LabVIEW™

Order Analysis Toolset
User Manual

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National Instruments Corporate Headquarters

11500 North Mopac Expressway   Austin, Texas 78759-3504   USA   Tel: 512 683 0100

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About This Manual

This manual provides information about the LabVIEW Order Analysis Toolset, 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 LabVIEW Order Analysis Toolset.

How to Use This Manual

If you are just beginning to gain experience with order analysis, read Chapter 2, *Order Analysis*, of this manual and experiment with the Order Analysis Start-Up Kit. Refer to Chapter 1, *Introduction to the LabVIEW Order Analysis Toolset*, for information about the Order Analysis Start-Up Kit.

If you have experience with order analysis, use the example VIs to learn about how to use the LabVIEW Order Analysis Toolset. Refer to Chapter 1, *Introduction to the LabVIEW Order Analysis Toolset*, for information about the example VIs.

If you want to learn more about the algorithm used in the LabVIEW Order Analysis Toolset, refer to Chapter 3, *Gabor Transform-Based Order Tracking*, and Chapter 4, *Resampling-Based Order Analysis*.

For information about individual VIs, refer to the *Order Analysis Toolset Help*, available in LabVIEW 6.1 by selecting **Help»Order Analysis**. In LabVIEW 7.0 and later, *Order Analysis Toolset Help* is part of the *LabVIEW Help*, which is available by selecting **Help»VI, Function, & How-To Help**.

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 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 variables or cross references.
`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.
Platform	Text in this font denotes a specific platform and indicates that the text following it applies only to that platform.

Related Documentation

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

- *LabVIEW Order Analysis Toolset Help*
- *Getting Started with LabVIEW*
- *LabVIEW User Manual*
- *LabVIEW Help*

1

Introduction to the LabVIEW Order Analysis Toolset

This chapter introduces the LabVIEW Order Analysis Toolset and the Order Analysis Start-Up Kit, outlines system requirements, and gives installation instructions.

Overview of the LabVIEW Order Analysis Toolset

The LabVIEW Order Analysis Toolset is a collection of virtual instruments (VIs) for LabVIEW. These VIs help you measure and analyze noise or vibration signals generated by rotating machinery by enabling you to perform the following analysis operations:

- 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 magnitude and phase of any order component as a function of rotational speed
- Presentation of data in a waterfall, orbit, or polar plot

The LabVIEW Order Analysis Toolset includes easy and advanced VIs. Use the easy VIs to perform simple tasks in just a few steps. The advanced VIs provide flexibility and increased control of the analysis process. Refer to the *LabVIEW Order Analysis Toolset Help* for information about individual VIs.

Overview of the LabVIEW Order Analysis Start-Up Kit

The Order Analysis Start-Up Kit is automatically installed when you install the LabVIEW Order Analysis Toolset. To open the Order Analysis Start-Up Kit, select **Start»Programs»National Instruments»Order Analysis»Order Analysis Start-Up**. The Order Analysis Start-Up Kit includes a LabVIEW application for order analysis. The order analysis

application is built with components found in the LabVIEW Order Analysis Toolset.

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

Important Considerations for the Analysis of Rotating Machinery

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

• Provide a signal directly related to the position of the shaft, such as a pulse train from a tachometer or key phasor. Although the LabVIEW Order Analysis Toolset can measure the magnitude of the order components without a tachometer signal, the measurement of the phase of the order components requires a tachometer signal.

• Do not use the LabVIEW Order Analysis Toolset for analysis of frequencies that are not excited by a fundamental frequency, such as the modes encountered in modal analysis. Although you can observe the different modes in the frequency domain, no simple relationship exists among those different modes. Usually, the frequencies of different modes are not simply a multiple of a fundamental frequency over time.

System Requirements

You must have LabVIEW 6.1 or later Full Development System or Professional Development System installed to run the LabVIEW Order Analysis Toolset.

Note   Refer to the *LabVIEW Release Notes* for the required system configuration for LabVIEW.

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

Installation

This section provides instructions for installing the LabVIEW Order Analysis Toolset.

Note   Some virus detection programs interfere with the installer. Disable any automatic virus detection programs before you install. After installation, check your hard disk for viruses and enable any virus detection programs you disabled.

(Windows 2000/NT/XP) Complete the following steps to install the LabVIEW Order Analysis Toolset.

1. Log on as an administrator or as a user with administrator privileges.

2. Insert the LabVIEW Order Analysis Toolset 2.0 installation CD into the CD-ROM drive and follow the instructions that appear on the screen. If the startup screen does not appear, select **Start»Run**, navigate to the Setup folder on the LabVIEW Order Analysis Toolset 2.0 installation CD, and double-click OAT.exe.

(Windows Me/98) Insert the LabVIEW Order Analysis Toolset 2.0 installation CD and follow the instructions that appear on the screen. If the startup screen does not appear, select **Start»Run**, navigate to the Setup folder on the LabVIEW Order Analysis Toolset 2.0 installation CD, and double-click OAT.exe.

Example VIs

If you have experience with order analysis, the example VIs, located in the `examples\Order Analysis` directory, can help you learn how to use the LabVIEW Order Analysis Toolset. The example VIs illustrate the following LabVIEW Order Analysis Toolset functions for both analog and digital tachometer signal processing:

- Acquiring data

- Presenting data

- Gabor order tracking

- Resample order tracking

The example VIs use VIs found on the LabVIEW Order Analysis Toolset palettes and illustrate the basic capabilities of the LabVIEW Order Analysis Toolset.

Acquiring Data for Example VIs

For most of the example VIs, you can use prerecorded data or data you acquire with data acquisition (DAQ) hardware. The example VIs that accept either prerecorded data or acquired data have a Boolean control named **Data Source**. The **Data Source** control has two choices, **Example** and **DAQ**. When you choose **Example**, the VI uses prerecorded data generated during a fan run-up as the data source. When you choose **DAQ**, the VI uses data you acquire with DAQ hardware.

When acquiring data through DAQ hardware, National Instruments recommends you follow 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.

Configuring DAQ Hardware Used with Examples

The example VIs that accept both prerecorded data and acquired data use either an analog tachometer signal or a digital tachometer signal. The front panel of the example VI specifies the type of tachometer signal the VI uses, for example, Gabor Order Tracking (Analog Tach) or Gabor Order Tracking (Digital Tach). Depending on whether the example is an analog tachometer example or a digital tachometer example, when **Data Source** is

set to **DAQ** and you click the **Run** button on the front panel of the example VI, one of the following VIs opens:

- Acquire Data (Analog Tach) VI
- Acquire Data with PXI 4472 and TIO VI

Refer to the *Acquire Data (Analog Tach) VI* section for information about the Acquire Data (Analog Tach) VI and the *Acquire Data with PXI 4472 and TIO VI* section for information about the Acquire Data with PXI 4472 and TIO VI.

Acquire Data (Analog Tach) VI

In analog tachometer examples, setting **Data Source** to **DAQ** and clicking the **Run** button opens the Acquire Data (Analog Tach) VI. The Acquire Data (Analog Tach) VI helps you acquire vibration data with a digital tachometer signal. Figure 1-1 shows the **Configuration** tab of the Acquire Data (Analog Tach) VI.
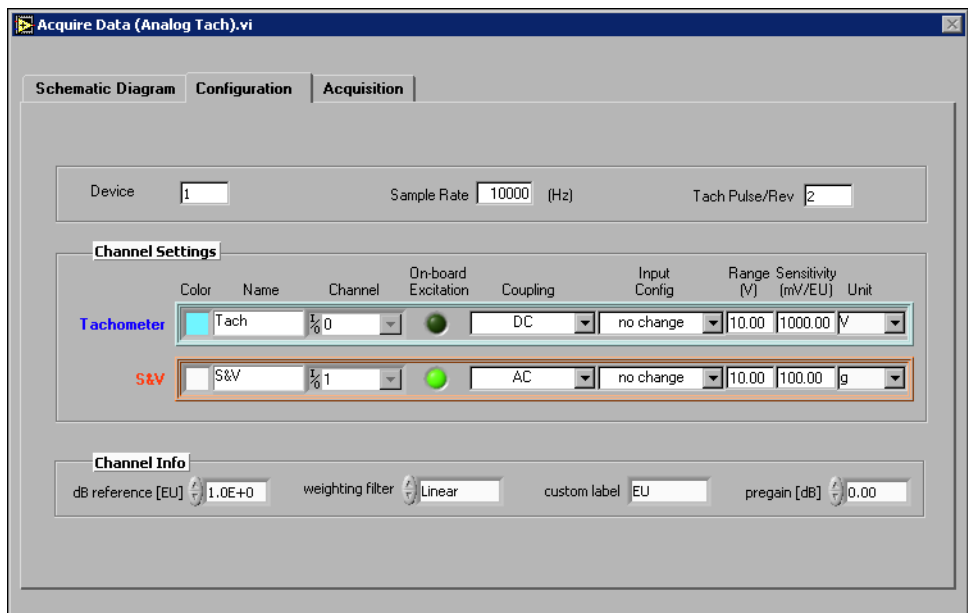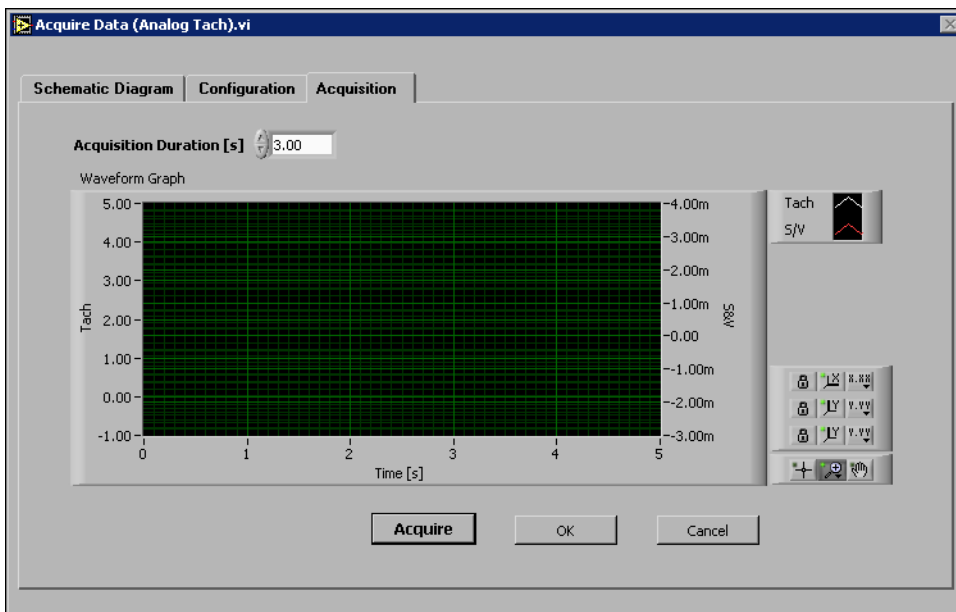

Figure 1-1. Acquire Data (Analog Tach) VI Configuration Tab

You must configure two channels of the DAQ device before you acquire data. Use the **Configuration** tab of the Acquire Data (Analog Tach) VI, shown in Figure 1-1, to configure your DAQ device. In the **Channel Settings** section of the **Configuration** tab, use **Tachometer** for the

tachometer signal and **S&V** for the sound or vibration sensor. After choosing data acquisition settings, enter the number of pulses you want the tachometer to generate per revolution in the **Tach Pulse/Rev** text box. Use the controls in the **Channel Info** section of the **Configuration** tab to specify the channel information for the sound or vibration sensor.

After configuring the DAQ device, click the **Acquisition** tab, shown in Figure 1-2.

