# Radial Piston Engine with Cone Valve Plates

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## Abstract

The Radial Piston Unit with Axial Cone Valve Plate (RAC) is a new type of hydraulic displacement unit, generated by the recombination of established and well controllable functioning principles. It uses a tilted piston design that enables direct torque generation in the cylinder star without inducing transverse forces on the piston. Moreover, the entire rotational group is hydrostatically supported and as a result no hydraulic forces act on the shaft and the shaft bearings.

KEYWORDS: radial piston, axial valve cone plate, direct torque generation

## 1. Introduction

The hydraulic pumps and motors market is widely dominated by axial piston machines using either the swashplate or bent-axis design. Both designs have been developed over the past half century and as a result perform well in regard to efficiency, noise emission and abrasion resistance. An important issue facing theses units is the lack of potential for further improvement.

This work gives insight into an attempt to achieve further improvements by using a new design. The objectives of the work are:

- Reduction of force redirections
- Reduction of friction
- Reduction of flow losses
- Aptitude for pump and motor applications
- Low noise generation
- Simplicity in design and manufacturing

The outlined development is conducted in the scope of a cooperative research project and funded by the Germen Federal Ministry of Economics and Technology.

## 2. Functioning Principle

The presented design is based on a radial piston concept with external piston support. The variable position of the cam ring enables the control of displacement in a simple manner.

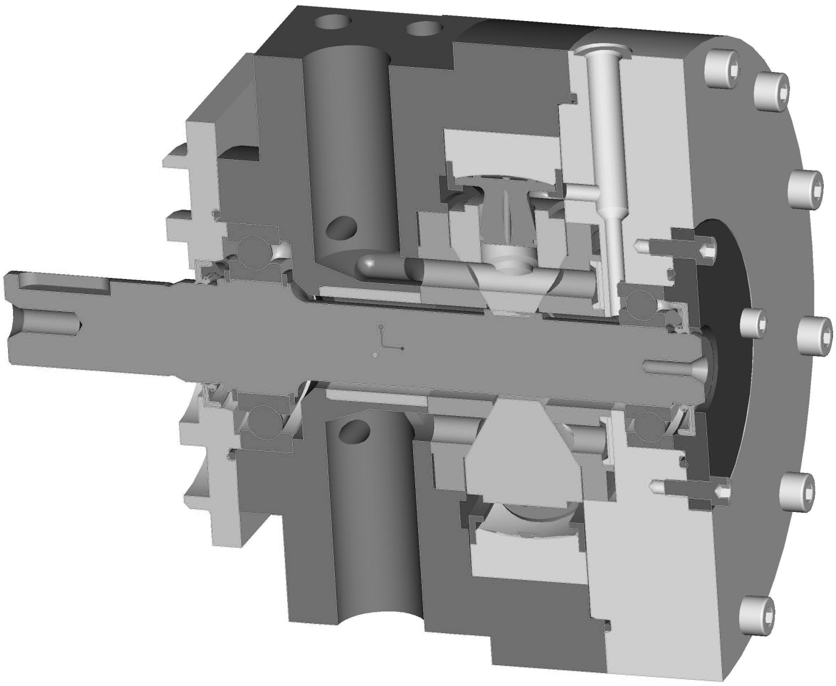

**Figure 1:** RAC hydraulic unit, longitudinal section

The main alterations in comparison to the established radial piston units are the one-piece tilt pistons and the pair of conical valve plates that substitute the common control journal. The first feature helps to reduce the number of tribological contacts, in which forces are transferred to other components. The second one provides large flow channels and an ample passage for the shaft.

