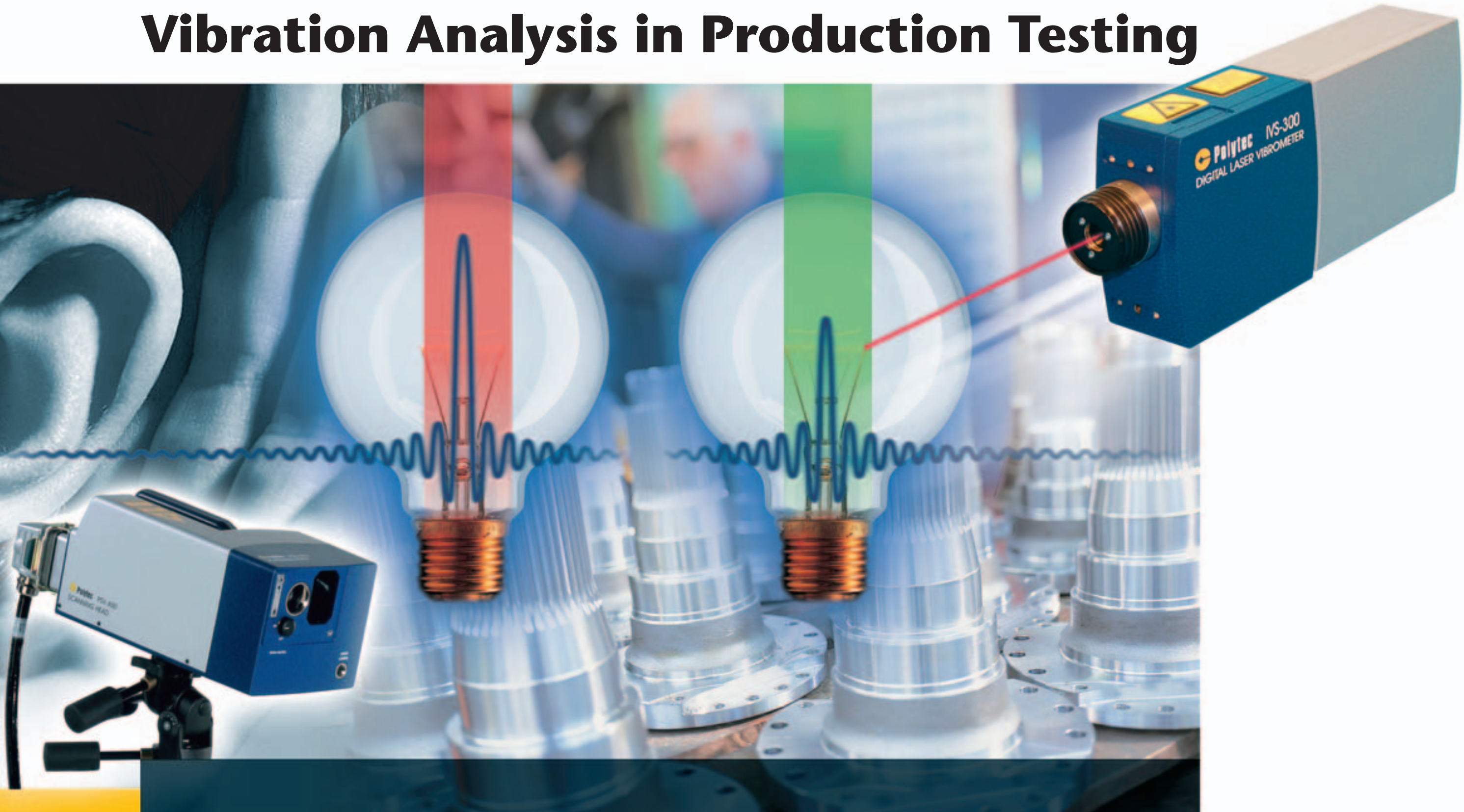
Polytec

Vibration Analysis in Production Testing



FOR BEGINNERS AND EXPERIENCED USERS

The dynamic properties of structures can be described with the aid of eigenfrequencies, attenuation and eigenshapes. Suitably measured, analyzed and classified, these properties can quickly determine quality for pass/fail selection of manufactured components.

