MONITORING OIL LEVELS OF JOURNAL BEARINGS BASED ON THE ANALYSIS OF VIBRATION SIGNALS

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Abstract. This paper presents a study of monitoring the oil starvation of a journal bearing based on vibration analysis. A diagnostic model is established by including asperity ploughs and collisions. These excitations are more significant as the oil level is reduced due to less oil film effect. However, it has been found by modulation signal bispectrum analysis that the instable oil whirls can affect the measured responses in the middle frequency range (3.5kHz to 5.5kHz), leading to a good detection of the instability but an inconsistent diagnosis. However, the structural resonances in the high frequency range (5.5kHz to 11kHz) can better reflect the excitations and result in a more agreeable separation of different levels under wide operating conditions.

Keywords: Journal bearing, vibration, oil leakage, modulation signal bispectrum.

1 Introduction

The main purpose of using lubrication in journal bearing is to change sliding friction to fluid friction [1]. Oil film can separate surfaces to reduce wear and friction at the contact points. The major common failure mode of journal bearing is oil starvation due to unsuitable operating conditions; bearing and shaft materials; oil type selection and oil leakage. When the oil film is not thick enough to separate the surfaces, asperity collisions have a high chance of occurrences. Thus, any problem affecting the oil film thickness might be a reason for metal-to-metal contact occurring especially during applying radial load. For that reason the oil leakage might cause catastrophic damage. Appropriate levels of oil keeps journal bearings operating efficiently and provides long service life. An effective test has been studied by simulating the oil leakage fault by reducing the oil level. The vibration signals were collected at constant speed under different radial loads.

Vibration monitoring analysis is one of the main techniques used to diagnose and predict various defects [2]. The journal bearing vibration sources are often generated by

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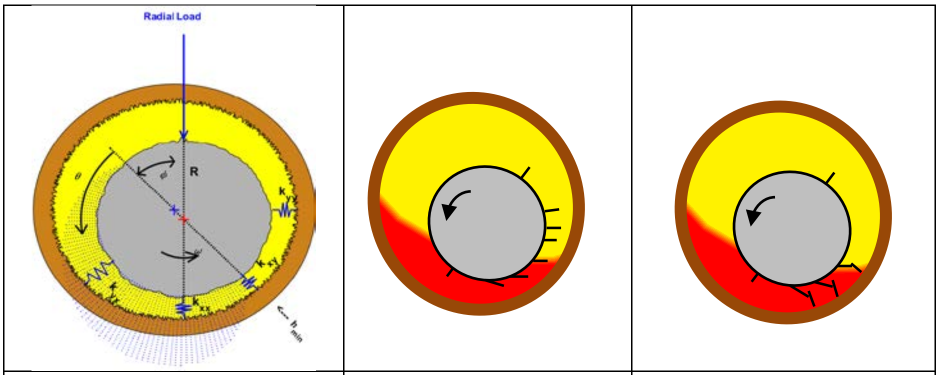
mechanical contact between the rotating shaft and stationary bearing [3]. High clearance causes looseness of bearing which generates more of a square wave than a sinusoid wave [4]. Another type of excitation is mechanical unbalance which causes a pure sinusoid and therefore generates a peak at one RPM [5]. Journal bearing problems often generate vibration peaks at frequencies lower than one RPM which is called sub-synchronous peaks [6]. Oil whirl is a vibration phenomenon excited by oil film. Oil whirl frequency is from 0.38 RPM to 0.48 RPM. Changes in viscosity and oil pressure and related loads can affect oil whirl [6, 7]. Furthermore, sliding asperity and fluid-asperity interactions are sources of self-excitation which result in high responses at structure resonances [8, 9]. High frequency bands around 10kHz of bearing are related with both asperity contacts and fluid friction through the method of clustering spectrum of vibration signals[9]. The interaction between periodic responses and resonant responses produce modulation signals

