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SYNTHESIZED SYNCHRONOUS SAMPLING TECHNIQUE FOR BEARING DAMAGE DETECTION (PREPRINT)

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14. ABSTRACT

Differential bearing between the low-pressure turbine (LPT) shaft and high-pressure turbine (HPT) shaft is one of the most vulnerable parts in a turbo machinery engine. Yet, it is one of the most difficult parts to detect the damage signatures, because the signal to noise ratio at the regular sensor locations is usually low. In addition, the speed variations in both the LPT and the HPT can further deteriorate the damage signature extracted by the conventional analysis. In this paper, we developed a “synthesized synchronous sampling” technique to enhance the differential bearing damage signature. With this technique, together with the conventional acceleration enveloping technique, we are able to detect differential bearing damage at much earlier stage, thus provide early warning of the machinery health conditions.

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Synthesized Synchronous Sampling Technique for Bearing Damage Detection

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Abstract

Differential bearing between the low-pressure turbine (LPT) shaft and high-pressure turbine (HPT) shaft is one of the most vulnerable parts in a turbo machinery engine. Yet, it is one of the most difficult parts to detect the damage signatures, because the signal to noise ratio at the regular sensor locations is usually low. In addition, the speed variations in both the LPT and the HPT can further deteriorate the damage signature extracted by the conventional analysis. In this paper, we developed a "synthesized synchronous sampling" technique to enhance the differential bearing damage signature. With this technique, together with the conventional acceleration enveloping technique, we are able to detect differential bearing damage at much earlier stage, thus provide early warning of the machinery health conditions.

1. Introduction

Vibration signatures are probably the earliest symptoms used for bearing and gear condition monitoring. The applications of the vibration based rotating machinery condition monitoring have been well documented.[1,2,3,4] With the further understanding of the bearing and gear damage mechanisms,[5,6,7,8] and the advancement of signal processing and computer technologies,[9,10,11,12,13] vibration signature becomes one of the most reliable technique for bearing and gear incipient fault detection.

On the bearing damage modeling side, one of the earliest models on bearing damage generation mechanism was proposed by McFadden and Smith.[5] In the paper, they proposed a model to describe the vibration excited by a single point defect on the inner race of a rolling element bearing under constant radial load. In a following paper, McFadden and Smith[6] extended their model to describe the vibration produced by multiple point defects. This model incorporates the effects of bearing geometry, speed, load distribution, transfer function and the decay of vibration. Su and Lin[8] extended the work by McFadden and Smith to include damages located at any parts of a bearing under various loading condition. Later on, Su *et al.*[14] proposed a mathematical model to describe the frequency characteristics of roller bearing vibrations due to surface irregularities.

On the signal processing side, the acceleration enveloping based technique, also known as the high frequency resonance technique[12] or the demodulation analysis,[15] has existed for over 30 years. Acceleration envelope signatures are essentially band passed bearing vibration signals where the rotating speed related low frequency component (usually large in amplitude) and high frequency noise are removed. The remaining vibration response is the bearing supporting structure resonance responses subject to the bearing defect excitations. Due to damping in the supporting structure, the impulsive response will decay after the excitations. By detecting the envelope of the decayed response, the repetition of the envelope is uniquely associated with the damage in the bearing, such as the outer race damage, the inner race damage, and the roller element damage.

The synchronous sampling technique is also widely used in bearing signature enhancement, especially in varying speed operations. The synchronous sampling technique converts the equal time sampling to the equal shaft circumferential angle sampling, so that the rotor speed dependency is eliminated. This is usually achieved by installing an encoder on to the bearing support, which monitors the shaft operation by counting the physical events passing by. The Synchronously sampled data are commonly used to carry out time synchronous averaging to enhance synchronous coherent signal component of the signal and to attenuate both non-coherent components and the non-synchronous components to negligible levels.[10,11]

There are many tools to enhance the signature of a conventional bearing with one fixed race, however, in a differential bearing operations, both bearing races are in motion and the race speeds are not in accurate control during operations. Furthermore, the differential bearing assembly is located between two shafts and under other mechanical components that further diminish the signature transmitted to the vibration sensor. Therefore the synchronous sampling is required to extract the inherently small signature. Due to moving races, the installation of such encoders is not physically feasible for a differential bearing. Thus there is no encoder available for synchronous sampling.

In this paper, we introduce a technique called the synthesized synchronous sampling to address this problem. Using the synthesized synchronous sampling technique, together with other signature enhancement techniques, such as the synchronous averaging and the acceleration enveloping, we are able to enhance the feature extraction for differential bearings using engine case mounted sensors.

This paper is organized as following: Section 2 introduces the kinematics of the differential bearing feature frequencies and the shaft speeds first; this is followed by brief descriptions of the acceleration enveloping technique, the synchronous sampling fundamentals, time synchronous averaging techniques and the order analysis. Section 3 contains a detailed description of the procedures of synthesized synchronous sampling. In Section 4, data from an engine test rig with seeded differential bearing outer race damage are analyzed and the results are presented. Finally, the conclusions from this research are drawn in the Section 5.

2. Fundamentals

2.1 Bearing Kinematics

Roller element bearings produce vibration excitation forces at specific frequencies dependent on the bearing geometry and rotation speed[16]. These vibration frequencies are called bearing tones. All such bearings, regardless of their condition, will produce some level of bearing tones -- the important fact is that their level increases as the bearing deteriorates.