Figure 1-2. Acquire Data (Analog Tach) VI Acquisition Tab

The **Acquisition** tab, shown in Figure 1-2, allows you to acquire and observe data. Click the **Acquire** button to acquire data. Continue to configure the data acquisition and acquire data until you acquire the data you want. Click the **OK** button to return to the front panel of the example VI to analyze the data.
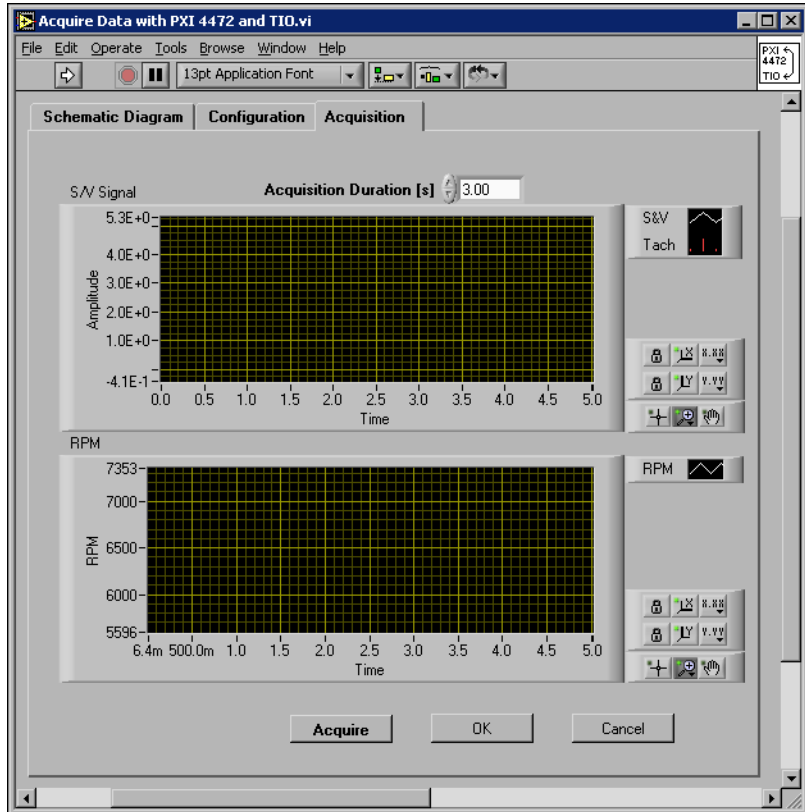
Acquire Data with PXI 4472 and TIO VI

In digital tachometer examples, setting **Data Source** to **DAQ** and clicking the **Run** button opens the Acquire Data with PXI 4472 and TIO VI. The Acquire Data with PXI 4472 and TIO VI helps you acquire vibration data with a digital tachometer signal. Figure 1-3 shows the **Configuration** tab of the Acquire Data with PXI 4472 and TIO VI.
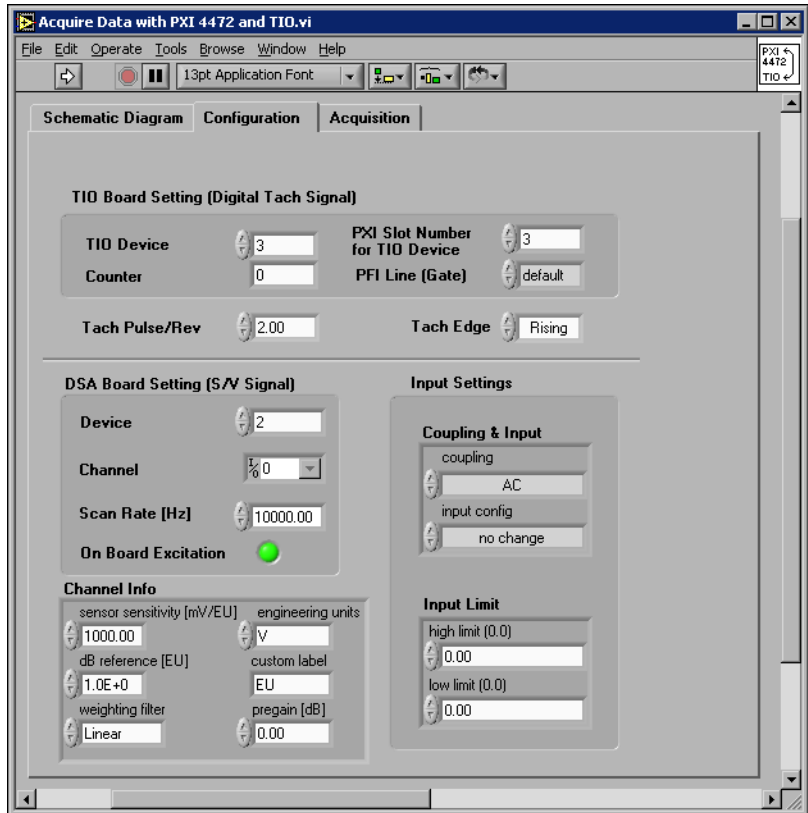
Figure 1-3. Acquire Data with PXI 4472 and TIO VI Configuration Tab

Use the **Configuration** tab of the Acquire Data with PXI 4472 and TIO VI, shown in Figure 1-3, to configure the DAQ devices. Use one of the counters on a TIO device to receive TTL-compatible tachometer pulses. Use the controls in the **TIO Board Setting (Digital Tach Signal)** section of the **Configuration** tab to configure the TIO device. Use an NI PXI-4472 to acquire the data from the sound or vibration sensor. Use the controls in the **DSA Board Setting (S/V Signal)** and **Input Settings** sections of the **Configure** tab to configure the NI PXI-4472. After configuring the DAQ devices, click the **Acquisition** tab, shown in Figure 1-4.

Figure 1-4. Acquire Data with PXI 4472 and TIO VI Acquisition Tab

The **Acquisition** tab, shown in Figure 1-4, allows you to acquire and observe data. Click the **Acquire** button to acquire data. Continue to configure the data acquisition and acquire data until you acquire the data you want. Click the **OK** button to return to the front panel of the example VI to analyze the data.

2

Order Analysis

This chapter gives brief descriptions of the need for order analysis, the basic concepts of order analysis, the effect of rotational speed on order identification, and the different order analysis methods.

Order Analysis Definition and Application

When it is impossible or undesirable to physically open up a system and study it, you often can gain knowledge about the 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.

You can use order analysis to study, design, and monitor rotating machinery. By measuring and analyzing sound or vibration signals generated by a system with rotational components, you can gain a better understanding of the system, associate features of noise and vibration with the physical characteristics of the system, and identify system characteristics that change with time and operating conditions. Systems with rotational components include automobiles, airplanes, air conditioners, and PC hard drives.

Order Analysis Basics

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 often can hear noise and feel vibration created by the parts associated with the rotating components. Parts associated with rotating components include bearings, gears, and blades. Vibration of the rotating components creates noise and vibration signals. The machine rotational speed is the source of the noise and

vibration signals. 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. 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, you can think of order analysis as an application of harmonic analysis for rotating machinery.

Figure 2-1 shows the relationship between frequency and order spectra.
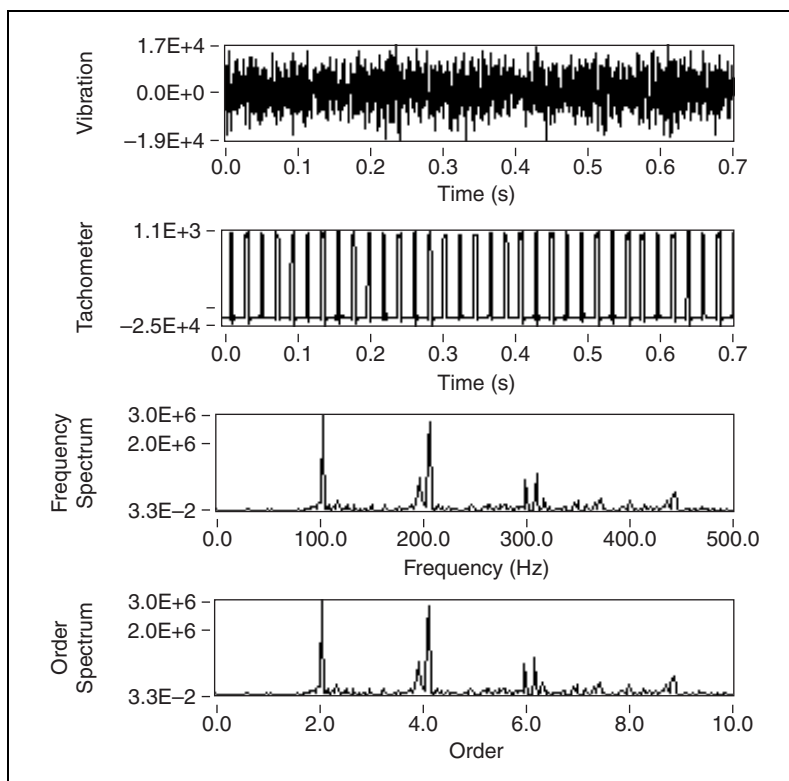
Figure 2-1. Order and Frequency Domain Display of a Shaft Rotating at 3,000 rpm

The top graph in Figure 2-1 shows a vibration signal from a machine running at 3,000 revolutions per minute (rpm). The rotational speed is computed from the tachometer signal, which is shown as the second graph in Figure 2-1. The frequency domain and order domain plots of the signal are shown in the third and fourth graphs, respectively, in Figure 2-1.

Assuming that speed remains constant during data acquisition, you can use the following equations to switch between the frequency domain and the order domain.

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

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

Orders often reflect the physical characteristics of rotating machines. As in classical harmonic analysis, by analyzing the phase and amplitude relationships between different orders, you often can discover a great deal about the system in which you are interested. For example, order analysis has enabled the observation of the following relationships:

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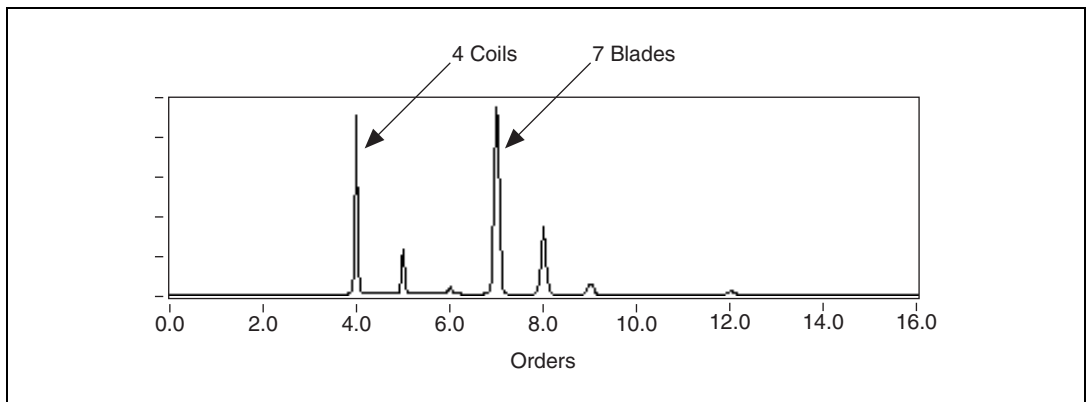
Figure 2-2. Order Spectrum of a PC Fan with Seven Blades and Four Coils

The vibration signal depicted in Figure 2-2 contains 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 seven blades of the fan pass the position of the sensor seven times per revolution and cause the strong seventh order.

Like classical harmonic analysis, order analysis is a powerful tool for gaining a better understanding of the condition of rotating machinery. However, compared to harmonic analysis, order analysis is more effective for the analysis of rotating machinery because you can use order analysis when a machine runs at a constant speed and when the rotational speed varies. As described in the *Effect of Rotational Speed on Order Identification* section, harmonic analysis is effective only when the rotational speed remains constant.

Effect of Rotational Speed on Order Identification

The ability to make a reliable identification of individual orders from the conventional power spectrum depends on whether rotational speed remains constant or varies. This section discusses the effect rotational speed has on the conventional power spectrum and discusses classical harmonic analysis and order analysis in relation to rotational speed.

