



NATIONAL INSTRUMENTS™
LabVIEW™

Order Analysis Toolset for LabVIEW User Manual

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About This Manual

This manual provides information about the Order Analysis Toolset for LabVIEW, including system requirements, installation, and suggestions for getting started with order analysis and the toolset. The manual also provides a brief discussion of the order analysis process and the algorithm used by the Order Analysis Toolset for LabVIEW.

Conventions

The following conventions appear in this manual:

» The » symbol leads you through nested menu items and dialog box options to a final action. The sequence **File»Page Setup»Options** directs you to pull down the **File** menu, select the **Page Setup** item, and select **Options** from the last dialog box.



This icon denotes a note, which alerts you to important information.

bold

Bold text denotes items that you must select or click on in the software, such as menu items and dialog box options. Bold text also denotes the names of parameters, dialog boxes, sections of dialog boxes, windows, menus, palettes, and front panel controls and buttons.

italic

Italic text denotes a cross reference.

monospace

Text in this font denotes text or characters that you should enter from the keyboard, sections of code, programming examples, and syntax examples. This font is also used for the proper names of disk drives, paths, directories, programs, subprograms, subroutines, device names, functions, operations, variables, filenames and extensions, and code excerpts.

Related Documentation

The following documents contain information that you might find helpful as you read this manual:

- *Order Analysis Toolset for LabVIEW Help*, available by selecting **Help»Order Analysis**
- *Getting Started with LabVIEW*

- *LabVIEW User Manual*
- *LabVIEW Help*, available by selecting **Help»Contents and Index**

Introduction

This chapter introduces the Order Analysis Toolset for LabVIEW and the Order Analysis Start-Up Kit, outlines system requirements, and gives installation instructions. The CD in your software package contains the Order Analysis Toolset for LabVIEW and the Order Analysis Start-Up Kit.

Order Analysis Toolset for LabVIEW

The Order Analysis Toolset for LabVIEW is a collection of virtual instruments (VIs) for LabVIEW. These VIs help you measure and analyze noise or vibration signals generated by rotating machinery. The Order Analysis Toolset for LabVIEW provides tools to assist you in completing the following analyses:

- Calculation and examination of rotational speed
- Measurement of the power distribution in the frequency domain or in the order domain as a function of either time or rotational speed
- Extraction of the order components from the original noise or vibration signal
- Measurement of the overall level of any order component as a function of rotational speed

The Order Analysis Toolset for LabVIEW includes easy, intermediate, and advanced VIs. The easy VIs and the intermediate VIs are built from the advanced VIs and group the advanced VIs into a tidy, logical sequence. Use the easy and intermediate VIs to perform simple tasks in just a few steps. For experienced LabVIEW users, the advanced VIs provide flexibility and increased control of the analysis process. Refer to the *Order Analysis Toolset for LabVIEW Help*, available by selecting **Help»Order Analysis**, for more information about individual VIs.

Using the Order Analysis Toolset in the Analysis of Rotating Machinery

Order analysis is a powerful tool for analyzing rotating machinery when the rotational speed may change over time. However, to successfully use the Order Analysis Toolset for LabVIEW, you must observe the following condition and restriction:

- A signal directly related to the fundamental rotational speed must be provided, such as a pulse train from a tachometer.
- Do not use the Order Analysis Toolset for LabVIEW for analysis of frequencies not excited by a fundamental frequency, such as the modes encountered in modal analysis. Although the different modes in the frequency domain can be observed, there is no simple relationship among those different modes. Usually, the frequencies of different modes are not simply a multiple of a fundamental frequency over time.

Order Analysis Start-Up Kit

The Order Analysis Start-Up Kit is automatically installed when you install the Order Analysis Toolset for LabVIEW. The Start-Up Kit includes a LabVIEW application for order analysis and source code. The application is built with components found in the Order Analysis Toolset for LabVIEW.

The simple processes included in the application enable you to perform data acquisition, tachometer analysis, and order analysis on the noise or vibration signals generated by rotating machinery. This application provides an example of how the Order Analysis Toolset for LabVIEW can help you successfully complete your analysis projects. You also can use it as a simple order analysis VI in your own projects or as a tool to learn the basics of building and using Order Analysis Toolset for LabVIEW VIs.

Getting Started

If you are just beginning to gain experience with order analysis, read Chapter 2, *Introduction to Order Analysis*, of this manual and experiment with the Order Analysis Start-Up Kit. Chapter 2, *Introduction to Order Analysis*, provides basic information about order analysis that you might find useful. The Order Analysis Start-Up Kit gives you the opportunity to see how the Order Analysis Toolset for LabVIEW can help in your analysis of the noise and vibration generated by rotating machinery.

Refer to Chapter 3, *Order Analysis Algorithm*, of this manual for a brief description of the algorithm used in the Order Analysis Toolset for LabVIEW.

If you have experience with order analysis, the example VIs can help you learn how to use the Order Analysis Toolset for LabVIEW. Refer to Chapter 4, *Example VIs*, in this manual for information about the example VIs.

Refer to the *Order Analysis Toolset Help*, available by selecting **Help»Order Analysis**, for information about individual VIs.

System Requirements

The following are the minimum system requirements needed to run the Order Analysis Toolset for LabVIEW:

- Pentium 233 or faster processor
- 64 MB of RAM minimum, 128 MB of RAM recommended
- 20 MB of disk storage space for full installation
- Microsoft Windows 95 or later or Microsoft Windows NT 4.0 or later with service pack 3
- LabVIEW 6.0 or later Full Development System or Professional Development System



Note Order analysis is a memory-intensive task, especially when you apply maps. Increasing the amount of RAM in your system can significantly increase system performance.

Installation

This section describes the procedures for installing the Order Analysis Toolset for LabVIEW.

Windows 95/98/Me

Complete the following steps to install the Order Analysis Toolset for LabVIEW on a computer running Windows 95, 98, or Me.

1. Insert the Order Analysis Toolset for LabVIEW CD into the CD-ROM drive.
2. The installation program will run automatically if the autoplay feature in Windows is enabled. If the installation program does not start automatically, run `setup.exe` in the `Toolset` directory on the CD.
3. Follow the instructions that appear on your screen.

Windows NT/2000

Complete the following steps to install the Order Analysis Toolset for LabVIEW on a computer running Windows NT or Windows 2000.

1. Log on to Windows as an administrator or as a user with administrator privileges.
2. Insert the Order Analysis Toolset for LabVIEW CD into the CD-ROM drive.
3. The installation program will run automatically if the autoplay feature in Windows is enabled. If the installation program does not start automatically, run `setup.exe` in the `Toolset` directory on the CD.
4. Follow the instructions that appear on your screen.

Introduction to Order Analysis

Often, it is neither possible nor desirable to physically open up a system and study it. In many such instances, we can gain knowledge about a system by measuring and analyzing signals associated with the system. For example, physicists and chemists use the spectrum generated by a prism to distinguish between different types of matter. Astronomers apply spectra, as well as the Doppler effect, to determine distances between planets. Physicians use the electrocardiograph (ECG), which traces the electrical activity of the heart, as a nonsurgical means of diagnosing heart problems. Signal analysis is a fundamental tool for understanding nature.

The analysis techniques provided by the Order Analysis Toolset for LabVIEW can assist engineers and scientists in the study, design, and monitoring of rotating machinery. With this toolset, engineers and scientists can better understand, through sound or vibration signals, systems that include rotational components, systems such as automobiles, airplanes, air conditioners, and PC hard drives. The automotive and other industries refer to the techniques included with this software as order analysis.

Order Analysis Fundamentals

Order analysis and harmonic analysis have much in common. The term harmonic refers to frequencies that are integer or fractional multiples of a fundamental frequency. When dealing with rotating machinery, you can often hear noise and feel vibration created by the parts, such as bearings, gears, and blades, associated with the rotating components. Vibration of the rotating components creates noise and vibration signals. The machine rotational speed is the source of these signals, and the frequency-domain representations of noise and vibration behave as harmonics of the machine rotational speed. In many industries, the harmonics related to the rotational speed are referred to as orders, and the corresponding harmonic analysis is called order analysis. The harmonic at the same frequency as that of the rotational speed is the first order; the harmonic at twice the frequency of the rotational speed is the second order and so on. Therefore, in one sense, order analysis can be thought of as an application of harmonic analysis for rotating machinery.

Figure 2-1 shows the relationship between frequency and order spectra. The top graph of Figure 2-1 shows a vibration signal from a machine running at 3000 revolutions per minute (RPM). The rotational speed is computed from the tachometer signal, which is shown as the second graph. Assuming that speed remains constant during data acquisition, we can easily switch from the frequency domain to the order domain and vice versa by using the following formulas:

$$Frequency = \frac{RPM}{60} \times Order$$

$$Order = Frequency \times \frac{60}{RPM}$$

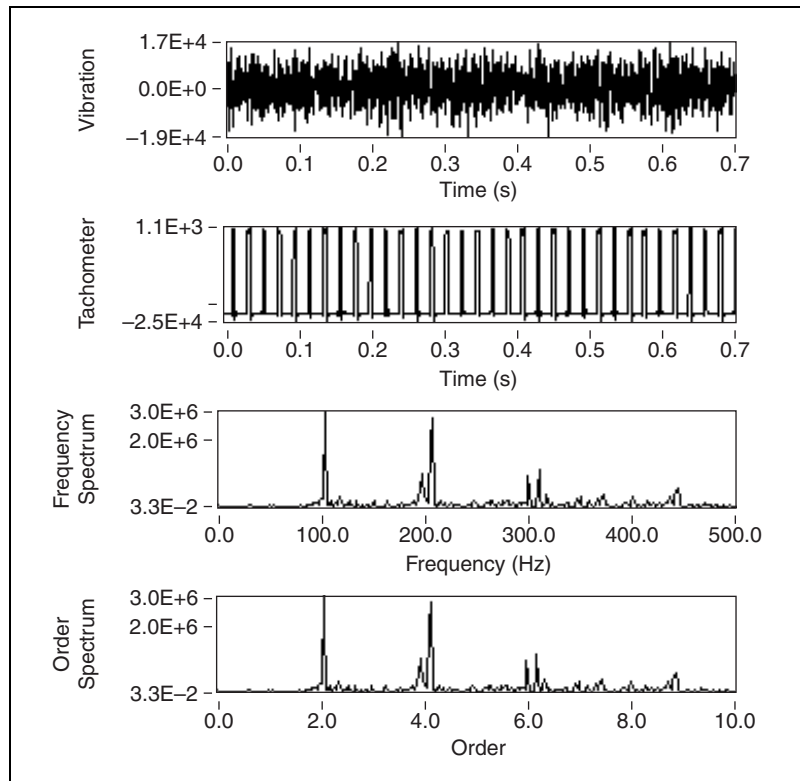


Figure 2-1. Order and Frequency Domain Display of a Shaft Rotating at 3000 RPM

The orders often reflect the physical characteristics of rotating machines. As in classical harmonic analysis, by analyzing the phase and amplitude relationships between different orders, engineers and scientists often can

discover a great deal about the system in which they are interested. For example, the following relationships have been observed:

- Imbalance results in a spectral peak at the first order.
- Misalignment or bending of the shaft generates a large second order.
- Oil whirl might lead to strong fractional orders.
- Gears, belts, and blades might enhance high orders.

Figure 2-2 shows the order spectrum of the vibration signal measured from a PC fan with seven blades and four coils. In Figure 2-2, there are strong fourth and seventh orders. The four coils inside the fan drag and push the shaft four times per revolution, causing the strong fourth order. The strong seventh order is caused by the seven blades, which pass the position of the sensor seven times per revolution.

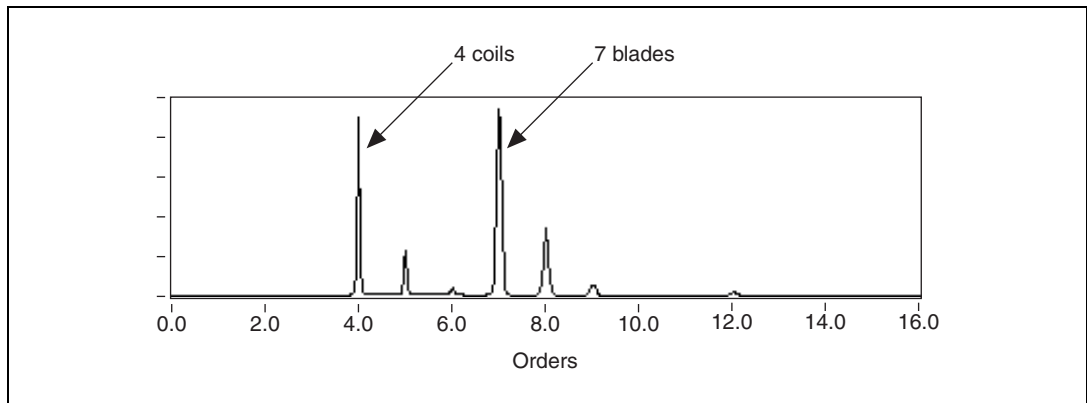


Figure 2-2. Order Spectrum of a PC Fan with Seven Blades and Four Coils

Like classical harmonic analysis, order analysis is a powerful tool for engineers and scientists to better understand the condition of rotating machinery. Compared to harmonic analysis, however, order analysis is more effective for the analysis of rotating machinery. Order analysis can be used when a machine runs at a constant speed or when the rotational speed varies.

Comparison of Order Analysis and Harmonic Analysis

In classical harmonic analysis, it is well understood that the fundamental frequency does not change over time. Although the phases and amplitudes of the individual harmonics can vary over time, the center frequencies of all the harmonics are constant. In other words, harmonic analysis is only suitable for rotating machinery when the rotational speed remains constant.

At a constant speed, orders can be well identified from both the conventional power spectrum and the frequency-time spectral map. Figure 2-3 depicts the analysis of a vibration signal acquired from a PC fan running at a constant speed. The bottom plot depicts the tachometer pulses and the signal from an accelerometer mounted on the fan. The plot on the left illustrates a conventional power spectrum based on the fast Fourier transform (FFT). The upper-right plot shows the frequency-time spectral map computed from the short-time Fourier transform (STFT) with a 1024-point Hanning window. Because the fan rotated at a constant speed during data acquisition, we can identify several peaks in both the power spectrum and the frequency-time spectral map. These peaks indicate different orders and appear in the STFT as white lines.