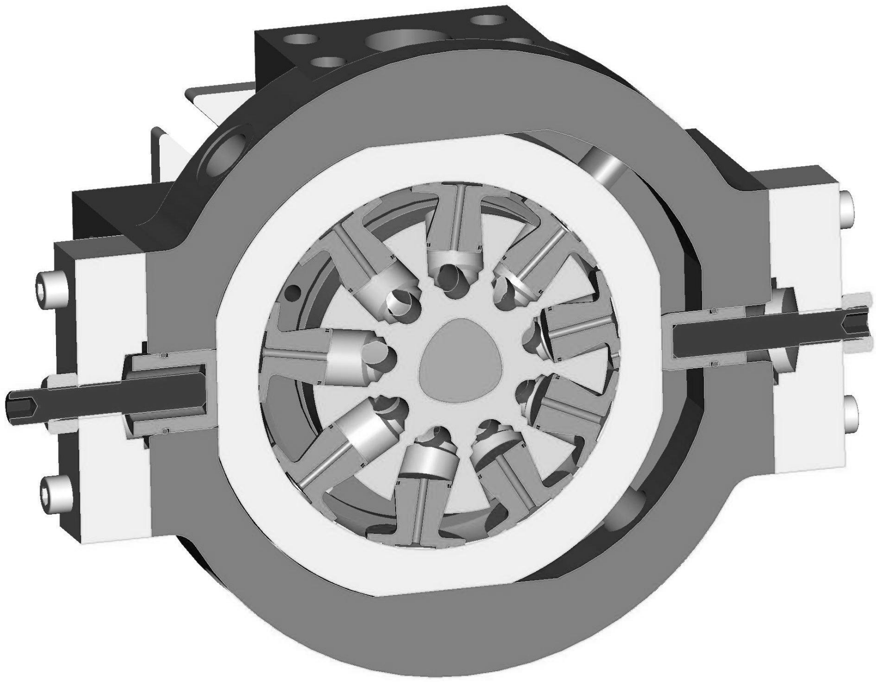

**Figure 2:** RAC hydraulic unit, cross section

The conical vavle plates generate a double sided hydrostatic bearing, thereby supporting the rotating cylinder star. Therefore the driving shaft is completely free from lateral forces coming from the hydraulic powertrain and has only to transfer torque. A further advantage of using conical valve plates is the increase in flow channel size, resulting in decreased pressure losses.

## 3. Tilting Pistons for Direct Torque Generation

The one-piece pistons are able to tilt in relation to the cylinder bore axis up to an angle of approximately 10°. A specially designed piston ring creates a sealing line which tilts with the same angle of the piston. This tilting sealing line generates a wedge-shaped area in the cylinder bore.

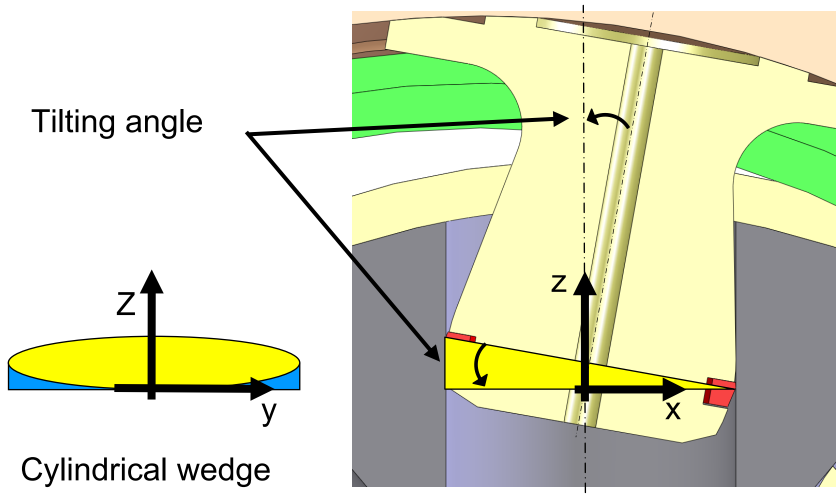


**Figure 3:** One-piece tilted piston in cylinder star

This property has two special consequences. Firstly, the pressure forces on the piston are parallel to its axis. The piston slipper has the usual shape for hydrostatic discharge, and the resulting discharge forces are also parallel (**Figure 4**). In a result, only negligible lateral forces emerge from the friction on the cam ring.

