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FREQUENCY ANALYSIS FOR TURBOMACHINERY DIAGNOSTICS

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ABSTRACT

Journal bearings are used extensively on small and large turbogenerator units in the process and power generation industries. The ability to predict the condition of the rotor system using proximity probe measurements of the shaft motion in two orthogonal planes can lead to a reduction in maintenance costs and can also improve the operational safety of the high speed rotating machines. The output signals from the proximity probes are typically used to produce orbit plots representing machine shaft centre line motion which can be used as an indicator of general machine condition as well as for detecting specific machine malfunctions. This paper presents an introduction to the frequency analysis techniques which relate specifically to turbomachinery with journal bearings. It is shown how the complex discrete Fourier transform of the orthogonal orbit shaft motion produces the full asymmetrical spectrum, which further leads to the concepts of forwards and backwards shaft whirl. The full spectrum can be used on run up and run down tests to highlight changes in the dynamic amplitude and phase motion of the shaft and is a very useful diagnostic tool for turbomachinery. The techniques are illustrated by experimental examples.

INTRODUCTION

The major aim of analysing the vibration from rotating machinery is to detect incipient failure of the machine so that maintenance can be carried out prior to catastrophic failure. With the large variation in different types of rotating and reciprocating machines, each with peculiar modes of failure, [Forrester 1996, Howard 1994, Gasch 1993, Muszynska 1996], there is scope for the continuing development of signal processing techniques to enhance the detection, diagnosis and prognosis of machinery faults.

Vibration analysis techniques specific to turbomachinery with journal bearings have been available for the last few decades based on the use of orthogonal proximity probes mounted on the bearing housing, and measuring the relative shaft motion with respect to the housing, [Ehrich 1992, Muszynska 1996, Bently 1995, Thomas 1995]. The most common form of representing the orthogonal shaft motion is based on the orbit plot which details the motion of the centreline of the shaft as a function of time or of phase rotation of the shaft. The orbit can be used to detect a variety of common machine malfunctions like preload, imbalance, resonance, etc, [Baker et al 1996]. For other types of failures, it is necessary to look at frequency domain techniques, and this has led to the development of the full asymmetrical spectrum [Muszynska 1996, Howard 1996]. This paper presents a derivation of the full asymmetrical spectrum based on the Fourier series of the orthogonal shaft motion and provides an example of its use for turbomachinery diagnostics during runup and rundown of shaft speed.

THE COMPLEX FOURIER SERIES

If the Fourier series is used on the periodic complex time motion from the proximity probe measurements, over exactly one shaft revolution, then the results will provide the amplitude and phase of the forwards and backwards whirl components which make up the elliptical shaft orbit motion, [Baker et al 1996]. The proof of this can be seen from the complex exponential form of the Fourier series of the shaft orbit motion with only a single frequency component, [Howard 1996]. Consider the vibration signal from exactly one shaft revolution shown in Figure 1, as measured from two orthogonal proximity probes x and y and having a component of motion at the shaft frequency ω_o with arbitrary phase and magnitude.

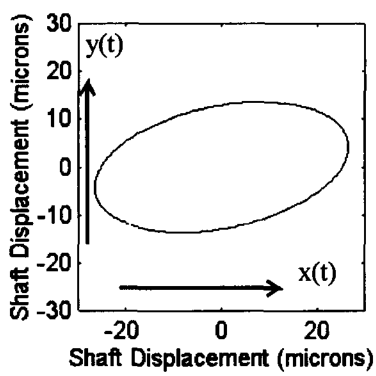

Figure 1. Orbit plot from a turbine filtered to show the X and Y once per revolution shaft motion.

The amplitude of motion in the two coordinate directions can be written as,

$$x(t) = X\cos(\omega_o t + \varphi_1), \text{ and } \quad y(t) = Y\cos(\omega_o t + \varphi_2), \tag{1}$$

where X and Y provide the amplitude of motion in the two directions, and φ_1 and φ_2 denote the corresponding phases at time t=0. If *x(t)* is plotted against *y(t)* in the complex plane where *y(t)* is in the imaginary direction then the resulting motion becomes *r(t)*, given by

$$r(t) = x(t) + i\,y(t), \qquad \text{where } i = \sqrt{-1}, \tag{2}$$

and from (1) this gives,

$$r(t) = X\cos(\omega_o t + \varphi_1) + iY\cos(\omega_o t + \varphi_2). \quad (3)$$

