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A NEW HYDRAULIC PUMP AND MOTOR TEST BENCH FOR EXTREMELY LOW OPERATING SPEEDS

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ABSTRACT

Most test benches for hydraulic pumps and motors are designed for operating speeds of 500 rpm or higher. Worldwide, there are only a few test benches which allow measurements at near zero operating speeds or startup conditions.

Low-speed testing is, however, of great importance for hydraulic motors, since the torque losses increase exponential at these conditions due to mixed lubrication and stick-slip effects. Low-speed operation is also important for hydraulic pumps which are used in electro-hydraulic actuators, in which the flow rate is controlled by the operating speed of the electric motors. Finally, measurements at low operating speeds can give detailed information about the pump or motor issues, since it is possible to measure the operation at many rotational positions of the rotating group, giving the ability to measure the losses of individual displacement volumes.

This paper describes the design and operation of a new test bench for testing hydraulic pumps and motors at extremely low operating speeds, below 1 rpm.

INTRODUCTION

Hydrostatic pumps and motors have operational limits. Aside from the maximum pressure and the maximum rotational speed, there is often also a certain minimum operating speed: most manufacturers don’t recommend to operate the pump or motor for an extended time below a certain minimum rotational speed. There is an obvious reason for this restriction. Most hydrostatic machines need at least a rotational speed of a few hundred rpm in order to create a sufficient hydrodynamic lubrication and avoid excessive wear due to a lack of bearing capacity.

Yet, near-zero operating speeds can not be avoided in many hydrostatic motor operations. A hydrostatic driven fork lifttruck will, for instance, have continuous stop-and-go operation, in which the hydraulic motors often have to breakaway from standstill and are frequently operated at low rotational speeds. At these conditions, the torque capacity of the hydraulic motor is strongly reduced because of mixed lubrication and high friction losses. In addition, the limited number of pistons causes additional torque variations and reductions. Consequently, the motor size needs to be enlarged and sometimes even doubled to overcome these additional torque reductions. In order to measure, analyse and possibly improve the motor capacity at startup and breakaway, measurements at close to zero rotational speed are needed.

Another important reason for the study of low-speed behavior is the recent development in the area of electro-hydraulic actuators, in which speed controlled electric motors determine the flow output of the pump. These machines often demand near-zero speed operation. However, due to the non-linear, stick-slip behavior of hydraulic pumps at low rotational speeds, the control of such systems can become unstable [1]. A test bench for low-speed operation is needed to investigate and improve the controllability (and efficiency).

Finally, low-speed testing can give valuable information about the leakage and friction of the individual displacement volumes, i.e. pistons and cylinders of the hydrostatic machine [2-9]. Different coatings or other design details can be studied in detail while operating the pump or motor at low rotational speeds [10-12].

The testing of pumps and motors at low rotational speeds has increasingly gained (somewhat) more importance. The test method is however not trivial. Stick-slip effects strongly depend on the operating speed and pressure, as well as on the oil temperature and viscosity, and it is difficult to keep these parameters constant and reproducible.

This paper describes a new test bed, which is developed and built by INNAS, for performing measurements at low, and even extremely low operating speeds, as low as 0.01 rpm. The new test bed is integrated in a performance bench for regular, high operating speeds. The new test facility can be used for pumps and motors, and can be operated in both rotational directions.

ISO-STANDARDS

The International Organization for Standardization (ISO) has three standards for determining the low-speed characteristics or startability of positive displacement rotary fluid power motors, of either fixed or variable displacement types:

- ISO 4392-1: At constant low-speed and constant pressure [13]
- ISO 4392-2: Startability [14]
- ISO 4392-3: At constant flow and at constant torque [15]

ISO 4392-1 and 4292-3 are largely overlapping. Both standards describe a method to determine the characteristics of positive-displacement fluid power motors at the minimum allowable rotational speed (ISO 4392-1) or at the lowest possible flow which causes the motor to stop rotating (ISO 4392-3). The advantage of the two methods is that the performance will be measured for all (or at least many) rotational positions of the rotating group of the motor. The disadvantage is that the motor is already rotating: the performance is not measured at real startup (0 rpm) conditions.

The measurement of the actual startup torque is described in ISO 4392-2. Since the startup torque strongly depends on the rotational position of the shaft, the measurement has to be repeated for many shaft positions. According to ISO 4392-2: “The number of measurements at different shaft positions shall be greater than the minimum number necessary for the maximum starting pressure over one revolution to be found with a confidence level of 95 %.”. That makes this procedure extremely time consuming and unpractical. Furthermore, it is almost impossible to create a thermal conditioning or equilibrium of the hydraulic motor and the oil.

