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Study on the rotational speed of bearing cage based on ultrasonic measurement

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Abstract

In this paper, a new method for measuring the cage speed based on the ultrasonic reflection principle is proposed. By emitting high-frequency ultrasound signal for penetrating the bearing outer ring and detecting its ultrasonic echo signal continuously, the time of each rollers passing under the probe can be recorded accurately by detecting the change in the ultrasonic echo signal. Then, the rotation speed of the roller can be obtained by counting the passing frequency of the rollers. For the cages under working conditions, the cages and the rollers share the same rotation speed, where the cage rotation speed is an indication of the bearing operation. Compared to the optical measurement method for the rotation speed of bearing cage, the new method does not need any special arrangement for the bearings and is not sensitive to the environmental factors such as oil mist. In this paper, the new method is used to measure the rotation speed of the cage under different working conditions. By comparing the experimental results with the traditional optical method measurement result and the theoretical calculation results, the measurement results are basically consistent, which verifies the credibility and validity of the new measurement method.

Keywords

Cylindrical roller bearing, angular contact ball bearing, cage, ultrasonic measurement, nonlinear load

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Introduction

The rolling bearing is widely used in various types of industries due to its radial bearing capacity and small friction coefficient.[1] It is used to transfer the force and moment as the key part in the rotating machinery. The failure of the rolling bearing is responsible for the majority of the mechanical failures. The performance and quality control of the rolling bearing is an important factor in determining the security of the rotating machinery and reducing the possibility of the bearing failure.[2]

Therefore, many researchers have always considered the accurate measurement of the dynamic performances of the bearing under different working conditions, and then developed a series of bearing dynamics theories.[3–5] In particular, the vibration of the bearing is highly considered, where many dynamic models were built based on that.[6,7] In the analysis of the causes of the various bearing failures, research demonstrates that the rolling element slipping is a common failure mode of the rolling bearing under high-speed conditions,[8] and accurate monitoring of the slipping of the bearing require accurate measurement of the cage speed.[9] In order to obtain the cage speed, many approaches have been developed, most of which are based on vibration,[10] optics,[11] stress analysis,[12] and ultrasonic,[13] among which the ultrasonic measurement is the powerful method of measuring the cage speed. This method may be applied in practical industrial applications.

In this paper, a new method for ultrasonic measurement of bearing cage speed based on the theory of ultrasonic reflection[14,15] in roller bearing is proposed, which does not require any treatment of cage, and is not sensitive to the environmental factors such as oil mist. Comparing the experimental results with the traditional optical method measurement result and the theoretical calculation result, the feasibility of this method for condition monitoring of roller tilt in industrial applications is analyzed.

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Measurement method

Basic principles of ultrasonic measurement

Ultrasound has many important characteristics such as good directivity, strong penetration ability, great concentration of energy, so that it can be used for the measurement of speed and film thickness.[16,17] In order to accurately obtain the time when the rollers pass under the probe, this paper establishes a model of the vertical incidence of the ultrasonic wave propagation in three-layer medium.

Figure 1 shows the schematic diagram of the cylindrical roller bearing when ultrasonics are emitted that penetrate water. Ultrasonics produce multiple reflections and transmissions in the water medium, and the inner and outer sides of the outer ring as shown in Figure 1. As shown in the figure, I represents the initial wave from the ultrasonic probe, which is reflected and transmitted in the outer ring, producing reflection wave F and wave transmission T. The transmission wave T continues to be reflected and transmitted on the inner side of the outer ring. The strongest reflection wave, which penetrates the steel–water interface, is called B1. Therefore, the first reflection signal received by the ultrasonic probe is the reflection of the water–outer ring interface. The second reflection signal is the reflection signal of the inner side of the outer ring, where the time of the roller rolling can be obtained by recording the change of the amplitude value of the second echo.

An oscilloscope is used to display the second echo signals of each frame for analysis, as shown in Figure 2 for the cylindrical roller bearing (N2204) load of 10 kN, speed of 200 r/min, and the repetition frequency of the signal up to 50 kHz.