From Eulers theorem, the equations for *x(t)* and *y(t)* and hence *r(t)* can be rewritten in terms of the complex exponential to give,

$$r(t) = \frac{X}{2}(e^{i(\omega_0 t+\varphi_1)} + e^{-i(\omega_0 t+\varphi_1)}) + i\frac{Y}{2}(e^{i(\omega_0 t+\varphi_2)} + e^{-i(\omega_0 t+\varphi_2)}). \quad (4)$$

If the function *r(t)* is periodic over one revolution, then it is appropriate to express (4) as a Fourier series. Using the complex exponential form of the Fourier series given by,

$$r(t) = \sum_{n=-\infty}^{n=+\infty} C_n e^{in\omega_0 t}, \quad (5)$$

the coefficients C_n can be defined as,

$$C_n = \frac{1}{T}\int_0^T r(t)e^{-in\omega_0 t}dt, \quad (6)$$

where T is the time period over one shaft revolution. After integration this reduces to give [Baker et al 1996],

$$C_1 = \frac{X}{2}e^{i\varphi_1} + i\frac{Y}{2}e^{i\varphi_2},$$

and

$$C_{-1} = \frac{X}{2}e^{-i\varphi_1} + i\frac{Y}{2}e^{-i\varphi_2}. \quad (7)$$

Substitution of these Fourier series coefficients into (5) gives the solution of *r(t)* as

$$r(t) = B\,e^{-i\omega_0 t} + A\,e^{i\omega_0 t}, \quad (8)$$

where $A = C_1$ and $B = C_{-1}$. The shaft orbit motion can thus be represented by two phasors, rotating as a function of time in the complex plane with amplitude and phase defined by constants A and B above. The two phasors rotate in opposite directions as defined by the sign of the exponential coefficient with the B component rotating in the -ve direction (backwards whirl) and the A component rotating in the +ve direction (forwards whirl).

This derivation has shown that if the complex exponential form of the Fourier series is used on the periodic complex time motion over exactly one shaft revolution then the results at the frequencies $\pm\omega_o$ will be the complex vectors A and B. In other words, the results from the Fourier series over one shaft revolution provide the amplitude and phase of all the forwards and backwards whirl components which make up the shaft orbit motion.

TURBOMACHINERY TEST RIG

An experimental test rig has recently been commissioned in the School of Mechanical Engineering at Curtin University of Technology, to aid in the development of diagnostic techniques for turbomachinery. A photo of the completed facility is shown in Figure 2. The shaft and the three lobe white metal journal bearings for the test rig were supplied by Western Power, from a 2 MW Ingersoll Rand boiler feed pump. The shaft was fitted with five impellers for added mass so that the first critical resonant frequency could be lowered. The average shaft diameter was 97mm while the shaft length was 2.15m, [Wood 1996].

As shown in the photo, the shaft was instrumented with Bently Nevada 8mm proximity probes to allow measurement of the orthogonal shaft motion with respect to the two bearing pedestals. The shaft was coupled to a 7.5 kW variable speed three phase motor with a maximum unloaded shaft speed of 67.5 Hz. The results shown in this paper are from proximity probe measurements from the left hand, non-drive end of the shaft.

To assist with the estimation of the first critical resonant frequency, a bump test was carried out with the shaft in the bearing housings, the drive motor attached and with the oil supply running. An accelerometer was attached to the shaft with a magnetic base and a series of impacts were applied to the shaft. The power spectrum after 10 averages was calculated using an analyser as shown in Figure 3, where the first transverse resonance appears at 56 Hz.

