INVESTIGATIONS ON FLUID DYNAMICS OF HYDRAULIC ACCUMULATORS

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ABSTRACT

In state of the art hydrostatic installations accumulators of various designs are implemented to enhance the efficiency or to affect the dynamics of the hydraulic system. The advantages offered by the application of these devices are well known and their thermodynamic properties have been described well in the past. Yet the optimization of their particular performance regarding fluid dynamics is an existing problem because of the lack of experimental and analytical investigation devices. Whilst operating hydraulic accumulators high dynamic flow rates and velocities including steep pressure gradients are occurring so that a special technique had to be created to detect these values.

In the Fluid Power Laboratory of Trier University of Applied Sciences a new self developed accumulator test rig recently was installed to measure the operating parameters of hydraulic accumulators with the required high dynamic and accuracy. Special test procedures could be implemented to evaluate and improve especially the performance of the accumulators internal flow control valves.

The experimental investigations were accompanied by modelling a hydraulic accumulator in a Computational Fluid Dynamic CFD environment where its internal flow phenomena could be simulated successfully.

This presentation introduces the new test rig, the developed measuring procedures and the simulation model. Results of high dynamic flow and pressure measurements as well as flow simulations of hydraulic accumulators are shown.

INTRODUCTION

Accumulators are used in virtually any hydraulic system. Like a capacitor or battery serving in an electric circuit or a flywheel in a mechanic system, they are designed to store hydrostatic energy which can then be made available again upon demand. While the capacitive effect of hydraulic accumulators has been sufficiently described, there remains scope for flow optimization particularly with regard to highly dynamic accumulator charging and discharging process.

The Fluid Power Laboratory within the Engineering and Technology Department of Trier University of Applied Sciences, in conjunction with the industrial company HYDAC Technology GmbH, Sulzbach, both located in Germany, has been conducting in-depth investigations into the operating behavior of hydraulic accumulators at both experimental and analytical level for quite a while.

The aim of this research is to describe and quantify pressure storage characteristics in the most diverse operating states with a view to driving selective performance improvements.

Thus, for instance, piston accumulators are examined with regard to their seal-to-housing friction characteristics and noise emissions. Bladder and diaphragm type accumulators are subjected to extensive fluid mechanical studies of their discharge behavior.

For the described experimental studies, a particular test setup had to be developed and installed (Figure 1) so as to support wide-ranging modifications addressing the respective research tasks. In addition to experimental research, numerical simulations using software tools such as, e.g., ANSYS® can be put to use at the Trier University of Applied Sciences.

To exemplify these capabilities, the present paper outlines studies aimed at determining the volumetric flow characteristics of small-sized membrane accumulators. Moreover, the fundamentals underlying the simulation of the discharge operation of a bladder accumulator poppet valve are described, taking into account valve kinetics.

Figure 1 Accumulator Test Set-Up

TESTING FACILITIES

In the Fluid Power Laboratory at Trier University of Applied Sciences recently a special test-rig for experimental investigations on hydraulic devices was designed and realized.

Its core is a hydraulic power supply unit built around a 9-piston Type A10VSO 71 ccm axial piston pump sourced from Bosch Rexroth Brueninghaus Hydromatik. This system is powered by a 55 kW asynchronous motor, the speed of which can be varied between 700 and 2700 rpm by means of a 90 kW frequency converter. Alternatively, a soft-start feature for constant-speed operation has been implemented. The tank has a capacity of 500 liters [1]. Figure 2 shows the testing facilities.