Figure 2(a) records the peak of the second echo extracted from each time. When the ultrasonics are focused into the contact zone, the reflected signal amplitude decreases gradually, and reaches the minimum in the center of the contact zone; when the roller leaves the contact zone, the amplitude of the ultrasonic reflected signal becomes larger; when the roller completely leaves after the contact zone, the amplitude of the ultrasonic signal goes back to normal. Figure 2(b) shows that since the reflection coefficient of steel–steel interface (the ratio of the reflected wave voltage to the incident wave voltage) is lower than that of the steel–air interface, majority of the ultrasonic wave spread through roller when a roller enters the contact zone. Therefore, the reflection coefficient is lower than the normal during the contact between the rollers and the outer ring, and reaches its minimum value when the roller and the outer ring contact completely. The process of a roller passing under the probe shown in Figure 2 is shaped like a pit. Appearance of each "pit" indicates a roller passing under the probe. The interval time between the two "pits" also indicates the interval time for two rollers, and then the roller rotating speed can be obtained, which is approximately equal to the cage speed as long as the bearing is not destroyed.

Thus, the cage speed is given by

$$v_c = \frac{d \times f_s}{N} \tag{1}$$

where d refers to the displacement between the two adjacent rollers, which can be obtained from the bearing parameters; N refers to the number of times of the second echo, which is received in the interval between the two adjacent rollers. f_s refers to the repetition frequency, the higher the frequency, the more the ultrasonic pulse emission per unit time. And it is worth noting that the high frequency ultrasonic repetition is required to ensure the accuracy of the measurement under high speed condition.[18]

Basic principles of optical measurement

As shown in Figure 1, the reflection sheet is attached to the cage, and photoelectric transducer is fixed facing the bearing. When the bearing rotates, the

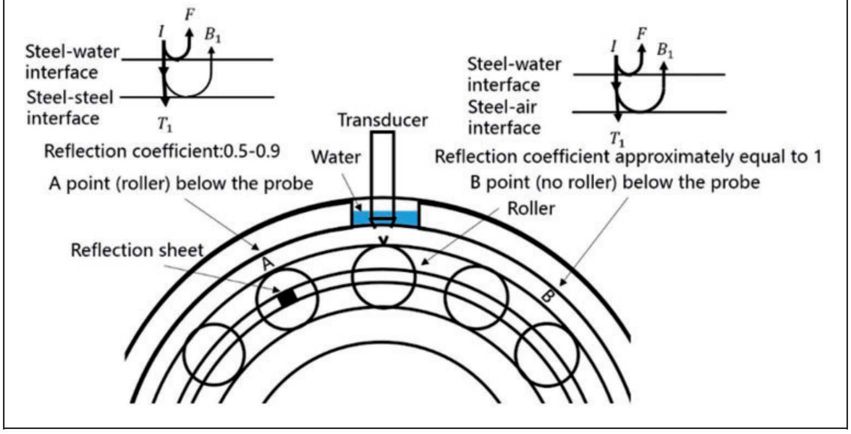

Figure 1. The echo of the ultrasonic transducer.

