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KINEMATIC EQUILIBRIUM OF ROLLERS IN TAPERED ROLLING BEARINGS

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INTRODUCTION

Tapered rolling bearings, commonly used in automotive and industrial applications, are known for their high capacity in load carrying and rigidity. Recent research work on tapered roller bearings has been focusing on the reduction of frictional torque. Therefore, it is interested to understand the slip phenomenon at their contacting surfaces. This will allow determining the friction which generates into heat loss. The roller and cage velocities, ω_C and ω_R, are important parameters in order to determine the slip. Moreover, the skew angle of the rolling element is a significant factor in tapered rolling bearings due to the heat generated from the rib-roller-end contact. Gupta [1] has found that the skew strongly depends on the bearing frictional behavior. Yang et al.[2] have showed experimentally that the skew varies with the applied load, rotational speed, and the lubricant viscosity. Many scholars have proposed analytical approaches in order to determine the cage and roller rotational speeds as well as the skew angle of rollers using quasi-static equilibrium [3, 4].This equilibrium is based on Newton-Raphson numerical method. Although Newton-Raphson method converges rapidly [5]; however, the drawback of this method is based on its difficulty in convergence when the initial values are badly introduced or in other words far from the final values. Moreover, this method can hardly solve for parameters with a large scale.
This work proposes a comprehensive numerical model through kinematic equilibrium analysis of each rolling element in order to predict the cage rotational velocity as well as the rotational velocity and skew angle of each roller in tapered rolling bearings. The kinematic equilibrium is based on Powell's minimization algorithm [6]. This numerical method minimizes the frictional forces acting on each roller as well as the frictional moments about the roller rotational and skew axes of each rolling element in order to predict the cage rotational speed in addition to the skew angle and rotational speed of each rolling element. The sliding and rolling behaviors of the roller are discussed after the kinematic equilibrium. Moreover, the influence of different geometrical parameters, operating conditions, and lubricant properties on the skew movement is studied in this paper.

TAPERED ROLLER BEARING GEOMETRY AND REFERENCE FRAME

A lubricated tapered roller bearing 32006 is considered in this study. Table 1 presents some geometrical properties of the bearing. Under external load, only the inner-race (IR) is displaced; however, the outer-race (OR) is defined to be constant. The bearing is defined in a system (O, e_x, e_y, e_z). O is the bearing center and e_z is along the bearing axis. The reference of each rolling element is defined in its own system (C_r, x,y,z); where C_r is the roller center, z is the roller rotational axis, and x is the skew axis of the roller. Figure 1 presents the reference frames of the bearing and roller.

Geometrical property	Roller number	½ OR angle (°)	½ IR angle (°)	Rib angle (°)	Roller length (mm)	Maximum roller diameter (mm)	Chamfer radius (mm)	Chamfer length (mm)
Value	18	15.996	12.0108	12.525	12.3	6.5	0.4	0.3

Table 1. Geometrical properties of the tapered roller bearing.

FRICTIONAL FORCES AND KINEMATIC EQUILIBRIUM ON EACH ROLLING ELEMENT

The frictional forces acting on each roller element are defined as follows:

- $F_{Ti,o}$: Traction friction forces at the roller and IR/OR contacts
- $F_{FTi,o}$: Traction friction force at the rib and roller end contact at the IR or OR side
- $F_{Ri,o}$: Elastohydrodynamic rolling resistance friction forces at the roller and IR/OR contacts
- $F_{Pi,o}$: Hydrodynamic fluid pressure friction forces at the roller and IR/OR contacts

- F_d: Viscous drag force

Figure 2 shows a schematic representation of the roller with the frictional forces acting on it. Each rolling element is divided into 32 laminae. The frictional forces are calculated on each lamina of the roller.

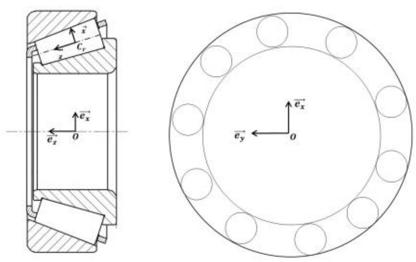

Figure 1. Reference frames of the tapered roller bearing and the rolling element;

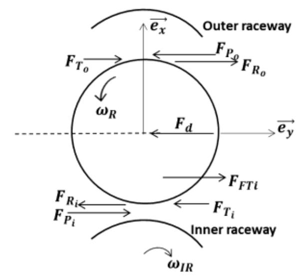

Figure 2. Frictional forces on each roller.

