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Friction of hydraulic rod seals at high velocities

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ABSTRACT

Hydraulic cylinders are preferred if a large power density and high dynamics are required because of the low mass which has to be accelerated. Maybe the most critical machine element in fluid power devices is the rod seal. A failure leads to a contamination of the environment and the friction is dominated by the seals. A test rig was developed to measure the seal friction at high accelerations and velocities. In an experimental study the influence of acceleration, sealed pressure and temperature was captured for a polytetrafluoroethylene (PTFE) step seal. Furthermore, the friction of different seal types was measured and the principle suitability of compact seals made from a polyurethane (PU) compound is highlighted.

1. Introduction

Seals are one of the most important machine elements in hydraulic devices. They enclose volumes and enable pressure build-up. Reciprocating seals are intensively investigated in academic and industrial research projects since the middle of the twentieth century. The complexity of the sealing mechanism avoid that the tribological system is clearly understood up to now.

Requirements to dynamic sealing systems are low friction and leakage near to zero over the whole lifetime. Leakage, friction, wear and ageing of the sealing material interact non-linear and are dominated by the design of the tribological system as well as the operation conditions. A sufficient lubricating film between the seal body and the counter surface at every moment during the operation is necessary. The formation of the lubricating film results from the operational conditions and the seal material properties as well as the seal geometries.

In principle, rod seals are more critical than piston seals. A failure causes a contamination of the environment by the hydraulic fluid. The friction does not only interact with the wear processes but also influences the dynamics of the device. High dynamic applications require low friction so that the acceleration can be maximised. One of the main usages of hydraulic cylinders is in the field of mobile machines like excavators. For such applications the velocity of the rod is normally lower than 0.5 m/s and acceleration is negligible. The hydraulic pressure inside the cylinder chambers is up to 350 bar. But there are many other applications where the seals have to handle higher requirements. Hydraulic rock drills are used in mining and construction industry to support a drilling process of rock and concrete by impacts. The sealed striking mechanism operates at velocities up to 10 m/s and accelerations higher than 1000 m/s². Usually the fluid pressure is limited a bit above 100 bar. Another high dynamic applications are circuit breakers which are used to break high voltage circuits very quickly avoiding the appearance of a critical electric arc. The linear movement of the used double acting cylinder is in a velocity range up to 10 m/s, too. The typical acceleration is up to 5000 m/s² and the sealed pressure reaches peaks of 500 bar. A third example is in the field of production machines. Some high productivity weaving machines are equipped with a special hydraulic cylinder which transports a filling thread across a chaining thread. Present rod velocities reach 30 m/s and accelerations are over 8000 m/s² with pressure peaks up to 1000 bar.

There are a few principles available to measure the friction force of hydraulic seals. According to ISO 7986 two rod seals orientated face to face are measured at the same time [1–4]. This results in one seal operating in the outstroke mode and the other in the instroke mode. It is well known that the friction is dependent on moving direction. Nevertheless, it is mostly assumed that the measured friction is twice the friction of a single seal. To avoid this problem, a more complex test rig design bases on the replacement of one contacting seal by a contactless gap seal [5–8]. The gap seal induces lower friction and the friction is less influenced by the moving direction. Furthermore, additional principles exist which allow detecting the friction force of a single seal, see e.g. [9–12]. All of the realised measurement principles, test rig designs and control strategies up to now are limited in the velocity. The typical limit is 1 m/s or less. Overviews on possible measurement principles are available in [8,13].

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2. Measurement principle and test rig design

The measurement of the seal friction requires a relative velocity at the investigated contact. A reciprocating movement can be generated by a hydraulic or a pneumatic cylinder, an electromechanical spindle drive, an electric linear motor or an electric motor combined with a crank mechanism. The disadvantage of linear driving devices is the complex control procedure. On the other hand, the mechanical design of a crank mechanism is more complex. One of the design principles especially for friction force measurements at high accelerations is the need of a very large stiffness of the test rig structure. This avoids vibrations distorting the friction force measurements due to a vibration of the force sensor.

The test rig shown in Fig. 1 was developed to determine the friction of hydraulic rod seals. A pressure chamber is sealed on one side with a test seal and on the other side with a non-contacting parallel gap seal. Pressurisation, which is measured in the inlet pipe, of the seal is possible in the range between 0 bar and 100 bar using a hydraulic pump. An accumulator reduces the pressure pulsation of the axial piston pump. The seal carrier can be equipped with different test seals and is assembled to the measuring box using three piezoelectric force sensors. A second gap seal at the pressure inlet minimises the force thrust. The volume flow across the gap seals is collected in the measuring box. The oil level is kept at about three fourth by a suction pump so that the rod bearings are well lubricated at every time.

