Computed Order Tracking Applied to Vibration Analysis of Rotating Machinery

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1. Introduction:

Vibration analysis of rotating machinery is an important part of industrial predictive maintenance programs. Accurate determination of machine condition can reduce down time by allowing maintenance to be scheduled and by providing longer intervals between servicing.

When performing vibration analysis on rotating machinery during run-up or run-down, the spectral results are most commonly viewed in the frequency domain, as in Figure 1. This format shows speed-related components as oblique patterns of peaks and fixed-frequency components (eg. structural resonances) as vertical patterns. However, it is often advantageous to view the spectral results in a speed-normalized fashion, known as the order domain (see Figure 2), since the defects of interest (eg. shaft imbalances, wear of bearings and gear teeth) are mostly related to the shaft speed.

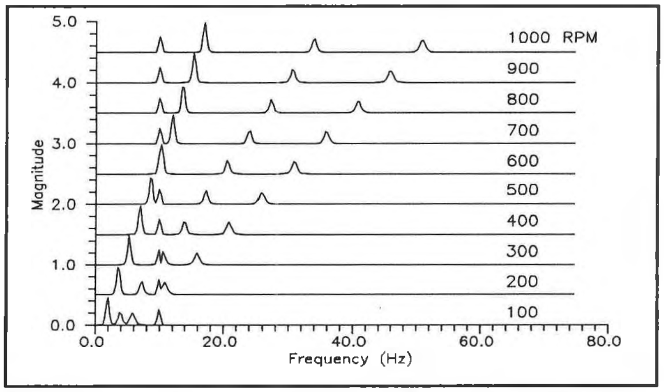

Figure 1: Simulated run-up viewed in frequency domain.

Speed-normalized analysis makes the speed-related vibration components evident, as they are shown as clear vertical patterns of peaks.

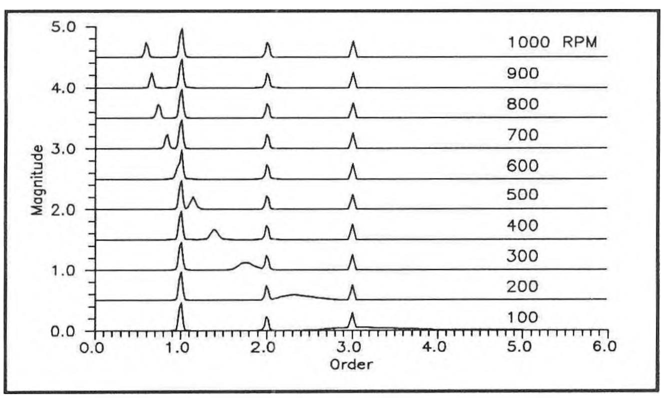

Figure 2: Simulated run-up viewed in order domain.

For spectral analysis to yield results in the frequency domain, the data must be sampled at constant increments of time; to yield results in the order domain, the data must be sampled at constant increments of shaft angle. Figure 3 shows a sine wave of increasing frequency sampled by the two methods. Notice that the constant-angle samples fall on the same location on the wave (peak, trough, etc.), while the constant-time samples change their position relative to the wave's shape.

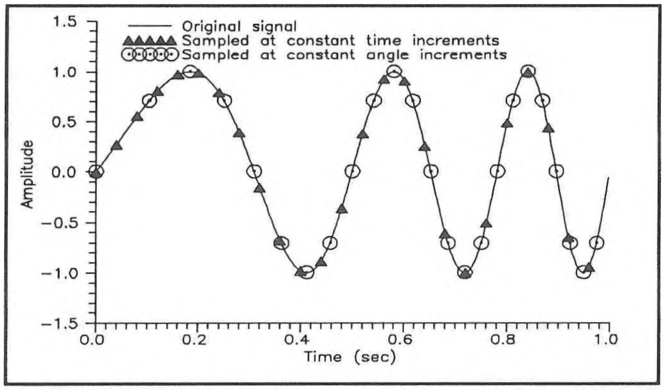

Figure 3: Swept sine sampled using constant time and shaft angle increments.

For order tracking, it is necessary to sample the vibration signal at constant angular increments and hence at a rate proportional to the shaft speed. Historically, this has been accomplished using analog instrumentation to vary the sample rate proportional to some tachometer signal, usually a keyphasor pulse [1]. Two pieces of expensive equipment are required: a ratio synthesizer and an anti-aliasing tracking filter. This is referred to as the classical method for order tracking.

Digital methods have been introduced which can resample a constant-time signal to provide the desired constant-angle data, also based on keyphasor pulses [2,3]. This is referred to as computed order tracking.

2. Procedure:

The two methods of performing order tracking analysis were compared using a computer simulation. To avoid distortion of the results by a low-pass filter, frequencies in excess of Nyquist's criterion were not included in the vibration signal. Both methods assume the keyphasor pulses arrive concurrently with vibration samples.

The varying sample rate of the classical method was approximated by determining the shaft speed each time a new keyphasor pulse arrived, and resetting the sample rate accordingly.

