Modelling Automotive Hydraulic Systems using the Modelica ActuationHydraulics Library

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Abstract

This paper describes applications in the automotive industry which require modelling and simulation of hydraulic systems and introduces a new library developed specifically for use in these applications.

Issues encountered whilst modelling hydraulic systems are discussed, from the numerical issues of simulating mixed hydraulic-mechanical systems to the more practical aspects such as the availability of parameter data for valve models.

A selection of case studies are described.

Keywords: hydraulics, automotive, power steering, transmission actuation, lubrication, braking systems, active 4wd

1 Introduction

An increasing number of automotive systems use some form of electro-hydraulic control, and with increasing levels of complexity in these devices simulation is an important part of the development process. Modelica provides an ideal environment for such simulation as it is necessary to include mechanical, electrical and hydraulic components in the same system, utilising Modelica's multi-domain capabilities.

2 Applications of Hydraulics Simulation in Automotive Industry

Key applications of hydraulics within automotive engineering are in the power steering, transmission, driveline and braking systems.

2.1 Power Assisted Steering

Power steering is standard on virtually every road car, racing car and off-highway vehicle, and in the majority of cases is a hydraulic system. A spool valve, either translational or rotational, translates the deflection of the steering wheel relative to the steering rack into a hydraulic flow into a piston to provide additional steering force. The dynamics of the hydraulic system affect the response of the vehicle to the driver input and therefore simulation is used to predict the effect of parameter changes such as the spool geometry.

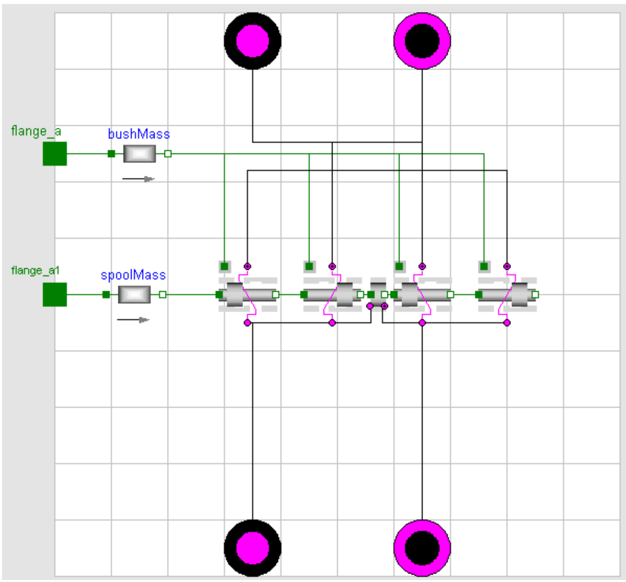

Figure 1: Power steering spool valve model

Figure 1 shows a Modelica model of a spool valve within a power steering system model. The spool model is built up of submodels, each representing one flow path through the valve. These "SpoolPort" models interface with translational mechanics components from the Modelica standard library, and the flow through each is a function of the spool displacement, the pressure drop and the port geometry.

This makes it easy to quickly build complex spool arrangements for this type of application.

2.2 Transmission Actuation and Lubrication

The trend in transmission technology is towards actuated transmissions such as Automated Manual Transmissions (AMT) and Dual-Clutch Transmissions (DCT or DSG), and these plus the continuation of development of conventional Automatic Transmissions and Continuously Variable Transmissions (CVT) lead to an overall growth in hydraulically actuated systems. Development of valve-blocks and the control system requires combined simulation of the hydraulics and the transmission dynamics [1]. These transmissions often also have lubrication systems combined for which simulation is required to determine flows at each outlet.

2.3 Driveline Control and Braking Systems

Active four wheel drive systems and Torque Vectoring systems for the enhancement of vehicle dynamics are increasingly popular. Development of these systems requires combined simulation of driveline components and vehicle dynamics, [2], and further extending this with models of the hydraulic system allows the effect of hydraulic dynamics on the vehicle behaviour to be studied.