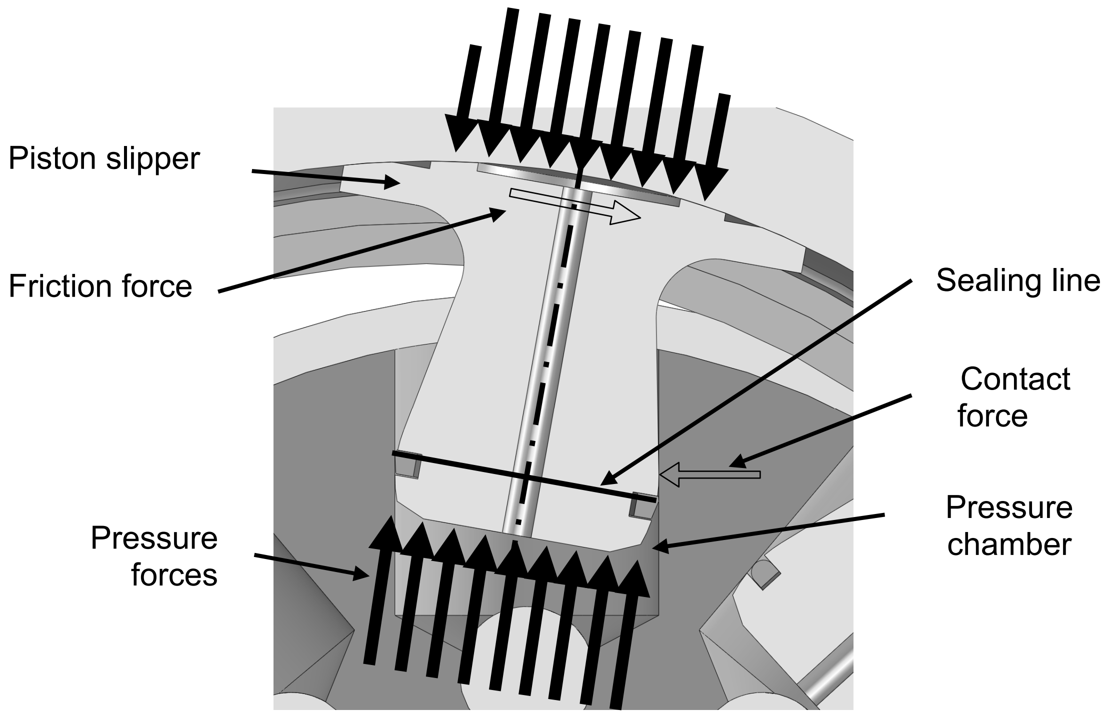


**Figure 4:** Forces at tilted piston

Secondly, and perhaps more important, the hydraulic pressure in a cylinder bore with tilted obstruction generates a lateral force to the cylinder wall (**Figure 5**). The pressure chamber can be thought of as being divided into cylindrical part, where all forces are balanced to zero, and a pressure sickle, that depends on the tilt angle. In this sickle the pressure forces are not compensated.

