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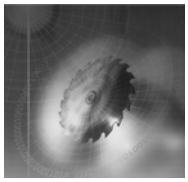

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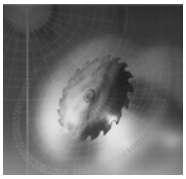

Journal bearing lubrication monitoring based on spectrum cluster analysis of vibration signals

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ABSTRACT- Journal bearings are critical components for many important machines. Lubrication analysis techniques are often not timely and cost effective for monitoring journal bearings. This research investigates into vibration responses of such bearings using a clustering technique for identifying different lubrication regimes, and consequently for assessing bearing lubrication conditions. It firstly understands that the vibration sources are mainly due to the nonlinear effects including micro asperity collisions and fluid shearing interactions. These excitations together with complicated vibration paths are difficult to be characterized in a linear way for the purpose of condition monitoring. Therefore, a clustering analysis technique is adopted to classify the vibration spectrum in high frequency ranges around 10kHz into different representative responses that corresponds to different bearing modulus values and lubrication characteristics. In particular, the analysis allows sensitive signal components and sensor positions to be determined for monitoring the journal bearing effectively. Test results from self-aligning spherical journal bearings show that it allows different lubricant oils and different lubrication regimes to be identified appropriately, providing feasible ways to online monitoring bearing conditions.

Keywords: Journal bearings, vibration, bearing modulus, lubrication regimes, spectrum clustering

1. Introduction

Journal bearings are critical components to undertake heavy dynamic and static loads in many rotating machines such as compressors, engines, turbines and centrifugal pumps. Different monitoring techniques are developed to detect, diagnose bearing faults at early stages so that preventive maintenance actions can be taken timely to avoid any possible major failures. The commonly techniques for condition monitoring of journal bearings are lubricant analysis, temperature measurement, and vibro-acoustic analysis. However, the vibration techniques can provides more timely detection results. Generally the oil film thickness is a clue factor for hydrodynamic journal bearing therefore lubricant film thickness measurement is a great method to monitor bearing condition. In practice, it is very difficult to measure the lubrication oil films less than 0.1 micron by general method [(1)]. Moreover, viscosity analysis such as Total Acid Number (TAN) and Total Base Number (TBN) are useful methods but they usually are implemented offline with costly instruments. Vibration analysis is one of the most commonly used condition monitoring techniques in industry for diagnose different faults such as unbalance, misalignment, looseness, rolling bearing defects, electrical faults, cavitation and surface cracks. Previously, Parno et al (2010) found experimentally that vibration signals in low frequency range (<2000Hz) contains useful information for monitoring journal bearing and that distant vibration sources such as driving motors significantly influence the vibration responses of journal bearings [(2)]. Vibration monitoring of journal bearings can be an effective tool to detect internal surface defects because vibration responses are well related to micro asperity collisions [(3)] and viscous frictional effects. Root mean squared (RMS) vibration values difficultly identify the water contamination effected [(4)]. The various faults including scratched surfaces in journal bearings are more effectively

diagnosed by the results of autocorrelation through fast Fourier transform (FFT) and short time Fourier transform (STFT) in the low frequency range [5].
This paper focuses on using high frequency vibration responses to monitor journal bearing lubrication conditions. The possible vibration excitations are understood in association with bearing friction and lubrication regimes. Then vibration responses were acquired from a test rig designed carefully with different types of oils and bearing modulus. To characterise the datasets, a hierarchical clustering method is applied to the spectrum to select frequency bands that allows the separation different lubrication regimes. Thereby, the boundary lubrication can be identified as a reference for detecting abnormal lubrication condition.

2. Vibration responses and cluster analysis

2.1 Vibration responses of journal bearings

In addition to low frequency vibrations due to oil whirl and whip instabilities within journal bearings[6], high frequency vibration responses can also be induced by various bearing lubrication regimes that are regarded as hydrodynamic, mixed and boundary lubrication regimes. The well-known Stribeck curve explains that a journal bearing usually operates at one of the three lubricant regimes: hydrodynamic lubrication (BL), mixed lubrication (ML) and boundary lubrication (BL) which are determined according to the bearing parameter or modulus values:

