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Experimental study on dynamic behavior of ball bearing cage in cryogenic environments, Part II: Effects of cage mass imbalance

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ABSTRACT

We studied the dynamic behavior of a ball bearing cage submersed in a cryogenic fluid and rotating at high speed as a function of the mass imbalance of the cage under various rotational speeds and light load conditions. The results include the whirling motions and distribution of whirling frequencies of the cage, the ball bearing torque, and the wear loss of the ball bearing elements for varying rotational speeds and mass imbalance conditions. The whirling motion of the cage tended to increase with the increase of the mass imbalance, and the influence of the mass imbalance was apparent with the increase of inner race speed. For all mass imbalance conditions, the whirling amplitude decreased with the increase of the inner race speed owing to the influence of the hydraulic force of liquid nitrogen. In addition, the standard deviation of the whirling frequency of the cage increased with the increase of the inner race speed. In particular, when the inner race rotational speed was 11,000 rpm, the standard deviation tended to increase markedly with increasing mass imbalance. The wear loss of the cage increased with the increase of the mass imbalance, and the wear loss at the bottom part of the cage increased owing to an abnormal motion caused by intermittent collision of the cage. The experimental results obtained under various mass imbalance conditions are consistent with existing interpretive literature and demonstrate the importance of the mass imbalance of the cage.

1. Introduction

Owing to the advancement of the manufacturing industry, there is a growing demand for rotary machines capable of operating in various environments and at a wide range of speeds. The dynamic behavior and reliability of the ball bearing supporting the rotating shaft are important factors affecting the overall performance and lifetime of the entire rotating system. Especially, in special environments such as liquid rocket oxidizer pumps, the use of oil and grease is not possible owing to the low operating environments and limited conditions. Thus, the polytetrafluoroethylene (PTFE) cage, which acts as a solid lubricant, is the only lubricating method that facilitates the interaction between the ball bearing elements. Abrasive particles generated mainly by the collision between the ball bearing elements (balls and races, etc.) and the cage are transmitted to the ball and race to aid smooth operation of the ball bearing. However, if excessive wear occurs, the strength of the cage may be reduced, resulting in the destruction of the cage structure. In addition, the change in cage shape due to abnormal wear reduces the performance of the ball bearing owing to the clearance change in the relationship between the ball

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bearing elements and the cage. On the other hand, unlike general lubrication methods (grease, oil, etc.), when the cage is used as a solid lubricant, the lubrication characteristics of the material as well as the dynamic behavior of the cage can be important factors in determining the performance of the ball bearing. Furthermore, the asymmetry of the circumferential mass due to partial wear caused by intermittent collision with the residual mass imbalance of the cage can reduce the lifetime and performance of the ball bearing by increasing the centrifugal force of the cage, which rotates at high speed. Therefore, in the case of ball bearings using a cage as a solid lubricant, the life of the cage can be directly linked to the life of the ball bearing.

Walters [1] performed a dynamic analysis of high-speed ball bearings for each element by using the fourth-order Runge-Kutta method. The analysis was performed for different contact conditions between the ball and the cage. The results of the analysis were compared with the test data obtained by describing the behavior of relative motion using constraints for each contact element. Kannel and Bupara [2] reported that the viscosity and quality of the oil used as lubricant directly affected the movement of the cage. Moreover, they explained that the unstable cage motion could be attributed to the friction between the rolling elements and the cage. They pointed out that unstable motion could increase with the increase in cage guidance and ball pocket clearance.

