Slip Length in Narrow Sealing Gaps – an Experimental Approach

M.SC. Tobias Corneli, Prof. Dr.-Ing. Peter Pelz, Dr.-Ing. Gerhard Ludwig

Technische Universität Darmstadt
- Chair of Fluid Systems, Darmstadt, Germany

1 Abstract

For narrow sealing gaps in average smaller ca. $\mathbf{1\,\mu m}$ it is expected that the no-slip boundary condition does not yield anymore. As a consequence the friction is reduced and the leakage is increased compared to the no-slip design case. Though the concept of slip length was introduced by Navier and Maxwell already in the 19th century, it is up to now costly to measure the slip length. This is due to the required measurement precision. Today the slip length is measured in laboratories for glass, silicium or sapphire wafers while using fluorescence methods to determine the flow velocity and is thus far from sealing applications. The present paper introduces an alternative method to measure the slip length for typical materials that are used in sealing technologies. A key advantage of the presented method is that the slip length can be evaluated while measuring the physical quantities torque and gap setting.

Within the paper the design of the apparatus including the measurement equipment is discussed in detail.

2 Introduction

Since the early 90s of the past century environmental impact of hydraulic fluids is an increasingly important issue for the fluid technology. From this point of view a hermetic sealing would be desirable. But for dynamic seals e.g. rotary shaft seals as presented in Figure 1 or rod seals a hermetical tightness is from principle aspects impossible to realize. In fact the design of those sealing systems is driven by the interests of friction and leakage flow.

Reprinted with permission from [Corneli, T.; Pelz, P. F.; Ludwig, G. (2014): Slip length in narrow sealing gaps – an experimental approach. In: 18th International Sealing Conference].

The leakage flow across the sealing system reduces with a decreasing gap height between shaft and sealing whereas the friction losses increase. Typical gap heights of dynamic sealing systems are in the order of some microns or below. At these length scales the continuum mechanics breaks down and the molecular dynamic has to be taken into account. Under these circumstances the no-slip boundary condition at the wall does not yield anymore. The concept to describe slip close to the wall is based on the geometrical quantity *slip length*. This concept was first introduced by Navier and Maxwell in the 19th century. From geometrical aspects the slip length constitutes an apparent magnification of the sealing gap. In succession of the slip velocity close to the wall the leakage flow across the sealing gap increases. Hence the knowledge of the slip length could have a major impact on the design of dynamic sealing system. At the current state of knowledge the leakage flow is underestimated in most cases.

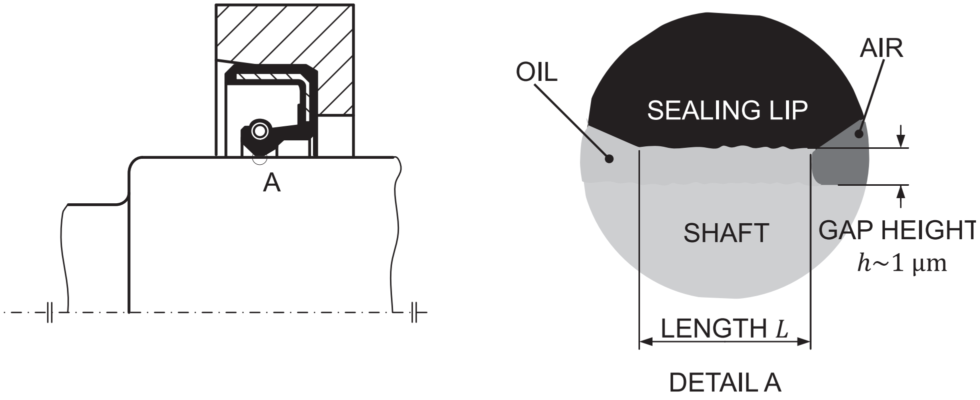

Figure 1: Sealing gap of a radial shaft seal.