Generally, there are four frequencies associated with a rolling element bearing:

- Cage frequency or Fundamental Train Frequency (FTF);
- Rolling element frequency;
- Inner raceway frequency;
- Outer raceway frequency.

In many industrial applications, either the outer race or the inner race is usually fixed and the other raceway is rotating with the shaft. However, in some special case, such as in an aircraft engine application, both inner raceway and outer raceway may rotate at different speeds.

As shown in Figure 1, the outer raceway is rotating at speed N_{OR} while the inner raceway is rotating at speed N_{IR}. At the contact points between a rolling element and raceways, the velocities are

$$V_{OR} = \frac{\pi N_{OR} D}{60}\left(1 + \frac{d}{D} cos\,\theta\right). \tag{1}$$

and

$$V_{IR} = \frac{\pi N_{IR} D}{60}\left(1 - \frac{d}{D}\cos\theta\right). \tag{2}$$

By assuming a perfect rolling between the rolling elements and the raceways, the velocity at the center of the rolling element or the cage is

$$V_{FTF} = \frac{V_{OR} + V_{IR}}{2} = \frac{\pi D}{120}\left[N_{OR}\left(1 + \frac{d}{D}\cos\theta\right) + N_{IR}\left(1 - \frac{d}{D}\cos\theta\right)\right]. \tag{4}$$

Thus the cage frequency is

$$f_{FTF} = \frac{V_{FTF}}{\pi D} = \frac{1}{120}\left[N_{OR}\left(1 + \frac{d}{D}\cos\theta\right) + N_{IR}\left(1 - \frac{d}{D}\cos\theta\right)\right]. \tag{5}$$

Similarly, for the rolling element, its spin frequency can be calculated as well. Assuming there is no slip at the interface of the ball and the outer race contact point. At the contact point, the ball speed is

$$\vec{V}_{OR} = \vec{V}_{RE} + \vec{\omega}_{Ball} \times \vec{r}\ . \tag{6}$$

where

$\vec{V}_{OR}$ is the velocity of the outer race at the contact point; $\vec{V}_{RE}$ is the velocity of the ball center; $\vec{r}$ is the vector from ball center to the contact point; $\vec{\omega}_{Ball}$ is the ball absolute angular speed. The ball angular speed consists of two parts: the cage angular speed $\omega_{FTF}\vec{k}$ and the rolling element angular speed $\omega_{RE}\vec{j}$. Keep in mind that the two components are not in the same direction.

$$\vec{\omega}_{Ball} = -\omega_{FTF}\vec{k} + \omega_{RE}\vec{j} \, . \tag{7}$$

and

$$\vec{r} = \frac{d}{2}\vec{i} \, . \tag{8}$$

Substituting Eqs. (7) and (8) and projecting both sides on to the tangential direction, we have

$$\frac{2\pi N_{OR} D}{120}\left(1+\frac{d}{D}cos\,\theta\right) = 2\pi f_{FTF}\,\frac{D}{2} + \left(2\pi f_{FTF}\,\frac{d}{2}cos\,\theta + 2\pi f_{RE}\,\frac{d}{2}\right). \tag{9}$$

or

$$f_{RE} = \frac{D}{d}\left(\frac{N_{OR}}{60} - f_{FTF}\right)\left(1+\frac{d}{D}cos\,\theta\right). \tag{10}$$

Substituting Eq. (5) into (10), we have

$$f_{RE} = \frac{D}{120d}\left(1-\frac{d}{D}cos\,\theta\right)\left(1+\frac{d}{D}cos\,\theta\right)\left|N_{OR} - N_{IR}\right|. \tag{11}$$

For a damage spot on a roller, the fundamental frequency will be $2f_{RE}$, since for each complete rotation of the roller with respect to the cage, the spot will contact inner race and outer race once, respectively.

On the other hand, for a damage spot on the outer race, each roller will roll over the spot once in each revolution of the cage with respect to the outer race, thus,

$$f_{OR} = n\left(\frac{N_{OR}}{60} - f_{FTF}\right) = \frac{n}{120}\left(1-\frac{d}{D}cos\,\theta\right)\left|N_{OR} - N_{IR}\right|. \tag{12}$$

Similarly, for an inner race damage spot, we have

$$f_{IR} = n\left(\frac{N_{IR}}{60} - f_{FTF}\right) = \frac{n}{120}\left(1+\frac{d}{D}cos\,\theta\right)\left|N_{OR} - N_{IR}\right|. \tag{13}$$