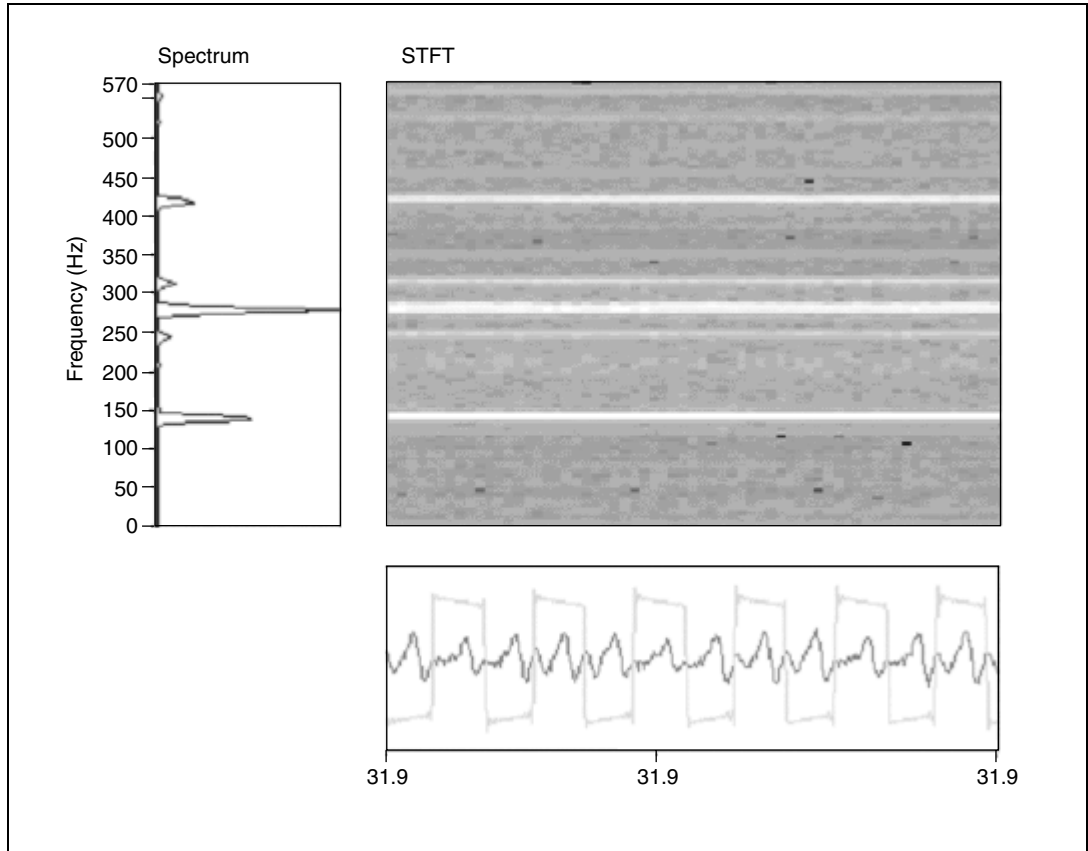


Figure 2-3. Fan Runs at Constant RPM

In addition to rotating machinery running at a constant speed, in practical applications, engineers and scientists are often interested in tests involving run-up and run-down. Like a swept-sine stimulus, testing run-up and run-down provides a stimulus over a wide range of frequencies. Run-up and run-down is a standard procedure for testing rotating machinery in many industrial applications.

What happens in the conventional power spectrum if the rotational speed changes? Fourier analysis theory tells us that the frequency bandwidth of a signal is proportional to the change in the frequency and amplitude of that signal. The faster the frequency changes, the wider the overall frequency bandwidth becomes, as measured from the power spectrum.

Figure 2-4 illustrates a conventional power spectrum on the left and the frequency-time spectral map on the right for a signal with constant frequency and amplitude. The overall frequency bandwidth is proportional to the change in frequencies. When the frequency and amplitude are constant with time, the overall frequency bandwidth, as measured from the conventional power spectrum, will be the minimum.

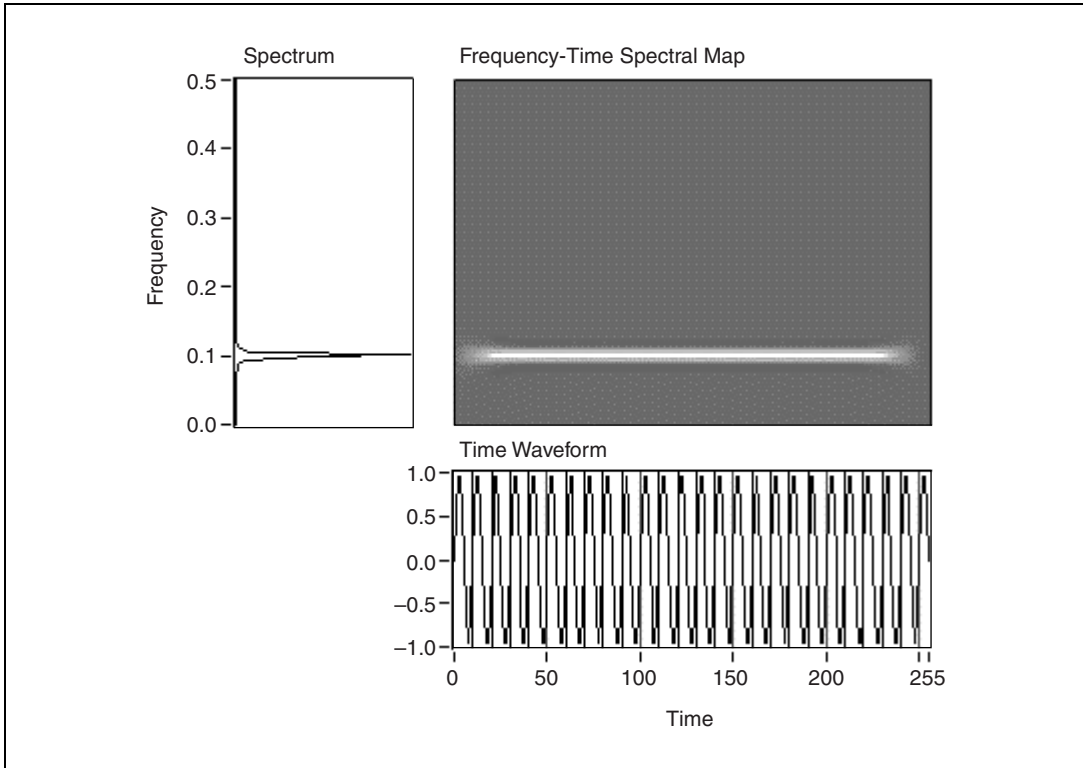


Figure 2-4. A Constant Frequency

Figure 2-5 depicts a signal with frequency content that changes as a function of time. Although at each time instant the signals in Figure 2-4 and Figure 2-5 have similar frequency bandwidths, the overall frequency bandwidths, shown in their corresponding power spectra, are rather different. As you can see from the two FFT-based power spectra in Figures 2-4 and 2-5, the overall frequency bandwidth of the signal whose frequency increases with time in Figure 2-5 is much wider than that of the signal whose frequency is constant in Figure 2-4. When frequency or amplitude vary with time, the corresponding overall frequency bandwidth, as measured from the conventional power spectrum, becomes wide.

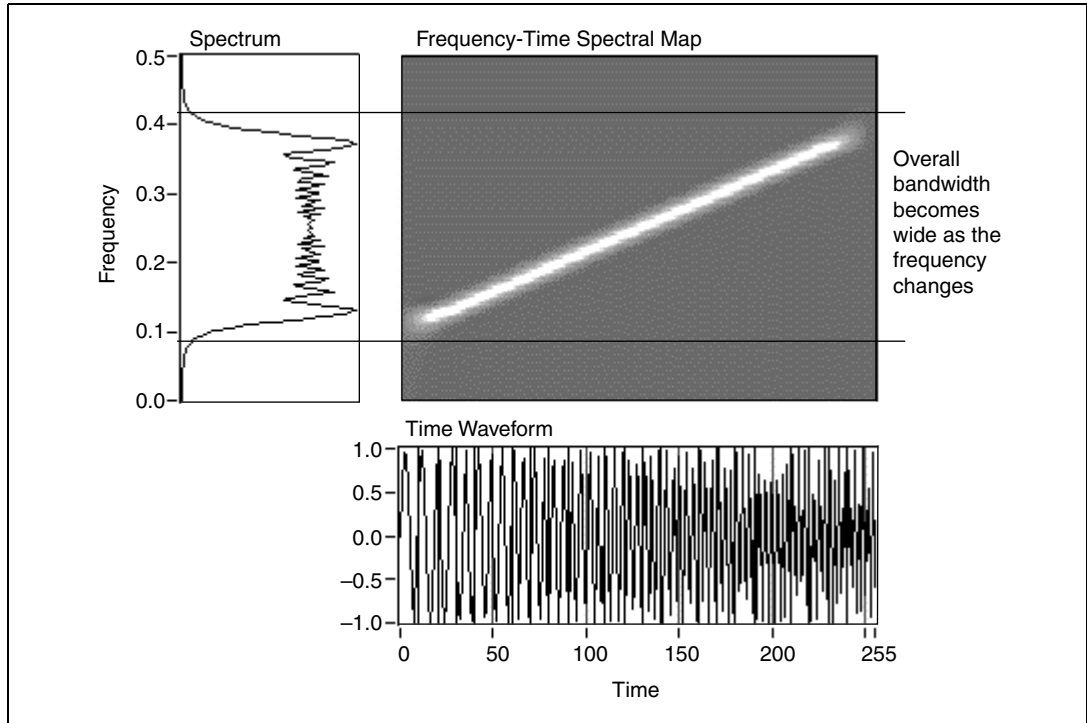


Figure 2-5. Frequency Changes Over Time

When the frequency bandwidth of the fundamental component widens, the bandwidths of the associated harmonics also widen. This spreading will eventually cause the frequency bandwidth of the harmonics to overlap in the conventional power spectrum. In this case, we will no longer be able to identify different harmonics from the power spectrum.

Figure 2-6 shows the signal from the same PC fan as the one depicted in Figure 2-3. However, in Figure 2-6, the rotational speed of the fan increases with time. As the rotational speed increases, both the fundamental frequency bandwidth and the frequency bandwidths of related orders widen, causing orders to overlap. Whether or not you can separate nearby orders in a power spectrum depends upon the rate of change in the rotational speed, the window used, and the highest order of interest. In Figure 2-6, the power spectrum has been measured over the entire duration of the fan run-up and does not really show any distinguishable orders. When the change of speed is large enough, the spectrum of orders will eventually overlap. Consequently, there will be no way to derive meaningful information about the individual orders.

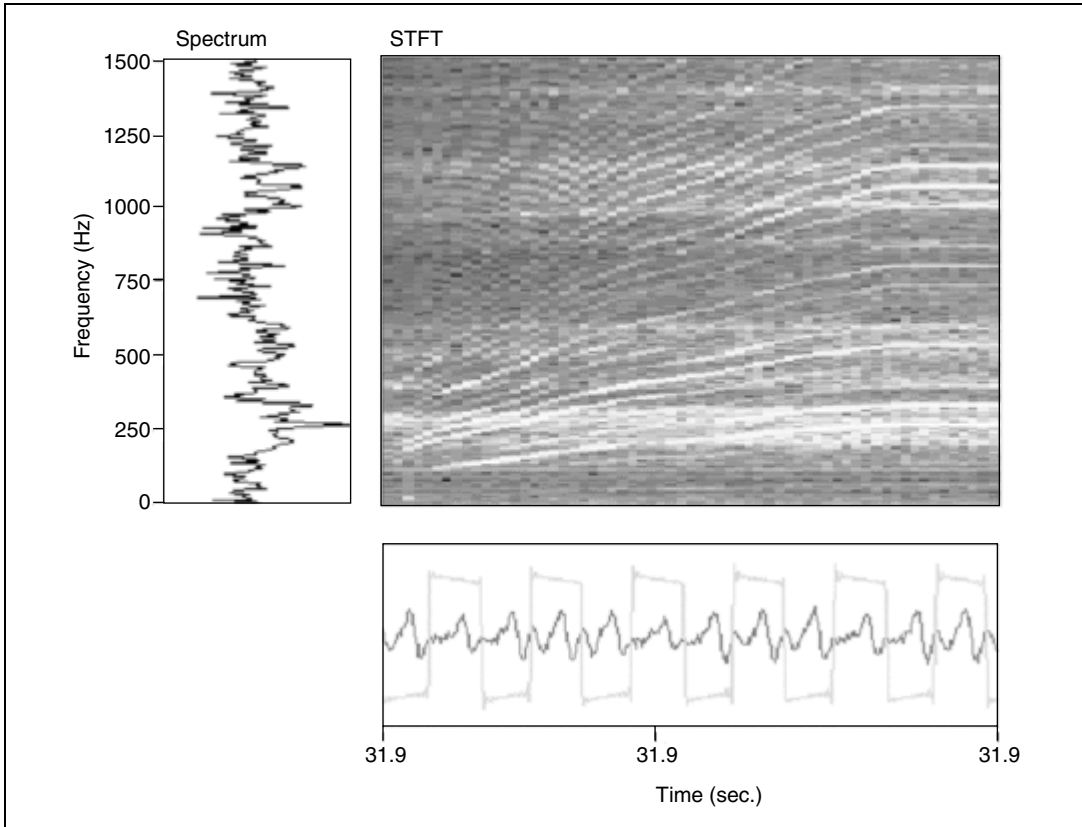


Figure 2-6. Fan Run-Up

When using the Fourier transform, you obtain the best results with the machine running at a constant speed while taking measurements. If you want to take measurements at a different speed, you have to run the machine to that speed and take another measurement. Such testing with discrete increments is time consuming and can be impossible when the speed cannot be well-controlled or the system is not allowed to run at the critical speed for a sufficient length of time.

