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THE DIAGNOSIS OF BEARING DEFECTS USING SYNCHRONOUS AUTOCORRELATION TECHNIQUE

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ABSTRACT

In the diagnosis of rolling bearing defects, the envelope spectrum technique is regarded as an effective method. Ensemble averaging of envelope spectra can be used to further enhance the detectability of the technique. However, in cases where signal-to-noise-ratio is poor, the inherent non-linearity of the enveloping process limits the effectiveness of this technique. In this paper, the synchronous autocorrelation technique is proposed to detect bearing defects under poor signal-to-noise-ratio conditions. The idea comes from the synchronous demodulation of amplitude modulation (AM) signals in communication systems. Using this technique, the original vibration signal is first bandpassed at a chosen high frequency resonance to produce the impulsive AM signal that is related to faulty bearings. The instantaneous angle information of the AM carrier is identified using Hilbert transform and the AM signal is then synchronously demodulated. The resulting signal may be resampled at a lower rate if required and then autocorrelated. Because this technique only involves linear operation, the signal identity should be maintained regardless of the noise level. Ensemble averaging can also be used to improve the autocorrelation estimate. Finally, the characteristic defect period will be identified in the autocorrelation function. The effectiveness of the synchronous autocorrelation technique is demonstrated in this paper using both numerical and experimental data. It is found that the synchronous autocorrelation technique provides good results for a signal-to-noise-ratio of –11dB.

1. INTRODUCTION

The envelope spectral analysis technique is widely accepted as a powerful tool to diagnose defects in rolling element bearings, particularly for outer race defects. However, the inherent non-linearity of the enveloping process produces a threshold effect [1,2] which limits the effectiveness of this technique as the signal to noise ratio is reduced. If the noise level is high or the signal components are faint, the spectrum of the vibration signal envelope may become ineffective even with ensemble averaging. In this case the non-linear enveloping process itself causes the signal and noise components to become statistically *dependent* in the envelope signal. Consequently, where signal-to-noise-ratios (SNR) are very poor, signal identity is virtually lost in the enveloping process.

In this paper, we propose a linear scheme (referred to here as the '*synchronous autocorrelation*') that does not involve enveloping for the conditions where the SNR is poor. The idea is brought in from the synchronous demodulation approach widely employed in the communication theory [1]. Firstly, we bandpass the vibration signal at the chosen high frequency resonance and then acquire the analytic signal of the bandpassed signal using Hilbert transform. Secondly, we compute the instantaneous angle of the analytic signal and thus synchronously demodulate the bandpassed signal using the instantaneous angle. We can re-sample the demodulated signal at a lower rate if necessary and then calculate the autocorrelation function. It is readily shown [1,2] that the demodulated signal and its corresponding autocorrelation are real-valued functions. Due to the linearity of the process, ensemble averaging can be used to improve the autocorrelation estimate. The effectiveness of the synchronous autocorrelation technique is demonstrated using both model generated and experimental data. From the simulated results, we find that the synchronous autocorrelation technique provides good results even with a SNR of −11 dB.

2. THE SYNCHRONOUS AUTOCORRELATION TECHNIQUE

As we know, the vibration signal produced by a bearing fault is an amplitude modulated (AM) impulsive signal. This signal has an amplitude of repetitive exponential functions and a carrier of structural resonant oscillations. However, the carrier may be of random phase change [3,4] due to the *asynchronization* between bearing defect frequency and resonant frequency. Therefore, the bearing defect signal can be represented by

$$x(t) = s(t)\sin[\omega_o t + \phi(t)] \tag{1}$$

where $s(t)$ is the amplitude signal - envelope (real-valued), ω_0 is the resonant frequency with which the bandpass filter is associated and $\phi(t)$ is the phase change associated with each impact produced by the bearing fault. The signal $x(t)$ can also be graphically described as follows