An alternative is to apply the test-procedure of ISO 4392-1 but now at extremely low, close to zero speed of the shaft. By integrating the low-speed test bench in the general test bench for normal operating speeds, it becomes easily possible to warmup the oil and the motor to the demanded equilibrium conditions. Furthermore, the same hydraulic circuitry, sensors and data-acquisition system can be used as for the general, higher speed test purposes.

DEMANDS FOR THE NEW TEST BENCH

The new test bench is first of all a general test bench for testing hydrostatic, positive displacement pumps and motors, according to ISO 4409 [16]. The main drive of this test bench is a water cooled, frequency controlled DC electric motor with distributed winding for achieving low torque variations. The motor has 48 stator coils and 16 magnet rotor poles. The motor can be operated between 50 and 5000 rpm. The electric motor has a through drive, enabling the mount of an additional hydraulic motor or pump. With this added hydraulic machine, the hydraulic power of the test object can be recirculated, which results in a strong reduction of the energy consumption and cooling demands. The remaining heat can, if needed, be used to heat the building.

The hydraulic test circuit is designed for a rated pressure of 500 bar. The supply-side can be self-priming or pre-charged, up to a pressure level of 20 bar.

The oil temperature can be precisely controlled by means of frequency controlled cooling fans and cooling pumps (Figure 1). The maximum oil temperature is 90°C. There is also an additional frequency controller for the electric motor, which drives a hydraulic pump for supplying high pressure oil during the low-speed test. At near-zero operating speeds, this pump foremost needs to compensate the volumetric losses, i.e. leakage of the hydraulic motor to be tested.

Fig. 1: Frequency controllers of the test bench.
From left to right:

- Hydraulic pump for low-speed tests;
- Cooling water pump;
- Low pressure supply pump;
- Dry-cooler, fan 1;
- Dry-cooler, fan 2;
- Cooling-pump main electric motor;
- Cooling fan;
- Controller drive motor.

A special oil reservoir is used with an integrated, hydraulically driven degassing and dewatering unit. An integrated membrane prevents direct contact with the ambient air. The system achieves a very low gas and water content in the fluid, thereby reducing the variation of the oil bulk modulus and compressibility [17].

The low-speed test bench is designed as an integrated part of the general test bench. It uses the same reservoir, cooling systems, and sensors. This part of the test bench is however designed for testing at much lower rotational speeds than the minimum rotational speed of 50 rpm of the general test bench. In order to get as close as possible to the real zero-speed starting condition, the low-speed test bench is designed for rotational speeds of 0.01 rpm. This is two orders of a magnitude lower than the minimum required speed according to ISO 4392-1. This makes the new test bench a crossover between ISO 4392-1 and ISO 4392-2. At these low operating speeds, the lubricated surfaces are operated with solid or boundary friction. Mixed and fluid friction are avoided.

As in the general test bench, the maximum operating pressure is 500 bar. The new test bench can test both pumps and motors, in both directions of rotations. The combined test bench allows a procedure in which the test unit can run for a while at higher operating speeds, thereby allowing both the oil, and the pump or motor to be tested, to warm up to the required test conditions. After the warming up, the test bench can be switched to low-speed testing.

DESCRIPTION OF THE TEST BENCH

Figure 2 shows a drawing of the main drive of the new, combined test bench. The bench has two modes of operation, for general performance measurements according to ISO 4409 and for low-speed measurements.

As shown in Figure 2, the bench is in the first mode, for general performance measurements in the range from 50 to 5000 rpm. In this mode, the main electric motor (nr. 2 in Figure 2) and the hydraulic motor (nr. 1 in Figure 2) are driving the pump to be tested. The drive or load for the low-speed drive is decoupled.

For low-speed testing, the coupling (nr. 4 in Figure 2) is switched, thereby disengaging the specimen from the main drive. Instead, a new drive or load is created by means of a linear actuator (nr. 1 in Figure 3), which is connected by a chain and a sprocket (nr. 3 or 4) to the output shaft. The chain can be mounted in two ways, thereby changing the direction of rotation. On the one end the chain is connected to the linear actuator, on the other side to a counter-weight. There are two sprockets, one for low-speed (36 teeth) and one for ultra-low-speed measurements.

