Study on Measurement of Dynamic Performance of Ball Bearing for Auto-tensioner*1

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In this paper, the authors have developed a method for the measurement of dynamic performance of ball bearings using a high-speed camera and image processing. The dynamic performance of a ball bearing used in a car auto-tensioner have been investigated as an example. The positions of the balls of the bearing have been measured using a ring light reflected on the balls. The positions of the cage and outer ring have been measured using the markers set upon them. The reaction between the balls and cage as well as the deformation of the pocket prongs while the bearing rotated were observed. It was found that bearing oscillation had a significant effect on the ball lead and lag as well as the deformation of the pocket prongs. It was also found that the ball lead and lag as well as the deformation of the pocket prongs varied significantly in the non-load zone. It can be assumed that these factors have a significant effect on the fatigue life of the cage.

Key Words: *ball bearing, dynamic performance measurement, deformation of cage, ball lead and lag, slip of ball revolution, auto-tensioner bearing*

1. Introduction

Various engine accessories are used in automobiles and these are driven by the rotational force of the crankshaft transmitted by the accessory belt. **Figure 1** shows the layout of engine accessories. The auto-tensioner serves the purpose of absorbing sudden changes in belt tension and is an essential component in increasing accessory belt reliability and reducing noise[1)]. Meanwhile, enhancing engine output and torque to improve vehicle running performance creates greater rotational speed fluctuation of the crankshaft which drives electronic accessories. Fluctuation in rotational speed causes accessory belt tension to fluctuate also and the auto-tensioner to oscillate[2)]. For this reason, auto-tensioner bearings must be capable of performing in the severe operating conditions of oscillation and load fluctuation (rotational fluctuation).

The bearing comprises of only four components, the inner ring, outer ring, balls and cage, however its motion mechanism is extremely complex. The optimal design of the bearing relies heavily on clarifying the dynamic performance of the balls and cage during rotation, and this has been the subject of research for many long years[3)]. The ball dynamic performances including ball

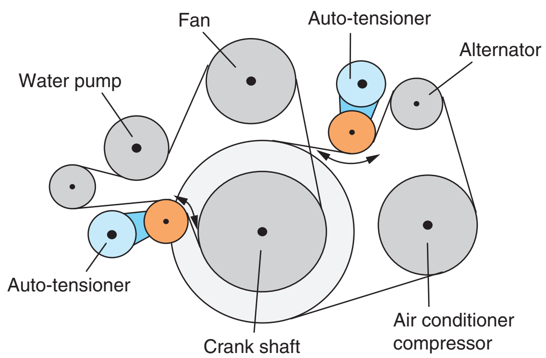

Fig. 1 Example of engine accessory layout

rotation, have been measured through magnetizing the ball and using coils or hall elements[4)-6)]. The balls revolution measurement has been carried out using a high-speed camera[7)]. The dynamic performance of the cage has been also measured using proximity sensors[8)-10)]. However, these methods only measured the performance of either the balls or cage in isolation and did not make it possible to ascertain the motion of the balls and cage in relation to each other. The force acting on the cage is created as a result of the relative motion of the balls and cage therefore, in order to consider the reason for stress acting on the cage, it is important that the relative motion of the balls and cage be ascertained. It has been suggested that the stress that acts on a cage can be measured

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by rotating the inner ring and outer ring in opposite directions, stopping the rotation of the cage and attaching a strain gauge to the cage[11], however this differs to the actual operating environment in several ways, including no centrifugal force being placed on the ball. Another method that has been suggested for many years is to attach a strain gauge to the cage, and receive signals from the strain gauge through a slip ring[12)-14)]. However, this method meant it was also difficult to recreate the actual operating environment due to concerns of the effect of noise and rotational speed limitations. In this research, a high-speed camera and image processing were used to establish a measurement technology to visualize the dynamic performance of a ball bearing during rotation. The example of a ball bearing for an auto-tensioner used in a car accessory belt was used to observe the change in ball bearing dynamic performance over time and the effect of bearing oscillation. The motion of the balls relative to the cage (the ball lead and lag) and the deformation of the cage pocket prongs, which is used to estimate the stress acting on the cage, have been measured quantitatively.

