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Test rigs and experimental studies of the slipper bearing in axial piston pumps: A review

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Many theoretical models and numerical simulations have been developed to predict the slipper behavior because it highly affects the pump performance. Experimental measurements are essential to validate these sophisticated prediction models. Also, they offer a unique opportunity to monitor the slipper behavior online and thus to identify the slipper's factors behind the pump failure. This paper aims to present a systematic review on the slipper test rigs used for experimental measurements. These test rigs will be presented in terms of fundamental principles, merits and demerits, measured parameters, and related experimental results. Finally, the challenges and future trends of the slipper test rig are also discussed.

Contents

1. Introduction

Among all types of positive displacement pumps, axial piston pumps have the potential to achieve high pressure, high efficiency, great power density, convenient flow regulation, and long service life [1]. They are widely used in fluid power drive systems thanks to the above striking attributes. The successful operation of axial piston pumps highly depends on three main bearing and sealing interfaces, i.e., the slipper/swash plate interface, the piston/cylinder block interface, and the cylinder block/valve plate interface, as shown in Fig. 1.

The slipper bearing is an essential design element in axial piston pumps. The slipper slides against the swash plate and carries the external loads acting on it. In addition, the lubricating gap between the slipper and the swash plate prevents the pressurized fluid in the slipper pocket from leaking to the pump casing. The slipper in axial piston pumps is mostly designed as a partial hydraulic bearing [2–4]. The majority of the clamping load from the piston is carried by the hydrostatic pressures generated in the slipper pocket and sealing land. The remainder has to be supported by the hydrodynamic pressures caused by the slipper's motions relative to the swash plate. Due to the multiple degrees of freedom on the macro and micro scales, the slipper/swash plate interface is the most complicated lubricating interface in terms of dynamics. Besides the macro motions governed by the pump kinematics, the slipper also exhibits some micro motions such as squeezing

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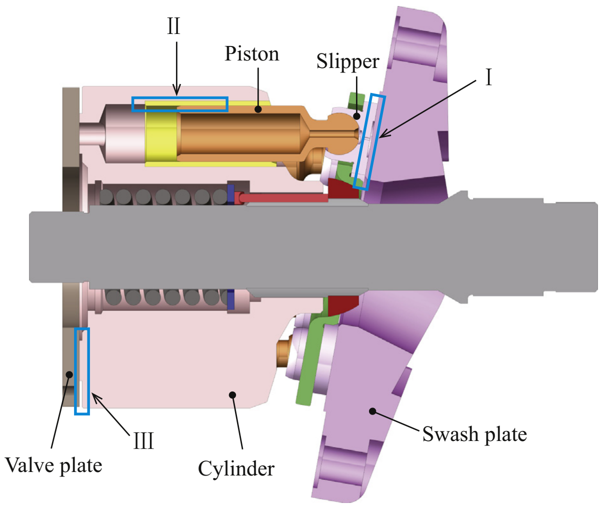

Fig. 1. Main bearing and sealing interfaces within an axial piston pump.

motion, tilting motion, and spinning motion, which are essential for the slipper operation [5–8]. Specifically, they produce additional squeezing effects and hydrodynamic effects, adjusting the pressure distribution across the slipper bearing to balance the varying external loads.

To achieve greater power density, the continued development of fluid power drive systems has put forward higher demand upon axial piston pumps for higher delivery pressures and rotational speeds [9,10]. However, the pressure deformation of the slipper and swash plate occurs when the slipper bearing is exposed to high pressure. This pressure deformation is generally on the order of the fluid film thickness in magnitude, changing the gap height and thus the pressure distribution in the slipper bearing. In the last ten years, some fluid-structure interaction models [8,11–15] have been developed to consider this pressure deformation based on the traditional rigid-body models [16,17] for the slipper bearing. Additionally, the combination of high speed and high pressure results in increased heat generation in the slipper bearing, which influences the fluid film in the following two ways. First, the generated heat changes the properties of the hydraulic fluid, for instance, the oil viscosity. Second, the heat generation causes a thermal deformation of the slipper and swash plate, which can also change the gap height between the slipper and the swash plate. Therefore, the thermal effect should be considered for the lubrication characteristics of slipper bearings [18–20]. Some fully coupled fluid-structure-thermal models have been established for slipper bearings to account for the thermoelastohydrodynamic effect [21–26].