2 Vibration models for oil level diagnosis

According to the hydrodynamic lubrication and friction generation mechanisms, vibration responses of a journal bearing can be modelled to take into account two more fault related excitations namely micro asperity collisions and ploughs. As illustrated in **Fig. 1** (b), the micro peaks on the lubricated surfaces can bend when they enter into the high pressure zones and recover elastically in the low pressure zones. Similarly, the bending deformation and restoration will happen for the asperity collisions as illustrated in **Fig. 1** (c). Thereby, the conventional vibration model [10, 11] [12, 13] for journal bearings can be extended to be in the form of m_s is the mass of the shaft; $\tilde{k}_i$ denotes the bending stiffness of an arbitrary micro asperity; k stiffness coefficients due to hydrodynamic pressure effect which includes inherent surface defects and journal elastic deformations of micro asperities and main load zones. Obviously, the unbalance and eccentricity often cause low frequency vibrations appearing at the shaft rotation orders: $i\omega$. Particularly, the oil whirl and whip phenomena due to the average unsteady flow will be at about 0.4ω [8]. On the other hand, due to the micro-scale and random distributions of asperities and dynamic pressures, their vibration responses would appear at high frequency range and high randomness. Moreover, these periodic and random excitations will be coupled due to the self-excitation mechanism which can lead to nonlinear modulation contents. Especially, these vibrations can be further influenced nonlinearly by structural resonances, making the measured responses highly complicated and nonlinear.

However, when the journal bearing operates under abnormal conditions such as the lack of lubricants, the characteristics of the internal excitations will change. Particularly, more asperity collisions can occur and consequently more vibrations. Therefore, by characterising these vibration responses it is possible to monitor changes in lubrication conditions.



(a) Vibration model (b)Asperity ploughs (c) Asperity collision

Fig. 1. Vibration excitation and modelling of a journal bearing

3 <u>Test facilities and methods</u>

To examine the performance of vibration based oil level detection, a self-aligning spherical journal bearing, SA35M, was tested based on a rig as shown in Fig. 2. The bearing was lubricated with 37 VG oil. The maximum recommended volume of oil in the reservoir is 100 ml. The test started with a full lubrication level of 100ml which was subsequently reduced by 20 ml at each successive test to simulate possible oil leakages. Table 1 details the operating conditions and lubrication status. Based on the eccentricity ratio (ε =e/c), the bearing was operating under acceptable lubrication regimes.
The vibration was measured by using a 10kHz wide band accelerometer. In addition, the shaft vertical and horizontal displacements were measured by using a laser displacement sensor. It can be seen that the distance between the journal and bearing becomes smaller with the successive reduction in oil levels, indicating that the hydrodynamic films become thinner and more asperity collusions occur due to oil starvation.

Table 1 – Test conditions

4 oil levels: Baseline 100%, 80%, 60%, and 40%								
	Speed	e/c	Speed	e/c	Speed	e/c	Speed	e/c
4 Speeds:	1500rpm	ε	1200rpm	ε	900rpm	ε	600rpm	ε
Load set 1	1bar	0.10	1 bar	0.12	1 bar	0.16	1 bar	0.23
Load set 2	2 bar	0.19	2 bar	0.23	2 bar	0.28	2 bar	0.37
Load set 3	5 bar	0.37	5 bar	0.42	5 bar	0.48	5 bar	0.56

Load set 4	10 bar	0.51	10 bar	0.56	10 bar	0.61	10 bar	0.67
Load set 5	20 bar	0.64	20 bar	0.67	20 bar	0.71	20 bar	0.76

