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NOVEL VIBRATION DIAGNOSIS TECHNOLOGY FOR INDUSTRIAL GEARBOXES

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Misalignment is a common source of vibrations in rotating machinery such as gearboxes. In this paper novel short-time higher order chirp-Fourier transform (STHOCFT) is applied for misalignment detection of multi-stage gearboxes. STHOCFT is an adaptive technique and is capable of handling non-linear polynomial variation of instantaneous frequency in time. The proposed technique is suitable for both constant and variable speeds of the gearbox. The technology for the misalignment detection is based on the analysis of magnitudes of the bicoherence components based on STHOCFT involving low shaft orders. Separation between the features corresponding to normal and misalignment condition are quantified by Fisher Criterion. Using the Weighted Majority Rule based decision making technique; the estimate of the total probability of correct diagnosis is 100% for the estimated features.
Keywords: Misalignment, Gearbox, STHOCFT, Fisher Criterion, Bicoherence

1. Introduction

Gearboxes operate in outdoor conditions enduring high temperature variations and are the most vulnerable units. The loads applied on the gearboxes and their variation is highly probabilistic in nature. Particularly for water treatment plants high levels of humidity increases the possibility of water ingress into lubricant oil of the gearbox. Most of the gearboxes operate in non-stationary start/stop conditions. Misalignment is the most common source of vibration in rotating machinery [1,2]. Misalignment is estimated to be responsible for more than 70% of the rotating machinery vibration problems [2,3]. Therefore, early root cause analysis (identification of misalignment) of gearboxes is an essential task. Hassan et al. [4] employed higher order spectra (HOS) techniques (bicoherence) for the identification of the misalignment. The authors compared the power spectra of (i) baseline and misalignment case and (ii) unbalanced and misalignment with unbalanced case. The comparison revealed minor difference in these spectra and therefore, power spectra might not be useful for identification of misalignment. The authors compared the amplitude of the bicoherence peaks of the cases with misalignment and unbalance with baseline case and a peak with amplitude more than 6 dB in comparison to baseline case was considered significant. The bicoherence analysis of the misalignment showed significant peaks corresponding to b(1,1) (denotes the interaction of 1x, 1x and their sum), b(1,2), b(1,3), b(1,4), b(1,9) in comparison to baseline. The Bicoherence of unbalance revealed higher b(3,6) and b(3,9) components in addition to b(1,1), b(1,2), b(1,3), b(1,4) and b(1,9) components. The Bicoherence plot of the combination of unbalance and misalignment showed strong b(1,1), b(1,2), b(1,3), b(1,4), b(1,5), b(1,6), b(1,7), b(1,9), b(3,4), b(3,6) and b(3,9) components with respect to the baseline case. Therefore, the authors successfully demonstrated the usage of the bicoherence technique for identification of misalignment and unbalance.

In this paper following novelty is presented,

1. Most of the techniques developed for root cause analysis (misalignment detection) are for stationary operation of the gearboxes. However, most gearboxes in industry operate under non-stationary conditions. Therefore, in the current work, short-time higher order chirp-Fourier transform (STHOCFT) is employed. STHOCFT (proposed by Gelman et, al[5,6,7]) is an adaptive technique and is capable of handling non-linear polynomial variation of instantaneous frequency in time.
2. Further, integration of different features into a single feature is demonstrated. The integrated feature is shown to have higher probability of correct diagnosis in comparison to individual features.

2. Theoretical Description

2.1 Short-time higher order chirp Fourier transform

In general gearboxes have to operate in harsh conditions. For practical conditions, the gearboxes may have variable load and speeds. The Short-Time Higher Order Chirp-Fourier Transform (STHOCFT) [5] is used for non-stationary operating conditions, which is capable of handling non-linear variation of instantaneous frequency in time. The short-time higher order chirp-Fourier transform is defined as [5]:

$$S(f,T,c_2,c_3,\dots,c_n) = \frac{1}{T_k}\int_{-\infty}^{\infty} h_k(t-T)x(t)\, e^{-j2\pi\left(ft+\frac{c_2(t)}{2}t^2+\frac{c_3(t)}{3}t^3+\frac{c_4(t)}{4}t^4+\dots+\frac{c_n(t)}{n}t^n\right)}dt \tag{1}$$

Where k varies from 1 to M; M is a number of non-linear parts in the non-linear frequency-time dependency; $c_2(t), c_3(t), c_4(t), \dots, c_n(t)$ are the variable chirp rate, frequency acceleration and higher-order parameters of the transform.

For the implementation of STHOCFT, the instantaneous frequency should be known apriory. The instantaneous frequency of the gearbox shaft may be obtained by processing data acquired from a speed sensor (tachometer). However, in certain practical cases, it may not be possible to employ speed sensor due to difficult environmental conditions. For such cases, a methodology proposed by Combet and Gelman [8] can be used. The methodology makes use of narrow-band demodulation of a harmonic of the mesh frequency and requires only approximate value of shaft rotational frequency and number of teeth of gears. For the present work, the automated instantaneous frequency computing methodology is used and variation in instantaneous frequency is captured by processing acquired vibration data.

