Vibrations based Lubricity Condition Monitoring of Journal Bearings

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Abstract. Journal bearings as the important components are widely used in the rotating machinery. Fault detection and condition monitoring of journal bearing have been attracting more attention of researchers. Actually, defects could be aggravated on the account of adverse operating conditions, especially, these parameters, including lubrication viscosity, speeds and loads, influence the lubrication oil film thickness and decide the lubrication regimes based on Stribeck curve. To avoid the unexpected breakdown, a real time monitoring of lubrication situations is necessary to effective the working condition of journal bearing. In this paper, experimental investigations have been carried out to monitor the lubrication regimes of journal bearing under varying loads ranged from 0 bar to 20 bar. Depending on the vibration analysis in time domain (RMS) and short-time Fourier transform (STFT), the main effect of loads on the lubrication regimes can be found in the low frequency response (100Hz-1000Hz). Based on the Stribeck curves, experimental results also displayed the critical load, which the lubrication regime changes from full-film to mixed lubrication regime.

Key words: Journal Bearing, Vibration Monitoring, Lubrication Regimes, RMS, STFT

1. Introduction

Journal bearings as the important components which is with the advantages of low cost and high reliability, have been widely used in rotating machineries, such as turbomachinery, motors, engines, compressors, pumps, fans and ships. For fluid film journal bearings, the rotational journal and the stable bearing are separated by the oil film which leads to reduce the noise based on the hydrodynamic lift force through converging-diverging wedge flow action[1][2]. The oil film thickness is in the level of microns, so any contaminant particles entrapped can lead to bearing scoring and wear[3][4][5]. Depending on past researches, the failure rate caused by lubricity, including particles contamination, water or liquid contaminant and insufficient lubricant, can be up to 70% [6]. Actually, Journal bearings can operate in any of three lubrication regimes: thick-film lubrication, thin-film lubrication, or boundary lubrication. Unexpected failures associated with the hydrodynamic journal bearing are mainly causes of the contact between the journal and the bearing, which the lubricating condition is boundary lubrication or partial lubrication. The friction produced from the contact interaction will result in surface heating, wiping, scuffing, wear and even 'bite' [7][8][9][10]. Therefore, condition monitoring and fault detection of a journal bearing in the early stages should be to monitor the situations of lubricants in real time [11].

Vibration analysis, acoustic measurements, temperature analysis, torsion measurements and axis center track analyzing as the common signals, are widely used in condition monitoring of the rotating machinery [12]. Vibration measurement technique as one of the most commonly methods is used to diagnose faults such as misalignment, unbalance, looseness, and surface cracks [13]. Recent application can be found in these literatures, Machado et al.[14] investigated the effect of the journal bearing wear on the characteristics of the vibration signal; Bernhauser et al. [14] studied the vibration response of turbochargers based on non-circular journal bearing shapes; Babu et al. [16] researched the effect on the vibration respect with bore defect, looseness and no lubrication condition in journal bearing. In recent years, Sadegh et al. [23] used the artificial neural network method to classify the AE signals generated from journal bearing under different lubrication status. Mirhadizadeh et al.[17] investigated the relationship between the generation of AE signals and the operational parameters including rotating speed of journal, oil film thickness, shear stress, and power loss. Comparing to the different non-detection methods, AE is the most sensitive for fault detection, however, the signal attenuates rapidly during transmission. The data obtained thus usually lost the important information.

This paper focuses on discussing the effect of various operating conditions on the lubrication film dynamical response of journal bearing depending on the vibration data that obtained by the accelerometer sensors. The lubrication regimes and vibration mechanism are introduced in Section 2. Section 3 describes the journal bearing rig and experimental procedure. Based on the vibration signals, time domain (RMS) analysis and time-frequency (STFT) analysis in the Section 4. The last section provides the conclusions.

2. Theoretical analysis

2.1 Lubrication regimes

For a contact of two fluid-lubricated surfaces, the Stribeck curve**Figure 1** shows the relationship between the dimensionless lubrication parameter and the friction coefficient as shown in **Figure 1**. Actually, the Stribeck curve shows the development of the bearing friction coefficient, dependent on rotational speed, lubrication viscosity and applied load. Based on the lubricant film thickness (h), three lubrication regimes have been recognized in **Figure 1**. For the full-film lubrication regime, $h>>\sigma$, the relative sliding surfaces are separated completely. The load is then carried by the hydrodynamic pressure from the lubricant. The boundary lubrication regime, which the film thickness is less than the height of surface roughness ($h< \delta$), may occurs during the equipment startup or shutdown. In this model, the oil film nearly loses the carrying capacity and the asperities directly support the load. The mixed regime ($h \sim \delta$) is usually between hydrodynamic and boundary, in the regime, asperities contact each other directly sometimes that leads to the lubrication film occur discontinues. The load is thus carried partly by the lubrication film, partly by the direct contract between asperities. Generally, lubrication regimes are affected by the operating conditions between the journal and the bearing that the load is carried from one surface to another.