For many production inspection applications, Laser-Doppler vibrometers offer significant advantages over conventional, structure-born noise sensors, such as contact accelerometers. Apart from the high dynamic range, wide bandwidth and small spatial measurement spot, it is the non-contact, non-reactive measurement of a laser vibrometer that plays a decisive role.

There are many high performance methods available to analyze vibration signals (see table on page E24). In this tutorial, the basic principles of frequency analysis are introduced including two versions of frequency band analysis: short-term Fourier analysis and order analysis.

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Frequency Analysis

Automatic digital analysis of vibration signatures for product final inspection is most commonly done using frequency analysis.

With a discrete Fourier transformation,

$$S(f_n) = \frac{1}{Nf_\Delta} \sum_{k=0}^{N-1} s(t_k) e^{-j2\pi nk/N}$$

a signal $s(t_k) = s(kT_\Delta)$ with N samples is mapped onto N discrete frequencies $f_n = nf_\Delta$ (Fig. 1). The frequency resolution $f_\Delta = f_A/N = 1/T = 1/NT_\Delta$ solely depends on the sample frequency f_A and the number of data points N and thus on the duration of the measurement, T. If the measurement time selected is too short, then individual frequencies close to each other will no longer be resolved, but will be seen as a single, broad frequency line (Fig. 2).

For real signals, only the Fourier spectrum $S(f_n)$ for $n = 0, 1, 2, \ldots, N$ needs to be calculated for symmetry reasons. Usually in frequency analysis, the power density spectrum $|S(f_n)|^2$ is analyzed; the phase of the individual frequencies nf_0 is of no importance. Because of the periodicity of the discrete Fourier spectrum in N, $e^{\pm j2\pi kn/N}$

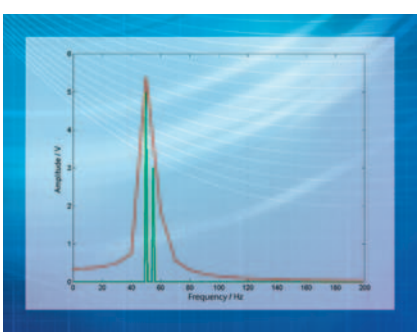


Figure 2: Results of both signals from fig. 1; green: $f_\Delta = 1$ Hz, red: $f_\Delta = 10$ Hz

$= e^{\pm j2\pi kn(k+\alpha N)/N}$, $\alpha \in N$ there can be an overlap of individual spectra, leading to an effect known as Aliasing (Fig. 3, 4). This can be avoided by selecting the sample frequency f_A according to Shannon's sample theory: to be at least twice as big as the highest frequency occurring in the signal f_{max}.

To prevent aliasing for real signals, the analog signal must be band-limited with a low-pass filter prior to digitalization. Since all real filters have a transitional area between the pass band and the stop band, frequency parts outside the cutoff frequency, f_C, of the filter are not fully attenuated and can lead to aliasing artifacts. To prevent this, a factor of 2.56 is usually selected in the digital signal processing and applied to the cutoff frequency of the selected low pass filter to determine an appropriate sampling frequency, $f_A = 2.56 \cdot f_C$.

Another effect in calculating the Fourier spectrum of a discrete signal is the so-called *Leakage*. Discret frequency variables $f_n = nf_\Delta$ with $f_\Delta = 1/T$ are the only way to display frequencies that are an integer multiple of the frequency resolution without error. Leakage must be expected if the product of the observation period T and the frequencies to be displayed f_n is not an integer. Leakage is noticed by additional frequencies in the spectrum. It can be reduced if the discrete time signal is weighted with a suitable window function (e.g. Hanning,

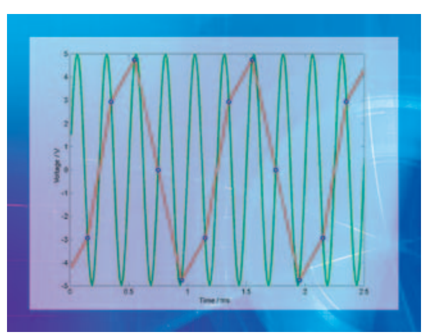


Figure 3: Digitalization of a 4 kHz signal; green: sample frequency 10 kHz, red: sam-ple frequency 5 kHz

Hamming) before the Fourier transformation.