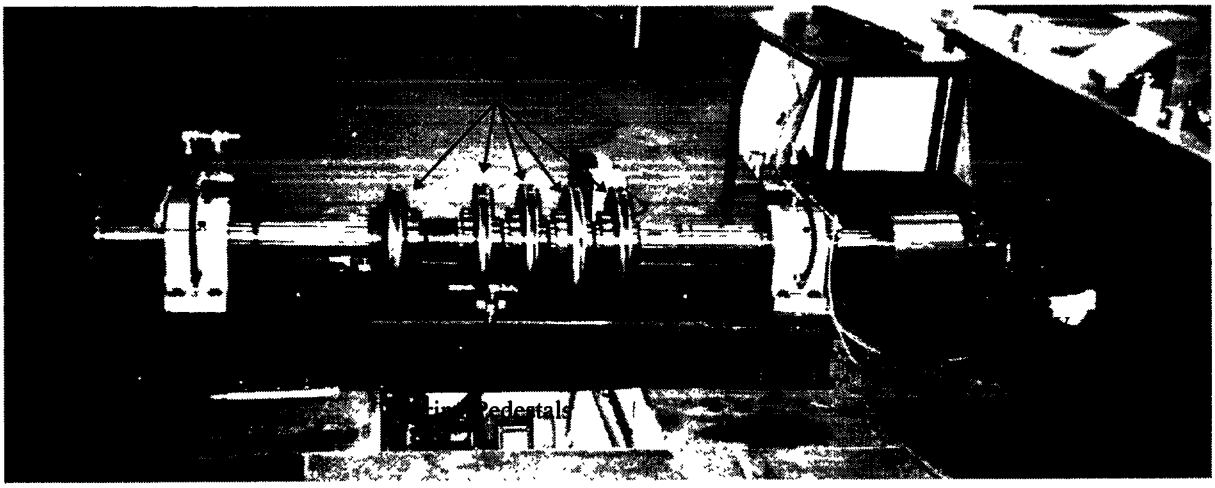

Figure 2. The test shaft from a 2MW boiler feed pump.

The diametral clearance between the shaft and white metal journal surface was known to be approximately 150μm.

THE ASYMMETRIC SPECTRUM

The analytical derivation of the forwards and backwards shaft whirl components has been developed above using the Fourier series. The application of the Fourier series using the sampled proximity probe data is via the discrete Fourier transform. The major signal processing steps are as shown in Figure 4, [Howard 1996, Baker et al 1996].

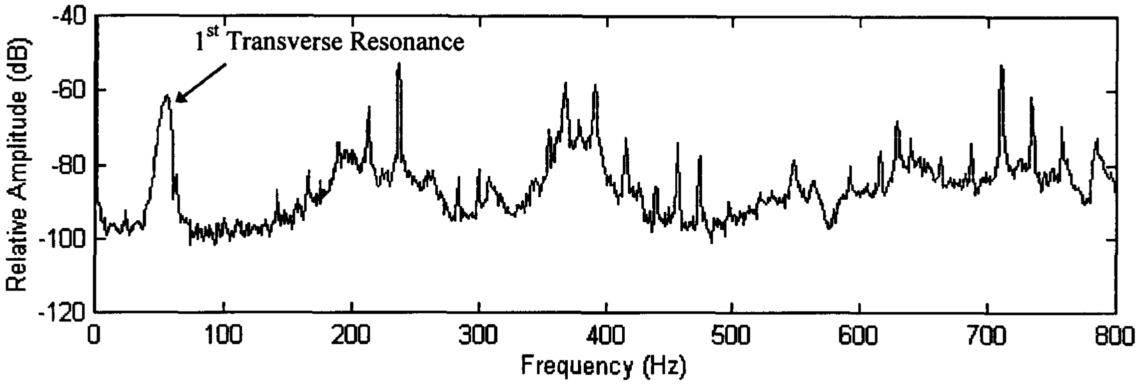

Figure 3. Power spectrum of the transverse shaft acceleration from a bump test.

Signal Processing Steps

(i) Acquire data simultaneously on all channels
(ii) detect trigger pulse at start of each revolution
(iii) resample x & y prox probe data to give n points per rev
(iv) reshape x & y vectors to give a matrix where each column corresponds to one revolution of shaft motion
(v) calculate the complex DFT of the orbit motion for each rev
(vi) shift the upper portion of the DFT to give the -ve and +ve Fourier series coefficients as required
(vii) display the -ve and +ve coefficient amplitudes

Figure 4. Signal processing steps for computation of the asymmetrical frequency spectrum.

One of the major Fourier series assumption is the periodicity of the time signal. To ensure that the complex time signals measured from the test rig were periodic, the signals were resampled to give a fixed integer number of data points per shaft revolution. The number of data points chosen for this analysis was 360, which provided one data point per degree of shaft rotation. Cubic interpolation was used for the resampling, taking the variable rotational speed of the shaft into account, [Blunt 1994, Forrester 1996, Howard 1995, Shilo and Rebbechi 1995]. The frequency content of the data was first analysed to ensure that the process of digital resampling did not introduce aliasing into the resampled and interpolated data. The resampled data was then reshaped to provide a matrix, where each column contained the 360 complex data points from a particular shaft revolution. The Matlab FFT command, [Mathworks 1996], was then used to compute the complex DFT of the real and imaginary shaft motion with the output being reshifted so that the upper half of the Fourier series coefficients (the negative frequency components), were positioned to the left of the DC term prior to the display of the coefficient amplitude and phase. To demonstrate the effectiveness of the resampling and complex DFT analysis, a runup of the test rig shaft through the first resonant frequency was investigated. Figure 5 shows the resampled orbit motion from the left end of the shaft at various shaft speeds.

