

Physical Design of Hydraulic Valves in Modelica

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Abstract

This paper focuses on the physical design of hydraulic relief and servo valves and its applications. Specifically, this paper serves to illustrate how the physical design parameters of hydraulic components can be incorporated into system modeling and their effect on the system dynamics and stability characteristics. Detailed physical models of a relief valve and a servo valve developed using the Hydraulics Library[®] are discussed in this paper with particular emphasis on the effect of design parameters on the stability characteristics. A simple design of experiment (DoE) to illustrate robust design methods for hydraulic system design is also shown with the use of the FMI Toolbox (FMIT) for MATLAB[®]. Furthermore with the help of these two valve models, we seek to bring to the attention of the community, a limitation in open loop controls analysis in an acausal modeling environment where the feedback loops are embedded in the physics of the model.

Keywords: Hydraulic Valves; Hydraulic Component Design; Mechanical feedback; Stability Analysis; Hydraulics Library; FMIT

1 Introduction

Hydraulic control valves use mechanical motion to control or regulate fluid power in a hydraulic circuit. These valves serve as the interface between the mechanics and fluid dynamics in hydraulic systems and their performance characteristics are therefore critical to the safe and optimal operation of the systems in which they are employed [1]. Relief and servo valves are among critical components used in a wide variety of hydraulic systems and are respectively operated to regulate supply pressure to the load and convert fluid power to mechanical actuation.

In this paper, we discuss detailed Modelica models of a pressure relief valve and a servo valve and include the physical design parameters of these valves

and study the effect of these on the stability characteristics.

For the modeling of these valves, the newly developed Elements package of the Hydraulics Library is used. The Hydraulics Library is a commercial Modelica library from Modelon AB that enables modeling of fluid power systems in Modelica. The Elements package is developed to incorporate hydraulic component sizing into the design and modeling process. The library provides a comprehensive set of components typically used in hydraulic system modeling and provides the flexibility to build complex models from the basic building blocks available from the library. The Hydraulics Library with the Elements package is available for use with both Dymola and MapleSim[®].

Due to its application in multiple engineering domains, the library provides a set of basic building blocks of components from which a more detailed model of a hydraulic system can be constructed. The elements package for example, provides models of a spool and a piston, which are connected through mechanical and hydraulic port connectors in any number of ways to construct detailed models of relief and directional control valves.

In this paper, we present detailed models of a Pressure Relief Valve and an Electro-Hydraulic Servo Valve (EHSV) constructed using components from the Hydraulics Library. Further, a Functional Mock-up Unit (FMU) of these models is imported into MATLAB[®] using the Functional Mock-up Interface Toolbox¹ for MATLAB [5] and linearized to study their stability characteristics and demonstrate robust design techniques. The two examples of the valves, apart from demonstrating the physical design of hydraulic components, also showcase a limitation in an acausal modeling environment where feedback loops embedded within the physics of the model need to be broken for analysis purposes. In controls analysis, such systems can only be linearized by manually

¹FMIT for MATLAB is a commercial FMI tool from Modelon AB for the integration of physical models in MATLAB/Simulink.

modifying the physical equations. In our opinion, this is not an elegant solution and we illustrate this point through the two examples of the valves.

2 Hydraulic Elements Package

The Elements package of the Hydraulics Library provides an easy to use interface to model both the mechanics and hydraulic characteristics of hydraulic systems. Figure 1 illustrates the elements package. The subsequent subsections briefly discuss the various components of the elements package and their features.

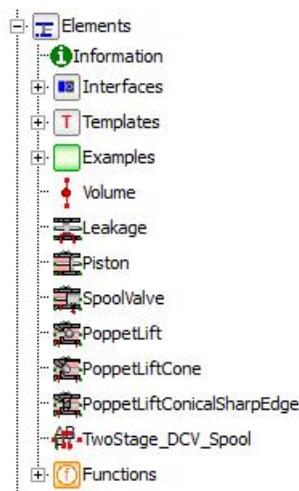


Figure 1: The Elements package of the Hydraulic Library

2.1 Connecting port interfaces

Three types of connecting ports are used in the components of the Elements package and these are illustrated in Figure 2.

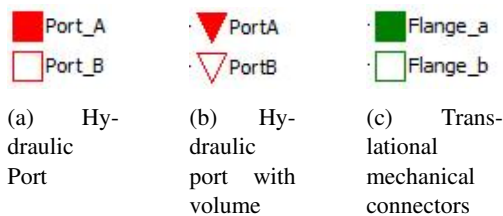


Figure 2: Connecting port interfaces used in the Hydraulics Library

The hydraulic port connectors in Figure 2(a) are the default connectors used throughout the hydraulics library with pressure and mass flow rate as the potential

and flow variables respectively. The connectors in Figure 2(b) are similar to those of Figure 2(a) except for the presence of the auxiliary volume variable. This port is used to connect the variable volume element with components where the volume change arises. The mechanical connectors in Figure 2(c) are the translational mechanical connectors from the Modelica Standard library with displacement and force as the potential and flow variables respectively.