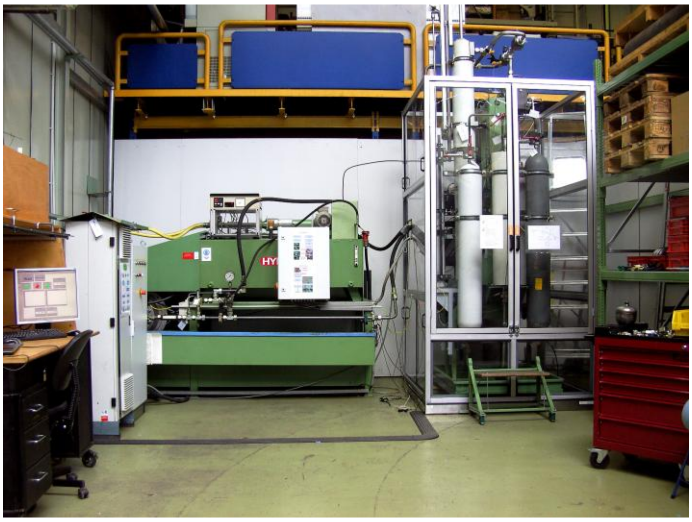

Figure 2 Test-Rig for Experimental Investigations on Hydraulic Devices at Trier University of Applied Sciences

This test-rig can be variously configured for accumulator tests so as to accommodate diverse objectives and it was modified to carry out the described investigations [2].

INVESTIGATING THE ACCUMULATORS DISCHARGE BEHAVIOUR

Membrane-type accumulators typically consist of a spherical to cylindrical, pressure-resistant steel vessel (Figure 3). The gas and hydraulic fluid compartments are separated by a diaphragm usually made of an elastomer. This diaphragm is fixed inside the storage reservoir via a holding ring. Membrane-type accumulators are of welded or bolted construction.

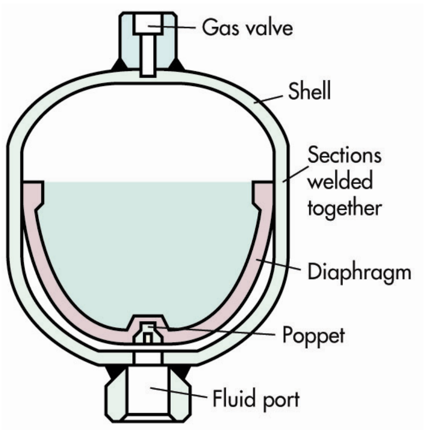

Figure 3 Membrane Type Hydraulic Accumulator [3]

The circuit diagram of the test rig shown before had to be modified specifically for research on membrane-type accumulators of low nominal volumetric capacity (Figure 4).

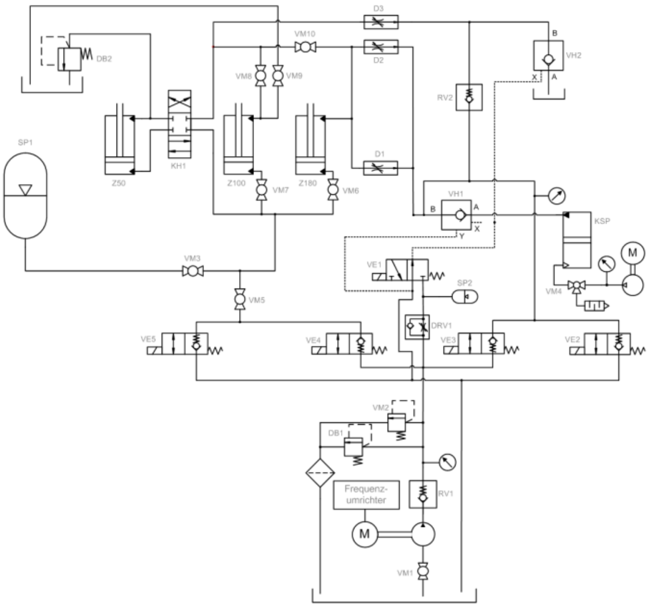

Figure 4 Test Set-Up: Hydraulic Circuit Diagram

The system can be used now to carry out discharge tests under defined boundary conditions. To this end, a specimen is first filled with a defined quantity of oil and is then emptied into a measuring cylinder via a throttle valve providing a variable volumetric flow rate. A displacement of a piston and its piston rod is thus produced. The amount of piston displacement is determined using an incremental position transducer attached to the piston rod of the measuring cylinder. Taking into account the geometry of the measuring cylinder and the time elapsed, it is possible to determine the volumetric discharge flow rate and the quantity discharged. Conversely, the residual oil content in the accumulator can be calculated from the difference between the filling volume and the discharged quantity. Every discharge cycle thus yields a measuring curve wherein the mean and maximum volumetric discharge flow rates are represented as the gradient of the plotted curves in Figure 5. In order to obtain an adequate resolution of the piston displacement even with very small filling quantities, special measuring cylinders had to be built and installed for the test series described herein.