One of the most important goals of order analysis is to uncover information about the orders that might become buried in the power spectrum due to a change in rotational speed. This goal is a central topic in the rest of this manual. While the orders are hidden in the overall power spectrum in Figure 2-6, we will see that they have distinguishable features in the frequency-time spectral map. This observation is the starting point for uncovering information about orders which are difficult to see in the power spectrum.

Applications of Order Analysis

In general, applying order analysis to noise or vibration data enables you to accomplish the following goals:

- Associating features of noise and vibration to the physical characteristics of machines
- Identifying characteristics that change with time and operating conditions, which is useful for machine troubleshooting, design, synthesis, and test and lifetime monitoring

Refer to the *Using the Order Analysis Toolset in the Analysis of Rotating Machinery* section in Chapter 1, *Introduction*, of this manual for information about a condition and restriction for using the Order Analysis Toolset for LabVIEW to analyze rotating machinery.

Order Analysis Algorithm

This chapter briefly discusses different methods of performing order analysis and introduces the algorithm used by the Order Analysis Toolset for LabVIEW.

Order Analysis Methods

The basic technique of order analysis involves obtaining the instantaneous speed of the rotating shaft of a machine from a tachometer or encoder signal. The speed is then correlated to the noise or vibration signal produced by the machine to obtain information about the order components such as waveforms, magnitudes, and phases. In order analysis, we focus on revolutions, rather than time, as the basis for signal analysis. Thus, in the spectrum domain, the focus is on orders rather than frequency components.

Currently, the following methods are generally used to perform order analysis:

- Re-sampling
- Adaptive filter
- Gabor transform

The Order Analysis Toolset for LabVIEW uses the Gabor transform method of order analysis.

Re-Sampling

Re-sampling is one of the most widely used solutions for order analysis. Figure 3-1 illustrates the re-sampling method. In the re-sampling method, time-samples are converted to angle-samples. The time-samples are samples of the physical signal which are equally spaced in time. The angle-samples are samples which are equally spaced in the rotation angle. The order components may then be analyzed by performing a traditional analysis method, such as the Fourier transform, on the angle-samples.

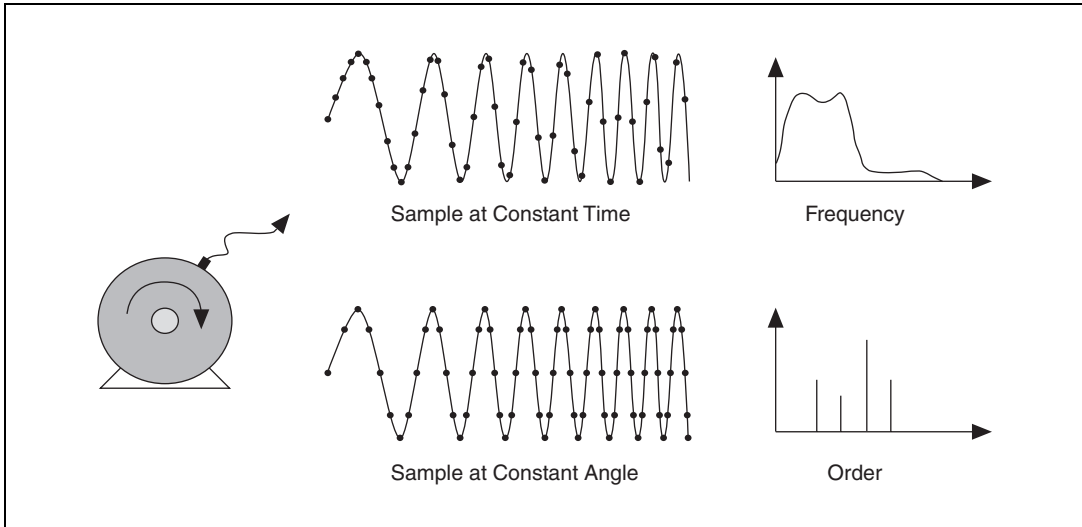


Figure 3-1. Re-Sampling

Angle-samples can be acquired by either hardware or software. The hardware solution uses an encoder or a multiplied tachometer signal to trigger the analog-to-digital conversion, which ensures a sampling process spaced equally in the rotation angle. This solution must use additional hardware devices and requires a tracking anti-aliasing filter.

The software solution first collects the measured signal and the tachometer signal at some constant rate. Then, interpolation or curve fitting is used to determine the instantaneous shaft angle at intermediate points between the tachometer pulses. The sampling time at the desired shaft-angular increment can then be calculated, and interpolation can be used to obtain new samples at the desired time.

After the angle-samples are obtained, they can be analyzed by performing a Fourier transform on them. Since the time domain has changed into the angle domain, the frequency domain now becomes the order domain. Thus, the order components can be separated and easily observed through either the order spectrum, which is actually the FFT spectrum, or the STFT spectrum.

Figure 3-2 shows the spectrum of angle-samples. The bottom plot, labeled Angle Samples, is the signal sampled at a constant angle-interval. The plot on the upper left, labeled Order Spectrum, shows the order spectrum by performing an FFT on the angle-samples. In the Order Spectrum plot, significant peaks appear at each order. At the top right, labeled Order vs.

Rev, is the result of a STFT on the angle-samples, where an order axis is used instead of a frequency axis. Each horizontal white line indicates the strong power at an integer order.

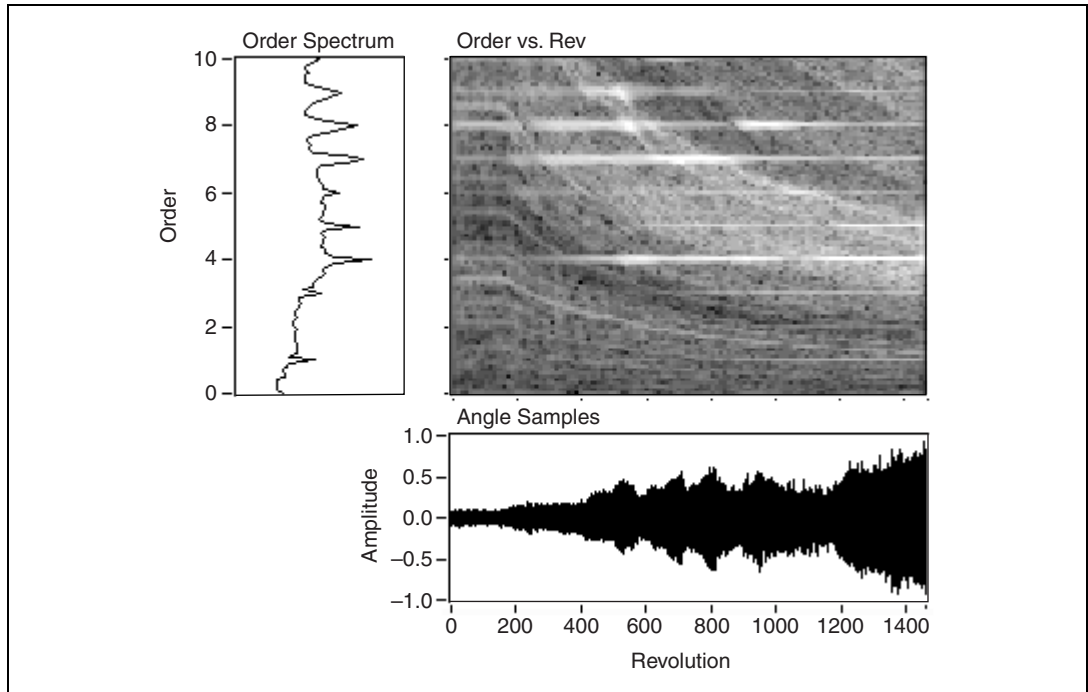


Figure 3-2. Spectrum of Angle-Samples

After the resampling process has taken place, recovery of a time waveform at a specific order can be difficult.

Adaptive Filter

Although the frequencies of the order components change as the rotational speed changes, in a relatively short time interval, the rotational speed and the frequency of order components can be considered to remain constant. The adaptive filter method of order analysis uses a band pass filter whose pass band frequency shifts according to the rotational speed and filters out the desired order.

The Vold-Kalman Order Tracking Filter is an example of the successful application of the adaptive filter method. With an accurate instantaneous speed signal as a guide, the Vold-Kalman Order Tracking Filter can extract two orders which are in close proximity to each other without ambiguity.

Gabor Transform

Gabor transform is one of the invertible joint time-frequency transforms. This means that any time-domain input signal, or an approximation thereof, can be recovered from its transform result by applying an inverse Gabor transform. The transform result is called a Gabor coefficient, and the inverse Gabor transform is known as Gabor expansion.

Gabor transform can be computed by short-time Fourier transform (STFT) or windowed Fourier transform. However, to ensure reconstruction, you have to take good care of the analysis window, the window shift step, or data blocks, and the signal edges. The following methods are used to ensure reconstruction:

- The ratio between the length of the analysis window and the window shift step must be greater than or equal to one. This ratio determines the time overlap. By default in the Order Analysis Toolset for LabVIEW, the ratio is set to four. For example, if the window length is 2048, then the window shift is 512.
- The analysis window has to be moved in such way that no information will be missed, especially at the beginning and the end of the data samples. Zero padding and wrap padding are two commonly used methods for dealing with the edge data.

In zero padding, as shown in Figure 3-3(a), the first window, as well as the last window, only covers one data block. The remaining area in the range of the window is filled with zeros. Thus, extra data samples are added. After Gabor expansion, the reconstructed data will be longer than the original data.

To avoid the reconstructed data being longer than the original data, an alternative is to consider the signal as periodic and use wrap padding. In wrap padding, when the first few data blocks are analyzed, data blocks at the end of the data samples are wrapped ahead to fill the windows. Data blocks may also be wrapped backward from the beginning of the data sample to the end. Figure 3-3(b) illustrates the wrap padding method. Figure 3-4 shows two examples of padding.

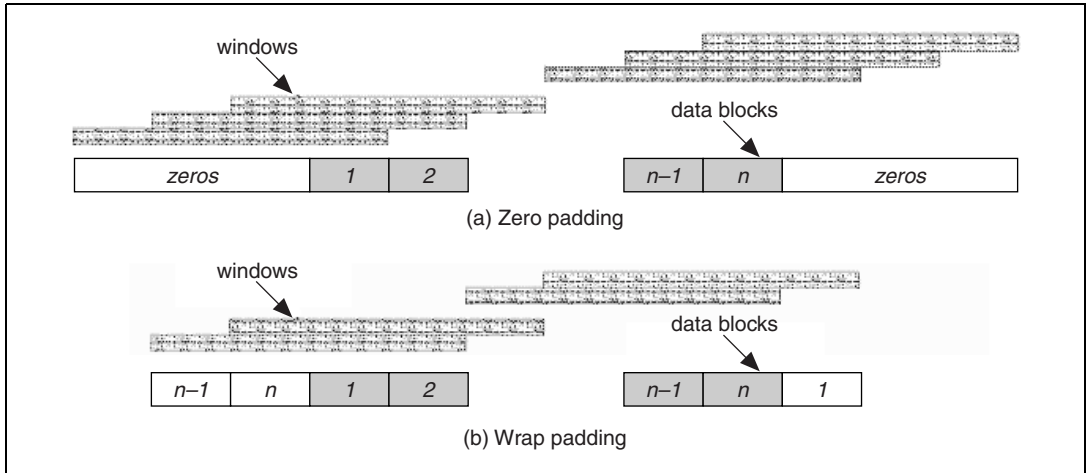


Figure 3-3. Padding Schemes

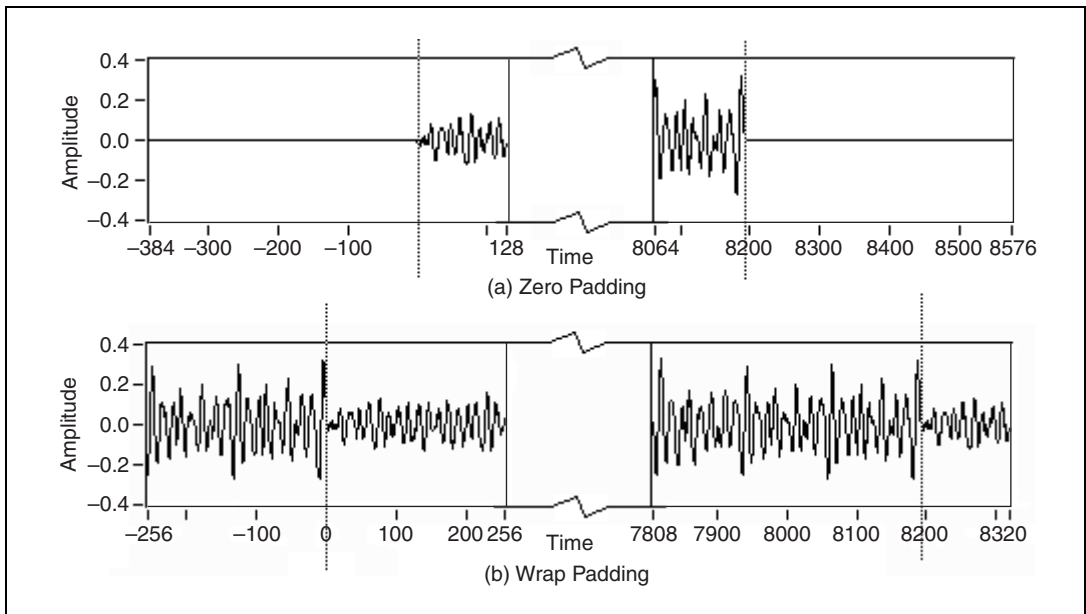


Figure 3-4. Padding Examples

The Gabor transform can be thought of as a specific STFT. While the signal can be recovered from its Gabor transform by means of the Gabor expansion, the general STFT cannot be reconstructed by inverse Fourier transform.

There are several other technical details concerning the computation of the Gabor transform. Refer to Appendix A, *Gabor Expansion and Gabor Transform*, of this manual for more information about the Gabor transform and the Gabor expansion.

Overview of the Order Analysis Toolset Algorithm

Based on the Gabor transform, the Order Analysis Toolset for LabVIEW provides a new method which enables you to complete the following tasks:

- Analyze the order components of a noise or vibration signal
- Reconstruct the desired order components in the time-domain

The Gabor transform can give the power distribution of the original signal as the function of both time and frequency. Figure 3-5 shows a frequency-time spectral map computed by performing a Gabor transform on a sample vibration signal from a rotating machine. The horizontal axis denotes time, and the vertical axis denotes frequency. The magnitudes of coefficients are denoted by gray scale, with full white areas indicating a maximal magnitude and full black areas indicating a minimal magnitude.