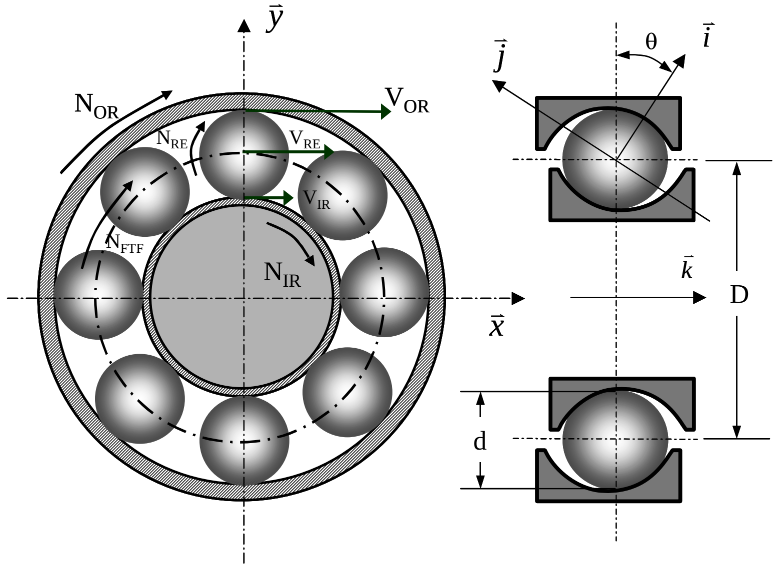


Figure 1 Ball Bearing

2.2 Acceleration Enveloping

Acceleration enveloping technique was originally called the high frequency resonance technique. It was discovered in early seventies of last century in a NASA funded project[17] almost accidentally from an oscilloscope display[18]. The acceleration enveloping technique is based the following assumptions: when a defect occurs in a bearing, repetitive impacts happen during rotations. This kind of impacts is a broadband excitation. This broadband excitation stimulates the resonant response of the bearing supporting system. However, the resonant response levels from the defect impacts are usually very low compared to the shaft excitation such as unbalance response, though the frequency contents of the resonant response is usually much higher. If the dynamic range of the vibration sensor and the consequent analyzer is low, the resonant response signals are down in the noise level. The key to detecting bearing faults is to capture the low amplitude response caused by bearing defect excitation without including the high amplitude rotational vibration signals and system fundamental resonant frequency responses. To accomplish this, a "band pass" filter is used to isolate the signal. Once the high frequency damage response is captured, the signal goes through a rectification device and the envelope of the signal is detected from the rectified signal. Applying FFT to the envelope signal will reveal the frequency and amplitude, which is uniquely associated with the damaged bearing component.

In theory, any vibration sensor can achieve the bearing damage detection through the enveloping or demodulation processes. Since the damage excited response is usually with high frequency content, accelerometer has advantage in capturing the damage response over velocity and displacement sensors.

In early days, this enveloping detection processes were accomplished by several analog devices. As shown in Figure 2, the conditioned vibration sensor signal is first pass through an analog filter to isolate the impulse response excited by the bearing damage. The filtered response is then passed through a rectifier to flip the negative half of the oscillation signal to the positive side. The rectified signal is fed into an envelope detector to identify the envelope of the signal. The envelope signal is then used to identify bearing damage signature through a signal analyzer. If necessary, a low-pass filter can be added before the analyzer.

The process shown in Figure 2 works well if all the analog devices are appropriately designed for a particular application. However, different application may require different parameter setting of the analog devices. For example, the bearing support system may have different resonant structure, thus it requires different cut-off frequency design for the band-pass filter to isolate the damage impulse response. For different structural damping, the envelope detector needs a different time constant design to match the impulse response decaying rate. More importantly, the bearing damage detection is usually conducted in a harsh environment. More electric components involved in the detection process usually decreases the system reliability.