2.2 Volumes

The Elements package provides two volume components that differs from the standard lumped volume component in the Volumes package of the library in that the volume is computed outside of the component and determined from the volume variable of the hydraulic port with volume. The first volume component (Figure 3(a)) represents a variable lumped volume where the pressure in the volume is calculated from the following continuity equation:

$$V \frac{dp}{dt} = \frac{\beta}{\rho} \frac{dm}{dt} - \beta \frac{dV}{dt} \tag{1}$$

where p is the pressure in the volume, V is the volume computed from the outside of the component and used through the port, ρ, β are the density and bulk modulus of the hydraulic fluid computed at pressure p and m is the mass flow through the volume component.

The second volume component (Figure 3(b)) does not include any pressure dynamics and is solely intended for connections between the standard hydraulic port and the port with volume.

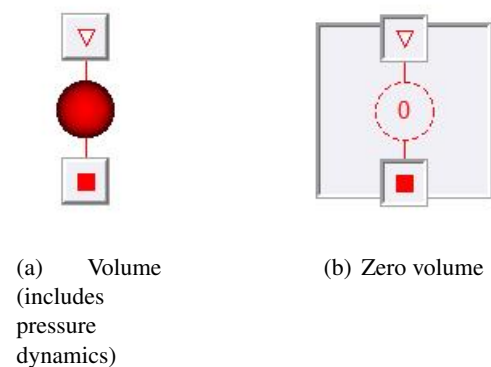


Figure 3: Hydraulic volumes used in the Hydraulics Library

2.3 Valve Components

The basic building blocks of valve components provided in the Elements package are for leakage, piston, spool and poppet lift and these are illustrated in Figure 4.

- The leakage component (Figure 4(a)) models laminar flow of fluid leakage due to radial clearance, underlap or overlap and the leakage path length is assumed to be a constant. Variable length leakage is expected to be included in a future release of the library.
- The piston (Figure 4(b)) component represents a hydraulic piston with an open chamber ending at both sides. The chamber volume is computed as a function of the displacement due to the net force on the piston head. The pressure and mass flow rate of the fluid into/out of the piston is computed as a function of this change in chamber volume.
- The spool valve (Figure 4(c)) component models the spool and sleeve of a 2-way single land spool valve. The fluid flow through the spool is a function of the spool displacement modeled as a variable area orifice. The flow area of this orifice is computed from the geometry of the valve opening and this option is parameterized with 4 options: linear, quadratic, circular or custom (tabular user input). The spool valve also includes the effect of flow forces computed from the spool displacement and pressure drop across the valve. The valve openings are modeled as orifices and the expressions are regularized for numerical stability in the orifice equations in these components.
- Three variations of a poppet valve (Figure 4(d)-4(f)) are also provided in the library, each differing in the geometry of the poppet lift and seat. Like the spool valve, each of these poppet valves includes the effect of flow forces and regularized expressions for numerical robustness.

3 Modeling and Open-Loop Stability Analysis of a Hydraulic Pressure Relief Valve

Hydraulic relief valves act to regulate pressure in a hydraulic system where the pressure to be controlled