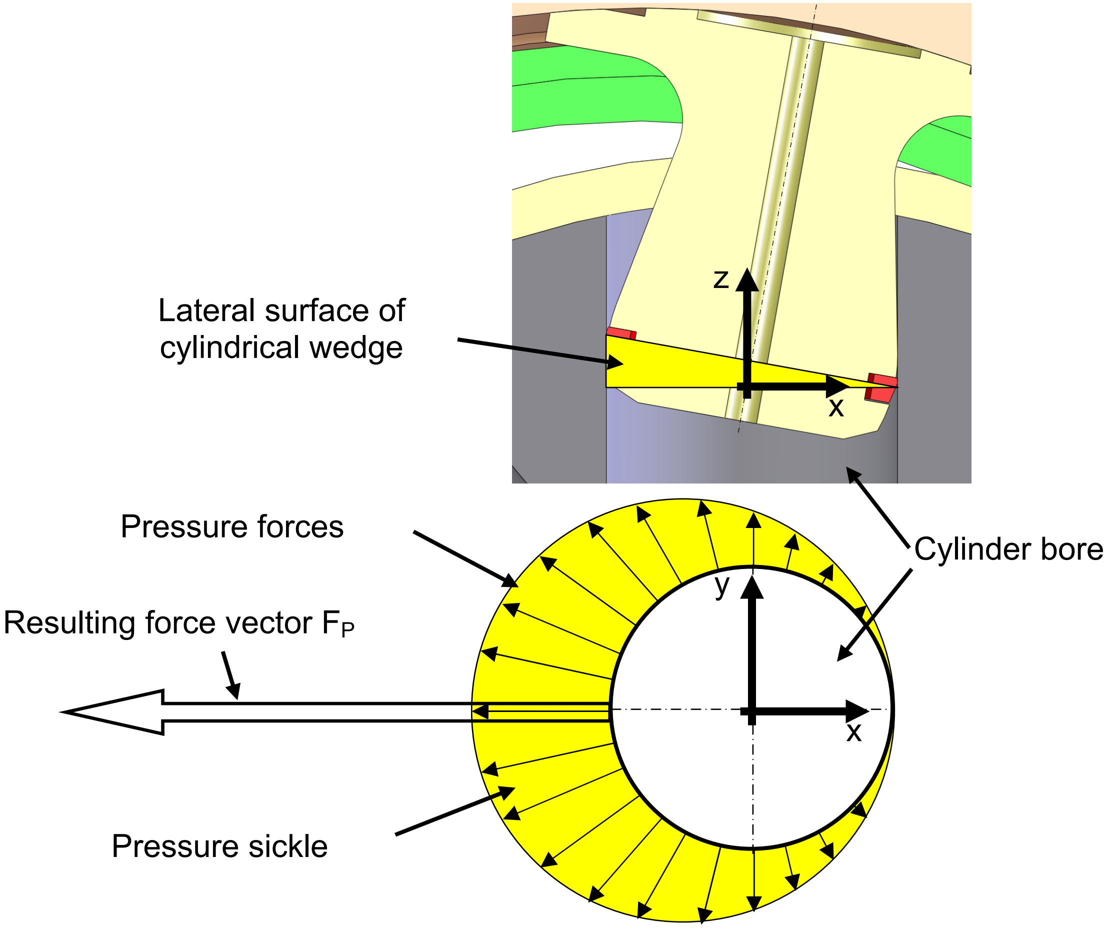


**Figure 5:** Pressure sickle and resulting force vector

The result is a force vector directly created by the pressure and the geometry of the sealing line. During the rotation of the cylinder star, the lateral force change with the tilt angle. In addition the distance between the sealing line and the center of rotation changes within a cycle. **Figure 6** shows a calculated torque curve as a function of rotation angle. The upper diagram shows the torque of a single cylinder, the lower one illustrates the resultant torque of a 9-piston unit obtained by vector addition of the individual components.

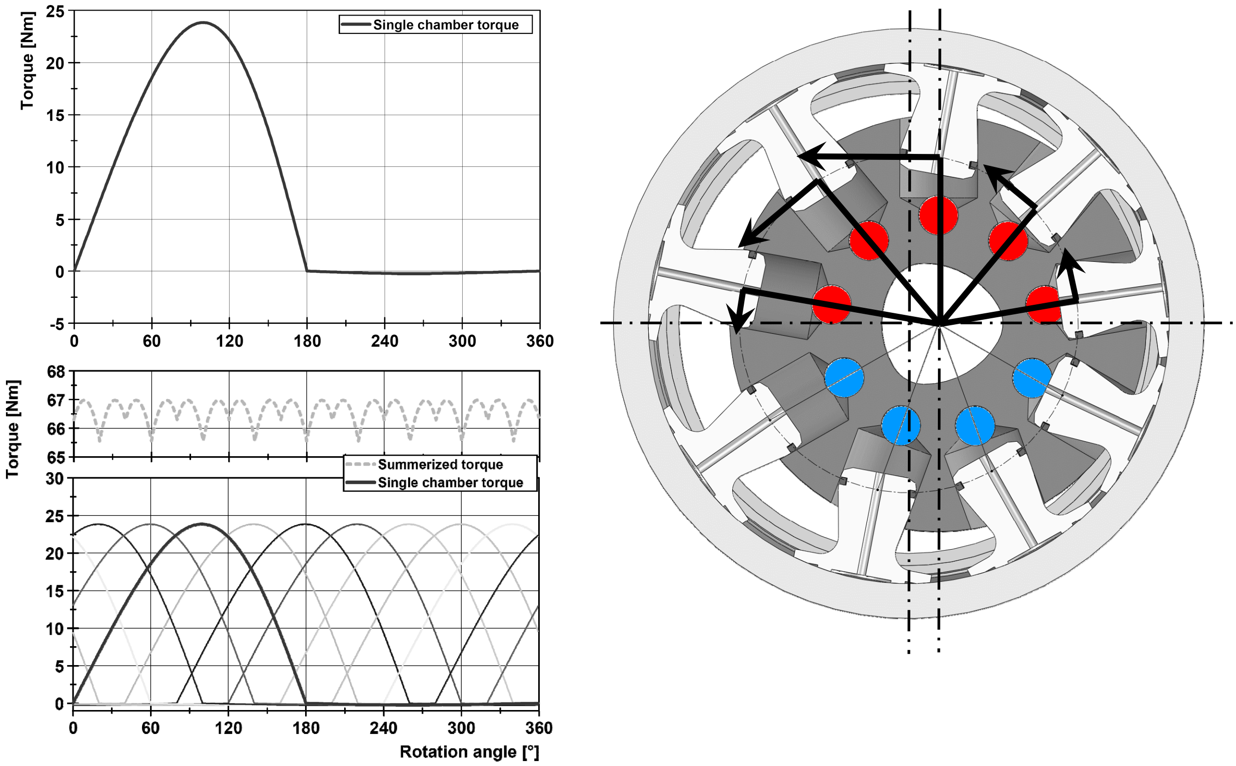


**Figure 6:** Summarized torque of a 9-piston unit

## 4. Hydrostatic Bearing of Piston Slippers

Even if the piston slippers are compensated in the well-known way, a minor amount of force has to be born in metallic contact, resulting in friction and perhaps abrasion. Especially in radial units with external piston support this friction may reduce the mechanical efficiency, as the friction forces are exerted on a larger radius than in axial piston units.