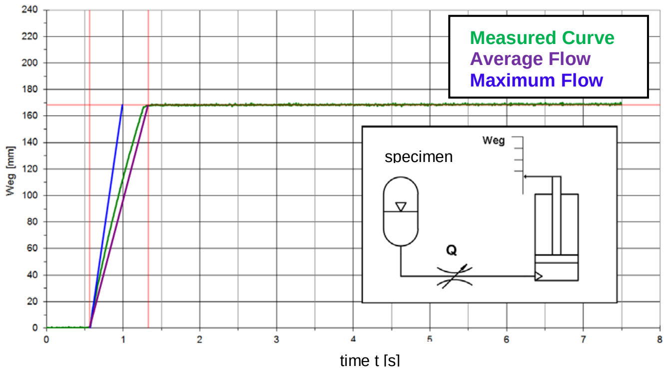

Figure 5 Discharge Curves of an Hydraulic Accumulator

Upon completion of several measuring runs using the same accumulator with variation of the flow rate, filling quantities and mounting orientation, the data obtained can be collated in a further diagram (Figure 6). In this summary presentation of the retained fluid quantity, as determined from the filling volume and discharge quantity over the volumetric flow rate, each individual measurement corresponds to exactly one point. The resulting family of characteristic curves supplies valuable information about the accumulator's discharge behavior for a given mounting orientation, thus providing engineers with an improved estimate of its operating behavior that facilitates the choice of a suitable accumulator at the system design and rating stage. However, measuring series conducted with different accumulators and accumulator configurations have also revealed different behavio patterns and hence provide a basis for a further optimization of these accumulators.

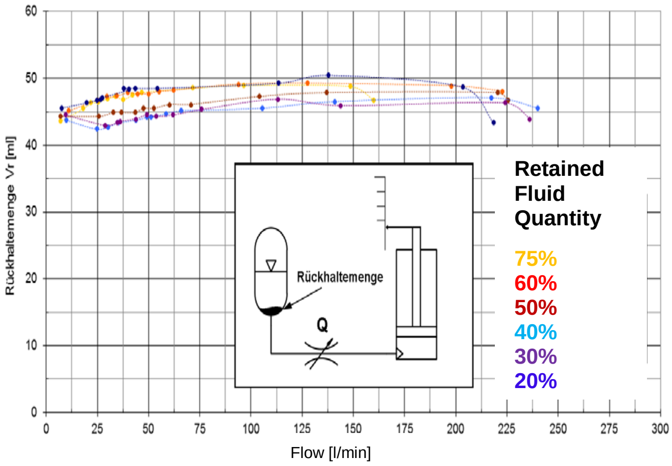

Figure 6 Characteristic Diagram

By representing these curve maps in an appropriate manner, the correlations between technical properties of different accumulators can be rendered more evident. Thus, for instance, the 3D diagram shown in Figure 7 below illustrates the design particularities of two accumulators which are otherwise very similar in design. The advantages provided by the design of Type 3 over Type 2 can be clearly seen.