$$BM = \mu N / p \tag{1}$$

where μ is dynamic viscosity of lubricant, N is rotational speed of the shaft and p is the pressure in bearing loading area. For high speeds and high oil viscosities but low radial loads, a bearing operates under HL regime in which the bearing surfaces are separated by oil film and under this condition wear is the minimum. However, the fluid shearing forces are high and consequently can cause high friction in the form of heat generation and vibration. This type of vibration can be understood to be the effect of fluid shearing that cause an alternation between surface asperity deformation and reclamation because the shearing stress field are not uniform or random close to bearing surfaces. In addition, fluid cavitation and turbulent flow also contribute to this type of vibration. For an asperity on the shaft surface, the energy for deflection deformation in entering the load zone where the fluid velocity is high can be expressed based on a cantilever model as

$$U_i \propto (s_i \tau L_i)^5 \tag{2}$$

where τ is the fluid sharing stress, s_i and L_i are the asperity width and height respectively. In addition to heat generation, some of the defection energy will be coupled to the bearing structure in the form of vibration because the deflection process occurs momently due to the facts of high velocity flow, micro sizes of asperity and random distribution of boundary flow lays. Furthermore, Newton's viscous law shows that the shearing stress τ on the surfaces is

$$\tau_{h,0} = \eta \frac{\partial u}{\partial z} = \pm \frac{dp}{dx} . \frac{h}{2} + (v_1 - v_2) \frac{\eta}{h} \tag{3}$$

where the positive sign is for z = h (bearing surface with a speed v_1) and the negative for z=0 (shaft surface with v_2). Therefore, it shows that the fluid sharing induced vibration is stronger when rotational speed, oil viscosity and pressure gradient are higher, which in turn induces stronger asperity deformation and larger vibration excitations. Obviously, because of the micro-scale size and randomness of surface asperities and high fluid velocity, the vibration excitation and corresponding responses will exhibit typically wide frequency bands and high randomness. However, as show Equation, this type of excitation has little connection with bearing load.

Boundary lubrication (BL) is mostly an unwanted operating regime for hydrostatic or hydrodynamic bearings, because it generates friction, wear, and causes quack damages to bearing. Unfortunately, during bearing's operating lives, they face boundary lubrication, during start-up, shutdown, low excitation speed, weak lubrication system and high radial load. Bearings operating in this regime have extensive metal-to-metal contacts and asperity collisions because of little hydrodynamic lubrication. Consequently, it shows high rate of wear which will company with vibration energy release[7]. In the meantime, similar to the effect of fluid shearing, the alternation of deformation and reclamation by the collision of asperities also produces vibration energy. For ease of analysis, the friction models are based to predict the amplitude of vibration responses[8]. However, the frictional effect needs to be extended to understand the mechanism of vibration generation. For the contact of a pair of asperities, the stored elastic energy can be expressed as [12]

$$U_i = \int W d\delta_i \tag{4}$$

where W is bearing radial load and δ is the maximum deformation of the asperity with a diameter of a_i. If the sliding velocity is v the time for the release of individual asperity contact is

$$\Delta t_i = a_i / v \tag{5}$$

Thus vibration excitation power p_i can be gained during the collision cycle, which is proportional to the rate of energy release:

$$p_i \propto \int \frac{Wv}{a_i} d\delta_i \tag{6}$$

Furthermore, the number of contacting asperities is proportional linearly with the normal load. The overall vibration excitation power is thus proportional to the both the normal load and the velocity. Similar to the fluid shearing induced vibrations, vibration responses due to direct asperity collisions will also be wide bands because the randomness of asperities. However it may induce discrete impulsive responses for the collisions and the removal of large asperities.

ML occurs during the transition between the BL and HL. At mixed lubricated surfaces, thin film lubrication is formed and sliding surfaces are partially separated, as lower

friction levels are achieved. The vibration excitation power can be the combination of that of HL and BL. It means that bearing load, velocity and viscosity all play effects on the vibration responses.

In order to prevent such conditions, the bearing should operate with a BM value at least three times the minimum value of the bearing modulus [9]. In this design, journal bearing is ensured to work at HL regime. In other word, low and very low bearing modulus values means that journal bearing operates at mixed or boundary lubricant regimes which is considered as abnormal operations and should be avoided.