2.2 Bicoherence

The bispectrum is a statistic based on three frequency domain components. The third frequency component is the sum of the first two frequencies. The bispectrum differentiates between non-linearly coupled and spontaneously excited frequencies and quantifies the power due to quadratic coupling between frequencies [9]. The bispectrum quantifies the interaction between the first two frequency components, it measures the statistical dependence between the frequency components [9,10]. The physics behind the concept is that if multiple frequencies are generated due to damage, these frequencies are non-linearly coupled. The Bicoherence is normalized version of bispectrum and is defined as [10]:

$$B(f_1, f_2) = \frac{\sum_{m=1}^{M}\{X_m(f_1)\}\{X_m(f_2)\}\{X_m(f_1+f_2)\}^*}{\sqrt{\sum_{m=1}^{M}|\{X_m(f_1)\}\{X_m(f_2)\}|^2 \sum_m|\{X_m(f_1+f_2)\}|^2}} \quad (2)$$

where X_m is a short time higher order chirp-Fourier transform of the time domain signal, M is the number of internal windows within an external window, f_1, f_2 are frequencies for which bi-coherence is being estimated and * denotes complex conjugate operation.

The Bicoherence is a complex quantity and its magnitude is always bounded between 0 and 1. For misalignment, f_1 and f_2 are selected as harmonics of shaft rotation frequency, as change is occurred in these frequency components due to misalignment. The magnitude of Bicoherence closer to unity represents misalignment while magnitude close to zero represents normal state.

3. Description of experiments

The gearbox considered for experiments is a two stage gearbox with helical teeth, the number of teeth for each stage. A hydraulic oil pump is connected to the gearbox for loading the gearbox. The motor connected to the gearbox is operated by a variable frequency drive. The maximum input speed of the motor is 24Hz. The tests are performed to capture data for different combination of load and input speed. The schematic of the gearbox is as shown in Fig. 1.

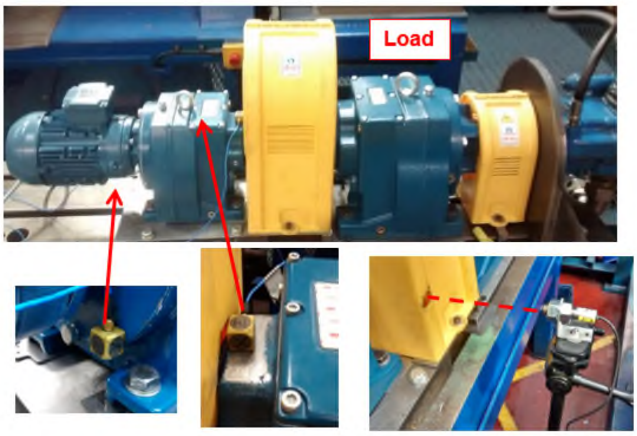

Figure 1 Gearbox test rig with two triaxial accelerometers and one laser speed sensor

Two triaxial accelerometers are connected to the gearbox surface using bolted mounts. To capture vibration data from both the stages of the gearbox, each accelerometer is connected as shown in Figure 1. The Laser tachometer is pointed on a reflective tape pasted on the output shaft to measure the tachometer pulses. The vibration data has been acquired for different speed and loading conditions. Data acquisition is performed using LabVIEW software and hardware tools. Two accelerometers connected to the data acquisition system could acquire 6 channels of vibration data in three directions and a single channel is dedicated to record the speed data. Signal conditioners and KEMO amplifier is connected to the output of the accelerometers to fine tune the voltage amplification output. The data is acquired for input rated speed equal to 1250 rpm and full load of 3.3Amps.

4. Results and Discussion

The misalignment is introduced at the input shaft or the motor using shims. The misalignment effect is developed due to the pull created by the shims attached at the input shaft end. The oil from the gear box is restrained from leaking using special sealant. For the identification of misalignment in the shafts of gearboxes, Bicoherence technique is used. Magnitudes of Bicoherence are used as features for misalignment. The vibration data is acquired for all the channels. The frequency resolution chosen is 0.6 Hz, no. of independent internal window is 20 and the overlapping between windows is 50%. The speed sensor is pointed on the output shaft to record the speed impulses. To estimate the input shaft speed the gear ratio of gear box is multiplied to the input speed signal. The correctness of the speed output is verified by using a digital tachometer by manual measurement.