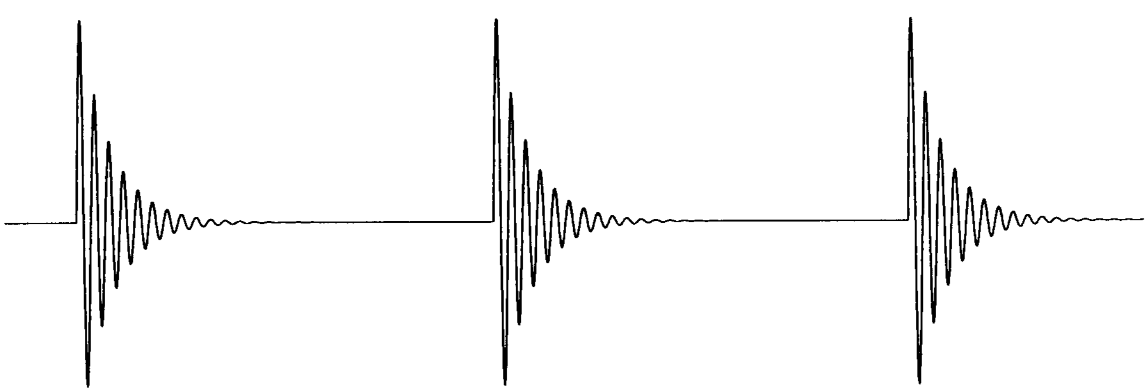

Figure 1. A graphical representation of vibration signal produced by a bearing fault

Our purpose here is to extract the amplitude signal $s(t)$ from the AM signal $x(t)$. There are two methods to do so: 1) non-linear enveloping method; 2) linear synchronous demodulation method. Using the latter, we must know the carrier frequency and phase information, ie. ω_o and $\phi(t)$. The carrier frequency ω_o may be obtained from a high frequency resonant peak of the baseband spectrum of $x(t)$, but the phase change $\phi(t)$ is difficult to extract.

Alternatively, we can obtain the analytic signal of $x(t)$ using the Hilbert transform [2,5]:

$$x_a(t) = x(t) + j\hat{x}(t) = s(t)\sin[\omega_o t + \phi(t)] - j \cdot s(t)\cos[\omega_o t + \phi(t)] = s(t)e^{j\theta(t)} \tag{2}$$

where $\hat{x}(t)$ is the Hilbert transform of $x(t)$, $\theta(t)$ is the instantaneous angle of the analytic signal $x_a(t)$, which is

$$\theta(t) = \arctan\frac{-\cos[\omega_o t + \phi(t)]}{\sin[\omega_o t + \phi(t)]} = \arctan\frac{\sin[\omega_o t + \phi(t) + \pi/2]}{\cos[\omega_o t + \phi(t) + \pi/2]} = \omega_o t + \phi(t) + \pi/2\,, \tag{3}$$

Having had the instantaneous angle information of the analytic signal $x_a(t)$, the amplitude signal $s(t)$ can be obtained by a synchronous multiplication

$$x_a(t)e^{-j\theta(t)} = s(t)e^{j\theta(t)}e^{-j\theta(t)} = s(t) \tag{4}$$

Now, the autocorrelation function of $s(t)$ can be calculated to acquire the defect periods associated with various bearing defects (outer race, inner race and rolling element defects).

In the case where the bandpassed bearing signal $x(t)$ is contaminated by a bandpass noise $n(t)$

$$y(t) = x(t) + n(t) = s(t)\sin[\omega_o t + \phi(t)] + n(t) \tag{5}$$

The analytic signal of $y(t)$ is derived as [1]

$$y_a(t) = x_a(t) + n_a(t) = s(t)e^{j\theta(t)} + [n_c(t) + jn_s(t)]e^{j\theta(t)} \tag{6}$$

where $n_c(t)$ is the in-phase component and $n_s(t)$ the quadratic component of the noise $n(t)$ in a phasor representation [1]. Both components are also random noises. Using the same synchronous multiplication, we have

$$y_a(t)e^{-j\theta(t)} = s(t) + n_c(t) + jn_s(t) \tag{7}$$

The real part of the above result provides us a demodulated bearing signal $s(t)$ plus an independent random noise $n_c(t)$. The autocorrelation components of the signal plus noise will remain independent. Because the autocorrelation function of a random noise is mainly concentrated in the vicinity of zero-lag region [1,6], the non-zero lag region should be dominated by the autocorrelation components from signal $s(t)$. Furthermore, because only linear operations are involved in the process, the signal identity should maintain no matter how high the noise level is. Thus we would expect that, for poor SNR conditions, the signal component will be obtained by ensemble averaging the autocorrelation functions of $s(t)$ plus $n_c(t)$. This scheme is described by the diagram shown in Figure 2.