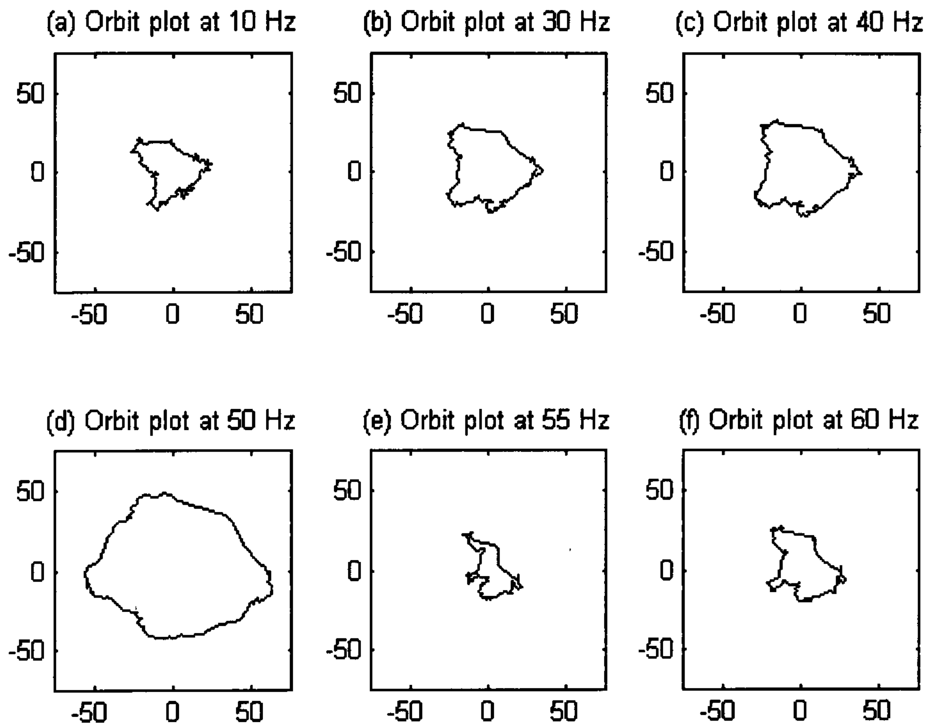

Figure 5. Shaft centerline motion on runup through resonance assuming horizontal and vertical alignment of the proximity probes. Amplitude scale in μm.

The shaft motion shown in Figure 5 has been scaled in terms of μm. The results clearly show the change in shaft centerline motion as the speed passes through the first resonance. Further analysis revealed that the peak in shaft resonant amplitude motion was very close to 50 Hz, and that as the shaft speed increased further, the shaft motion reduced dramatically until a minimum motion was obtained at 55 Hz. Figure 6 shows the corresponding asymmetrical frequency spectrum (± 10 shaft orders) resulting from the shaft orbit motions as given in Figure 5. The asymmetrical frequency spectrum shows that the major shaft motion comes from the once per revolution forward shaft whirl, which is typical of shaft imbalance. An inspection of the frequency components reveals that the only significant amplitude change occurs with the ± 1 shaft order components, particularly around the resonant frequency of 50 and 55 Hz. To investigate these changes further, an analysis of the ± 1 shaft order forwards and backwards whirl components was made. The resulting amplitude and phase as a function of shaft frequency is shown in Figures 7 and 8.