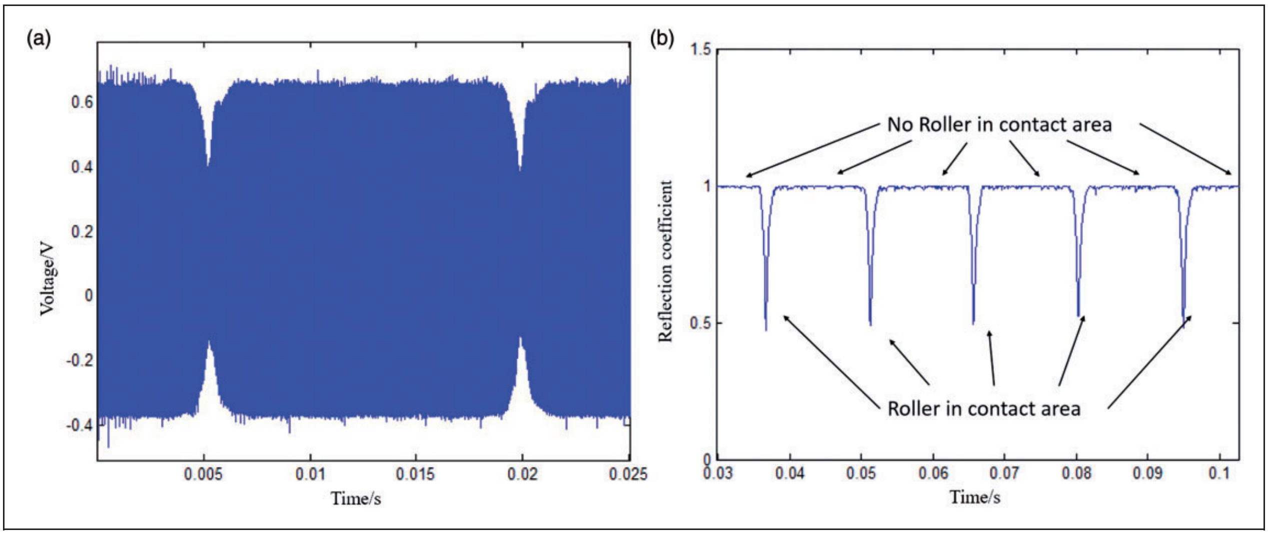

Figure 2. Second echo signal received by the probe: (a) the original signal of the second echo; (b) the reflection coefficient of the second echo.

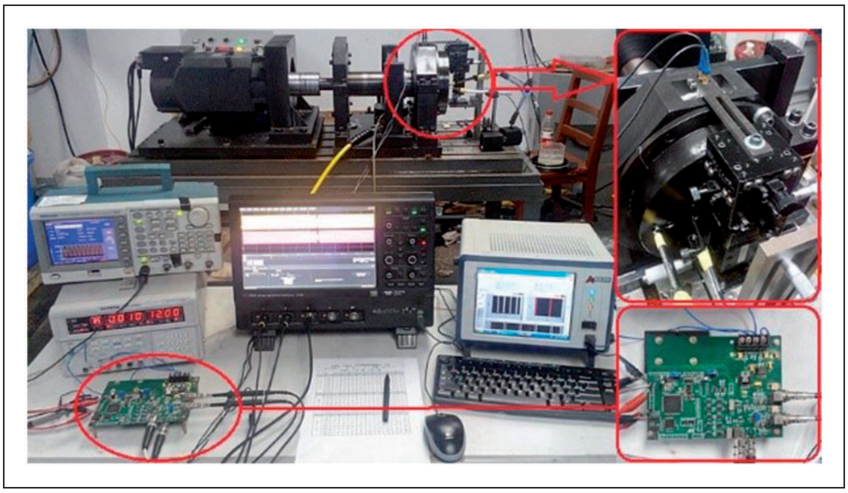

Figure 3. Photograph of the experimental apparatus.

reflection signal is generated each time the sheet passes just under the probe. Usually, when there is only one reflection sheet, the reflection signal frequency is equal to the cage revolution frequency, which can be used to calculate the cage speed.

Theoretical speed of cage

In order to verify the experimental results, the theoretical calculation of the cage speed can be carried out by using the following equation.[19,20] For a given parameter of the bearing, the speed of the cage is given by

$$v_c = \frac{v}{2} \times \left(1 - \frac{d_w \cos\alpha}{d_m}\right) \tag{2}$$

where v_c refers to the cage speed, v refers to the speed of bearing, d_w refers to the roller diameter, d_m refers to the pitch circle diameter, and α refers to the contact angle. It can be seen that the bearing cage speed is proportional to the speed of the bearing, and it is not related to the load on the bearing. Thus, Figure 6 has been remedied according to the formula above.

Experiment process

Experimental apparatus

The experimental system used in this paper is shown in Figure 3.

The test bearing was installed on the right end of the shaft, and the radial loads were applied on the shaft through the middle bearing. An immersion ultrasonic transducer was fixed on a micro-motion platform with 5-DOF on the top of the bearing in a special pocket. The water was injected into the pocket as medium, and the transducer was connected with the ultrasonic-excitation receiving board, which can be directly observed from the oscilloscope;

The photoelectric probe was fixed facing the bearing cage to measure the cage speed; the deep groove ball bearing was adopted as the support bearing and load bearing.