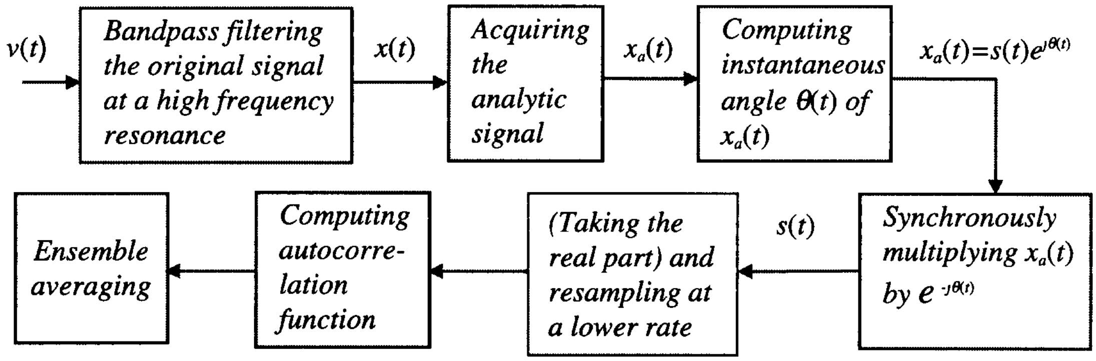

Figure 2. The diagram of the synchronous autocorrelation process

From this diagram, we can see that the resampling (decimation) of the demodulated signal will reduce data amount significantly, which makes ensemble averaging of autocorrelation functions more efficient.

3. APPLICATION OF SYNCHRONOUS AUTOCORRELATION ANALYSIS TO SYNTHETIC DATA

The vibration signal generated by a bearing fault can be described by combining Braun's [4] and Mcfedden's [7] models. This signal plus other vibration sources and noise produces the measured vibration signal. It is as follows

$$x(t) = \left\{ m(t) \sum_k \exp[-(t-kT)/\alpha] \cdot \sin[2\pi f^*(t-kT)] \cdot U(t-kT) \right\} \otimes h(t) + n(t) \qquad (8)$$

where $\otimes$ denotes the convolution operation, T is the characteristic defect period (ie. the reciprocal of the defect frequency $1/f$), and f^* the structure resonant frequency exited by the bearing defect. α denotes the time constant for the exponential decay of the resonant oscillations, which is determined by system damping. $U(t)$ is a unit step function and $n(t)$ is the vibration produced by other machine components (narrow band) plus broadband noise. $m(t)$ represents another amplitude modulating function [6,7,8] determined by the defect location. $m(t)$ is uniform for outer race defects, and has a waveform similar to a half-wave sinusoid pulse train with the shaft rotation period for inner race defects and cage rotation period for roller/ball defects respectively. In practice, the actual measured signal will convolve the impulse response $h(t)$ of the vibration propagation path (dependent on the machine structure) with the bearing fault induced vibration. For simplicity, it is assumed in the following synthetic data, that the mechanical systems have a unity gain propagation path, ie. $h(t) = \delta(t)$.

Figure 3 shows the result of the synchronous autocorrelation analysis for a synthetic-bearing signal contaminated by high level noise. With a noise standard deviation of 8 units and the impulse amplitude of 10 units, the SNR after bandpass filtering is about -11dB. After 100 times of ensemble averaging, the synchronous autocorrelation function shown in Figure 3b clearly indicate the defect period of the inner race and its integer multiples. The performance of the synchronous autocorrelation method for the above example shows that it is potentially an effective method to diagnose bearing faults when signal-to-noise-ratio is very poor.