Park et al. [3] introduced the minimum variance cepstrum (MVC) to detect the breakage of ball bearings in order to observe periodic impulse signals in noisy environments, such as very small signals occurring at initial failure. The experimental results indicated that MVC can consistently provide fault information in the form of the fault period without considering frequency-spectrum changes due to system and measurement conditions such as vehicle type, change of other parts near bearings, error location, and measurement location. Thus, the results of the study demonstrate that MVC determines the bearing failure time more clearly than other methods under given conditions. William et al. [4] analyzed the faults of bearings by using zero crossing (ZC) characteristics to detect and identify single-point bearing defects on rotating machines early, since the ZC feature is extracted directly from the time-domain oscillation signal using only the duration between consecutive ZC intervals. In this method, the rotation frequency need not be estimated. The results have shown that training neural networks using features extracted from events with greater fault severity is more advantageous in detecting small and large bearing defects. In addition, it has been confirmed that ZC features combined with an artificial neural network (ANN) can exhibit high classification performance and low false alarms in all classes. Karacay and Akturk [5] studied the local defects of ball bearings using the peak-to-peak value, RMS, crest factor, and kurtosis. They confirmed that the magnitude and severity of vibration increase as the number of defects increases, but it has been experimentally proven that no correlation exists between the severity of the defect and the amplitude of vibration. Therefore, spectral analysis was used to predict the defect location, since the characteristics of the vibration are partially dependent on the system. They have successfully analyzed the local defects of ball bearings in systems with poor alignment and confirmed them by microscopic photographs at the end of the experiment. The results of these experiments emphasize the practical applicability of statistical and spectral analysis. Sathtan et al. [6] experimentally investigated the ball bearing torque and failure behavior of cages with different pocket designs. A rectangular-pocket cage exhibited more stable performance with marginal lubrication under extreme temperature conditions, whereas a circular-pocket cage showed a lower frictional torque compared to that of the rectangular-pocket cage under excessive lubrication. On the other hand, a double-step rectangular-pocket cage showed the most stable overall performance under minimal lubrication at extreme temperatures. Nosaka et al. [7] evaluated the performance of ball bearings for different cage pocket designs in a cryogenic environment for a liquid-hydrogen rocket turbopump. The shapes of the cage pocket were circular and elliptical. The cage with the elliptical pocket exhibited better performance in the cryogenic environment, but the elliptical pocket could be cooled adequately by increasing the amount of cryogenic coolant, provided the pocket was larger. These factors allowed for the transfer of a durable PTFE film between the cage and the balls and raceways, and increased the load capacity of the bearing.

Halminen et al. [8] introduced two detailed models of backup bearings with and without cages for the dynamic analysis of rotor drop-down events supported by an active magnetic bearing (AMB). The study applied Hertz contact theory to the dissipation of force in the modeling of forces, uses nonlinear friction for tangential forces, and applies a multibody system approach to solve the equations of motion. The authors noted that, generally, ball bearings are damaged frequently owing to the failure of the cage. In addition, the performance of the bearing was improved by changing the characteristics of the cage including the ball-cage clearance, inertia, and stiffness/damping characteristics. Komba et al. [9] investigated the performance degradation characteristics of ball bearings with large vibrations simultaneously under high loads in both greased and ungreased conditions. The ungreased bearings exhibited deterioration caused by wear on the contact pair and had a low lifetime. In addition, SEM analysis showed that torque and relative displacement during wear stages are more complicated in ungreased bearings than in greased bearings. Conversely, grease protects against excessive damage to the bearing contact surface, which significantly increases bearing life. The protection offered by grease demonstrates that the deterioration of high-load vibration bearings is due to the ball, which is highly affected by plastic deformation. From these experimental results, the authors suggested the steps of surface deterioration of bearings that are not formed with oil film. Niu et al. [10] proposed a dynamic model with six degrees of freedom (DOFs) for investigating the dynamic and vibration response of angular-contact ball bearings with ball defects. The study showed that the probability of a ball hitting the race depends on the initial position of the defects on the race and the complex behavior of the ball. In addition, when the bearings are subjected to axial and radial loads, the frequency response of the envelope spectrum is much more complex than that of deep-groove ball bearings loaded by pure axial loads. Tandon et al. [11] compared condition monitoring techniques for the detection of a defect in the outer race of a ball bearing. Measurements were performed using various monitoring meth-