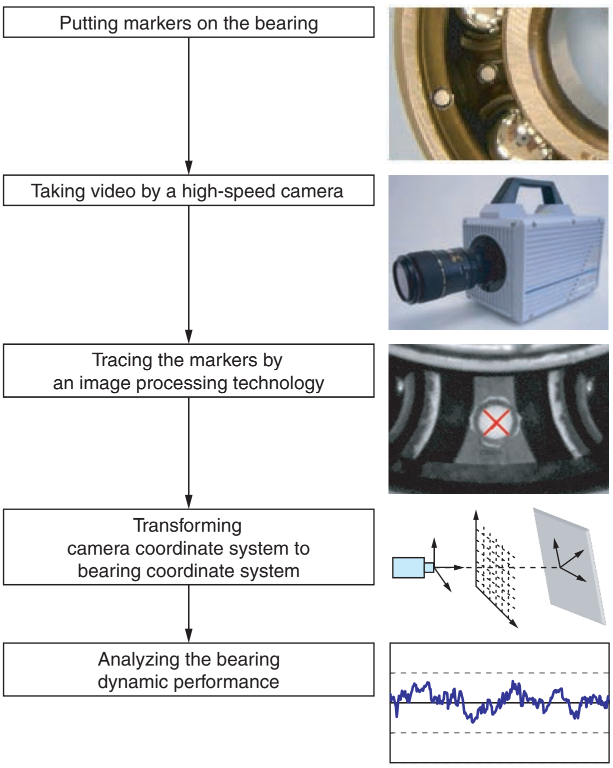

Fig. 2 Measurement process of bearing dynamic performance

2. Measurement Methods and Conditions

2. 1 Measurement Process

Figure 2 shows the process used to measure the dynamic performance of a ball bearing. Markers are placed on the outer ring and cage, the dynamic performance of the bearing during rotation is captured using a high-speed camera and the markers placed on the outer ring and cage are tracked using image processing. The marker positions obtained through tracking are expressed by camera coordinates (whereby the horizontal and vertical directions of the image have been established as the X axis and Y axis, unit: pixels), then this is converted into coordinates where the X axis and Y axis have been taken on the bearing radial plane (bearing coordinates, unit: mm). The bearing coordinates will be fixed and therefore not subject to change due to bearing rotation. The dynamic performance of the ball bearing during rotation is observed from the relative positions of the markers after the aforementioned conversion had been made.