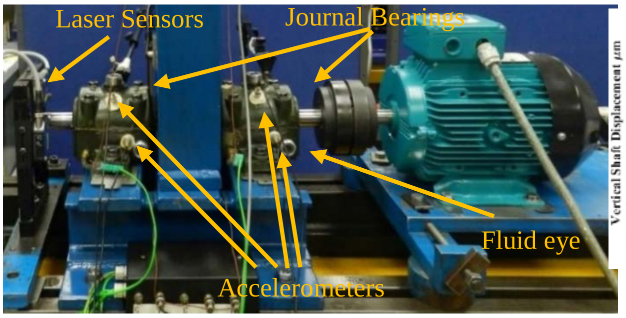


Fig. 2. Journal bearing test rig

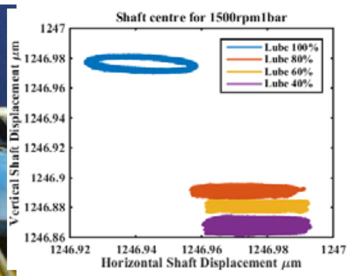


Fig. 3. Shaft displacement

4 Vibration characteristics in the time and frequency domain

A comparison was made between raw vibration signals for different oil levels and operating conditions. It was found that the vibration amplitudes exhibited a significant increase with operating conditions. To quantify the differences, the root mean squared (RMS) values were calculated and shown in **Fig. 4**. The RMS values increase with the decrease in oil levels along with the increase in speed and load. This change agrees with the characteristics of the two excitation mechanisms. Therefore it can be effective to indicate the lubrication conditions using vibration responses.

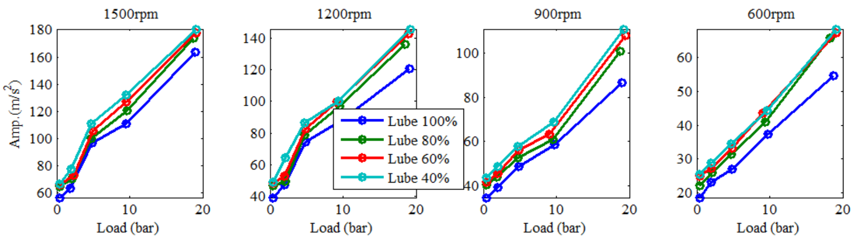


Fig. 5. Vibration RMS with operating conditions and oil levels

However, as shown by the RMS, some of the oil level conditions cannot be spectated adequately. In addition, vibrations of low frequencies can be affected by other sources such as that of the driving motors and couplings, leading to an unreliable diagnosis. To refine the results, spectrum analysis was carried out to find an optimal frequency band for making a better separation.

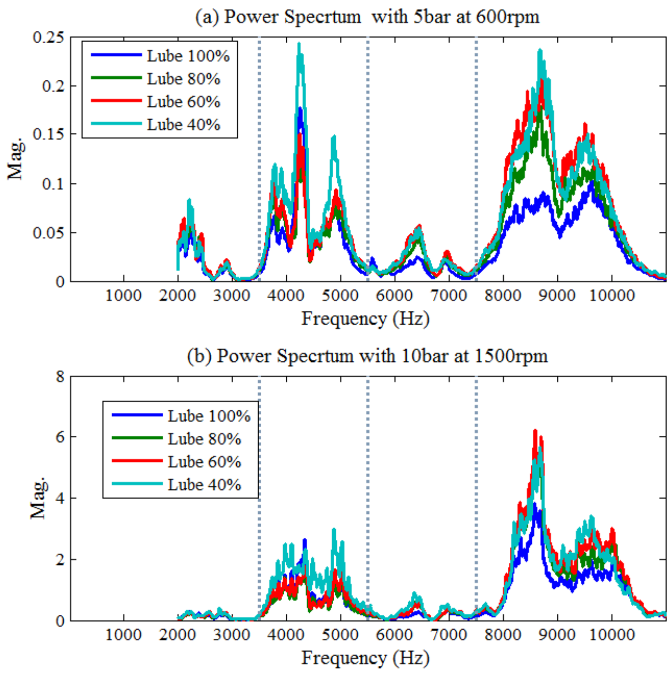


Fig. 6. Spectrum characteristics for different oil levels and operations

As shown in **Fig. 6**, the spectrum in the high frequency range can be regarded to have three sub-bands: SB1 for 3.5k-5.5k, SB2 for 5.5k-7.5k and SB3 for 7.5k-11k, according to the distinction of the spectral amplitudes. In each band, spectrum exhibit continuous profiles due to the random excitations of asperity ploughing and collisions. In addition, these profiles are also magnified by the nonlinear transfer paths of structural resonances. Nevertheless, the amplitude in each band increases with the speed and loads showing they can be a good indication for operating conditions. Moreover, these amplitudes are also sensitive to change in oil levels therefore the averages of the spectral amplitudes were extracted for differentiating the oil levels.