In the RAC unit a transition from a hydrostatic compensation to a hydrostatic bearing of the piston slippers is realised (**Figure 7**). For this purpose the compensation area $A_2$ is larger than the pressure area $A_1$. In equilibrium, the pressure $P_2$ is reduced by a laminar restrictor between cylinder chamber and compensation area.

If designed appropriately the result is a self regulating hydrostatic bearing that provides a constant gap between cam ring and slipper. Metallic contact is avoided completely. To witness this effect, a set of pistons was covered with marker paint on the slipper surfaces and tested in a single piston test bench (**Figure 9**). After several hours with variing pressures and temperatures no adverse effects in the paint coat were found.

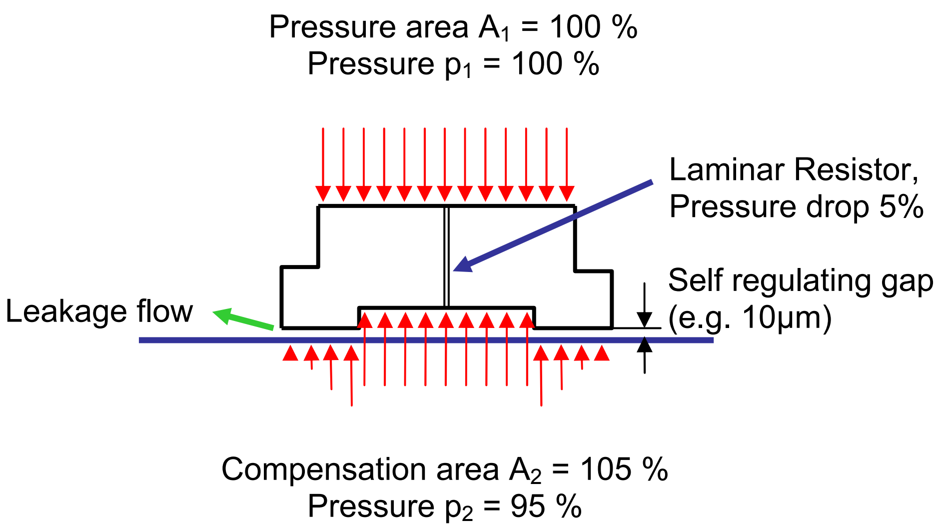


**Figure 7:** Principle of frictionless hydrostatic piston slipper

The absence of static friction enables optimal stop-and-go-properties, as needed in motor applications. By regulating the gap to a few micrometers - just enough to bridge the sum of mechanical tolerances - the leakage flow remains low. The energy-consumption of summarised leakage flow can be much lower than the energy-losses caused by friction. Additionally, particles smaller than the gap measure cannot cause abrasion between slipper and cam ring.

## 5. Hydrostatic Bearing of Axial Cone Valve Plates

Axial piston units have a flat or spherical port plate, and established radial piston designs show a cylindrical journal, that contains the fluid channels and ports. This journal is also the bearing for the cylinder star.

In the new design, the rotating cylinder star is mounted between two non-rotating conical plates that are guided in the pump housing and pressed together by spring loads and hydraulic forces.

One of these cones (the left one in **Figure 8**) has the function of a port plate as in standard axial piston units. It is radially and axially supported in the housing. The other plate has the function of a compensator; it is pressed towards the left plate by well balanced hydraulic forces, braced to the housing cap.

