Failure diagnosis and prognosis of sliding bearings

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Abstract. Sliding bearings are widely used machine elements from which the correct operation depends on the availability of many technical systems and great attention is paid to the study of the prediction method for sliding bearings. Problems that occur with sliding bearings lead to high levels of vibration and noise. One of the important parameters in the diagnosis and prediction of the failure of sliding bearings is the thermal analysis. In addition to these parameters, frequent vibration spectrum analysis, oil film thickness and other relevant parameters are often used. Using advanced technologies, it is possible to significantly reduce the duration of measurement, and on the other hand increase the accuracy of diagnostic methods. Phase logic is a mathematically formalized mode of representation modeling uncertainty. In this paper, a selection of damage in the operation of a sliding bearing has been made and the way of diagnosing these problems is shown. Methods that integrate several diagnostic parameters into one show reliable methods of early detection of slip bearing damage.

1. Introduction

The predictive concept of maintenance consists of the use of non-destructive techniques for the very early detection of potential failures, so appropriate corrective actions, that is, repairs are only planned for the time when there is a real need for it. Proactive maintenance involves taking corrective actions with the emergence of the basic causes of degradation and failure, and based on the appearance of symptoms of the resulting damage and upcoming failures or on the basis of the plan, regardless of the real state of the system. In Figure 1, a comparison of the concept of a predictive and proactive approach to maintenance is presented.

Figure 1: Comparison of predictive and proactive approach to maintenance.
Small problem in process oriented complex production system, as sliding bearing failure, can often cause long deadlocks during plant working, which results to huge financial costs in company business [1]. Monitoring and diagnostics sliding bearings failure are given in the literature [2]. Plain or sliding bearings are lubricated by the formation of a hydrodynamic film of lubricant, where the wedge formed lifts the shaft or journal off the bearing [3].

Basic causes that cause damage and failure of sliding bearings include many aspects of construction, material selection, materials mistakes, production and processing, assembly, control, testing, storage, transportation, maintenance, unforeseen exposure to overload, direct mechanical or chemical damage during operation [4]. Often, multiple causers contribute to the sliding bearing failure. The frequency of the individual causers given in Table 1 was obtained by monitoring 530 cases of sliding bearing leakage [5].

| Failure type | Appearance | Cause | Manifest | Solution |
|--------------|------------|-------|----------|----------|
| Abrasion | Presence of solid impurities | Visible rolling of the bearing surface | The bearing damaged by abrasive wear should be dismantled and a new one installed |
Wear and tear

- Inadequate gap
- Inadequate supply of lubricants or inadequate supplies characteristics of lubricants
- Frequent color surface change due to heating
- The bearing can be used again if the causes are removed

Surface fatigue

- Dynamic loading of sliding bearings
- Cracks occurrence
- Eliminate the cause of surface fatigue

Cavitation erosion

- Fluctuation of pressure in the bearing, vibration of the shaft, inadequate flow lubricants through holes and channels
- The occurrence of material destruction is always at the same or similar bearing location
- Improving the bearing construction by increasing the oil pressure in the lubrication system

Corrosion

- Corrosive action of the material
- Visible corroded surfaces of materials
- Changes in lubricant characteristics

Plastic deformation

- Irregularities in the lubrication system, inadequate lubricant layer
- Roofing of the bearing material on the surface and plastic streaming
- Changes in lubrication system or lubricant characteristics

Fracture

- Overload, impact load
- Loss of bearing material from larger surfaces
- Removing possible overloads or expressive impact loads
3. Diagnostics of sliding bearing damage

Problems that occur in sliding bearings lead to high levels of vibration and noise. These problems mainly arise as a result of an inadequate gap in the bearing (oil gap) or the appearance of oil instability. An excessive gap in the bearing results in looseness and irregular lubrication. A sliding bearing with excessive grip, which is mainly caused by the wearing of white metal, causes a relatively small imbalance, a disturbance of centricity or the appearance of some other disturbing force that will cause mechanical looseness, Figure 2.

Oil instability is manifested in the appearance of oil vortex and oil whip. The oil vortex occurs as a result of the orbital motion of the rotor and occurs at a frequency that is proportional to the rotation frequency and amounts usually 0.4 to 0.5 from the main frequency, Figure 3.

In machines that operate above the first critical speed, the oil vortex usually passes into an oil whip which frequency is equal to the frequency in the formation of the same.