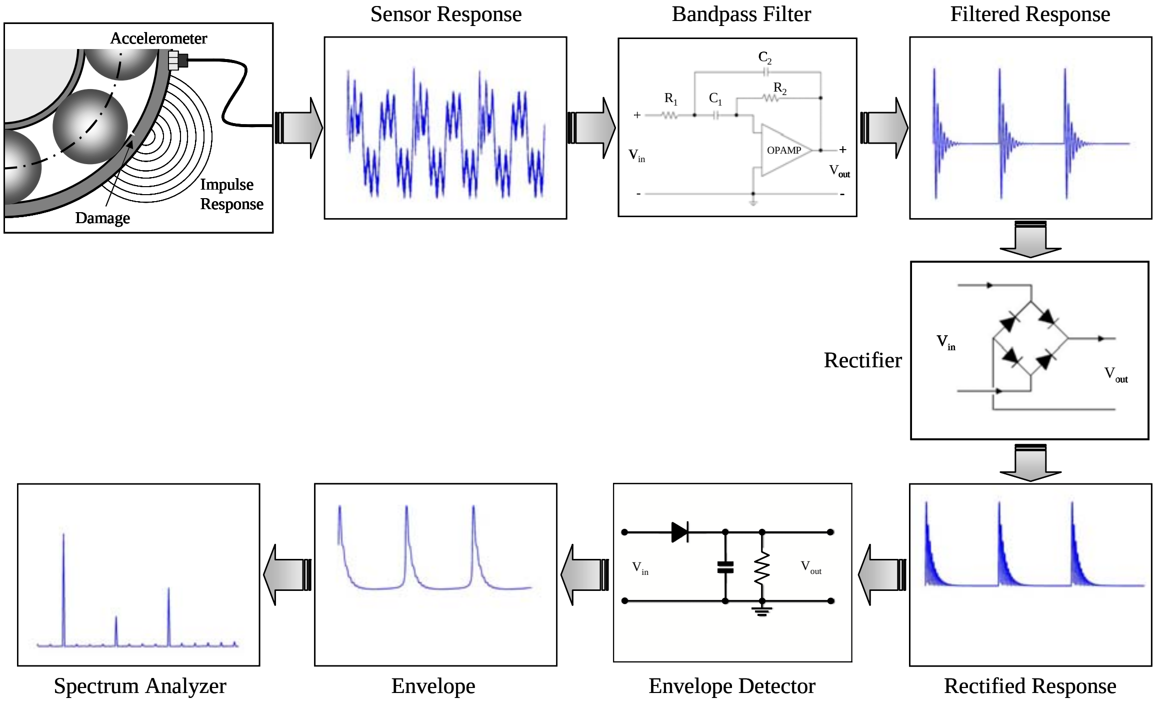


Figure 2 Analog Devices Based Approach

With the improvement of computer technology and the development of high dynamic range analog to digital (A/D) converter, the acceleration enveloping based bearing damage detection becomes much easier to implement nowadays. Many of the analog devices as shown in Figure 2 can now be replaced by digital signal processing, thus improving the detection accuracy and system reliability. One possible digital signal processing based realization of the acceleration enveloping is shown in Figure 3. The conditioned acceleration signal is first digitized with high speed and high dynamic range A/D converter. The high speed and high dynamic range A/D is especially important because it ensures the digitized vibration data contains the low amplitude high frequency resonant responses excited by the bearing damage impulse. The digitized data is then passing through a digital band pass filter to isolate the resonant response excited by the bearing damage. The enveloping detection algorithm is then used to detect the envelope of the filtered data. In digital domain, this process can be achieved by the Hilbert transform. The digital Hilbert transform is related to the FFT and can be easily achieved.[19] If an accurate enveloping detection is required, a local maximum interpolation technique can provide a good result.[20] The bearing damage detection is then accomplished by spectrum analysis on the enveloped data.

The digital based approach eliminates multiple analog devices, thus improving the system reliability and reducing the cost. The detection accuracy can also be improved by using advanced A/D converters with higher dynamic range and high sampling rates.

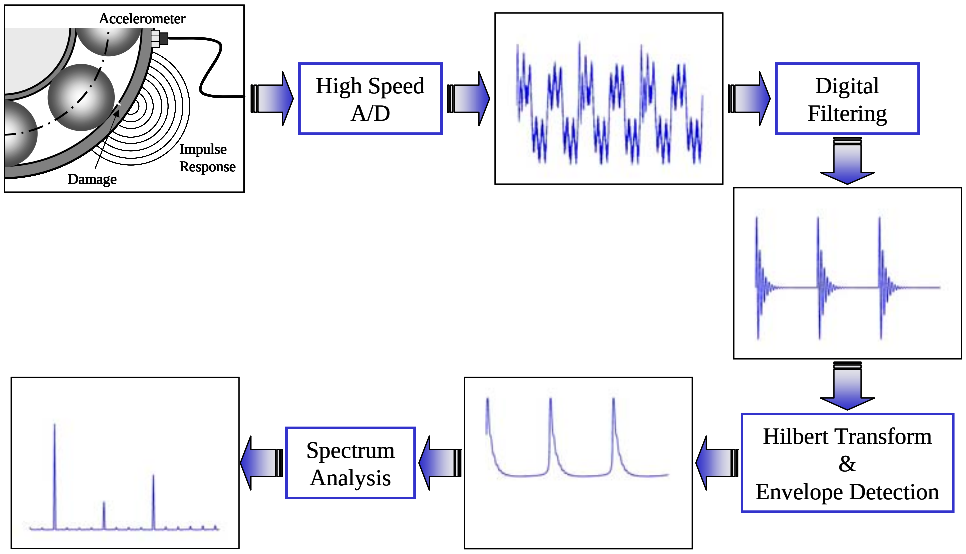


Figure 3 Digital Processing Based Approach

2.3 Synchronous Sampling and Synchronous Analysis

For rotating machinery, vibrations may occur at multiples and submultiples of the shaft speed. For example if the shaft is rotating at 3600rpm, which is 60 Hz, then vibration responses at multiples of this frequency, sometime at a fraction of this frequency, can be seen. These multiples are called the orders (or harmonics in musical terms). The general relationship between the order (ODR), the shaft speed (RPM), and the frequency (*f*) in Hz is

$$f = \frac{ODR \times RPM}{60} \tag{14}$$

If the rotating speed is fixed, regular FFT analysis can give desired results. However, if the rotor speed changes within time window of data acquisition, the variation of the rotor speed will cause the fundamental and harmonics in the frequency domain smeared out in the neighborhood. That is why in rotor dynamics, the order analysis is preferred over the frequency spectrum analysis. In the order domain, the orders of the fundamental and the harmonics remain constants with respect to the shaft speed: first order is always at the shaft speed; second order is always twice shaft speed, and so on.

To achieve order analysis in rotating machinery applications, instead of sampling at equal increments of time, a different sampling technique has to be used: sampling at equal increments of rotation. This is called synchronous sampling. The synchronous sampling technique is a very useful for rotating machinery related data processing, especially for those with varying shaft speed, but is difficult to realize in practice.

Generally, there are two approaches to achieve the synchronous sampling - analog and digital approaches.