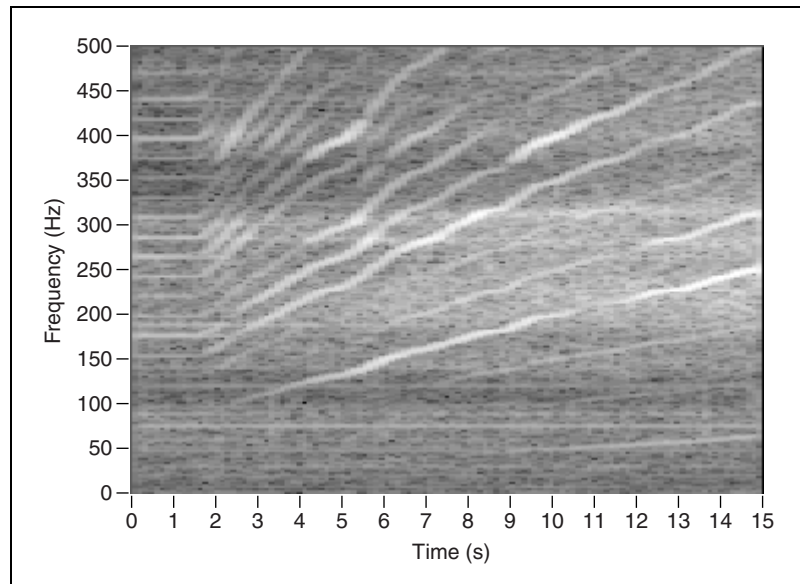


Figure 3-5. Frequency-Time Spectral Map of a Vibration Signal

Because the rotational speed changes little in each time portion of the frequency-time spectral map, the spectrum of each order can be clearly distinguished. As the rotational speed varies over time, the frequency of one certain order component changes. Thus, it forms a curve with a large magnitude in the frequency-time spectral map, as shown in Figure 3-5. The white curves have magnitudes larger than the magnitudes in local neighborhoods off the curves. These white curves indicate the order components and are referred to as order curves.

From the frequency-time spectral map, we can separate the order curves, or any other part of the signal in which we are interested, from the intact original signal. Then, time waveforms of the orders can be reconstructed using the Gabor expansion.

Figure 3-6 illustrates the order analysis process which the Order Analysis Toolset for LabVIEW follows. The toolset completes the following steps when performing order analysis.

1. Acquires data samples from tachometer and noise or vibration sensors synchronously at some constant sample rate.
2. Performs Gabor transform on the noise or vibration samples to produce an initial Gabor coefficient array.
3. Calculates rotational speed from the tachometer signal.
4. Generates a 2D spectral map from the initial coefficient array to observe the whole signal over frequency-time, frequency-RPM, order-RPM, or RPM-order.
5. Generates a modified coefficient array, based on the rotational speed and the order of interest, from the initial array by performing a masking operation.
6. Generates a time domain signal from the modified coefficient array by performing a Gabor expansion.
7. Calculates the waveform magnitude as a function of RPM.

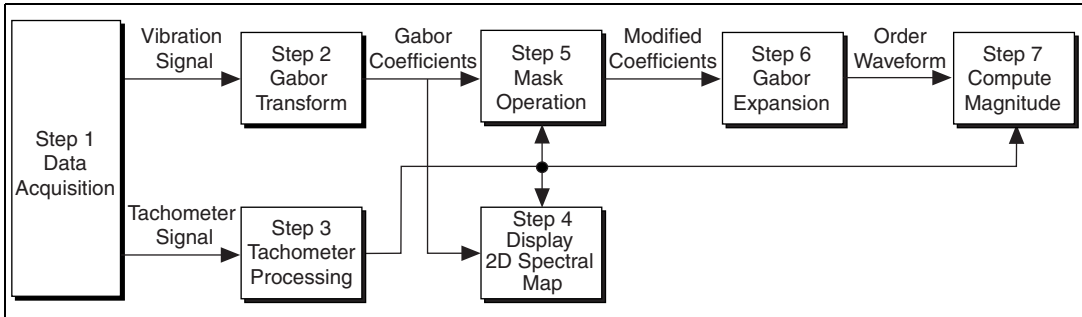


Figure 3-6. Order Analysis Diagram

Extracting the Order Components

After the initial Gabor coefficient array is generated through Gabor transform, one or more order components may be selected for analysis. The coefficient corresponding to the selected order component may be converted back into a time domain signal. The resulting time domain signal contains information only on the selected order component.

The selection of order components can be achieved by inclusion of the coefficients along the corresponding order curves. Therefore, the position index of the coefficient on each order curve must be determined. Because the frequency of an order component is an integer or fractional multiple of the fundamental frequency, such as the rotational speed, the position index of a given order curve at each time interval can be calculated by multiplying the order number and the fundamental frequency index at the time interval. If a signal sampled at the frequency f_s is processed by Gabor transform with N frequency bins, which equals the window length in this toolset, the index of the n^{th} order can be calculated by the following formula:

$$index = \text{round}\left(\frac{RPM}{60} \times \frac{N}{f_s} \times n\right)$$

RPM is the averaged instantaneous rotational speed in the time interval. Refer to the *Tachometer Signal Processing* section of this chapter for information about obtaining the rotational speed.

Each order component in the order domain, as well as each harmonic in the frequency domain, has a side band. Thus, in the joint time-frequency domain, each order component contains not only the coefficients along the order curve, but also some coefficients in the neighborhood. These coefficients in the neighborhood also must be included when selecting the order component.

Constant frequency bandwidth and constant order bandwidth are two ways to define the bandwidth of the neighborhood for an order curve.

Figure 3-7(a) illustrates constant frequency bandwidth. The neighborhood is considered as the region between $n\frac{RPM}{60} + \frac{\Delta f}{2}$ and $n\frac{RPM}{60} - \frac{\Delta f}{2}$, where Δf is a constant frequency. The frequency of the bandwidth, Δf , remains constant over time.

Figure 3-7(b) illustrates constant order bandwidth. The neighborhood is

considered as the region between $\left(n + \frac{k}{2}\right) \times \frac{RPM}{60}$ and $\left(n - \frac{k}{2}\right) \times \frac{RPM}{60}$.

While the frequency bandwidth $k\frac{RPM}{60}$ varies in time, the order bandwidth k remains constant.

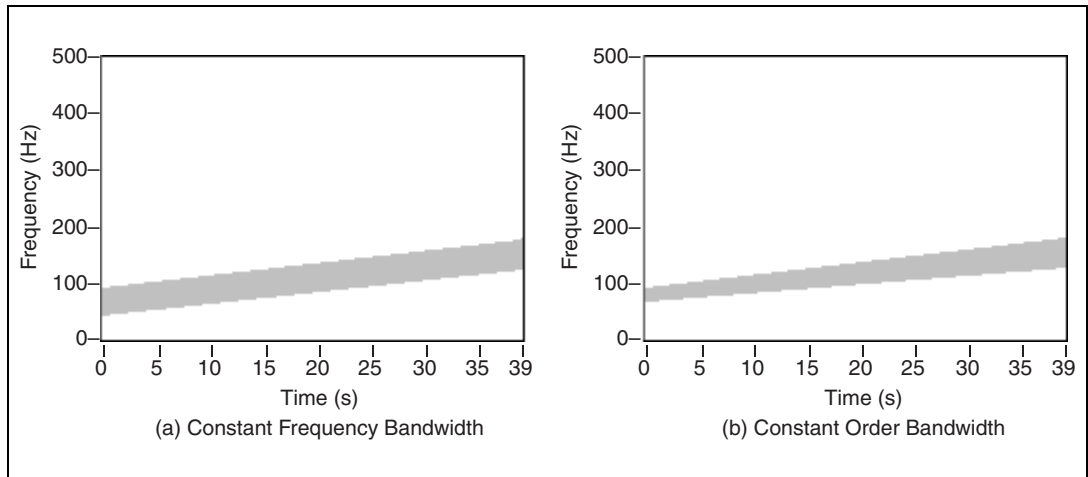


Figure 3-7. Mask Schemes

The frequency bandwidth or order bandwidth can be determined automatically or in response to your input. For example, a bandwidth can be automatically determined for the time-frequency neighborhood based on an estimate of minimum order-distance to nearest neighbor order-components. Normally, the bandwidth should not exceed the distance between two nearby orders, which is the fundamental frequency, or first order.

After you determine the coefficient positions and the bandwidth of the given order curves, select a subset of the initial Gabor coefficient array. This subset contains only the coefficients in the neighborhood of the selected order curves and can be generated from the original array by performing a mask operation.

To perform the mask operation, you must construct a mask array. The mask array is a 2D array the same size as the coefficient array, but all of the mask array elements are Boolean. When masking is performed, the coefficients at value TRUE are kept unchanged, while the coefficients at value FALSE are set to zero. The following formula represents the mask operation:

$$\hat{c}_{m,n} = \begin{cases} c_{m,n} & \text{mask}_{m,n} = \text{TRUE} \\ 0 & \text{mask}_{m,n} = \text{FALSE} \end{cases}$$

where $c_{m,n}$ denotes the initial Gabor coefficient array; \hat{c}_{mn} denotes the masked coefficient array; and $\text{mask}_{m,n}$ denotes the mask array.

A mask array can be built according to the order number you wish to analyze. In each row, elements within the bandwidth of the designated order number are set to either TRUE or FALSE. The Order Analysis Toolset for LabVIEW contains the Template to Mask VI, which you can use to perform the mask operation. Refer to the *Order Analysis Toolset for LabVIEW Help*, available by selecting **Help»Order Analysis**, for more information about the Template to Mask VI.

The mask operation can be considered a time-variant band pass filter in the joint time-frequency domain. The center frequency of the pass band is equal to the frequency of the order curve. The number of elements set to TRUE determines the bandwidth of the pass band.

Figures 3-8 and 3-9 illustrate the order extraction and signal reconstruction process, with the time waveform shown in Figure 3-9.

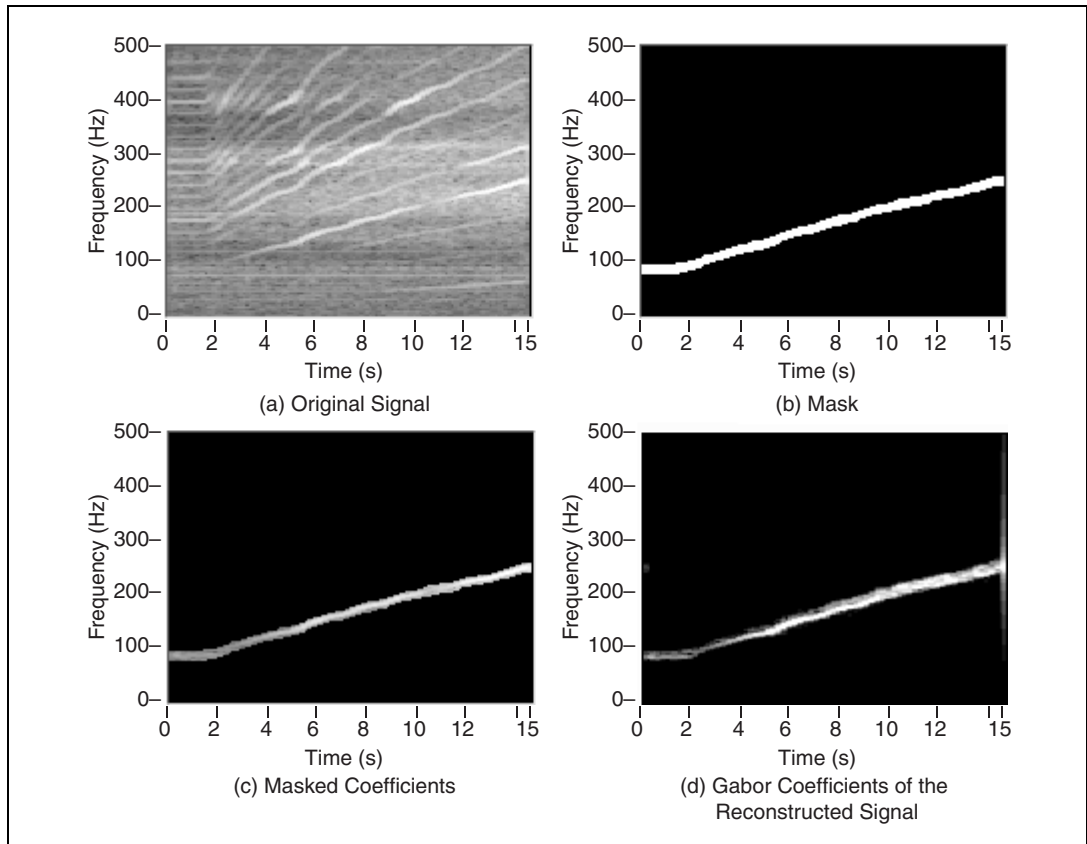


Figure 3-8. Gabor Coefficients

Figure 3-8(a) shows a frequency-time spectral map after Gabor transform.

Figure 3-8(b) shows a mask array around the fourth order with a constant frequency bandwidth. The TRUE values compose the white area, while the FALSE values compose the black areas.

Figure 3-8(c) shows the masked coefficients. The black areas indicate values set to zero, which correspond to the FALSE values in the mask array. The white area contains values copied from the original coefficient array. These values correspond to the TRUE values in the mask array.

Figure 3-8(d) shows the frequency-time spectral map of the reconstructed signal.

Figure 3-9 shows the fourth order waveform, which was reconstructed by performing Gabor expansion on the masked coefficients.