Until today several methods to evaluate the slip length are published and are summed up e.g. in (Lauga, et al., 2007) or (Neto, et al., 2005). One of the latest measurement technologies is the photobleached-fluoresecence imaging velocimetry presented by (Ponjavic, et al., 2013). But common to all of them is their unsuitability in practical applications of the fluid technology. Due to the fact that the investigated sliding partners are made out of glass, silicium or other for the hydraulic non practical materials. Furthermore commonly laser measurement technologies are applied. Those measurement techniques require an immense financial effort and physical knowledge and are inapplicable for measurements that should be quick, rugged and easy to accomplish.

Aim of the presented measurement technique is to evaluate the slip length for typical materials used in sealing applications while measuring the quantities torque and distance with commercially available sensor techniques.

Therefore the present paper is dived into three parts. In following third paragraph the theory of the slip length is briefly presented. The theory part is continued by the main part of the paper where the measurement concept as well as the design engineering of the test rig is presented. The paper closes with a discussion and a conclusion.

3 Theory slip length

In this paragraph the fundamental concept of the slip length λ is introduced in brief. Most engineers and scientist know two kinds of boundary conditions for fluid flows close to solid walls. The slip boundary condition and the no slip boundary condition as presented in Figure 2. The slip boundary condition assumes that the fluid velocity close to the wall and in the undisturbed flow is the same. This boundary condition yields for inviscid fluids – as they are employed for potential flows. The most common boundary condition close to solid walls in flow mechanics is the no slip condition. It acts on the assumption that the velocity of the fluid layer close to the wall and the wall are equal. This assumption applies for nearly all macroscopic flow conditions and today nobody questions the no slip boundary condition.

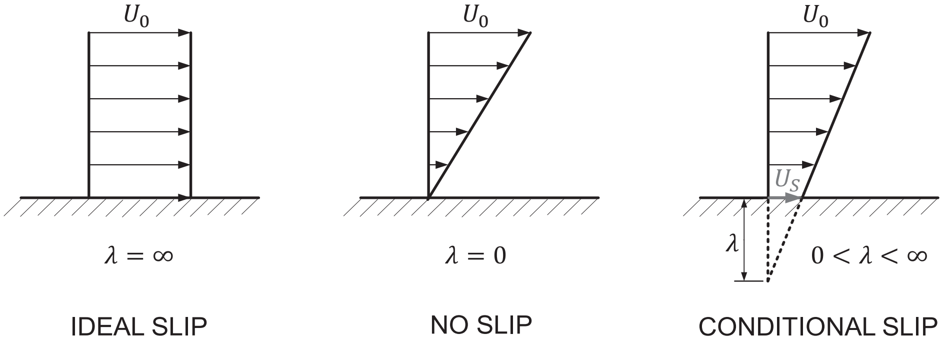

Figure 2: Boundary conditions close to the wall

In the mid of the 19th century when the Navier-Stokes-Equations were derived for the first time the situation was completely different. All well-known scientists as e.g. Navier, Stokes and Maxwell discussed the fluid behavior close to the wall. A brief summary of the historical perspective is given in (Lauga, et al., 2007) as well as in (Neto, et al., 2005). Basically two different boundary conditions have been discussed at the time. The no slip boundary condition and the linear boundary condition. The linear boundary condition is presented on the right hand side of Figure 2 and acts on the assumption that a conditional slip close to the wall occurs. The undisturbed velocity in the far field U_0 and the slip velocity U_S close to the wall form a linear flow field. The slip length λ is closely linked with the linear boundary condition close to the wall. It is the distance beyond the solid wall if the linear velocity profile is linearly extrapolated to zero. Slip velocity and slip length are associated by the shear rate $\dot{\gamma}$:

$$U_S = \lambda\dot{\gamma}.$$

Lauga (Lauga, et al., 2007) referred Navier (Navier, 1827) and Maxwell (Maxwell, 1879) as the first scientists who introduced the linear boundary condition. Whereas Stokes favored the no slip boundary condition, as stated in (Neto, et al., 2005). In the 20th century the no slip boundary condition was generally accepted due to the fact that it was impossible to measure the slip velocity close to the wall. On this basis it was assumed that its influence on typical flow phenomena is negligible small. But today with the continuous progress in manufacturing and measuring techniques slip has to be taken into account for small sealing gaps and boundary surface phenomena.