Constant Rotational Speed

At a constant rotational speed, you can identify orders from both the conventional power spectrum and the frequency-time spectral map. Figure 2-3 illustrates the analysis of a vibration signal acquired from a PC fan running at a constant speed.
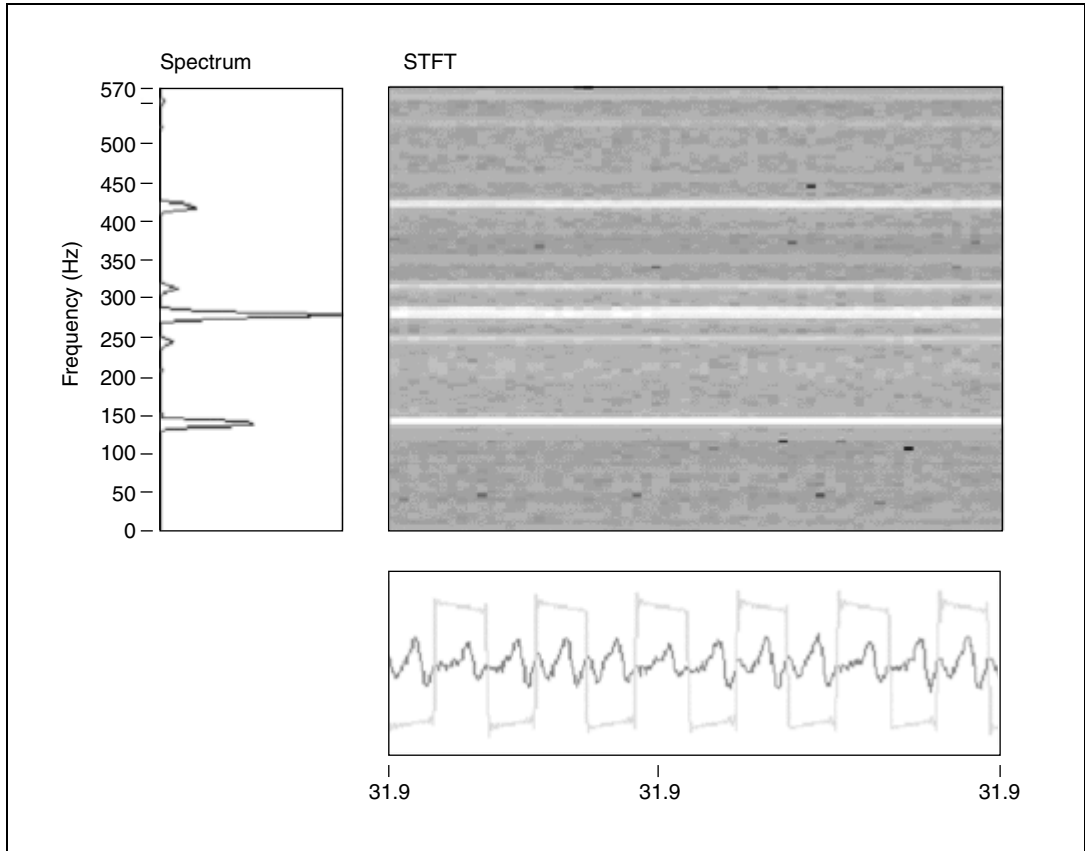
Figure 2-3. PC Fan Running at Constant Speed

The bottom plot in Figure 2-3 depicts the tachometer pulses and the signal from an accelerometer mounted on the PC fan. The plot on the left in Figure 2-3 illustrates a conventional power spectrum based on the fast Fourier transform (FFT). The upper-right plot in Figure 2-3 shows the frequency-time spectral map computed from the short-time Fourier transform (STFT) with a 1,024-point Hanning window. Because of the constant rotational speed of the fan during data acquisition, you can identify several peaks in both the power spectrum and the frequency-time spectral map. The peaks indicate different orders and appear in the frequency-time spectral map as white lines.

Variable Rotational Speed

In addition to testing rotating machinery running at a constant speed, researchers often perform 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.

According to Fourier analysis theory, the frequency bandwidth of a signal is proportional to the change in the frequency and amplitude of the 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.
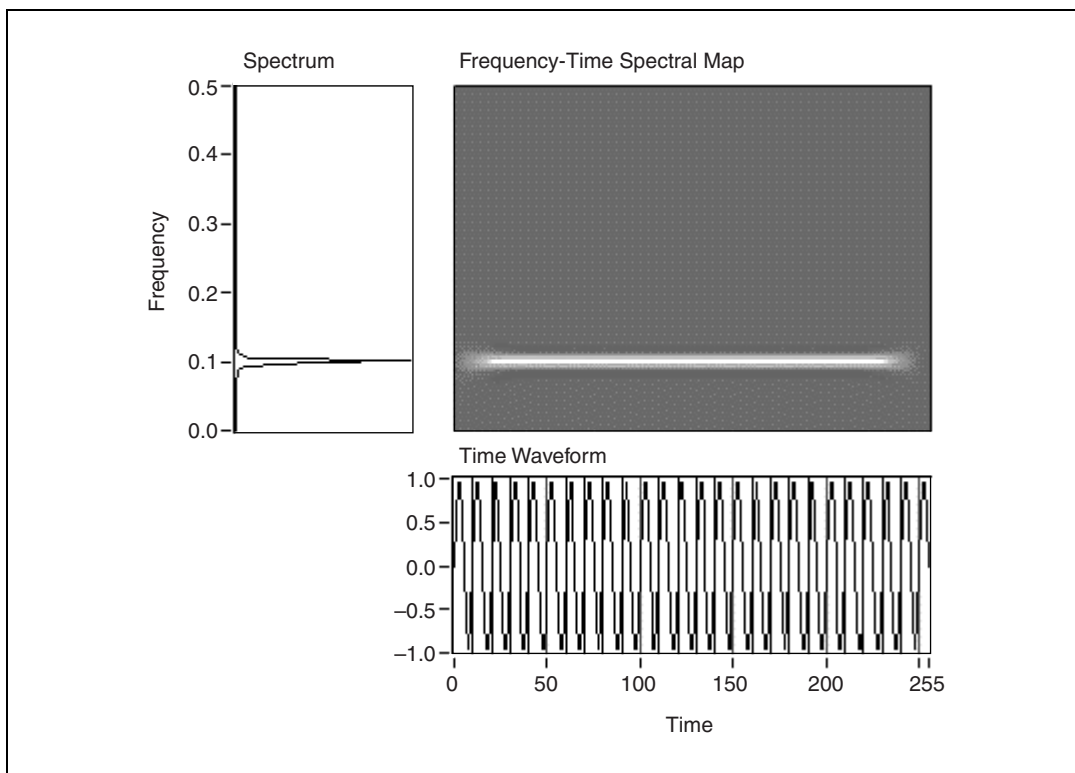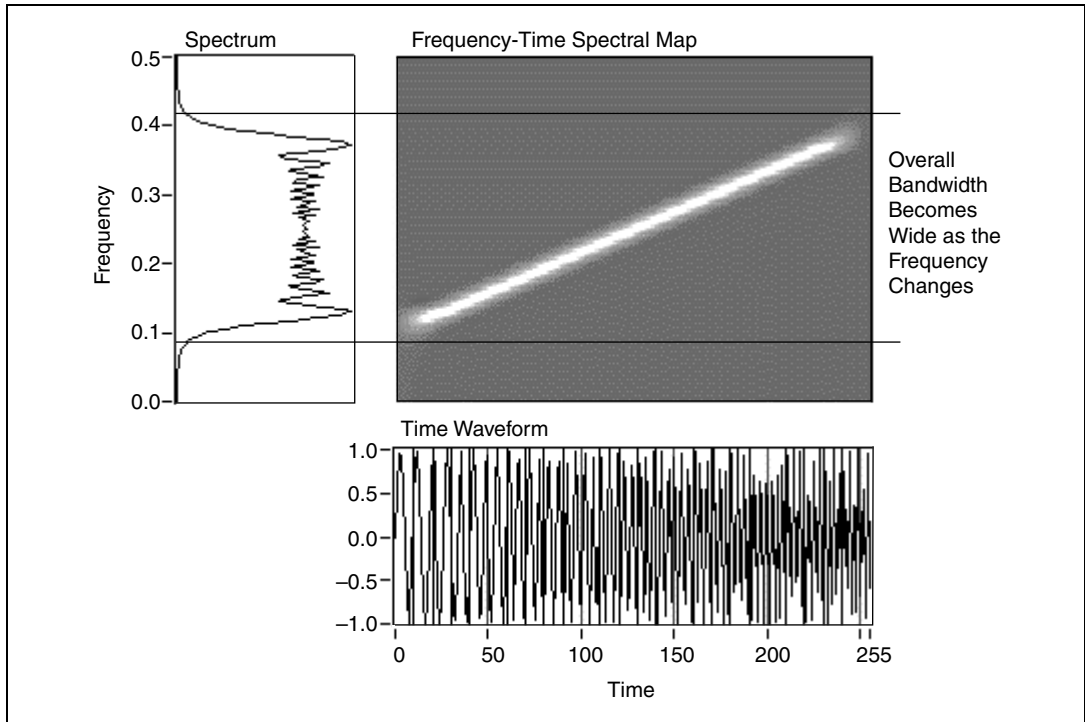

Figure 2-4. Constant Frequency

In Figure 2-4, the overall frequency bandwidth is proportional to the change in frequencies. When the frequency and amplitude are constant over

time, the overall frequency bandwidth, as measured from the conventional power spectrum, is the minimum.

Figure 2-5 depicts a signal whose frequency changes as a function of time.

Figure 2-5. Frequency Changes Over Time

Although the signals in Figures 2-4 and 2-5 have similar frequency bandwidths at each time instant, 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.

When the frequency bandwidth of the fundamental component widens, the bandwidths of the associated harmonics also widen. The widening of the bandwidths of the harmonics eventually causes the frequency bandwidth of the harmonics to overlap in the conventional power spectrum. When the

harmonics overlap in the conventional power spectrum, you are unable to identify different harmonics by using the conventional 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.
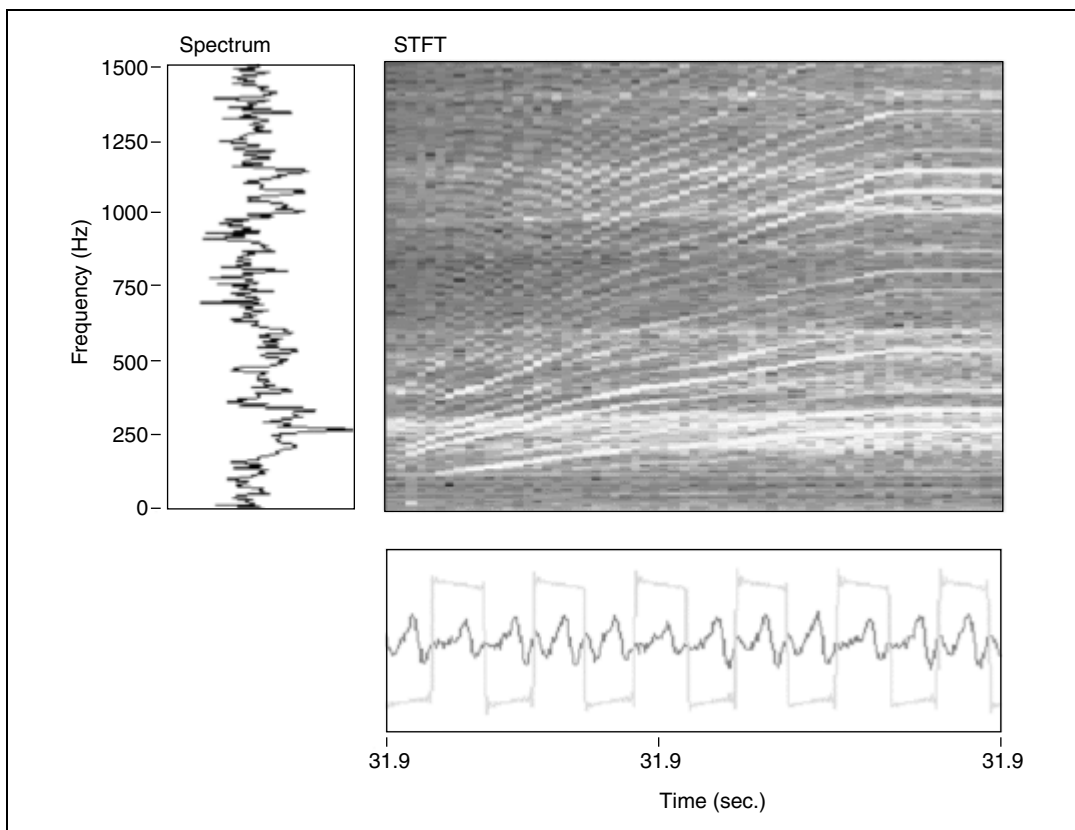
Figure 2-6. Fan Run-Up

In Figure 2-6, as the rotational speed increases, both the fundamental frequency bandwidth and the frequency bandwidths of related orders widen, causing orders to overlap. Whether you can separate nearby orders in a power spectrum depends on the rate of change in the rotational speed, the window used, and the highest order of interest. In Figure 2-6, the power spectrum is 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 spectra of orders eventually overlap. When the spectra of

orders overlap, you are unable to derive meaningful information about the individual orders.