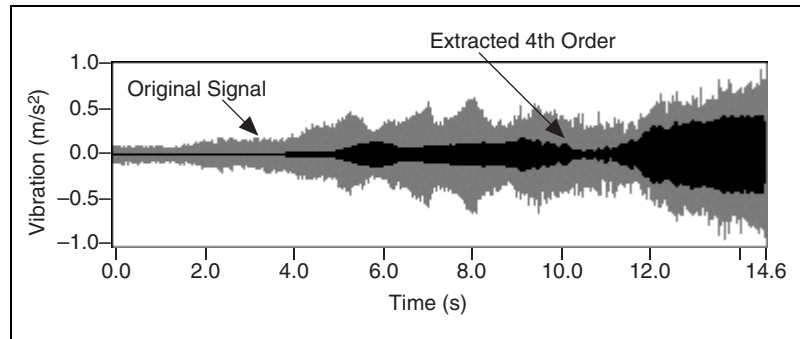


Figure 3-9. Original Signal and Extracted Order Component

Unlike the reverse discrete Fourier transform, the Gabor expansion, in general, is not a one-to-one mapping. A Gabor coefficient is the sub-space of a two-dimensional function. For an arbitrary two-dimensional function, such as the masked coefficient array, there might be no corresponding time waveform. Usually, the Gabor coefficients of the reconstructed time waveform might not be exactly the same as the desired coefficients you masked, but they are the closest in terms of the least mean square error (LMSE).

Like conventional time-invariant filters, the time-variant filters implemented by the Gabor expansion have a certain passband and attenuation. The extracted time waveform is only a part of the original signal whose frequencies fall into the passband determined by the Gabor time-variant filters. In Figure 3-10, one row is selected from the joint time-frequency coefficient array. The selected row is nothing more than a windowed FFT power spectrum in the time interval. The original Gabor coefficients compose the solid line in Figure 3-10. When performing a mask operation, coefficients outside the expected pass band are set to zero. After reconstruction, the spectrum of the reconstructed signal is formed. In Figure 3-10, the dashed line represents the spectrum of the reconstructed signal. Within the pass band, the reconstructed signal keeps the same magnitude as the original signal. While outside the pass band, the magnitude of the reconstructed signal is no longer zero. Instead, the magnitude does have some certain value, but the value decreases quickly as the frequency leaves the pass band.

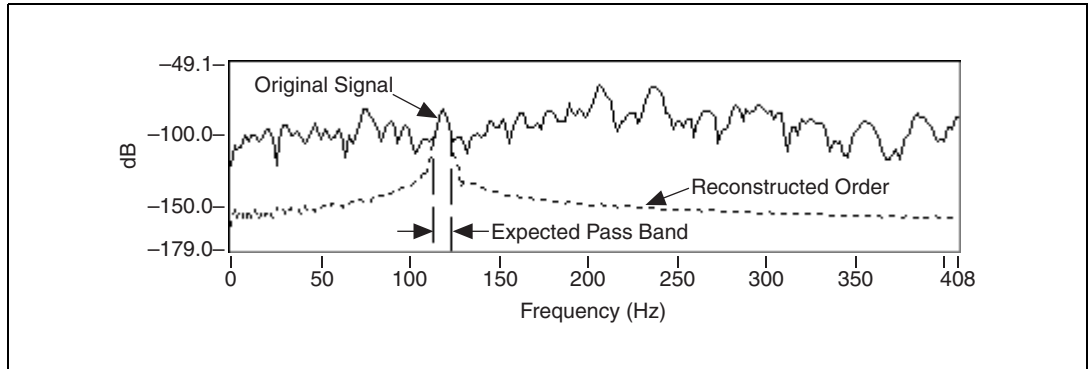


Figure 3-10. Spectrum of Reconstructed Signal

Displaying Spectral Maps

Before extracting order components from the joint time-frequency domain, you might want to find which order components you are most interested in, such as which order is the most significant or which order contributes the most at a certain rotational speed. Yet, by using order extraction and reconstruction, you might have to process a large number of order components before you can obtain this information.

The Order Analysis Toolset for LabVIEW provides several methods of obtaining a 2D spectral map over the whole signal in the frequency-time, frequency-RPM, and order-RPM domains. Figure 3-11 shows these three types of spectral maps for a vibration signal.

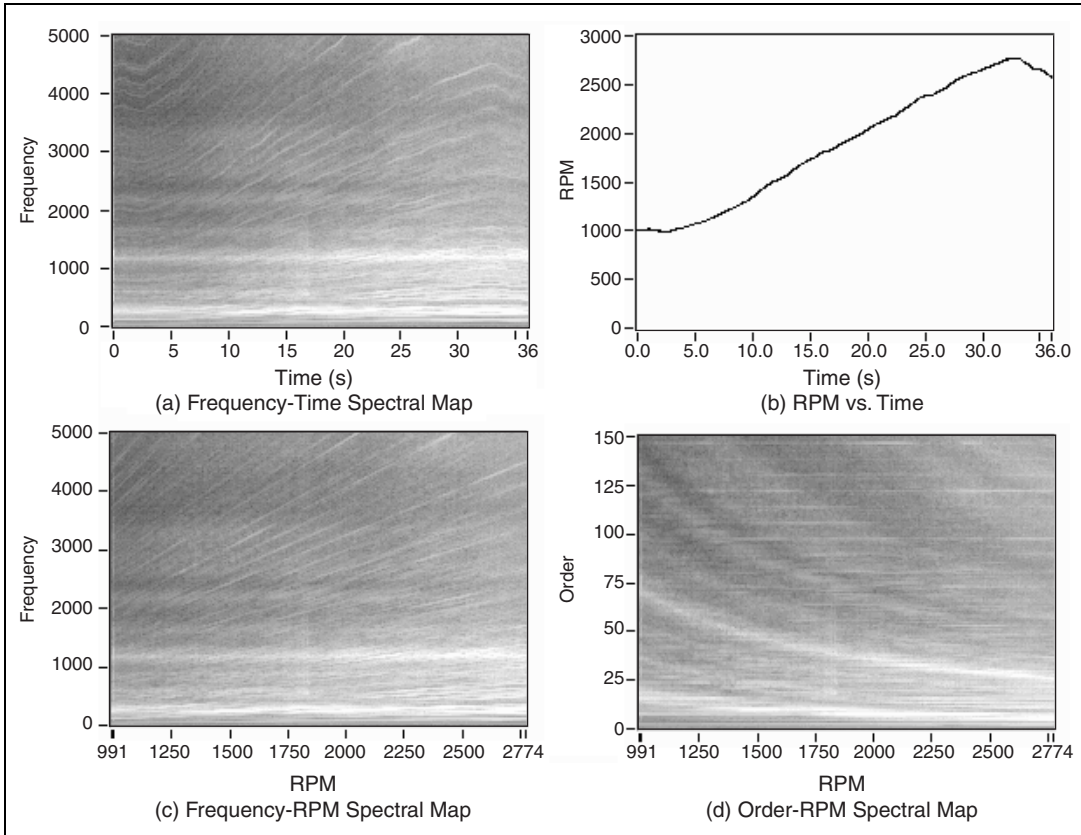


Figure 3-11. 2D Intensity Plots

Figure 3-11(a) is the frequency-time spectral map generated directly from the Gabor coefficients. The horizontal axis denotes time, and the vertical axis denotes frequency. The magnitudes of coefficients are shown as gray scale, with full white indicating a maximal magnitude and full black indicating a minimal magnitude. Order components are shown as curves. Because the frequency of each order component shifts as the rotational speed varies over time, the outline of each curve is similar to the RPM-time function shown in Figure 3-11(b).

In Figure 3-11(a), there are some horizontal white lines. These white lines indicate the large power around the resonance frequencies. The physical characteristics of the system containing the rotating machinery determine the resonance frequency. The resonance frequency does not change as the rotational speed changes.

Figure 3-11(c) shows the frequency-RPM spectral map. The horizontal axis represents RPM, or rotational speed. The RPM axis can be mapped from the time axis in the frequency-time spectral map by the RPM-time function. The frequency of each order component can be calculated by using the following formula:

$$Frequency = \frac{RPM}{60} \times Order$$

Because it is a linear function between RPM and frequency, order components appear as lines with a slope of $\frac{Order}{60}$ in Figure 3-11(c). The resonance beams appear as horizontal lines.

Applying a frequency-to-order-number transform to the frequency-RPM spectral map generates the order-RPM spectral map, shown in Figure 3-11(d). The order-RPM spectral map displays the order components as horizontal lines and the resonance beams as hyperbolas.

Using the frequency-time spectral map, the frequency-RPM spectral map, and the order-RPM spectral map, you can clearly and efficiently observe all the order components in the entire time and RPM ranges.

Calculating Waveform Magnitude

The reconstructed time waveform of the selected order contains only a few frequency components in a relatively short time interval. Thus, it displays like a sine waveform in which the frequency and magnitude have been modulated.

In practical applications, such as product testing for comparison with reference curves, it is useful to calculate the waveform magnitude as a function of RPM. The Order Analysis Toolset for LabVIEW uses the root mean square (RMS) of the time waveform to calculate the waveform magnitude. The magnitude at each time instance is the RMS in a short time interval around the time instance. By means of the time-RPM function, the Order Analysis Toolset performs a mapping operation from time to RPM to

obtain the waveform magnitude as a function of RPM. The following equation represents the mapping operation:

$$M_{(RPM)} = \sqrt{\frac{1}{n_2 - n_1} \sum_{i=n_1}^{n_2} X_i^2}, \text{ for any } n_1 \leq i \leq n_2, \text{ have}$$

$$|rpm_{(i)} - RPM| \leq \frac{\Delta RPM}{2}$$

where X_i represents the waveform data samples, $M_{(RPM)}$ represents the magnitude at speed RPM , $rpm_{(i)}$ represents the rotational speed at time sample i , and ΔRPM represents the RPM resolution.

Tachometer Signal Processing

In order to successfully extract the order components, create the spectral map display, and calculate the waveform magnitude, you need rotational speed as a function of time during the data acquisition process. Traditionally, the two methods used to calculate rotational speed have been counting pulses in a given time interval and timing the interval between given pulses.

The Order Analysis Toolset for LabVIEW uses a non-causal filter to calculate rotational speed. The length of the non-causal filter is five, two before and two after the current time instant. Because all the data in the test process is available when doing offline analysis, the Order Analysis Toolset for LabVIEW can use tachometer pulses occurring before and after each time instance when calculating rotational speed. Using tachometer pulses occurring before and after each time instance improves the accuracy of the calculated rotational speed.

Figure 3-12 illustrates a typical tachometer pulse train and the cumulative rotation angle θ of the shaft as a function of time t . The arrival time t_k of the pulses $P(k)$ in the tachometer signal correspond to the cumulative rotation angle $\theta(t_k)$. The cumulative rotation angle function $\theta(t)$ increases by a fixed angle $\Delta\theta$ in the time interval between times t_k and t_{k+1} . As shown in the following equation, rotational speed can then be presented as the first derivative of $\theta(t)$:

$$\omega(t) = \frac{d\theta}{dt}$$

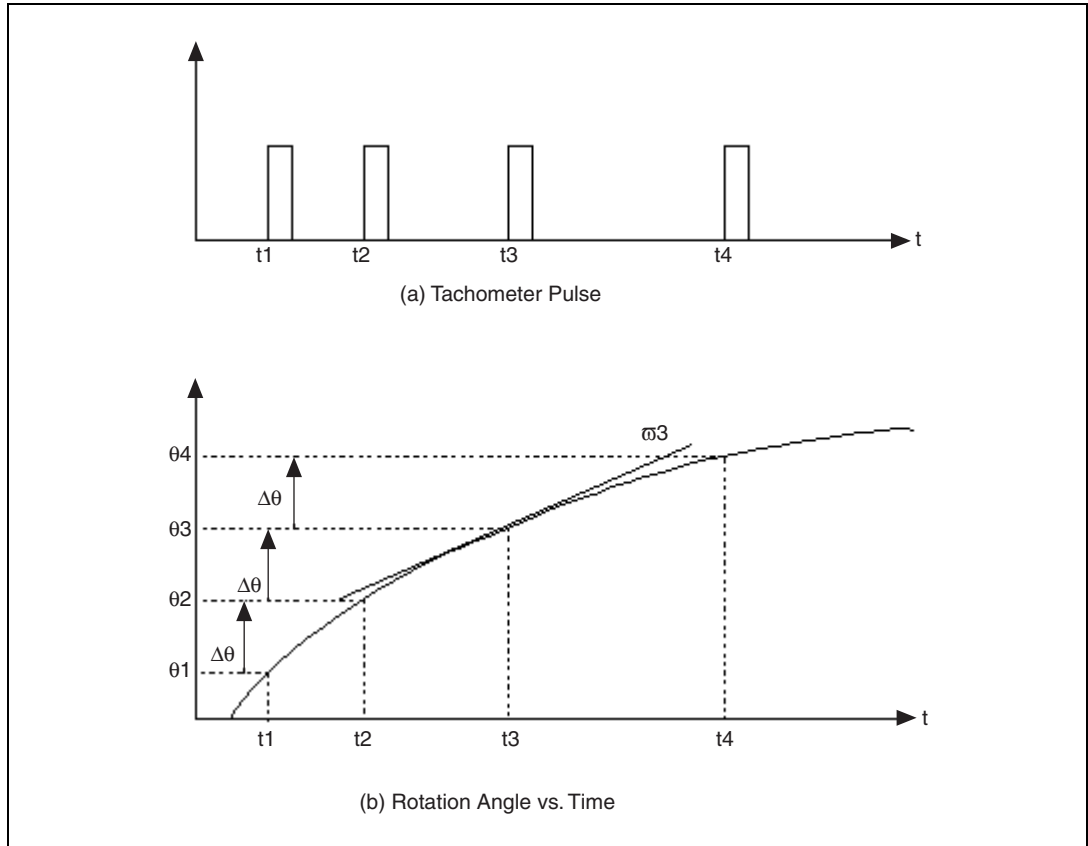


Figure 3-12. Tachometer Signal and Rotation Angle

While the time interval between pulses varies with the rotational speed, the cumulative angle increment remains constant. Instead of observing $\theta(t)$ directly, we chose to observe $t(\theta)$. $t(\theta)$ is the inverse function of $\theta(t)$.