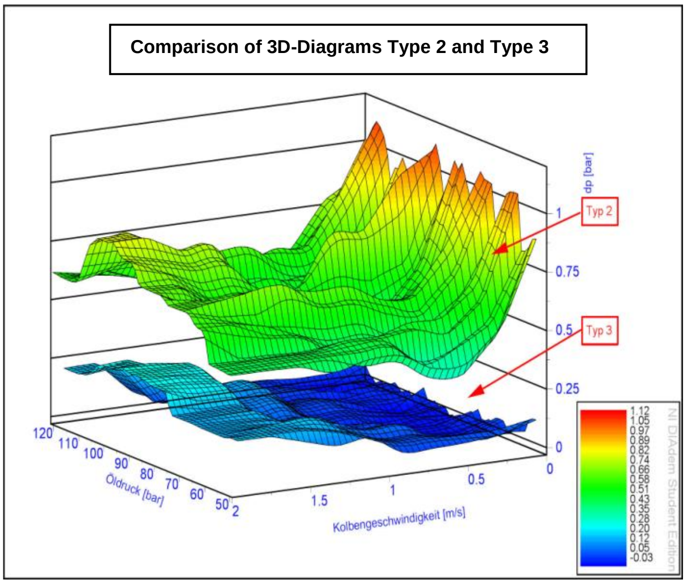

Figure 7 Detected Performance Advantage

CFD-SIMULATION OF THE ACCUMULATORS POPPET VALVE

Bladder-type accumulators (Fig. 8) consist of a fluid compartment and a gas compartment which are separated by a bladder. The bladder typically contains nitrogen. The fluid present between the bladder and the tank is linked to the hydraulic system. When the system pressure rises, the bladder accumulator fills with hydraulic fluid and the gas in the bladder is compressed. When the pressure drops, the compressed gas expands and thereby forces the stored fluid into the hydraulic circuit.

Unlike a membrane accumulator, a bladder -type accumulator is closed off by a poppet valve in its completely empty state; this valve is commonly actuated by the gas bladder or by the fluid flow when the pressure falls abruptly.

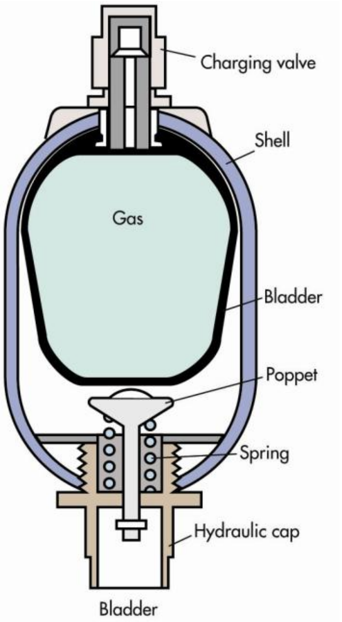

Figure 8 Bladder Type Accumulator [3]

In order to characterize the valve's dynamic behaviour with a view to pursuing further R&D aimed at boosting the accumulator's operating efficiency, it is necessary first of all to derive the fundamentals for a subsequent transient (non-steady) simulation of the valve closing operation.

In an initial step this involves the creation of a two-dimensional rendering of the valve geometry in the simulation environment, the meshing of this structure, and the associated steady-state calculation. For the sake of obtaining realistic simulations, the boundary conditions – pressure, volumetric flow – can be defined from volumetric flow curve maps established in previous test rig measurements so that the parameters can be set accordingly for the simulation. These real-life boundary conditions are applied to the two-dimensional model via suitable conversion procedures.

