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Experimental study on dynamic behavior of ball bearing cage in cryogenic environments, Part I: Effects of cage guidance and pocket clearances

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In cryogenic environments, it is not possible to apply oil or grease to ball bearings, owing to the extreme temperature conditions. Thus, polytetrafluoroethylene (PTFE) cages are used as solid lubricants in such environments, because PTFE has a low coefficient of friction. PTFE cages increase the rotational stability of the ball bearings by reducing the frictional force of the rolling elements. In addition, design parameters such as the cage guidance and ball-pocket clearances significantly affect the stability of the ball bearings. In this study, the dynamic behavior of a ball bearing cage submerged in a cryogenic fluid was investigated for different cage clearances and rotation speeds. For experimental verification, a test rig was designed to realize a cryogenic environment. The test rig could be driven to 11,000 rpm using a DC motor and provided loads of up to 20 kN using a pneumatic cylinder. A metal ring was employed to measure the cage whirling amplitude using a fiber optic displacement sensor. The parameters considered included the cage whirling amplitude, ball bearing torque, and cage wear. The effects of the clearances and rotation speed on the cage stability and performance were analyzed using the probability density function of the cage whirling frequency, and the standard deviation of this function decreased as the outer guidance clearance decreased. In addition, the cage wear loss increased with decreasing cage ball-pocket clearance, owing to the collisions between the balls and cage pocket. The experimental results agreed partially with the existing theory and demonstrated that the cage instability increased as the cage guidance clearance increased.

1. Introduction

Rolling elements such as ball bearings play important roles in supporting rotating shafts. Thus, the stability of the ball bearings should be strictly maintained to ensure the adequate performance of the entire rotating systems in which they are utilized. In particular, the ball bearings used in turbo–pumps in space launch vehicles or in liquefied natural gas pumps are constantly exposed to cryogenic conditions (i.e., temperatures lower than −183 °C). Therefore, the ball bearings should be designed to ensure stable operation in such extreme environments. In general, it is not possible to apply oil or grease to the ball bearings in cryogenic environments due to the extreme temperature conditions. Instead, under such severe

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Nomenclature

a	minimum range of a function [–]
b	maximum range of a function [–]
B_c	cage width [mm]
B_r	race width [mm]
C_{dg}	outer guidance clearance of the cage [mm]
C_{di}	inner diameter of the cage [mm]
C_{do}	outer diameter of the cage [mm]
C_{db}	ball–pocket clearance of the cage [mm]
D_b	ball diameter [mm]
D_i	inner race bore diameter [mm]
D_o	outer race outside diameter [mm]
D_p	cage pocket diameter [mm]
d_i	inner race shoulder diameter [mm]
d_m	ball bearing pitch diameter [mm]
d_o	outer race shoulder diameter [mm]
$f(x)$	probability density function of x [–]
X	random variable [–]
Z	number of balls [–]
α^o	free contact angle of ball bearing [degrees]
ω_c	rotating frequency of the cage [Hz]
ω_I	inner race rotating frequency [Hz]

conditions, a cage is used with the ball bearings, acting as a self-lubricant in the absence of other lubrication systems. Generally, polytetrafluoroethylene (PTFE) cages are employed as solid lubricants, since PTFE has a small coefficient of friction [1]. Furthermore, the cage design directly influences the performance of the cryogenic ball bearings. In fact, such cages commonly fail in cryogenic environments. Therefore, ensuring cage stability is essential to achieve stable driving of the ball bearings.

Kingsbury [2,3] proved analytically that the torque fluctuations are related to the cage whirling motion and demonstrated this dependence experimentally. The experimental results showed that the frequency of the radial cage motion increased as the cage whirling motion increased. Kannel and Snediker [4] suggested that cage instability increases cage wear owing to momentary changes in torque and force that increase the possibility of cage damage and is a major cause of ball bearing failure. Furthermore, Merriman and Kannel [5,6] performed stability analysis of various cage shapes using the lubricant film theory in a cryogenic environment by employing a dynamic simulation program. They noted that the thickness of the lubricant film between the ball and race, as well as the cage guide clearance and cage imbalance, significantly impacted the cage stability.

Klein et al. [7] suggested a different solution in which image processing techniques are applied to time-frequency or RPM-order representations (TFRs) of the vibration signals in the RPM-order domain in complex machines. After calculating the distance between the TFR of a properly functioning machine and the actual measured TFR, analysis was performed using ridge tracking and other image processing algorithms. As a result, an automatic method of extracting bearing condition indicators was developed and proposed to be effective for detecting damaged bearings. Bourbatache et al. [8] presented a new method of monitoring and diagnosing bearing defects in which the sensitivity of the local electrical properties of the ball bearings is utilized. In addition, a new ball bearing model was proposed based on the discrete element method, which accurately reproduces the mechanical behaviors of ball bearings. The equivalent electrical resistance of ball bearings increased with the angular velocity of the inner race owing to the increase and decrease in the total force on the outer and inner races of the ball bearing. The presence of defects affected all the contact responses of the ball bearings, causing perturbations in the numerical electrical signals. Furthermore, fast Fourier transforms (FFTs) of electrical signals were utilized to determine the defect frequency, which was in good agreement with the theoretical frequency. Dolenc et al. [9] studied the distributed azimuth diagnostic method using vibration analysis and modeled the generated vibration pattern by integrating the geometric imperfections of the bearing components. Comparison of the envelope spectra of the vibration signals confirmed that local defects could be distinguished from distributed defects, and a diagnostic procedure for the detection of dispersion defects was proposed. In conclusion, it was experimentally proven that the features of vibrations in defect-free as well as local and distributed defect conditions enable diagnosis by forming clearly separable clusters. Niu et al. [10] investigated stable cage whirling using ball bearings with an outer race guided cage by performing a dynamic simulation under solid lubrication conditions. In particular, the roles of the cage force and ball spacing characteristics in stable whirling were investigated under stable and unstable conditions. The results showed that cage whirling radius was highly dependent on the ball pocket contact and friction forces. In addition, cage instability occurred under severe slip conditions, and non-uniform spacing between balls was observed under these conditions.