The analog approach uses the A/D sampling clock to achieve the synchronous sampling. The key to this approach is to generate an appropriate sampling clock based on shaft rotation conditions. As shown in Figure 4, the sampling clock is derived from the shaft tachometer by a ratio generator to meet desired order analysis requirements (such as order resolution and maximum order). In cases where only lower order components are of interest, the tachometer output can be used as a sampling clock directly.

In the digital approach, both vibration and the tachometer signals are discretized simultaneously, preferably at high speed. Different signal processing techniques can be used to resample the data and convert time domain data into shaft cycle domain data, with the help of a tachometer signal from the shaft. Nevertheless, the availability of the shaft tachometer/synchrophaser is crucial to both analog and digital synchronous sampling approaches.

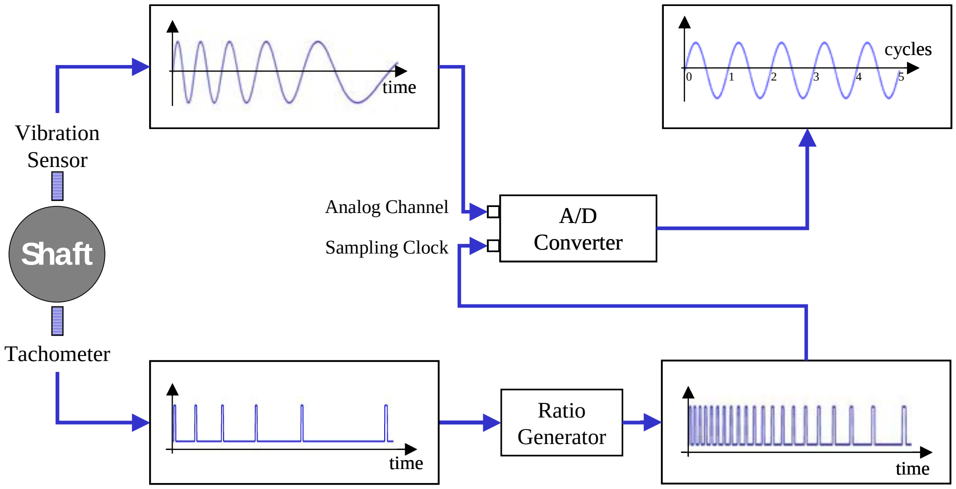
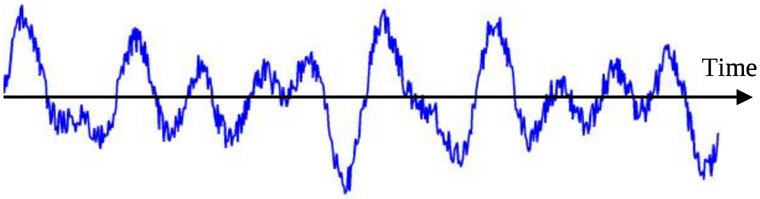


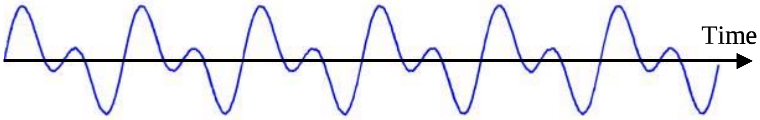
Figure 4 Synchronous sampling – Analog approach

With the synchronously sampled data, a common way to enhance the signal components of interest is through the time synchronous averaging[10]. With a shaft tachometer, the vibration signal detected contains three major components: the synchronous coherent signal component, the synchronous non-coherent components, and the random noise. Conventional time synchronous averaging can only enhance the synchronous coherent signal component. The synchronous non-coherent components and the random noise will be averaged out with sufficient number of averages.

As seen in Figure 5, the top portion of the figure is a simulation results with combination of the shaft response, $a\,sin\left(2\pi f_0 t\right)$, its second harmonic, $b\,sin\left(4\pi f_0 t\right)$, a nonsynchronous coherent signal, $c\,sin\left(2\pi \cdot 1.3 \cdot f_0 t\right)$, and a uniform random noise. After 250 times synchronous averaging, the results are shown in Figure 5(b), where the random noise and the nonsynchronous coherent component have been successfully removed.



(a) Simulated Raw Vibration



(b) Result after 250 Synchronous Averaging

Figure 5 Time synchronous averaging

When applying the synchronous sampling technique to the bearing damage detections, there are two problems that need to be resolved. The first is that the bearing damage signatures are nonsynchronous component to the shaft order, as seen in Eq. (5) and Eqs. (11)-(14). So, if the regular time synchronous averaging technique is applied to the vibration response, the bearing damage signatures will be averaged out. The second problem is unique to a differential bearing. In this case, both races are moving, and the damage frequencies are function of race speed difference. However, a tachometer with respect to the speed difference is physically impossible. A digital signal processing is mandatory to achieve synchronous sampling – the synthesized synchronous sampling technique.

3. Synthesized Synchronous Sampling

With help of a tachometer, the equal time sampled data can be converted into equal space data as shown in Figure 6.

