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An investigation on the occurrence of stable cage whirl motions in ball bearings based on dynamic simulations

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ABSTRACT

The occurrence of stable cage whirl in ball bearings with outer ring guided cage under solid lubrication conditions is investigated based on dynamic simulations. The roles of the cage forces in stable whirls and the ball spacing characteristics under stable and unstable conditions are investigated. Results show that the stable whirl motion significantly depends on the ball-cage pocket contact force and the cage-guiding ring forces. Unequal ball spacing is important to the increase of the whirl radius for stable whirl. Furthermore, the ball cannot drive the cage continuously under severe skidding conditions, and thus increase the cage instability.

1. Introduction

Cage is one of the most problematic components in a rolling bearing from the point of view of bearing dynamics [1]. Different dynamic models have been developed to investigate the dynamics of a cage, such as the effects of unbalance [2–5], flexibility [6–8], wear [2–4], clearance [1,7,9,10] and moment load [11].

One of the significant dynamic characteristics of a cage is the cage instability. The cage instability has a great influence on bearing failure and noise. Generally, the stability of a cage can be investigated by its whirl motion characteristics. By now, the most famous model for cage whirl motions was proposed by Kingsbury for explaining the occurrence of cage whirl motions [12,13]. The Kingsbury model can be described briefly as follows. Fig. 1 shows a ball bearing with a fixed outer ring. The cage shown in Fig. 1 is guided by the outer ring, and the ball-cage pocket clearance equals the cage-guiding ring clearance. The inertial frame *Oxyz* is established at the outer ring center (i.e., the bearing center). At a time instant shown in Fig. 1(a), ball 2 and ball 4 contact the cage, and the cage contacts the guiding ring at point *D*. The angle between the z axis and the line connecting the cage center and the guiding ring center (angle α shown in Fig. 1(a)) is π. The friction forces of the cage applied by balls 2 and 4 (F_{cbt_2} and F_{cbt_4} in Fig. 1(a)) push the cage center to move along the positive direction of the y axis. The cage center will then rotate by 90° (see Fig. 1(b)) relative to the original position shown in Fig. 1(a), the cage contacts balls 1 and 3, and the resulting friction forces (F_{cbt_1} and F_{cbt_3} in Fig. 1(b)) push the cage to move along the positive direction of the z axis. In Fig. 1 (b), $\alpha = -\pi/2$. In this fashion, the ball-cage friction forces maintain the cage to whirl, and the whirl radius (r_c) equals half of the cage-guiding ring clearance.

Moreover, Kingsbury defined the following four modes for cage motion [13].

- Whirl mode (or squeal mode). The cage motion is 'pure whirl' when the whirl radius r_c and the whirl speed $\dot{\alpha}$ are both constant, or 'squeal', when r_c and $\dot{\alpha}$ vary irregularly with time. In this mode, $\dot{\alpha}$ is very high compared to the rigid body rotation speed of the cage (ω_c).
- Synchronous whirl. In this model, the whirl speed $\dot{\alpha}$ equals the wheel speed (the wheel speed equals the rotation speed of the inner ring for a bearing with a fixed outer ring and a rotated inner ring.). As discussed in Ref. [13], this mode is insignificant for practical applications as it is developed only at low preloads.
- Stable mode. In this mode, the whirl speed $\dot{\alpha}$ is the same as the cage rotation speed ω_c, and the cage has zero whirl rate relative to its rotation [12].
- Ball-jump mode. In this mode, a ball jumps within the cage pocket. This mode can be classified into six different characteristics. Details can be found in Ref. [13].

The main conclusions of Kingsbury model are [12]:

(1) The driving force for the cage to whirl is the friction force applied by rolling elements ("friction coupling").