The smallest rotational speed in which fluid instability occurs, and this is theoretically in the case of zero-eccentricity, is called the threshold of stability. In actual rotary machines, the eccentricity is significantly greater than 0 (usually from 0.4 to 0.6). However, due to the action of one-way forces on the rotor (such as force due to the non-centering of the coupling, fluid forces due to the working fluid, the electric forces, etc.), the rotor shaft can be brought into the bearing axis and then the mean eccentricity approaches to zero. These problems are best seen by monitoring the cascaded spectral display during the machine slip as in Figure 4 [13].

Bearing temperature measurement is necessary to determine possible overheating of the bearing. The cause of overheating of the sliding bearing can be poor lubrication, insensibility, overload, and also the bearing can be overheated due to the presence of an external heat source.
4. Predicting of sliding bearings failure

In order to reliably determine the condition and prediction of sliding bearing failure, it is necessary to observe and analyze simultaneously several parameters of the condition. One such method is based on the fuzzy logic and enables the diagnostics of the state of the element and determining the urgency of the need for intervention on the machine element. Thus, by applying the disjunctive probabilistic fuzzy operator, a vibration-thermal indicator of malfunction of the sliding bearings (defect factor DFJB) can be defined which contains information about both the temperature and the vibration of the bearing defined as [17]:

$$DFJB = (x(q) + \omega(v)) - x(q) \times \omega(v)$$  \hspace{1cm} (1)

If the temperature and vibrations are within the allowed limits, i.e. below the warning limit, then the value of the DFJB indicator = 0, and if at least one of the parameters (temperature or vibration) is above the limit, then the value of the DFJB indicator = 1 in accordance with the rules for disjunction. If any of the parameters are in the fuzzy warning area, then the indicator of the malfunction in the fuzzy area. It should be noted that in this factor of malfunction, besides the level of absolute and rotor vibrations in the analysis, other parameters such as the vibration spectrum or the thickness of the oil film can be included, which depends on the need for diagnosis.

When it comes to considering the frequency spectrum of vibrations then it is necessary to take into account the fact that the failure of the slide bearing in the frequency spectrum of vibrations is manifested in the form of higher harmonic components of the base frequency $\omega$ as illustrated in Fig.
Therefore, they take into consideration the more harmonic component of the frequency $2\cdot\omega$, $3\cdot\omega$, $4\cdot\omega$, etc. and for the amplitudes of these harmonic components, the limits $v_a$ and $v_d$ are given in the same way as they are set for total vibrations.

The basic harmonic component of the frequency $\omega$ is not taken into account due to the fact that the imbalance of the rotor, which is always present, to a greater or lesser extent, leads to the appearance of this harmonic component in a spectrum with an amplitude that is significantly large. By processing harmonic components using the disjunctive probabilistic phase of the operator, a frequency spectrum is obtained on the basis of which a much more precise diagnosis can be made, since the effects of the interference signal are eliminated.

5. Case Study

The first example. The electric power mill of the raw material of 1.6 MW has sliding bearings with a diameter of the shaft 180 mm, Figure 6.

![Electric motor of 1.6 MW.](image)

By measuring the temperature and absolute vibration velocity in the vertical direction on the housing of said sliding bearings, absolute vibrations at the housing $v = 9.3 \text{ mm/s}$ and temperature $\Theta = 66 ^\circ\text{C}$ were measured on the first bearing. For concrete application, the vibration limits were $va = 4 \text{ mm/s}$ and $vd = 12 \text{ mm/s}$, and the temperature limits were $\Theta a = 60 ^\circ\text{C}$ and $\Theta d = 90 ^\circ\text{C}$. After the phasisation of the measured values of the vibrational speed and temperature is carried out, the following is obtained:

$$x(\Theta) = (66 - 60) / (90 - 60) = 0.20$$

that is

$$w(v) = (9.3 - 4) / (12 - 4) = 0.66.$$  

By calculating the vibration-thermal indicator of malfunction, we obtain:

$$DFJB = (0.20 + 0.66) - 0.20 \cdot 0.66 = 0.73.$$  

It can be noted that the value of the vibration-thermal indicator is greater than the two-phase variables $x$ and $w$. After the bearing was dismantled, significant damage was observed on the lower bearing hemisphere which is visible in Figure 7. Thus, this example demonstrates the applicability and reliability of the vibration-thermal indicator of the defect of the sliding bearing.
Figure 7. Damage to the bottom half of the sliding bearing.

The frequency spectrum of absolute vibrations on the housing of the bearing is given in Figure 8 and the shape of the frequency spectrum characteristic of the bearing wear can be seen. In other words, the form of the FFT spectrum of Figure 8 indicates that this is a worn-out bearing.

Figure 8. Frequency spectrum of absolute vibrations measured on the housing.