In the event that the tachometer signal is missing, yet the speed, as a function of time, is known, a synthesized tachometer signal can be generated from the speed signal and an equal circumferential space sampling can be carried out. A synthesized synchrophaser includes the following steps (refer to Figure 7):

1. Assuming a synchrophaser pulse at time zero.
2. Once the ith synchrophaser pulse is located, at t_1, assuming the (i+1)th pulse is located at t_2. Calculating the averaged shaft speed, n, from t_1 to t_2 and formulate:

$$\Delta t_1 = t_2 - t_1 \tag{15}$$

and

$$\Delta t_2 = 60 / n \tag{16}$$

3. Searching t_2 such that $|\Delta t_1 - \Delta t_2|$ is minimized. The t_2 is then the approximate location of the (i+1)th synchrophaser pulse.
4. The tachometer can be generated from the synchrophaser, say, by equal spacing between the consecutive synchrophaser pulses.

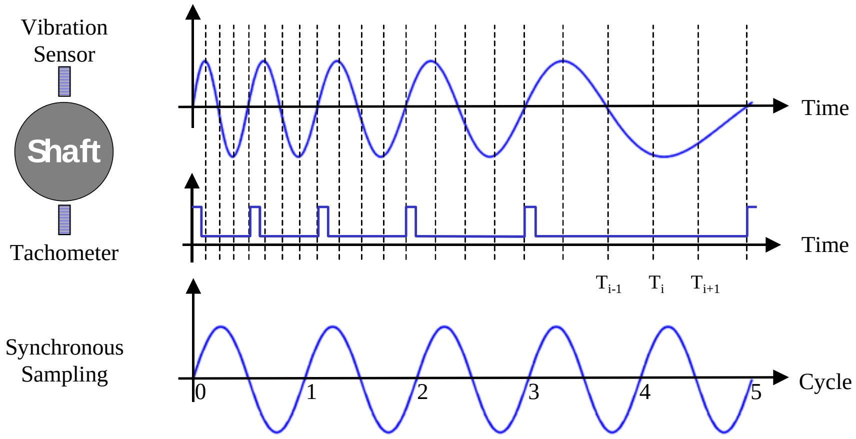


Figure 6 Synchronous sampling

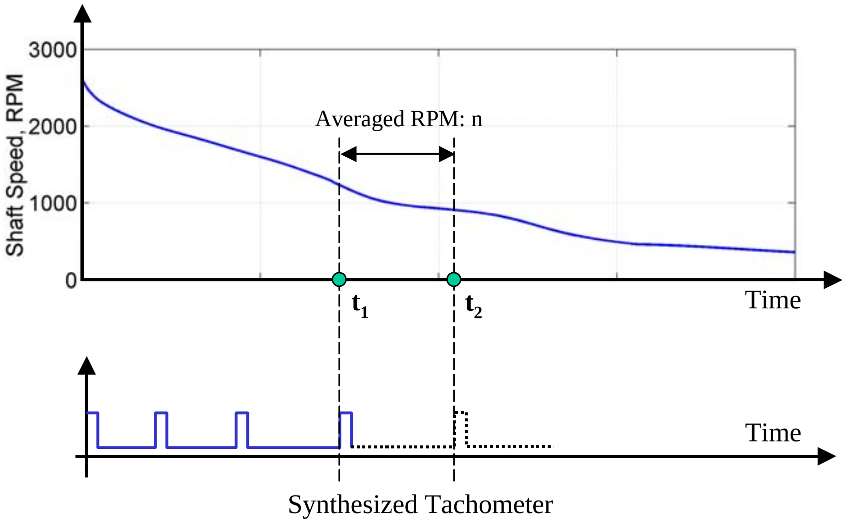


Figure 7 Synthesized tachometer generation from speed function

4. Synthesized Synchronous Sampling Based Algorithm Implementation

We have implemented the synthesized synchronous sampling based differential bearing detection algorithm following the flow charts as shown in Figure 9.

1. Digitize the conditioned vibration sensor at high sampling frequency with high dynamic range A/D converter;
2. Apply digital band-pass filter to the digitized vibration data to isolate the damage induced impulse response, by removing low frequency shaft responses and very high frequency noise;
3. Apply Hilbert transform to the band-passed data to detect the envelope of the signal;
4. Digitize both the LPT and the HPT shaft speeds simultaneously with the vibration data;
5. Derive the instantaneous speed difference form the speed signals;
6. Generate the synthesized synchrophaser pulses according to Section 3;
7. Generate synthesized tachometer based on order analysis requirements (i.e. Maximum Order and order resolution);
8. Carry out “synchronous sampling” to the envelope data derived in Step 3, which will convert the envelope in time domain into “synthesized” cycle domain;
9. Apply FFT onto the cycle domain data to get the order spectrum
10. Average in order domain to further enhance the signature as needed.

With the processes as stated, the damage signatures associated with the races and rolling elements are fixed in the order domain. They will not change with the shaft speeds.

To validate the algorithm, signals from a bearing test rig with differential bearing were used. The outer race of the differential bearing was embedded with an EDM scratch as shown in Figure 8. Based on Eq.(12) the frequency at the speed configuration is about 1850 Hz, or 14.835 order of the speed difference at a given shaft speed combination similar to engine idle operation.

