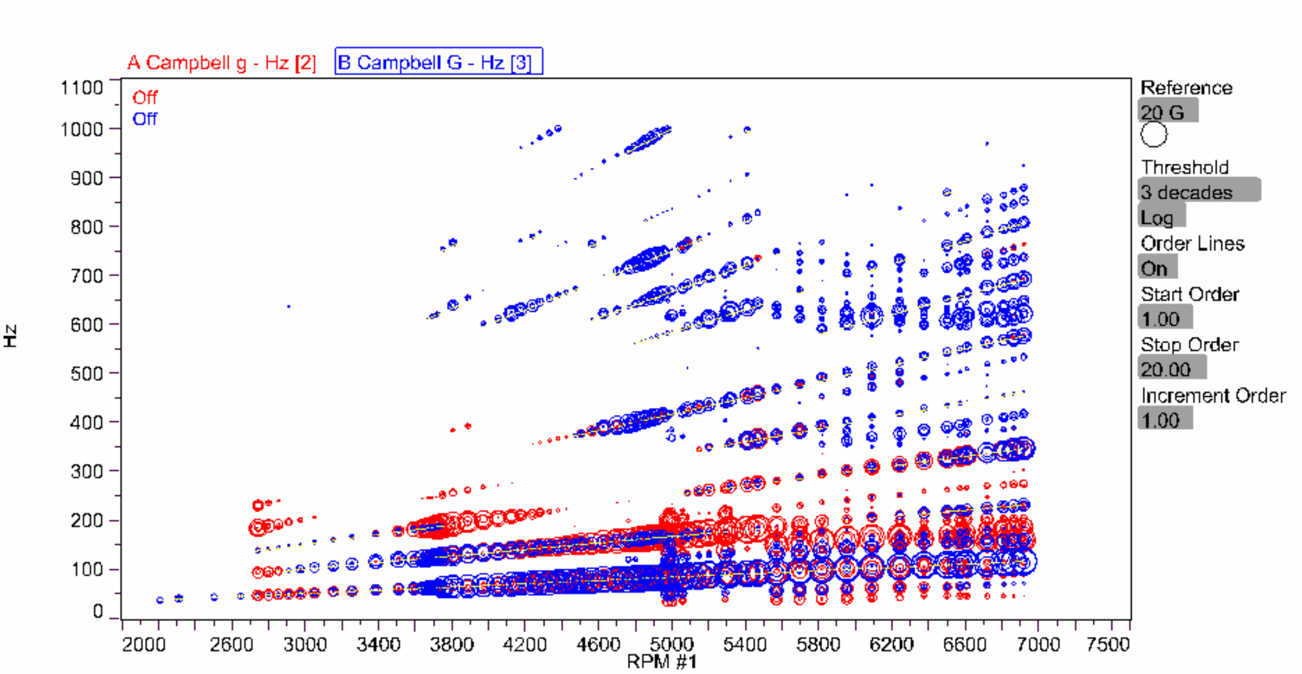


Fig. 18; Dual Campbell Diagram overlaying Channels 1 and 2

By selecting from the wide variety of choices available, many other displays are possible. And all displays can be viewed as data is being collected, in Real-Time. Some additional details are given in the Appendix.

Appendix A. Synchronous (Tracking) Sampling:

One of the challenges facing an Engineer who is trying to analyze rotating machinery vibration with an FFT, is to relate the measured vibration to specific machine properties, thus perhaps to particular machine components and possibly to gain an edge in predicting incipient machine failure. One of the best ways to do this is to move from the traditional fixed sampling FFT domain to the "machine speed" domain. If done correctly, this will eliminate many of the problems which occur when trying to determine precise machine/vibration relationships on a moving target. To do this requires several things including a good Tachometer or speed reference and a thorough and precise way of performing sampling and signal processing using this speed information.

