

Modeling and Simulation of a Hydraulic Steering System

QingHui Yuan

Eaton Corp Innovation Center

Bo Xie

Purdue University

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ABSTRACT

Conventional hydraulic steering systems keep improving performance and driving comfort by introducing advanced features via mechanical design. The ever increasing mechanical complexity requires the advanced modeling and simulation technology to mitigate the risks in the early stage of the development process. In this paper, we focus on advanced modeling tools environment with an example of a load sensing hydraulic steering system. The complete system architecture is presented. Analytical equations are developed for a priority valve and a steering control unit as the foundation of modeling. The full version of hydraulic steering system model is developed in Dymola platform. In order to capture interaction between steering and vehicle, the co-simulation platform between the hydraulic steering system and vehicle dynamics is established by integrating Dymola, Carsim and Simulink. Finally, the complete hydraulic steering system is executed in Opal-RT RT-Lab HIL simulator to allow human in the loop testing. The simulation results verify the functions and performance of the hydraulic steering system.

NONMENCLATURE

β_e	Effective bulk modulus of hydraulic fluid
δ	Angle of steering wheel (spool) in SCU
δ_{left}	Wheel steering angle: front left wheel
δ_{right}	Wheel steering angle: front right wheel
θ	Angle of sleeve in SCU
A_{p1}	Orifice area in Priority Valve (Figure 2)
A_{p2}	Orifice area in Priority Valve (Figure 2)
A_{p3}	Orifice area between P and CF in Priority Valve
A_p	Spool end area in DS side in Priority Valve
J_1	Inertia of momentum of spool in SCU
J_2	Inertia of momentum of sleeve in SCU

K_v	Damping coefficient of spool-sleeve in SCU
$K_{v,p}$	Damping coefficient of spool in Priority Valve
K_s	Spring coefficient of spool-sleeve in SCU
$K_{s,p}$	Spring coefficient of spool in Priority Valve
M_{left}	Moment about Kingpin: front left wheel
M_{right}	Moment about Kingpin: front right wheel
P_{DS}	Pressure at point DS in Priority Valve
P_{LS}	Pressure at point LS in Priority Valve
Q_1	Flow rate from LS to DS in Priority Valve
Q_2	Flow rate from DS to CF in priority Valve
V_{DS}	Volume of DS in Priority Valve
T_u	Torque from user to steering wheel (spool) in SCU
T_{ge}	Torque generated from Gerotor in SCU
m_p	Spool mass of Priority Valve
x_p	Spool displacement of Priority Valve
x_{p0}	Spool neutral position due to spring preload in Priority Valve

DEFINITIONS, ACRONYMS, ABBREVIATIONS

HILS	Hard In the Loop Simulation
SCU	Steering Control Unit
LS	loading Sensing port in PV
DS	Dynamic Signal port in PV
CF	Control Flow port in PV
EF	Excess Flow port in PV

INTRODUCTION

Electronically controlled steering units have been drawing attention of research in the steering community in the past decades. There are many advantages of steering-by-wire devices [1, Kamp, 2002], such as

programmable steering functions, improved ergonomics, flexibility in cabin design, and reduction of noise in cabin. However, there are not many systems that have been put into production today. It is partially because matching the dependability of mechanical/hydraulic steering components with electronics is a challenge [R Hammett, 2003]. In order to achieve dependability requirement, it needs to address the complex electronics architecture design, like dual-dual or triplex systems, and the safety critical software development following System Safety Standards, like IEC 61508 or DO-178B [Czerny, 2003]. All of the above will create a concern of market acceptance due to potential high cost for such steer-by-wire devices.

By contrast, the development of the conventional hydraulic steering unit involves minimum software electronics complexity and less safety concerns. Hydraulic steering system still keeps the edge over the mechanical steering system because it can minimize the steering linkage, provide flexibility in design, and offer continuous control action with very low input torque via power assist. There have been many advanced features achieved in pure mechanical manner, like flow amplifier, wide angle, and cylinder damping, through mechanical design in order to improve the system safety and performance. [Eaton Corp, 2006]. Therefore, it is obvious that the reduction of complexity of software/electronics development in hydraulic steering system is actually achieved by the complex mechanical hardware design. For such complex mechanical system, it is necessary, by means of model based modeling and simulation tools, to predict the system performance in order to capture any design flaws in early development phase. It would be much more expensive if problems were only uncovered in the later phase of the product development.