2.2 Hierarchical clustering

To understand and differentiate the complicated vibration responses from different lubrication regimes, cluster analysis techniques are used to characterise the complicated data sets. Cluster scheme represents a large data set to be easily understood by grouping them into small subsets that provide brief description, similarities and differences, of the data patterns were provided [10]. There are many approaches in implementing cluster analysis. A hierarchical clustering method is a more popular one that works by grouping data set into a tree of clusters[11]. A common agglomerative hierarchical clustering method starts by placing each object in its own cluster and then merges these atomic clusters into larger and larger clusters, until all the objects are in a single cluster or until certain termination conditions are satisfied. The single (complete) linkage algorithm measures the similarity between two clusters as the similarity of the closest (farthest) pair of data points belonging to different clusters, merges the two clusters having the minimum distance, repeats the merging process until all the objects are eventually merged to form one cluster. The Ward's minimum variance algorithm often used to merge the two clusters that will result in the smallest increase in the value of the sum-of-squares variance. At each clustering step, all possible mergers of two clusters are tried. The sum-of-squares variance is computed for each and the one with the smallest value is selected. It means that cluster analysis allows a set of representative signals to be determined based on only incomplete knowledge of signal mechanisms. This is particular useful as it is difficult to obtain full understanding of high frequency vibration contents because they are very complicated in modelling the interactions between fluid and mechanical dynamics as shown in Section 2.1.

3. Experimental studies

3.1 Journal bearing test system

To evaluate vibration based journal bearing monitoring approaches, a journal bearing test rig is constructed as shown in Figure 1. It consists of an AC driving motor with a variable speed drive, a DC load generator and a bearing test system that allows two journal bearings tested in parallel under the same operating conditions. The two self-aligning spherical journal bearings, named as drive end (DE) and non-drive end (NDE) respectively were employed. The self- self-aligning construction reduces possible influences of low frequency vibrations due to shaft misalignments and remote driving and loading motors. The bearing radial load is applied vertically by a hydraulic cylinder whose pressure is adjustable and proportional to the radial load to the bearings.

3.2 Test procedure

To simulate lubricant degradation during services, three types of common lubrication oils, denoted as Oil-15, Oil-37 and Oil-46 respectively, were tested under a number of load and speed conditions. These operating conditions achieve a consecutive increase and wide ranges of bearing modulus values as illustrated in Figure.