Synchronous or Tracked sampling requires that the sampling rate, and thus the low pass anti-aliasing filter cutoff points, be adjusted continuously with respect to machine RPM changes. As the machine RPM changes, so does the sampling rate and low pass filter cutoff change to maintain a synchronous relationship between the data samples and the fundamental machine speed. In the SD implementation, the sampling time increment is continuously modified from data point to data point. Instead of using a fixed delta time increment, the RMA data domain is often referred to as the angle or Order domain. In this domain, true Order related events are completely synchronous with the reference RPM and do not display the typical smearing observed by fixed sampling rate processing. The ability to accurately observe Order related events often requires that the sample rate be constantly adjustable to maintain the proper digitizing perspective. For Tracking Sampling, since the delta time increment is constantly changing, the data frame (block) time value is also constantly changing.

The user typically specifies the desired maximum Order and the software selects the proper tracking ratios to be utilized during the sampling rate/filter tracking process. Tracking sampling is also useful for fixed machine speed cases where accuracy of Order extraction is important since there is no "smearing" of the Order data due to slight fundamental speed variations or drift. Of particular importance is the fact that both the sampling rate and associated low pass filter cutoffs are continuously modified thus maintaining alias-free data at all times. Tracking sampling can only be utilized when the Spectral Dynamics (SD) Tacho channel hardware is used in the PUMA or COUGAR. The quality of the tracking sampling is tied to the quality of the input Tacho signal and the maximum Order required.

Note that when the "Tracked Sampling" mode is selected, together with a "Sample Rate Source" such as RPM#1 and the desired number of "Max Orders", the Aliasing Filter cutoff frequency and the corresponding sampling rate are changed every input sample! Thus Spectral Dynamics is the only company today offering Real-Time, alias-free, Order related signal processing in addition to all of the Real-Time displays shown earlier.

In the next section Order related displays will be shown both with and without the use of Tracked Sampling.