4 Test Rig

Purpose of the presented test rig is to measure the slip length for hydraulic applications (sliding surfaces, fluids, …) in an industrial environmental. Hence a rugged and reliable test rig is required. The present section is divided into two main parts: In paragraph 4.1 the physical principles of the test rig are identified. In section 4.2 the realization of the test rig is presented in detail.

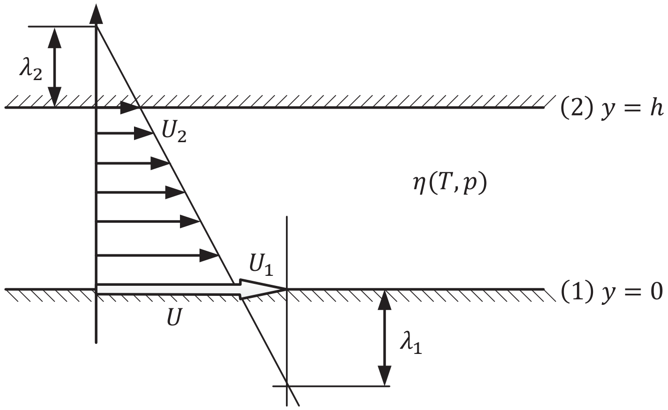

Figure 3: The main principle of the rheometer.

4.1 Conception

The basic concept of the rheometer is presented in Figure 3: It consists out of two disks spaced by the gap height h. One disk is moved by the velocity U and the other one is fixed in space. Inside the gap a simple shear flow arises. If the gap height is in the order of some microns slip occurs at the moving as well as at the stationary disk. For practical applications it is more suitable to arrange the test rig in a rotatory design. So the experiments can be conducted continuously. Instead of the friction force induced by the fluid on the stationary disk we measure the friction torque that is given by the integration of the shear stresses among the surface of the disk

$$M = \iint r\tau_{z\varphi}\,\mathrm{d}A = \eta\frac{\Omega}{h+\lambda_1+\lambda_2}\iint r^2\,\mathrm{d}A.$$

In above expression for the friction torque the integral $\iint r^2\,\mathrm{d}A$ denotes the polar moment of inertia I_p. Hence the friction torque can be expressed in the following manner

$$M = \eta\frac{I_p}{h+\lambda_1+\lambda_2}.$$

It contains two geometrical parameters and one fluid parameter. With above equation we are able to estimate the slip length by measuring the friction torque as well as the gap height. The measuring principle is explained as follows: The inverse friction torque as a function of gap height is presented in Figure 4. For zero slip and diminishing gap height the inverse friction torque would tend to zero. With slip the

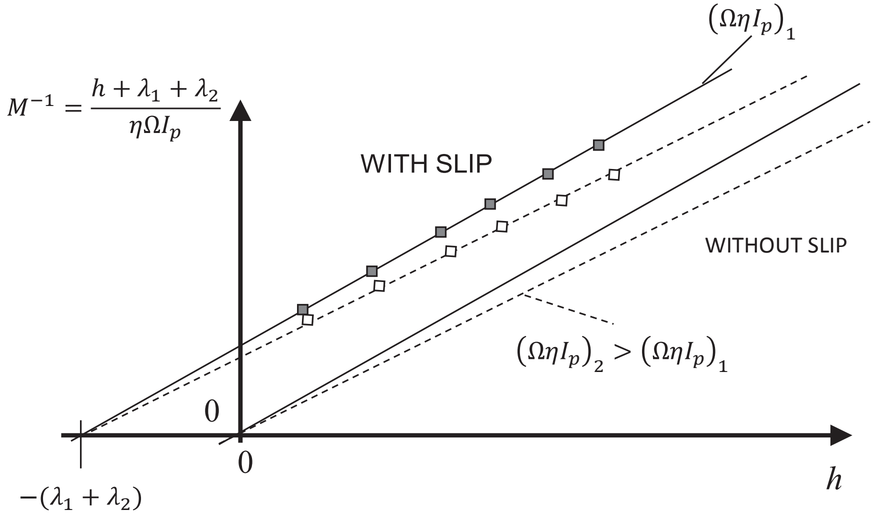

Figure 4: Friction torque as a function of gap height with and without slip.

