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Impact of the thermal effect on the load-carrying capacity of a slipper pair for an aviation axial-piston pump

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Abstract A thermal hydraulic model based on the lumped parameter method is presented to analyze the load-carrying capacity of a slipper pair in an aviation axial-piston pump under specified operating conditions. Both theoretical and experimental results are presented to demonstrate the validity of the thermal hydraulic model. The results illustrate that the squeezing force and thermal wedge bearing force are the main factors that affect the film thickness and load-carrying capacity. At high oil temperature and high load pressure, the film thickness decreases with increasing clamping force due to a combined action of the squeezing bearing force and the thermal wedge bearing force, but the load-carrying capacity will increase. An increase of the film thickness is proven to be beneficial under high shaft rotational speed but especially dangerous as it strongly increases the ripple amplitude of the film thickness, which leads to decreasing the load-carrying capacity. The structural parameters of the slipper can be optimized to achieve desired performance, such as the slipper radius ratio and orifice length diameter ratio. To satisfy the requirement of the load-carrying capacity, the slipper radius ratio should be selected from 1.4 to 1.8, and the orifice length diameter ratio should be selected from 4 to 5.

1. Introduction

An aviation axial-piston pump is widely used in an aircraft hydraulic system for supplying hydraulic power to a flight actuator because it has high output pressure, high efficiency, and high reliability. For the development of an axial piston pump with a higher efficiency rate and a simultaneously high service life, an optimal gap design allowing a minimum of friction and volumetric losses in the given parameter range of a

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machine is urgently necessary. A large number of studies have been concerned about optimization gap design,[1] vibration and noise reductions,[2,3] and variable control about axial piston pumps.[4] A slipper pair is one of the key friction pairs, which provides extremely low friction and high positional accuracy, and is often preferred in an aviation axial-piston pump.

In a slipper pair, a fluid film separating the contacting surfaces is maintained by external pressure. The separating film has a high load-carrying capacity and, therefore, does not break down even at extremely low speed during starting, stopping, or changing the direction of rotation. However, an aviation axial-piston pump generates strengthened interactions among thermal, fluid, and structures in the conversion process from mechanical energy to hydraulic energy at high-pressure and high-rotational speed conditions. The strengthened thermal-fluid-structure coupling effect makes the oil viscosity drastically change, the load-carrying capacity drop, lubrication failure, and wear in the slipper pair. Therefore, it is an urgent need to study the load-carrying capacity of the slipper pair.