For the evenly separated function series t_k , the first derivative can be calculated with the following formula:

$$\left. \frac{dt}{d\theta} \right|_{\theta = \theta_k} \approx \frac{1}{12\Delta\theta} (t_{k-2} - 8t_{k-1} + 8t_{k+1} - t_{k+2})$$

Rotational speed at each pulse-arrival-time instant will then be calculated by the following formula:

$$\omega(t_k) = \left. \frac{d\theta}{dt} \right|_{t=t_k} = \frac{1}{\left. \frac{dt}{d\theta} \right|_{\theta=\theta_k}}$$

This algorithm gives the third-order approach of the rotational speed, but it is sensitive to measurement error. Either a tachometer pulse with a slow slew rate or a low tachometer sampling rate causes an inaccurate determination of the pulse arrival time. As a result, an even larger error in the calculated rotational speed occurs.

If either a tachometer pulse with a slow slew or a low tachometer sampling rate is encountered, a low-order approach can be used. The following formula is an example of a low-order approach:

$$\left. \frac{dt}{d\theta} \right|_{\theta=\theta_1} \approx \frac{t_{k+1} - t_{k-1}}{2\Delta\theta}$$

An alternative to the low-order approach is averaging the pulses. One of the averaging approaches considers two or more pulses as a single pulse by decimating the original t_k series. Also, the angle increment between two sequential pulses must be multiplied by the corresponding factor. Because the measurement error of the pulse arrival time is non-cumulative, widening the pulse interval decreases the relative error.

Figure 3-13 shows an example of the rotational speed calculated from the tachometer pulses. One of the results is calculated with no average, while another is averaged by five. As Figure 3-13 shows, the averaged rotational speed is smoother than the non-averaged rotational speed.

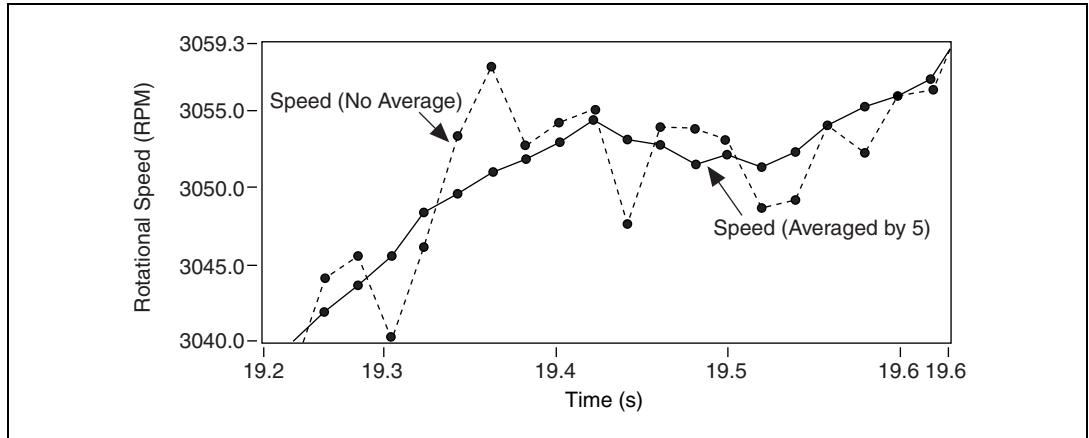


Figure 3-13. Cumulative Revolution and Rotational Speed

Example VIs

This chapter describes the example VIs for the Order Analysis Toolset for LabVIEW.

Overview of Example VIs

The example VIs illustrate the following Order Analysis Toolset for LabVIEW functions for both analog and digital tachometer signal processing:

- Compute Order Spectrum
- Compute Spectral Map
- Extract Individual Orders
- Extract Most Significant Orders
- Extract Sum of Orders

The example VIs are built around high-level VIs and are intended to illustrate the basic capabilities of the Order Analysis Toolset for LabVIEW. The toolset contains intermediate and advanced VIs to provide you with LabVIEW programming experience flexibility in application design.

In addition to the example VIs, the Order Analysis Toolset for LabVIEW CD contains the Order Analysis Start-Up Kit. With the start up kit, you can see a more extensive example of the capabilities of the toolset. Refer to the *Order Analysis Start-Up Kit* section of Chapter 1, *Introduction*, in this manual for more information about the Order Analysis Start-Up Kit.

Accessing the Example VIs

You can access the example VIs from either the **LabVIEW** dialog box or the LabVIEW toolbar. After you have opened the example VI you want to see, select **Window»Show Diagram** from the front panel toolbar to view the block diagram for the example.

LabVIEW Dialog Box

Complete the following steps to access the Order Analysis Toolset for LabVIEW example VIs from the **LabVIEW** dialog box.

1. Start LabVIEW.
2. Click the **Open VI** button in the **LabVIEW** dialog box.
3. Navigate to Program Files\National Instruments\LabVIEW 6\examples\Order Analysis
4. Double-click the file name of the LabVIEW library you want to open, either `Analogue Tach Examples.llb` or `Digital Tach Examples.llb`, or highlight the file name and click the **Open** button in the **Choose the VI to open** dialog box.
5. Double-click the name of the example VI you want to open or highlight the VI name and click the **OK** button in the **File Dialog** dialog box.

LabVIEW Toolbar

Complete the following steps to access the Order Analysis Toolset for LabVIEW example VIs from the LabVIEW toolbar.

1. Select **File»Open** from the LabVIEW toolbar.
2. Complete steps 3 through 5 in the *LabVIEW Dialog Box* section of this chapter.

Data Acquisition

For all the example VIs, you can use pre-recorded data, or you can acquire your own data. Each example VI has a Boolean control named **Data Source**. This control has two choices, **Example** and **DAQ**. When you choose **Example**, the VI uses pre-recorded data generated during a fan run-up as the data source. When you choose **DAQ**, the VI uses data you acquire with your own data acquisition (DAQ) hardware.

When you set **Data Source** to **DAQ** and click the run button, the window shown in Figure 4-1 opens. You must configure two channels of the DAQ device in order to acquire data. Use **Tach Channel** for the tachometer signal and **S/V Channel** for the sound or vibration sensor. After choosing your data acquisition settings, use the **Tach Pulse/Rev** control to specify the number of pulses the tachometer generates per revolution. Use the **S/V Channel Info** control to specify the channel information for the sound or vibration sensor.

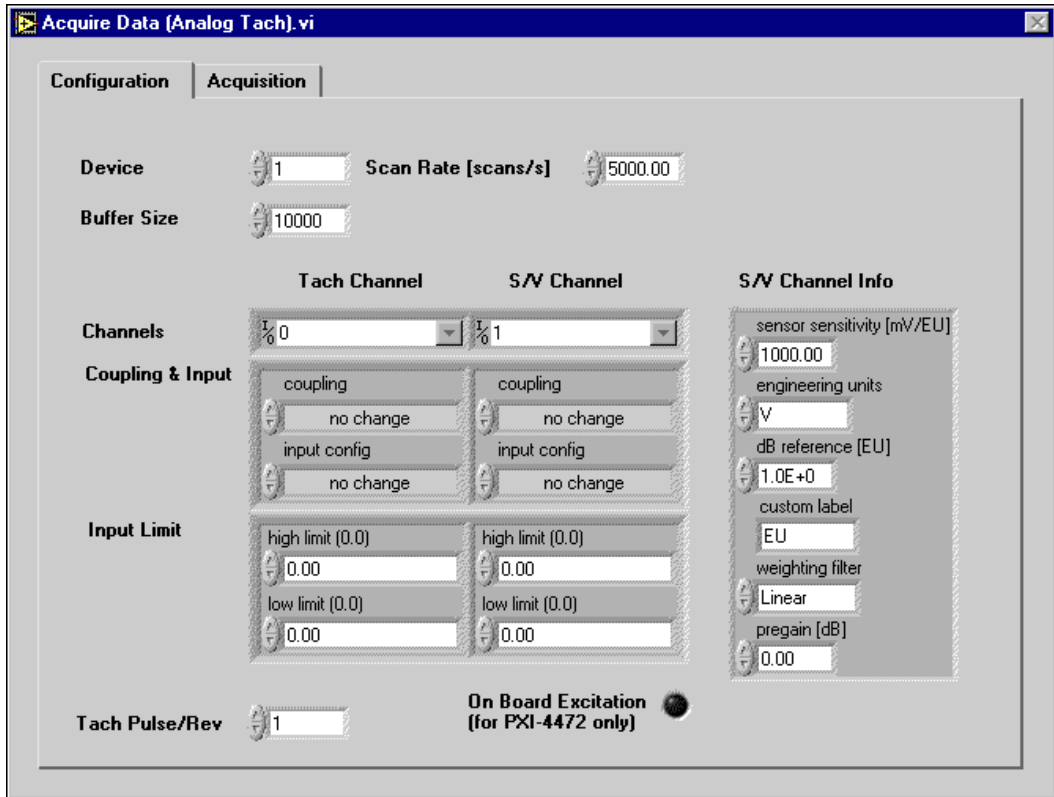


Figure 4-1. Configure Data Settings

After properly configuring your DAQ device, click the **Acquisition** tab. The **Acquisition** tab, shown in Figure 4-2, allows you to acquire data and to observe the data acquisition. Click the **Acquire** button to acquire data. Continue to configure the data acquisition and observe the data until you acquire the proper data. Click the **OK** button to analyze the data.

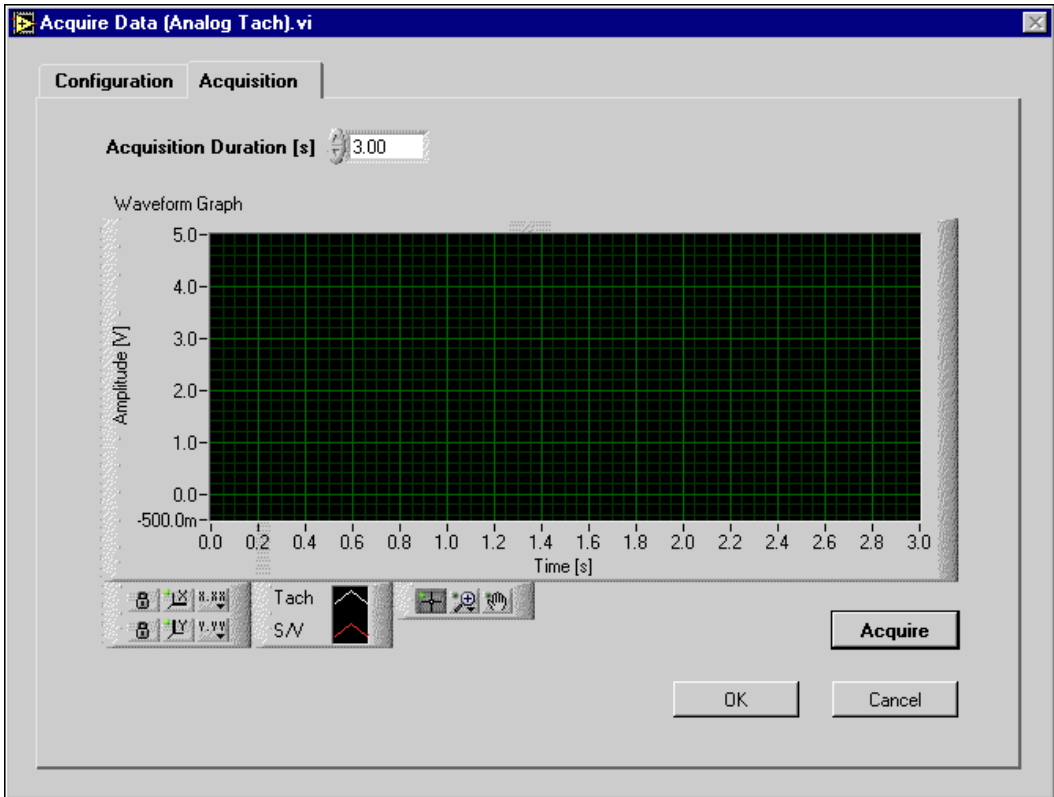


Figure 4-2. Acquire Data

When acquiring data through your DAQ hardware, National Instruments recommends adhering to the following guidelines:

- Use an anti-aliasing filter before data acquisition to avoid the frequency alias.
- Sample the data from different channels simultaneously to maintain the phase relationship between channels, such as a tachometer signal and a vibration signal.

Compute Order Spectrum

The Compute Order Spectrum example demonstrates the use of the simplified order spectrum to analyze the noise or vibration signal generated by a rotating machine at an essentially constant rotational speed. Figure 4-3 shows the Compute Order Spectrum Example VI front panel.

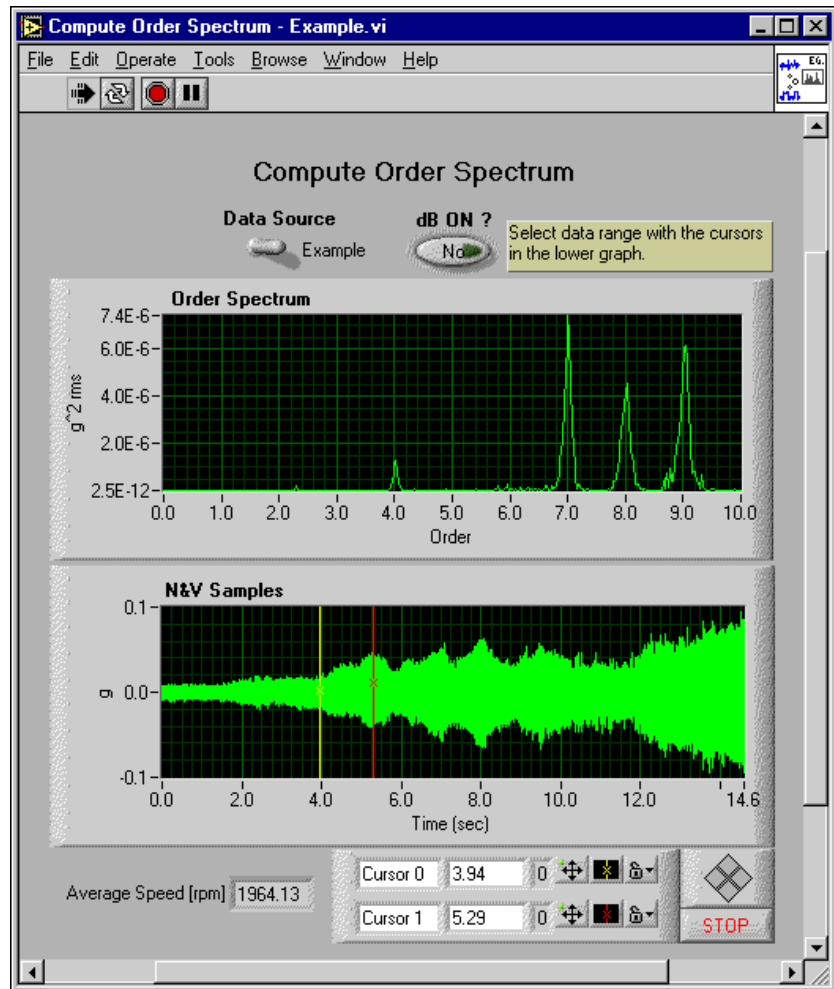


Figure 4-3. Compute Order Spectrum Example

The N&V Samples graph displays the vibration signal. The Order Spectrum graph displays the order spectrum of the data gathered between the two cursors of the N&V Samples graph.