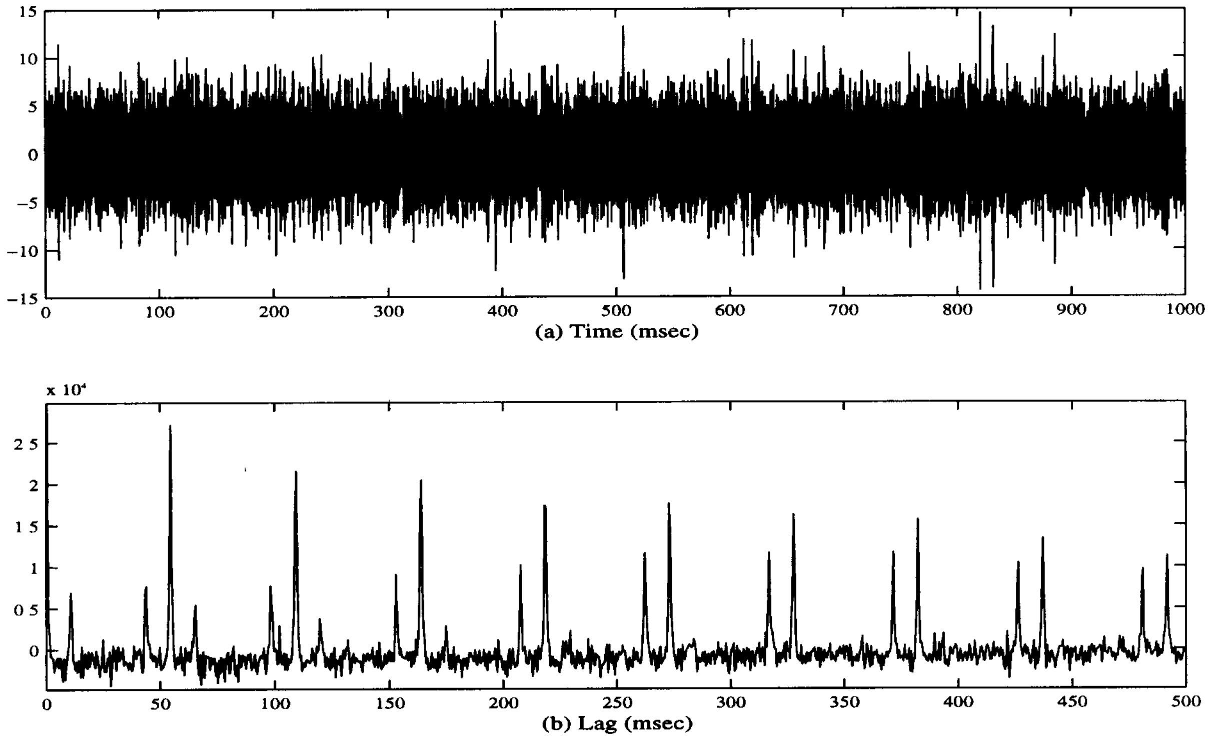

Figure 3. Synchronous autocorrelation analysis of a synthetic signal produced by an inner race defect and noises (**100 averages**). $\sigma_n = 8.0$, $A = 10$, $\alpha = 50$, **SNR = -11dB**; f_i=91.53Hz, (T_b = 10.925ms), f_r=18.5Hz (T_r = 54.05ms). **(a)** Bandpassed signal $x(t)$; **(b)** Synchronous autocorrelation function.

4. EXPERIMENTAL ANALYSIS USING SYNCHRONOUS AUTOCORRELATION METHOD

An experiment was performed on a machine fault demonstration rig with NSK EN202 test bearings. Because of the difficulty of simulating an initial bearing fault, a small fault (about 0.5 mm in diameter) was introduced to the inner race using nitric etching method and a random noise was then added to the acquired data. During the experiment, a radial load of 100N (light load) was applied to the test bearing and the shaft was running at 18.4Hz (low speed) which gives a nominal characteristic defect frequency of 91.59Hz.

In the synchronous autocorrelation analysis, 1921 ensemble averages were performed. The analysis result for the bearing signal considered here is shown in Figure 4. It is evident from Fig. 4a that the bearing signal is totally buried by noise. The synchronous autocorrelation function (Fig. 4b) clearly reveals the characteristic defect period of the inner race and its integer multiples (ie. T_i=10.92ms, 21.84ms, 32.75ms and 43.67ms as indicated by the arrows).

This example has further shown that the synchronous autocorrelation analysis technique is potentially a powerful tool for the diagnosis of incipient damage within rolling bearings or the detection of bearing faults under conditions of high background noise levels. This is because the synchronous process involves only linear procedures whereas the enveloping process includes a non-linear rectifying operation. The autocorrelation function of the synchronously demodulated signal maintains additive signal and noise components, and therefore, the subsequent ensemble averaging is able to reduce the noise components and enhance the detectability. This method may be of great value for the diagnosis of crucial bearings.