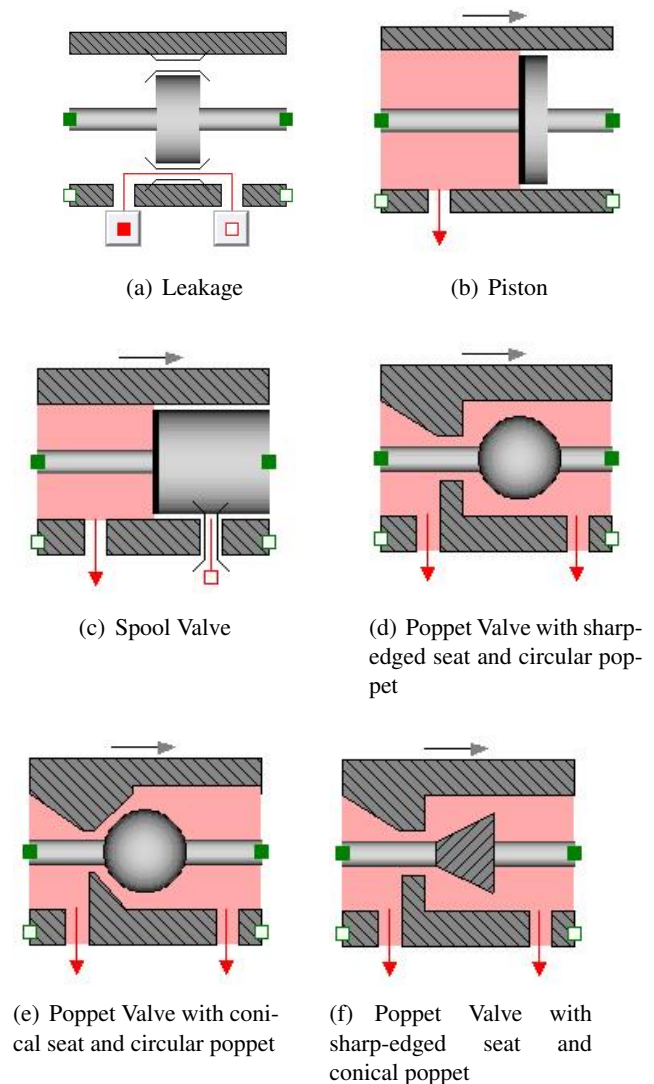


Figure 4: Building blocks to model hydraulic valves

is sensed in the valve end area and compared with a spring force setting [1]. In this work, the pressure relief valve described in [1] is modeled as a 3-way 2-land spool valve in Dymola using components from the Modelica Standard Library and the Hydraulics Library and the schematic of the valve is shown in Figure 5.

The spring with spring constant K_s , is preloaded with a force of F_0 . This preloading sets the pressure P_c , in the spool valve chamber such that the valve is open with a displacement of x at steady state. As the supply pressure to the load increases, the spring is compressed to open the spool valve to allow more flow through the valve and into the tank maintained at atmospheric pressure. This relieves the excess pressure in the supply line. The opening of the valve is restricted between the geometric constraints of the spool and the supply

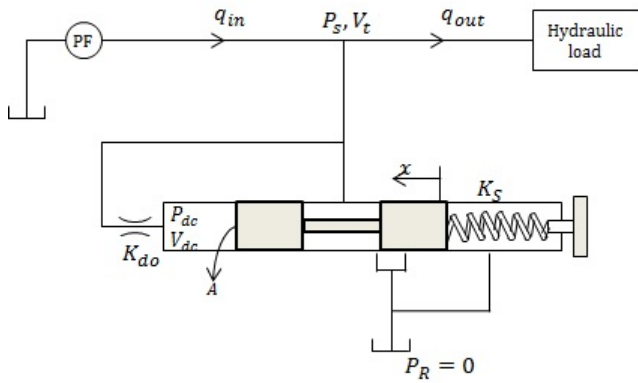


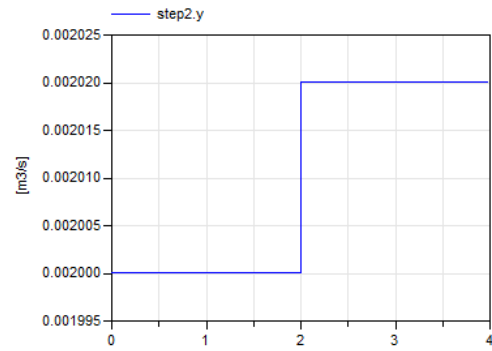
Figure 5: Pressure Relief Valve [1]

pressure determines the level of opening of the valve. The Modelica model of the relief valve is shown in Figure 15.

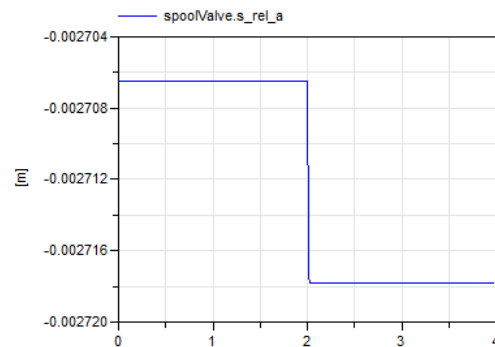
The geometric parameters of the valve were obtained from data sheets from Eaton Corp. [3] and the procedure for the derivation of valve parameters from data sheets is described in [4]. These parameters and the boundary conditions of the system are tabulated in Table 1. In Figure 15, the pistons are identical with the exception of one having a real input for the purpose of open loop analysis. With the boundary conditions from Table 1, the trajectories of the spool displacement and the pressures in the volumes are shown in Figure 6. Figure 6(a) shows an increase in the flow rate of 1% in the supply line pressure modeled as a step function. This increase in the supply flow increases the net pressure force in the spool valve and opens the valve more (Figure 6(b)) resulting in a larger flow area (Figure 6(c)) and hence more flow through the valve. This relieves the excess pressure in the supply line resulting in an increase in pressure of in the supply line of about 1.6% (Figure 6(d)).

