

Detection of bearing damage by statistic vibration analysis

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Abstract. The condition of bearings, which are essential components in mechanisms, is crucial to safety. The analysis of the bearing vibration signal, which is always contaminated by certain types of noise, is a very important standard for mechanical condition diagnosis of the bearing and mechanical failure phenomenon. In this paper the method of rolling bearing fault detection by statistical analysis of vibration is proposed to filter out Gaussian noise contained in a raw vibration signal. The results of experiments show that the vibration signal can be significantly enhanced by application of the proposed method. Besides, the proposed method is used to analyse real acoustic signals of a bearing with inner race and outer race faults, respectively. The values of attributes are determined according to the degree of the fault. The results confirm that the periods between the transients, which represent bearing fault characteristics, can be successfully detected.

1. Introduction

Feature extraction of mechanical fault signals is vital for early fault diagnosis of mechanical equipment. In a rotating machine, a rolling bearing is a key component in various electromechanical devices, and it plays an important role in the entire system. Any defects in bearings, regardless of size, will lead to a series of failures in the parts of the connection. The non-linear and non-stationary characteristics of the fault vibration signals and the interference of the random noise complicate the feature extraction process. Allowing total characteristic of the system state, the signal processing method is generally applied to fault diagnosis [1]. Currently many methods are used to analyze fault vibration signals, such as time-domain synchronous average analysis, an development of the analysis method [2], singular value decomposition (SVD) [3], spectral kurtosis [4-5], wavelet (packet) transformation, fuzzy pattern recognition, neural networks, genetic algorithms, and empirical mode decomposition (EMD) [6-9].

2. The vibration characteristics of rolling bearings

Vibrations measured on the body of the rolling bearing are generated by four major sources [10]:

- the rotation of bearing elements;
- the resonance of bearing elements and their mounting;
- acoustic emission;
- external vibration.

The rotation of bearing elements consists in the following. Each element of bearing (an inner ring, a cage, rolling elements and an outer ring) has a characteristic frequency at which the vibrational energy is excited due to cyclic stresses or periodic attacks on a defect. A set of characteristic frequencies can be defined for each type of the bearing with original geometry. In practice, ideal



geometry is a rare phenomenon, and there are usually additional frequency components generated by inaccuracies such as lobing, out-of-roundness of the ring and different sizes of the rolling elements.

The resonances of bearing elements. Each bearing member has a proper frequency that may be varied during assembly and element loading in the presence of a lubricant. Proper fluctuations excite load changes that occur at specific frequencies, and under the influence of irregular contact in defective areas.

Acoustic emission. Acoustic emission is due to vibrations excited by the movement of the material at the atomic level. When the material deforms, dislocations are generated, and their subsequent movement leads to an unsteady stress wave. In rolling bearings significant local stresses occur in the areas of elastic-hydrodynamic loading and this stress can be a source of active radiation of elastic waves.

External vibration. Bearings are usually a single natural connection between rotating and stationary units of machinery and therefore can be considered as a main place of vibration transmission. This vibration may occur on the rotating member under the influence of unbalance, gearing, impeller blades and other bearings. In combination with radiation in a fixed structure, they provide a complete picture of the vibration measured on a bearing housing.

3. Browse vibratory monitoring methods of bearing condition

The main method of the vibration data analysis for diagnosis of bearing damage is to monitor changes in root mean square levels (hereinafter referred to as a RMS level) and the spectral density of acceleration. The RMS level increases with the development of damage [10].

Refinement of a simple measurement of the RMS level is enabled by the analysis of changes in different octave or third-octave frequency bands; more details can be obtained from the narrow-band frequency ranges.

Currently it is a well established fact that impulse vibration can be seen in bearings with fatigue damage and chipping. Changes in the maximum level of vibration in the high frequency range of 10 kHz are a good indicator of incipient damage, and the ratio of maximum vibration to RMS is independent of changes in load and speed (crest factor).

The measured values of the RMS level, the maximum level, the spectral density and a shock pulse depend on the load on the bearing, speed, seating density, lubrication and bearing clearance. Consequently, it is difficult to determine the condition of the bearing by a separate measurement, except when there is a significant amount of additional information. The ratio of the maximum level to RMS provides a more direct assessment of the bearing condition with minimal reference to previously obtained information, because this method is less sensitive to changes in operating conditions.