Harmonic Analysis

Harmonic analysis is suitable for the analysis of rotating machinery only when the rotational speed remains constant. In classical harmonic analysis, 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 remain constant.

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

Order Analysis

An important goal 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. While the orders are hidden in the overall power spectrum in Figure 2-6, the orders have distinguishable features in the frequency-time spectral map. The observation that orders have distinguishable features in the frequency-time spectral map serves as the starting point for uncovering information about orders that are difficult to see in the power spectrum.

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, revolutions, rather than time, serve as the basis for signal analysis. Thus, in the spectrum domain, the focus is on orders instead of frequency components.

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

- Gabor transform
- Resampling
- Adaptive filter

The LabVIEW Order Analysis Toolset provides the Gabor-transform-based method and the resampling method of order analysis.

Gabor Transform

The Gabor transform is one of the invertible joint time-frequency transforms. With invertible joint time-frequency transforms, you can recover any time-domain input signal or an approximation of the signal by applying an inverse transform to the transform of the signal. The Gabor transform result is called a Gabor coefficient. The inverse Gabor transform is known as the Gabor expansion. You can think of the Gabor transform as a specific STFT. Even though you can recover a signal from its Gabor transform by using a Gabor expansion, you cannot reconstruct the general STFT using an inverse Fourier transform.

You can compute the Gabor transform by either STFT or windowed Fourier transform. However, to ensure reconstruction of the signal, you have to carefully manage the ratio of the analysis window to the window shift step and the capture of information at signal edges. Use the following methods to ensure reconstruction of the signal.

- Make sure that the ratio between the length of the analysis window and the window shift step is greater than or equal to 1. The ratio between the length of the analysis window and the window shift step determines the time overlap. By default in the LabVIEW Order Analysis Toolset, the ratio is set to 4. For example, if the window length is 2,048, the window shift is 512.
- Move the analysis window in such way that no information is 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. Figure 2-7 illustrates zero padding and wrap padding.
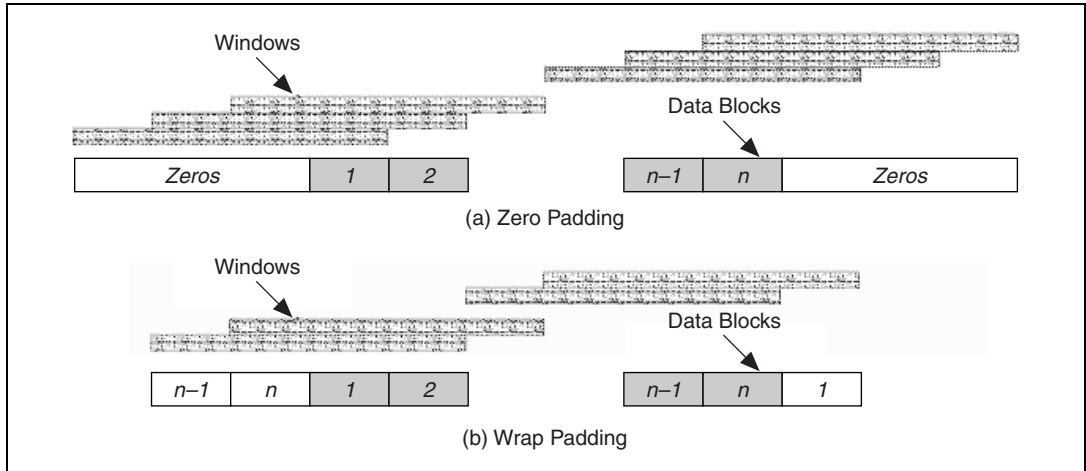
Figure 2-7. Padding Schemes

In zero padding, shown in Figure 2-7(a), the first window and the last window only cover one data block each. 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 is longer than the original data.

To avoid the reconstructed data being longer than the original data, consider the signal as periodic and use wrap padding, shown in Figure 2-7(b). 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. You also can wrap data blocks backward from the beginning of the data sample to the end.

Figure 2-8 shows two examples of padding.
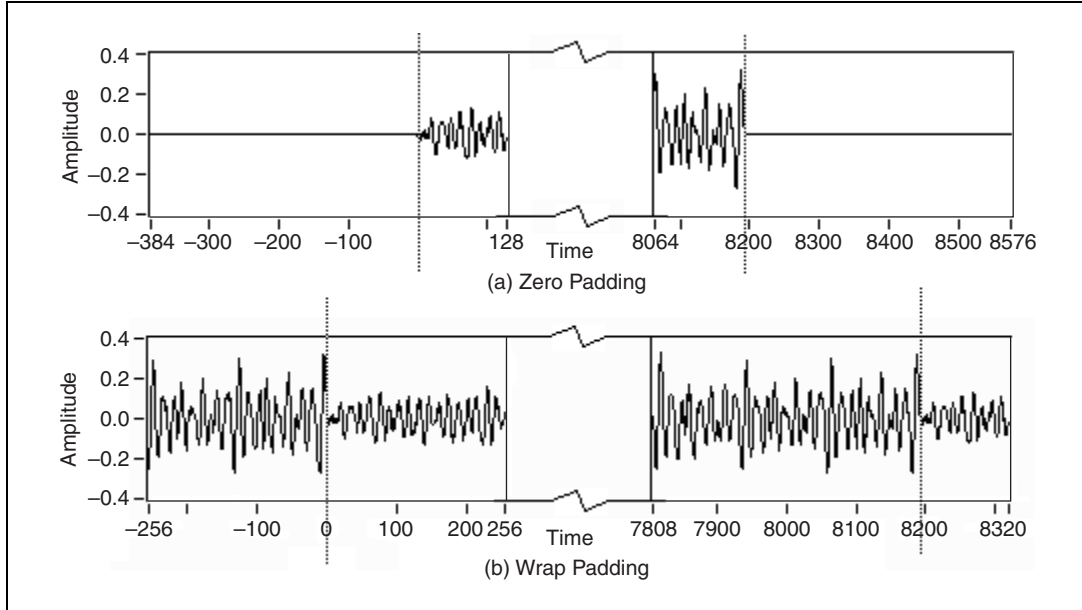

Figure 2-8. Padding Examples

Refer to Appendix A, *Gabor Expansion and Gabor Transform*, for more information about the Gabor transform and the Gabor expansion.

Refer to Chapter 3, *Gabor Transform-Based Order Tracking*, for information about how the LabVIEW Order Analysis Toolset uses a method based on the Gabor transform for order tracking.

Resampling

Resampling is a widely used method of order analysis. Figure 2-9 illustrates the resampling method.
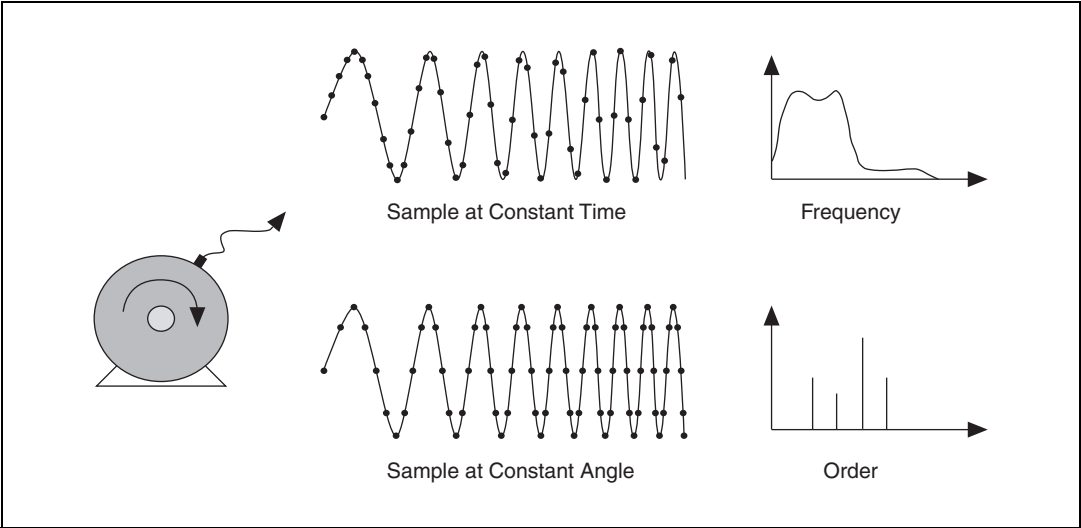
Figure 2-9. Resampling

In the resampling method, time-samples are converted to angle samples. The time-samples are samples of the physical signal that are equally spaced in time. The angle samples are samples that are equally spaced in the rotation angle.

You can acquire angle samples with 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. The hardware solution requires additional hardware devices and a tracking anti-aliasing filter.

Software programs designed to acquire angle samples complete the following steps to acquire the angle samples.

1. Collects the measured signal and the tachometer signal at some constant rate.

2. Uses interpolation or curve fitting to determine the instantaneous shaft angle at intermediate points between the tachometer pulses.

3. Calculates the sampling time at the desired shaft-angular increment.

4. Uses interpolation to obtain new samples at the desired time.

After acquiring angle samples with either hardware or software, you can perform a Fourier transform on the angle samples to analyze them. Because the time domain has changed into the angle domain, the frequency domain now becomes the order domain. You can separate and observe the order components through either the STFT spectrum or the order spectrum, which is actually the FFT spectrum.

Figure 2-10 shows the spectrum of angle samples.
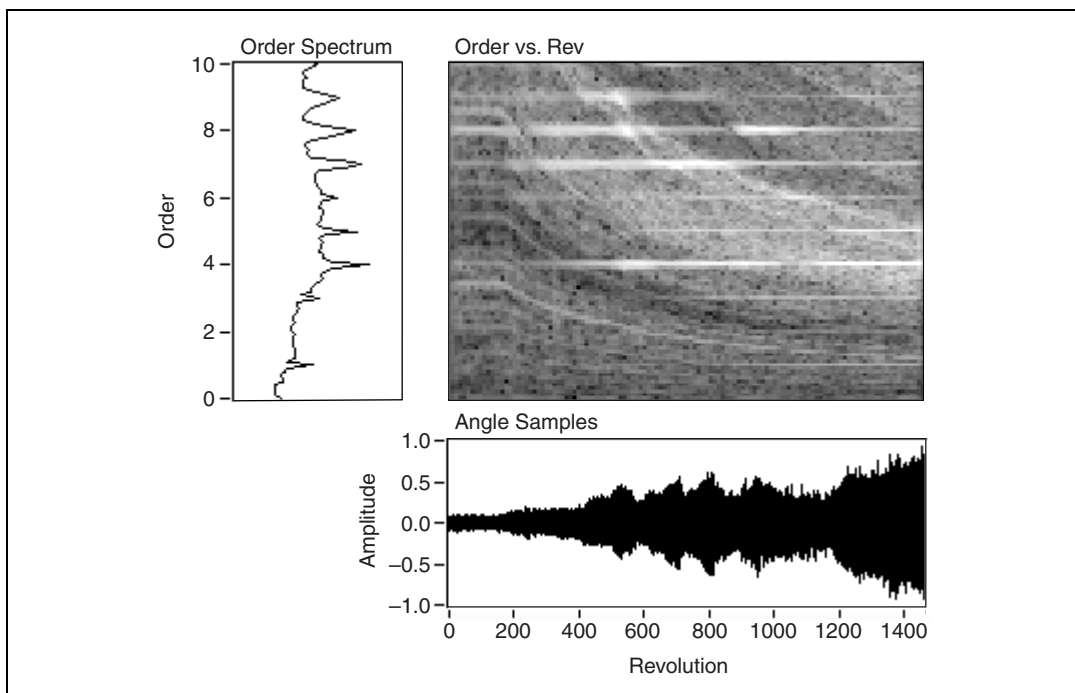
Figure 2-10. Spectrum of Angle Samples

In Figure 2-10, the Angle Samples plot shows the signal sampled at a constant angle-interval. The Order Spectrum plot shows the order spectrum obtained by performing a FFT on the angle samples. In the Order Spectrum plot, significant peaks appear at each order. The Order vs. Rev plot shows the result of a STFT on the angle samples, where an order axis is used instead of a frequency axis. Each horizontal white line in the Order vs. Rev plot indicates the strong power at an integer order.