In *material testing*, the position of the spectral frequency lines is usually evaluated directly by the frequency analysis. Independent of whether the components are excited in a pulse

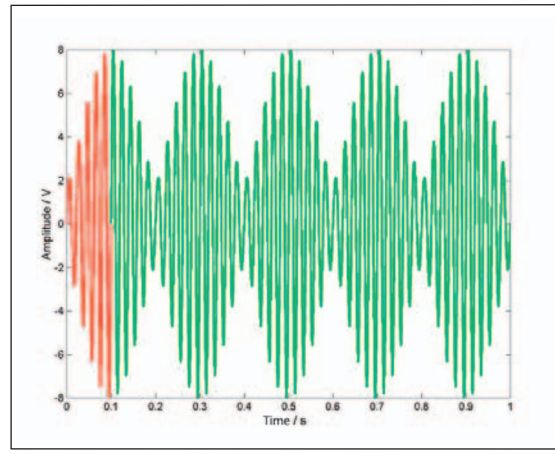


Figure 1: The increased resolution of a long measurement versus a short measure-ment time; red: 0.1 s measurement duration; green: 1 s measurement duration

shape or continuously with a shaker, only the characteristic resonant frequencies of the component are ascertained. From these characteristic frequencies, the status of the test item is determined.

Frequency Band Analysis

In contrast to material testing, *operational vibration analysis* is not entirely concerned with the structural resonances; but, also, the forced vibrations

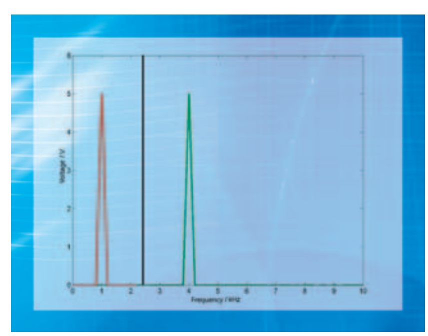


Figure 4: Results of frequency analysis of both signals from fig. 3; green: real fre-quency, red: pseudo-frequency through Aliasing

generated through the interaction of assembled components. This vibration content depends on both the resonant frequencies of the components and the driven movement velocity that often corresponds to an RPM value.

In simple applications, such as testing

electric motors or cooling fans, the individual frequency lines are not analyzed; instead, groups of frequencies , called *frequency bands*, are examined. Identical products with similar behavior are analyzed at a constant RPM and can be reliably qualified, even with a slight deviation in the RPM value.

In the case of *narrow band analysis*, the signal spectra are divided up into frequency intervals which are seamlessly strung together, whereby the average frequencies of the bands are arranged equidistantly. The power density is determined for every frequency band and the so-called narrowband spectrum is used for analysis.

In contrast to narrow band analysis, *proportional band analysis* uses spectra that are divided into joined frequency intervals, where the bandwidth of the frequency intervals increases with increasing average band frequency. In this case, the proportion, q_B, of the respective neighboring frequency bands, B_i, B_{i+1} is constant and equal to the proportion q_f of the corresponding band average frequencies, $f_{m,i}$, $f_{m,i+1}$. If $q_B = q_f = 2^{1/3}$ applies, the calculated frequency bands are designated as 1/3 octave bands, and the analysis as *one-third octave band analysis*. The partitioning of the frequency bands for one-third octave band analysis is oriented towards the subjective perception of the human ear, in which doubling the physical frequency is seen as a proportional frequency increase (Figure 5/6).

