Modeling and Analysis of Power Steering Systems

by

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ABSTRACT

A hydraulic power steering systems is widely used for motor vehicles, and it works as a hydraulic servo system. During the development of a power steering system, sometimes the pressure vibration is observed, and the vibration is not acceptable. The purpose of this thesis work is to understand the dynamics of the vibration behavior, and find out the efficient method to reduce the vibration. This thesis investigates the dynamics of a hydraulic power steering system using a bond graph method. Each component of the power steering system is described by the bond graph model and simulated. The total system is also modeled, and simulation for the vibration is presented. Linearization method is applied to analyze the system behavior. The hydraulic line connecting the oil pump and pressure control valve is found to play an important part for the vibration behavior.

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Chapter 1
Introduction

1.1 Motivation

A power steering system is used for motor vehicles to assist a driver to steer the tires to change its direction. Recently a number of power steering system is increasing because of increase of motor vehicle weight. Most power steering systems used current motor vehicles are hydraulic power steering system that contains a hydraulic servo system. Hydraulic pressure used for supporting the driver is usually controlled by the pressure control valve with mechanical feedback system. Improvement of motor vehicle requires additional characteristic of power steering system such as proper steering effort corresponding to the counter force from the road. Only the steering effort is the information from the road a driver can receive, supply proper steering effort to the driver is an important issue. This characteristic is mainly determined by the pressure control valve design. Therefore, dozens of experiments with prototypes of valve are taken to determine the proper power assist ratio. During these experiments, sometimes the pressure vibration at the valve inlet port is observed. The pressure vibration causes a noise and body shaking; the vibration is not desirable. If the valve specification can satisfy the requirement from the motor vehicle, reducing the vibration without changing the valve shape.

From experience, it's known that changing the combination of the hydraulic line that consists of pipes and hoses and connecting the oil pump and the pressure control valve. However, there is no theoretical way to reduce the pressure vibration, and trial and error method is the only way to find out the correct hydraulic line combination.

Although there are some papers examining this problem, they have assumed one metal pipe as the hydraulic line. Using a single metal pipe as the hydraulic line is too simplified to apply its result for a real system. Therefore it is useful to find an efficient way to predict the vibration and reduce it.

1.2 Research Objective

This research work is divided into two parts. One is modeling of a power steering system and the other is simulation of the vibration behavior. First of all, using the bond graph method, a power steering system is modeled. Making a feasible model of power steering system helps not only understand the system structure but also analyze the system behavior. After the feasible model is obtained, the pressure vibration behavior is analyzed using numerical simulations. The goal is to figure out where the vibration comes from and how to reduce the vibration.

1.3 Thesis Overview

The second chapter of this thesis describes the general explanation of the power steering system and its components. Describing each component makes its function clear so that when the component is modeled, proper bond graph expression can be chosen.

The third chapter presents a bond graph model of each component of the power steering system. These models are based on the general idea obtained in the second chapter. Simulation results of each model and several comparison with the experiment data are also presented.

The fourth chapter presents a bond graph model of the whole power steering system and its simulation results. The dynamics of the system and the validity of the model is briefly discussed. This chapter also analyzes the primary factor of the pressure vibration. To analyze the vibration behavior, linearization method is applied.

The fifth chapter contains the conclusions and suggestions for further research.

Chapter 2

Power Steering System Components

2.1 Introduction

A power steering system consists of several subsystems. These subsystems have mechanical, hydraulic, and/or electric functions. In this section, the function of a power steering system and each of its subsystems are described in general in order to describe its principle of operation.

2.2 Power steering system description

The power steering system considered in this thesis is shown in Figure 2.1.

A power steering system consists of two main units: a manual power transfer unit and a power assist unit. The manual unit consists of a steering wheel, a main shaft, and a gear mechanism. Usually the output shaft of the gear mechanism is connected to the front tires of the vehicle by several links so that angular or linear displacement of the output shaft corresponds to the front wheel steering angle. The Driver's steering torque is transmitted from the steering wheel to the gear through the main shaft. The gear mechanism and links change the input power direction so that the front wheels angle can be changed.

The power assist section consists of a power source, a steering torque sensor, and a power generating mechanism. The torque sensor detects steering torque, and the power generating mechanism produces assist power corresponding to the signal from the torque sensor. A hydraulic pump and an electric torque motor are mainly used

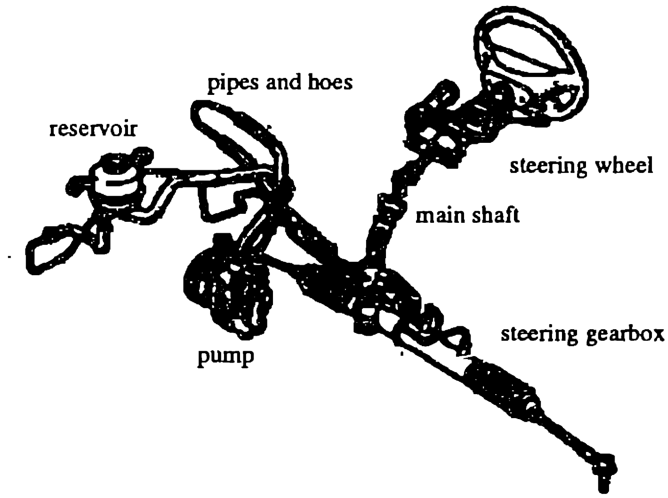

Figure 2.1: A power steering system

as a power source for a power steering system, therefore, there are two types of power steering system; hydraulic power steering system and electric power steering system.

A hydraulic power steering system gains an assistant force from the hydraulic pressure controlled by a pressure control valve. A hydraulic pressure control system is very efficient in delivering high power with compact components.

An electric system is more convenient than the hydraulic system because of its ease of use. However, an electric power steering system may not be used for large motor vehicles because the necessary motor size tends to be heavy and occupies too large a volume. In addition to these drawbacks, electric power steering systems also have reliability and safety problems. Thus, hydraulic power is the preferred mechanism for power steering systems. Because of this reason, a hydraulic power steering system is discussed in this thesis.

A hydraulic power steering system consists of an oil pump, hoses and pipes, an oil reservoir , a steering wheel, a main shaft, and steering gear box that contains a pressure control valve, a rack and pinion gear mechanism, a piston and power cylinder.

Steering torque from a driver is transferred from the steering wheel to the pinion gear. The pressure control valve is placed between the main shaft and the pinion gear so that the valve moves corresponding to the input torque.

The valve displacement from the neutral point produces oil pressure change, and the pressure is guided to one of the cylinders corresponding to the valve movement direction. The pressure is converted to the force by the piston attached to the rack bar, and the force assists the driver to steer the front wheels.

2.3 Hydraulic pump

Hydraulic pumps are used to convert the mechanical energy into hydraulic energy. The mechanical action of the pump takes the fluid from the reservoir into the pump by producing a partial vacuum. This action also forces the fluid in the pump to go into the hydraulic system. The pressure is determined by the resistance of the hydraulic system or imposed load to the system. In the industrial field, positive displacement pumps are widely used. Displacement pumps are categorized into three types: gear type, vane type and piston type. For power steering system, gear pumps and vane pumps are commonly used.

2.3.1 Gear pump

A schematic of a gear pump is shown in Figure 2.2.

Two gears mesh at a point between the outlet port and inlet port in the pump housing, and they rotate in opposite directions. The volume between the gear teeth increases at the inlet port that produces a partial vacuum, and fluid enters the pump. The fluid trapped in the space between the gear teeth is carried to the outlet port. At the outlet port, the teeth of two gears mesh and the space decreases in volume. As the result, fluid is forced out of the pump into the hydraulic system.