After the resampling process takes place, recovering a time waveform at a specific order might be difficult.

Refer to Chapter 4, *Resampling-Based Order Analysis*, for information about how the LabVIEW Order Analysis Toolset uses software-based resampling for order analysis.

Adaptive Filter

Although the frequencies of the order components change as the rotational speed changes, you can consider the rotational speed and the frequency of order components to remain constant in a relatively short time interval. The adaptive filter method of order analysis filters out the desired order by using a bandpass filter whose passband frequency shifts according to the rotational speed.

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, without ambiguity, two orders that are in close proximity to each other.

3

Gabor Transform-Based Order Tracking

This chapter discusses a new order analysis method based on the Gabor transform and provided by the LabVIEW Order Analysis Toolset that 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

Overview of Gabor Order Analysis

The Gabor transform can give the power distribution of the original signal as the function of both time and frequency. Figure 3-1 shows a frequency-time spectral map computed by performing a Gabor transform on a sample vibration signal from a rotating machine.
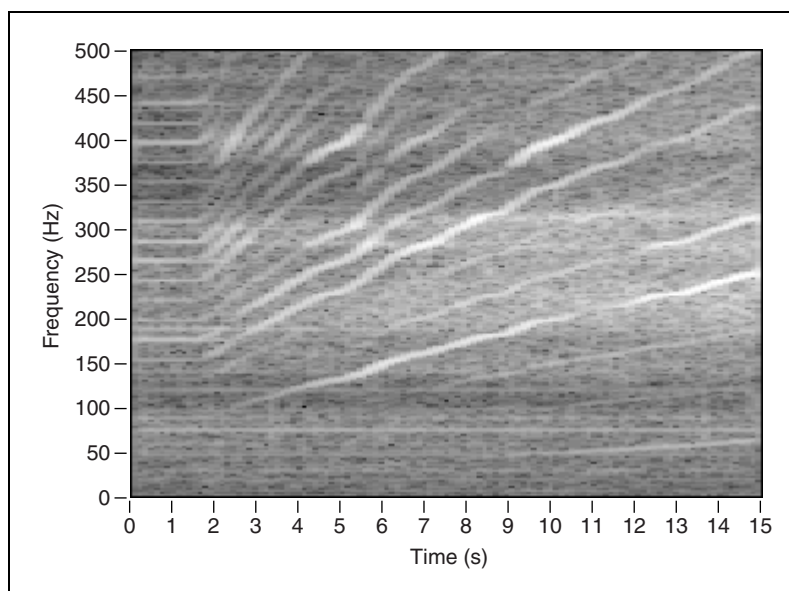
Figure 3-1. Frequency-Time Spectral Map of a Vibration Signal

In Figure 3-1, the magnitudes of coefficients are shown as gray scale, with full white indicating a maximal magnitude and full black indicating a minimal magnitude.

Because the rotational speed changes little in each time portion of the frequency-time spectral map, the spectrum of each order is clearly distinguishable. As the rotational speed varies over time, the frequency of one certain order component changes. Thus, the order component forms a curve with a large magnitude in the frequency-time spectral map, as shown in Figure 3-1. The white curves have magnitudes larger than the magnitudes in local neighborhoods off the curves. The white curves indicate the order components and are referred to as order curves.

From the frequency-time spectral map, you can separate the order curves, or any other part of the signal in which you are interested, from the intact original signal. You then can use Gabor expansion to reconstruct time waveforms of the orders.

Figure 3-2 illustrates the Gabor order analysis process provided by the LabVIEW Order Analysis Toolset.
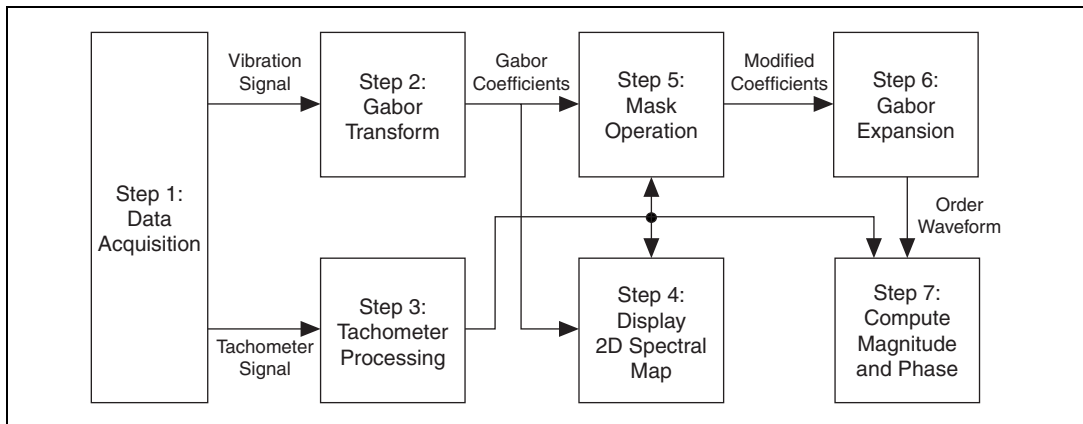
Figure 3-2. Gabor Order Analysis Diagram

Complete the following steps to perform Gabor order analysis.

1. Acquire data samples from the tachometer and noise or vibration sensors synchronously at some constant sample rate.

2. Use the LabVIEW Order Analysis Toolset VIs to complete the following steps.

    a. Perform a Gabor transform on the noise or vibration samples to produce an initial Gabor coefficient array.

    b. Calculate the rotational speed from the tachometer signal. Refer to Chapter 5, *Calculating Rotational Speed*, for information about calculating rotational speed.

    c. Generate a 2D spectral map from the initial coefficient array to observe the whole signal over frequency-time, frequency-rpm, order-rpm, or rpm-order.

    d. Generate a modified coefficient array, based on the rotational speed and the order of interest, from the initial array by performing a masking operation.

    e. Generate a time domain signal from the modified coefficient array by performing Gabor expansion.

    f. Calculate the waveform magnitude and phase.

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

Extracting the Order Components

After generating the initial Gabor coefficient array through a Gabor transform, you can select one or more order components for analysis. You can convert the coefficient corresponding to the selected order component back into a time domain signal. The resulting time domain signal contains information only about the selected order component.

You select order components by including the coefficients along the corresponding order curves. Therefore, you must determine the position index of the coefficient on each order curve. 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 is calculated by multiplying the order number and the fundamental frequency index at the time interval. If a signal is

processed by a Gabor transform, the index of the nth order is given by the following equation.

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

where *RPM* is the averaged instantaneous rotational speed in the time interval, *N* is the number of frequency bins, and f_s is the sampling frequency. In the LabVIEW Order Analysis Toolset, the number of frequency bins *N* equals the length of the window.

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 the coefficients along the order curve and some coefficients in the neighborhood. You must include the coefficients in the neighborhood 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 3-3 illustrates constant frequency bandwidth and constant order bandwidth.
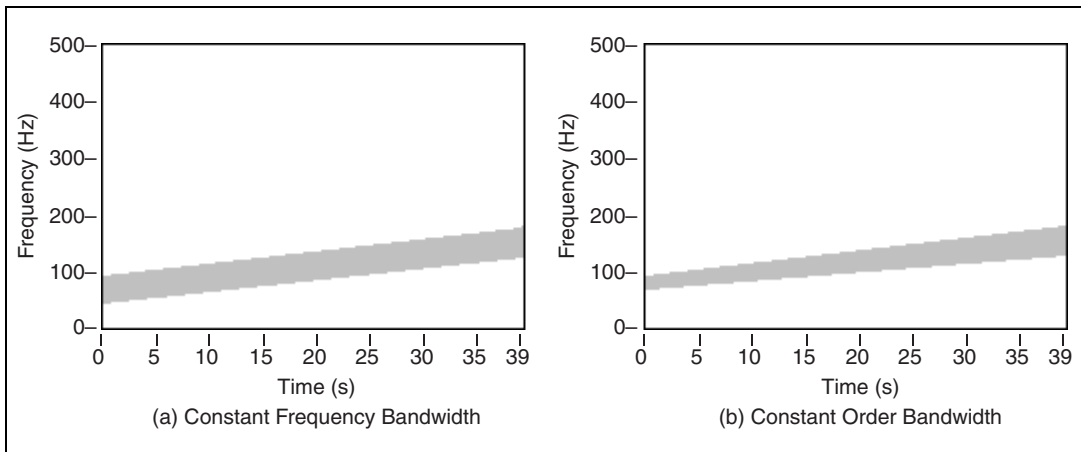
Figure 3-3. Constant Frequency Bandwidth and Constant Order Bandwidth

Figure 3-3(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 3-3(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.

You can use the Gabor Order Analysis VIs to determine the frequency bandwidth or order bandwidth automatically or in response to your input. For example, you can automatically determine a bandwidth 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.

Masking

After you determine the coefficient positions and the bandwidth of the selected order curves, select a subset of the initial Gabor coefficient array. The subset of the initial Gabor coefficient array contains only the coefficients in the neighborhood of the selected order curves. You can generate the subset by performing a mask operation on the initial Gabor coefficient array.

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. However, the mask array contains only Boolean elements. When masking is performed, the coefficients at value TRUE are kept unchanged, while the coefficients at value FALSE are set to zero. The following equation represents the mask operation.

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

where $c_{m,n}$ is the original coefficient array, $\hat{c}_{m,n}$ is the masked coefficient array, and $mask_{m,n}$ is the mask array.

You can build a mask array according to the order number you want to analyze. In each row, elements within the bandwidth of the designated order number are set to either TRUE or FALSE. Use the Template to Mask

VI to perform the mask operation. Refer to the *LabVIEW Order Analysis Toolset Help* for information about the Template to Mask VI.

You can consider the mask operation a time-variant bandpass filter in the joint time-frequency domain. The center frequency of the passband equals the frequency of the order curve. The number of elements set to TRUE determines the bandwidth of the passband.