3.1 Open Loop Stability Analysis of Pressure Relief Valve

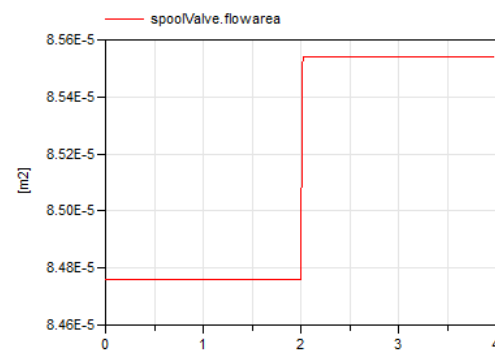
The dynamic model of the pressure relief valve in Figure 15 was perturbed from its steady state (Figure 6) by an increase in the supply pressure. This model was set-up at this steady state operating point and linearized for open loop analysis. The open loop model was set-up such that the pressure in the piston and the force the pressure exerts on the spool are decoupled (or “broken”). This means that the transients in the pressure are de-coupled from the pressure-force equation. This is an example of a feedback loop embedded within the physics of the model. There ap-



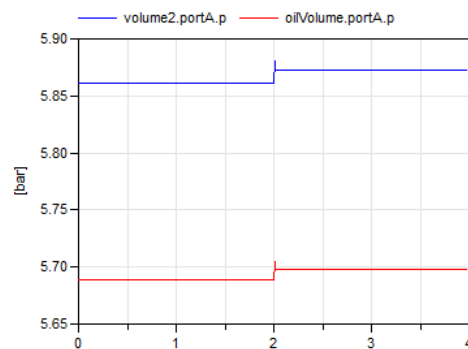
(a) Supply flow



(b) Spool displacement (also valve opening)



(c) Flow area of valve compared with maximum flow area of $4.8919 \times 10^{-4} \text{m}^2$



(d) Supply line pressure

Figure 6: Trajectories of the inlet flow, line pressure and valve opening

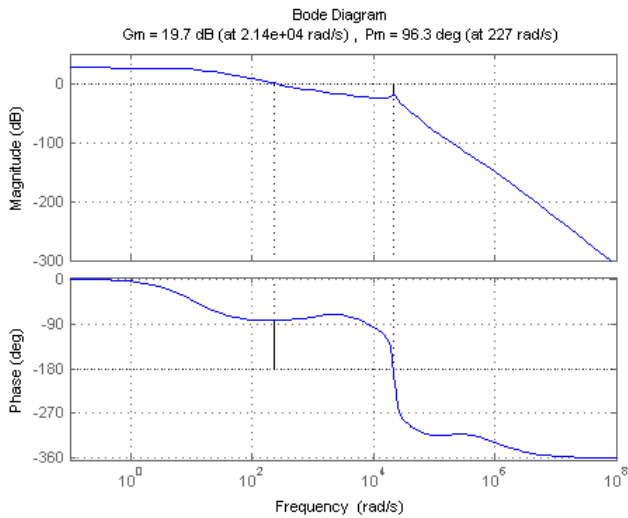


Figure 8: Bode plot of the linearized pressure relief valve system

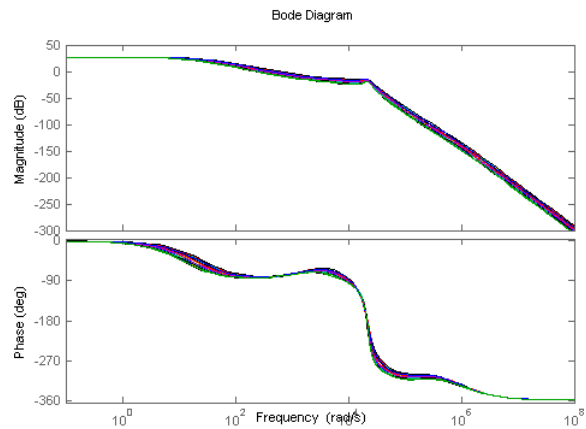
therefore the stability characteristics. Further design rules for relief valves can be found in [1].