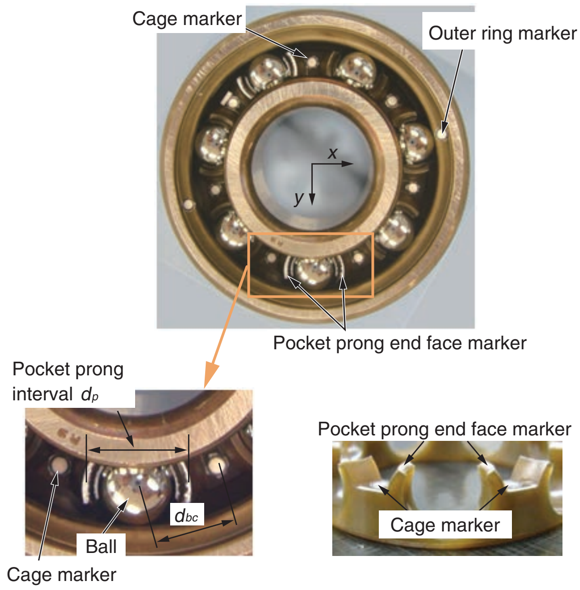

Fig. 3 Markers on sample bearing

2. 2 Measurement Method

Figure 3 shows the bearing used in the measurement. A circular marker is attached to the outer ring and cage in order to calculate rotational speed. Moreover, the change in the interval between the marker attached to the cage pillar and balls (d_{bc}) was used to calculate the motion of the balls relative to the cage. Pocket prong deformation is measured by putting markers on the end faces of the cage's pocket prong and observing the change in the prong end face interval (d_p). Placing markers on the outer ring and cage does not affect bearing dynamic performance however the ball dynamic performance would be affected if the same marker was used on the balls. Consequently, an original approach of measurement based on the reflection of a ring-shaped light was established in order to calculate ball positions. As shown in **Fig. 4**, a ring-shaped light was used and the camera and light were set up on the central axis in a coaxial direction. As a result, the reflection of the ring-shaped light (light ring) appears close to the center of all ball positions. This is shown in **Fig. 5**. As **Fig. 6** (a) shows, the spot light cannot be positioned symmetrical to the bearing center, therefore the light reflecting from the ball appears closer to the position where the spot light is located. Therefore, if the ball revolves, the reflective light moves in relation to the ball and it becomes difficult to calculate the ball position from the reflective light. By using a ring-shaped light as shown in **Fig. 6** (b), the light ring will appear symmetrical to the bearing center regardless of ball revolution. By tracking the positional change of this light ring, it is possible to determine ball positions. However, in reality, it is difficult to capture images by positioning a camera, ring-shaped light and bearing on the same axis and, in the case of the subject of measurement for this paper, i.e., the auto-tensioner bearing, oscillation is also a factor and it is extremely difficult to align the centers of the camera and light with the center of the bearing, then maintain this state. In order to solve this problem, the below correction method has been devised. **Figure 7** shows the process for determining ball positions while **Fig. 8** shows the concept of ball position correction. First, the center coordinates (the circle center of light rings, C_1) were calculated by circle approximation using all ball light ring centers R_1, R_2, … R_z (where z = No. of balls). Next, the center of the bearing (inner ring) was calculated as C_2 and the difference between C_1 and C_2 was calculated. This difference is considered to be the amount, the center of ring light needs to be displaced relative to the bearing center. Therefore the corrected positions for each ball, B_1, B_2, … B_z, were calculated.