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Nomenclature

A, B, C, D	quadrant points
$\mathbf{F}$	force vector
F_a	axial load
F_r	radial load
F_{cbt_1}, F_{cbt_2}, F_{cbt_3}, F_{cbt_4}	friction force of the cage applied by balls 1, 2, 3 and 4
F_{cbt}, F_{cbn}	friction force and contact force at ball-cage pocket described in the inertial frame
F_{cb_yg}	ball-cage pocket contact force of a ball described in the ball-cage pocket-contact frame
F_{crt}, F_{crn}	friction force and contact force at cage-guiding ring described in the inertial frame
F_{cbt_ya}, F_{cbn_ya}	the y_a components of the friction force and contact force at ball-cage pocket which are described in the cage azimuth frame
F_{crt_ya}, F_{crn_ya}	the y_a components of the friction force and contact force at cage-guiding ring which are described in the cage azimuth frame
F_{cbt_za}, F_{cbn_za}	the z_a components of the friction force and contact force at ball-cage pocket which are described in the cage azimuth frame
F_{crt_za}, F_{crn_za}	the z_a components of the friction force and contact force at cage-guiding ring which are described in the cage azimuth frame
F_c	centrifugal force of the cage
J	principal moment of inertia
m	mass of a bearing component
m_c	mass of a cage
$\mathbf{M}$	moment vector
n_b	number of balls in a bearing
r_c	whirl radius
$\ddot{\mathbf{r}}$	acceleration vector
v_c	the norm of the cage translational velocity vector
y, z	axes of the inertial frame
$\dot{y}_a$	the y_a component of the translational velocity of the cage
$\ddot{y}_a$	the y_a component of the translational acceleration of the cage
$\ddot{z}_a$	the z_a component of the translational acceleration of the cage
α	angle between the z axis and the ling connecting the outer ring center and the cage center
$\dot{\alpha}$	whirl speed
μ_∞	traction coefficient (i.e., friction coefficient)
$\dot{\boldsymbol{\omega}}$	angular acceleration vector
ω_b	ball rotation speed
ω_c	rigid body rotation speed of a cage
ω_i	bearing rotation speed
θ_{b1}, θ_{b2}, θ_{b3}, and θ_{b4}	orbit positions of balls 1, 2, 3, and 4, respectively
$\Delta\theta_b$	spacing between balls
$\Delta\omega_c$	instability degree index
$Oxyz$	inertial frame
$O_a x_a y_a z_a$	cage azimuth frame
$O_g x_g y_g z_g$	ball-cage pocket-contact frame

(2) Rolling elements should contact the cage pockets at the right place and at the right time ("geometric coupling").

The Kingsbury model was proposed based on measurements and experimental observations [12,13]. In order to explain the mechanism of the whirl motions observed in experiments, Kingsbury proposed the whirl mechanism model (shown in Fig. 1). As discussed before, the ball-cage pocket friction force was recognized as the main driving force for whirl motions in Kingsbury model. The main reasons can be discussed as follows. First, the ball-cage pocket friction forces shown in Fig. 1(a) and (b) make the cage center translate along the tangential direction of the whirl circle to make the motion of each point on the cage is circular, and the diameter of the circle corresponds to the cage-guiding ring clearance. Second, large ball-cage pocket friction forces usually result in severe squeal. Third, under the action of the ball-cage pocket friction forces, the whirl sense is opposite to the ball rotation, and is the same as the cage rotation when the inner race of the bearing rotates, which was observed in experiments. Moreover, the ball-cage pocket contact force was not mentioned in Kingsbury model. A possible reason is given as follows. As shown in Fig. 1(a), balls 2 and 4 contact the cage pockets, and the corresponding contact forces (these forces are not shown in Fig. 1(a)) are along the positive direction of the z axis, and have the potential for making the cage center translate along the positive direction of the z axis. These show that the contact forces under the condition shown in Fig. 1(a) do not have the potential for making the cage center translate along the whirl circle. Similar characteristics of the contact forces can also be found in Fig. 1(b). The above discussion may be a possible reason why the ball-cage pocket contact force was not considered in Kingsbury model. Indeed, the translation of the cage center is the total effect of the forces acting on the cage, i.e., ball-cage pocket friction and contact forces and cage-guiding ring friction and contact forces. However, only the ball-cage pocket friction force was modeled in the Kingsbury model.

Furthermore, the cage whirl can be classified as stable or unstable. Based on Refs. [1,12,13] it can be found that, under stable conditions, the whirl speed $\dot{\alpha}$ is a constant value (equals the cage rotation speed ω_c), the whirl orbit is regular and the whirl radius is also constant. In this paper, the same definition of stable whirl is used. Moreover, under unstable conditions, the whirl orbit is erratic, and very high frequency whirl motions occur [1]. Depending on the relationship between $\dot{\alpha}$ and ω_c, the whirl motions under "squeal mode", "synchronous whirl" mode, and "ball-jump mode" conditions may be unstable based on this definition.

As the stability of the cage plays an important role in bearing temperature rise, noise and failure, many researchers have investigated the cage whirl characteristics under stable conditions. By now, two important issues on the effect of cage forces on stable whirls have been widely studied [7,8,14–24]. The first one is the driving factors to increase the whirl radius [8,14–19]. Sakaguchi [14,15] pointed out that the cage center turned about the bearing center at the cage rotation speed with a certain whirl radius under stable whirl conditions. The whirl radius of the cage under stable conditions relies on the operating conditions, and the intrinsic reason for the increase of the whirl radius can be attributed to the unequal steady distribution of rolling elements which can provide sufficient excitation forces. It indicates that the rolling element spacing has certain effect on the stable whirl motion. Weinzapfel [8] pointed out that the cage center translates in a circle, and the whirl speed is the same as the rotation speed of the cage under stable conditions. Moreover, as reported in Ref. [8], under stable conditions, the centrifugal force makes the cage maintain its radial position as the cage rotates. Moreover, when the centrifugal force is small and cannot overcome the friction force of the cage, the whirl radius decreases and the constant whirl radius cannot be