In the past 40 years, the lubrication performance of a slipper pair in an axial piston pump has been studied from theoretical and experimental aspects. Koc and Hooke[5] experimentally studied the effects of the clamping ratio and orifice size on the performance of slippers. The results showed that the slippers ran satisfactorily with no orifice and had their greatest resistances to tilting couples and minimum film thickness. Kazama and Yamaguchi[6] experimentally examined mixed lubrication characteristics of hydrostatic thrust bearings. They measured the frictional force and leakage flow rate under a lubrication range from mixed to fluid film based on an apparatus featuring circular hydrostatic thrust bearings acting on concentric loads. Harris et al.[7] developed a dynamic model to investigate the dynamic behavior of slipper pads. This model was incorporated into the Computer Aided Pump Performance Analysis (CAPPA) suite of models for use as a part of the simulation package Bathfp, and was used to examine the dynamic stability of slipper pads. It was found that the slipper of an axial piston pump ran heavily tilted for high speeds, and touched both the swash-plate and the retaining plate during a pumping cycle. Borghi et al.[8] investigated the dynamic behavior of a slipper bearing of an axial piston machine. A numerical procedure was used to solve the Reynolds equation with respect to the slipper-swash plate gap. Lu et al.[9] studied the fluid lubrication characteristics and the anti-turnover ability of a three-cavity independent slipper based on a computational fluid dynamics (CFD) model, taking into account the inertia and the surface roughness. Murrenhoff and Scharf[10] studied the influences of the gaps geometry and their tribological characteristics on the total efficiency based on a test rig. Deeken[11] developed a computer tool DSHplus to evaluate the dynamic behavior of an axial piston machine. The hydraulic characteristics and frictions between the key tribo-pairs were analyzed. Canbulut et al.[12] used artificial neural networks to analyze the performance of slipper bearings, which included experimental results and a consideration of the elastohydrostatic problem. Manring et al.[13] experimentally investigated the performance of slippers using different assumed socket geometries at low speed. The results showed that the leakage and capacity were affected by elastic deformation. Nie et al.[14] analyzed the influences of structural parameters and running conditions on the wear behavior for a swash plate/slipper pair of a water pump, and drew conclusions by conducting testing. An analytical solution for the hydrostatic leakage and lift characteristic of slippers with multiple lands was outlined by Bergada and Watton,[15] and another work by Bergada et al.[16] considered tilt but with no tangential speed effect. Kumar et al.[17] described the static and dynamic characteristics of a piston pump slipper with groove. Three-dimensional Navier-Stokes equations in cylindrical coordinates were applied to the grooved slipper/swash plate gap. Ma et al.[18] presented a method on the basis of an elasto hydrodynamic lubrication (EHL) model to analyze the wear behavior of a swash plate/slipper pair. Based on the analysis of film thickness, the associated internal factors affecting the wear behavior were identified by considering comprehensively structural parameters, working conditions, and material properties. Chen et al.[19] developed a computational fluid dynamics (CFD) simulation method based on a 3-D Navier-Stokes equation and the arbitrary Lagrangian-Eulerian (ALE) method to analyze the grooved slipper performance of a piston pump. Farid Ayada et al.[20] performed a parametric study to investigate the effect of the side clearance width on the pump impeller efficiency and head. The pump performance was highlighted through monitoring the changes of the pump head and efficiency. Lin and Hu[21] proposed a tribo-dynamic model of slipper bearings in axial piston pumps. The tribo-dynamic model was produced that considered the fluid–solid coupling to accurately describe the behavior of slippers. The behavior of the slippers was affected by factors such as the pressure field, the slipper profile, the non-uniform gap between the slipper and the swash plate, external forces and motions, and elastic deformation.

In recent years, Kazama[22] investigated the effects of oil physical properties on the thermo-hydrodynamic performance of hybrid thrust bearings and considered various operation conditions. In 2014, the thermo-elasto-hydrodynamic (TEHD) performance of a slipper pair under high pressure and high rotation speed condition was validated using an experimental setup.[23] Meanwhile, the TEHD performance of the slipper pair was studied by solving the Reynolds equation and energy equation using numerical methods. These methods suffered significant limitations, such as wavelet finite element[24] or B-spline wavelet finite element,[25] when advanced fluid-structure coupling and thermal analysis of the slipper pair were discussed. Ivantysynova and Huang[26] analyzed the elastohydrodynamic effect in the gap flow model of a slipper pair. In 2015, a transient TEHD lubrication model for a slipper in an axial piston machine was developed, in which a non-isothermal fluid model, the micro dynamic motion of the slipper, as well as pressure and thermal deformation were considered,[27] and the temperatures at the port and case of the pump were predicted.[28] Hashemi et al.[29] developed a thermal elastohydrodynamics and mixed lubrication model for the sliding interface between a slipper and a swash plate in an axial piston pump. A model for calculation of multibody dynamics incorporating a transient, three-dimensional, thermal elastohydrodynamic pivot pad contact in swash plate axial piston pumps was presented. Xu et al.[30] established a numerical model of the lubrication between a slipper and a swash plate based on kinematic analysis and laminar flow assumption. This model can calculate the dynamic micro-motion, pressure distribution, and leakage of a slipper/swash-plate friction pair, which helps to reveal the principles for carrying ability and partial abrasion. In 2015,[31] they used the numerical model of the lubricating oil film to study the effect of the case drain pressure on the

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