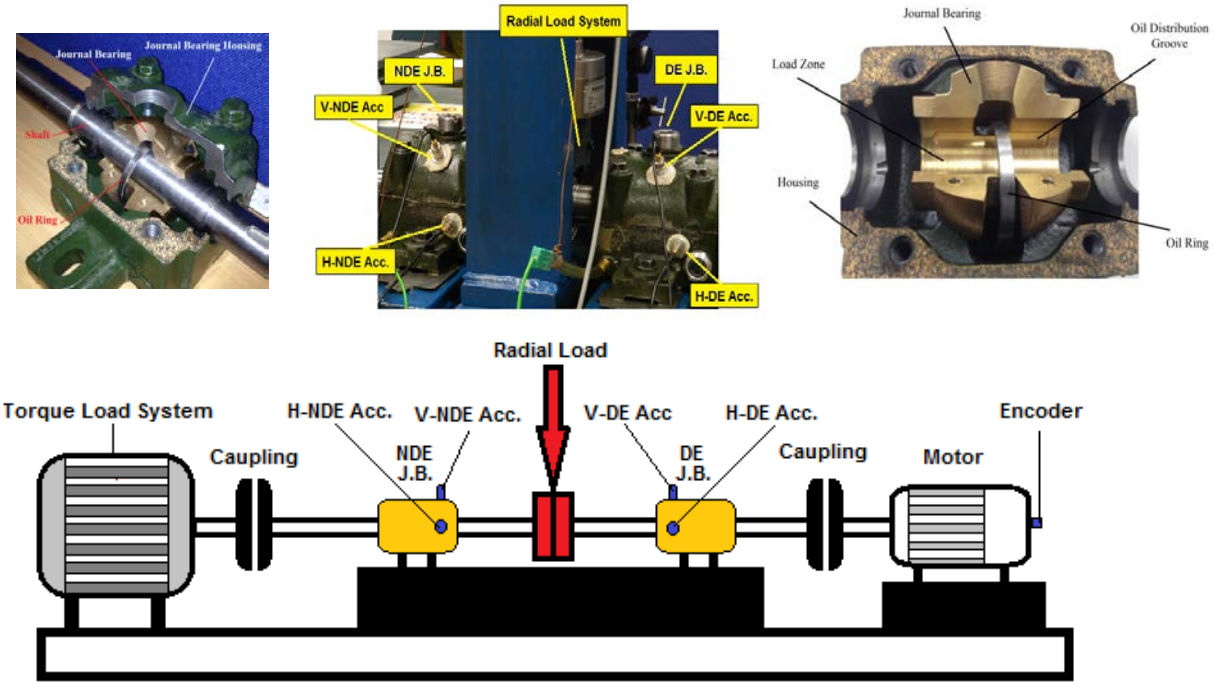

Figure 1. Schematic of journal bearing test rig

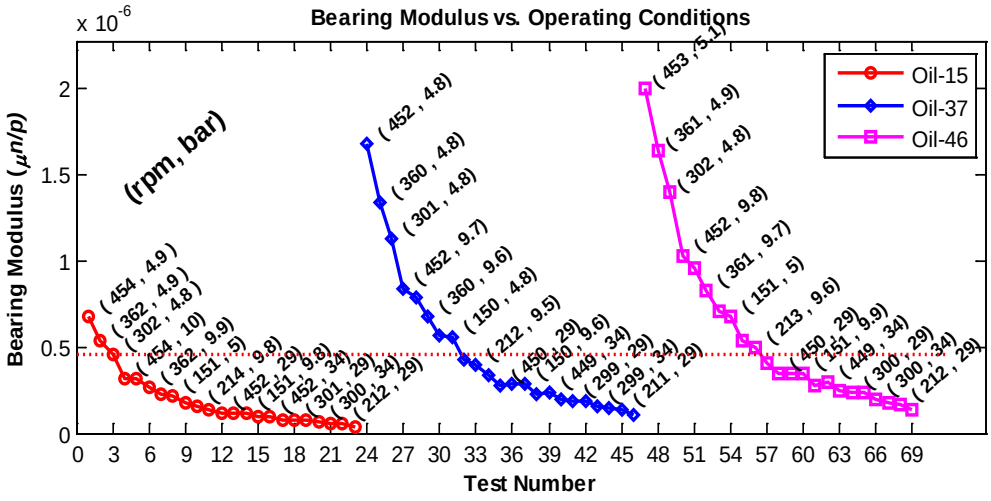

Figure 2. Bearing modulus vs. operating conditions of different oils

According to bearing design standard, the operation with low BM values are more likely to be BL or ML regimes as shown by the test conditions below the horizontal dashed line in Figure 2, whereas the high BM values are hydrodynamic lubrication (HL). In this way, characteristics of vibration responses can be examined under different

lubrication conditions so that they can be based to differentiate abnormal lubrications such as BL and ML from HL. In general, most of test cases for Oil-15 have smaller BM values compared with other two, which have higher chances operating under BL and ML. In addition, each 23 test runs for each type of oils started with operating conditions under large BM values to avoid possible wear influences on high BM operations.

3.3 Results and discussion

The test obtained 3×23=69 vibration datasets, each 23 datasets corresponding to an oil case. In order to use vibration responses for lubrication regime identification, the data sets were processed with both the common time and frequency analysis and the advanced wavelet analysis, in which, both raw data and feature parameters based cluster techniques were applied to separate different test samples. Especially, the discrete wavelet analysis was used with attempt to highlight the responses from asperity collisions that may induce impulsive responses. Unfortunately, it was not successful in separating the 69 tests to obtain a result that accord with the bearing modulus. As an alternative, the common spectrum analysis produces results which can be observed to agree better with the bearing modulus. Therefore, the discussion are made on the results obtained using the commonly used spectrum analysis techniques. Moreover, it has also found that the horizontal vibration response is higher than that of the vertical one. This can be explained to be that the sensor at the horizontal direction is closer to the load zone and hence the horizontal vibration signal has higher signal to noise ratio in reflecting bearing lubrication conditions. Thereafter, the vibration responses from horizontal sensors are the main focuses.