Measurement scheme

In the experiment, the influence of different factors on the speed of the cage was studied, and different measurement methods were needed to control the variable. According to the different needs of the experiment, there were two kinds of measurement schemes.

1. Single probe ultrasonic measurement
   A single probe was used to collect the ultrasonic signal reflected by each roller, by calculating the interval of the adjacent ''pits'' appearing under different conditions. The roller rotation speed can be obtained, which is also equal to the cage speed.
2. Optical method measurement
   With the reflection sheet attached to the cage, the reflection ultrasonic signal was collected under different working conditions by the photoelectric transducer. A pulse will be generated when the roller passes under the probe. By recording the interval time of each pulse, the cage speed can be calculated.

Data processing

After setting the repetition frequency, the ultrasonic probe began to work according to the set repetition frequency. The second echo signal was adjusted to fit the monitor, and then the oscilloscope was set to the sequential pattern. The original signal segmented and the peak value of each segment and the location of the value in this section was recorded. In this paper, the average value of the maximum of the first 10,000 peaks was used as the reference value of the amplitude of the ultrasonic wave in the steel–air interface. The peak value divided by the reference value could be considered to be approximated as a reflection coefficient of that point. The point with the lowest reflection coefficient in a signal was the complete contact point between the roller and the outer ring, and according to the position of the point in the whole signal, the time of the point that roller rotate under the probe was obtained.

Sometimes the interference signal due to vibration, roller extrusion, and other reasons will affect the peak extraction, which needs to be removed. In order to analyze the frequency of the cage accurately, many effective methods can be used, such as fast Fourier transform (FFT), auto-regressive(AR), auto-regressive moving average (ARMA), and indicated repeatable runout with wavelet decomposition (IRR-WD);[21] however, in this paper, the major concern is the information of the cage speed, which can be easily extracted. Meanwhile, the system was built as online-based real-time system, which needs fast algorithm to implement, thus the signal processed by the simple median filtering method is acceptable. The result is shown in Figure 4(a), which is the angular contact bearing (7210 C) under the operating conditions for the load of 10 kN, speed of 480 r/min, and the peak signal of repetitive frequency of 50 kHz. Figure 4(b) shows the local enlarged image of the black circle in Figure 4(a), the figures represent the time of these points.

It is shown in Figure 4(b) that the time interval of the two roller rolling was about 0.018 s, and the roller revolution speed can be calculated by equation (2), which was about 0.020 s where both were basically consistent.

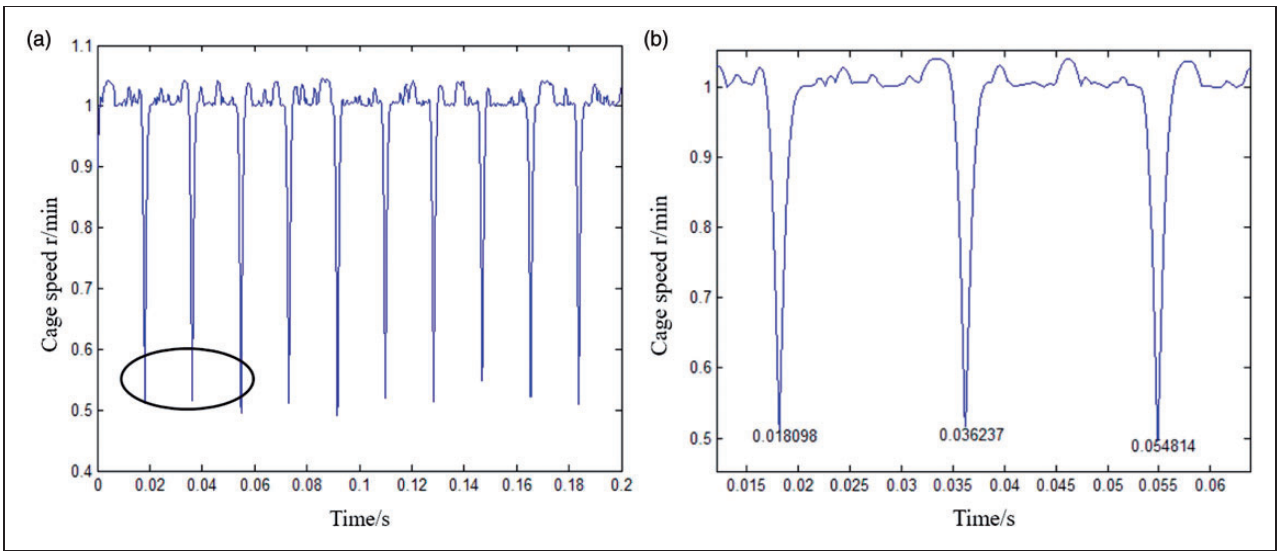

Figure 4. Peak signal after removal.