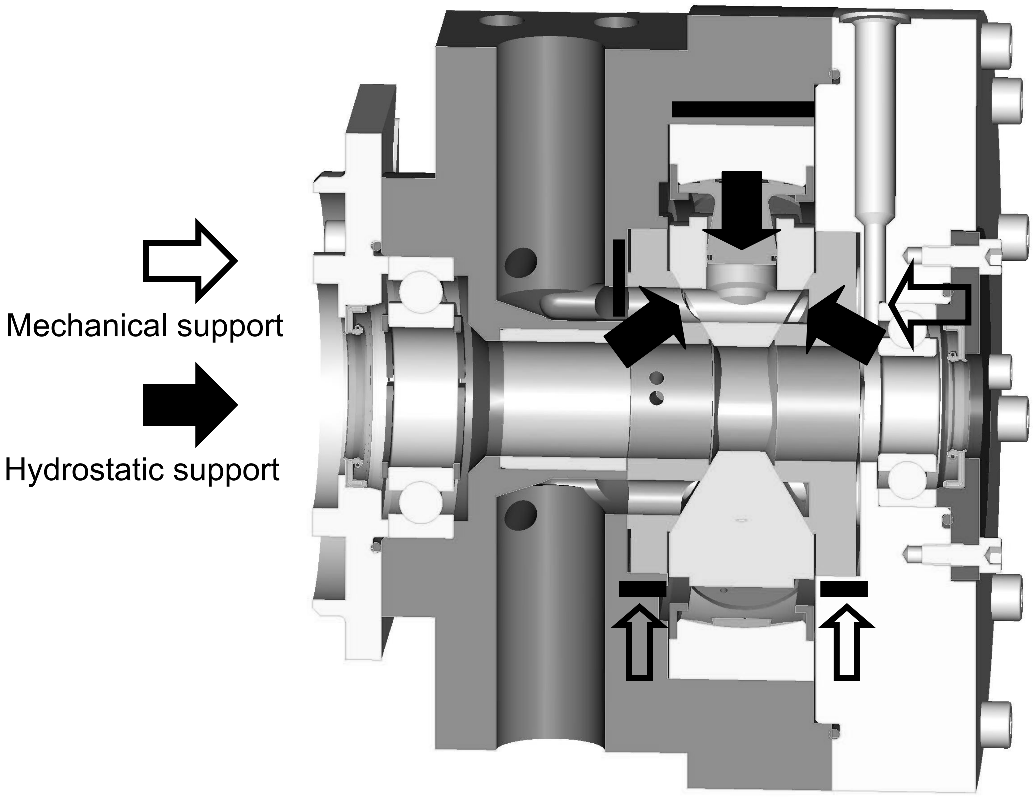


**Figure 8:** Balance of forces between piston, cylinder star and two cone valve plates

In the moving gap between the rotating cylinder star and the cones - symmetrical on both sides - a pressure field is formed, when the unit is pressurised. This field strives to increase the gap. The compensating forces act against this pressure field: They keep the gap closed without creating much friction.

Additionaly the geometry of the cones has to grant another condition: The radial quota of the pressure field has to compensate the radial reactions of the piston forces. By dimensioning the diameters and angles of the cones, this three-dimensional task can be solved.

The balance between inner pressure fields and well-fitted gap compensation creates a complete hydrostatic bearing for the rotating cylinder star. The double-cone structure may resemble a pair of tapered roller bearings, it provides a guide in radial as well as in axial direction.

## 6. Test Bench Results

For the systematic development of the RAC unit the system is divided into subsystems that can be investigated separately. For the examination of the subassembly cylinder-piston-cam ring a test bench with a modified cylinder star is used. This rotor is constantly pressurised via a rotary joint and can incorporate up to four pistons. If the cam ring is located excentrically, the pistons conduct a pump stroke in the first 180 degrees and a motor stroke in the rest of the cycle.