Extracting Orders

Figure 3-4 illustrates the order extraction and signal reconstruction process.
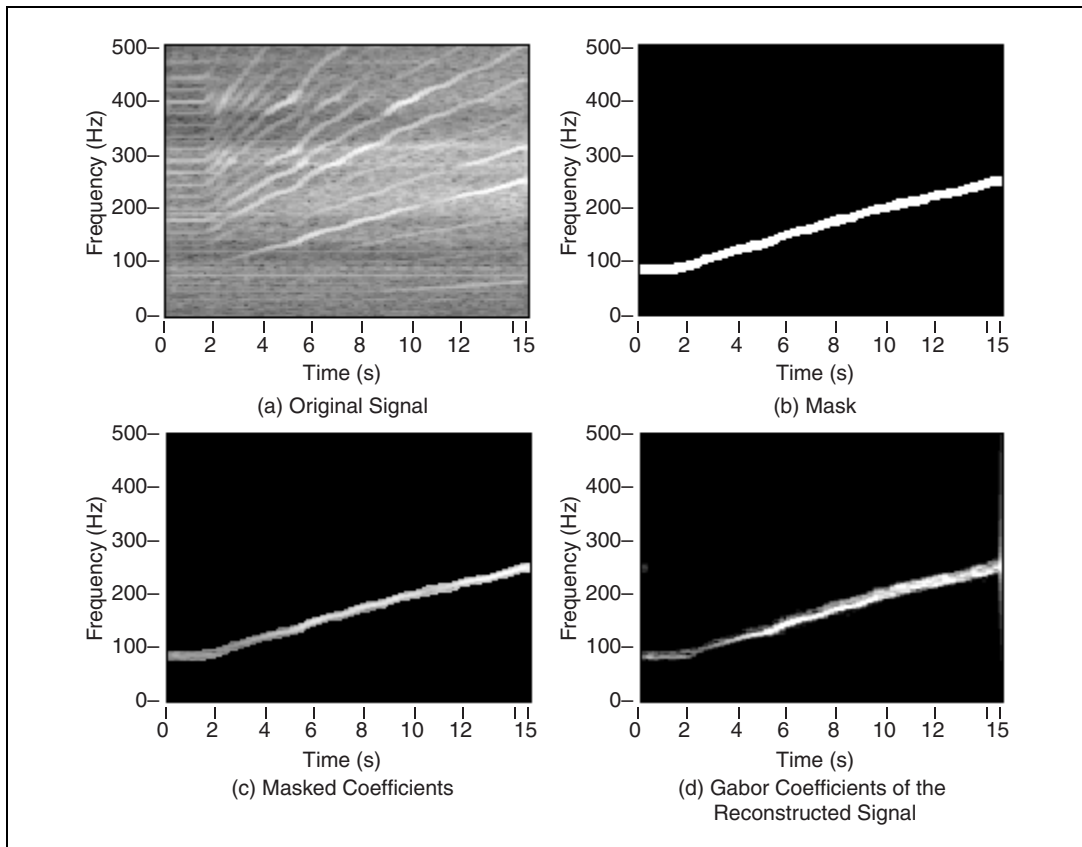
Figure 3-4. Gabor Coefficients

Figure 3-4(a) shows a frequency-time spectral map after the Gabor transform.

Figure 3-4(b) shows a mask array around the fourth order with a constant frequency bandwidth. The TRUE values comprise the white area, while the FALSE values comprise the black areas.

Figure 3-4(c) shows the masked coefficients. The black areas indicate values set to zero and correspond to the FALSE values in the mask array. The white area contains values copied from the original coefficient array and corresponds to the TRUE values in the mask array.

Figure 3-4(d) shows the frequency-time spectral map of the reconstructed signal.

Reconstructing the Signal

Figure 3-5 shows the fourth-order time waveform that was reconstructed by performing a Gabor expansion on the masked coefficients from Figure 3-4.
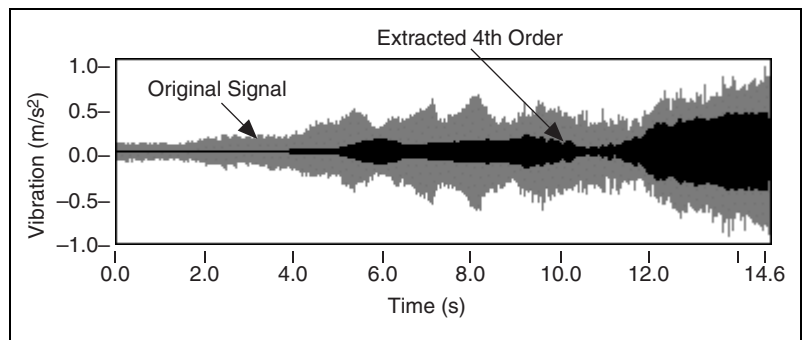
Figure 3-5. Original Signal and Extracted Order Component

Unlike the reverse discrete Fourier transform, the Gabor expansion, in general, is not a one-to-one mapping. A Gabor coefficient is the subspace of a two-dimensional function. An arbitrary two-dimensional function, such as the masked coefficient array, might not have a corresponding time waveform. Usually, the Gabor coefficients of the reconstructed time waveform are not exactly the same as the desired coefficients you mask. However, in terms of the least mean square error (LMSE), the Gabor coefficients of the reconstructed time waveform are the coefficients closest to the desired coefficients you mask.

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. Figure 3-6 shows an original signal and the spectrum of
the reconstructed signal.
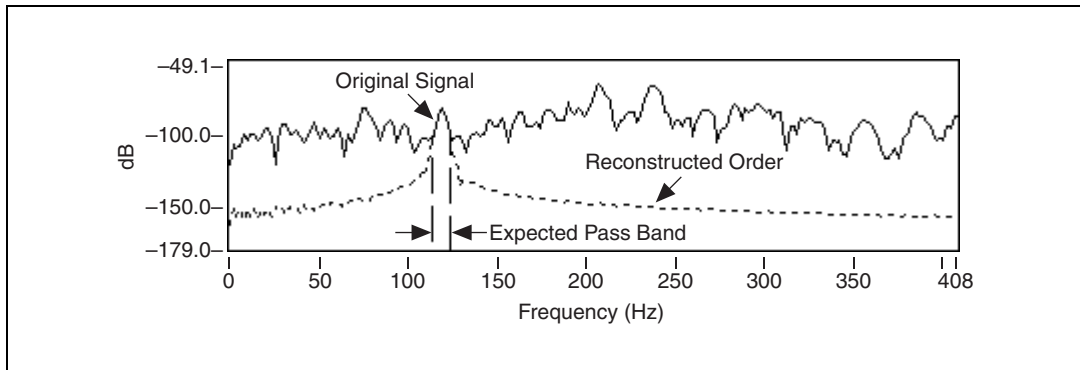
Figure 3-6. Spectrum of Reconstructed Signal

In Figure 3-6, 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 comprise the
solid line in Figure 3-6. When performing a mask operation, coefficients
outside the expected passband are set to zero.

After reconstruction, the spectrum of the reconstructed signal is formed.
In Figure 3-6, the dashed line represents the spectrum of the reconstructed
signal. Within the passband, the reconstructed signal keeps the same
magnitude as the original signal. While outside the passband, the
magnitude of the reconstructed signal is no longer zero. Instead,
the magnitude does have some certain value. However, the value of
the magnitude quickly decreases as the frequency leaves the passband.

Displaying Spectral Maps

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

The LabVIEW Order Analysis Toolset provides several methods of
obtaining a 2D spectral map over the whole signal in the frequency-time,
frequency-rpm, and order-rpm domains. Figure 3-7 shows the three types
of spectral maps for a vibration signal.
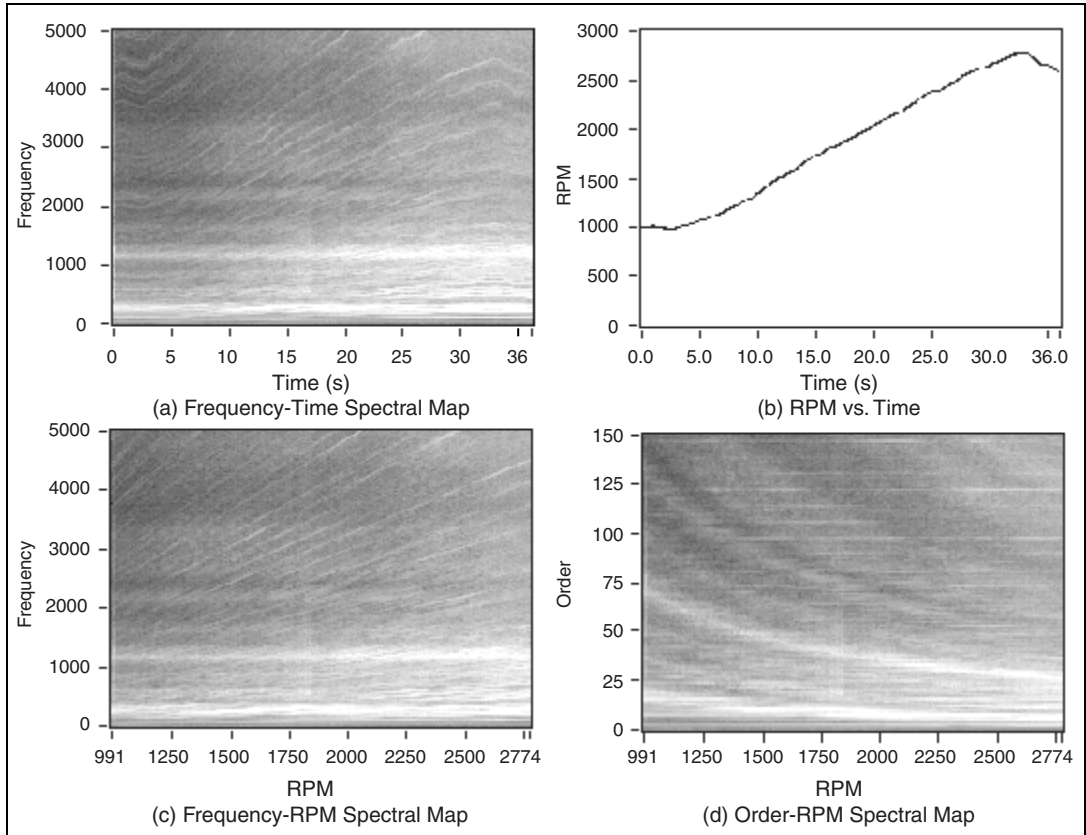
Figure 3-7. 2D Spectral Maps

Figure 3-7(a) is the frequency-time spectral map generated directly from the Gabor coefficients. 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 3-7(b).

In Figure 3-7(a), notice the horizontal white lines. The horizontal 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 3-7(c) shows the frequency-rpm spectral map. The horizontal axis represents rpm, or rotational speed. You can map the rpm axis from the time axis in the frequency-time spectral map by the rpm-time function. The frequency of each order component is calculated by the following equation.

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

Because the relationship between rpm and frequency is a linear function, order components appear as lines with a slope of $\frac{RPM}{60}$ in Figure 3-7(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 3-7(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. Therefore, the reconstructed time waveform of the selected order 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, calculating the waveform magnitude as a function of rpm is useful. The LabVIEW Order Analysis Toolset uses the root mean square (RMS) of the time waveform to calculate the waveform magnitude and correlate the sine waveform with the tachometer pulses to obtain the waveform phase. Both the magnitude and the phase are computed in a short time interval. By means of the time-rpm function, the LabVIEW Order Analysis Toolset performs a time-to-rpm mapping operation to obtain the waveform magnitude and phase as a function of rpm.

4

Resampling-Based Order Analysis

This chapter describes the resampling method provided by the LabVIEW Order Analysis Toolset, determining the time instance for resampling, resampling vibration data, and slow roll compensation.

LabVIEW Order Analysis Toolset Resampling Method

With software resampling, the LabVIEW Order Analysis Toolset enables you to complete the following tasks:

- Resample even time-space samples to even angle-spaced samples
- Obtain magnitude and phase information for each order

Figure 4-1 illustrates the resampling-based order analysis process provided by the LabVIEW Order Analysis Toolset.
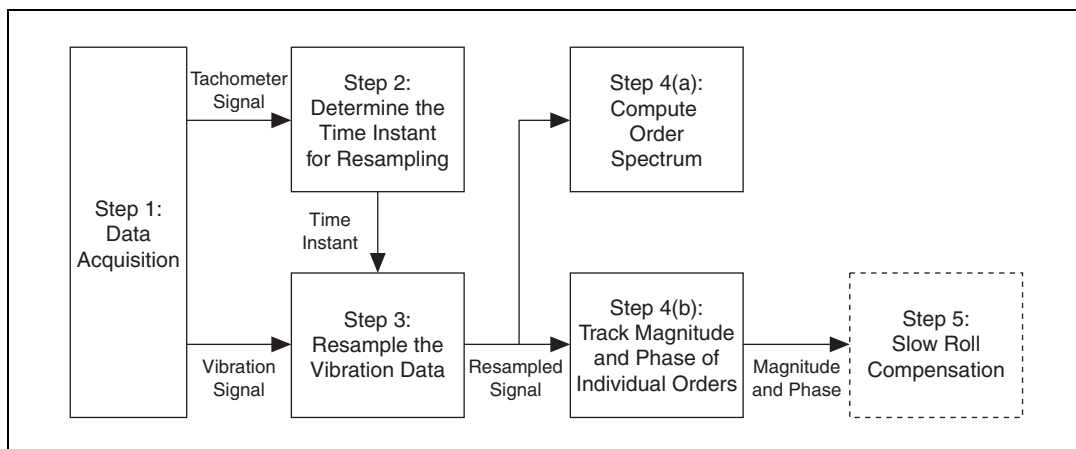

Figure 4-1. Resampling-Based Order Analysis Diagram

Complete the following steps to perform resampling-based order analysis.