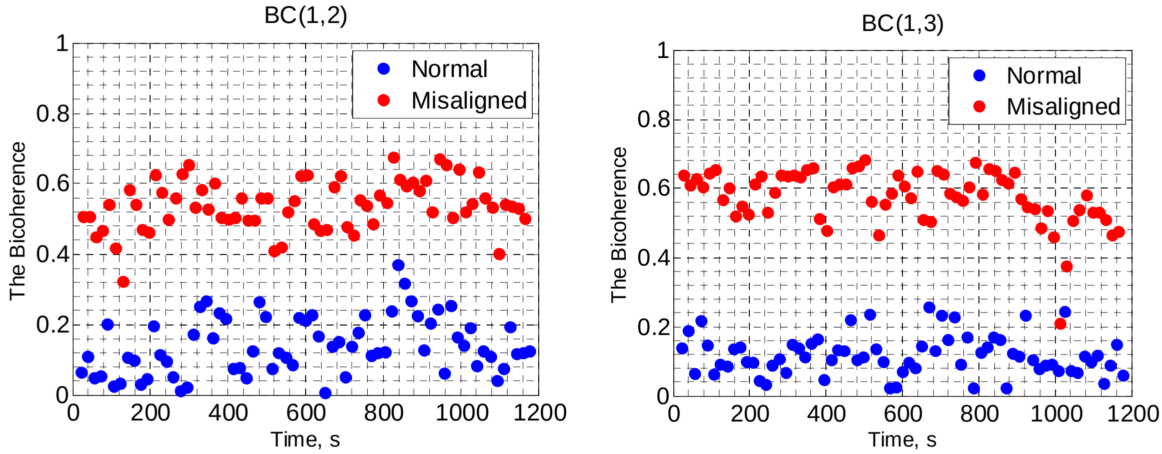

Figure 2 Bicoherence estimates along vertical direction for 1250 rpm Speed and Full Load case, for BC (1,2) Harmonic list and for BC(1,3) harmonics

For the full load case the harmonics with respect to (1,2) and (1,3) have significant results. The separation between the normal and misaligned bicoherence features was noted to be high. Fishers' criterion [11, 12] (FC) is used to measure the separation between the normal and misaligned bicoherence features. The FC criterion for BC(1,2) is observed to be 4.6 for vertical direction. Also using the weighted majority rule the probability of correct diagnosis is found to be 100 %.

Figure 2 shows the bicoherence features for vertical direction. The misaligned features are higher in amplitude when compared to the normal data sets. For the integrated features as shown in Fig.3 the probability of correct diagnosis is estimated as 100%. Along vertical direction the individual features have shown less probability of correct diagnosis. The effectiveness of the integrated features is realized by adding a noise value SNR= 40dB.

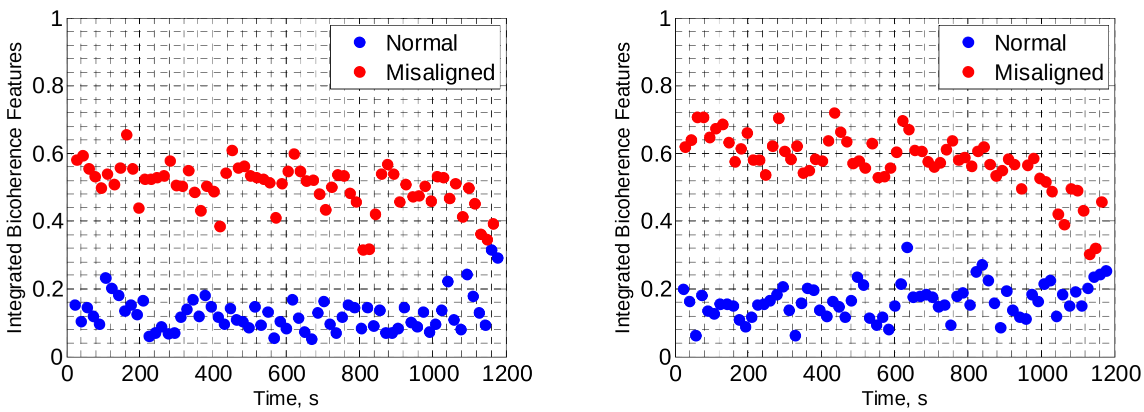

Figure 3 Integrated Bicoherence Features along vertical direction for 1250 rpm Speed and Full Load case, for BC (1,2) Harmonic list and for BC(1,3) harmonics

The above algorithm for processing the vibration data is developed at Cranfield University and the experiments are performed at ERIKS, UK with the valuable support of Mr. Mahesh and Mr. David.

5. Conclusions

The novel technologies for the gearbox misalignment detection are proposed and validated. These technologies are suitable for both constant and variable speeds of the gearbox. Similarly, the technology for the misalignment detection is based on the analysis of magnitudes of the bicoherence components based on STHOCFT involving low shaft orders. Separation between the features corresponding to normal and misalignment condition has been observed. This separation has also been quantified by Fisher Criterion for normal and misalignment conditions. Using the Weighted Majority Rule based decision making technique; the estimate of the total probability of correct diagnosis is 100% for all individual features.

For misalignment, BC(1,2) and BC(1,3) components based features are integrated into a single feature. The advantage of integrated feature over individual feature is demonstrated by comparing estimated total probability of correct diagnosis for a higher noise value in the data. For experimental data, the total probability of correct diagnosis is estimated as 100% for the integrated features, for the individual features the estimates are 86% (14% error) and 89% (11% error).

6. Acknowledgments

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