For evaluation of vibration characteristics of rolling bearings a series of tests has been completed outside the bearing life, in the range from new bearings prior to the mass of fatigue failure.

4. Probability of the bearing vibration function

The amplitude response of vibration signal $X(t)$ (which is considered to be a stationary random process) can be expressed in terms of the instantaneous probability density [11]. This function is assessed by the length of stay in each signal of the plurality of amplitude windows, and for a typical window width and amplitude x and width Δx . Instantaneous probability can be written as

$$P(x \leq X(t) \leq x + \Delta x) = \sum_{i=1}^N \frac{\Delta t_i}{T}. \quad (1)$$

The solution of equation (1) for all X with small Δx gives the probability density estimate of X . The logarithmic scale change increases the likelihood of low probability, which is important for the detection of bearing damage. At the early stages of testing, when the bearing is damaged, i.e. 0.067LB₁₀ in (3.35 h), the probability density of an inverted parabola indicates normal or a Gaussian distribution (in a linear scale, it would have a more familiar bell shape). Incipient damage in 1.4LB₁₀, causes a distinct change in the tail of the distribution curve. This is consistent with the observation that can be made by studying the behavior of the peak-factor, where the measured maximum acceleration

level increases, but the RMS level remains relatively unchanged. The tail of the distribution curve initially expands with increasing operating time and the development of a damage. This characteristic can be enhanced by calculating the integral of the probability density, which gives the probability of event $X(t) > X_0$ (probability of exceeding a predetermined level):

$$P(X(t) \geq X_0) = 1 - \int_{-\infty}^{X_0} p(x) dx. \quad (2)$$

The result is that the information on the probability signal exceeds a specific value of amplitude X_0 . An obvious measure of the bearing condition is obtained by comparing the probabilities for specific levels of amplitude. Levels above 3σ provide the most relevant information.

5. Statistical vibration acceleration moments of a bearing housing

The shape of the probability density is described by consistency of statistical moments, and these moments are determined by generalized integral

$$M_n = \int_{-\infty}^{+\infty} x^n p(x) dx, \quad n = 1, 2, 3, \dots, \quad (3)$$

the first and the second of which are well known: $n = 1$ gives a mathematical expectation, $n = 2$ – dispersion. They are similar to the first and the second mechanical moments, i.e. the coordinate of a central axis and the moment of inertia of a plane figure correspond to the shape of the probability density.

Odd moments (i.e. $n = 1, 3, 5, \dots$) provide information about the position of the maximum density with respect to the median value. Even moments (i.e. $n = 2, 4, 6, \dots$) indicate the spread of the distribution.

Moments ($n > 2$) can be normalized by eliminating expectation \bar{x} and dividing it by standard deviation σ , raised to the power of the order of time, i.e. by σ^n . For example, the third central moment is:

$$\sqrt{\beta_1} = \frac{\int_{-\infty}^{+\infty} x^3 p(x) dx}{\sigma^3}, \quad (4)$$

$$\beta_2 = \frac{\int_{-\infty}^{+\infty} x^4 p(x) dx}{\sigma^4}, \quad (5)$$

where β_1 is defined as asymmetry, β_2 – excess.

The first six moments of the measured accelerations housing units have been studied for testing of bearing durability. They are evaluated using less precise, but a more practically convenient operator of averaging over time

$$M_n = \frac{1}{T} \int (x(t) - \bar{x})^n dt. \quad (6)$$

Odd moments are close to zero, indicated on the distribution symmetry of the acceleration amplitudes, while higher even moments are very sensitive to impulsive signals associated with damage to the bearing. The normalized fourth moment (or excess) is a measure of compromise between slightly lower sensitive moments and hypersensitive higher moments. For the intact bearing it is close to 3 ($\pm 8\%$), RMS and maximum levels vary respectively between ± 50 and $\pm 65\%$ over the same range of load and speed.

Some common waveforms have a specific, but ambiguous excess value [12]:

- 1.0 – square wave;
- 1.5 – sine wave;
- 3.0 – wave with a Gaussian distribution.

Thus, the measured excess value for the intact bearing is equal to three points for the Gaussian distribution of acceleration amplitudes.