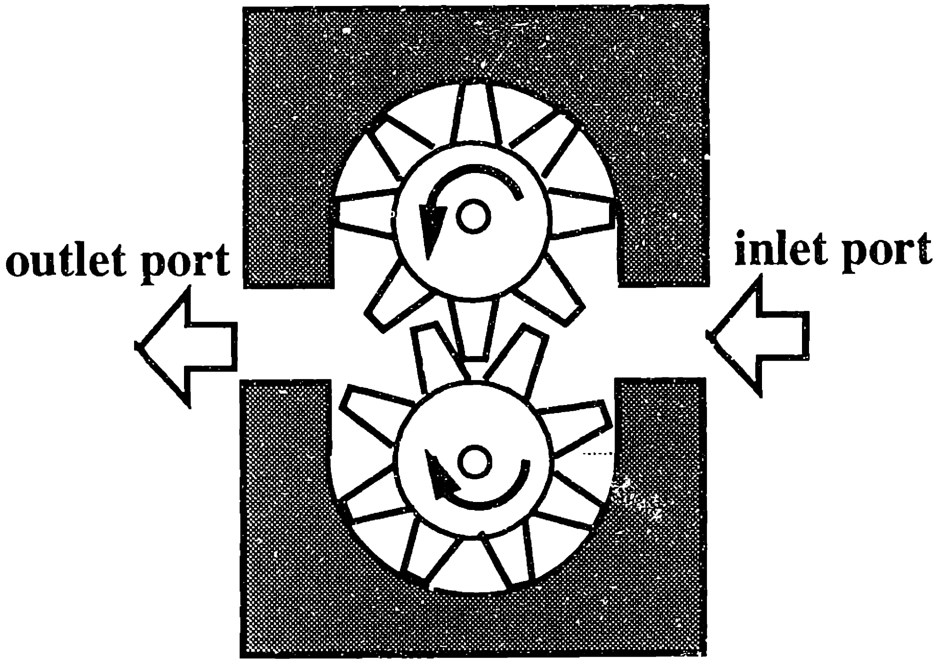

Figure 2.2: A gear pump

2.3.2 Vane pump

A schematic of a vane pump is shown in Figure 2.3.

A vane pump consists of slotted rotor, vanes, a cam ring, end caps, and bearings. Vanes are free to move in the radial direction in the slot but the motion in the axial direction of the rotor is limited by the end caps. When the pump is operated, the rotor is rotated, and the pump vanes are ejected from the rotor, and contact with the cam ring because of centrifugal force so that vanes forms several chambers. With the rotation of the rotor, vanes follow the oval cam ring and change the chamber volume . The volume increases at the inlet port draws the fluid into the pump and the volume decreases at the outlet port pushes out the fluid into the hydraulic system.

2.3.3 Piston pump

A schematic of a piston pump is shown in Figure 2.4.

A piston pump consists of pistons and cylinders. A piston moves back and forth in

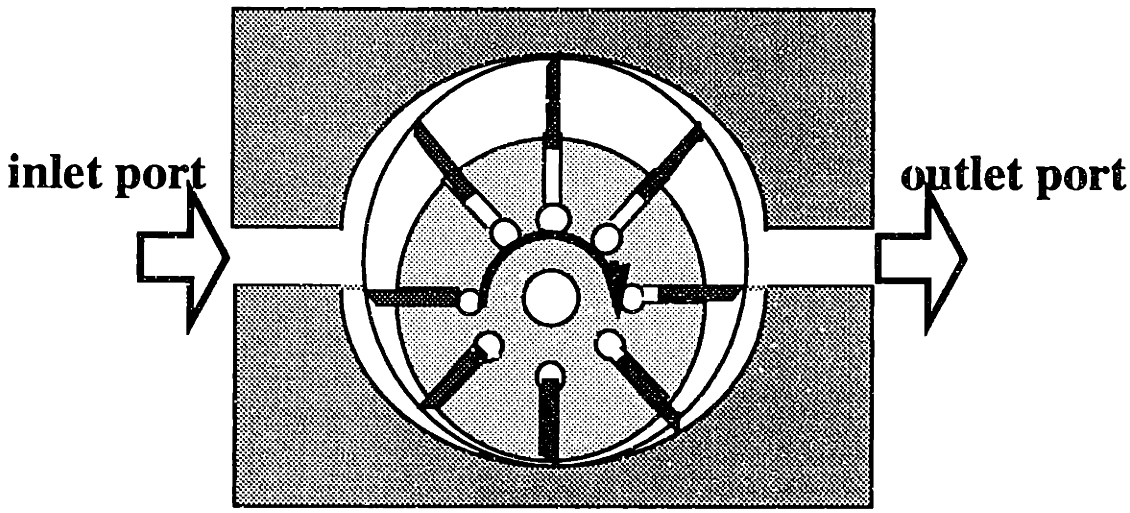

Figure 2.3: A vane pump

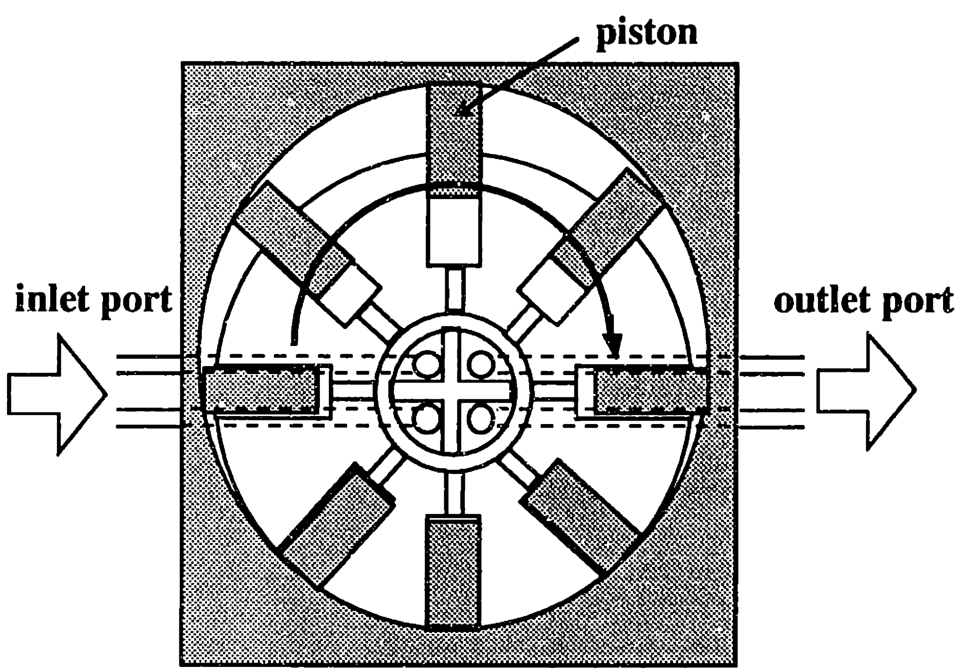

Figure 2.4: A piston pump

a cylinder, and fluid is drawn into the cylinder and then pushed out from the cylinder. Usually several pistons are put in the same cylinder block to produce a continuous liquid flow.

2.4 Hydraulic line

Hydraulic power steering systems have two main hydraulic lines: high pressure line and return line. The high pressure line connects the pump and the inlet port of the pressure control valve, and the return line connects the outlet port of the pressure control valve and the reservoir. These lines can be rubber hoses and metal pipes. The hoses and pipes used in the high pressure line are made so that they can bear the desired high pressure of the system.

2.4.1 Hose

A hose is used in hydraulic systems when the hydraulic line requires flexibility. Hose is composed of three elements: inner tube, reinforcement, and cover. A schematic of hose is shown in Figure 2.5.