friction torque stays finite. In that case the slip length can be obtained by a linear extrapolation of friction torques at different gap heights h, denoted by the red quads in Figure 4. With the presented method it is only possible to measure the sum of slip length at the top and the bottom disk. Hence in a first step the sliding partners have to be made out of the same material to evaluate the slip length for one material before a mixture of materials could be investigated.

The basic scheme of the test rig is presented in Figure 5. The main parts are the split disks, the gap height as well as the torque meter. The operating principle can briefly described as follows: The fluid enters the test rig with initial pressure p throughout a hole in the stationary disk. The sliding disks have an initial gap height h of zero and are pre-loaded in axial direction by an elastic element. When the pressure force within the gap exceeds the pretensioning force the gap between the two disks increases with increasing pressure. At a gap height of approximately 10 microns the measurement can be started. The top disk is brought into rotation and the friction torque at the stationary disk is measured by a torque meter. With dropping inlet pressure the gap height depletes and the torque increases. With the different friction torques we can evaluate the sum of the slip length as presented in Figure 4.

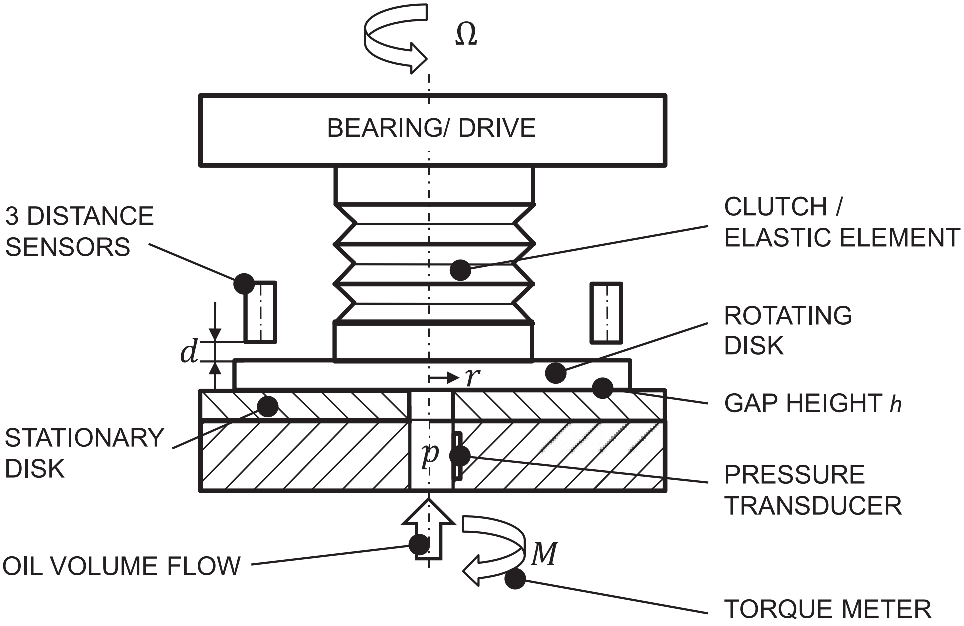

Figure 5: Conception of the test rig

For the measurement of the gap height three distance sensors are used. Due to the fact that the gap height at the initial conditions is zero we are only interested in the changes. Hence if the surfaces of the rotating disk are coplanar it is sufficient to measure the horizontal displacement of the rotating top disk. The differential measurement method offers us two advantages. First we do not need an exact positioning of the sensor as long as the changes of the disk are within the measurement range of the sensors. Secondly capacitive distance sensors can be used instead of leaser measurement techniques or inductive distance sensors, because we do not have to carry out the measurements in an oil-ambience. Capacitive sensors have the advantage of a better spatial resolution than any other measuring principles.