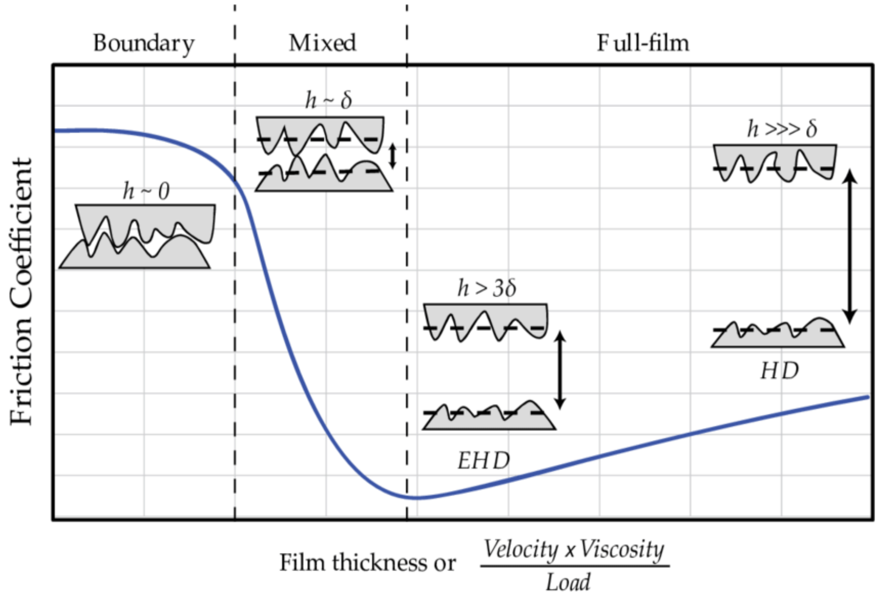


Figure 1. Stribeck curve [18].

2.2 Vibration Mechanisms and characteristics in different regimes

In order to establish the connection between vibration signals and lubrication regimes at different operating conditions or identify any early wear signs of rotating machineries, vibration mechanisms associated with hydrodynamic forces need to be understood sufficiently. Previous studies show that dynamic forces of oil film can make the shaft oscillate violently. Furthermore, asperity contact between the journal and bearing surfaces can cause random vibrations spreading over a wide frequency band.

According to previous studies, the vibration mechanisms and characteristics in the different lubrication regimes have be concluded that in the full-film lubrication regime, the excited force is the hydrodynamic pressure. Petroff's equation is well known to calculate the bearing friction in this model. Some assumptions have been explained as following: the fluid is Newtonian, incompressible laminar flow; the pressure is constant in the axial direction; also, the effect of inertial and gravitational force is neglected. According to the equation, it is clearly that the first quantity in the bracket stands is related with bearing modulus and second one stands for clearance ratio. Also, for the full-film lubrication regime, it becomes reasonable to directly calculate the friction coefficient based on operating perimeters.

$$f = 2\pi^2 (\frac{\mu N}{P})(\frac{r}{c}) \tag{1}$$

where，μ is the lubricant viscosity with unit Pa·s, N denotes the shaft speed with unit 1/s, p denotes the load with unit Pa, c is the oil film thickness and r is the radium of journal bearing.

For the boundary lubrication model, the Hertz contact theory and the theory of Greenwood, Williamson, and Tripp [19] [20] are widely used to construction of numerical models, while it is limited to surfaces with a Gaussian height distribution of the asperities. Then, the elastic half-space theory was introduced which was coupled with a simplified linear-elastic ideal-plastic material law. Therefore, the magnitude of the pressure was limited by the plastic flow pressure of the softer material.

In the mixed lubrication regime, the excited force partly depending on the hydrodynamic pressure, and partly obtained by the asperities contact.