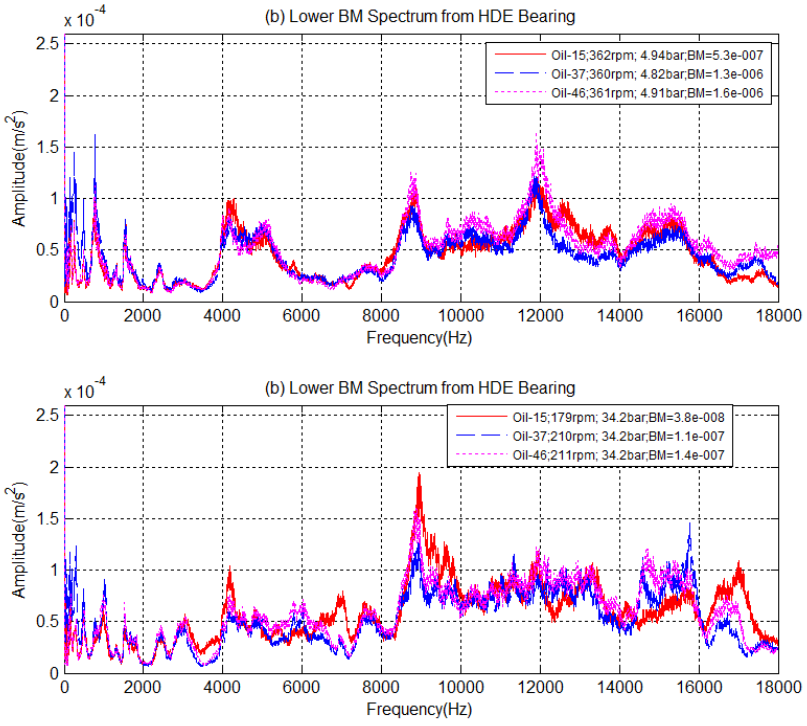

Figure 3. Spectrum comparison of vibrations under different oils and operating conditions.

Firstly, the spectrum of the data sets are examined to find if any frequency bands can give clear differences in different test runs. Figure 3 shows a spectrum comparison of the horizontal vibration at the DE bearing between different type of oils for higher and lower BM values. It can be seen that they have distinctive peaks at a number of discrete peaks below the frequency of 2000Hz. These low frequency contents can come easily from remote interference excitations such as the unbalances, eccentricity and motor bar/slot component excitations, therefore they are not considered in this study. In the meantime, the high frequency vibrations from asperity collisions and fluid shearing effects are the main concerns. By inspecting the spectra in the high frequency range above 2000Hz, it can be found that:

1) Clear differences exists between higher and lower BM values, showing that the fluid shearing induced vibration responses are different from that of asperity collisions.
2) The differences between different oils vary significantly from frequency bands to bands, indicating that high complicity of vibration responses due to combined excitation mechanisms.

These characteristics of vibration responses mean that there is a close connection between vibration responses and lubrication conditions. However, the connection is very nonlinear that cannot be resolved directly with common linear methods such as threshold based approaches.

To connect the vibration responses to different lubrication conditions, an agglomerative hierarchical clustering approach is employed to attempt to group the 3×23 data so that they can correspond to both their BM values and oil types respectively. In the clustering method, correlation measures are used to show the similarity between different spectrum segments and the Ward's minimum variance algorithm is used to merge two clusters. However, it has found that it is difficult to obtain a consistent result by applying it to the conventional feature values from the time domain, the frequency domain and the wavelet coefficients. Therefore, the spectrum values in different frequency bands are directly used for cluster analysis. By tuning the centre frequency from 4,000Hz with bandwidth step of 1000Hz, it has found that the spectral amplitudes between 9,000Hz and 12,000Hz can produced more consistent results. Through a fine tuning, it results in cluster results as shown in Figure 4. It can be seen from the dendrogram in Figure 4 (a) that the data set can be grouped into two subclasses illustrated by red and cyan colours which are subsequently denoted as '1' and '2' respectively for ease of discussion. Once subclasses are presented according to oil types and BM values, which is shown in Figure 4 (b), it can be seen that nearly all of the tests for Oil-15 are classified as '2' corresponding to the BM values which are lower than the designing threshold, whereas for Oil-46 most tests are classified as '1' which corresponds to the BM values higher than the design threshold. In addition, the tests for Oil-32 are classified into two subgroups of similar sizes, each corresponding to HL and ML respectively. Moreover, according to the connection between the subgroups and the BM values, the vibration responses associated with subgroup '2' can be used to show the effects of asperity collisions. Thereby it allows the abnormal lubrication conditions associated with the mixed and boundary lubrication to be detected.