Likewise the effect of antilock braking systems and brake force distribution on vehicle dynamics can be studied.

3 Issues with Hydraulic Simulation

A library previously developed [3] in Simulink has been successfully used for a number of projects, but requires an expert user. Lessons learnt from this work which have been applied in the ActuationHydraulics library include accounting for numerical issues and the availability of parameter data.

3.1 Numerical Issues

Numerical issues in hydraulic simulation are well discussed in [4], small volumes around valves lead to numerically stiff systems and non-linear systems of equations containing discontinuities arise due to interconnected components with non-return valves and shuttle valves. These characteristics exploit well the capabilities of Modelica.

3.2 Data Availability

The ideal source of data is a disassembled component as in figure 2, as specifying orifice areas for valves is not necessarily compatible with the data made available by manufacturers. Data for hydraulic components is available in a wide range of forms, such as flow areas, lookup tables of flow against pressure or special forms such as the Lohm unit devised by Lee Hydraulics. The ActuationHydraulics library uses “replaceable” flow-models for orifice flows, each compatible class defines flow as a function of pressure drop and parameters according to the data available.

Figure 2: Typical hydraulic spool

For some components a pressure drop across the component is the only data available. With some modelling tools it would be necessary to reverse-engineer an orifice size and flow coefficient to achieve this pressure drop. However the ActuationHydraulics library exploits the acausal capabilities of Modelica and allows the choice of a flow-model where pressure drop is specified as a function of flow.

4 ActuationHydraulics Library

The modelling library was developed specifically for the applications described and with the aim of overcoming the issues described. Although hydraulics libraries in Modelica already existed [5,6,7], these were either unavailable or did not fulfil all the needs of the target applications.

The library components are isothermal, the effects of temperature can be studied by running the models with different fluid parameters, but thermodynamic effects within the fluid are not taken into account.

All components in the library extend from a base class, PartialHydraulicComponent, which defines an "outer" instance of HydraulicsGlobal. This allows the fluid used in the model to be selected in one location and works in a similar manner to the "World" component within the Modelica MultiBody library.

A wide range of components are included in the library, including valves, pipes, accumulators, pumps and actuators.

4.1 Valves

As described earlier, complex spool arrangements can be modelled, with variation of parameters as illustrated in figure 3. Flow through spools utilise the improved flow formula described in [8].

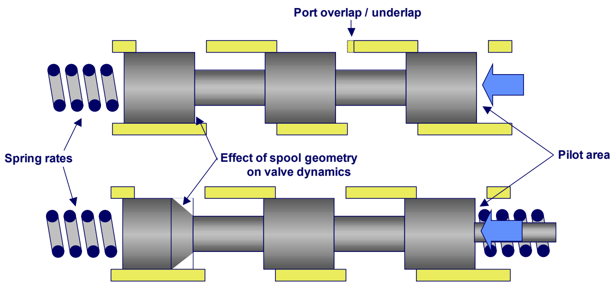

Figure 3: Modifiable parameters for spool modelling

Simple valves are modelled using the data available as described earlier. A range of simple valve types such as non-return valves are included.

4.2 Pipes and Accumulators

Models of pipe flow including inertia, compressibility and friction effects, including pipe wall expansion [9], are included. Lumped or distributed models can be used depending on the level of detail required. Gas-charged and spring-charged accumulator models are also included.

4.3 Pumps

The pump and motor models include volumetric losses due to leakages and compressibility, and mechanical losses due to friction and inertia. Variable swashplate models are included, as shown in figure 4.