1. Acquire data samples from tachometer and noise or vibration sensors synchronously at some constant sample rate.

2. Use the LabVIEW Order Analysis Toolset VIs to complete the following steps:

    a. Determine the pulse edges from the tachometer signal and interpolate the pulse edges to get the time instance for resampling.

    b. Perform software resampling on the vibration signal according to the time instance determined in step a and generate the angle-samples.

    c. Perform one of the following analyses:

        •   Obtain the order spectrum of the signal by performing a FFT on the angle-samples.

        •   Track the magnitude and phase of each individual order along time, revolution, or rpm.

    d. Perform slow roll compensation to the order magnitudes and phases, if necessary.

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

Determining the Time Instance for Resampling

To software resample even time spaced samples into even angle spaced samples, you first must know at what time a certain angle is reached, that is, the time instance for resample. After processing either an analog or digital tachometer signal, you obtain a time sequence that indicates the time when the shaft rotates at a certain angle. For example, if a tachometer generates N pulses in one revolution, you can express the time sequence as a function of angle, as shown in the following equation.

$$t_k = t\left(\frac{2k\pi}{N}\right)$$

When you use even angle-samples to study orders, you also need to follow the Nyquist sampling theorem. That is, if you want to study the Kth order, resample at least $2K$ samples in one revolution. However, you usually need

a larger margin of samples for analysis and need to resample 2.5K samples in one revolution.

Most of the time, a tachometer does not produce enough pulses in one revolution. Therefore, you need to multiply the number of pulses generated by the tachometer, that is, interpolate the time sequence for a smaller angle interval. When you interpolate the time sequence for a smaller angle interval, you need a constant rate integer factor interpolation filter. The LabVIEW Order Analysis Toolset uses a cascaded integrator-comb (CIC) filter when interpolating the time sequence for a smaller angle. The transfer function of the CIC filter is given by the following equation.

$$H(z) \; = \; \frac{1}{L^n}\left(\frac{1 - z^L}{1 - z}\right)^n ,$$

where L is the interpolation factor and n is the order.

The CIC filter has the advantage of only using a few samples in the original time sequence to obtain a single, resampled point, while maintaining good accuracy when the original signal is a narrow-band signal. Rotational speed usually does not change very quickly in a couple of revolutions. Therefore, the original time sequence is an exactly narrow-band signal and suitable for interpolating with the CIC filter. You can implement the CIC filter using only addition and subtraction operations, which makes the CIC filter very efficient for online processing. Figure 4-2 shows the power spectrum of the original time sequence and the CIC interpolation filter with an interpolation factor of eight.
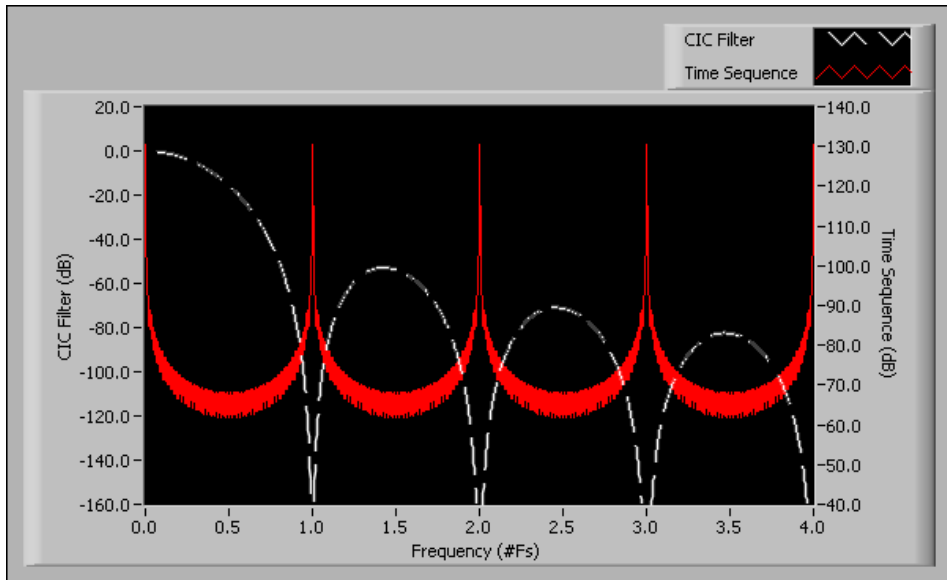
Figure 4-2. Original Time Sequence and CIC Interpolation Filter with
an Interpolation Factor of Eight

Resampling Vibration Data

The resampling operation converts a vibration signal from the time domain
into the angle domain. To resample vibration data into even angle spaced
samples, you must be able to calculate the value of the vibration signal at
any time instance.

According to the Nyquist sampling theorem, you can exactly reconstruct
the signal for all time instances using band-limited interpolation if and only
if the original signal is band limited to half of the sampling rate.

For example, a continuous time signal $x(t)$ that is band limited to $f_s/2$ Hz and
sampled at a sampling rate of f_s samples/second yields a discrete sample
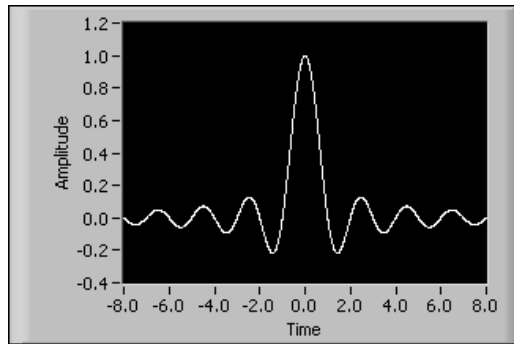given by the following equation.

$$x_n = x(nT_s),$$

where $T_s = 1/f_s$ and is the sampling time interval.

According to the Nyquist sampling theorem, you can exactly reconstruct the time signal $x(t)$ from samples $x(nT_s)$ with the following equation.

$$\hat{x}(t) \;=\; \sum_n x(nT_s)h_s(nT_s - t) \tag{4-1}$$

where h_s is a sinc function defined by $h_s(t) \;=\; \mathrm{sinc}(f_s t) \;=\; \dfrac{\sin(\pi f_s t)}{\pi f_s t}$.

Figure 4-3 shows the plot of $h_s(t)$ with $f_s = 1$.

Figure 4-3. $h_s(t)$ with $f_s = 1$

You can resample the signal at the equal angle interval time instance by evaluating Equation 4-1 at the desired time. Before resampling, you might need a lowpass anti-aliasing filter if the new sampling rate is lower that the previous sampling rate.

The LabVIEW Order Analysis Toolset uses a digital adaptive-interpolation filter to complete the entire resample process. The bandwidth of the adaptive-interpolation filter automatically changes according to the new sampling rate to prevent the aliasing phenomenon. The stopband attenuation of the interpolation filter controls the accuracy of the resampling. As the stopband attenuation becomes higher, the accuracy of the resampled signal improves.

Slow Roll Compensation

In machine condition monitoring applications, engineers often use a proximity probe to measure the movement of a shaft. The proximity probe can convert the distance between the probe and the shaft into an electrical signal.

When monitoring shaft vibration with a proximity probe, the acquired
signal contains not only the vibration of the shaft but also the shaft runout,
such as a nonconcentric shaft condition at the probe measurement plane.
You can measure the shaft runout at a slow roll speed and can compensate
for it in the raw proximity probe signal. Figure 4-4 shows the raw signal
acquired from a nonconcentric shaft and the compensated signal.
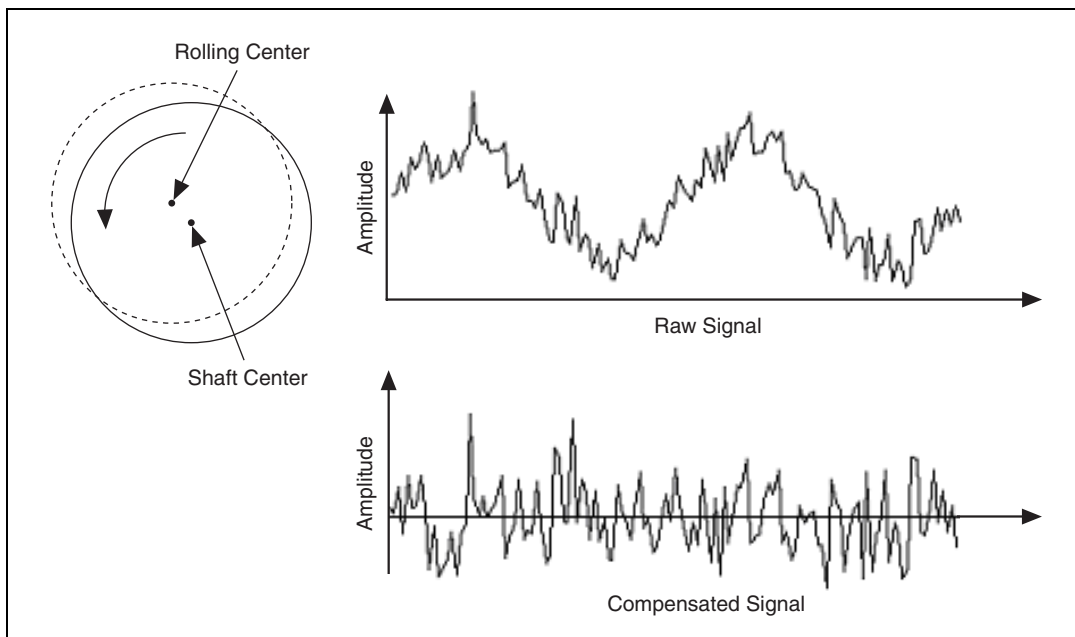
Figure 4-4. Slow Roll Compensation

The LabVIEW Order Analysis Toolset can perform the vector-based slow
roll compensation on order magnitudes and phases. The toolset performs
slow roll compensation subtracting a slow roll vector from the measured
magnitude and phase. Use the OAT Extract Slow Roll Vector VI to compute
the slow roll vector from a slow roll signal. Use the OAT Slow Roll
Compensation VI to remove the runout components from the measured
magnitude and phase. If no slow roll vector is provided, the OAT Slow Roll
Compensation VI automatically uses the first magnitude and phase pair as
the slow roll vector.

5

Calculating Rotational Speed

This chapter describes the digital differentiator method used by the LabVIEW Order Analysis Toolset to calculate rotational speed and describes averaging pulses to smooth noisy calculated rotational speed results.