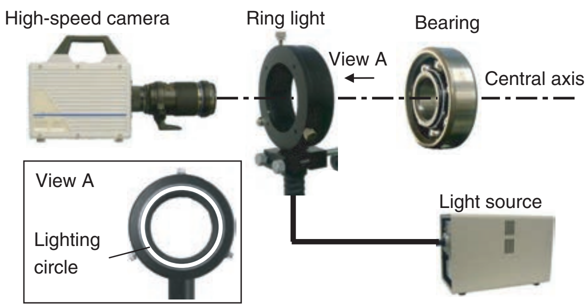

Fig. 4 Measurement system

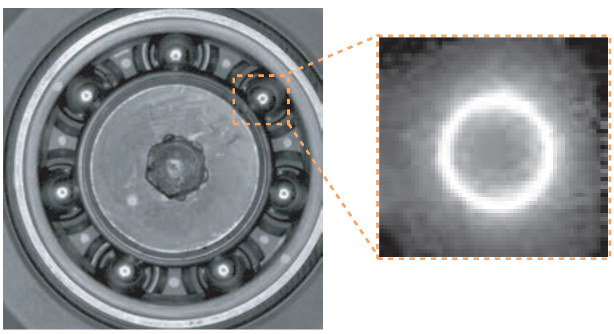

Fig. 5 Ring-shaped light reflected on balls

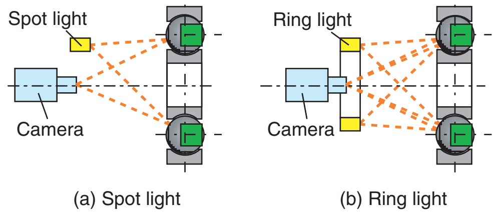

Fig. 6 Difference between spot light and ring light

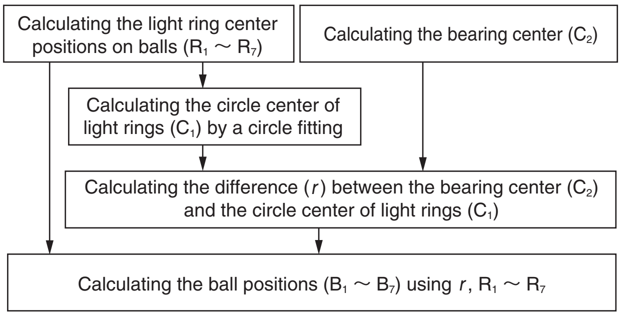

Fig. 7 Process for determining ball positions

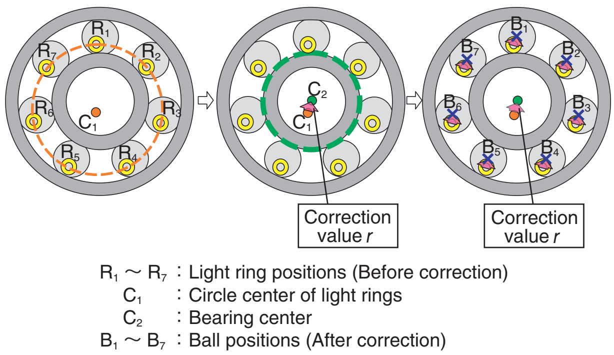

Fig. 8 Concept of correction of ball positions

2. 3 Measurement Conditions

As shown in **Table 1**, if the photographing resolution of the high-speed camera used in this research is 1 024×1 024 pixels, the maximum filming speed is 5 400 frames/s. The specifications of the sampling bearing are shown in **Table 2**. As a result of determining the filming range with consideration to the bearing O.D. of 52mm and auto-tensioner's oscillation, the resolution of the photographed image was approximately 0.06mm/pixel. The shutter speed of the high-speed camera was set at 1/41 000s so that the marker exposed to the image sensor would move less than the resolution of the photographed image. The configuration of the device used in this research allows a bearing revolution speed of 1 800 min^{-1}.

In order to verify the effectiveness of the ball position correction method while the centers of the camera, light and bearing were displaced away from the same axis, an experiment was conducted to confirm the measurement accuracy in advance by using an XY axis stage. This experiment system is shown in **Fig. 9**. The relative positions of each bearing component do not change, therefore the change in relative position of each component when the XY axis stage moved was considered measurement error. The XY axis stage was moved 10mm therefore it would be greater than the maximum displacement after considering the central axis displacement due to displacement when the camera, light and bearing are set up, in addition to oscillation. A dynamic performance measurement was performed using an experimental device which simulated the actual operating environment of an auto-tensioner. **Figure 10** is a schematic diagram of the experiment device and the auto-tensioner as a major component. The belt is looped on a drive pulley and an idler pulley and the auto-tensioner pulley pushes the belt via a spring, which in turn applies a fixed tension on the belt. The rotation of the drive pulley passes via the belt to rotate the bearing's outer ring, which is attached to the auto-tensioner pulley. By causing the rotation of the drive pulley to fluctuate, the belt tension was changed and the auto-tension oscillation reproduced. The bearing is subjected to a load from the belt via the pulley. As shown in **Fig. 10**, the direction receiving the belt load was made the datum (0 degree) and the bearing rotating direction was considered the forward direction, while the ball rotating direction was made ϕ. The main experimental conditions are shown in **Table 3**. The difference in performance depending on the presence/absence of oscillation was also considered by measuring a state without auto-tensioner oscillation while not creating drive pulley rotational fluctuation.

Table 1 Photographing conditions of experiments

High-speed camera	Maximum photographing speed, frame/s	675 000
	Maximum shutter speed, s	1/2 700 000
	Photographing resolution, pixel	1 024×1 024
	Image scale, mm/pixel	About 0.06
Ring Light	Output power, W	250

Table 2 Specifications of sample bearing

Bearing number	6304
Outer size, mm	52
Cage material	Plastic
Number of balls, *z*	7