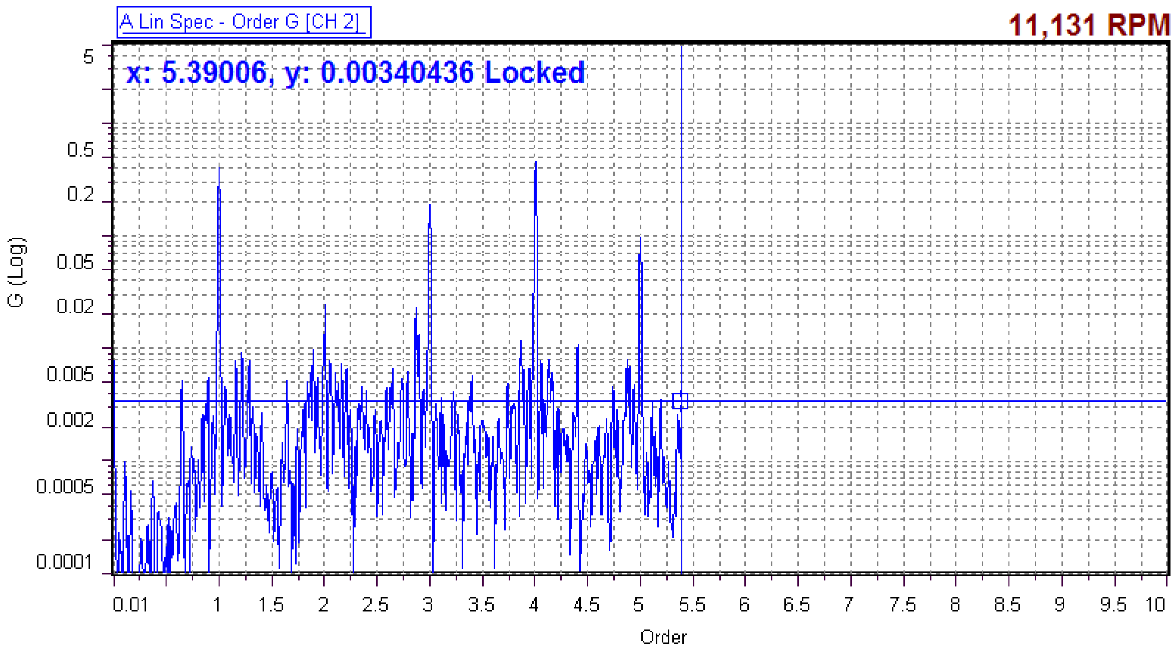


Fig. A1; Order related Vibration Spectrum with fixed sampling rate

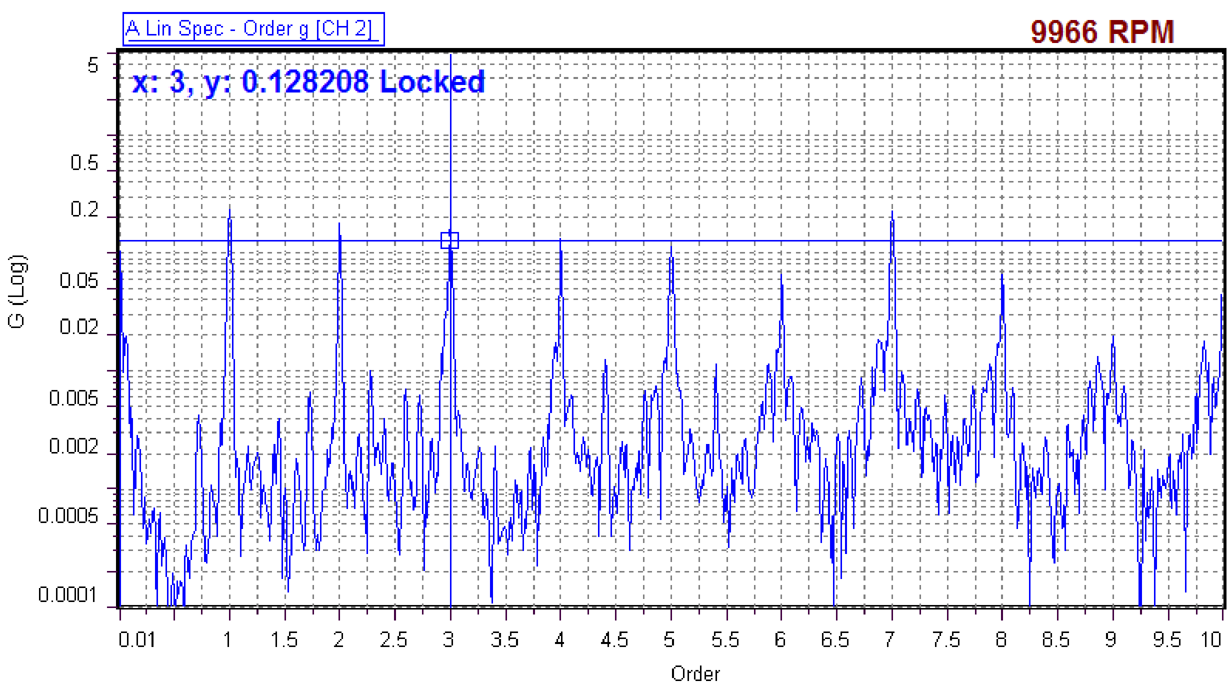


Fig. A2; Order related Vibration Spectrum with Tracking Sampling

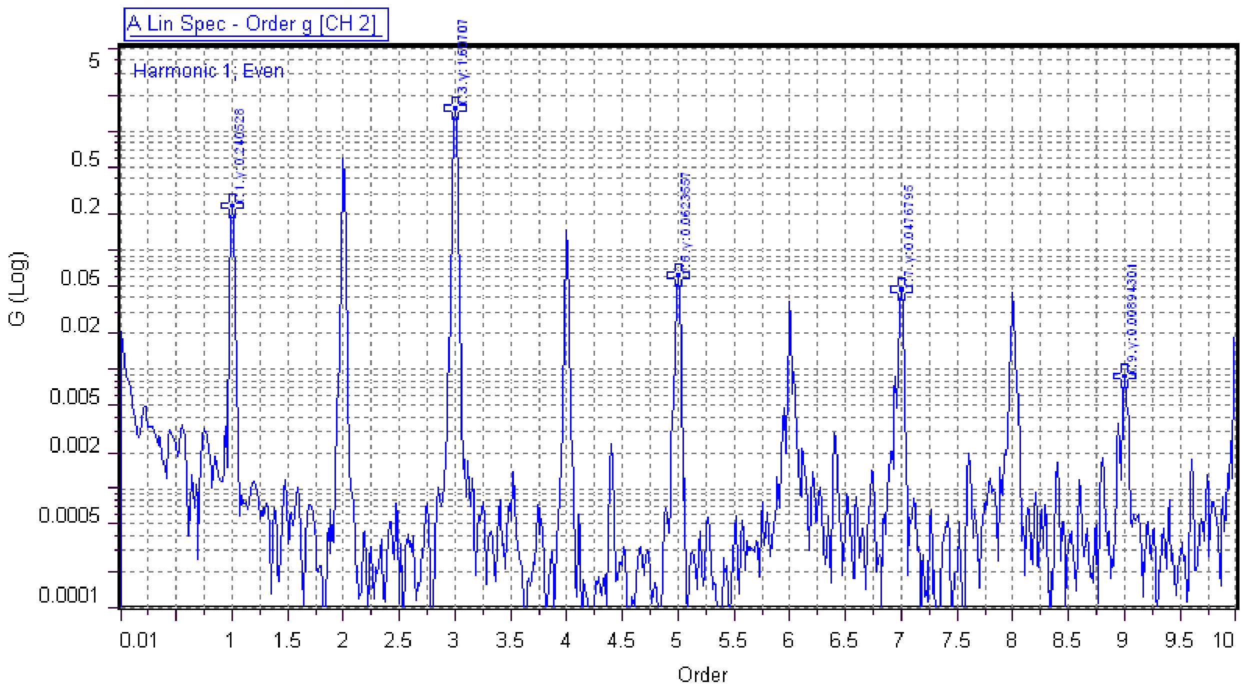


Fig. A3; Order related Vibration Spectrum with Tracking Sampling and Harmonic Cursors

First notice Figure 8 on page 7. This analysis was done with fixed sampling. Thus although Orders can be shown correctly, the maximum Order achievable at 6,918.47 RPM with a full scale frequency range of 1,000 Hz was 8.672. But note also that the cursor indication, for the first Order shows 0.997 Orders, not 1.0, even with excellent interpolation. On the other hand, in Figure A2 on the previous page, an exact