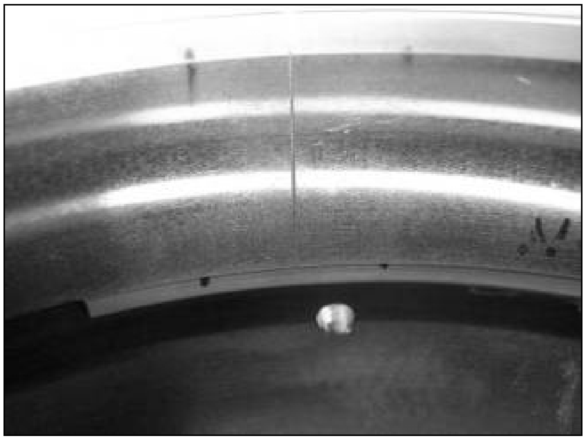


Figure 8 Test bearing with EDM notch on router race

Without the technique proposed here, it is almost impossible to identify any signature from a regular FFT spectrum of an accelerometer signal, as seen in Figure 10(a). With regular acceleration enveloping, we can barely see a small bump around 1850 Hz, as seen in Figure 10(b). This is because both race speeds are not precisely controlled. A small drift in the race speeds is amplified at the bearing signature frequency. As a result, the bearing signature was smeared out in the neighborhood of the 1850Hz.

Only when the “synthesized sampling technique” was applied, the damage signature was then greatly enhanced, as seen in Figure 10(c), where the damage signature is precisely located at 14.835 Orders.