For computed order tracking, the resample times are computed assuming a linear angular acceleration with time, t, so the shaft angle, Φ, can be described by the quadratic equation:

$$\Phi(t) = b_0 + b_1 t + b_2 t^2$$

which is solved for t,

$$t_k = \frac{1}{2b_2}\left[\sqrt{4b_2(\Phi_k - b_0)+b_1^2} - b_1\right] \; ; \; k=0,1,2...$$

and the values of the coefficients b_0, b_1, and b_2 are found by fitting the keyphasor arrival times, which occur at known shaft angle increments,

$$\Phi(t_1) = \Phi_1 = 0$$
$$\Phi(t_2) = \Phi_2 = \Delta\Phi$$
$$\Phi(t_3) = \Phi_3 = 2\Delta\Phi$$

to the first equation. The resample times are calculated only over the centre half of the interval $0 \leq \Phi \leq 2\Delta\Phi$ to avoid overlap. Thus,

$$\frac{\Delta\Phi}{2} \leq \Phi_k < \frac{3\Delta\Phi}{2} \; ; \; \Phi_k = k\Delta\Theta$$

where $\Delta\Theta$ is the angular increment desired for resampling. The values for k to be used in the second equation are then found from

$$\frac{\Delta\Phi}{2\Delta\Theta} \leq k < \frac{3\Delta\Phi}{2\Delta\Theta} \; ; \; k=0,1,2...$$

The constant-time signal is resampled at these times using only linear interpolation; it will be shown in Section 3 that this simplification can cause inaccuracies.

3. Discussion and Results:

Both the approximation of the classical method and the computed order tracking method yield acceptable results, similar to Figure 4.

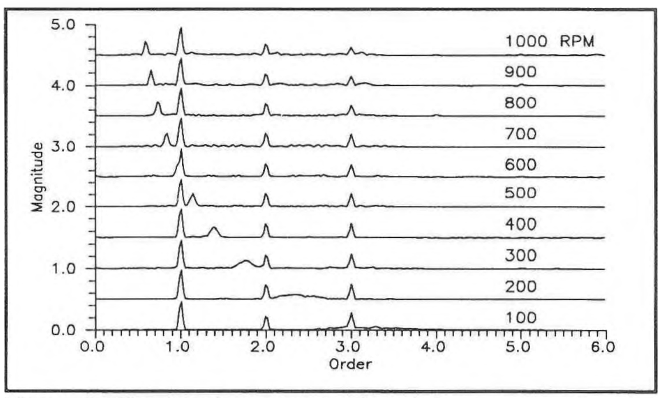

Figure 4: Simulated run-up analyzed by computed order tracking.

The main difference between the two methods is the amount of noise present in the spectra. Figure 5 illustrates that the method of computed order tracking has a noise level approximately one order of magnitude less than the approximation of the classical method.

In the computed order tracking method, linear interpolation works well when the signal is greatly oversampled. However, at sample rates closer to Nyquist's criterion, data resampled by linear interpolation do not coincide with the original signal, as shown in Figure 6. In Figures 5 and 6 only speed related components are shown.

The computed order tracking method assumes that the keyphasor pulses arrive as the shaft angle passes through zero. Notice that, since the keyphasor pulses arrive with

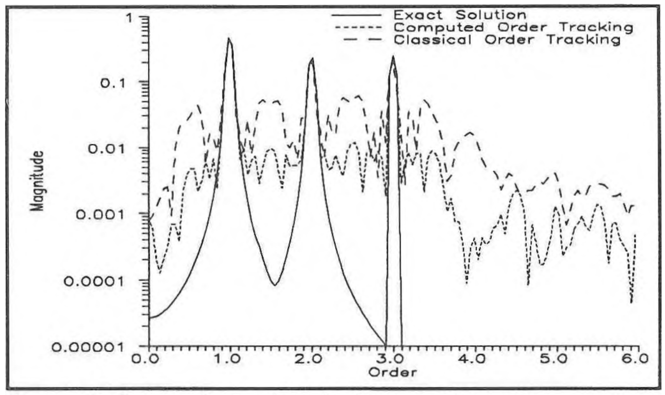

Figure 5: Comparison of typical spectral results.

the first time signal *after* the shaft passes through zero, a low sampling rate causes the assumption to be erroneous.

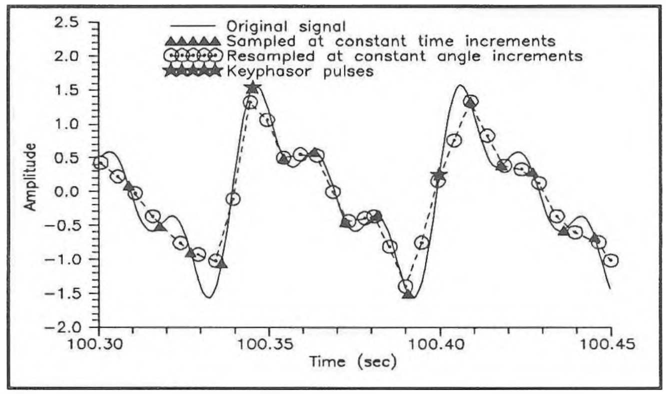

Figure 6: Computed order tracking resampling detail.

The approximation of the classical method has a higher noise level partly because it assumes a linear increase in shaft angle with time. This results in occasional errors in the number of samples taken per revolution, and hence large side lobes appear in the spectra.

4. Conclusions:

Even crude methods of computed order tracking work quite well. Improvements in keyphasor timing (using higher sampling rates or an external keyphasor monitor) and a higher-order interpolation routine would both improve accuracy. For the method to be truly useful, the interpolation method must also provide anti-aliasing filtering of the time signal.

5. References:

1) Hewlett-Packard Application Note 243-1, *Dynamic Signal Analyzer Applications.*

2) Potter, R. and Gribler, M., *Computed Order Tracking Obseletes Older Methods*, SAE Noise and Vibration Conference, May 16-18, 1989, pp. 63-67.

3) Potter, R., *A New Order Tracking Method for Rotating Machinery*, Sound and Vibration, Sept 1990, pp. 30-34