indication of Order 3 is shown on the cursor since the sampling and the resulting processed data is “locked” to the machine speed. This is seen even more dramatically in the Harmonic Cursor readout in Figure A3 above. Here each of the odd-numbered orders is shown as an exact integer Order with no interpolation required.

Appendix B. Using Gates for flexible Acquisition:

The use of dual Tacho inputs and Real-Time Tracking Sampling is even further enhanced through the use of a flexible Gating arrangement in RMA.

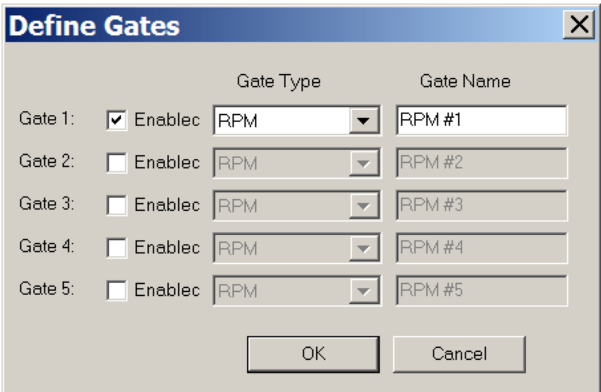


Fig. B1; Basic Gate definitions

Up to 5 Gates may be established with 4 different types of Gates available. In the current example a single RPM Gate was used to "trigger" the beginning of the data run.