Experimental results

Cylindrical roller bearing experiment

Figure 5 shows the comparison of the cage speed of the cylindrical roller bearing (type N2204) under different conditions and their theoretical calculation results. As seen in the figure, with the increase in the bearing speed, basically the rotation speed of the cage increases linearly; the effect of the load difference is not so obvious in that range of load under the experimental circumstances, which means the slippage does not change to a greater extent. The results of the ultrasonic measurement are close to the results of the theoretical calculation, but it is a little larger than the theoretical value.

Angular contact bearing experiment

Figure 6 shows the cage speed of the angular contact ball bearing (type 7210 C) measured by the ultrasonic measurement and optical measurement under different working conditions. It can be seen from the figure that the results of the ultrasonic measurement are close to the theoretical value, while the deviation of the optical measurement method is gradually produced due to the oil mist blocking the optical path.

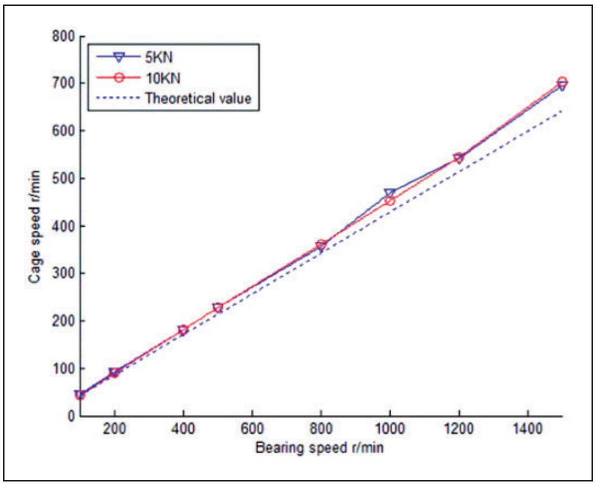

Figure 5. Cage speed under different conditions.

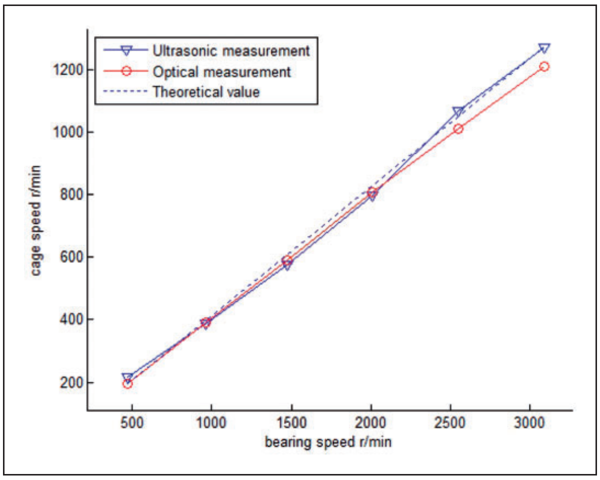

Figure 6. The results of the measurement of the instantaneous speed of the cage.

Conclusion

In this paper, the change in the law of rotational speed and load of the cylindrical roller bearing cage is measured by the ultrasonic measurement. The cage speed of the angular contact ball bearing under high-speed condition is compared between the optical method and the new method, and the following conclusions are obtained:

1. By comparison, the ultrasonic measurement method is applicable to the cylindrical roller bearing and angular contact ball bearings, and the results are close to the calculation results and the optical measurement results, which verify the feasibility of the new method.
2. Compared with the traditional optical methods, the new method does not require any processing on the bearing, and is not sensitive to the environmental factors. The ultrasonic method is expected to be applied to the high-speed bearings when the optical method is difficult to measure.