3.2 Robust design study of the relief valve model

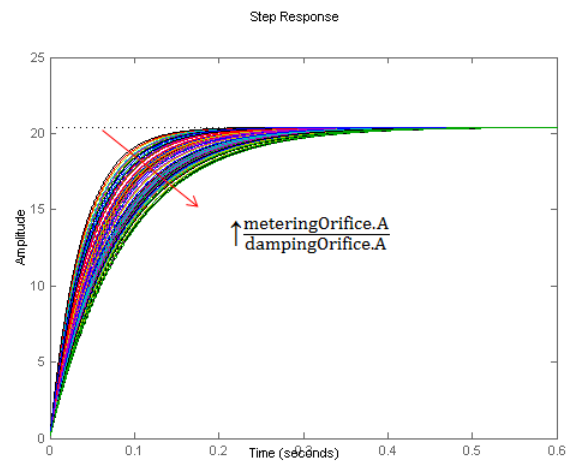
The effect of design parameters on the gain and the phase margin of the system is discussed next. A Functional Mock-up Unit (FMU) of the model is imported into MATLAB using the FMI Toolbox for MATLAB. FMIT has tools for conducting Design of Experiments [5] and a simple design of experiment is illustrated here to show the effect of the geometric parameters of the valve on the stability characteristics.

The orifice areas of the damping and outlet orifices in the PRV model of Figure 17 are set with respect to a constant factor of the area of the metering orifice. These multiplicative factors are then varied in the DoE and the changes in the frequency response analyzed. First, the damping orifice area is varied through 100 points uniformly distributed between factors of 0.01 to 0.025 in comparison to the metering orifice area which is constant at $5 \times 10^{-5} \text{m}^2$.

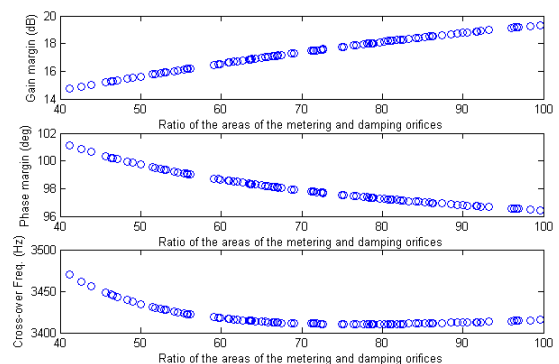
Figure 9 shows the bode plots, step response and the variance in the gain, phase margins and the cross-over frequency for different sizes of the damping orifice. The bode plot of Figure 9(a) shows differences in the open-loop gain at higher frequencies. While the damping orifice area has no influence on the steady-state gain, it can be observed that the response time is clearly affected by the damping orifice. As the damping orifice area increases, the damping ratio of the system also increases. The gain margin and phase



(a) Bode plot

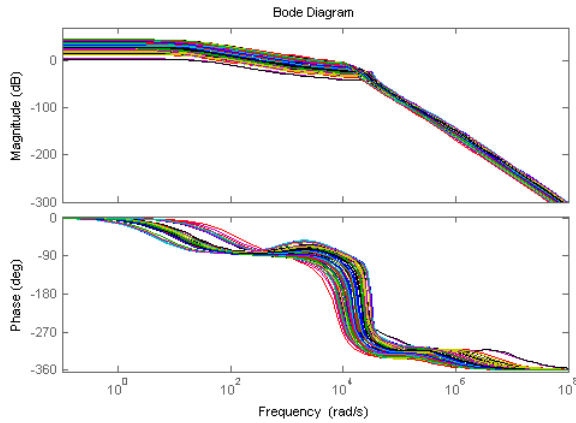


(b) Step response

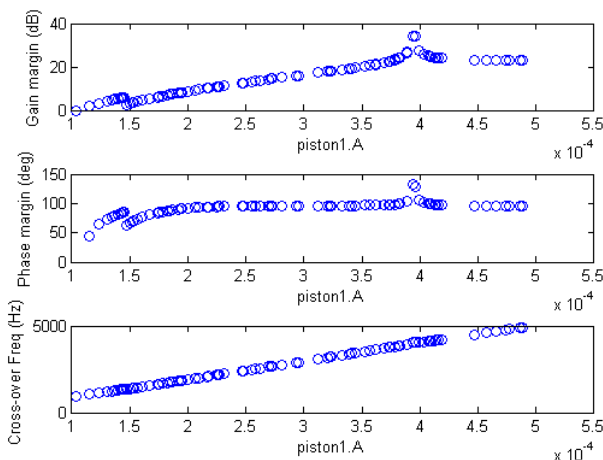


(c) Gain, phase margins and cross-over frequency

Figure 9: Effect of the damping orifice area on the frequency response



(a) Bode plot



(b) Gain, phase margins and cross-over frequency

Figure 10: Effect of the piston area on the frequency response

margins also do not show significant sensitivities to changes in the damping orifice area as seen by a change of 6dB and 6 deg in these quantities respectively.

The next design parameter of interest is the area of the piston in the valve. It is assumed that the pistons in the spool valve, and both pistons in the PRV model of Figure 15 are assumed to have equal areas and for the sake of simplicity, the rod areas in these pistons are assumed to be negligible. The piston areas are then varied over 100 uniformly distributed points across a range of 1×10^{-4} to $5 \times 10^{-4} \text{m}^2$ and linearized about the respective steady state points.

