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Multi-phase and Multi-component CFD Analysis of a Load – Sensing Proportional Control Valve

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Abstract: The paper analyzes the flow through a directional control valve for load –sensing application by means of a multi-phase and multi-component CFD approach. Numerical modeling includes both cavitation and aeration; in particular, the Rayleigh-Plesset equation and the inertia controlled growth model for bubble formation are adopted. The effects of gas release and vapor formation as well as turbulence on the main valve metering characteristics are investigated. The results show a remarkable influence of the aeration phenomena on the recirculating zones downstream of the metering area and thus on the cavitation onset region. The flow forces on the valve spool are also analyzed and different calculation approaches are compared.

Keywords: CFD, cavitation, aeration, control valve

1. 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 Yang (2004 and 2005) the CFD analysis was used to study the flow field and the flow-induced forces in hydraulic valves, as well as in Borghi et al. (2000, 2005 and 2005) and in Del Vescovo et al (2003) and in Franzoni et al. (2008), theoretical approaches and experimental investigations have been compared to CFD predictions for the hydraulic valves design and optimization.

In this paper the metering characteristics of a closed center load – sensing proportional control valve are investigated using the multi-phase multi-component numerical simulation. The CFD tool is used to simulate the effects of different operating conditions on the valve flow characteristics. In particular, several opening displacements and pressure drops are analysed and the onset regions for aeration and cavitation are addressed.

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

2. CONTROL VALVE GEOMETRY

The control valve under study (see Figure 1) is the main metering part of an electro-hydraulic load-sensing proportional valve, usually adopted in multi-slice blocks to control parallel actuations of industrial, agricultural and earthmoving applications.

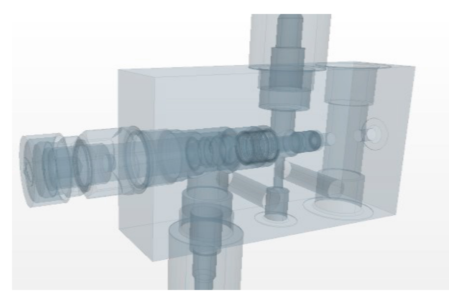

Figure 1. The analysed geometry.

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.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 work-load.

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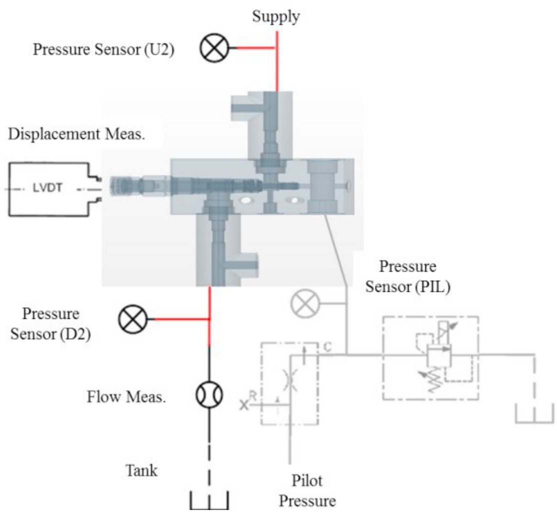

Figure 2. Layout of the test rig.

The Figure 2 shows the schematic of the layout of the test rig used in the Manufacturer's R&D Department for measuring the flow rates and pressure drops for the load-sensing proportional control valve studied here. In particular, the valve is designed for operational field limits up to 150 l/min as maximum flow-rate and up to 350 bar as maximum pressure.

Figures 3 and 4 detail the metering characteristics of the proportional control valve central edge, as determined for an operating condition involving the flow-rate addressed to the control block for a varying pressure drop between the inlet and outlet ports (i.e. D2 and U2 respectively).

More in details, Figure 3 highlights the flow-rate metering curve, as obtained by varying the pressure drop across the valve for a constant spool displacement. Due the slow transient condition the curve is practically symmetrical with respect to the mid point of the time history.