4.2 Experimental setup

In the previous section the basic scheme was introduced. In the following section the experimental setup of the whole test facility is described in detail: It consists of the design of the rheometer, the split disks and the hydraulic circuit to provide the pressure for the gap height adjustment.

4.2.1 Design Engineering

The final design of the rheometer is presented in detail in the following section. It varies in a meaningful manner from the schematic illustration in Figure 5 and is influenced by a preliminary test rig. The manufactured test rig is presented on the left hand side of Figure 6. It has a height of approximately 500 mm and a diameter of 300 mm. The detail view of Figure 6 shows the measurement chain for the friction torque as well as the split disks - the core of the test rig.
It consists of the torque sensor, mounted at the bottom of the base disk of the test

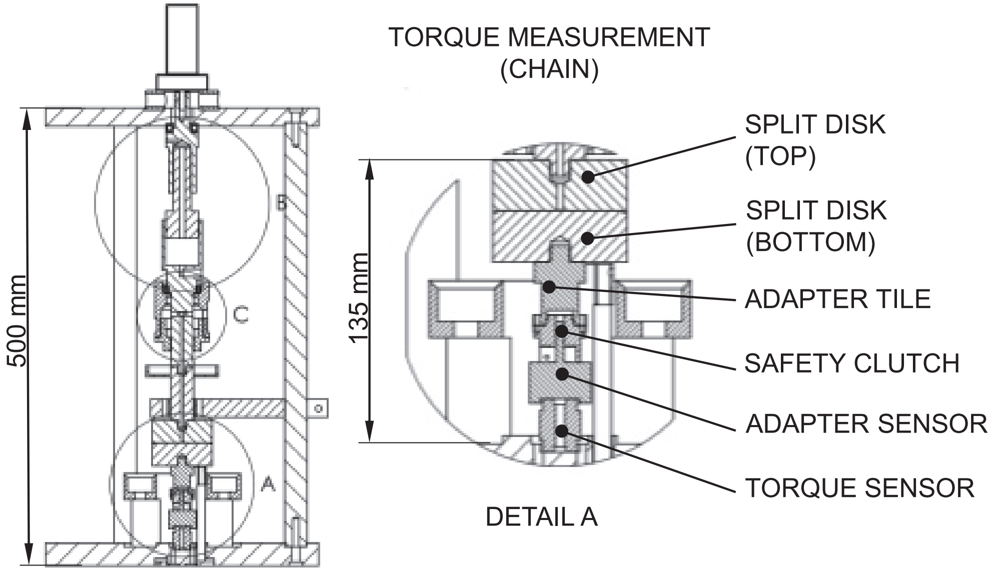

Figure 6: Test rig and a detailed view on the measurement chain.

rig, a safety clutch and the bottom split disk. As torque sensor a KISTLER reaction torque sensor (9329A) with a maximum measuring range of $\pm 1\ \mathrm{Nm}$ is used. The safety clutch opens at a torque of $1\ \mathrm{Nm}$ and protects the sensor against overload. The adapter of the split disk is necessary due to the fact that the screw in procedure of the clutch would affect the planarity as well as the plane parallelism of the split disks. The detailed explanation of the gap measurement and the manufacturing effort of the split disks will be given later on in section 4.2.2.