The kinematic equilibrium of each rolling element is attained by minimizing the 3 nonlinear systems defined by the frictional forces acting on each rolling element and the frictional moments about the rotational and skew axes, z and x axes respectively, of each roller. This procedure uses the hybrid numerical method based on Powell minimization algorithm in order to predict the values of the cage rotational speed ω_C, rotational speed of each roller ω_R, and the roller skew angle Θ_{skew}. The Powell minimization algorithm is described by a powerful iterative method that determines a local minimum of a function with multiple variables.

KINEMATIC EQUILIBRIUM RESULTS

It is shown that the Powell minimization numerical solver always converges rapidly due to easily evaluating the first derivative even if the initial approximations are poorly introduced. Figure 3 represents the frictional forces and moments about the roller and skew axes of a rolling element as a function of number of iteration. This shows that the 3 nonlinear systems perfectly converge.

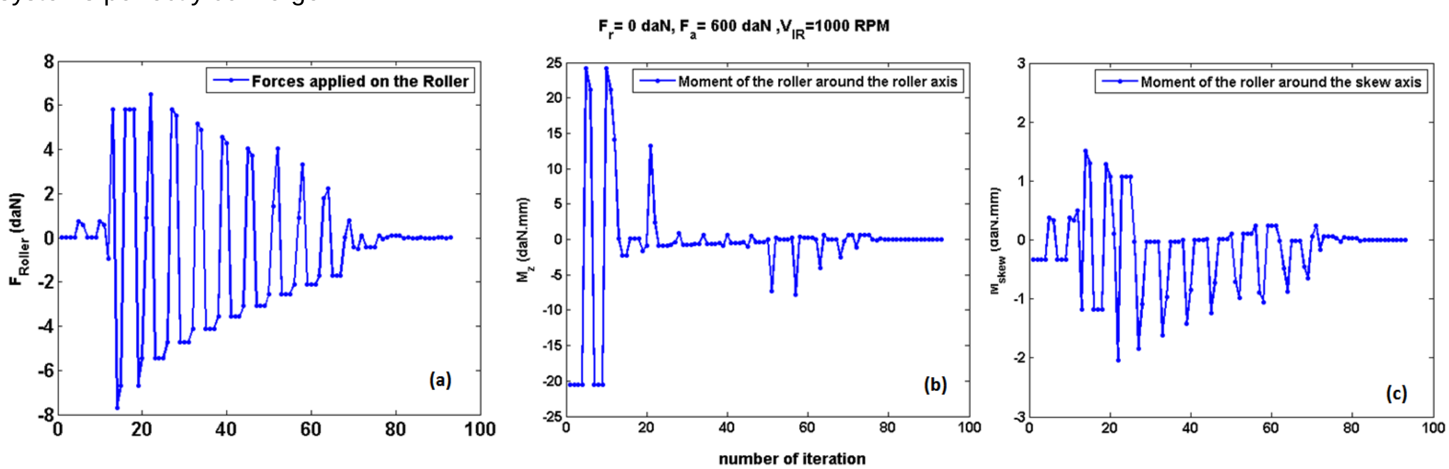

Figure 3. (a)Frictional forces acting on the roller, (b) frictional moments about the roller rotation axis (z-axis), and (c) frictional moments about the roller skew axis (z-axis) as a function of the number of iteration;

It is also noticed that the kinematic equilibrium has a significant effect on the sliding behavior at the roller-inner and outer races contacts. The kinematic equilibrium of the rolling elements results in a decrease in the sliding velocities along the roller. This latter leads to lower the slip-to-roll ratio and thus decreases the friction coefficient at the roller-inner and outer races contacts. Before kinematic equilibrium, pure rolling does not exist. However, after attaining the kinematic equilibrium, there exist at least 2 points (see Figure 4) at the roller-IR and OR contacts, represented as A_{IR}, B_{IR}, A_{OR}, and B_{OR} where the roller is purely rolling without any sliding behavior.