Many tools can be used for dynamic modeling and simulation. In the hydraulics domain, the most popular ones include Easy5, AMESim, SimHydraulics and Dymola. Easy5 [MSC, 2004] is schematic based simulation software tool to model and simulate the complex dynamic system with long history initiated from Boeing. Many applications prove its reliability. It is also possible to be extended into real time platforms by auto generating C or FORTRAN code. SimHydraulics [Mathworks, 2006] is a new product from Mathworks in 2006. It is extension of Simulink for hydraulic circuit modeling. More than 45 hydraulic and mechanical components are provided. Popularity of Matlab/Simulink in industry makes SimHydraulics a very compelling modeling software tool candidate. AMESim gains more popularity due to its rich hydraulic library (more than 120 library elements) offering comprehensive hydraulic consideration with rigorous treatment of fluid properties [LMS, 2007]. Dymola [Dynasim, 2008] has drawn attention both from academia and from industry in the past decade. This software tool offers all the benefits provided by the others, like multi-domain modeling in mechanical, electrical, hydraulic, chemical and thermodynamic, availability of read-to-use libraries, and the interface with multiple platforms, like Matlab/Simulink

and Dspace. In addition, this software tool provides the unique features compared to the above tools [P. Fritzson 2003] :

- Open specification process by Modelica Association
- Non causal modeling with Differential Algebraic Equation (DAE)
- Object Oriented language to facilitate model reuse

In this paper, we will use Dymola as the modeling platform.

In order to capture the interaction between steering and vehicle, the co-simulation platform between the hydraulic steering system and vehicle dynamics is established by integrating Dymola, Carsim and Simulink. The platform has been further extended in Opal RT RT-Lab real time target so that the plant models can execute in real time. Therefore, human in the loop testing can be achieved via a steering wheel simulator that communicates with Opal RT in real time.

The paper will be organized as follows. First, the complete system architecture of a hydraulic steering system is introduced. Next, analytical equations are developed for a priority valve and the steering control unit as the foundation of modeling. We then discuss the modeling of hydraulic steering unit in the Dymola platform. The models are then being executed on the realtime platform by integrating various types of software. Finally, the concluding remarks are included.

SYSTEM DESCRIPTION OF HYDRAULIC STEERING SYSTEM

In this section, we will introduce the architecture and function of a typical hydraulic steering system, in particular considering a load sensing hydraulic steering system.

The system is illustrated in Figure 1 that consists of a load sensing pump, a priority valve, a steering control unit, and two cylinder actuators.

The load sensing pump is also called a pressure flow compensation pump, which delivers the flow to steering or the auxiliary circuits based on the system demands.

The priority valve guarantees that the steering control unit has the flow and pressure priority. The flow required by steering maneuver goes to steering circuit via port CF. Flow not required by the steering circuit will be redirected to auxiliary circuits via port EF.

The steering control unit consists of a steering valve, a torque generator, two relief valves and two check valves. The function of the steering control unit is similar to a conventional three-position four-way proportional valve.

The steering input will change the orifice between the pressure port to one work port of cylinders, and the orifice between the other work port to tank. In addition to these basic configurations, many orifices have been modified or added to improve steering response, system stability, and other performance attributes. The torque generator, as shown as a bidirectional hydraulic motor inside the steering control unit in Figure 1, is introduced for power steering for better operational comfort. The relief valves and check valves are used to protect the system from damage from unexpected high pressure spikes.