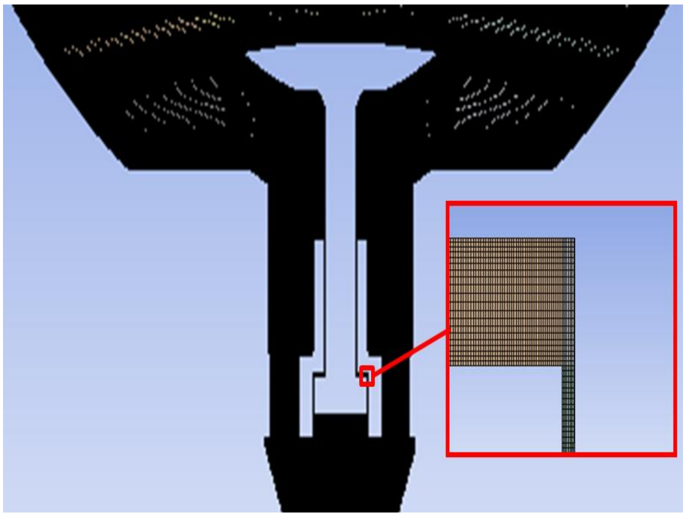

Figure 9 Accumulators Valve Mesh in ANSYS®CFX

Figure 9 shows the geometry in meshed form by way of an example. The area between the valve disc damping sleeve and the housing plays a particularly important role since the flow originating here can be expected to have a major impact on the valve's behaviour. Accordingly, the mesh must exhibit a particularly high resolution in this area so that the subsequent simulation will deliver realistic results. With the geometry thus meshed, it is possible to calculate the flow velocities using the specific boundary conditions and appropriate settings within

ANSYS®CFX. Fig. 10 shows a velocity profile derived from such a steady-state flow simulation.

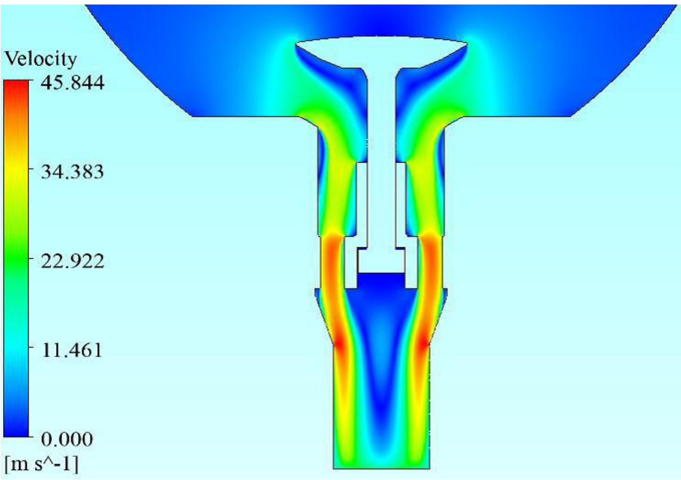

Figure 10 Accumulators Velocity Profile in ANSYS®CFX

FURTHER INVESTIGATIONS

At a subsequent stage, simulations can be carried out using the *RigidBody* function in ANSYS®CFX. Here the valve disc which is represented by a hollow body in the mesh (i.e., it is not meshed itself) is defined as a rigid body. With the aid of a system of coordinates, the valve disc is assigned a center of mass on which the prevailing forces can act. In addition, this center of mass can be given certain degrees of freedom so that the direction of movement will be unambiguously defined. In the case considered here, the resulting translation corresponds to a change in the momentum equation for the force acting on the rigid body:

$$\frac{dP}{dt} = F \tag{1}$$

For a displacement of the center of mass x, the motion equation can be written thus:

$$m\ddot{x} = F \tag{2}$$

Here, *m* is the mass of the rigid body and *F* represents the sum of all forces, with due consideration being given to fluid mechanics, the weight of the rigid body, as well as spring forces and/or external forces:

$$m\ddot{x} = F = F_{Aero} + mg - k_{spring}\ (x - x_{so}) + F_{ext} \tag{3}$$

The impulse equation is solved using the NEWMARK integration method. The conventional method can be expressed as follows:

$$h_{n+1} = h_n + \Delta t_n \dot{h}_n + \Delta t_n{}^2 \left((\frac{1}{2} - \beta)\, \ddot{h}_n + \beta \ddot{h}_{n+1} \right) \tag{4}$$

$$\dot{h}_{n+1} = \dot{h}_n + \Delta t_n\ (1-\gamma)\, \ddot{h}_n + \gamma \ddot{h}_{n+1} \tag{5}$$

where *t* is the time and *h* stands for a value denoting, e.g., a position in space. The indices *n* and *n+1* represent the known solution at time *t* and the unknown solution at time *t+1.*

NEWMARK's integration scheme depends on two real parameters, β and γ, which have a direct influence on the stability and accuracy of the integration process. In typical applications of the NEWMARK method the values of β and γ are put at 0.25 und 0.5, respectively; this also holds true for the *RigidBody* function.