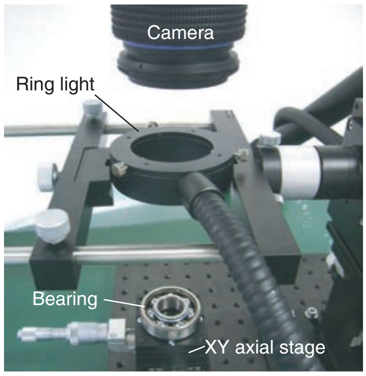

Fig. 9 Appearance of experimental system

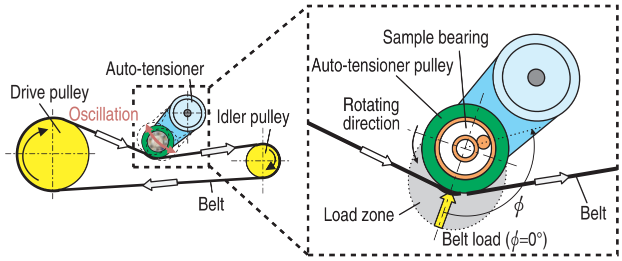

Fig. 10 Schematic diagram of auto-tensioner

Table 3 Experimental conditions

Drive pulley rotating with oscillation	Yes, No
Initial tension of belt, N	900
Revolution speed of sample bearing, min^{-1}	1 800
Photographing speed, frame/s	5 400
Photographing shutter speed, s	1/41 000

3. Experiment Results and Observations

3. 1 Measurement Accuracy

Figure 11 shows the measurement error for the pocket prong interval which expresses the amount of cage pocket prong deformation, while **Table 4** shows the measurement error for the interval between the ball and the cage marker, which is an indication of the lead and lag of the ball in relation to the cage. As can be seen from **Fig. 11**, even if the XY axis stage carrying the bearing is moved 10mm, the maximum measurement error for the pocket prong interval was around 7 μm and the maximum measurement error for the interval between the ball and the cage marker was around 21 μm. This equates to around 3.9% of the pocket prong's maximum deformation (180 μm). It also equates to around 7.4% of the maximum clearance between the ball and the pocket (285 μm). The subjects of measurement for the purpose of this research, namely the cage pocket prong deformation and the lead and lag of the ball relative to the cage are relative values calculated from the distances between two points within the bearing, therefore are not affected by oscillation of the bearing overall or camera vibration. Consequently, it is feasible that the measurement error for a bearing during rotation is equal to the results of this experiment. This demonstrates that the measurement method used in this research is sufficiently accurate.

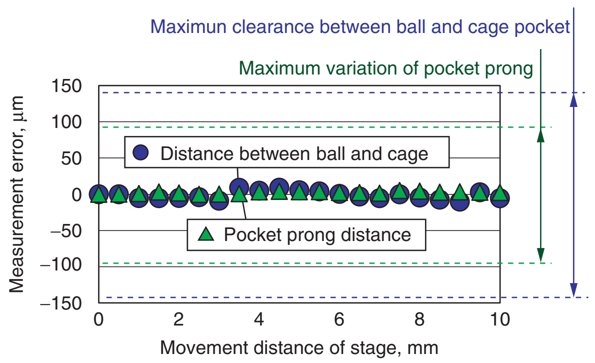

Fig. 11 Confirmation of measurement accuracy

Table 4 Results of measurement accuracy

Item	Pocket prong interval	Distance between ball and cage marker
Maximum measurement error, mm	0.007	0.021
Maximum variation of pocket tongue interval, mm	0.18	–
Maximum clearance between ball and cage pocket, mm	–	0.285
Error percentage, %	3.9	7.4

3. 2 Ball Revolution Slip

Figure 12 shows one example of the rotational speeds of the outer ring and cage due to fluctuation in drive pulley rotation, and the revolution speed of the ball. **Figure 12** represents two revolutions of the ball. Furthermore, the ball revolution speed is shown for only one of the seven balls, while the cage rotational speed is an average calculated from the seven markers place at equal intervals. **Figure 12** shows that, in contrast to the outer ring rotational speed, which is synchronized with the drive pulley rotational speed and changes with each revolution, the cage rotational speed and ball revolution speed fluctuate in sync with outer ring rotational speed however because the ball revolution speed does not change evenly it is predicted that the ball is slipping relative to the outer ring.