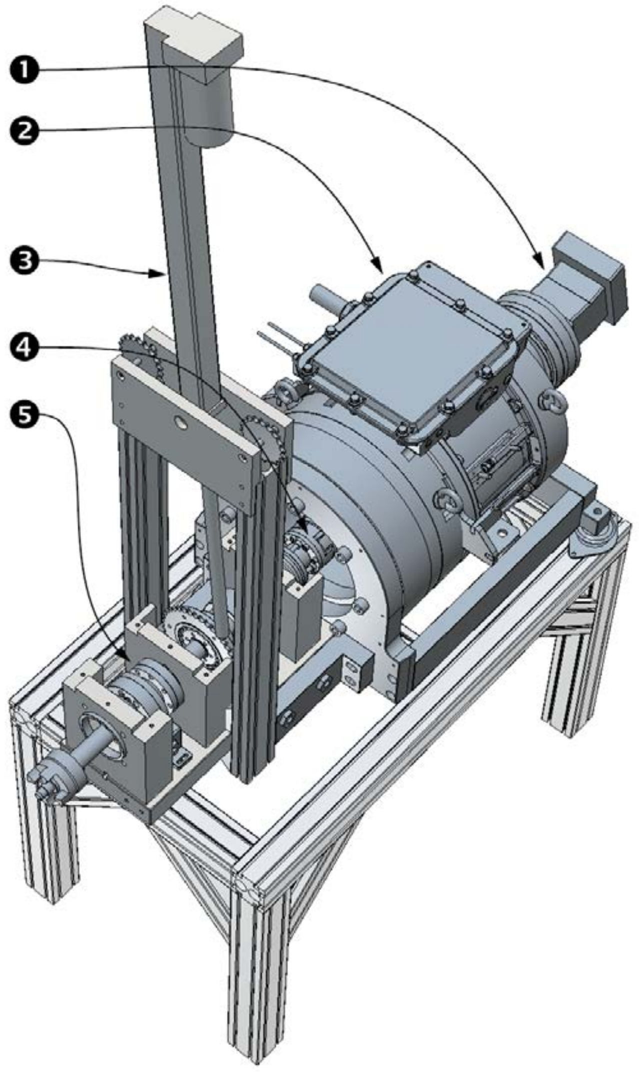

Fig. 2: INNAS combined test bed

1. Hydraulic motor or pump for power recirculation
2. Frequency controlled, water cooled electric motor
3. Linear electric actuator
4. Switchable coupling
5. Torque and speed sensor

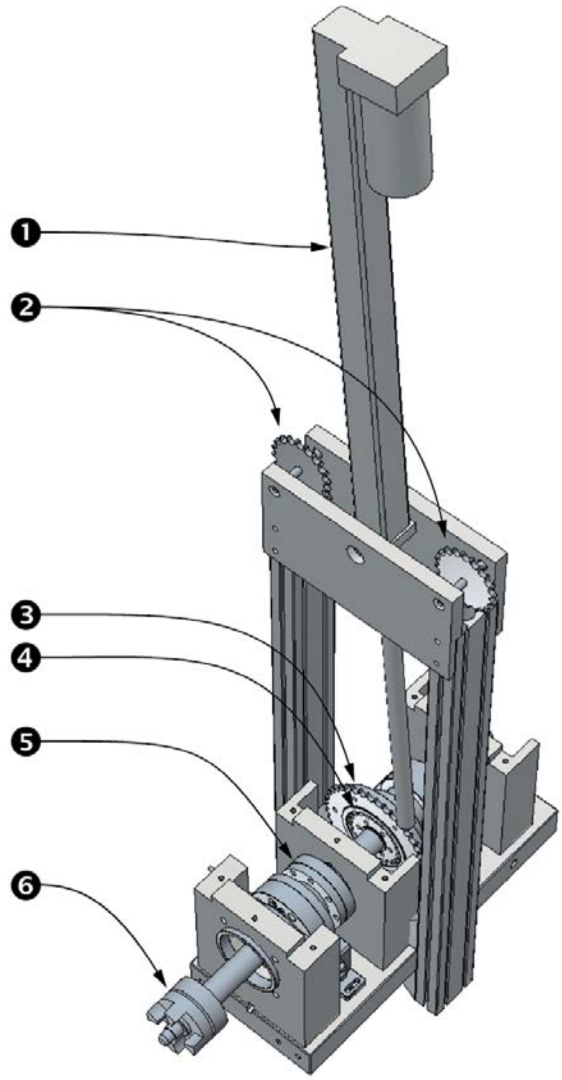

Fig. 3: Low-speed test bed
(the chain and counter weight are not shown)

1. Linear actuator with build-in position sensor
2. Sprockets for the counter weight,
   one for each direction of rotation
3. Sprocket with 60 teeth
4. Sprocket with 36 teeth
5. Torque sensor
6. Coupling for the pump or motor to be tested

SPECIFICATIONS OF THE LOW-SPEED TEST BENCH

The linear actuator is a ball screw which is driven by a speed controlled electric motor, coupled with a planetary gear transmission, having a transmission ratio of 50:1. The actuator can be loaded up to 6 kN. With the large sprocket, this would result in a maximum torque of 546 Nm, which is more than the design specification of the test bench, which is limited to 500 Nm. The spindle ratio is 5 mm per revolution. The speed of the electric motor can be varied between 50 and 3280 rpm. The actuator can make a stroke of 700 mm.