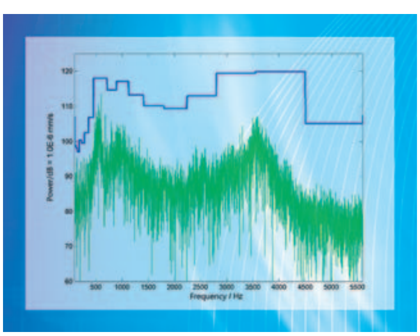


Figure 5: Green: spectrum of a signal, blue: one-third octave band level of the spectrum

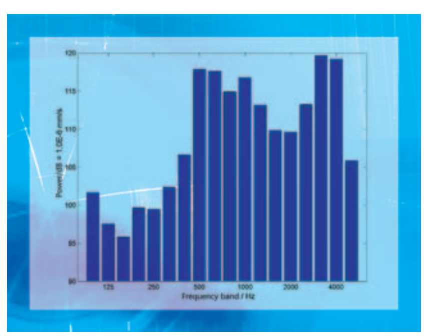


Figure 6: One-third octave band level spectrum from fig. 5 (frequency axis is llogarithmic)

Modulation Analysis is used to evaluate the spectral composition of the envelopes of signals caused by amplitude modulation. In principal, modulation analysis is based on frequency analysis of the rectified signal. Since carrier frequencies with a different frequency can be modulated differently, in modulation analysis the frequency analysis is usually applied to several carrier frequency bands. Apart from the spectral analysis of the envelopes, in modulation analysis, the degree of modulation, i.e. the ratio between the carrier frequency amplitude and the modulation amplitude is also determined.

Short-time Fourier Analysis

For certain applications, such as testing gearboxes, actuators or attenuators, the mechanical construction has no stationary condition that can be attained which means that the test sample is in different operating modes at different points in the process. This means that during operation, the vibration characteristics continually change. An initial impression of the change in the vibration characteristics at different operating modes allows analysis of the *level progression*. In doing so, the average performance is not determined for the whole signal, but continuously for joined time periods. How-ever, to be able to carry out detailed analysis of the vibration characteristics at certain points in time, *short-time Fourier analysis is often used* (Fig. 7).

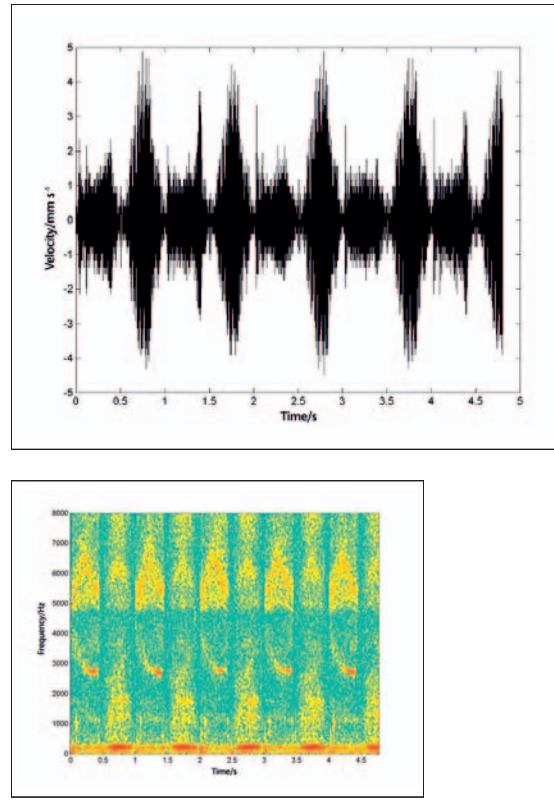


Figure 7: Fourier transformation; on the left: output signal; on the right: spectrogram (short-time FFT)

In short-time Fourier analysis, the discrete time signal is weighted in a window function $w(k-m)$ which depends on a translation parameter and subsequently the Fourier transformation is applied to it.