The elastic element for the adjustability of the gap height is presented in Figure 7. Since for the test rig are very small gap heights required there are two ways for the arrangement of pressure p and axial flexibility: The usage of a commercial available compression spring and an inlet pressures in the order of magnitude of some Pascal. Or the usage of a very stiff spring element and an inlet pressure in the order of magnitude of some bars. It was decided to use an inlet pressure from 1 to 10 bar for the test rig. This has three advantages: At first it is easier to obtain a pump with low pulsations for this application. Secondly standard hydraulic components can be used for the hydraulic circuit. Thirdly the whole system is more suitable in terms of gap height adjustment. The stiff spring element is realized by an oil pressure spring, it consists of a hydraulic cylinder and a hydraulic piston. The flexibility of the oil filling counts for the elastic characteristic. The flexibility of a liquid column is given by

$$K = -V_0 \frac{\mathrm{d}p}{\mathrm{d}V}$$

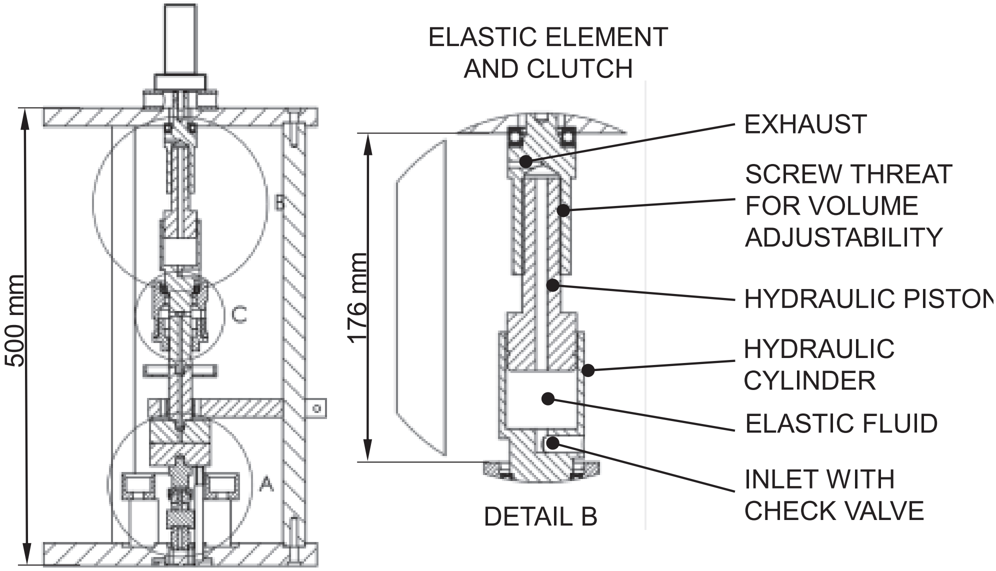

Figure 7: Test rig and a detailed view on the measurement chain.

and can be changed by the adaption of the height of the liquid column. For the test rig this fact gives the advantages that the slip length can be investigated as a function of the surface pressure, because (Ponjavic, et al., 2014) reported an influence on the slip length with the surface pressure.

In comparison to the basic scheme the fluid enters the test rig through the top disk. This modification is owed by the fact that the measured friction torques are smaller than $1\ \mathrm{Nm}$. If the fluid would be feed into the gap through the bottom disk a wire or pipe connection would be necessary in the measurement chain. In our case the measurement would be influenced by the bearing reactions of the wire/pipe connection. Hence in Figure 7 our centre post is expressed in detail. The liquid enters the stationary part which is closed by the sealing cover. The centre post is sealed by two rotary shaft seals. The cavity in between the stationary and the rotary part contains the fluid that is fed into the rotating system by six bore holes evenly spaced around the circumference. By this modification the torque measurement chain remains free from any external influences.