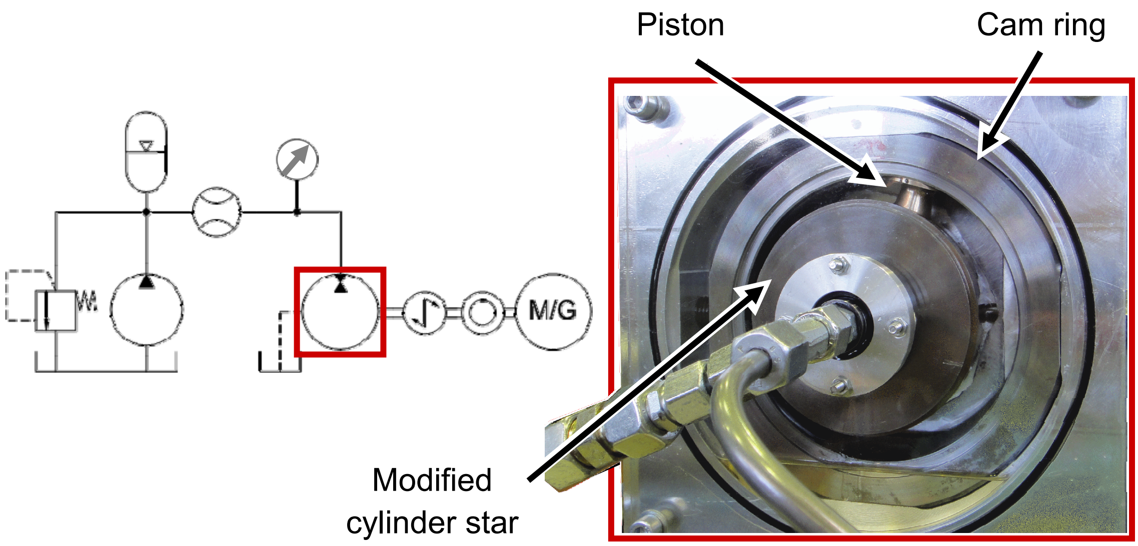


**Figure 9:** Single piston test bench

With a centred cam ring it is possible to measure the friction of the piston slippers. In both positions it is possible to meter the leakage losses of piston rings and discharged slippers.

The test unit has a piston diameter of 20 mm, representing a 9-piston pump with a displacement of 40 $cm^3$.

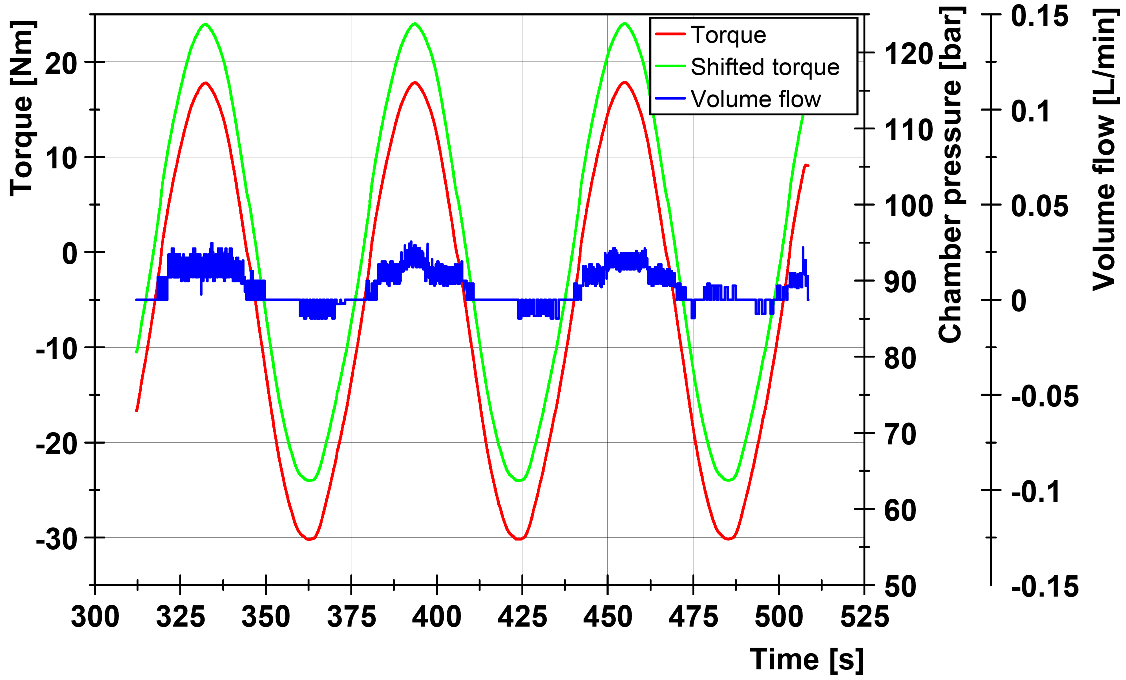


**Figure 10:** Torque and volume flow at slow rotation speed

**Figure 10** shows a typical diagram from measurements at 100 bar with a single piston and excentric cam ring. The hydraulic torque curve resembles a sine wave, symmetrical to the zero line and in accordance with expectations and the simulated torque shown in figure 6. The measured output torque is shifted by the friction of the piston slipper, in this case with a rather low factor of discharge. The torque difference is about 5.5 Nm in average.

The measured flow changes with the slow stroke of the piston. On the average there is a leakage flow of about 0.015 l/min. Recapitulated this is a measurement with low leakage and high friction.

The friction can be reduced by increasing the factor of compensation, up to the point at which the slipper lifts and the leakage flow increases rapidly /2/. As the point of lifting depends on various characteristic values such as pressure, speed and displacement, it is rather diffcult to determine the suitable maximum of the compensation factor.