The bode plot of Figure 10(a) shows that there is a significant sensitivity in the steady state gain to changes in the piston area. In fact, the steady state gain decreases with increasing piston area with iden-

tical damping characteristics. The gain and the phase margin (Figure 10(b)) also show significant increase with increasing piston areas. A suitable choice of piston area can be made from this plot with a gain of 3dB (or more) and a phase margin between 30 and 60 degrees to result in reasonable trade-offs between bandwidth and stability.

4 Modeling and Open Loop Stability Analysis of an Electro-Hydraulic Servo Valve

A single stage Electro-Hydraulic servo valves is modeled in this work with a torque motor directly attached to a 2-land 4-way directional control valve. A representation of this valve used to actuate an aircraft control surface is shown in Figure 11 [2].

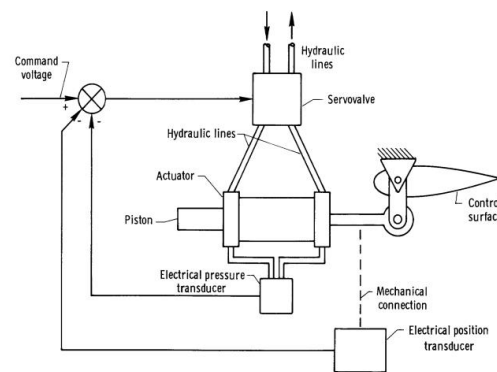


Figure 11: Schematic of a single stage servo valve to actuate an aircraft control surface

The directional control valve used in this hydraulic actuation system was modeled using a combination of volumes, spool valves and pistons from the Elements package and is shown in Figure 12.

Each pair of the spool valve and the piston are identical and the sizing of these are identical to that of the pressure relief valve discussed in Table 1. The complete model of the system is shown in Figure 16.

The function of the torque motor in Figure 16 is to convert the input voltage into the corresponding spool displacement to displace the directional control valve by an appropriate amount in the desired direction to open one of the spool valves that connect port P to port A or port P to port B for flow from port P which correspondingly opens the spool valves that connect port B to port T and port A to port T for flow into port T. Ports A and B are connected to the two hydraulic ports of a

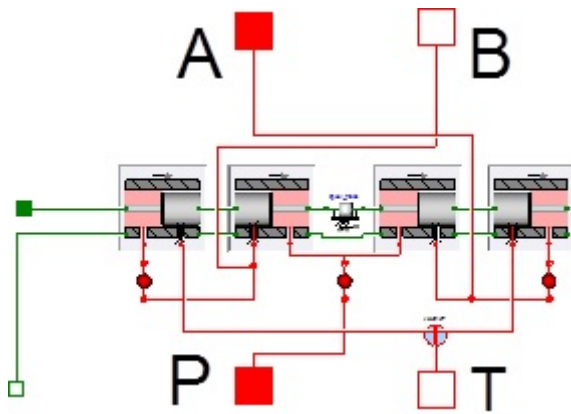


Figure 12: Model of a direction control valve made from components of the Elements package

differential cylinder to convert the fluid power into mechanical displacement to actuate the control surface.

The torque motor dynamics are not modeled in this work for simplicity but are represented as the following transfer function [2]

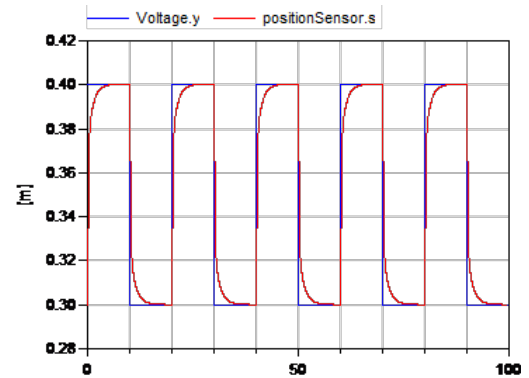
$$X_s(s) = \frac{0.003}{0.0025s + 1} E(s) \quad (3)$$

where $X_s(s)$ and $E(s)$ are the Laplace transform representation of the spool displacement of the directional control valve and the voltage signal to the torque motor respectively.