The inner part of the hose carries the fluid. Hose reinforcement surrounds an inner tube and its material is the fabric, cord, or metal layers. These elements strengthen the hose against the internal pressure and external force. A hose cover is the outer hose layer. It is designed to protect the inner tube and reinforcement layers form external environment protection.

2.4.2 Pipe

Pipes are used to connect hydraulic components, carry the hydraulic fluid, and consequently transfer the hydraulic power. Pipes are made of various materials such that steel, copper, brass, aluminum, stainless steel, and plastic. Hydraulic power steering

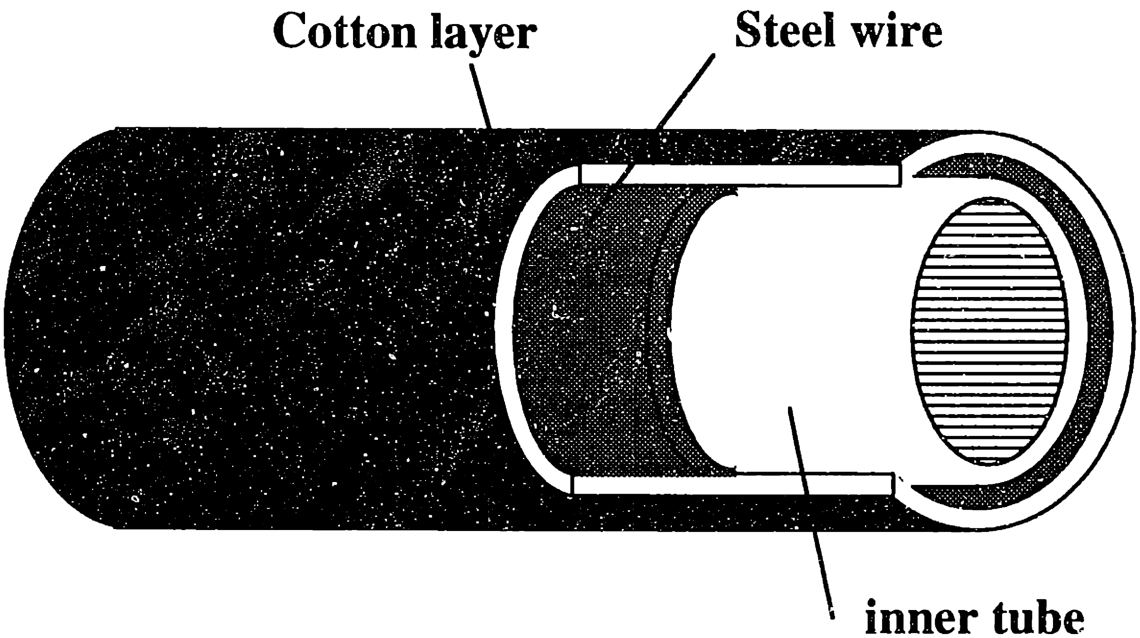

Figure 2.5: A hose

systems generally use brass pipes. An inside diameter of the pipe determines how much fluid flow can pass thorough the pipe efficiently. A wall thickness of the pipe is determined by the maximum fluid pressure and the material used.

2.5 Control valve

A control valve consists of an inner and an outer part. An inner part can be a spool, a piston, a ball, or a poppet. An outer part can be a stationary valve housing. The inner part is operated manually, electrically, pneumatically, or hydraulically. The relative displacement of the inner part to the outer part achieves the desired control. Usually the displacement of the inner part open some valve ports while other ports are closed. There are three different types of valves: directional control valves, volume control valves, and pressure control valves. Directional control valves are used to start, stop, and reverse cylinders and motors. Volume control valves are used to adjust fluid flow rate or speed of the load. The pressure control valves are used to adjust the force applied onto the system.

2.5.1 Directional control valve

Directional control valves control the fluid direction by closing some ports and opening other ports. Four-way directional valves are widely used in hydraulic systems. Its common application is to reverse the motion of a double-side cylinder piston. One port of the four-way valve is for a pressure line, one is for a line to the tank, and the other two ports are for the actuator lines. When the valve is operated and the spool moves, the pressure line is connected to one actuator line, and at the same time, the other actuator line is connected to the tank line. Thus, the spool of a directional control valve can take three positions: neutral position, one side position and the other side position. There are several types of center position of four-way directional valves. Some popular ones are open-center, closed center, tandem-center, and float-center. These valve designs are shown in Figure 2.6.

An open-center valve has P, R, L, and T ports and all ports are connected to each other in the neutral position. In the neutral position, an actuator can move freely while the pump flow goes through the valve to the tank. A closed-center valve has P, R, L, and T ports and all ports are closed in the neutral position. A closed-center stops the motion of the actuator at the neutral position and each actuator can be operated independently. A tandem-center valve has P and T ports connected and R and L ports closed at the neutral position. A tandem-center design stops the motion of an actuator while the pump flow goes through the valve to the tank without going through a relief valve. A float-center valve has the P port closed T, R, and L ports connected at the neutral position. This design makes it possible to operate the actuators tied the same power source independently, and each actuator can move freely. Directional valves has a centering mechanism to hold the spool in the neutral

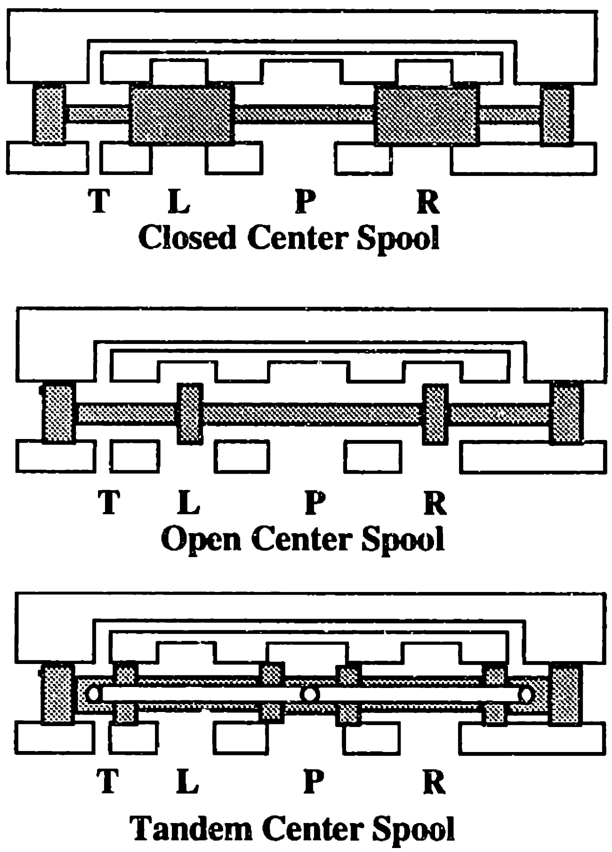

Figure 2.6: A valve center

position. A spring is commonly used to center the spool; when the valve is moved form the center, the spring is compressed, and when the force that moves the spool vanishes, the spring push back the valve to the neutral position.

2.5.2 Flow control valve

Setting a resistance in the flow line is one way to control the flow. Flow control valves have an orifice as resistance and placed in the flow line. The flow rate changes according to the change of the orifice area of the flow control valve.

2.5.3 Pressure control vale

There are two types of pressure control valves. One type is activated at a specified pressure point to bypass the liquid flow. It is usually called a relief valve or a one-way valve. A relief valve consists of an orifice, a ball to block the orifice , and a spring. The spring is given pre-compression so that the spring pushes the ball against the orifice. Pilot pressure is guided to the hole and when the pilot pressure rises up and pushes the ball back against the spring force, the flow goes through the orifice to the tank. Another type is to change the pressure corresponding to the spool movement continuously. Four-way valves are used in this manner. The construction of a four-way pressure control valve is the same as that of a four-way directional control valve. As a pressure control valve, the spool can take infinite positions between the full open position and the full closed position. The controlled pressure depends on the input flow rate or supplied pressure. The pressure control valve of the power steering system considered is a rotary valve; the spool makes a rotary motion instead of a linear motion. A schematic of this valve is shown in Figure 2.7.