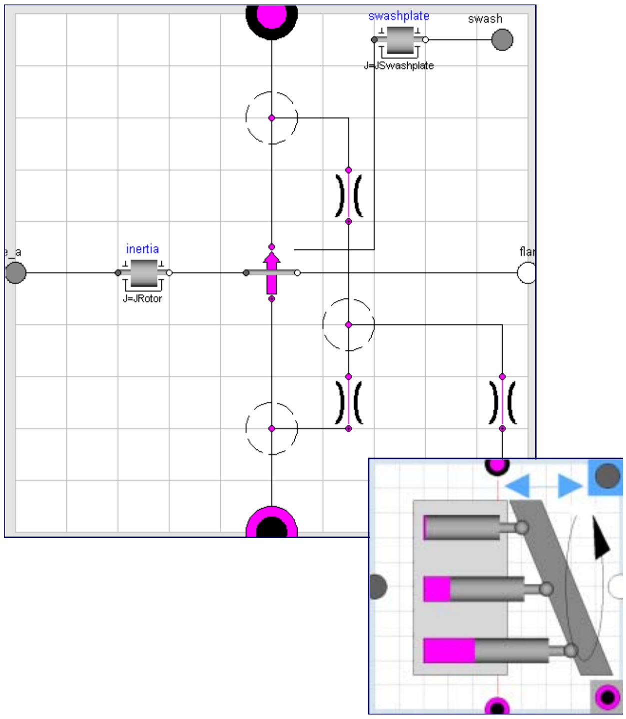

Figure 4: Diagram and Icon of Variable Swashplate Pump model

Flow ripple due to the number of pistons, teeth or lobes in the pump can be included, this can be useful for analysing noise and vibration aspects of hydraulic systems and ensuring volumes around pumps provide enough damping of these vibrations. Figure 5 shows the different magnitudes and frequencies of ripple for different pump configurations.

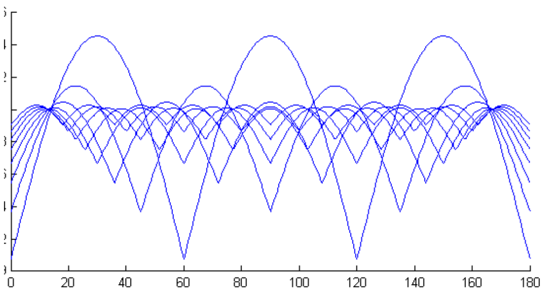

Figure 5: Pump flow ripple against angle for range of pumps with different numbers of pistons / lobes

4.4 Actuators

Translational and rotary actuators with inertia, friction, fluid compressibility and leakage effects are included.

Actuator, pump and spool components all interface with the Modelica standard library mechanics components, allowing connection to mechanical models from other libraries. Current signals to valves are applied using interfaces from the Blocks package within the standard library.

5 Case Studies

These case studies are recent typical uses of the library.

5.1 Continuously Variable Transmission

The most common form of Continuously Variable Transmission (CVT) utilises hydraulic actuators on conic "variators" to control the radius of a belt on either variator.

A CVT of this design was simulated using the ActuationHydraulics library in order to identify solutions to improve the poor controllability of the pressure at the primary variator. The relationship between current duty ratio at the solenoid valve and the pressure at the variator was validated against test data.

A parameter study was performed for spring rates and port overlaps in the main spool valve, resulting in a 100% increase in duty ratio range over which pressure is controlled and 25% reduction in hysteresis.

