Chinese Journal of Aeronautics, (2016), 29(3): 814–823

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

cja@buaa.edu.cn
www.sciencedirect.com

Performance optimization of grooved slippers for aero hydraulic pumps

Juan Chen [a], Jiming Ma [b,*], Jia Li [c], Yongling Fu [a]

[a] Department of Mechanical Engineering and Automation, Beihang University, Beijing 100191, China
[b] Sino-French Engineer School, Beihang University, Beijing 100191, China
[c] AVIC Xi'an Flight Automatic Control Research Institute, Xi'an 710065, China

Received 31 May 2015; revised 21 August 2015; accepted 12 October 2015
Available online 23 December 2015

KEYWORDS

Arbitrary Lagrangian–Eulerian (ALE);
Computational fluid dynamics (CFD);
Grooved slipper;
Hydraulic pump;
Navier–Stokes equation;
Performance analysis

Abstract A computational fluid dynamics (CFD) simulation method based on 3-D Navier–Stokes equation and Arbitrary Lagrangian–Eulerian (ALE) method is presented to analyze the grooved slipper performance of piston pump. The moving domain of grooved slipper is transformed into a fixed reference domain by the ALE method, which makes it convenient to take the effects of rotate speed, body force, temperature, and oil viscosity into account. A geometric model to express the complex structure, which covers the orifice of piston and slipper, vented groove and the oil film, is constructed. Corresponding to different oil film thicknesses calculated in light of hydrostatic equilibrium theory and boundary conditions, a set of simulations is conducted in COMSOL to analyze the pump characteristics and effects of geometry (groove width and radius, orifice size) on these characteristics. Furthermore, the mechanics and hydraulics analyses are employed to validate the CFD model, and there is an excellent agreement between simulation and analytical results. The simulation results show that the sealing land radius, orifice size and groove width all dramatically affect the slipper behavior, and an optimum tradeoff among these factors is conducive to optimizing the pump design.

1. Introduction

The research on slipper behavior is imperative because the leakage and power loss of piston pumps are largely caused by slipper/swash plate tribological pair. Good performance and reliability of the pump are directly linked with smooth slipper/swash plate running, being necessary to avoid metal to metal contact, excessive film thickness and force/torque acting on the swash plate. Therefore, volumetric and mechanical efficiencies, reliability, durability and lifetime of piston pump will be affected by slipper performance. Some well-known optimization approaches for slipper, such as cutting a pressure balancing groove on the slipper, adding a vented slot across the inner non-sealing land to balance the force on the slipper, narrowing sealing land width, regulating the clamping ratio, and introduction of the orifice in piston, have been proven

* Corresponding author. Tel.: +86 10 82339159.
E-mail address: jiming.ma@buaa.edu.cn (J. Ma).
Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2015.12.021
1000-9361

to be effective to improve the performance of piston pump. While the majority of current researches pay little attention to the effects of the environmental conditions (rotate speed, viscosity, etc.) on some important features (friction, film thickness and tilt torque) related with the volumetric, hydraulic and mechanical efficiencies. Even though the effects of the working conditions are not expected to be very remarkable, the introduction of their effects on performance through complicated mathematical or simulation approach is necessary when aiming to fully understand slipper/swash plate behavior and making a tradeoff between performance and durability.

This paper attaches much importance to the effects of environmental conditions on the pressure distribution, friction, tilt torque and leakage. Compared with traditional experimental methods, numerical computation based on the computational fluid dynamics (CFD) method makes it easier to deeply understand the relationship between performances and running conditions. Moreover, the change of performance could be observed overtly with minor modification on structure and size of the critical components (slipper and piston), which makes it practicable to optimize the pump with minimum power loss and maximum durability.

The piston and slipper assembly used in this paper (Fig. 1) is one of the nine pistons for a piston pump with a maximum volumetric displacement of 9.05 mL/r. The piston pump runs under the rated condition of high pressure (21 MPa) and rotate speed (4000 r/min). It can be seen that the slipper has been designed with a single full sealing land, groove, vented slot, and orifice hole in a hollow piston. The vented slot crossing the non-sealing land is designed to balance the groove and slipper recess pressure. This design is utilized widely by current slipper manufacturer, and some structure parameters, such as sealing land width, groove width and radius, and slot width, influence oil film thickness, friction and leakage directly.