The function of the valve is a combination of the directional control valve and pressure control valve. Orifices R1 and R2 mainly work as a directional control valve, and orifices R3 and R4 works as a pressure control valve. The inner shaft that works as a spool is connected with the outer valve body by the torsion bar. The torsion bar has a function as a centering spring. When a steering torque is applied, the torsion bar is twisted, and when the torque disappears, the shaft goes back to the neutral position. The outer valve body is rigidly attached to the pinion shaft and the valve is integrated into the steering gear box.

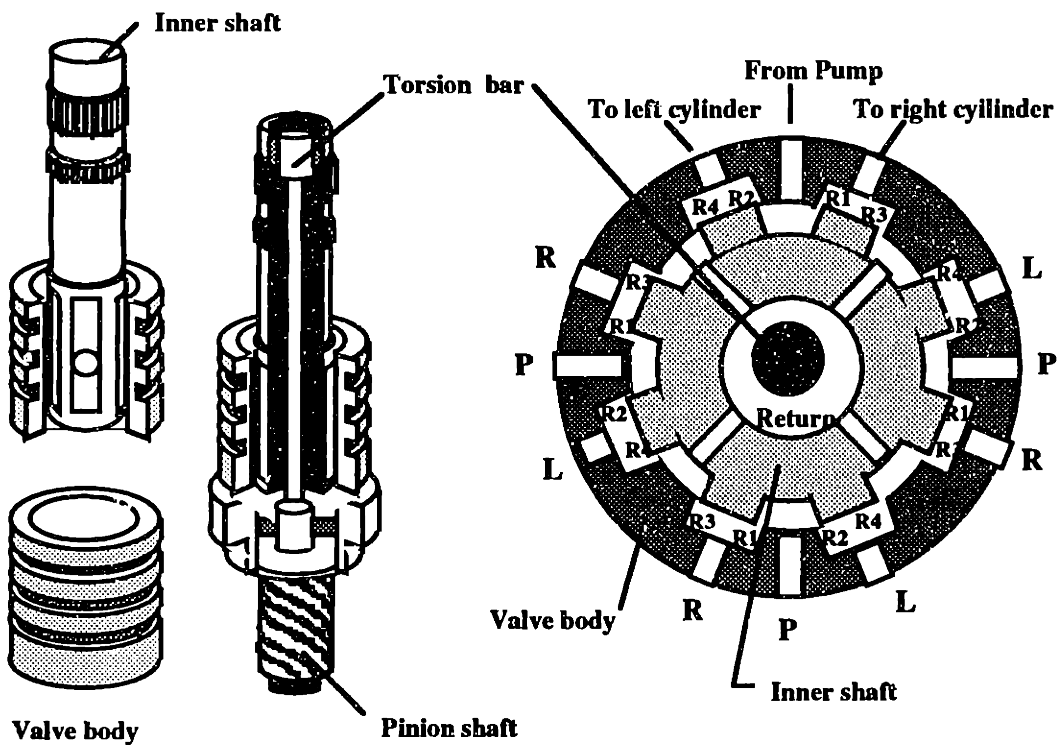

Figure 2.7: A rotary valve

2.6 Power cylinder

Cylinders are used to take the pressure or the power in a fluid system and convert it to mechanical force or power. The motion of the piston in the cylinder is linear, but rotary motion can be obtained by using proper linkages,. A schematic of a cylinder is shown in Figure 2.8.

A cylinder consists of a cylinder body, a piston, and a rod attached to the piston. The cylinder body ends are sealed with oil seals. A cylinder of power steering system is generally integrated into the steering gear box.

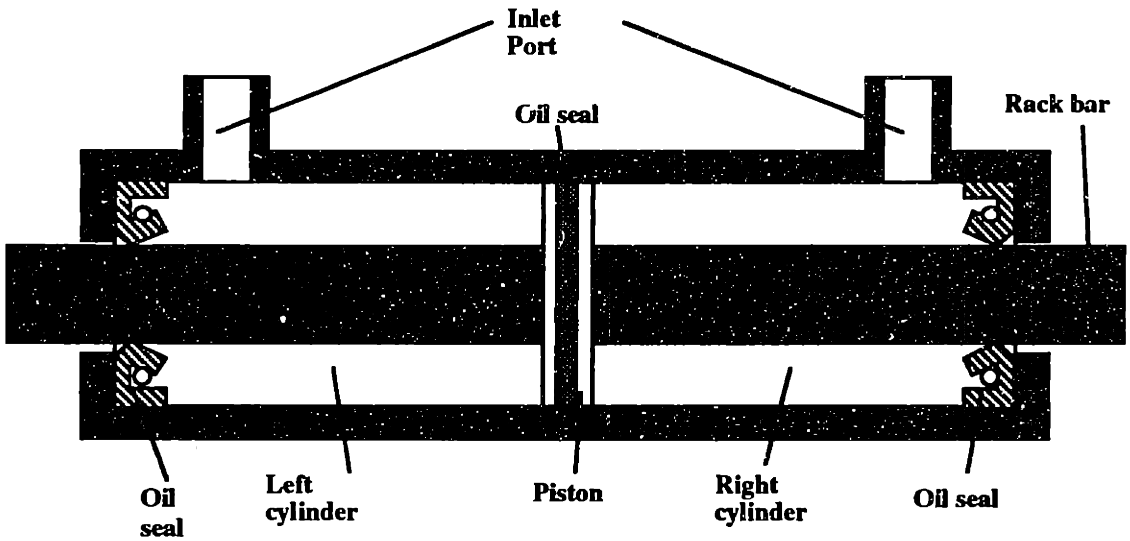

Figure 2.8: A power cylinder

2.7 Gear

Rack and pinion gear mechanism and recirculating ball mechanism are commonly used for power steering systems. Schematic diagrams of these mechanisms are shown in Figure 2.9.

Recirculating ball system consists of an input shaft, balls, a ball recirculator, a piston, and an output shaft. The balls exist between a piston and an input shaft and act as a ball bearing. The piston has a rack gear on its side, and it meshes with the gear of the output shaft. when the input shaft rotate, the piston moves back and force corresponding to the direction of the shaft rotation. The output shaft rotates following the piston motion. A recirculating ball system is generally used for heavy motor vehicles because high rigidity of the mechanism can be achieved. However, the weight of the gear component is much heavier than the rack and pinion gear component, and its mechanism is more complicated than the rack and pinion