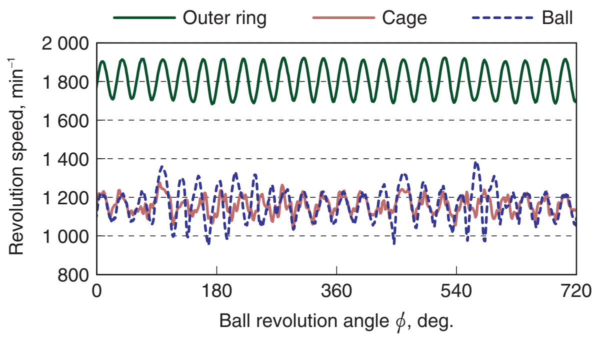

Fig. 12 Rotational speed of outer ring and cage, revolution speed of ball

3. 3 Ball Lead and Lag

It can be ascertained from **Fig. 12** that there is a difference in the rotational speed of the cage and the revolution speed of the ball. This means there is lead and lag of the ball relative to the cage. **Figure 13** shows one example of the ball lead and lag relative to the cage. The median of the distance between the ball and cage marker was made the point where there is neither lead nor lag. If the ball lead and lag is a positive value, the ball moves in front of the rotational direction relative to the cage, or in other words, takes the lead. **Figure 13** shows that in a non-load zone, the ball lead and lag is repeated and the ball moves vigorously within the pocket. This is considered to be due to the bond between the balls created by the inner ring and outer ring being weaker in the non-load zone, therefore making the balls susceptible to bearing oscillation. Meanwhile, it can be seen that the ball lead and lag changes slowly in load zones.

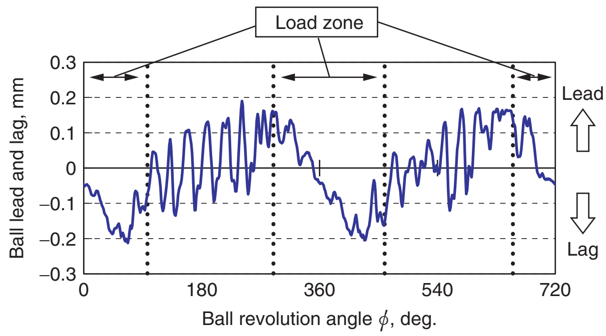

Fig. 13 Ball lead and lag (With oscillation)

3. 4 Deformation of Cage Pocket

Figure 14 provides one example of measuring the deformation of the pocket prong. The median of the pocket prong intervals was considered as having zero deformation. A positive value means that the pocket prong is deforming in the direction that the prong opens. It can be seen from **Fig. 14** that, at most, pocket prong deformation is around 0.18mm. It is also obvious that pocket prongs deform frequently in non-load zones. This is predicted to be due to the ball colliding with the pocket wall in non-load zones which can easily result in fatigue failure of the cage. While the change is not as frequent in load zones as it is in non-load zones, the maximum deformation is equivalent. The stress acting on the pocket can be predicted from pocket deformation and this is considered to contribute to elucidation of the cage failure mechanisms and optimal design.

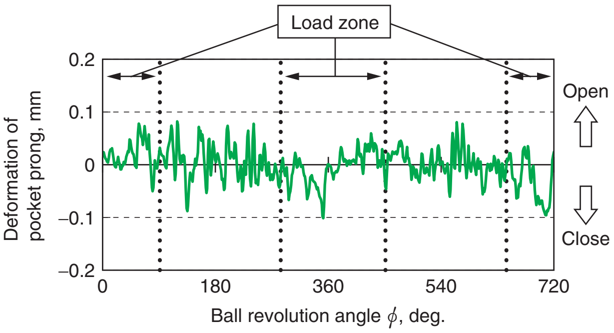

Fig. 14 Deformation of pocket prong (With oscillation)

3. 5 Effect of Bearing Oscillation

The rotational fluctuation of the drive pulley passes through the belt and pulley to be transmitted to the bearing outer ring and this causes the bearing to oscillate as it rotates. **Figure 15** shows one example of measuring the trajectory of the bearing center (inner ring center). The coordinate origin was made the average position of the bearing center trajectory. Bearing oscillates repeatedly while tracing an oval path in the opposite direction to outer ring rotation. It is considered that this movement causes inertia to work on the balls and cage, and affect the ball lead and lag and cage deformation. The frequency of the oval movement is consistent with the rotational fluctuation frequency of the drive pulley. In order to consider the difference in the ball lead and lag depending on the presence/absence of bearing oscillation, **Fig. 16** shows the ball lead and lag when there is no rotational fluctuation, therefore no bearing oscillation. This shows that, compared to cases such as **Fig. 13** when there is bearing oscillation, the change in the ball lead and lag is slower. This demonstrates that bearing oscillation has a significant effect on the ball lead and lag. **Figure 17** shows the pocket prong deformation when there is no bearing oscillation. It can be seen from **Fig. 17** that, compared to cases such as **Fig. 14** with bearing oscillation, no oscillation means that the pocket prong deformation is extremely small, with the maximum amount being under 0.04mm. Therefore, it is clear that bearing oscillation has a significant effect on the pocket deformation.