Digital Differentiator Method

To successfully extract order components, create spectral maps, and calculate waveform magnitudes, you need rotational speed as a function of time during the data acquisition process. The LabVIEW Order Analysis Toolset uses a digital differentiator to calculate the rotational speed. The tachometer processing VIs buffer the input tachometer pulses. Because the tachometer-processing VIs buffer the input tachometer pulses, they 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 5-1 illustrates a typical tachometer pulse train and the cumulative rotation angle θ of the shaft as a function of time *t*.
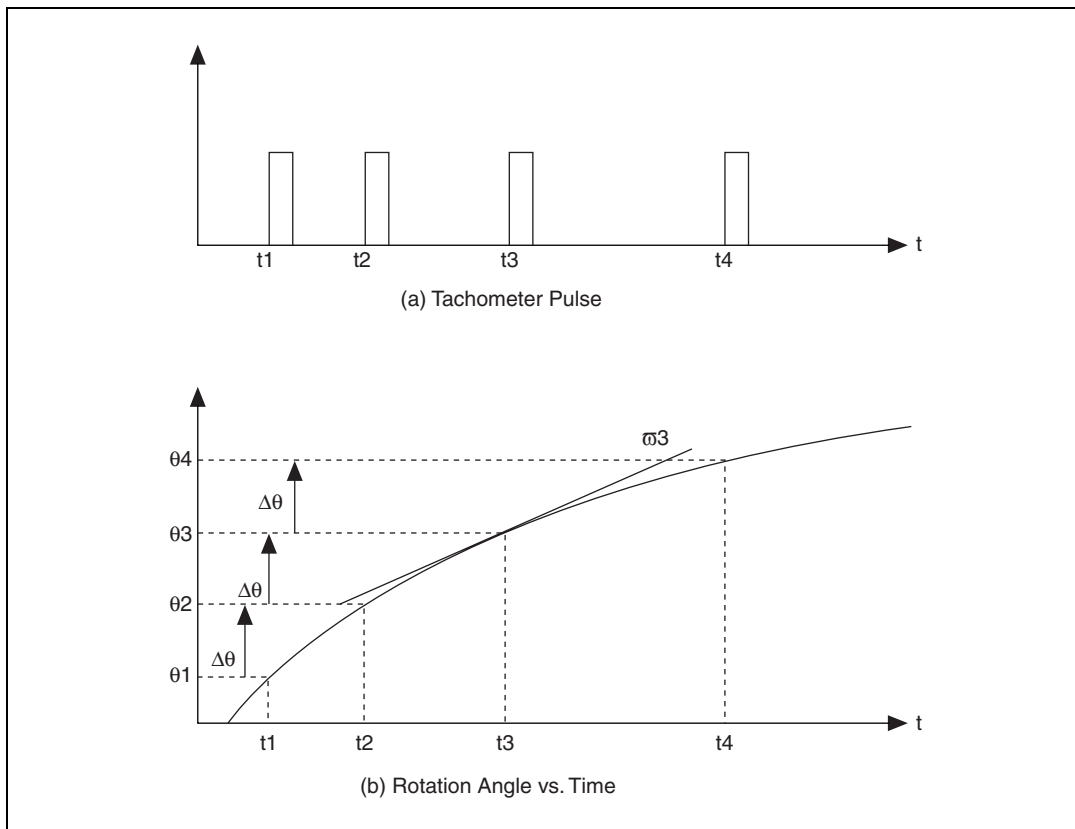
Figure 5-1. Tachometer Signal and Rotation Angle

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 θ in the time interval between times t_k and t_{k+1}. As shown in the following equation, you can present rotational speed as the first derivative of $\theta(k)$.

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

While the time interval between pulses varies with the rotational speed, the cumulative angle increment remains constant. Calculating the first derivative of $\theta(t)$ usually involves step-by-step polynomial curve fitting, which requires multiple computations in each iteration. Instead of observing $\theta(t)$ directly, the LabVIEW Order Analysis Toolset observes $t(\theta)$, which is the inverse function of $\theta(t)$, because calculating the first derivative

of an equally spaced sequence requires fewer computations than calculating the first derivative of an unequally spaced sequence.

For the evenly separated function series t_k, you can use a digital differentiator to calculate the first derivative. The digital differentiator is implemented as a special FIR filter with the following equation.

$$\frac{dt}{d\theta}\bigg|_{\theta = \theta_k} \approx \frac{1}{\Delta\theta} \sum_{i = -M}^{M} h_i t_{k-i} , \qquad\qquad (5\text{-}1)$$

where h_i represents the differentiator coefficients.

Rotational speed at each pulse-arrival time instant then is calculated by the following equation.

$$\omega(t_k) = \frac{d\theta}{dt}\bigg|_{t = t_k} = \frac{1}{\dfrac{dt}{d\theta}\bigg|_{\theta = \theta_k}}$$

The differentiator in Equation 5-1 has an order of 2M. As the order becomes larger, the accuracy of the calculated rotational speed improves. However, as the order becomes larger, the number of pulses needed to calculate the rotational speed also increases. The LabVIEW Order Analysis Toolset can automatically adjust the order of the differentiator according to the number of pulses in the buffer. Automatically adjusting the order of the differentiator improves the accuracy of the calculated rotational speed when the buffer contains a large number of pulses and makes it possible to generate a result even if the buffer contains only two pulses.

Averaging Pulses

Sometimes, the calculated rotational speed is noisy because of error in measuring the arrival time of each pulse. Averaging pulses can smooth noisy calculated rotational speed results. 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 noncumulative, widening the pulse interval decreases the relative error.

Figure 5-2 shows an example of the rotational speed calculated from the tachometer pulses.
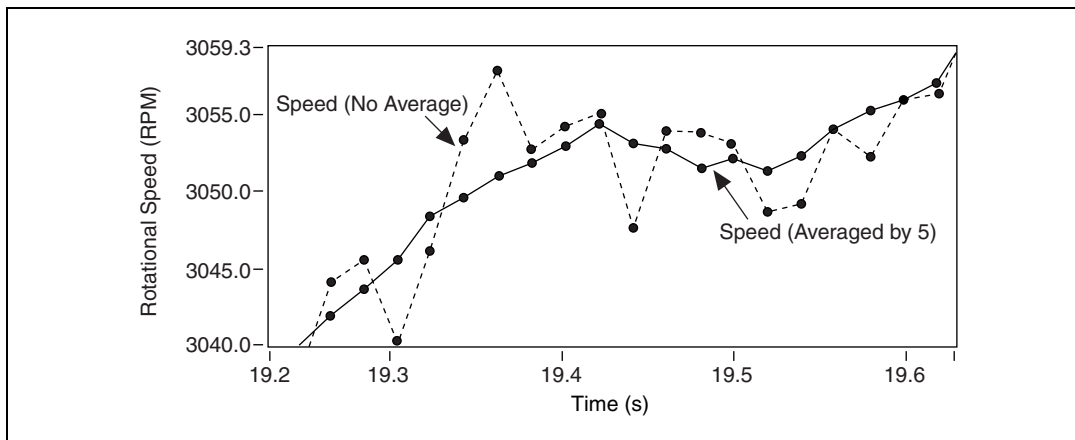
Figure 5-2. Cumulative Revolution and Rotational Speed

In Figure 5-2, the dotted line represents the results of calculating the rotational speed with no averaging. The solid line in Figure 5-2 represents the results of calculating the rotational speed averaged by five. As Figure 5-2 shows, the averaged rotational speed is smoother than the non-averaged rotational speed.

A

Gabor Expansion and Gabor Transform

This appendix presents an overview of the Gabor expansion and the Gabor transform methods used in the LabVIEW Order Analysis Toolset. This appendix also describes application issues associated with using the discrete Gabor-expansion-based time-varying filter.

Gabor Expansion and Gabor Transform Basics

The Gabor expansion characterizes a signal jointly in the time and frequency domains. Although Dennis Gabor introduced the Gabor expansion more than half a century ago, its implementation was 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 were proposed. The LabVIEW Order Analysis Toolset uses an extension of the method originally developed by Wexler and Raz to implement the discrete Gabor expansion. In the method used by the LabVIEW Order Analysis Toolset, 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.

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

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.

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

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 coefficients $c_{m,n}$ 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, the redundancy in Equation A-2 provides freedom for the selection of better window functions, $h[k]$ and $\gamma[k]$.

Notice that the positions of the window functions $h[k]$ and $\gamma[k]$ are interchangeable. In other words, you can use either of the window functions as the synthesis or analysis window function. Therefore, $h[k]$ and $\gamma[k]$ are usually referred to as dual functions.

The method of the discrete Gabor expansion developed in this appendix requires $\tilde{s}[k]$ in Equation A-2 to be a periodic sequence, as shown by the following equation.

$$\tilde{s}[k + iL_0] = \begin{cases} s[k] & 0 \le k < L_s \\ 0 & L_s \le k < L_0 \end{cases} \tag{A-3}$$

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. L_0 must be evenly divided by the time sampling interval ΔM. For a given window $h[k]$ that always has unit energy, you can compute the

corresponding dual window function from ΔM independent linear systems with the following equation.

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

where L denotes the window length. $\tilde{a}[k]$ denotes a periodic auxiliary function[1] given by the following equation.

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

Notice that the solution of Equation A-4 is not unique for over sampling. A particularly interesting solution for Equation A-4 is the least mean square error (LMSE). For the LMSE solution, the Euclidean distance between the dual functions is minimum, as given by the following equation.

$$\min_{A\gamma=u} \left\| \frac{\vec{\gamma}}{|\vec{\gamma}|} - \vec{h} \right\|$$

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

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

Equations A-5 and 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 $h[k]$.

---

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

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

Discrete Gabor-Expansion-Based Time-Varying Filter

Initially, discrete Gabor expansion seems to provide a feasible method for converting an arbitrary signal from the time domain into the joint time-frequency domain or vice versa. However, discrete Gabor expansion is effective for converting an arbitrary signal from the time domain into the joint time-frequency domain or vice versa only in the case of critical sampling, $\Delta M = N$. For over sampling, which is the case for most applications, the Gabor coefficients are the subspace of two-dimensional functions. In other words, for an arbitrary two-dimensional function, a corresponding time waveform might not exist. For example, the following equation represents a 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 0 or 1. Applying the Gabor expansion to the modified two-dimensional function results in the following equation.

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

The following inequality results from Gabor expansion.

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

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

To overcome the problem of the reconstructed time waveform not equaling the selected Gabor coefficients, use an iterative process. Complete the following steps to perform the iterative process.

1. Determine a binary mask matrix for a set of two-dimensional Gabor coefficients.

2. Apply the mask to the two-dimensional Gabor coefficients to preserve desirable coefficients and remove unwanted coefficients.

3. Compute the Gabor expansion.

4. Compute the new Gabor coefficients after you obtain the time
    waveform.

5. Repeat steps 1 through 4 until the time waveforms converge.

Without a loss of generality, rewrite the Gabor expansion from
Equation A-1 and the Gabor transform from Equation A-2 in matrix form,
as shown in the following equations.

$$C = G\vec{s}$$
$$\vec{s} = H^T G \vec{s}$$

where *H* denotes the analysis matrix and *G* denotes the synthesis matrix.
Notice that for over sampling, the following relationships are true.

$$H^T G = I \qquad GH^T \neq I$$

Therefore, in the case of over sampling, the iterative process is described
by the following equations.

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

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

$$C^2 = G\vec{s}^{\,1} = GH^T \Phi C$$

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

$$\vec{s}^{\,2} = H^T \hat{C}^2$$

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

$$\dots$$

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

C^k and $\overset{>}{s}^k$ converge. $C^k = \Phi C^k$ with $k \to \infty$. For $C^k = \Phi C^k$ with $k \to \infty$, the support of C^k in the time-frequency domain is inside the masked area if and only if the following equation is true.

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

(A-6)

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

In critical sampling, $N = \Delta M$. Notice that in the case of critical sampling, 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 the 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, the LabVIEW Order Analysis Toolset uses the orthogonal-like representation introduced at the end of the *Gabor Expansion and Gabor Transform Basics* section. 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.

B

References

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

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C

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Glossary

Numbers/Symbols

∞   Infinity.

2D   Two-dimensional.

A

adaptive filter   A type of filter that 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   Pair of window functions for Gabor transform and Gabor expansion. The two dual functions are interchangeable. That is, you can use either of the dual functions for a Gabor transform while using the other dual function for a Gabor expansion.

F

FFT	Fast Fourier transform.
fundamental component	Portion of a signal whose frequency is at the fundamental frequency.

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 harmonic 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 a 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

resampling	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 LabVIEW Order Analysis Toolset, it is always equal to a quarter (0.25) of the window length. For example, if the window length is 2,048, the window shift is 512.

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