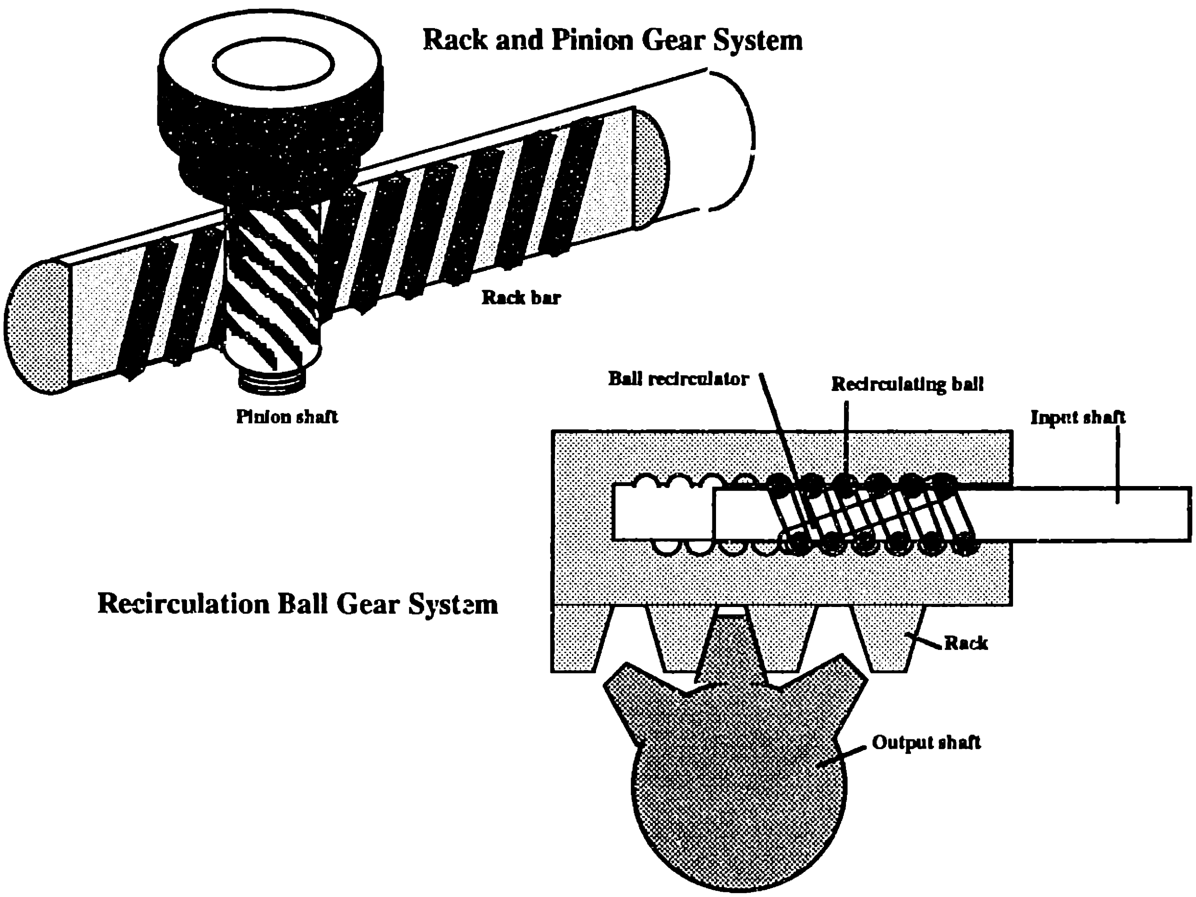

Figure 2.9: Gears: (a) A rack and pinion gear, (b) A recirculating ball system

gear mechanism. Therefore, the rack and pinion gear system is preferable than the recirculating ball system for passenger motor vehicles. A rack and pinion gear system consists of an input shaft with pinion gear and a rack bar. This system can be designed in light weight because of its simple structure. The system converts a rotary motion to a linear motion. The power steering system considered in this thesis has a rack and gear mechanism.

2.8 Summary

Although there are two types of power source for power steering system, hydraulic and electric, hydraulic system is widely used for motor vehicles. A hydraulic power steering system has a vane pump as a power source, the pressure control valve, a power cylinder and a gear mechanism. For hydraulic power steering system, when the steering torque is applied, the torque is transferred to the pinion shaft and converted into the rack force. At the same time, the torque acts as a input signal to activate the pressure control valve so that appropriate pressure supports the driver to steer the front wheels.

Chapter 3
Power Steering Component Models

3.1 Introduction

The power steering system investigated in this paper consists of several subsystems such as an oil pump, a pressure control valve, a hydraulic line and a power cylinder. To model the whole power steering system, each subsystem must be modeled properly. Then, a model of the whole system can be assembled from each model of subsystem. In this chapter, each component of the system is modeled and examined to assure its feasibility. The bond graph method is used for modeling. Based on the assumed constitutive equations, the state equations are derived from the developed system bond graph models.

3.2 Pump

3.2.1 Working principles of pumps

The oil pump used in the investigation of this system is a vane pump. The diagram of the pump used is shown in 3.1.

The pump consists of a rotor, ten vanes, a flow control valve, a relief valve, a driven shaft, and bearings. The bearings support the driven shaft. One end of the driven shaft is attached to the rotor rigidly and the other end has a pulley. The pulley is connected with the engine of the motor vehicle with a v-belt, therefore, the rotor angular velocity is proportional to the engine rotation speed, which means that the flow rate the rotor and vanes produce changes according to the engine rotation speed.

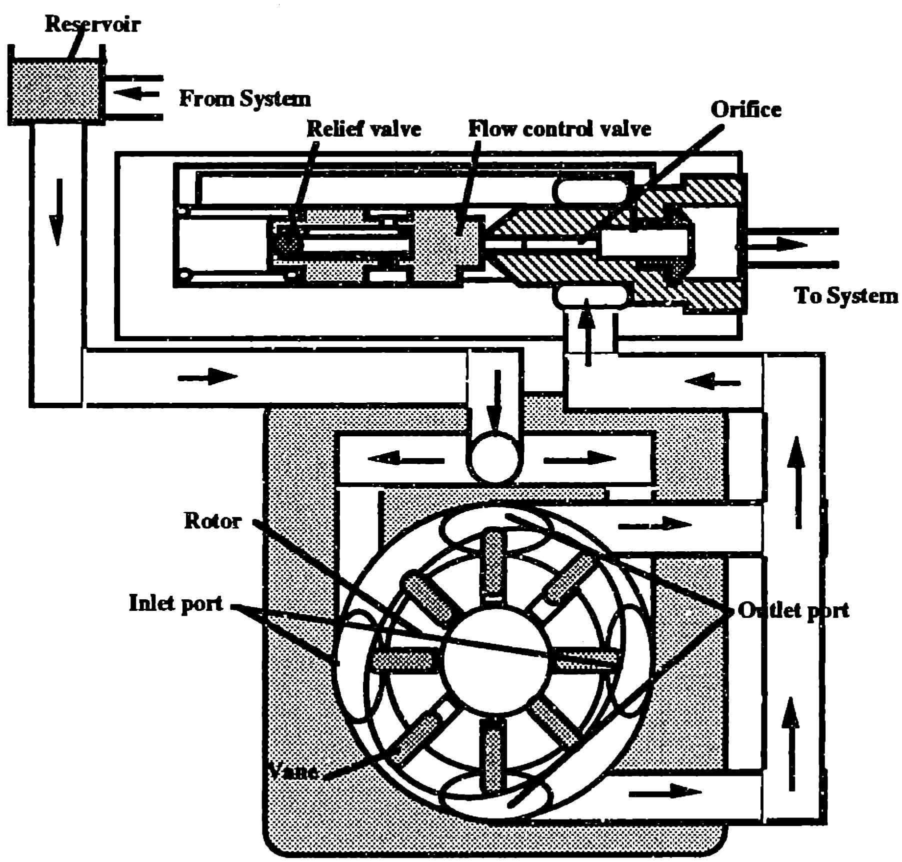

Figure 3.1: Schematic diagram of a vane pump

For a hydraulic power steering system, keeping an invariant relationship between the orifice area of the pressure control valve and the produced pressure is preferable so that the output flow rate from the pump should be constant.

The flow control valve is to keep the flow rate constant although the rotor angular velocity changes. There is an orifice in front of the flow control valve and a spring behind the valve. The spring is given a pre-compression to push the valve to the orifice. The orifice makes a pressure difference between the front and the rear of the orifice. The pressure at the rear of the orifice is guided to the backside of the flow control valve. Thus, the front part and rear part of the flow control valve receive different pressures because the pressure at the front of the valve is the same as that of the front of the orifice. When the flow that goes through the orifice increases, the pressure difference between the front and the rear of the valve pushes back the valve against the spring force, and the bypass to the tank is connected to the main stream. When the flow decreases, the pressure difference also decreases, and the spring pushes forward the valve; the bypass is closed. In this way, the pressure difference and the spring move the valve back and forth, and the flow rate from the pump outlet is kept constant.