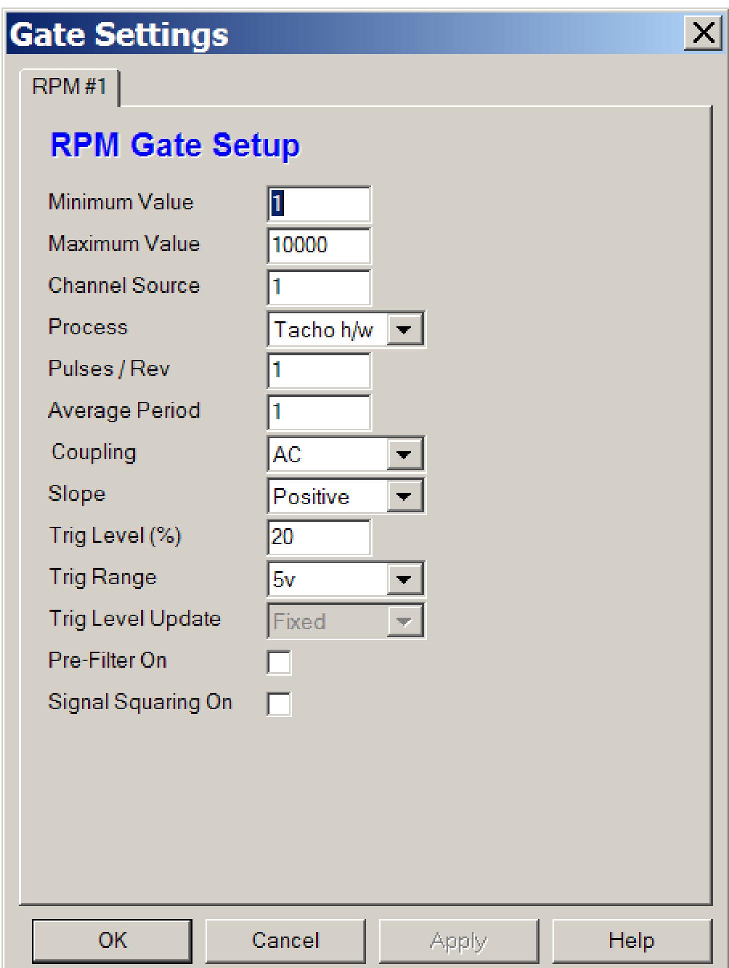


Fig. B2; RPM Gate Settings

Setup page for establishing key parameters prior to a data run. Desired Min and Max values as well as # of Pulses per Rev and trigger values are set here. Each Gate Type entered in Fig. B1 creates a corresponding page in the Gate Settings.

Acquisition Tags

	Data Tag	Start Condition	Value
1	Time	Not Used	Not Used
2	RPM #1	Greater Than	20.00
3	RPM #2	Inactive	0.00
4	RPM #3	Inactive	0.00
5	RPM #4	Inactive	0.00
6	RPM #5	Inactive	0.00

	Data Tag	Stop Condition	Value
1	Time	Inactive	0.00
2	RPM #1	Greater Than	9000.00
3	RPM #2	Inactive	0.00
4	RPM #3	Inactive	0.00
5	RPM #4	Inactive	0.00
6	RPM #5	Inactive	0.00

	Data Tag	Gate Change	Value
1	Time	Inactive	0.00
2	RPM #1	Either	5.00
3	RPM #2	Inactive	0.00
4	RPM #3	Inactive	0.00
5	RPM #4	Inactive	0.00
6	RPM #5	Inactive	0.00

OK Cancel

Selections for Acquisition Start and Stop conditions as well as direction of Δ RPM triggering are set here for each defined Gate.

Fig. B3; RPM related Acquisition Tags and Settings

Gating acts like a data Channel trigger and operates on Processed data. In conjunction with the functions described earlier, added elements of flexibility and processing power are available through the judicious use of the Gates.