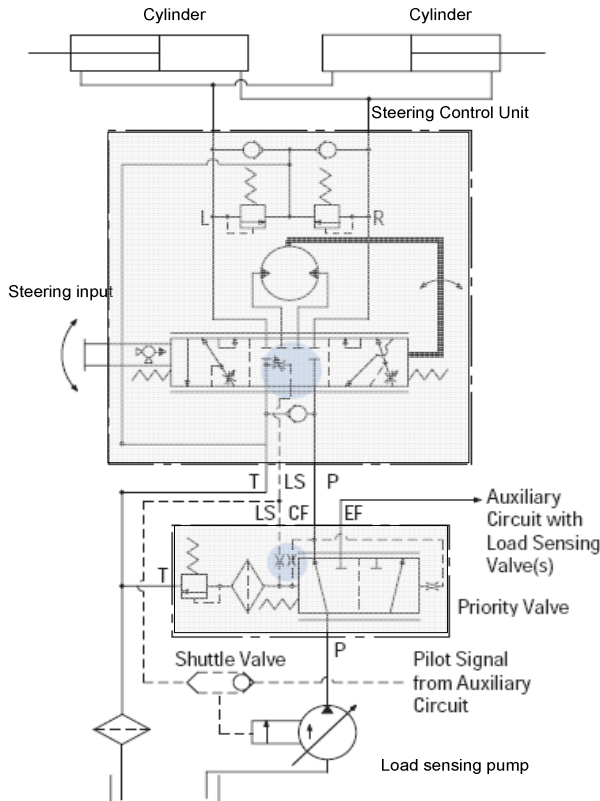


Figure 1 Diagram of hydraulic steering system

Hydraulic cylinders are connected to the steering control unit as steering actuators. In Figure 1, two cylinders are cross connected for redundancy in either Ackerman steering or articulated steering. Change of the displacement of cylinders will cause change of wheel steering angles in Ackerman steering type, or the relative angle between the front mass and the rear mass in articulated steering type. In this paper, modeling of hydraulic steering system is generic. However, in the simulation section, we will only consider Ackerman steering type.

The detailed description of each component will be followed in the next section.

DYNAMIC MODELS OF HYDRAULIC STEERING SYSTEM

Dynamic models of the key components, in particular for priority valve and steering control unit, are developed in this section.

PRIORITY VALVE

As aforementioned, priority valve provides several functions:

1. Provide high priority of flow/pressure to steering control unit
2. Divert flow to auxiliary circuit for extra flow
3. Match the pressure and flow rate with steering control unit

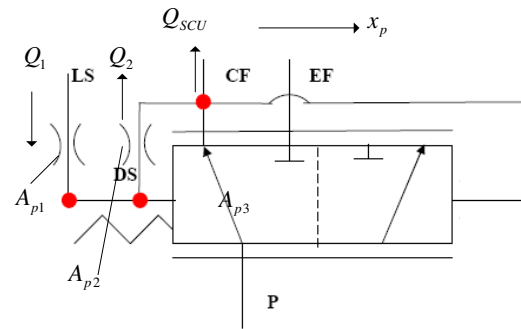


Figure 2 Schematic of priority valve. P- pressure line, LS- loading Sensing line, DS-Dynamic Signal (internal), CF- Control Flow to steering control unit, EF – Excess Flow to auxiliary circuits.

Figure 2 illustrates the schematic of priority valve by zooming in it from system diagram in Figure 1. The spool dynamics is given by

$$m_p \ddot{x}_p + K_{v,p} \dot{x}_p + K_{s,p} (x_p - x_{p0}) = P_{DS} - P_{CF} \quad (1)$$

The pressure dynamics in DS is given by

$$\frac{V_{DS}(x_p)}{\beta_e(P_{DS})} \dot{P}_{DS} = -A_p \dot{x}_p + Q_1 - Q_2 \quad (2)$$

Where Q_1 is the flow rate from LS to DS, and Q_2 is the flow rate from DS to CF. Based on the orifice equation [Merritt, 1967], the flow rate is a nonlinear function of orifice area and pressure drop. We have

$$Q_1 = C_d A_{p1} \sqrt{\frac{2}{\rho} |P_{LS} - P_{DS}| \text{sign}(P_{LS} - P_{DS})}$$

$$Q_2 = C_d A_{p2} \sqrt{\frac{2}{\rho} |P_{DS} - P_{CF}| \text{sign}(P_{DS} - P_{CF})}$$