The relief valve is incorporated in the flow control valve. It consists of a ball and a spring that is given a pre-compression. The spring pushes the ball to a hole that connects the main stream and bypass line so that the ball closes the line. When the pressure in the pump exceeds the pre-set force by the spring, the pressure pushes back the ball against the spring force, and oil flow goes into the bypass line.

The experimental data of the pump is shown in Figure 3.2. The horizontal axis shows the pressure measured at the pump outlet port. The vertical axis shows the flow rate of the pump. The angular velocity of the driven shaft is $52.4[rad./sec.]$. Although the shaft is driven with a constant speed, the flow rate decreases gradually corresponding to a pressure increase. This shows that the internal leakage exists in the pump. When the pressure reaches $8[MPa]$, the pump shows a drastic flow rate decrease because of the activation of the relief valve.

3.2.2 Modeling of the pump

In this research, the angular velocity of the rotor is assumed to be constant because the situation considered is at steady state where no acceleration of the engine ex-

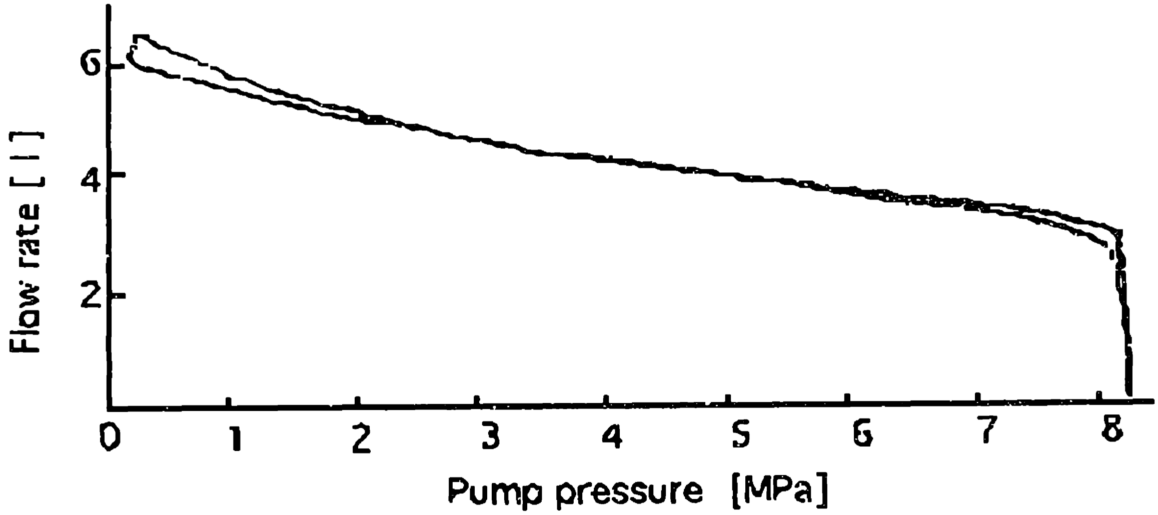

Figure 3.2: Experimental data of the vane pump

ists. Therefore, the function of the flow control valve is neglected. The inertia of the pump's moving parts and internal friction in the pump are also neglected. Then, the pump can be modeled primarily as a flow source, however, the effects of the relief valve and internal leakage must be considered. The pump characteristic can be represented by the bond graph of Figure 3.3, where

ω_{S1} is the pump shaft angular velocity

τ_{S1} is the torque developed at the driven shaft

V_P is the geometric displacement per radian rotation of the pump

Q_S is the ideal flow rate of the pump

R_l is the resistance associated with the internal pump leakage

R_d is the resistance associated with the relief valve

R_P is an equivalent resistance for R_l and R_d

Q_l is pump leakage flow rate

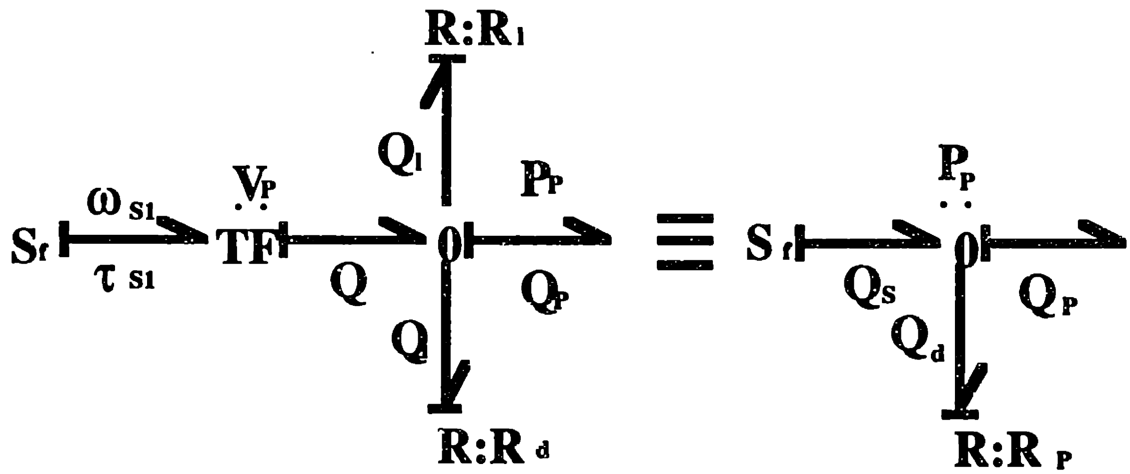

Figure 3.3: Bond graph of a vane pump

Q_d is pump discharge flow rate

Q_P is actual pump flow rate to the outer system

P_P is back pressure determined by the outer system

The constant angular velocity of the rotor is represented as the flow source, and transformer converts the angular velocity into a flow rate. Both discharge flow rate and internal leakage flow rate are related with the back pressure by the zero-junction. For the discharge flow rate, only P_P can detect Q_d, and Q_d can not detect P_P. The causality for R_d is determined as a conductive causality. For the internal leakage, there are two choices of causalities. However, if the internal leakage is enough small or zero to be negligible, the output of the pump unit is flow. To keep consistency, here the conductive causality is chosen.

Assuming that Q_l is proportional to the square root of P_P and Q_d is linear, the internal leakage flow rate Q_l and discharge flow rate Q_d can be described as a function of P_P:

$$
\begin{aligned}
Q_l &= \tfrac{1}{R_l}\sqrt{P_P} \\
Q_d &= \begin{cases} \tfrac{1}{R_d}(P_P - P_{set}) & \text{for } P_P > P_{set} \\ 0 & \text{for } P_P < P_{set} \end{cases}
\end{aligned}
$$

here, P_{set} is a set pressure at which the relief valve is activated.

The Q_P - P_P relationship is described as

$$Q_P = V_P \omega_{S1} - Q_l - Q_d \tag{3.1}$$

The simulation result is shown in Figure 3.4. The parameters used for the simulation are determined from experimental data, and they are:

$$
\begin{aligned}
\omega_{S1} &= 52.4\ [rad./sec.] \\
R_l &= 5.504 \times 10^7 \\
R_d &= 2.420 \times 10^7
\end{aligned}
$$

Comparing the simulation result with the experimental data in Figure 3.2, it can be said that the model considered here describes the real pump well.