Many publications have been finished in the past 40 years and mainly focused on improving the slipper performance of piston pump through analyzing the leakage, tilt angle, forces and torques on slipper experimentally and analytically.[1,2]

In a research series presented by Hooke, the effects of slipper structure and parameters were deeply analyzed, including degree of non-flatness,[3,4] over-clamped ratio of slippers,[5] and tilting couple acting on slipper.[6,7] Hooke et al. also described the effect of clamping ratio and orifice size on the performance of slippers[8] after the experimental and theoretical investigation. Koc and Hooke[9,10] outlined the design procedure whereby the slipper behavior, minimum film thickness and loss of high pressure fluid can be estimated.

Considering the displacement velocity and tilt, Iboshi and Yamaguchi deduced a set of equations based on the Reynolds equation of lubrication which gave the flow and main moments acting on the single land slippers. They also defined a diagram to check the performance of slipper considering metal to metal contact.[11–13]

Based on the Reynolds equation of lubrication, Kazama and Yamaguchi[14] presented a time-dependent mathematical model for slipper/swash plate under film lubrication condition. The model considered the effects of eccentric and moment loads, supply pressure and rotate speed on the friction, flow rate and power losses. Fang[15] introduced a method to evaluate the lubrication characteristics between the piston and cylinder in a swash plate type axial piston pump-motor under mixed lubrication conditions.

Using the Reynolds equation of lubrication, Tsuta et al.[16] analyzed the slipper dynamics in a piston pump, where the effects of slipper spin, tangential velocity over the pump axis, angular and radial pressure distribution were considered. In view of the complexity of the hydraulics and dynamics of a piston pump, Wieczoreck and Ivantysynova[17,18] developed a package called CASPAR which employed the Reynolds equation of lubrication and the energy equation in differential form.

Deeken[19] analyzed the factors affecting friction by simulation. Manring et al.[20] studied the dynamics of a slipper/swash plate. Brajdic-Mitideri et al.[21] focused on the low friction pad bearing in a two-dimensional Cartesian coordinate system, taking fluid compressibility into account. Houzeaux and Codina[22] presented a numerical strategy for the simulation of a gear pump. Because the two gears of the pump are rotating, the intersection between them changes with time. The problem caused by the changing computational domain is resolved by the ALE method.

Niels and Santos[23] formulated a numerical model based on Reynolds equation to minimize the friction of tilting pad and the results showed that a large amount of energy can be saved using low length to width ratio of the cavity. Analytical solution for slippers with multiple lands was outlined in Refs.[24–26] and more clearly defined in Ref.[27]. In these studies, the authors considered the flow only existing in radial direction, and the effect of tangential velocity was neglected. Bergada et al.[28] analyzed the pressure distribution, leakage, force, and torque between the cylinder and the port plate of an axial piston pump. Kumar et al.[29] 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.

Due to complexities in geometry and physics, CFD pump simulation has historically been very challenging and time-consuming, especially for cases with cavitation. Ding et al.[30] presented a novel CFD methodology and an advanced cavitation model, through which grids for the moving and stationary parts are created as separate volumes. It is an efficient, accurate and robust solution if implemented properly.

Most literatures studied the slipper performance and took the effect on the oil film thickness and friction into account in design and analysis. Even though a degree of non-flatness was essential to ensure the perfect performance of the slipper, the increment of film thickness with reduction of slipper non-flatness was very small.[3,5] The oil film thickness of slipper is mainly affected by the orifice size,[5,9,10] over-clamped ratio[6,8–10], number of full lands[11–13,20] and running conditions.[29,31,32] Slippers operate perfectly with the orifice blanked and, indeed, are generally most stable in this condition. Introduction of the orifice in under-clamped slippers increases

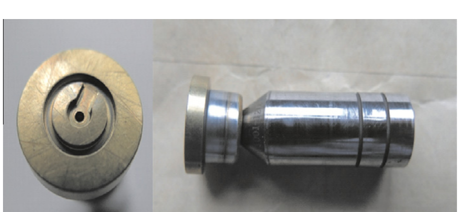

Fig. 1 Piston and slipper.