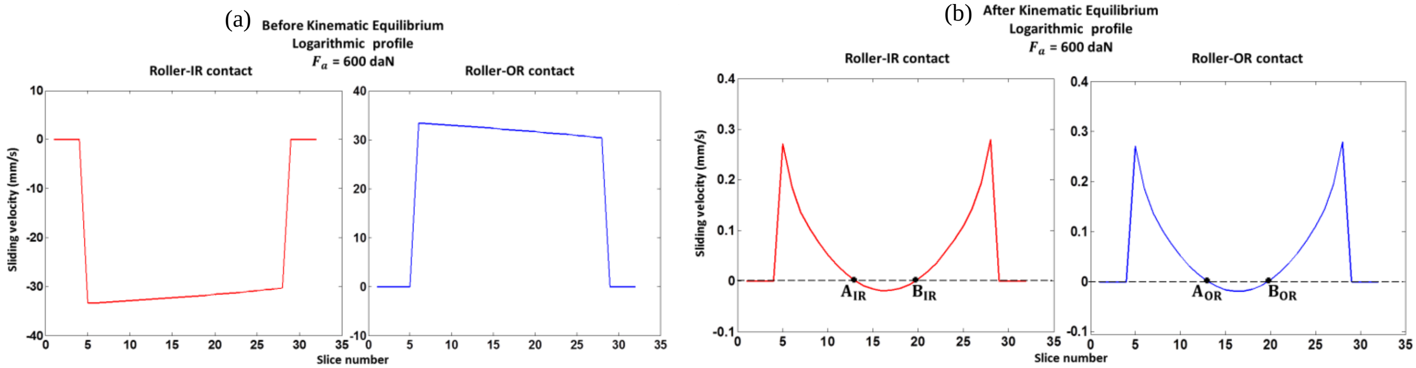

Figure 4. Sliding velocities at roller-IR (in red) and OR (blue) contacts (a) before kinematic equilibrium and (b) after kinematic equilibrium.

INFLUENCE OF SOME PARAMETERS ON THE SKEW

The skew is mainly caused from the friction force at the roller end-rib contact. In our studied tapered roller bearing, the skew angle is calculated with a range between 0.025° and 0.5°. It has been observed that the skew is influenced by some operating conditions as well as the lubricant properties. The skew increases along the roller position for axially and radially loaded bearings; however, the skew is uniformly distributed along the roller for pure axially loaded bearings (see Figure 5(A)). Figure 5(B) represents the skew angle as a function of the inner-raceway rotational speed at 20°C and 60°C. It is shown that the skew increases with the rotational speed and also the skew decreases with the temperature. It can also be concluded from Figure 5(C) that the values of skew angle for grease lubricated bearings is much smaller than that lubricated with oil. These results are qualitatively in good agreement with the experimental measurements of Yang et al. [2, 7] and the numerical results of Nelias et al. [4].

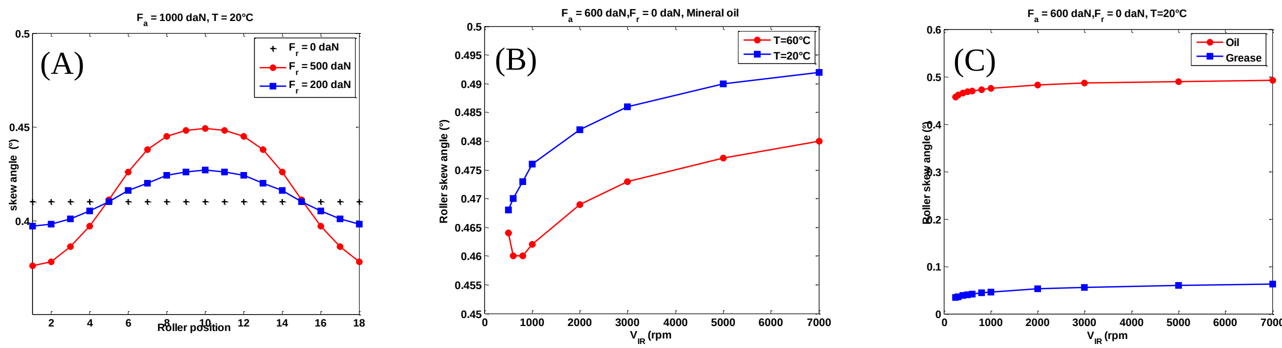

Figure 5. Skew angle as a function of (A) the roller position, (B) of the IR rotational speed at 20° and 60° and (C) of the IR rotational speed for oil and grease lubricated bearings.

ACKNOWLEDGMENTS

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KEYWORDS
Tapered roller bearings, equilibrium, Powell minimization method, sliding, rolling, skew, friction, force, moment.