3.3 Control valve

3.3.1 Operation of control valves

The pressure control valve used in the system is a rotary valve. A rotary valve consists of an input shaft, an outer valve body and a torsion bar. The inner shaft is connected to the steering wheel by the shaft, and the valve body is attached rigidly on the pinion shaft on which system load is imposed through the rack bar. The inner shaft and the valve body is connected with the torsion bar. When steering torque is imposed on the inner shaft, torsion bar is twisted and the inner shaft rotates relatively to the valve body. As shown in Figure 2.7, each quadrant of the rotary valve forms a four-way valve. Thus, the function of the rotary valve is explained as that of a four-way valve.

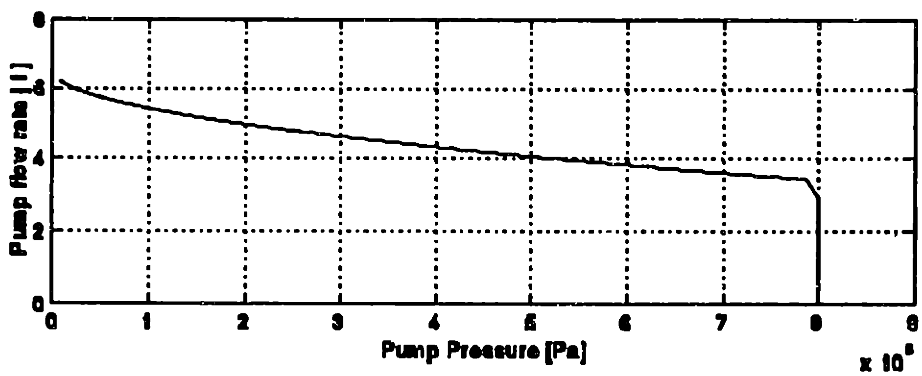

Figure 3.4: Simulation result of the vane pump

A schematic diagram of the four-way valve is shown in Figure 3.5. The spool valve motion to the right corresponds to the clockwise rotation of the rotary valve and vice versa. When the spool moves to the right In Figure 3.5, orifice R_1 and R_4 open and orifice R_2 and R_3 close. The pressure drop are caused mostly at R_2 and R_3, and raised pressure is guided into the right cylinder. When the spool moves to the left, every thing goes the other way.

3.3.2 Modeling of the rotary valve

A bond graph of the rotary valve is shown in Figure 3.6, where

P_V is pressure at the valve inlet port

Q_V is flow rte from the hydraulic line

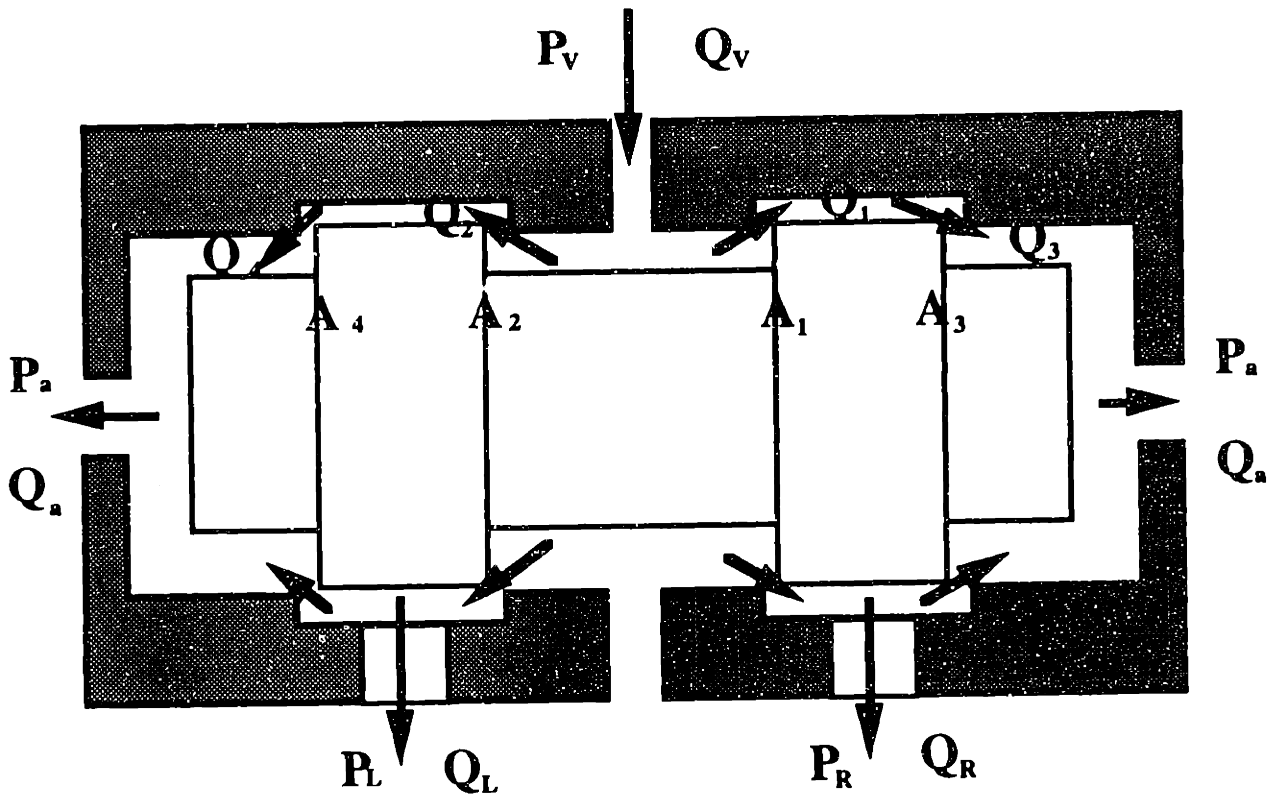

Figure 3.5: A schematic diagram of the four-way valve

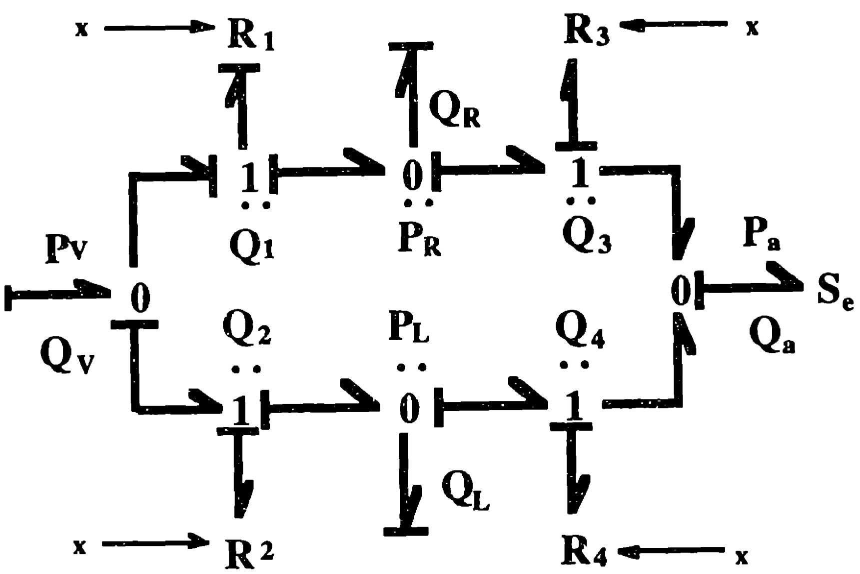

Figure 3.6: A bond graph of the rotary valve

R_n is resistance corresponding to the valve orifice

Q_n is flow rate that goes through the orifice A_n

P_R is pressure at the right cylinder

P_L is pressure at the left cylinder

Q_R is flow rate into the right cylinder

Q_L is flow rate into the left cylinder

P_a is ambient pressure

Q_a is flow rate into the tank

x is spool displacement that modulates the orifice resistance

The flow Q_V comes from the hydraulic line and separates into two flows: Q_1 and Q_2. Four orifices determine the separate ratio of Q_V. Right cylinder pressure P_R is determined by the orifice A_3 and left cylinder pressure is determined by the orifice A_4. The value of the resistance R_1, R_2, R_3, R_4 are modulated by the spool displacement. The ambient pressure is represented as the effort source.