In the pre-recorded data, the rotational speed increases significantly over time. However, within the relatively short time interval between the two cursors of the N&V Samples graph, the rotational speed hardly changes and can be considered to be constant. The different order components can be clearly separated in the Order Spectrum graph.

If you drag the two cursors of the N&V Samples graph to another area of the graph, the Order Spectrum display adjusts accordingly. If the new data range is too large, there will be some smearing in the order spectrum plot. This is because the rotational speed changes too much within the larger range for the speed to be considered constant.

Compute Spectral Map

The Compute Spectral Map example demonstrates how to use different types of intensity plots to observe the whole signal over RPM-order, order-RPM, frequency-time, and frequency-RPM. Figure 4-4 shows the Compute Spectral Map example VI front panel. The default for **Type** is `RPM-Order`, and the default for **dB On?** is `Yes`.

The default setting of `RPM-Order` generates a spectral map with RPM on the Y axis and order on the X axis. In the Spectral Map display, each order component appears as a vertical line. With the `RPM-Order` setting, you can observe the difference between order components and how the order components vary from the rotational speed.

If **Type** is set to `Order-RPM`, the VI displays the order-RPM spectral map, with order on the Y axis and RPM on the X axis. With the `Order-RPM` setting, you can observe the difference between order components and how the order components vary from the rotational speed.

If **Type** is set to `Frequency-Time`, you can observe the signal power distribution as a function of frequency and time, with frequency on the Y axis and time on the X axis. In the Spectral Map display, each order component appears as a curve with an outline similar to the RPM-time function.

If **Type** is set to `Frequency-RPM`, you can view the signal power distribution over frequency and RPM, with frequency on the Y axis and RPM on the X axis. The order components appear as straight lines in the Spectral Map display.

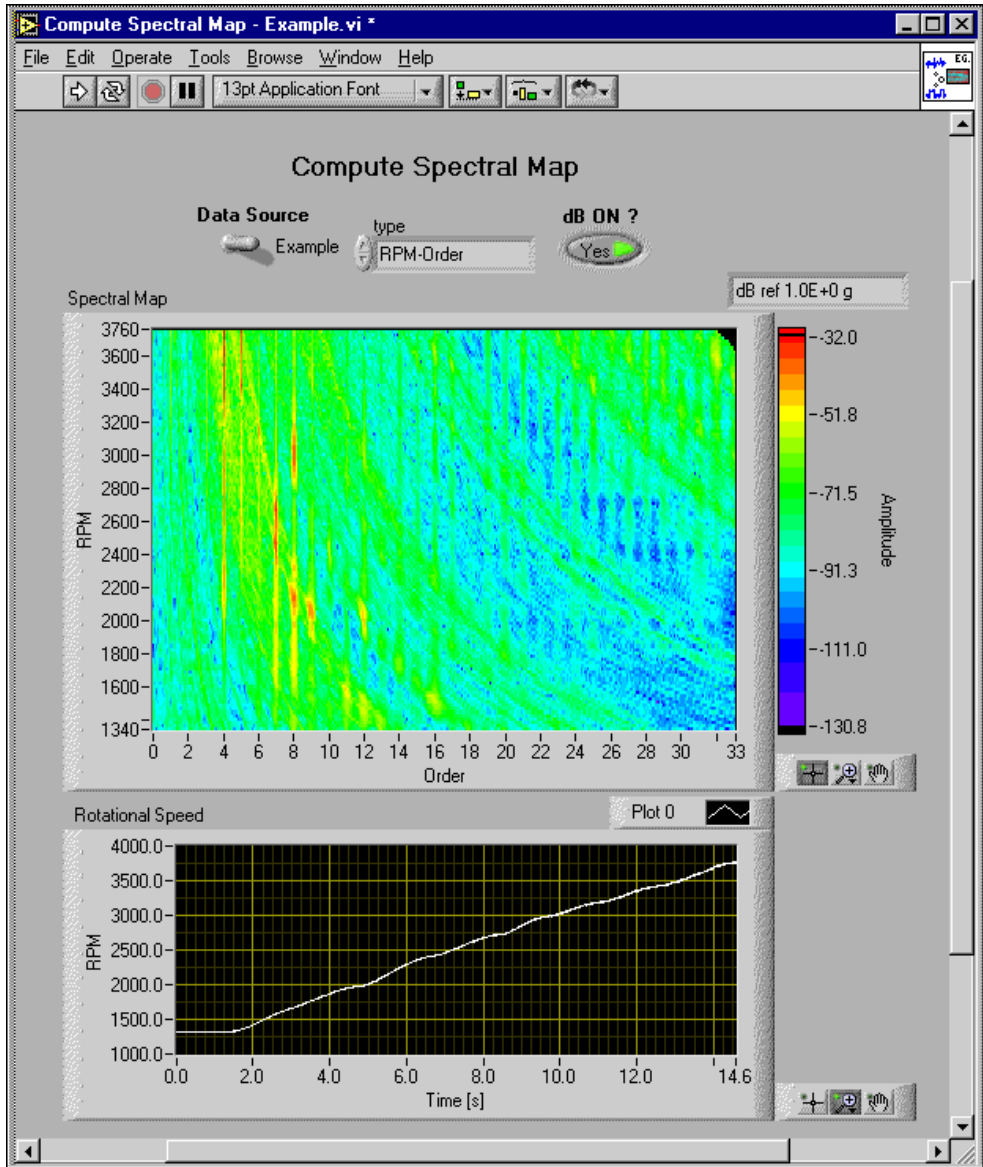


Figure 4-4. Compute Spectral Map Example

Setting **dB ON?** to **Yes** enhances the Spectral Map display, because the original magnitudes have a large dynamic range. When **dB ON?** is set to **No**, Spectral Map displays the original power.

Extract Individual Orders

The Extract Individual Orders example uses the Order Analysis Toolset for LabVIEW Order Tracking VI and extracts a set of order components from the original signal. The example VI displays the order components in both time waveform and magnitude versus RPM formats. Figure 4-5 shows the Extract Individual Orders Example VI front panel.

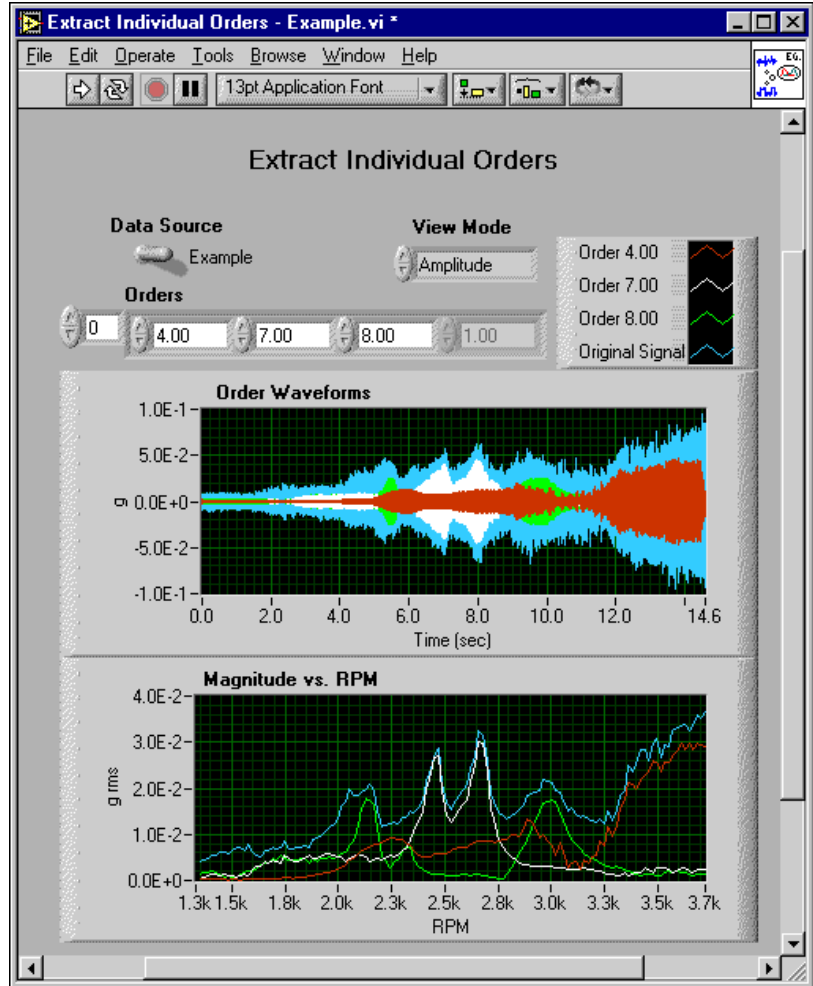


Figure 4-5. Extract Individual Orders Example

Enter a series of order numbers in the **Orders** control and click the **run** button. When the VI finishes, the time waveform of both the original signal and the extracted order components appears in the Order Waveforms graph. The overall level as a function of RPM appears in the Magnitude vs. RPM graph.

You can change the **View Mode** setting to `Amplitude`, `dB`, or `Power`. The default is `Amplitude`. Changing the **View Mode** setting changes the display format of the Magnitude vs. RPM graph.

Extract Most Significant Orders

The Extract Most Significant Orders example demonstrates how to find the most significant orders in a given signal using the Significant Order Tracking VI from the Order Analysis Toolset for LabVIEW. Figure 4-6 shows the Extract Most Significant Orders Example VI front panel.

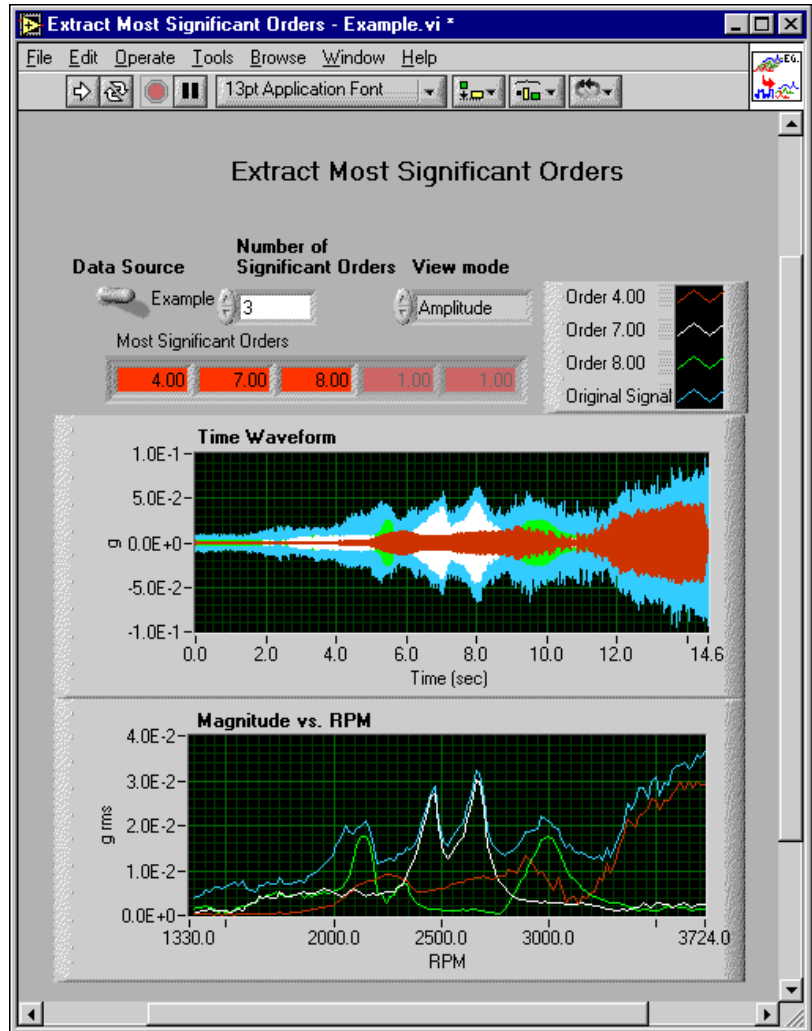


Figure 4-6. Extract Most Significant Orders Example

You specify how many of the most significant orders you want to find with the **Number of Significant Orders** control. When the VI finishes, the order numbers of the most significant orders appear in the Most Significant Orders indicator. The waveforms of orders, as well as the original signal, appear in the Time Waveform graph. The magnitudes appear in the Magnitude vs. RPM graph as a function of the rotational speed in RPM.

Extract Sum of Orders

The Extract Sum of Orders example demonstrates how to extract a combination of orders in a given signal using Advanced Order Analysis VIs from the Order Analysis Toolset for LabVIEW. Figure 4-7 shows the Extract Sum of Orders Example VI front panel.