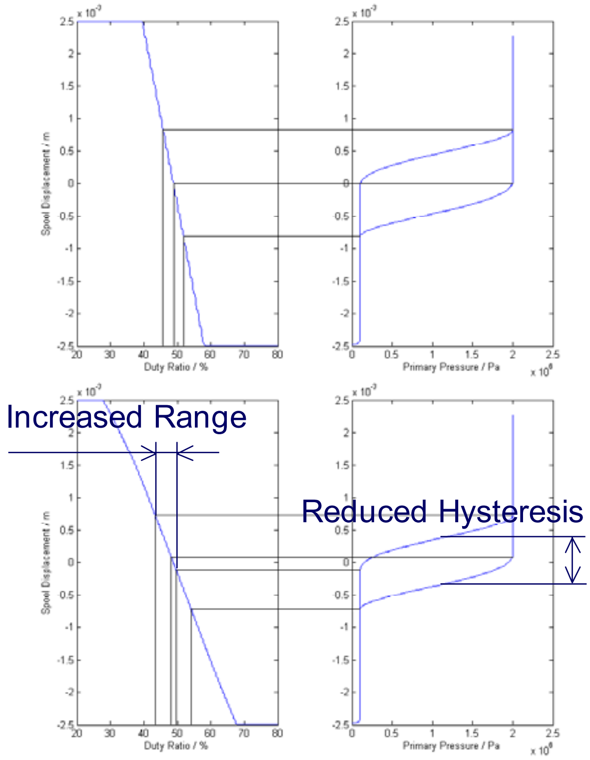

Figure 6: Increased controllability of CVT

5.2 Dual Clutch Transmission

Simulation using the ActuationHydraulics library was performed on the actuation and lubrication systems for the 750Nm 7 Speed Dual Clutch Transmission developed for the Chrysler ME4-12 vehicle.

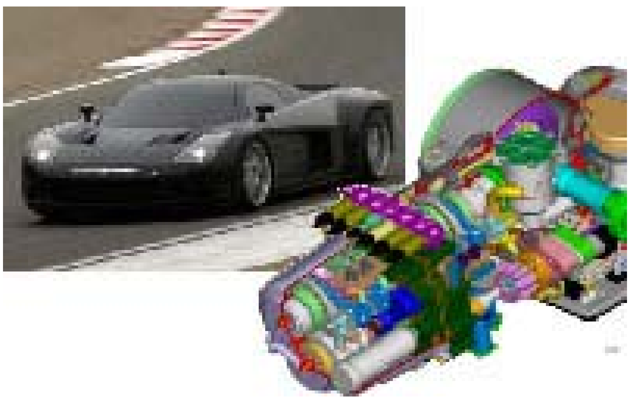

Figure 7: Chrysler ME4-12 with Ricardo DCT

A key aim during design of the transmission was to minimise complexity and cost of the hydraulic system in order show a transmission suitable for mass production. One result of this was the use of a shared pump between the lubrication system and the gearshift actuation system. The sizing of the pump and accumulator needed to be sufficient to allow the vehicle to change gear sequentially from 7th through to 1st whilst undergoing maximum deceleration at the minimum engine speed and hence minimum pump flow. It also had to provide enough lubrication flow to each of the bearings in the transmission.

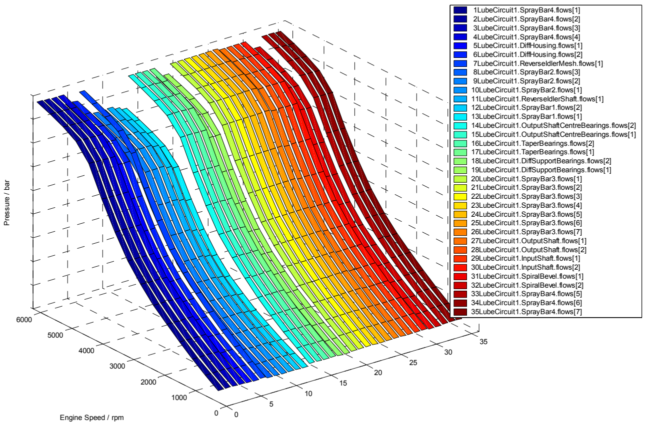

Figure 8: Lubrication flow against shaft speed at each bearing

The simulation was used, together with optimisation techniques, to define the pump and accumulator sizes and the sizes of each hole in the lubrication spray bars.

5.3 Formula 1 Hydraulics

Calculation of component sizes for F1 hydraulics is not a straightforward task as the pump and accumulator provide fluid for the gearshift, clutch, throttle, differential, power steering and fuel flap. A solution for this and control system testing and development has been provided by using Modelica simulation models which can either connect to race simulations or be driven by replays of test data, allowing engineers to study the effects of parameter changes.

6 Conclusions

The ActuationHydraulics library provides a solution for all automotive hydraulics applications, with connectivity to other Modelica packages. Successful use of the library has been shown for a number of applications.

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