In the same way, the vibration spectrum datasets from the NDE bearing can be also clustered to produce consistent results. As shown in Figure 5, the results are very similar to that of the DE bearing, except for a reversed order of the class labels because the algorithm always sets one with the higher distance value to be class '2'. However, it is obtained from a slightly different frequency band. This may be due to slight differences in vibration transmission paths between two bearings which are likely caused by the discrepancy of accelerometer frequency responses at resonance ranges.

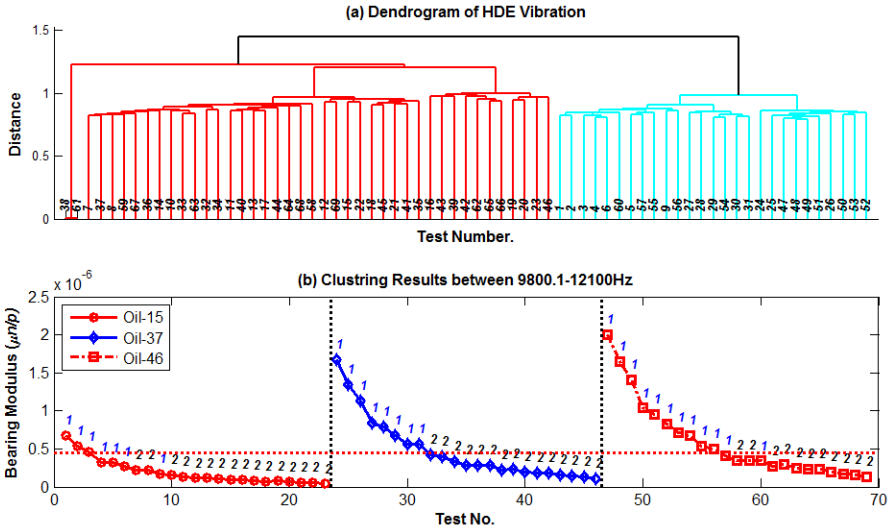

Figure 4. Clusters of vibration spectrum from HDE journal bearing

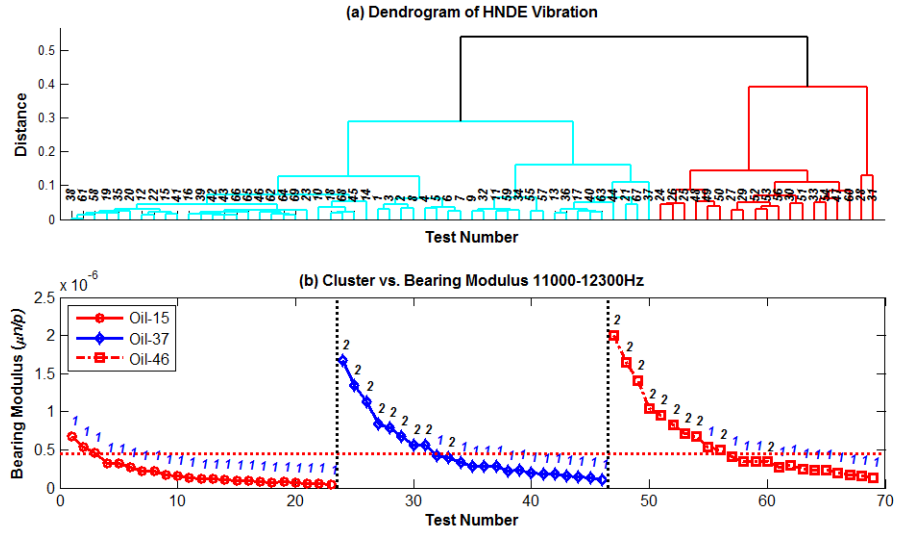

Figure 5. Clusters of vibration spectrum from HNDE journal bearing

4. Conclusion

High frequency vibration responses are mainly from two frictional effects in a journal bearing. The surface asperity collision in the boundary lubrication explain main vibration responses, whereas fluid shearing induced asperity deformation and recovery

in the hydrodynamic lubrication regime can also be an effective vibration generation mechanism. Analytic and experimental studies show that these vibration responses in the high frequency range are complicated and difficult to separate according to the oil types and lubrication regimes.
Through a hierarchical clustering approach, the similarity and difference between the spectra of test samples can be recognised step by step in a relatively narrow frequency band. Finally it obtains a classification result in the frequency band around 10kHz that allows different oils and operating conditions to be seperated in consistent with lubrication regimes.

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