$$S^{ST}(f_{m,n}) = \frac{1}{Nf_\Delta}\sum_{k=0}^{N-1} s(t_k)\, w^*(t_k - t_m)\, e^{-j2\pi nk/N}$$

$$m = 0, 1, \ldots, M-1, M \le N$$

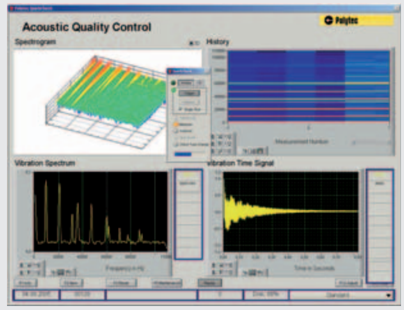
The window function $w(k-m)$ then ensures that just one time section of the signal $s(k)$ is transformed at a time. The time period of the signal section observed is defined by the width of the window function and determines the spectral bandwidth. Therefore, the resolution of the time period/bandwidth product is equal for all values n and m. The short-time Fourier transformation provides a constant time-frequency resolution.

Order Tracking

For high performance machines, such as car engines or gearboxes, which are tested and operated over a long period, frequency analysis does not provide meaningful results. Such machines are usually tested in one or more cycles with continuous run-up. Due to the permanently changing operating mode, it is not possible to analyze events which occur briefly using short-time Fourier transforms.
In such cases, order analysis is used in which the vibration amplitude instead of the short-time Fourier transform is applied to the RPM value in place of the time, and also to the order (multiple of the RPM) in place of the frequency.

Conclusion

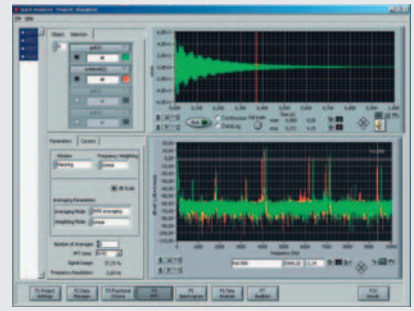
High-performance, non-contact vibrometers, combined with appropriate signal analysis, enable in-line 100% quality inspection and control of components and products. Polytec's ruggedized laser-Doppler vibrometers and easy-to-use Quality Control Software offer optimal solutions for more efficient inspection, enhancing process throughput, lowering product cost and increasing customer perception of product quality.



QuickCheck – Hardware and Software Package for Acoustic Quality Control

QuickCheck is a multi-channel, PC-based software for semi or fully automatic process monitoring and control using the vibration behavior of the product.. Typical applications include noise and vibration testing, 100% in-line quality inspection, material testing, flaw (crack) testing, solidity testing, operational vibration analysis and process control.

The range limits for each product test are assigned a priori during quality examinations of good and bad products, entered into the software and stored in a database. During the test process, a pass/fail decision is calculated by comparing the vibration response of each test sample with the limits corresponding to that product test. The pass/fail decision is indicated on the display, transferred to the production controller and stored in a log file for future statistical evaluation.



QuickAnalyzer – Efficient Analysis of Vibration Signals

QuickAnalyzer is a PC-based, single-channel signal analyzer that is designed for pass-fail evaluation of acoustic signatures emanating from a product or machine under test. It is designed for research and development of process and quality control applications.

The software has various modeling techniques that are available for analyzing measurement data. By simply selecting a new analysis window, the user can quickly and efficiently differentiate between unique signal criteria. The software can then group measurement data into fault classes which are clearly arranged and displayed in the analysis window.
Many methods, including Fourier transformation and octave analysis, are included as standard software for analyzing vibration signals. In addition, an "audition" module enables digital filtering and audio playback of the saved signal.

To learn more visit: **www.polytec.com/usa/industrial**

Application	Type of excitation	Excitation	Function	Analysis
Material testing	external	pulse-shaped (e.g. pulse hammer)	– crack detection – resonance testing	– frequency analysis
		continuous, periodic (e.g. with shakers)	– resonance testing	– frequency analysis
Noise testing Operational vibration analysis	self-excitation, continuous, constant	at a constant velocity	– engines – cooling fans – bearings	– total level – narrowband analysis – 1/3 octave band analysis – modulation analysis
	self-excitation, continuous, not constant	subject to changing operating modes	– drives – actuators – attenuators	– level progression – short-time Fourier analysis
		run-up or run-down	– combustion engines – gearboxes	– order analysis

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