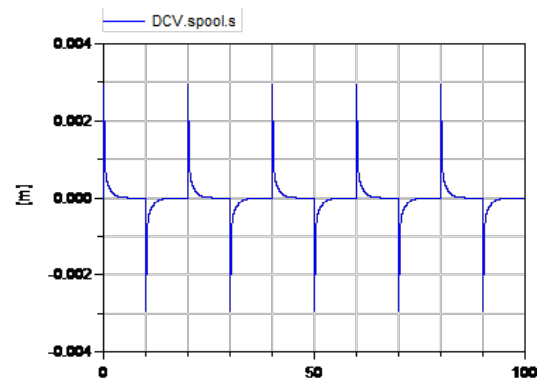
The pressure differential in the cylinder moves the piston against the preload force of the spring. This displacement of the piston in the cylinder is then sensed and acts as the feedback signal. The error between the input signal and the piston position is then amplified to be the voltage input of the torque motor.

The piston is assumed to be at a steady state at a position of 0.3 m. A pulse signal is sent as the input and the trajectories of the spool displacement of the directional control valve and that of the piston are plotted in Figure 13.

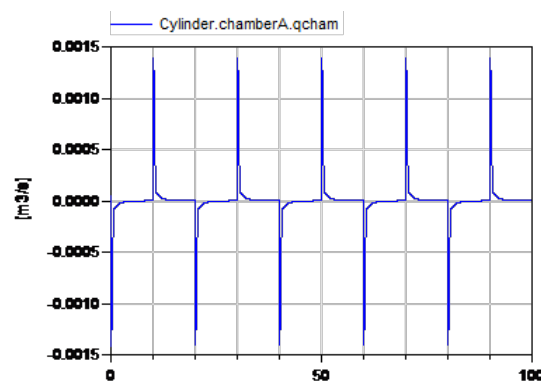
From Figure 13(a), as the piston is commanded to shift in the positive direction, the torque motor causes the directional control valve spool to displace in the positive direction (Figure 13(b)) to open the spool valves connecting ports P to A and ports B to T. The flow from port P through port A enters the piston and increases the pressure in that chamber to cause an increase in the net force on the spring to push the piston in the commanded direction. The pulse command shows the movement of the piston in both directions and the flows into the cylinder from the valve are plotted in Figure 13(c).



(a) Piston position and command



(b) Spool displacement of DCV



(c) Flow rate into cylinder

Figure 13: Trajectories of the piston, spool positions and flow rate into cylinder

The stability characteristics can be studied by breaking the feedback loop and setting the piston position as the output and the commanded position as the input. The model is linearized and the Bode plot of Figure 14 shows the frequency response of the system.

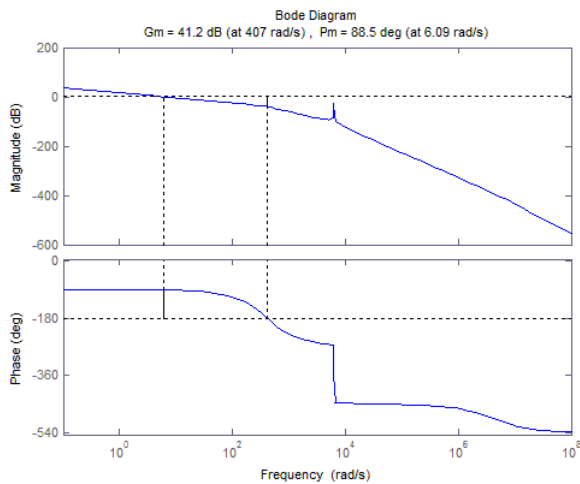


Figure 14: Bode plot of the linearized servo valve actuation system

It might be noted that the loop opening in this example is straightforward since the control law is outside of the physics of the model. In the case of the relief valve, the pressure force equation is part of the physics of the valve and there appears to be no elegant way with any Modelica based tool to break these loops other than to manually modifying the equations to enable the model to be used for controls analysis. For modeling, Modelica provides the great advantage that the modeler does not have to transform the model manually to block diagram form. For open loop control analysis, and a feedback loop that is embedded into the physics, the modeler will have to derive a block diagram form also in Modelica in order to obtain the open loop equations. It is however possible to integrate the open loop variant for certain typical feedback situations in library models. This will be made available in the upcoming version of the Hydraulics Library. In a block diagram based modeling environment like Simulink where there is no clear distinction between the physics of the model and the control system, such loop breakage is straight forward. The Simulink feature to automatically apply the steady-state value as offset at the input at which the loop is broken should also be available in Modelica tools.

It may however be possible to provide improved automated support for open loop stability analysis in Modelica tools, because the symbolic processing in

Modelica compilers for efficient code generation is very similar to the causalization process when deriving a block diagram from model equations. Another issue with open loop analysis of hydraulic components is that SI units, which are typically used in the model equations, are very badly scaled for the open loop analysis. The scaling that Modelica tools apply internally through the use of the nominal attribute does not help, because for the stability analysis the user would like to have properly scaled equations that are consistent between the linearized system and the closed loop model.