Fig. 7 presents the average amplitudes for different operating conditions along with different oil levels. It shows that the two high frequency bands SB2 and SB3 give more consistent separation for the oil levels in that they agree more with the excitation mechanisms. Especially, SB2 band can provide nearly full separation for all the test cases which are more reliable compared with that of RMS values. SB3 band however can show better differences from the base line oil level. However, due to its high nonlinear effect, the separation between different levels is not as good as that of SB2.

More interestingly, the amplitude of the lower frequency band of SB1 shows a very nonlinear behaviour with loads, which is inconsistent with the understandings of vibration mechanisms.

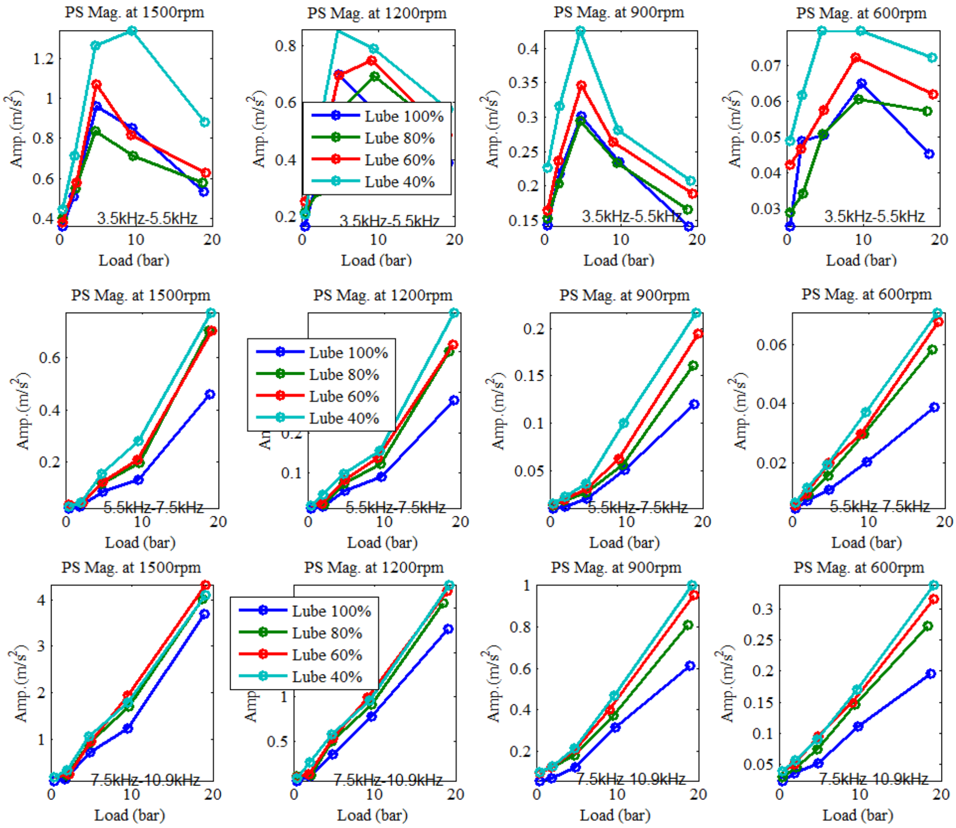


Fig. 7. Diagnostic results using spectral magnitudes in different frequency bands