Table 1 shows the full specifications of the low-speed drive. The rotational speed of the pump or motor to be tested can be varied between 0.015 and 0.96 rpm with the small sprocket, and between 0.009 and 0.57 rpm with the larger sprocket having 60 teeth. With both sprockets, the test object can at least make one full revolution with a single stroke of the linear actuator. At the lowest speed, a single measurement for a full rotation takes almost 2 hours. At the highest operating speed (0.96 rpm) one full rotation takes about one minute. The bench can test units up to 63 cc at a pressure of 500 bar.

SENSOR SPECIFICATIONS

The low-speed test bench is also developed for a detailed analysis and diagnosis of the torque losses and volumetric losses for each rotational position of the test unit. The rotational position can be determined with great precision by the sensors, which are build into the electric motor of the linear actuator. Each rotation of the electric motor gives 16 pulses for the rotational position. With the small sprocket having 36 teeth, this results in a resolution of 152 pulses per degree rotation of the test unit. With the larger sprocket, this resolution is increased to 254 pulses per degree of rotation. For a full rotation, this results in a resolution of 91440 steps. This allows a precise measurement of the variation of the torque. Simultaneously, the pressure level at the input and output are measured, as well as the leakage flow and the supply flow. The combined measurement data of the pressure transducers and the torque sensor allows a calculation of the torque losses for each rotational position of the test unit. Similarly, the flow sensors and the measured rotational speed allow an analysis of the volumetric losses. A complete overview of the sensor specifications is given in Annex A.

Table 1: Specifications of the low-speed test bench

	sprocket with 60 teeth				sprocket with 36 teeth			
	n = 50 rpm		n = 700 rpm		n = 50 rpm		n = 700 rpm	
rotational speed of the motor	50	rpm	3280	rpm	50	rpm	3280	rpm
transmission ratio of the gear box	50	-	50	-	50	-	50	-
spindl ratio	5	mm/rev	5	mm/rev	5	mm/rev	5	mm/rev
spindl rotational speed	1	rpm	65.6	rpm	1	rpm	65.6	rpm
spindl translational speed	5	mm/min	328	mm/min	5	mm/min	328	mm/min
number of teeth of the sprocket	60	-	60	-	36	-	36	-
gear pitch	9.525	mm	9.525	mm	9.525	mm	9.525	mm
gear circumference	571.5	mm	571.5	mm	342.9	mm	342.9	mm
rotational speed of the test unit	0.00875	rpm	0.574	rpm	0.0146	rpm	0.957	rpm
duration of 1 revolution	114.30	minutes	1.74	minutes	68.58	minutes	1.05	minutes
stroke length	700	mm	700	mm	700	mm	700	mm
maximum number of revolutions	1.225	-	1.225	-	2.041	-	2.041	-
rotational sensor	16	pulses/ rotation	16	pulses/ rotation	16	pulses/ rotation	16	pulses/ rotation
total transmission ratio	5715	-	5715	-	3429	-	3429	-
accuracy rotational position	254	pulses per °	254	pulses per °	152	pulses per °	152	pulses per °
Max. Force	6000	N	6000	N	6000	N	6000	N
Max. torque	500	Nm	500	Nm	327	Nm	327	Nm
Max. motor/pump size @ 500 bar	63	cc	63	cc	41	cc	41	cc

CONCLUSIONS

Low-speed performance measurements allow a detailed analysis of the performance and losses of a hydrostatic machine. The measurements are also of great importance for improving the torque capacity of a hydrostatic motor at startup. Furthermore, the recent trend to the development of electro-hydraulic actuators demands a strong improvement of the low-speed capabilities of hydrostatic pumps. Also for these developments, a low-speed test bench is of great importance.

The Dutch company INNAS has developed a new test integrated test bench which allows measurements between 50 and 5000 rpm to be combined with low-speed measurements between 0.001 and 1 rpm. At these ultra low rotational speeds, the behavior is close to real breakaway conditions from 0 rpm. The rotational speed is two orders of a magnitude lower than is described in ISO 4392-1.

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ANNEX A

LIST OF SENSORS AND SENSOR SPECIFICATIONS

Measurement	Sensor	Range	Accuracy	Brand
Torque (stator)	KiTorque 4541A	-	-	Kistler
Torque (rotor)	KiTorque 4550A500	-500…500 Nm	0.05% fso	Kistler
Low pressure level	THE	0…35 bar	0.05% fso	Honeywell
High pressure level	STJE	0… 520 bar	0.05% fso	Honeywell
Temperature	Type 13 PT100 class B	-50 … +400 C	±0.3 °C	Testo
Flow leakage	EF 0.1	0.1 … 10 l/min	2%	VSE
Flow high pressure	VS2	0.1 … 120 l/min	± 0.3 %	VSE