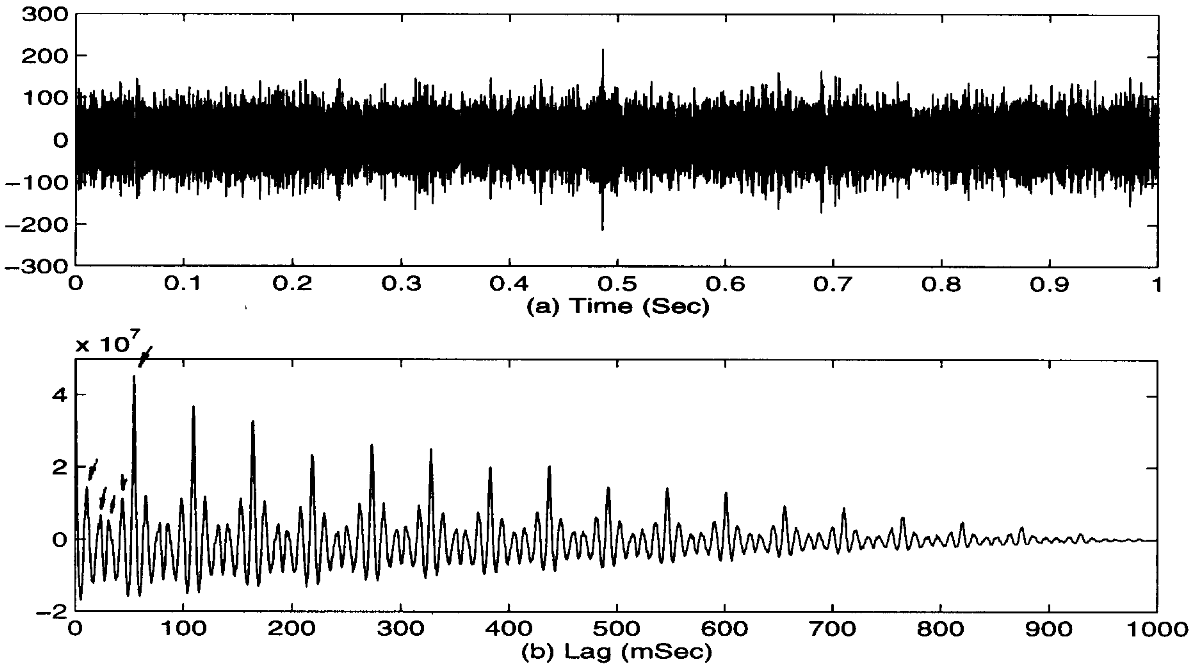

Figure 4. Synchronous autocorrelation analysis of a vibration signal produced by an *inner race fault* and random noise (the standard deviation is eight percent of the max. signal amplitude). The bearing fault was etched by nitric acid and small debris (about 0.5mm in diameter and microns in thickness) was found in the cleaning bath.
Test conditions are: 100N radial load, 18.4Hz shaft speed (T_r = 54.35ms, T_i = 10.92ms), National Instruments' DAQCard-AI-16E-4 data acquisition card, 65536Hz sampling rate.
(a) The bandpass bearing signal (with centre frequency of 12370Hz and frequency span of 3200Hz). **(b)** Averaged synchronous autocorrelation function (**1921 averages**).

5. CONCLUDING REMARKS

In the preceding sections, we have examined the synchronous autocorrelation technique both theoretically and experimentally (with synthetically generated data and rig-test data). In the remaining part of the paper, the proposed technique is reviewed and an overall comparison between the autocorrelation method and the traditional envelope spectral method is presented.

Conventional envelope analysis has focused on the spectral analysis of the envelope signal of bearing vibration. The envelope spectrum reveals outer race defects effectively provided noise contamination is low. With the detection of inner race and rolling element defects, the intertwinement between the defect harmonics and their accompanying sidebands is encountered using the envelope spectral method. The problem becomes serious when the bearing fault produces very narrow impulse transients and the loading zone of the bearing is narrow and sharp. This is because, in this situation, the defect harmonics and modulation sidebands are widely spread. Background noise of the bearing signal also generates difficulties for the detection of bearing faults using the envelope spectral analysis.

The autocorrelation analysis has traditionally been applied to raw bearing signals or bandpassed bearing signals. This kind of application of autocorrelation analysis doesn't show any advantage in revealing bearing defect information because of the predominance of structural resonances. The autocorrelation analysis of envelope signals [6], on the other hand, can avoid the influence of resonances, and resolve the above mentioned intertwinement problem. The envelope autocorrelation function exhibits a series of lag impulses corresponding to various integer-multiples of the characteristic defect periods. The periods related to modulation sidebands are not directly acquirable from the envelope autocorrelation function, but the lag impulses in the vicinity of those periods have relatively large amplitudes. The envelope autocorrelation function presents a superior detectability to the envelope spectral analysis for the diagnosis of inner race and roller/ball faults. This superiority is particularly obvious if the signal is subject to noise disturbance. The envelope autocorrelation technique probably has sufficient detectability for usual monitoring purposes. However, the use of this technique is limited by the threshold effect [1,2] of the envelope detection, which is the result of a non-linear rectification (full-wave or square-law) process.

The synchronous demodulation process only involves linear operations. The autocorrelation function of the synchronously demodulated signal is therefore an appropriate option when it is desirable to maintain the additive nature of the signal and noise components during processing. This process allows the use of ensemble averaging to reduce the noise components and enhance the detectability. The synchronous autocorrelation technique is potentially an effective method for the diagnosis of bearing faults under severe SNR conditions.

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