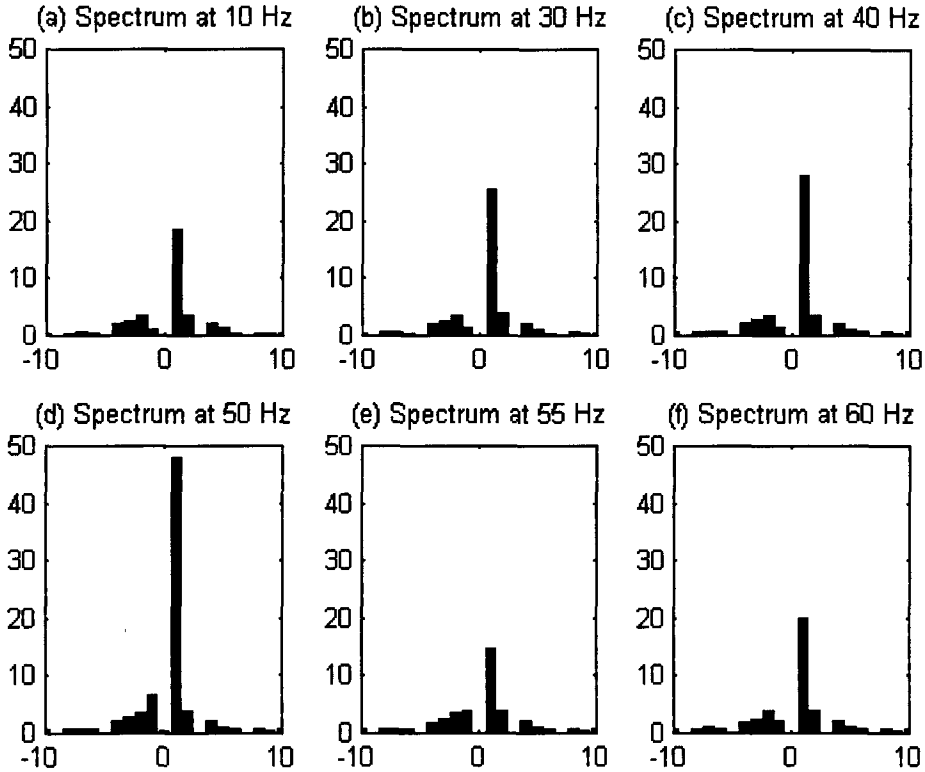

Figure 6. Asymmetrical spectrum in terms of shaft orders from the complex DFT of the orthogonal shaft motion. X axis scale - shaft orders, Y axis scale - peak amplitude in μm.

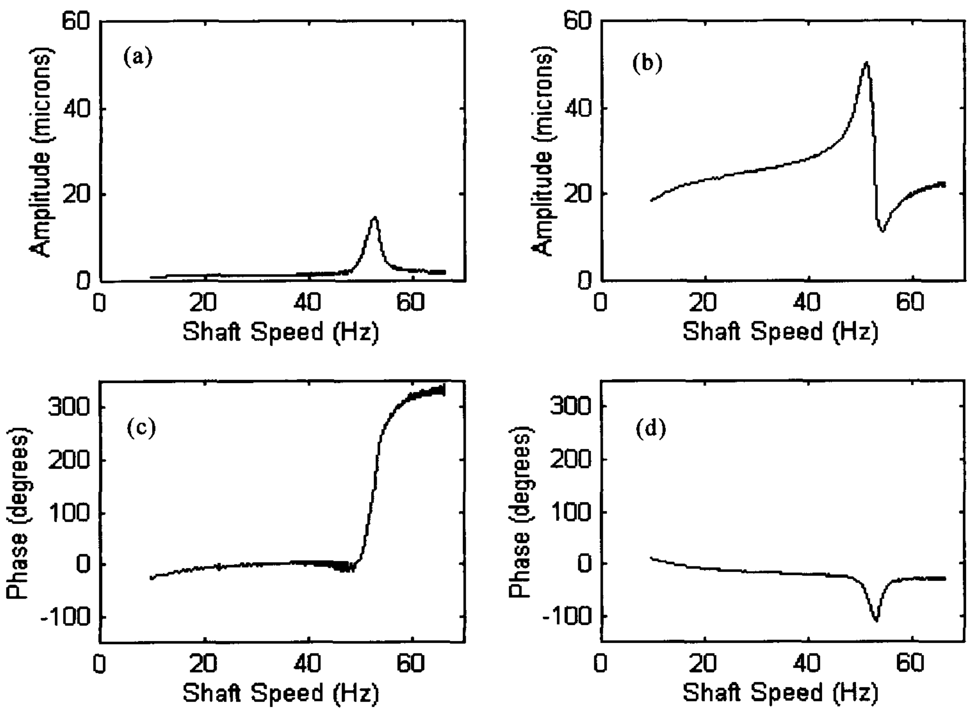

Figure 7. Amplitude (μm peak) and phase (degrees) of the ± once per revolution forward and backwards shaft whirl components as a function of shaft speed. (a) -1 shaft order amplitude, (b) +1 shaft order amplitude, (c) -1 shaft order phase and (d) +1 shaft order phase.