Changes in excess, RMS and maximum levels of acceleration in the process of durability testing during 1.6LB₁₀ showed that the value of the excess increases markedly above three immediately after 1.23LB₁₀, and this increase is consistent with the change of the maximum level, but far ahead of the

change of RMS. Maximum is reached in the vicinity of $1.47LB_{10}$, and at that time the RMS level increases significantly.

6. A change of excess in different frequency bands with damage development

The value of excess increases rapidly near $9 LB_{10}$, reaching at $9.6 LB_{10}$ the maximum value of 6.7. At this point the lesion is located on the inner ring and has the form of a fatigue crack.

At first, a subsequent rotation of excess declined, but then it rose again to a maximum of 6.7 at $11.3 LB_{10}$. Then the change has become quite chaotic, and excess has found a tendency to return to a level equal to three. Appropriate acceleration versus time clearly shows that at an early stage of development of damage in $9.1 LB_{10}$ (454 h), transient vibrations are generated by packets (one for each revolution of the inner ring). This pattern persists until $13 LB_{10}$ (653 h), followed by a quiet period between packets, then it begins to fade, and the packages become less distinct. The amplitude of the acceleration is normalized with respect to the RMS level, and it is important to note that between $3LB_{10}$ (149 h) and $13.15 LB_{10}$ (657 h) the RMS level increases from 0.53 g to 19.1 g.

The disappearance of a clearly discernible pattern of unsteady shock vibration occurs with increasing damage. Initially the fatigue crack length is much less than the circumferential distance between two rollers, whereby the system is subjected to discrete shock loading. The shock loading becomes more continuous, and consequently bursts become a seeming continuous signal due to the damage extent and exceeds the distance between adjacent rollers. When damage captures more than 60 % of the inner ring, it is always in the loading zone, which leads to continuous shock loading and vibration bursts with a set of the indistinguishable pattern. It is at this stage that excess is reduced to 3 (or the value inherent in undamaged bearings), so at first glance it seems that this circumstance prevents the application of the proposed method for the defects detection. However, information about the extent of the defect can be extracted by the observing of excess changes in selected frequency bands. This conclusion is illustrated by examining the value of excess in four frequency bands at certain moments of the durability test. Excess equals 3 in all frequency bands when a defect is absent for $0.06 LB_{10}$ (3 h), i.e. the instantaneous distribution of acceleration amplitude is Gaussian. A marked increase of excess occurs in the lower frequency band with defect nucleation at $9.1 LB_{10}$. With increasing operating time (amplification defect) the excess value in the low band drops again to 3 and the maximum value is moved to the higher frequency band. At $13.15 LB_{10}$ the damaged area exceeds 60 % of the inner ring and captures a greater number of rollers and a maximum of the selected frequency bands available. The importance of these changes can be assessed by analyzing the acceleration versus time for each band at a particular point in the test. In the frequency range of 3 Hz to 5 kHz, it is difficult to identify any specific time-dependent pattern, but in the band range of 5...10 kHz one can see the frequency of bursts corresponding to the frequency of passage of the rollers on the inner ring. At higher frequencies, the quiet periods between bursts of consecutive packets appear once again during each revolution of the inner ring.

Thus it can be seen that in this method the initial lesion causes changes mainly in the low frequency band, while more advanced damage to the greatest extent affects the high frequencies. However, the degree of damage can be defined only by monitoring the excess distribution in selected frequency bands. This situation provides a unique opportunity to determine the condition of the bearing of a set of measurements of excess. If all values are close to 3, the bearings are not damaged. Deviation from three indicates a damage, the dimensions of which can be specified from the shift of the distribution excess maximum towards lower or higher frequencies [13].

7. The proposed mechanism for transfer of discrete frequency pulses with increasing bearing damage

The vibration acceleration of a bearing housing is a result of a complex interaction between the compelling forces and a transfer characteristics design. Building an accurate model, which would allow one to study the development of defect from the transfer of frequencies, requires a full understanding of the driving forces at different stages of bearing damage, as well as the dynamic

characteristics of the structure [14]. The system simulation is necessary using the idealized characteristics of the driving forces and structures, because this full information is absent.