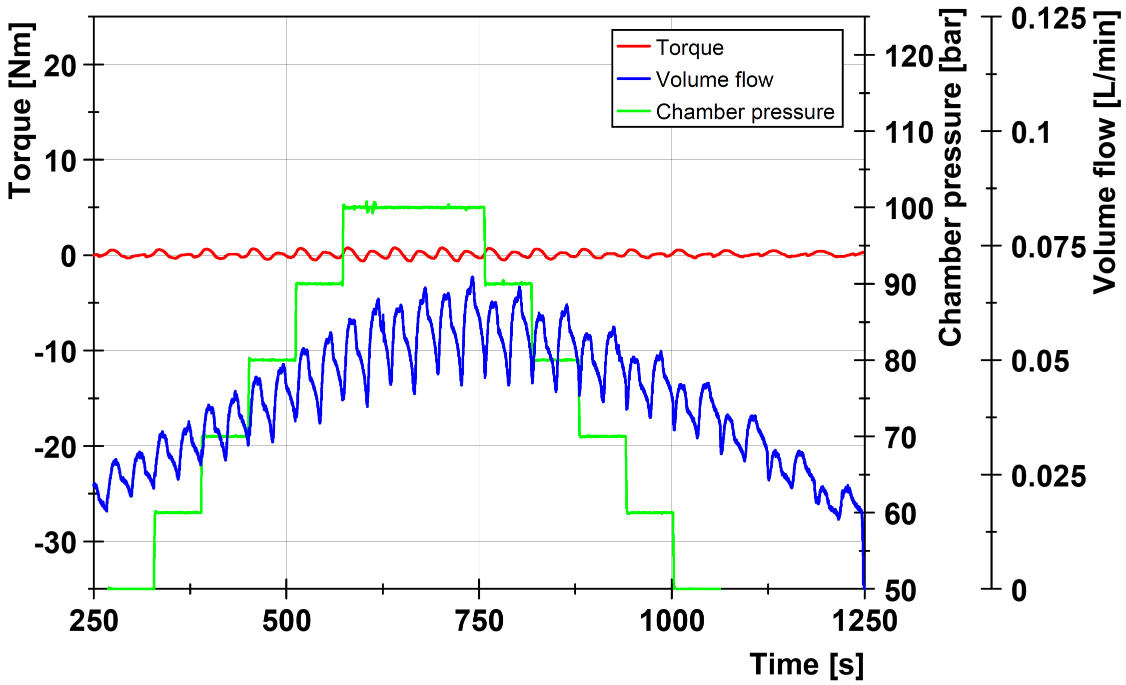


**Figure 11**: Friction torque and leakage flow with "frictionless" hydrostatic piston slipper

To show the effect of the self regulating hydrostatic bearing in the piston slippers, the same measurement with two pistons and a centered cam ring are inducted. **Figure 11** shows these measurements with a variation of pressure up to 100 bar. The measured torque displays a signal noise near the zero-line, caused by the rotary joint and the coupling. In fact no friction torque could be measured in this test set-up.

The price to pay for this "frictionless" slipper is an increased leakage flow. In this experiment the gap was about 12 µm, and the leakage of two pistons at 100 bar was 0.056 l/min or 0.028 l/min for each slipper.

The power consumption of one slipper at 100 bar is 4.67 W. This consumption increases with the square of the pressure ratio. At 400 bar it has a value of about 75 W.

## 7. Prospect

The outlined concept of the Radial Piston Unit with Axial Valve Cone Plate (RAC) is validated in subsystem test assemblies and also as an entire unit. Further work aims to prove the suitability of the new design for tasks as in real hydrauic systems. In this way, a number of detailed problems can be solved.

To achieve high efficiency, the hydrostatic balancing subsystems have to be optimized for the full range of operating conditions. Satisfactory lifetime has to be ensured by selection and treatment of the materials and surfaces of the tribological contact partners.

## 8. References


/1/ Murrenhoff, H.: Grundlagen der Fluidtechnik, Teil 1: Hydraulik; 5. edition, 2007, IFAS, RWTH Aachen, Germany

/2/ Ivantysyn, J.; Ivantysynova, M.: Hydrostatische Pumpen und Motoren, Konstruktion und Berechnung; 1. edition, 1993, Vogel, Würzburg, Germany

/3/ Jang, D.: Verlustanalyse an Axialkolbeneinheiten; 1. edition., 1997, Aachen/ Mainz, Germany


## 9. Symbols

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| $A$ | Area | $mm^2$ |
| $p$ | Pressure | $N/mm^2$ |
| $F$ | Force | N |