

Metering Characteristics of a Closed Center Load – Sensing Proportional Control Valve

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ABSTRACT

The investigation of the flow through the metering section of hydraulic components plays a fundamental role in the design and optimization processes. In this paper the flow through a closed center directional control valve for load –sensing application is studied by means of a multidimensional CFD approach.

In the analysis, an open source fluid-dynamics code is used and both cavitation and turbulence are accounted for in the modeling. A cavitation model based on a barotropic equation of state and homogeneous equilibrium assumption, including gas absorption and dissolution in the liquid medium, is adopted and coupled to a two equation turbulence approach.

Both direct and inverse flows through the metering section of the control valve are investigated, and the differences in terms of fluid – dynamics behavior are addressed. In particular, the discharge coefficient, the recirculating regions, the flow acceleration angle and the pressure and velocity fields are investigated and compared.

INTRODUCTION

Numerical analysis is gaining an important role in the design of hydraulic components and systems. In particular, multidimensional simulation is increasingly applied to the investigation of the fluid dynamics behavior of hydraulic component in order to broaden and complete the experimental campaigns. Moreover, the human and computational resources to be involved in the numerical analysis are now not only acceptable, but

also advantageous, due to the continuous development of computational platforms and CFD tools.

In literature many examples are available concerning the advantages gained by using the numerical analysis. Among them, several applications on the study of hydraulic valves can be pointed out; for instance, in [1 - 3] the CFD analysis was used to study the flow field and the flow-induced forces in hydraulic valves, as well as in [4 - 8] theoretical approaches and experimental investigations have been compared to CFD predictions for the hydraulic valves design and optimization.

Because of more powerful computational resources and the developing of more accurate numerical models, it is possible to account for more complex geometries and physical phenomena in the CFD simulations. Nevertheless the accuracy and reliability of the numerical results must be addressed when approaching a new problem, since they are demonstrated to be very sensitive to the fluid-dynamics characteristics of the case studied (such as the Reynolds number in the critical sections, the geometry complexity and the boundary conditions).

For example, the widely used cylindrical orifices (metering valves, directional valves, injectors, instruments, ...) show fluid dynamic performances significantly affected by geometrical details; consequently, a sharp-edge inlet presents an efflux coefficient lower than a rounded one [2, 3], while small modifications in the curvature can determine remarkable differences both in the flow field, and in pressure losses.

This paper focuses on the development and the tailoring of an open source multidimensional CFD code to the

analysis of the internal flow-field in hydraulic components. In this paper the metering characteristics of a closed center load – sensing proportional control valve are investigated using the numerical simulation.

The open source OpenFOAM [9] code is applied to predict the direct and inverse flow through the metering edge of the control valve under different operating conditions. The numerical models used in the analysis include cavitation, gas absorption and release and turbulence.

The hydraulic valve performance is addressed in terms of overall discharge coefficient, efflux angle, flow forces and pressure and velocity distributions in the critical region.

THE CLOSED CENTER CONTROL VALVE DESIGN

The multiple notched edge under study is the main metering part of a closed center electro-hydraulic load-sensing proportional control valve, usually adopted in multi-slice blocks to control parallel actuations of industrial, agricultural and earthmoving applications.

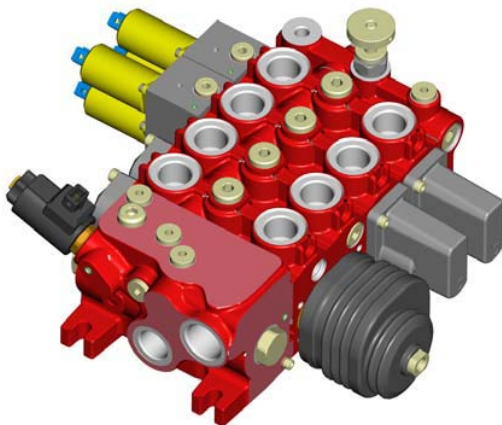


Figure 1. The control block for load-sensing application

As well known, the application of the load-sensing concept to hydraulic circuit enables efficient management of the hydraulic power delivered to actuators and improves the overall system efficiency. The reference architecture of a load-sensing control block is depicted in Figure 1, and it presents:

- an inlet cover, which generally includes the main compensator for managing the total pressure drop across the control block, and the pressure relief valve setting the maximum workload for actuators;

- two, or more, proportional control valves, normally equipped with a local pressure compensator and a direct connection to the load-sensing piloting line;
- an outlet cover.

In its simpler design, the proportional control valve for load-sensing applications is intended to directly react to a pressure signal (coming from the actuator) in order to maintain as constant as possible the pressure drop across their metering edges. This action is normally influenced by a local pressure compensator which could have either a single or a double stage configuration, and is usually placed upstream or downstream the control valve center. Therefore, for a given operating position of the control valve spool, and for the flow-rate across the efflux area of metering orifices the pressure drop can be maintained constant independently by the actuator workload.

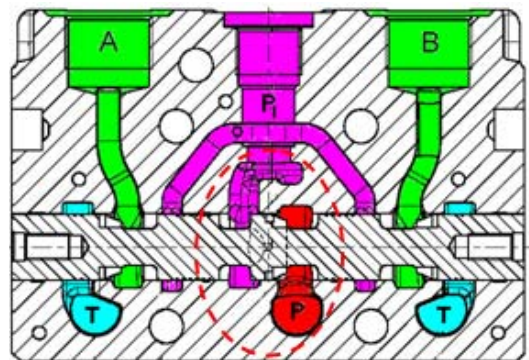


Figure 2. The proportional control valve main section

The Figure 2 details the closed center load-sensing proportional control valve studied here. It is designed for operational field limits up to 100 l/min as maximum flow-rate and up to 350 bar as maximum pressure. As shown, the center presents a Z connection between the high pressure port (P, in red) and the internal volume (P1, magenta), which is metered in all spool directions by a twice notched edge. At the same time, both connections between the internal volume and the actuator ports (A and B, green), and those between the actuators ports and the discharge line ports (T, blue) are metered by multiple notched edges. It is worth mentioning that the central volume indicated as P1 normally hosts the local pressure compensator (not included in the sketch of in Figure 2).