5 Conclusion

In this paper, we discussed the physical design of hydraulic components using the Hydraulics library and illustrated the application of robust design techniques to improve the physical design of valves with Modelica and FMI based tools. The application of the Elements package demonstrated both the modeling of relief valves and also in constructing more complex components from the basic building blocks already available from the library. We also highlighted a limitation in controls analysis of models where the feedback loops are embedded within the physics. There is a new paradigm developing in emerging physical systems where the feedback loops are embedded tightly within the physics of these systems and it is imperative that these aspects are addressed in Modelica and its associated tools.

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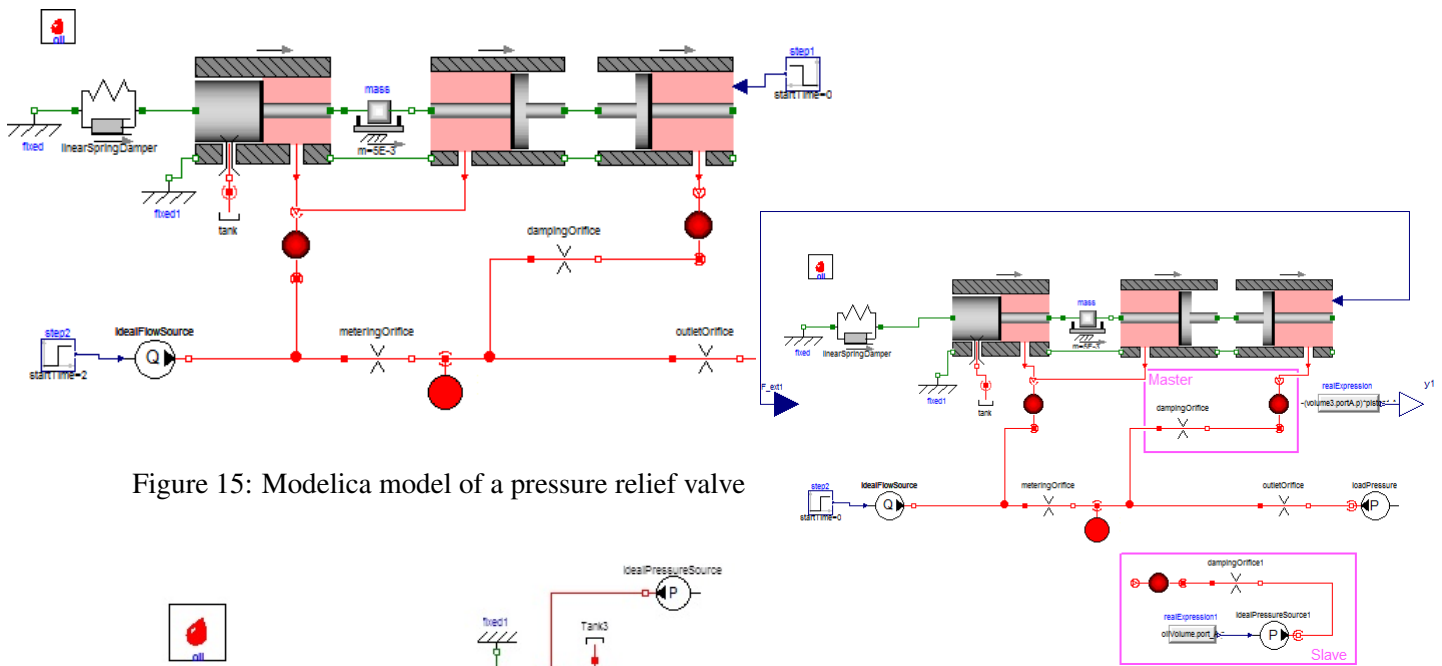


Figure 15: Modelica model of a pressure relief valve

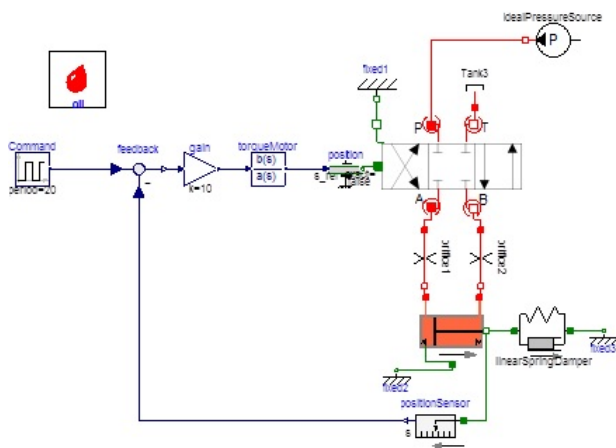


Figure 16: Modelica model of an Electro-hydraulic servo valve

Figure 17: Open loop model of the PRV system