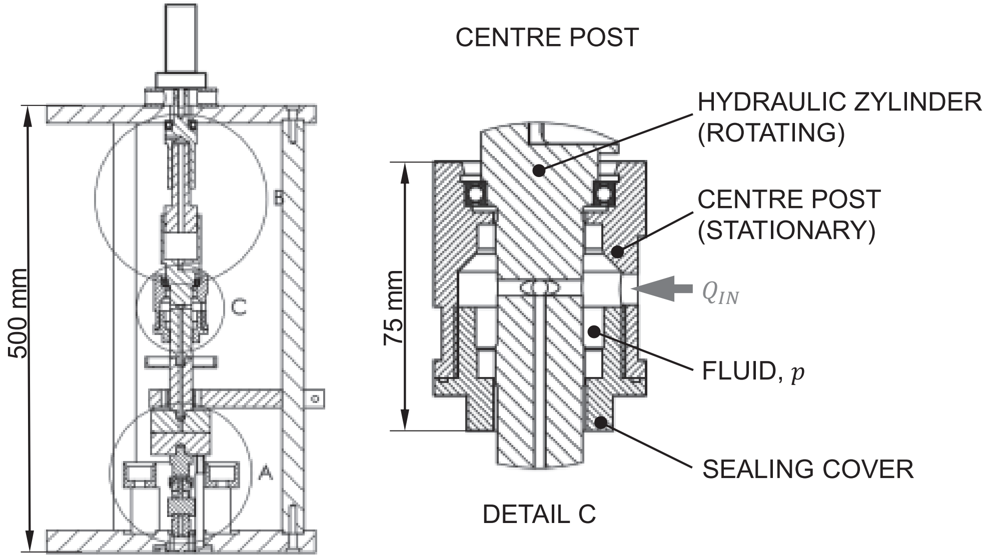

Figure 8: Test rig and a detailed view on the key feature centre post.

4.2.2 Distance measurement and manufacturing effort of the split disks

Essential for the working principle of the test rig are the split disks. They affect the gap geometry as well as the accuracy of the measurement of the gap height. Because the gap height is measured by the relative horizontal displacement of the top surface of the top disk. Therefore high-definition distance sensors are mounted above the top split disk as presented in Figure 9. At the beginning of the measurements both split disks fit onto each other – the resulting gap height tends to zero. Due to a fluid infeed the sealing gap increases and the relative horizontal displacement of the top disk is measured. This approach has the advantage that and exact absolute positioning of the sensors is not necessary. But for this measurement principle each warping and non-parallelism of the disks affects the measurement accuracy of the gap height. For the distance measurement a high resolution capacity measurement system from MICRO-EPSILON (capaNCDT 6500) is used. For a high spatial resolution the sensor type CS005 with a measurement range $0.05\ \mathrm{mm}$ and a spatial resolution of $1\ \mathrm{nm}$ was selected.

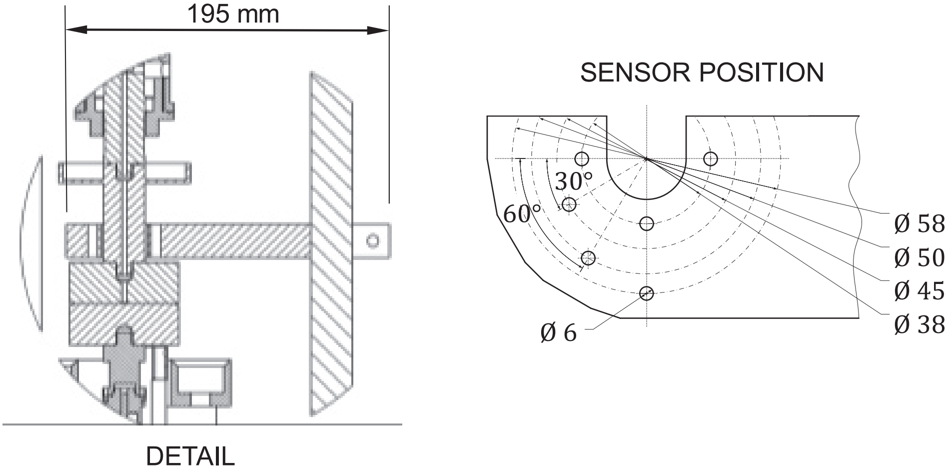

Figure 9: Distance Measurement

For a counter check of the measurements it is possible to measure the gap height at different angles of revolution: This allows us to check whether the gap height is constant or not. The accuracy of this measurement principle is limited by the plane parallelism as well as the flatness of the disk. The used disks are manufactured in a multi-stage production process. In the final step they were lapped at a precision measuring equipment manufacture. The flatness of the disks accounts for approximately $30\ \mathrm{nm}$.