5 MSB analysis

Modulation signal bispectrum (MSB) analysis was carried out to attain a better understanding of the vibration mechanisms as it is more effective in characterising the nonlinear behaviours embedded signals[15, 16]. Particularly, it suppresses the more random components and highlights the modulating deterministic components. **Fig. 8** presents the MSB magnitude results in the low frequency band of SB1 from 3.5kHz to 5.5kHz. It can be seen that MSB shows significant modulation components for the low load operations (lower than 5bars). Particularly, for the results at the speed of 1500rpm, MSB peaks at (10, 4500)Hz and at (20, 4500)Hz cases can be accounted by oil whirls and peaks at (25, 4500)Hz is from the effect of rotor eccentricity. In other words, the random excitations of asperity ploughings and collisions are marked. Conversely, for the high load operations, MSB magnitudes show much more random patterns, which can reflect more the effect of random excitations. Based on this analysis, it can be understood that the magnification of vibration in this band is more dominated by the instability of hydrodynamic interactions. Therefore, this band produces less agreeable results for differentiating the oil levels and operating conditions. However, this band can be particularly useful to detect the instability operations at the low load operations that can be very negative to the entire rotor system.

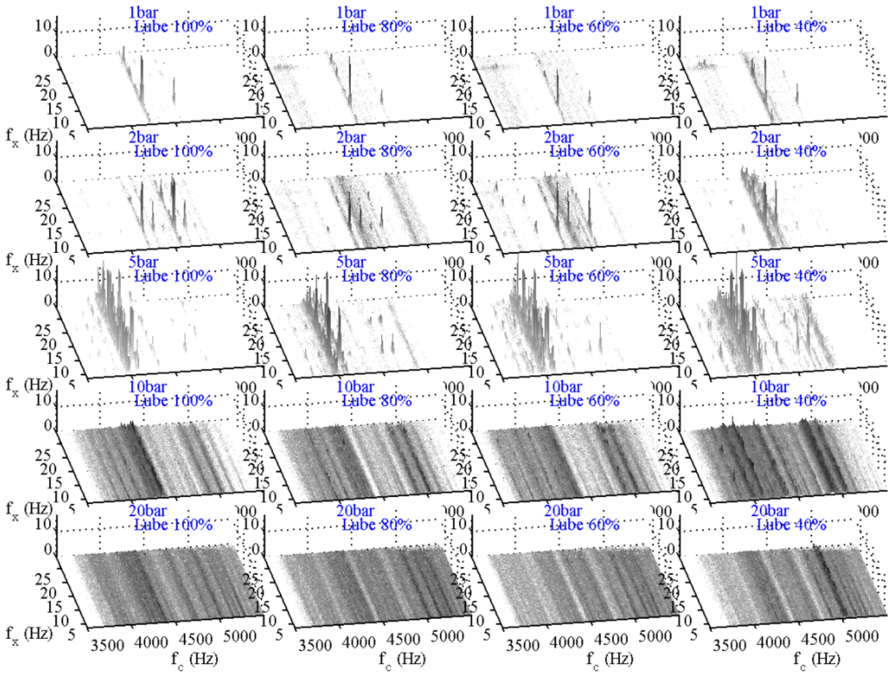


Fig. 8. MSB Magnitude images at speed 1500rpm

6 <u>Conclusion</u>

Based on the vibration mechanisms established and experimental studies, the vibration signals collected under different operating conditions and lubricant levels can be separated adequately for the purpose of condition monitoring. Journal bearing vibration responses are induced by the combination of the conventional hydrodynamic effect and the asperity ploughs and collisions between the lubricated rough surfaces, the combination of which can be characterised by modulation bispectrum analysis. The hydrodynamic effect can interfere with the asperity effect in the middle frequency range (3.5kHz to 5.5kHz), resulting in good detection of the instability but an inconsistent diagnosis of oil levels. Meanwhile, the structural resonances in the high frequency range (5.5kHz to 11kHz) can better reflect the excitations of frictional effects and result in a more agreeable separation of different levels under wide operating conditions.

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