3. NUMERICAL APPROACH

The CFD analysis of the load sensing proportional control valve is carried out by means of the computational fluid dynamics code STAR-CCM+, licensed by CD-Adapco. Bounded central differencing is used for the discretization of the momentum, second-order scheme for subgrid kinetic energy, and the mixture fraction. The conservation equations for mass, momentum, and energy are solved simultaneously using a pseudo-time-marching approach The second-order implicit method is used for time integration scheme.

The cavitation model available in the code and used in this work is based on the Rayleigh-Plesset equation and uses the inertia controlled growth model for bubble formation. The mutli-component cavitation bubble growth rate is estimated using the inertia controlled growth model described in Sauer (2000):

$$\left(\frac{DR}{Dt}\right)^2 = \frac{2}{3}\left(\frac{p_{sat,m} - p_\infty}{\rho_l}\right) \quad (1)$$

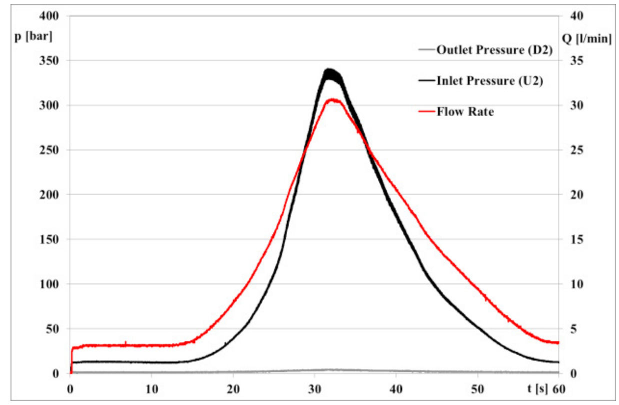

Figure 3. Measured flow parameters for 0.2 mm displacement.

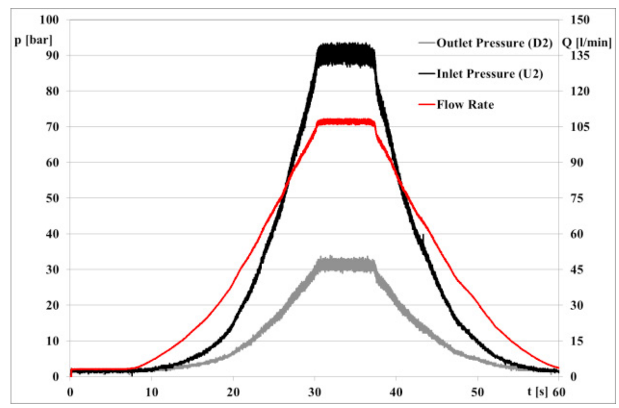

Figure 4. Measured flow parameters for 1.5 mm displacement.

where the mixture saturation pressure is defined as follows:

$$p_{sat,m} = \sum_{i}^{N_c} X_{i,l,s}\, p^*_{sat,i} \quad (2)$$

This expression is Raoult's Law, with $p^*_{sat,i}$ indicating the saturation pressure of the pure component. The interfacial molar fraction of the liquid components is approximately their value in the bulk, so $X_{i,l,s} \approx X_{i,l,\infty}$.

In Eqn. (1), $p_{sat,m}$ is the saturation pressure corresponding to the temperature at the bubble surface, p_∞ is the pressure of the surrounding liquid and is the liquid density. Eqn. (1) is a simplification of the more general Rayleigh-Plesset equation which takes into account the inertia, viscous, and surface tension effects:

$$R\frac{d^2R}{dt^2} + \frac{3}{2}\left(\frac{dR}{dt}\right)^2 = \frac{p_{sat} - p_\infty}{\rho_l} - \frac{2\sigma}{\rho_l R} - 4\frac{\mu_l}{\rho_l R}\frac{dR}{dt} \quad (3)$$

μ_l is the liquid viscosity and σ is the surface tension coefficient. Research results suggest that for most practical applications, it is not necessary to account for the viscous and surface tension effects as described in Brennen (1995).