4.2.3 Hydraulic circuit

For the adjustment of the gap height a continuous volume flow with a constant pressure is required. To fulfil this requirements a hydraulic circuit was arranged. A schematic illustration of the used components is presented in Figure 10. Main part of the hydraulic circuit is the nearly pulsation free screw pump (LEISTRITZ L3NG). It provides a volume flow of approximately 10 litres per minute and a maximum pressure of 10 bar. Due to the fact that the required volume flow through the gap is much smaller than 10 l/min a flow diving is used. Hence most of the delivered fluid is circulated continuously. Furthermore a hydraulic damper is applied to reduce the pressure oscillations at the inlet of the test rig. To avoid the damage of the surfaces of the split disks a filter with a fineness of filtration of $1\ \mu\mathrm{m}$ is implemented. The fluid reservoir has a maximum capacity of 70 litres. Thus the fluid can settle for almost 7 minutes in a continuous operation.

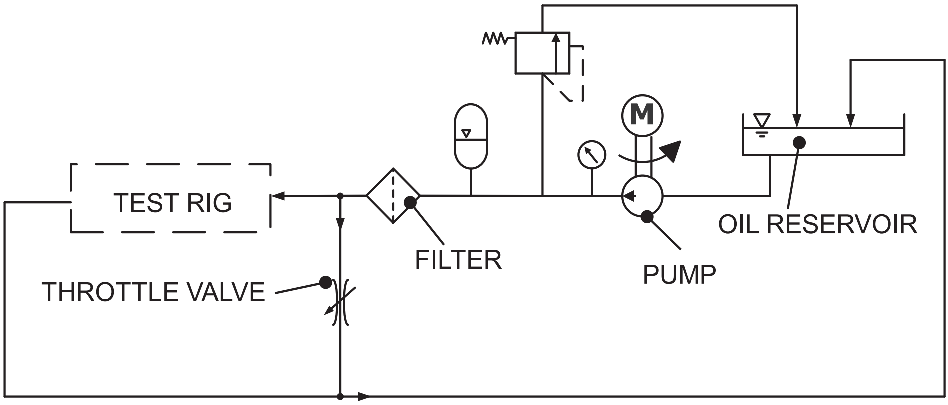

Figure 10: Hydraulic circuit

5 Summary and Conclusion

Within this paper a new measuring procedure to evaluate the slip length in an industrial environment was presented.

6 References

[1] **Lauga Eric, Brenner Michael und Stone Howard** Microfluidics_ The Non.Slip Boundary Condition [Buchabschnitt] // Handbook of Experimental Fluid Dynamics / Buchverf. Tropea Cameron, Yarin Alexander und Foss John. - New York : Springer, 2007.

[2] **Maxwell James Clerk** On Stresses in Rarefied Gases Arising from Inequalities of Temperature [Artikel] // Philosophical Transactions of the Royal Society of London. - 1879. - S. 231-256.

[3] **Navier Claude Louis** Memoire sur les lois du mouvement des fluides [Book]. – 1827

[4] **Neto Chiara [et al.]** Boundary slip in Newtonian liquids: a review of experimental studies [Artikel] // Reports on Progress in Physics 68. - 2005. - S. 2859-2897.

[5] **Ponjavic Aleks und Wong Janet** The effect of boundary slip on elastohydrodynamic lubrication [Artikel] // RSC Advances. - 23. April 2014. - S. 20821-20829.

[6] **Ponjavic Aleks, Chennaoui Mourad und Wong Janet** Through-Thickness Velocity Profile Measurements in a Elastohydrodynamic Contact [Artikel] // Tribology Letters 50. - 2013. - S. 261-277.