3. Test methodologies

3.1. Journal bearing test rig

In order to investigate the effects of various operating conditions on the lubrication regimes of the journal bearing. Tests of the journal bearings are carried out to obtain the dynamic responses. The rig mainly consists of two self-aligning spherical journal bearings (SA35M), a shaft, a torque meter, an induction motor, a set of hydraulic system for control the vertical loads, four accelerometer sensors located on the bearing housing to collect the vibration signals and an encoder installed on the end of motor to measure the output rotating speed, as shown in **Figure 2.**

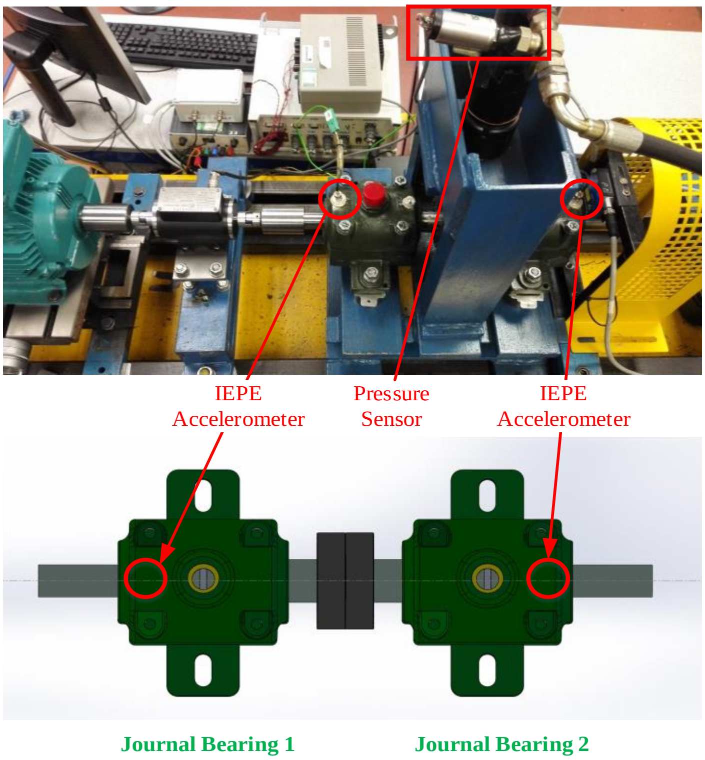


Figure 2: Journal bearing rig

3.2. Test procedure

In this test, the journal bearing was lubricated by the Milmax HV32 lubricant. And all of the experimental data were collected by the data acquisition instrument YE6232B. The sampling frequency is set up to 96k Hz and the acquisition time is 180s. For the investigation, a continuous increase of load from 0bar to 20bar in time was introduced by the hydraulic system, as shown in **Figure 3**. The motor controlled the shaft under a constant speed 1200rpm. In order to get the comprehensive information, the data collection started before loading and stopped after loading.

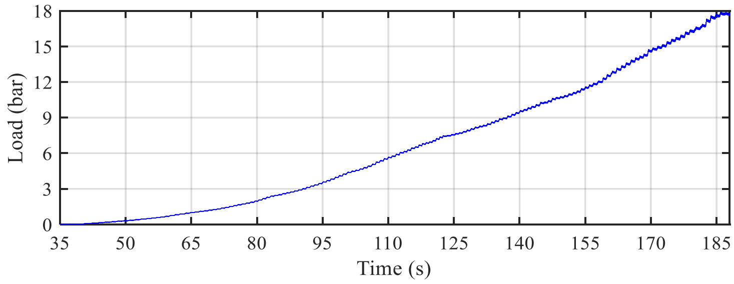


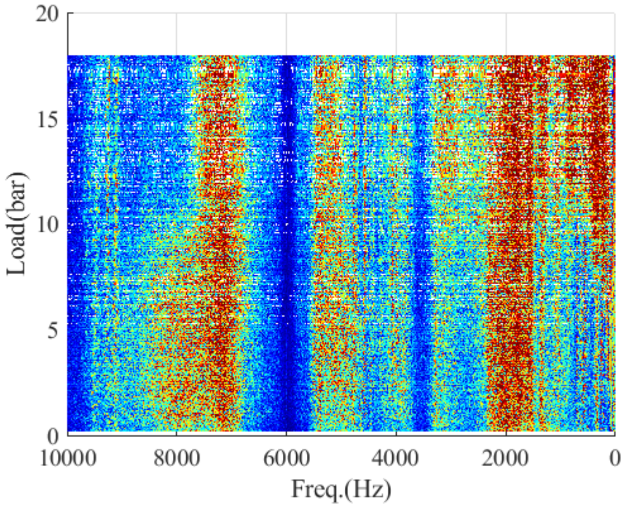
Figure 3: Test stages of the load sweep

4. Results and discussion

4.1. Results from STFT

Short-time Fourier transform (STFT) is a method to divide a longer time signals into shorter segments and then base a sequence Fourier-related transforms to provide the time-localized frequency information for situations. This method is used to obtain the frequency changes in times intuitively.