A condition of a 'new' bearing is characterized by compelling force that gradually decreases in amplitude with increasing frequency, and is a combination of the dynamic characteristics of the bearing and a machine. Small surface cracks occurring under generation of fatigue damage dramatically change the distribution of loads by contacting a loading area that can be modeled in the form of a pulse power sine half-wave. If such a waveform summarizes the background noise, the characteristics of its impulse will occur only at low frequencies. Consequently, the time-dependent excitation of the structure will occur only in this region, it indicates the excess above 3. Broadband background noise still dominates at high frequencies so the excess value is equal to three.

The damage is distributed by deepening and expanding the initial crack in conjunction with formation of additional cracks and surface spalling. The transition to an intermediate state is simulated by sine half-waves, but with increased amplitude and recurrence frequency. It causes an increase at the level of the spectrum at all frequencies. Now impulsive characteristics are distinguished above the background noise in the higher frequency scale, and the value of excess increases in this area. With increasing damage the frequency of impact repetition reaches the value when the time between beats is not sufficient for the natural damping of the structure reaction. The resulting interaction between successive bursts has random character, and the resulting signal has the Gaussian distribution of amplitudes in the low frequency band. However, the impact of energy at high frequencies will have a relatively low repetition rate and therefore generates more discrete reaction designs, which can be identified by analyzing a signal with an appropriate band pass filter. Therefore, the development of damage to the value of the low-frequency excess returns to 3, and the value of the high excess remains high.

The basic premise of this model is to ensure that:

- a) the relative levels of shock loading are mixed in background noise;
- b) the frequency of shock repetition is comparable to the time decay response of the structure.

Consequently, the area in which discrete bursts with defect nucleation appear for the first time depends on the excitation spectrum of the background and the nature of damage.

8. The classification of the damage extent

The terms 'nascent' and 'development' damages have been used earlier, but their definitions have not been given.

The nascent damage refers to damage at the macroscale, which in the case of fatigue is a primary surface crack, and not previous microscale movement of dislocations within the material. The rate of transition in the development of damages defined as a state, in which the damage is continuously in contact with rollers in a loading area, depends mainly on the particular nature of damage to an element and a load. If damaged, the outer ring of continuous contact will occur when the extent of damage exceeds the distance between successive rollers and the inner ring, for continuous contact occurs when damage covers 60...70 % of the circumference (for pure radial load). Damage to a single element alone rarely increases and the continuous contact can be an interaction result of elements damage. It should highlight a fact that the absolute area of contact should not be a major factor in predicting failure rates. The intensity of the spread depends to a large extent on the intensity of the impact and frequency of their recurrence. And since these factors result in transfer of frequency corresponding to the maximum excess, then it is obvious that a predisposition to failure can be predicted by the instantaneous values of excess aggregate.

Conclusion

It is shown that values of excess in selected bands are potentially a powerful tool for quantitative evaluation of the bearing condition. The main advantages of this parameter are insensitiveness to changes in speed and load bearing and an ability to indicate damage extent and the tendency to damage spread. 'Maximum operating time of failure' cannot be determined by this method. However,

the obtained information allows one to estimate a bearing condition. This evaluation together with such factors as production schedules, the effects of secondary injury, availability of spare parts, allows one to take a decision to replace the bearing.

The method is applicable to all types of bearings, which is confirmed by laboratory and field tests. Particular difficulties arise in explaining the results of split bearings and bearings operating under conditions close to cavitation. However, by revising the frequency bands and interpretation of the measurements it is still possible to determine the condition of the bearing, but with less sensitivity and reliability.

The results of this study are the beginning of the solution of the contradiction of the 'best' frequency ranges for detection of bearing damage. Discrete bursts are normally associated with a defect and occur in different frequency bands with different degrees of damage. This feature can be explained qualitatively by considering the relative levels of damage associated with the disturbance and background noise, so the efficiency of detection of damage depends on the level of background noise. Simple rules for evaluating detection effectiveness depending on the position of the sensor can be formulated, but in the meantime placing the sensor as close as possible to the bearing can be recommended.

The size of damage is determined beforehand on the basis of the absolute spalling area. A more reasonable interpretation, reflecting the rate of spread of damage, should take into account this area due to the frequency of its contacting loading area.

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