A third hydraulic circuit includes cooling and heating devices to temper the hydraulic fluid in a range between 20 °C and 100 °C. The frictional heating of the measuring box induced at the rod bearings and the sealing contacts can be compensated by flooding the box with tempered oil via a bypass. Oil temperature is measured inside the measuring box and in the inlet pipe.

The measuring box including the test seal and the force sensors is screwed to the machine base and the rod is moved. Therefore, an electric motor with flywheel and crank mechanism is used. A frequency converter allows driving different rotational speeds of the motor. An additional linear guidance of the slider supports the forces induced by the connecting rod. The bearing of the test rod itself is free of lateral forces. This test rig design allows measurements at rod velocities up to 10 m/s. The velocity as well as the acceleration of the rod dependent on the rotational frequency of the electric motor is shown in Fig. 2. The velocity–stroke-characteristic is at constant rotation speed of the drive nearly sinusoidal. The velocity maximum is not in the middle of the stroke but is shifted to the top dead centre. This results in different accelerations in both of the extended positions. The maximum of the acceleration is in the top dead centre and reaches values up to 1000 m/s². It is well known, that seal friction is very strong dependent on rate and state e.g. velocity, velocity history, breaking away from rest, or time spent in a steady-state. Due to the crank mechanism, all of the parameters are dependent on each other. It is not possible to investigate a single effect with this test rig. For simplicity, all effects are summarized under the term acceleration and deceleration.

The friction force measurement using piezoelectric force sensors has the advantage of a very large stiffness but it has also a serious problem: It is not possible to measure absolute values of the friction force. The friction of common seals is dependent on the direction of movement. Measurements show that friction during outstroke is not the same as during instroke at the rated range of use, e.g. [14]. In literature there is a calibration method to determine the zero point of the friction force. The method is based on calibration measurements at very low and constant velocities of about 2 mm/s where the friction is dominated by boundary effects and not by hydrodynamics [9,15]. It is assumed that the friction for outstroke and instroke is the

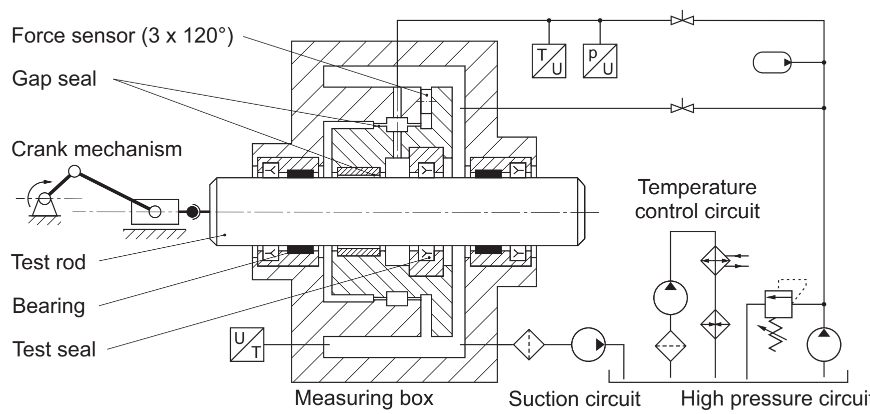

Fig. 1. Schematic of the test rig for hydraulic rod seals.

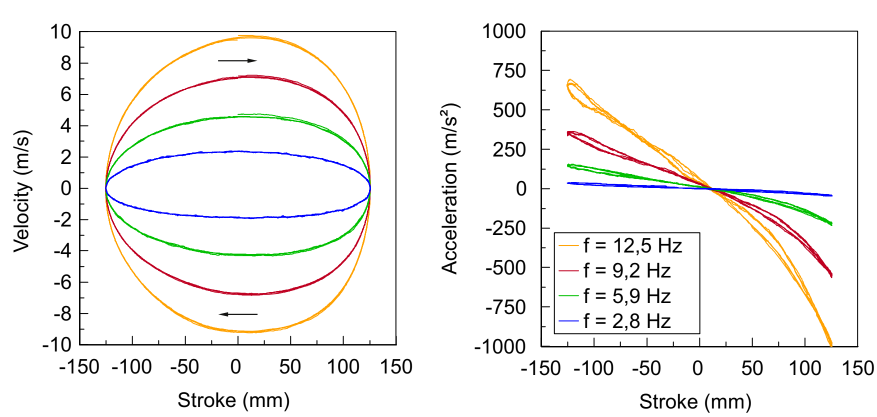

Fig. 2. Velocity and acceleration of the rod dependent on rotational frequency.