(a)



(b)

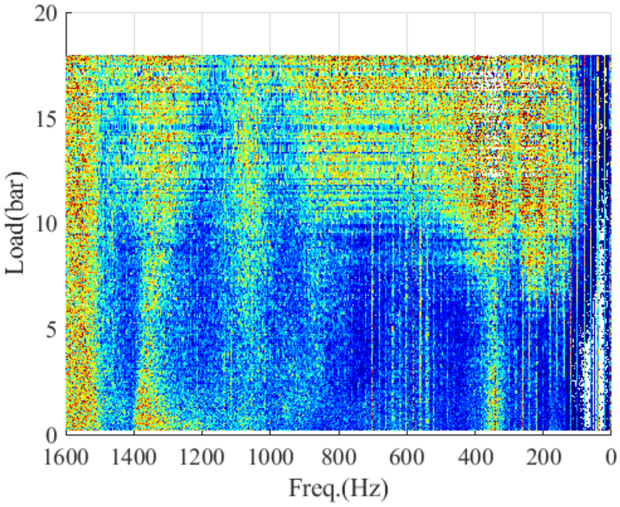


Figure 4. STFT of vibration signals from journal bearing housing under the increasing load.

(a) Frequency band between 0 and 10k Hz (b) Frequency band between 0 and 1.6k Hz

Figure 4 shows the results of vibration analysis in time-frequency domain with the different frequency ranges. In fact, the system resonance is the tendency of a machine to respond at greater amplitude when the frequency excitation sources is approaching to the system's natural frequency as shown in **Figure 4** (a). To discuss the effect of different loads, it can be found that the significant changes of the vibration signals' amplitude occur at low frequency (100Hz-1000Hz), as shown in **Figure 4** (b).

4.2. Detection of lubrication regimes

Due to the simple design of a journal bearing, time domain features of vibration signals are good for the overall investigation. The root mean square (RMS) values of vibration signals can be calculated by the follow Equation (2) and the results are good indicators to track journal bearing situation.

$$\mathrm{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2} \tag{2}$$

Figure 5 shows the contented power in the vibration signature by measuring RMS of filtered vibration data. The results present that as the load increase, the value of RMS decreases first and then increases. According to the equation of Summerfield number, the pressure is inversely proportional to the coefficient of friction in the Stribeck curve.

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{p} \tag{3}$$

Thus, under the premise of constant speed and lubrication viscosity, the coefficient of friction depends only on the load. In the initial loading stage, the oil film thickness decreases and the journal tends to be more stable gradually. At the same time, oil film stiffness and damping become larger, while, the influence of the latter on the response of the dynamic characteristics of the rotating shaft is small, so when the load is less than 9bar, the vibration response of the housing wakens as the load increases. However, as the load continues to increase, the forced response is not only caused by random perturbation of relative sliding surfaces' asperities, but also accompanied by shear jump as the load between 9bar and 10.2bar. Continue to increase the load, some asperities on the relative sliding two surfaces appeared a direct contact. Then, the lubrication model transits from full-film to mixed lubrication regime.

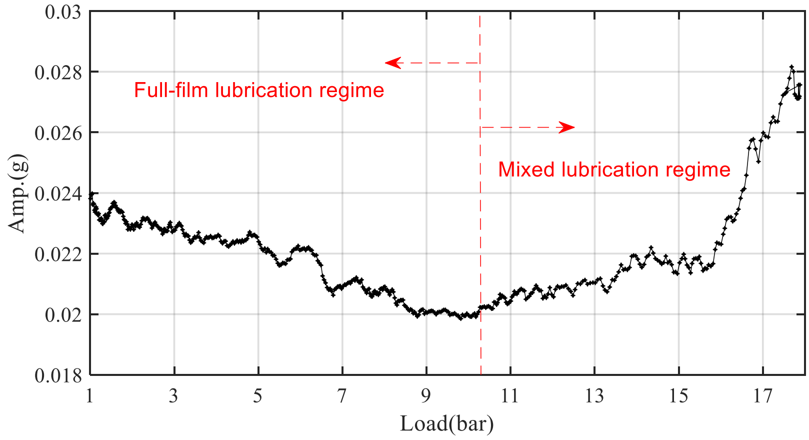


Figure 5. RMS of vibration filtered with the frequency band between 100Hz and 1000Hz.