It can be seen that the slipper performance highly depends on slipper's micro motions and fluid film parameters. Therefore, in parallel to the development of simulation models [8,11–26], many experimental studies have also been conducted to validate these simulation models. Furthermore, experimental investigations offer a better understanding of the physical phenomena occurring within slipper bearings. The crucial micro motions and fluid film parameters such as fluid film thickness, pressure, and temperature are good indicators on the slipper performance. A deep look into them can offer unique information on how the slipper bearing fails during operation. This may provide some valuable guidance for further optimization of slipper bearings. Additionally, to improve the efficiency and reliability of slipper bearings, it is useful to try different material combinations and coating applications on slipper bearings [27–31]. These attempts also require much experimental work on the slipper bearing.

Obviously, experimental investigations on the slipper bearing require slipper test rigs. The goal of this paper is to review various existing slipper test rigs and to compare them in terms of fundamental principles, merits and demerits, and measured parameters. Additionally, experimental research on these slipper test rigs is also presented and main experimental results are summarized. The references attempt to cover the technical literature in English language over the last fifty years. There may be other work in the field of slipper test rigs that has been published in other languages, particularly in German and Japanese. Also, those unpublished internal reports and conference proceedings are not cited in this review.

2. Review of slipper test rigs

An overview of the created slipper test rigs over the last fifty years is illustrated in Fig. 2. These slipper test rigs can be generally categorized into four types in terms of the slipper kinematics [7,32]. The simplest slipper test rig is shown in Fig. 2(a) where both cylinder block and swash plate are stationary. The high degree of simplification allows the researchers to conduct experimental investigations conveniently. Besides, this simple configuration has the advantage of high repeatability and reliability of tests since it contains a small number of components. However, this type of slipper test rig has a critical limitation that the slipper operates as a purely hydrostatic bearing. All speed effects are eliminated, thus the hydrodynamic effect, reciprocating inertia force, and centrifugal force of the slipper cannot be considered.

The second type (Fig. 2(b)) and the third type (Fig. 2(c)) of slipper test rig can realize partially kinematic simulations rather than keeping the slipper stationary. They use inverse kinematics, i.e., the swash plate rotates while the cylinder block remains stationary. The only difference between these two types of slipper test rigs is whether or not the swash plate is inclined. For the second type of slipper test rig, the swash plate is not inclined and runs flat, which only allows the sliding motion of the slipper on the swash plate. However, the reciprocation, inertia force, and viscous friction in the cylinder bores are not considered. For the third type, it appears to be an improved version of the second one due to the inclined swash plate, which allows an additional reciprocating motion of slippers along cylinder bores. At the same time, the third type of slipper test rig requires a hold-down device to keep the slipper in full contact with the swash plate surface as the slipper is pulled out from the cylinder bore. Earlier researchers usually adopt the second or third types of slipper test rigs since they offer a good trade-off between the simplification and real working conditions. Nevertheless, these two popular types of slipper test rigs still eliminate the centrifugal forces acting on slippers which have a significant influence on the lubrication characteristics of slipper bearings.

Therefore, some researchers attempt to build model pumps for the slipper test rigs to consider as many physical effects of the slipper bearing as possible. These model pumps are usually modified based on standard commercial products, thus allowing for almost all motions of slippers. This means that like the actual pumps, the model pumps have a rotating cylinder block and a stationary swash plate, as shown in Fig. 2(d). In addition to available real slipper kinematics, another advantage of the last type of slipper test rig is that it takes into account transition effects of the displacement chamber pressure. However, the test pump design is the biggest challenge for this type of slipper test rig. This is because standard pumps are so compact that it is difficult to install sensors in them.