For fixed values of the external forces, a time-related solution can be derived using the following method:

Equation (3) is written thus:

$$m\ddot{x}_{n+1} = F = F_{Aero} + mg - k_{Linear}\ (x_{n+1} - x_{so}) + F_{ext} \tag{6}$$

which is then inserted into “Eq (4)”, with *x* being substituted for *h*. After Transposition x_{n+1} is defined to:

$$x_{n+1} = \frac{\frac{m}{\beta \Delta t^2} x_n + \frac{m}{\beta \Delta t} \dot{x}_n + m\left(\frac{1}{2\beta} - 1\right) \ddot{x}_n + F_{Aero} + mg + k_{linear} x_{so} + F_{ext}}{\frac{m}{\beta \Delta t^2} + k_{linear}} \tag{7}$$

From “Eq (4)”, $\ddot{x}_{n+1}$ is determined as follows after substitution of *x* for *h* and due transposition:

$$\ddot{x}_{n+1} = \frac{1}{\beta' \Delta t^2}\ (x_{n+1} - x_n) - \frac{1}{\beta \Delta t} \dot{x}_n - 1\left(\frac{1}{2\beta'} - 1 \right) \ddot{x}_n \tag{8}$$

Following substitution of *x* for *h* in “Eq (5)” and transposition, $\dot{x}_{n+1}$ finally is determined thus:

$$\dot{x}_{n+1} = \dot{x}_n + \Delta t\ (1-\gamma)\, \ddot{x}_n + \gamma \dot{x}_{n+1} \tag{9}$$

An iterative solution by the method described above is needed in order to reflect the dependence of the forces on the position of the rigid body. By means of the simulation method thus outlined, we can then vary the geometry of the valve body so as to optimize the valve's discharge behavior and hence, improve the efficiency of the entire bladder -type accumulator without having to laboriously fabricate specimens and subjecting each of them to extensive rig testing.

CONCLUSION

Means and methods whereby hydraulic accumulators can be investigated experimentally and analytically in the Fluid Power Laboratory of the Trier University of Applied Sciences have been shown on the basis of some examples. The accumulator test rig custom-built there has been employed to investigate hydraulic accumulators of the most diverse types and nominal capacities with a view to quantitating, for the first time, the parameters characterizing their charging and discharging behavior so as to establish a map of characteristic performance curves. By adding a special measuring cylinder to a test rig built specifically for accumulator trials it has become possible also to examine the discharge flow behavior of membrane accumulators of ultra-small nominal volumetric capacities. The performance curve sets ('maps') derived from the measurement readings obtained provide insights into the operating behaviour of the most diverse accumulators in different operating states. In the future, these findings will facilitate the selection of a suitable accumulator at the system design and rating stage. CFD-simulations of a closing poppet valve have created the prerequisites for gaining new insights in the field of bladder accumulators as well. More particularly, the results of these simulations provide data on the valve's flow and damping behaviour and will thus form the basis for further improvements in bladder accumulator design.

REFERENCES

[1] ORTWIG, H. Experimental and Analytical Vibration Analysis in Fluid Power Systems; IJSS International Journal of Solids and Structures 42 (2005), S. 5821 – 5830

[2] BALTES, H.; BUSS, A.; KLOFT, P.; ORTWIG, H.; SCHIFFMANN, J. Verbesserungspotential nutzen - Experimentelle und analytische Untersuchung von Hydrospeichern; O+P Fluidtechnik für den Maschinen- und Anlagenbau 06/2013, S. 34 – 38

[3] COSFORD, J. Accumulators Add Functionality to Hydraulic Circuits; hydraulicspneumatics.com, April 2014