5. Conclusions

Depending on the experimental observations, the conclusions can be investigated: According to analyze the STFT of vibration signals, the main effect of loads on the lubrication regimes can be found in the low frequency response (100Hz-1000Hz); The partial of Stribeck curve can be obtained based on the varying loads based on vibration analysis in time domain (RMS); Based on the Stribeck curves, experimental results also displayed the critical load, which the lubrication regime changes from full-film to mixed lubrication regime.

Acknowledgment

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References

[1]. Sun DC, Brewe DE, Abel PB. Simultaneous pressure measurement and high-speed photography study of cavitation in a dynamically loaded journal bearing. J Tribology 1993; 115:88-95.

[2]. Natsumeda S, Someya T. Paper III (ii) Negative pressures in statically and dynamically loaded journal bearings. Tribol Ser 1987; 11:65-72.

[3]. Ronen A, Malkin S. Investigation of friction and wear of dynamically loaded hydrodynamic bearings with abrasive contaminants. J Tribol 1983; 105:559-567.

[4]. Ronen A, Malkin S. Wear mechanisms of statically loaded hydrodynamic bearings by contaminant abrasive particles. Wear 1981; 68:371-389.

[5]. Hargreaves D, Sharma SC. Effects of solid contaminants on journal bearing performance. Proc. 2nd World Tribol. Congr. 3-7 Sept., Vienna, Austria: 2001, p. 237-240.

[6]. Dale J, Chang AW. The Benefits of Proactive Lubrication. Reliab Plant 2013 Conf Proc 2013.

[7]. McKee SA. Effect of Abrassive in Lubricant. SAE Int 1927; 22:73-77.

[8]. Branagan LA. Survey of Damage Investigation of Babbitted Industrial Bearings. Lubricants 2015; 3:91-112.

[9]. Chandrasekaran S, Khemchandani M V, Sharma JP. Effect of abrasive contaminants on scuffing. Tribol Int 1985; 18:219-222.

[10]. Pascovici MD, Khonsari MM. Scuffing failure of hydrodynamic bearings due to an abrasive contaminant partially penetrated in the bearing over-layer. J Tribology 2001; 123: 430-433.

[11]. Surojit Poddar, N. Tandon. Detection of particle contamination in journal bearing using acoustic emission and vibration monitoring techniques. Tribol Int 2019; 134:154-164.

[12]. Sadegh H, Mehdi AN, Mehdi A. Classification of acoustic emission signals generated from journal bearing at different lubrication conditions based on wavelet analysis in combination with artificial neural network and genetic algorithm. Tribology International. 2016 Mar 1; 95:426 -34.

[13]. Machado TH, Alves DS, Cavalca KL. Investigation about journal bearing wear effect on rotating system dynamic response in time domain. Tribol Int 2019; 129:124-136.

[14]. Bernhauser L, Heinisch M, Schörgenhumer M, Nader M. The Effect of Non-Circular Bearing Shapes in Hydrodynamic Journal Bearings on the Vibration Behavior of Turbocharger Structures. Lubricants 2017;5-6.

[15]. Babu TN, Devendiran S, Aravind A, Rakesh A, Jahzan M. Fault Diagnosis on Journal Bearing Using Empirical Mode Decomposition. Mater Today Proc 2018; 5:12993-3002.

[16]. Sadegh H, Mehdi AN, Mehdi A. Classification of acoustic emission signals generated from journal bearing at different lubrication conditions based on wavelet analysis in combination with artificial neural network and genetic algorithm. Tribol Int 2016; 95:426-34.

[17]. Mirhadizadeh SA, Moncholi EP, Mba D. Influence of operational variables in a hydrodynamic bearing on the generation of acoustic emission. Tribol Int 2010; 43:1760-1767.

[18]. Berro H. A molecular dynamics approach to nano-scale lubrication (Doctoral dissertation, Ph. D. thesis, MEGA, INSA de Lyon, 2010ISAL0084.

[19]. Greenwood, J.A.; Williamson, J.P. Contact of nominally flat surfaces. Proc. R. Soc. Lond. A 1966, 295, 300–319.

[20]. Greenwood, J.A.; Tripp, J.H. The contact of two nominally flat rough surfaces. Proc. Inst. Mech. Eng. 1970, 185, 625–633.