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Declaration of Conflicting Interests

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References

1. Dong JX. *Lubrication principle and lubricating oil*. Beijing: Hydrocarbon Processing Press, 1987.
2. Han J and Zhang RL. *Fault mechanism and diagnosis of rotating machinery*. Beijing: Mechanical Engineering Press, 1997.

3. Zhang JZ and Ma GH. Research progress on dynamics of rolling bearing cages. *Bearing* 2016; 1: 56–60.
4. Li M. *The dynamic characteristics of cylindrical roller bearing at the stop stage*. Master's Thesis, Henan University of Science and Technology, China, 2015.
5. Liu XM. *Dynamics analysis model of high-speed rolling bearings and dynamic performance of cages*. Doctor's Thesis, Dalian University of Technology, China, 2011.
6. Wardle FP. Vibration forces produced by waviness of the rolling surfaces of thrust loaded ball bearings Part 2: Experimental validation. *Proc IMechE, Part C: J Mechanical Engineering Science* 1988; 202: 313–319.
7. Lynagh N, Rahnejat H, Ebrahimi M, et al. Bearing induced vibration in precision high speed routing spindles. *Int J Mach Tools Manuf* 2000; 40: 561–577.
8. Arthanari S and Marappan R. Experimental analysis of factors influencing the cage slip in cylindrical roller bearing. *Int J Adv Manuf Technol* 2011; 53: 635–644.
9. Ding HF, Jing MQ, Wang FT, et al. Skidding analysis of high speed cylindrical roller bearing considering acceleration of bearing. *Mach Des Manuf* 2016; 2: 64–67.
10. Shi JJ and Ming L. A fractal-dimension-based envelop demodulation for rolling element bearing fault feature extraction from vibration signals. *J Mech Eng Sci* 2016; 230: 3194–3211.
11. Zheng DZ, Wang LQ, Gu L, et al. High speed rolling bearing cage rotate. *Proc. SPIE Int Soc Opt Eng* 2012; 8417.
12. Yin F. A new method for the test of high speed bearing skid of aero engine. *Meas Control Technol* 1994; 13: 22–24.
13. Xu C, Li M, Jing MQ, et al. Measurement of lubricant film thickness of cylindrical roller bearing using ultrasound. *J Xi'an Jiaotong Univ* 2015; 49: 61–66.
14. Li M, Liu H, Xu C, et al. Ultrasonic measurement of cylindrical roller bearing lubrication using high pulse repletion rates. *ASME J Tribol* 2015; 137.
15. Dwyer-Joyce RS, Drinkwater BW and Donohoe CJ. The measurement of lubricant film thickness using ultrasound. *Proc Roy Soc Lond Ser A* 2003; 459: 957–976.
16. Drinkwater B, Dwyer-Joyce R and Cawley P. A study of the interaction between ultrasound and a partially contacting solid–solid interface. *Proc Roy Soc Lond Ser A* 1996; 452: 2613–2628.
17. Drinkwater B, Dwyer-Joyce R and Cawley P. A study of the transmission of ultrasound across solid–rubber interfaces. *J Acoust Soc Am* 1997; 101: 970–981.
18. Wan Ibrahim MK, Gasni DRS and Dwyer-Joyce RS. Profiling a ball bearing oil film with ultrasonic reflection. *Tribol Trans* 2012; 55: 409–421.
19. Harris TA. *Advanced concepts of bearing technology*. 2nd ed. New York: John Wiley & Sons, Inc., 2006.
20. Lynagh N, Rahnejat H, Ebrahimi M, et al. Bearing induced vibration in precision high speed routing spindles. *Int J Mach Tools Manuf* 2000; 40: 561–577.
21. Vafaei S and Rahnejat H. Indicated repeatable runout with wavelet decomposition (IRR-WD) for effective determination of bearing-induced vibration. *J Sound Vib* 2003; 260: 67–82.

Appendix

Notation

d	displacement between two adjacent rollers
d_m	pitch circle diameter
d_w	roller diameter
v	speed of bearing,
v_c	cage speed
f_s	repetition frequency
N	the number of times the second echo, which is received in the interval between two adjacent rollers