Figure 3 presents an explanatory section of the proportional control valve spool including a zoomed view of the design of the central edge. As shown, two equal notches located at 180° characterize each side of the central edge, and each couple of notches has a 90° rotation with respect to the other one. Moreover, the notches on the left side of the central edge meter the

hydraulic power during the spool motion from the center to the right (when P1 opens to A, and B opens to T), while the notches on the right side works during the motion from the center to the left (when P1 opens to B, and A opens to T). In this way, the high pressure port P is connected to the control valve internal volume through an asymmetric path, which depends on the spool direction of motion.

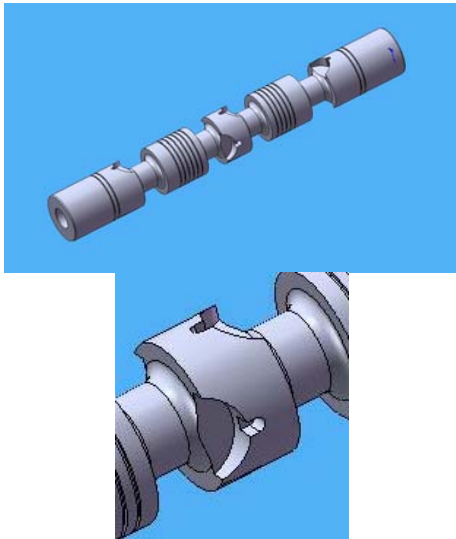


Figure 3. The proportional control valve spool

Figures 4 and 5 detail the metering characteristics of the proportional control valve central edge, as determined for an operating condition involving the maximum flow-rate addressed to the control block and a maximum equivalent work-load of 130 bar applied to A and B ports.

More in details, Figure 4 highlights the flow-rate metering curve, as obtained for a complete spool travel between the end-stops. As shown, the curve is practically symmetrical with respect to the spool position, and the flow-rate addressed both to port A and to port B is monotonically increasing as the spool travel (and, obviously, to metering area) increases. Moreover, the flow-rate increases following two consecutive linear trends, with a relevant variation of the gradient occurring at the end of notches. Finally, looking at the flow-rate behaviour no evidence about the influence of the fluid path in the notches can be found.

Analogous considerations can be done also accounting for the pressure variation at the high pressure port of the proportional control valve, see Figure 5. As shown, the main compensator (located in the inlet cover) regulates the pressure value close to 15 bar until the connection between P and P1 is closed. When the metering area becomes greater than zero and the fluid efflux interests the twice notched edges, the pressure increases following a parabolic trend; afterward, when the metering

area is not defined by notches, pressure tends to its maximum value with a linear tendency.

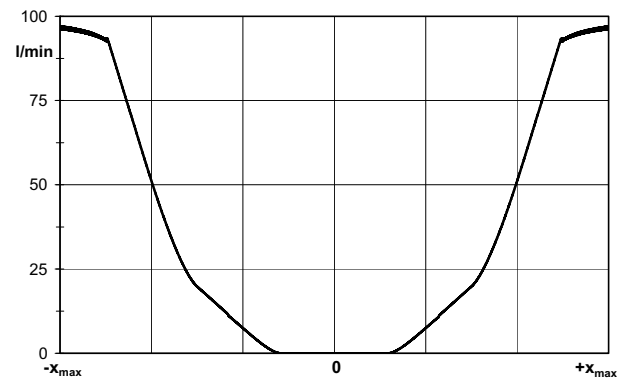


Figure 4. Flow-rate metered by the central edge.

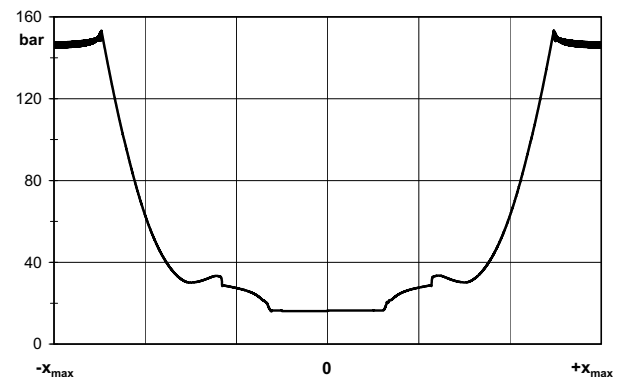


Figure 5. Pressure variation at the control valve high pressure port.

NUMERICAL APPROACH

The CFD analysis of the closed center load sensing proportional control valve is carried out by means of the open source computational fluid dynamics code OpenFOAM. Bounded central differencing is used for the discretization of the momentum, second-order upwind for subgrid kinetic energy, and the mixture fraction. Pressure-velocity coupling is achieved via a PISO (Pressure Implicit Splitting of Operator algorithm) similar procedure. The second-order implicit method is used for time integration scheme.

The cavitation model used in this work is based on a barotropic equation of state approach and it assumes that the two phases (gas and liquid) have equal velocities and temperatures at any point of the flow (i.e. homogeneous equilibrium). The assumption of isothermal flow is also made. The amount of dissolved gases which are locally released is calculated by introducing the Henry law for the equilibrium condition and accounting for the time dependence of solubility on a Bunsen coefficient basis.