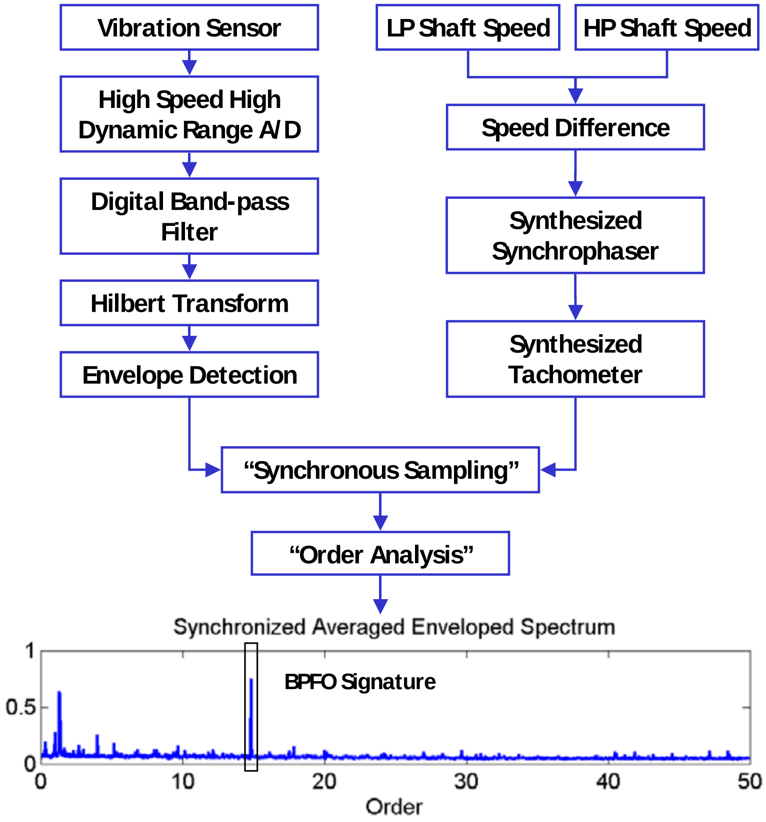


Figure 9 Implementation Flow Chart

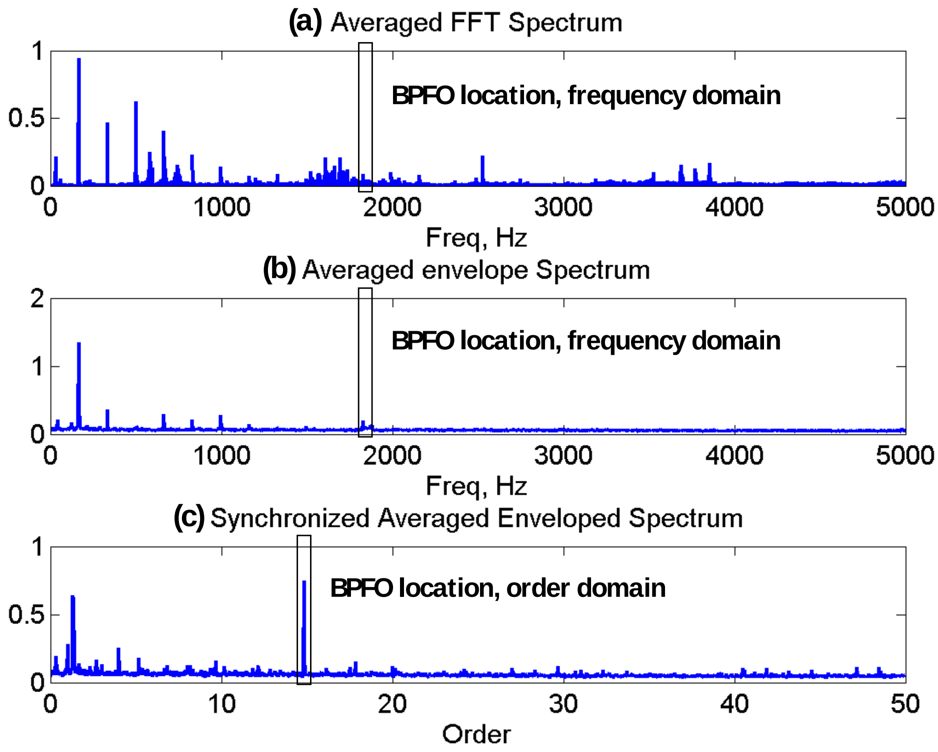


Figure 10 Initial Results

5 Conclusions

A procedure for the detection of differential bearing damage was developed and presented . The key for the differential bearing damage detection is the construction of a synthetic tachometer signal for the case of a bearing with both races moving. In such a case, a conventional tachometer is physically not feasible. The digital synthesizing technique provided in this paper confirmed the possibility for differential bearing damage detection using synchronous sampling technique. Together with the acceleration enveloping technique, the synthesized synchronous sampling technique has proven to greatly enhance the damage signature.

It also worth noting that with the development of computer technology and data processing techniques, those damage detection system functionalities traditionally achieved by analog components can be replaced by digital signal processing after high speed and high dynamic range A/D conversion. The benefits of digital processing are multi-folds: it can improve the damage detection accuracy, sensitivity, and flexibility; it can also improve reliability by reducing the number of system components; and finally, it can reduce the damage detection cost by eliminating analog components.

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References

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[1] P. D. McFadden and J. D. Smith, “The vibration monitoring of rolling element bearings by the high-frequency resonance technique - a review,” *Tribology International* 17(1), 3-10, 1984.

[2] I. Howard, “A review of rolling Element Bearing Vibration Detection, Diagnosis and Prognosis,” DSTO-RR-0013, DSTO Aeronautical and Maritime Research Laboratory, Melbourne, Australia, October 1994.

[3] J. S. Rao, *Vibratory Condition Monitoring of Machines*, New Delhi : Narosa Publishing House, 2000.

[4] R. Eshleman, *Machinery Vibration Analysis: Diagnostics, Condition Evaluation, and Correction*, Vibration Institute, Clarendon Hills, IL : Vibration Institute, 2002.

[5] P. D. McFadden and J. D. Smith, “Model for the vibration produced by a single point defect in a rolling element bearing,” *Journal of Sound and Vibration*, 96(1), 69-82, 1984.

[6] P. D. McFadden and J. D. Smith, “Model for the vibration produced by multiple point defect in a rolling element bearing,” *Journal of Sound and Vibration*, 98(2), 263-273, 1985.

[7] R. G. Harker and J. L. Sandy, "Rolling Element Bearing Monitoring and Diagnostics Techniques," ASME J. Eng. Gas Turbines Power, 111, pp. 251–256, 1989.

[8] Y.T. Su and S.J. Lin, “On initial fault detection of a tapered roller bearing: frequency domain analysis,” *Journal of Sound and Vibration* 155 (1), pp. 75–84, 1992

[9] R. M. Stewart, “Some Useful Data Analysis Techniques For Gear Box Diagnostics”, Institute Of Sound And Vibration, University of Southampton, 1977.

[10] D. Hochmann, and M. Sadok, “Theory of Synchronous Averaging”, IEEE Aerospace Conference, Big Sky, MT, 2004.

[11] F. Combet, and L. Gelman, “An automated methodology for performing time synchronous averaging of a gearbox signal without speed sensor,” *Mechanical Systems And Signal Processing* 21, (6), pp. 2590-2606, 2007.

[12] M. S. Darlow, R. H. Badgley, and G. W. Hogg, “Application of High-Frequency Resonance Techniques for Bearing Diagnostics in Helicopter Gearboxes,” ADA004014, October 1974.

[13] B. P. Bogert, M. J. R. Healy, and J. W. Tukey: “The quefrency alanysis of time series for echoes: cepstrum, pseudo-autocovariance, cross-cepstrum, and saphe cracking.” Proceedings of the Symposium on Time Series Analysis (M. Rosenblatt, Ed) Chapter 15, 209-243. New York: Wiley, 1963.

[14] Y. T. Su, M. H. Lin, and M. S. Lee “The effect of surface irregularities on roller bearing vibrations,” *Journal of Sound and Vibration* 165 (1993) (3), pp. 455-466.

[15] D. R. Harting, “Demodulated Resonance Analysis - A Powerful Incipient Failure Detection Technique,” ISA Trans, Vol. 17: 35-40. 1978.

[16] T. A. Harris, *Rolling Bearing Analysis*, 4th Edition, Wiley-Interscience, December 15, 2000.

[17] J. J. Broderick, R. F. Burchill, and H. L. Clark, “Design and fabrication of prototype system for early warning of impending bearing failure,” MTI-71TR1/NASA-CR-123717, Jan., 1972

[18] J. L. Frarey, “The History and Application of the Envelope Detector,” Technology Showcase: Integrated Monitoring, Diagnostics and Failure Prevention, Proceeding of a Joint Conference, Mobile, Alabama, April 22-26, 1996

[19] S. L. Marple, Jr., “Computing the Discrete-Time Analytic Signal via FFT,” *IEEE Transactions on Signal Processing*, Vol. 47, No. 9, pp.2600-2603, 1999.

[20] H. Luo, X. Fang, and B. Ertas, “Hilbert transform and its engineering applications,” 49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA-2008-2196, Schaumburg, IL., 2008.