The frequency spectrum of the vibration-thermal indicator of DFJB defects obtained by processing harmonic vibration components using the disjunctive probabilistic phase of the operator is given in Figure 9 and it can be observed that this is a spectrum characteristic of the sliding bearing failure which, by its form, corresponds to the FFT spectrum of Figure 8, which means that the frequency spectrum of the vibration-thermal indicator of the defect of the DFJB can also be used to identify the type of malfunction of the bearing in the same manner as well as the frequency spectrum of absolute vibrations.

Figure 9. Frequency spectrum DFJB.

The second example. Electric motor of receptor with power of 18.5 kW, sliding bearings are on 50 mm shaft diameter, Figure 10.
Figure 10. Electric motor of 18.5 kW.

The nominal speed of the electric motor is 1456 rpm. By measuring the temperature and absolute vibration velocity on the housing of said sliding bearings on the second bearing, the absolute vibrations measured on the housing $v = 2.8$ mm / s and the temperature $\Theta = 35$ °C. For the concrete application of the bearing, the vibration limits were $v_a = 1.5$ mm / s and $v_d = 4$ mm / s, and the temperature limits $\Theta_a = 40$ °C and $\Theta_d = 60$ °C. After the phasisation of the measured values of the vibrational speed and temperature is carried out, the following is obtained:

$$x(\Theta) = 0 \text{ i w(v) = (2.8 - 1.5) / (4 - 1.5) = 0.52.}$$

(5)

The value of the vibration-thermal indicator of malfunction is:

$$DFJB = (0 + 0.52) - 0 \cdot 0.52 = 0.52.$$  

(6)

After the bearing was disassembled it was observed that the bed of the bearing (bearing shaft) was significantly worn out. Thus, this example demonstrates the applicability and reliability of the vibration-thermal indicator of the defect of the sliding bearing.

The third example. Cement mill, built-in sliding bearings with a diameter of 1554 mm. The nominal speed is 15.7 rpm and the mill diameter is 4.1 m. The mill is shown in Figure 11.

Figure 11. Cement mill.

The lubrication of the bearings during startup is performed hydrostatically, using a high pressure pump of 200 bar, and after starting, a hydrodynamic lubrication is carried out with a low
pressure pump of 2 bar. By measuring the temperature and the absolute vibration velocity on the housings of said sliding bearings, the absolute vibration in the horizontal direction was measured on the second bearing, at the housing $v = 16$ mm/s and the temperature $\Theta = 81 ^\circ C$. For the concrete application of the bearing, the vibration limits were $v_a = 18$ mm/s and $v_d = 30$ mm/s, and the temperature limits were $\Theta_a = 50 ^\circ C$ and $\Theta_d = 90 ^\circ C$. After the phasisation of the measured values of the vibration and temperature velocity is carried out

$$ x(\Theta) = (81 - 50) / (90 - 50) = 0.77 \text{ and } w(v) = 0. $$
(7)

The value of the vibration-thermal indicator of malfunction is:

$$ DFJB = (0.77 + 0) - 0.77 \cdot 0 = 0.77. $$
(8)

After analyzing the cause of abnormal warming, it was found that the pressure of the oil pump, due to the wear of the rotor, fell below the required level. It can be noted that in this example the vibration-thermal indicator of malfunction pointed to the present fault, which means that this example also proves the applicability and reliability of the vibration-thermal indicator of the defect of the sliding bearing.

6. Conclusion

Failures and damage of sliding bearings are manifested most often as wear, fracture and plastic deformation of materials. These are, at the same time, the basic forms of failure, which can be divided, in relation to the characteristics of the material, into two categories. One that is connected and depends primarily on the strength of the material and the other that is the function of tribological processes on the coupled surfaces of the housing-shaft.

Fracture and plastic deformation are damage in the function of strength, while wear with all its manifestations is related to tribological processes.

By applying the defined vibration-thermal indicator of the defects of sliding bearings (factors of malfunction), the procedure for diagnosing sliding bearings is considerably simplified, because the two most important technical indicators (temperature, vibrations) are integrated intelligently into a single technical indicator of malfunction. This is particularly important when it comes to complex systems with a large number of measurement points where there is often an overload of operators.

Vibration-thermal malfunction indicator (fault factor) $DFJB$ contains processed temperature information and bearing vibration, but in some applications, other than temperature and vibration, other parameters such as, for example, the thickness of the oil bearing film or the strength of the ultrasonic bearing, etc., which in some cases would increase the level of reliability of the method shown for the prediction of the sliding bearing failure.

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