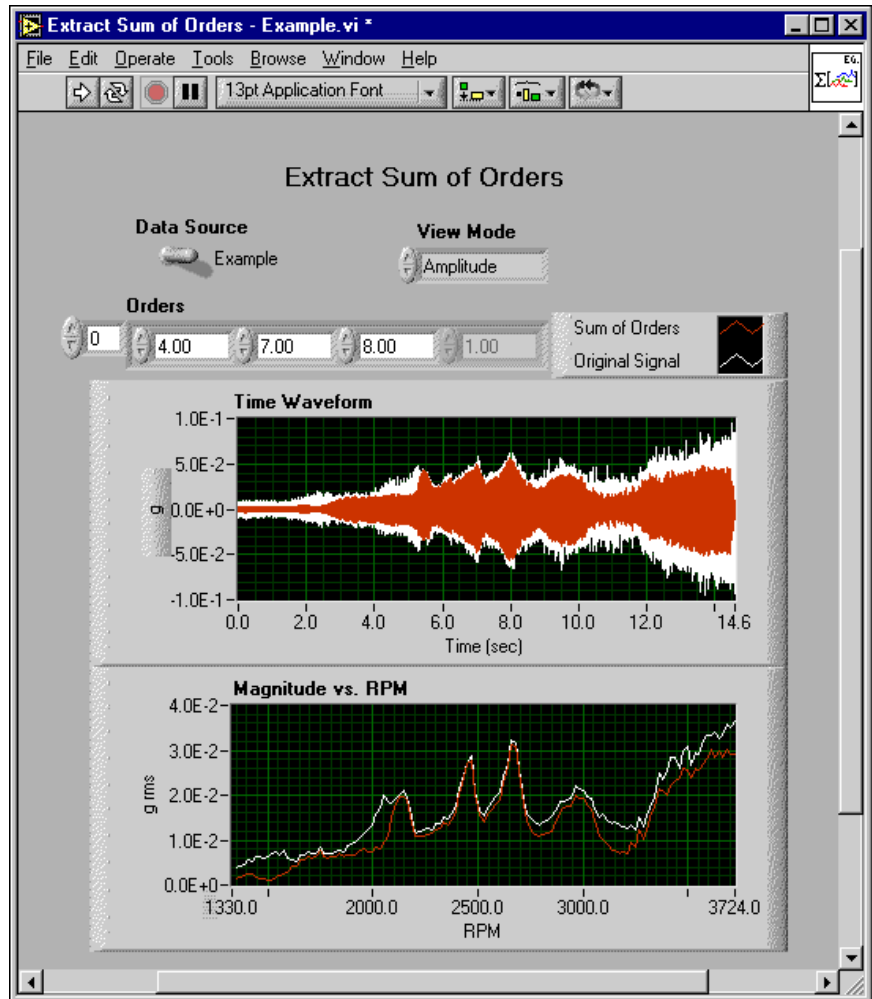


Figure 4-7. Extract Sum of Orders Example

Enter a series of order numbers in the **Orders** control and click the **run** button. When the VI finishes, the waveform of the original signal and the combination of the orders appear the Time Waveform graph. The magnitude appears in the Magnitude vs. RPM graph as a function of the rotational speed in RPM.

Gabor Expansion and Gabor Transform

This appendix presents a basic discussion of the Gabor expansion and the Gabor transform methods used in the Order Analysis Toolset for LabVIEW. It also discusses application issues associated with using the discrete Gabor-expansion based time-varying filter.

Gabor Expansion and Gabor Transform Basics

The Gabor expansion, a mathematical tool, characterizes a signal jointly in the time and frequency domains. Although Nobel laureate Dennis Gabor introduced the Gabor expansion more than half a century ago, its implementation had been an open research topic until Bastiaans discovered the relationship between the Gabor expansion and the short-time Fourier transform (STFT) in the early 1980s. Over the years, many different implementation schemes for the discrete Gabor expansion have been proposed. The one employed in the Order Analysis Toolset for LabVIEW is an extension of the method originally developed by Wexler and Raz. In this method, lengths of the analysis and synthesis window functions are the same, while perfect reconstruction is guaranteed.

For a discrete sample $s[k]$, the corresponding Gabor expansion is defined by the following equation:

$$s[k] = \sum_{m=0}^{N-1} \sum_{n=0}^{N-1} c_{m,n} h[k - m\Delta M] e^{j2\pi nk/N} \quad (\text{A-1})$$

where the Gabor coefficients $c_{m,n}$ are computed by a sampled STFT. The sampled STFT is also known as the Gabor transform and is represented by the following equation:

$$c_{m,n} = \sum_{n=0}^{N-1} \tilde{s}[k] \gamma^*[k - m\Delta M] e^{-j2\pi nk/N} \quad (\text{A-2})$$

where ΔM represents the time sampling interval and N represents the total number of frequency bins. The ratio between N and ΔM determines the Gabor sampling rate. For numerical stability, the Gabor sampling rate must be greater than or equal to one. Critical sampling occurs when $N = \Delta M$. In critical sampling, the number of Gabor coefficient $c_{m,n}$ equals the number of original data samples $s[k]$. Over sampling occurs when $N/\Delta M > 1$. For over sampling, the number of Gabor coefficients is more than the number of original data samples. In over sampling, the Gabor transform in Equation A-2 contains redundancy, from a mathematical point of view. However, that redundancy provides freedom for the selection of better window functions, $h[k]$ and $\gamma[k]$.

Note that the positions of the window functions $h[k]$ and $\gamma[k]$ are interchangeable. In other words, either of them can be used as the synthesis or analysis window function. Therefore, we usually refer to $h[k]$ and $\gamma[k]$ as dual functions.

The method developed here requires $\tilde{s}[k]$ in Equation A-2 to be a periodic sequence, as follows:

$$\tilde{s}[k + iL_0] = \begin{cases} s[k] & 0 \leq k < L_s \\ 0 & L_s \leq k < L_0 \end{cases} \quad (\text{A-3})$$

where L_s represents the length of the signal, $s[k]$, and L_0 represents the period of the sequence $\tilde{s}[k]$. L_0 is the smallest integer that is greater than or equal to L_s , and it must be evenly divided by the time sampling interval ΔM . For a given window $h[k]$ that always has unit energy, we can compute the corresponding dual window function from ΔM independent linear systems with the following equation:

$$\sum_{p=0}^{\frac{L}{\Delta M} - 1} \tilde{a}[k + p\Delta M + qN] \gamma^*[k + p\Delta M] = \frac{\delta[q]}{N} \quad 0 \leq k < \Delta M \quad (\text{A-4})$$

where L denotes the window length. $\tilde{a}[k]$ denotes a periodic auxiliary function¹ given by

¹ If the window length is equal to the signal length, the periodic auxiliary function $\tilde{a}[k]$ is simply

$$\tilde{a}[k + iL] = h[k] \quad 0 \leq q < \frac{L}{N}$$

$$\tilde{a}[k + i(2L - N)] = \begin{cases} h[k] & 0 \leq k < L \\ 0 & L \leq k < 2L - N \end{cases} \quad 0 \leq q < \frac{2L}{N} - 1$$

Note that the solution of Equation A-4 is not unique for over sampling. A particularly interesting solution for Equation A-4 is least mean square error (LMSE). It can be shown that for the LMSE solution, the Euclidean distance between the dual functions is minimum

$$\min_{A\gamma = u} \left\| \begin{matrix} \vec{\gamma} \\ \vec{\gamma} \\ \vec{\gamma} \end{matrix} - \vec{h} \right\|$$

where $A\gamma = u$ denotes the matrix form of Equation A-4. When $\vec{\gamma} \approx \vec{h}$, the error is small, and Equation A-2 becomes

$$c_{m,n} \approx \sum_m \tilde{s}[k] h[k - mT] e^{-j2\pi nk/N} \quad (\text{A-5})$$

Equation A-5 and Equation A-1 form an orthogonal-like Gabor transform pair. In the case of an orthogonal-like Gabor transform pair, the Gabor coefficients $c_{m,n}$ are the projection of the signal on the synthesis window function $h[k]$.

Discrete Gabor-Expansion Based Time-Varying Filter

At first glance, the discrete Gabor expansion seems to provide a feasible vehicle for converting an arbitrary signal from the time domain into the joint time-frequency domain or vice versa. As a matter of fact, it is only true for critical sampling $\Delta M = N$. For over sampling, which is the case for most applications, the Gabor coefficients are the sub-space of two-dimensional functions. In other words, for an arbitrary two-dimensional function, there might be no corresponding time waveform. For example, assume that we have the following modified two-dimensional function:

$$\hat{c}_{m,n} = \Phi_{m,n} c_{m,n}$$

where $\Phi_{m,n}$ denotes a binary mask function whose elements are either zero or one. Then, apply the Gabor expansion to obtain

$$\hat{s}[k] = \sum_m \sum_{n=0}^{N-1} c_{m,n} h[k-mT] e^{j2\pi nk/N}$$

We will find

$$\sum_m \hat{s}[k] \gamma[k-mT] e^{-j2\pi nk/N} \neq \hat{c}_{m,n}$$

The Gabor coefficients of the reconstructed time waveform $\hat{s}[k]$ will not be equal to the selected Gabor coefficients $\hat{c}_{m,n}$.

To overcome this problem, we apply an iteration. That is, for a set of two-dimensional Gabor coefficients, first determine a binary mask matrix. Apply the mask to the two-dimensional Gabor coefficients to preserve desirable coefficients and remove unwanted coefficients. Then, compute the Gabor expansion. Once the time waveform is obtained, compute the new Gabor coefficients. Repeat this process until the time waveforms converge.

Without a loss of generality, let us rewrite the Gabor expansion from Equation A-1 and the Gabor transform from Equation A-2 in matrix form

$$\begin{aligned} C &= G \vec{s} \\ \vec{s} &= H^T G \vec{s} \end{aligned}$$

where H denotes the analysis matrix and G denotes the synthesis matrix. Note that for over sampling

$$H^T G = I \quad G H^T \neq I$$

Then in the case of over sampling, the iterative process can be described as

$$\hat{C}^1 = \Phi C$$

$$\vec{s}^1 = H^T \hat{C}^1$$

$$C^2 = G\overset{\succ 1}{s} = GH^T\Phi C$$

$$\hat{C}^2 = \Phi C^2$$

$$\overset{\succ 2}{s} = H^T\hat{C}^2$$

$$C^3 = G\overset{\succ 2}{s} = GH^T\Phi GH^T\Phi C = (GH^T\Phi)^2 C$$

...

$$C^k = (GH^T\Phi)^{k-1} C$$

It can be shown that C^k and $\overset{\succ k}{s}$ converge and that $C^k = \Phi C^k$ with $k \rightarrow \infty$. For $C^k = \Phi C^k$ with $k \rightarrow \infty$, the support of C^k in the time-frequency domain is inside the masked area, if and only if

$$\sum_{i=0}^{\frac{L}{N}-1} \gamma^*[iN+k]h[iN+k+m\Delta M] = \sum_{i=0}^{\frac{L}{N}-1} h^*[iN+k]\gamma[iN+k+m\Delta M]_{(A-6)}$$

for $0 \leq k < N$ and $0 \leq m < \frac{L}{\Delta M}$. Two trivial cases for Equation A-6 are critical sampling and when $\gamma[k] = h[k]$.

In critical sampling, $N = \Delta M$. Note that in this case, the analysis and synthesis windows cannot both be localized in the joint time-frequency domain.

In the case of $\gamma[k] = h[k]$, the Gabor coefficients C^2 , after the first iteration, are the closest in terms of LMSE to the masked Gabor coefficients ΦC . The masked Gabor coefficients are the desirable Gabor coefficients. The case of $\gamma[k] = h[k]$ usually implies considerable over sampling, which results in a huge amount of redundancy. The amount of redundancy causes slow computation speed and huge memory consumption, making $\gamma[k] = h[k]$ an impractical Gabor Transform method.

Usually, we pursue the orthogonal-like representation introduced at the end of the *Gabor Expansion and Gabor Transform Basics* section of this appendix. It has been found that for commonly used window functions, such as the Gaussian and Hanning windows, the difference between the analysis and synthesis windows is negligible when the over sampling rate is four.

References

This appendix lists the reference material used for the Order Analysis Toolset.

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Glossary

Numbers/Symbols

- ∞ Infinity.
- 2D Two-dimensional.

A

- adaptive filter A type of filter which operates on a recursive algorithm to achieve the goal of optimum. It is self-designing and suitable for tracking time variations of the input signal, but complete knowledge of the relevant signal characteristics is not available.
- aliasing A phenomenon in which an analog signal of a frequency greater than half the sampling frequency, or Nyquist frequency, appears after sampling at a frequency less than half the sampling frequency. *See also* anti-aliasing filter and Nyquist frequency.
- anti-aliasing filter Analog lowpass filters used before analog to digital conversion to filter out the frequencies greater than half the sampling frequency. *See also* aliasing and Nyquist frequency.

C

- critical sampling Occurs in Gabor transform when the window length equals the window shift step. In critical sampling, the number of Gabor coefficients $c_{m,n}$ equals the number of original data samples $s[k]$.

D

- dB Decibel.
- dual functions Window functions for Gabor transform and Gabor expansion. They are interchangeable, and either of them can be used in Gabor transform, while the other is used in Gabor expansion.

F

FFT Fast Fourier transform.

G

Gabor coefficient The result of Gabor transform.

Gabor expansion The inverse Gabor transform used on Gabor coefficients to recover a time-domain input signal.

Gabor transform One of the invertible joint time-frequency transforms.

H

harmonic Frequencies that are integer or fractional multiples of a fundamental frequency.

L

LMSE Least mean square error.

N

Nyquist frequency Half the sampling frequency. Any analog frequency component above the Nyquist frequency will, after sampling, be converted, or aliased, to a frequency below the Nyquist frequency. *See also* aliasing and anti-aliasing filter.

O

order A harmonics related to the rotational speed of a machine.

order analysis The analysis of harmonics related to rotational speed. The application of harmonic analysis to rotating machinery

order curves The high power density curves in a spectral map which indicate order components.

orthogonal-like Gabor transform pair	The pair is composed of a Gabor transform and a Gabor expansion when the Gabor coefficients $c_{m,n}$ found by each method are the projection of the signal on the synthesis window function $h[k]$.
over sampling	Occurs in Gabor transform when the window length is greater than the window shift step. In over sampling, the number of Gabor coefficients $c_{m,n}$ is more than the number of original data samples $s[k]$.

R

re-sampling	A method to sample a time sequence at a different time interval.
RMS	Root mean square.
RPM	Revolutions per minute.

S

STFT	Short time Fourier transform.
------	-------------------------------

W

window shift step	The shortest time interval between two windows. In the Order Analysis Toolset for LabVIEW, it is always equal to a quarter (0.25) of the window length. For example, if the window length is 2048, the window shift is 512.
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