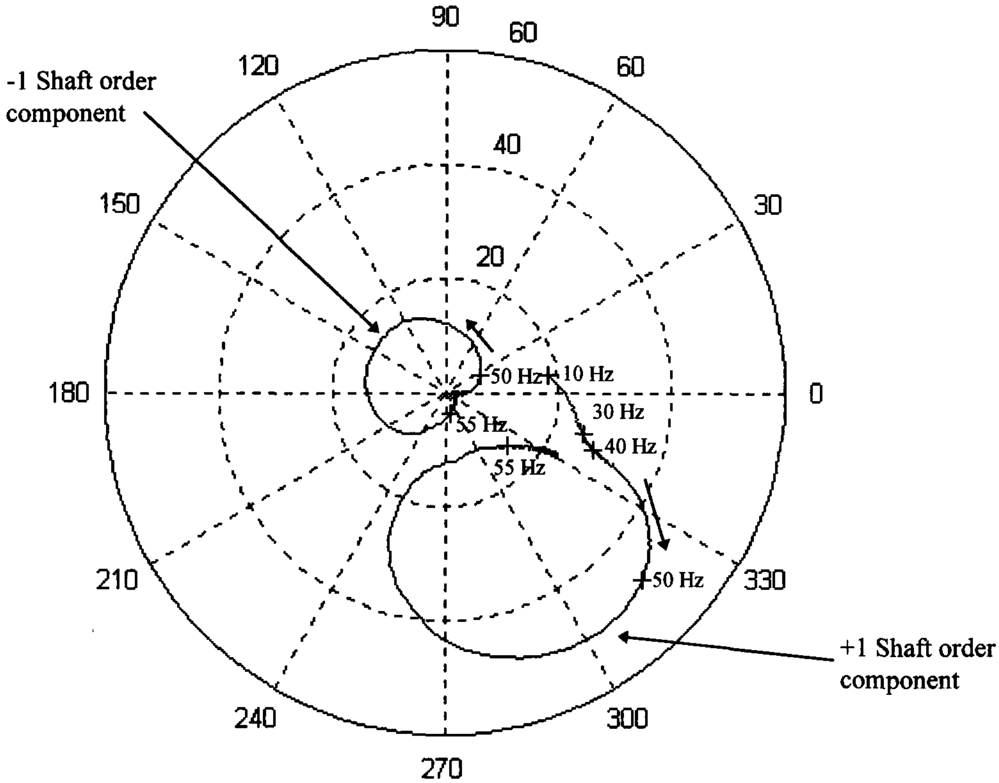

Figure 8. Polar plot of the ± 1 shaft order whirl amplitude (peak μm) and phase (degrees) components as a function of shaft speed during a run-up test.

The amplitude and phase Bode diagrams and the resulting polar plots of the ± 1 shaft order components clearly show that both +ve and -ve frequency components from the asymmetrical spectrum contain significant information. The work by Gasch [Gasch 1993], Muszynska, [Muszynska 1996] and others, has demonstrated that for certain types of machine faults, such as cracks in the shaft, etc, the asymmetrical spectrum provides the important means of detection and diagnosis by being able to separate the forward and backwards whirl components at particular frequencies. The derivation and development as presented above has shown that the asymmetrical spectrum is a natural outcome of the Fourier series of the orthogonal shaft motion. Rather than dealing with the bode and polar plot diagrams from both proximity probes, [Bently 1995], it has been shown that the bode and polar diagrams of the ± shaft whirl components can be obtained separately. This should be particularly useful for common turbomachinery diagnostic tasks such as balancing, as the +1 whirl component relates directly to the shaft imbalance. The need to coordinate rotate the phase position of the proximity probes until internal loops disappear, [Bently 1995] should no longer be required.

DISCUSSION & CONCLUSIONS

This paper has shown how the asymmetrical spectrum can be derived and developed as a natural outcome of the Fourier series of the orthogonal X-Y proximity probe shaft motion. The forwards and backwards shaft whirl components can thus be obtained from the complex DFT of each shaft revolution. The asymmetrical spectrum has been illustrated using a run-up of a test rig shaft through a resonance. The bode and polar plots of the +/-1 shaft whirl components have been obtained and have been shown to provide quite different types of information. The +1 shaft amplitude and phase information should be particularly useful for balancing as it relates directly to the forward shaft whirl. It is known that the asymmetrical whirl components can be used for diagnosis of turbomachinery faults and it is the purpose of ongoing research to clarify the range of faults which could specifically be detected and diagnosed using the asymmetrical spectrum.

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