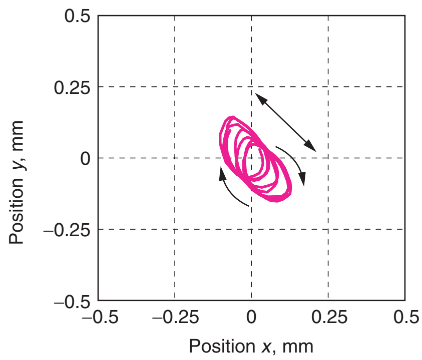

Fig. 15 Movement of bearing center

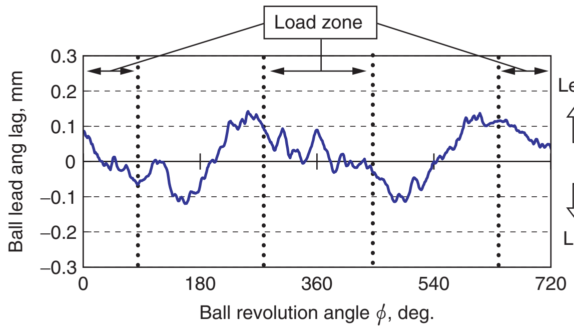

Fig. 16 Ball lead and lag (Without oscillation)

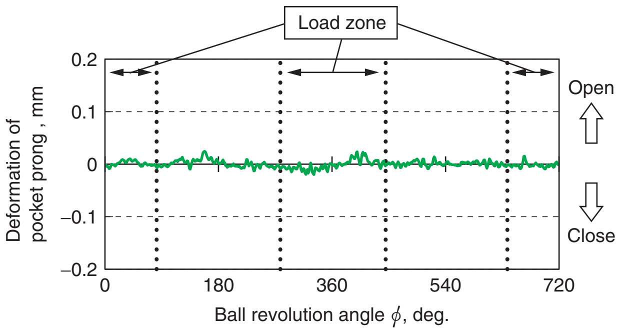

Fig. 17 Deformation of pocket prong (Without oscillation)

4. Conclusion

This research has established a method to measure the dynamic performance of a ball bearing by utilizing a high-speed camera and image processing. Below are the results obtained by using this method to examine a ball bearing for auto-tensioner used in a car accessory belt to consider the change over time of bearing dynamic performance.

(1) By utilizing the reflective light from the balls, it was possible to measure the position of balls during rotation, which was previously difficult to achieve with conventional measurement techniques.

(2) By tracking the positional fluctuation of the ball and outer ring markers, it was possible to measure the changes over time in ball revolution speed and outer ring rotational speed. In turn, this made it possible to observe the slip of balls relative to the outer ring quantitatively. If this measurement method is applied to inner ring rotation, it would be possible to observe the slip of balls relative to the inner ring quantitatively.

(3) By measuring the relative distance between the ball and cage, it was possible to observe the lead and lag of balls quantitatively, which reflects the ball movement relative to the cage. An experiment showed notable difference between movement trends in load zones versus non-load zones. The bearing oscillation has more effect in non-load zones, causing the lead and lag of balls to change frequently. This is considered to affect the cage fatigue failure.

(4) Deformation of the cage pocket prong was calculated by measuring the change in intervals between pocket prongs. Therefore, it became possible to predict the stress acting on a pocket from pocket prong deformation. This is consdered to contribute to elucidation of the cage failure mechanisms and optimal design.

(5) Bearing oscillation caused by rotational fluctuation of the drive pulley has a significant effect on the bearing dynamic performance. With oscillation, the deformation of the cage pocket prong increases significantly. In addition, there is greater change in the lead and lag of balls relative to the cage.

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