To determine the causalities, the following is considered..

The purpose of the control valve of the power steering system is to change the pressure corresponding to the rotation angle of the valve. From this point of view, it is assumed that the pressure is supposed to be output and, therefore, the flow is input.

The oil compressibility in the cylinders is assumed to be negligible so that the $Q_R = Q_L = A\dot{X}$. Here, A is the piston area and $\dot{X}$ is the rack bar speed.

The three of the four orifices must have resistive causality and one must has conductive causality. However, they can be determined arbitrary.

The corresponding constitutive equations are:

$$Q_1 = \frac{1}{R_1}\sqrt{P_{R1}} \tag{3.2}$$

$$P_{R2} = R_2 Q_2^2 \tag{3.3}$$

$$P_{R3} = R_3 Q_3^2 \tag{3.4}$$

$$P_{R4} = R_4 Q_4^2 \tag{3.5}$$

The junction equations are:

$$P_V = P_{R2} + P_L \tag{3.6}$$

$$P_R = P_{R3} + P_a \tag{3.7}$$

$$P_L = P_{R4} + P_a \tag{3.8}$$

$$P_{R1} = P_V - P_R \tag{3.9}$$

The resistance of the orifice R_n must be described as a function of the valve displacement.

The shape of the valve orifice is shown in Figure 3.7 (a).

To simplify the calculation of the orifice area, the shape is assumed to be like Figure 3.7 (b). Thus, each resistance R_n is described by:

$$R_1 = \frac{\rho}{2l_V}(b + r\theta)^2$$
$$R_2 = \frac{\rho}{2l_V}(b - r\theta)^2$$
$$R_3 = \frac{\rho}{2l_V}(b - r\theta)^2$$
$$R_4 = \frac{\rho}{2l_V}(b + r\theta)^2$$

Here,

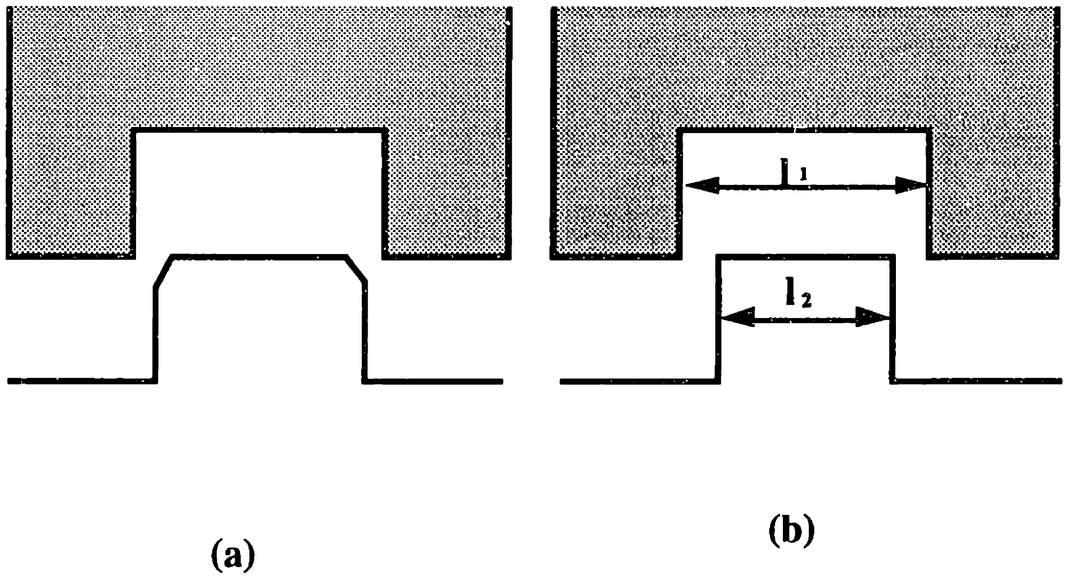

Figure 3.7: Schematic diagram of the control valve edge

ρ is oil density 0.83×10^3 $[kg/m^3]$

$l_V$is orifice groove length 15 $[mm]$

r is valve body radius 10.5 $[mm]$

θ is valve rotation angle $[rad.]$

b is $\frac{l_1-l_2}{2}$

The result of the simulation is shown in Figure 3.8, and corresponding experimental data is shown Figure 3.9.

The horizontal axis shows that the valve rotation angle, and the vertical axis shows the pressure at the valve inlet port. In the simulation, ambient pressure is set to be zero and no pressure drop from the valve outlet port to the tank is assumed. In reality, the pressure drop exists after the valve outlet port that makes the disagreement of the pressure at the zero rotation angle. The simplification of the orifice shape also causes the inaccuracy from 0 to 3 $[MPa]$. However, this model is sufficient to use for

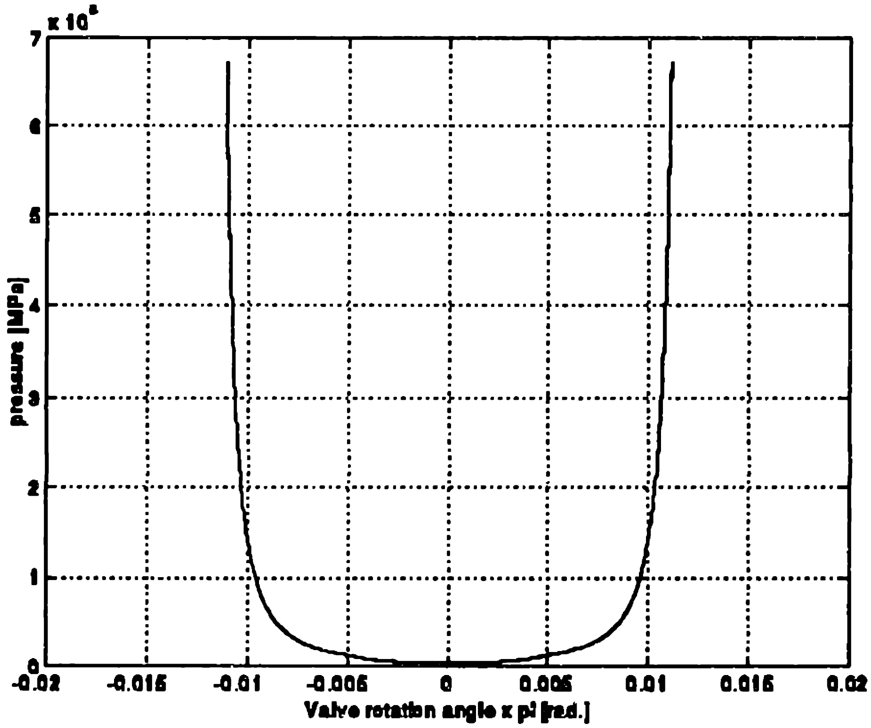

Figure 3.8: Simulation results of the pressure control valve

the analysis, which is interested in the dynamics of the power steering system around 5 $[MPa]$.

3.4 Hydraulic lines

The hydraulic line of this system consists of two hoses and three pipes. The schematic diagram of the hydraulic line is shown in Figure 3.10.

To model the hydraulic line, the following has been considered;

- Mass of the oil in a pipe is treated as inertance.
- Pressure drop associated with a pipe is treated as resistance.
- Compressibility of the oil in a pipe is treated as capacitance.
- Expandability of the hose is treated as capacitance.

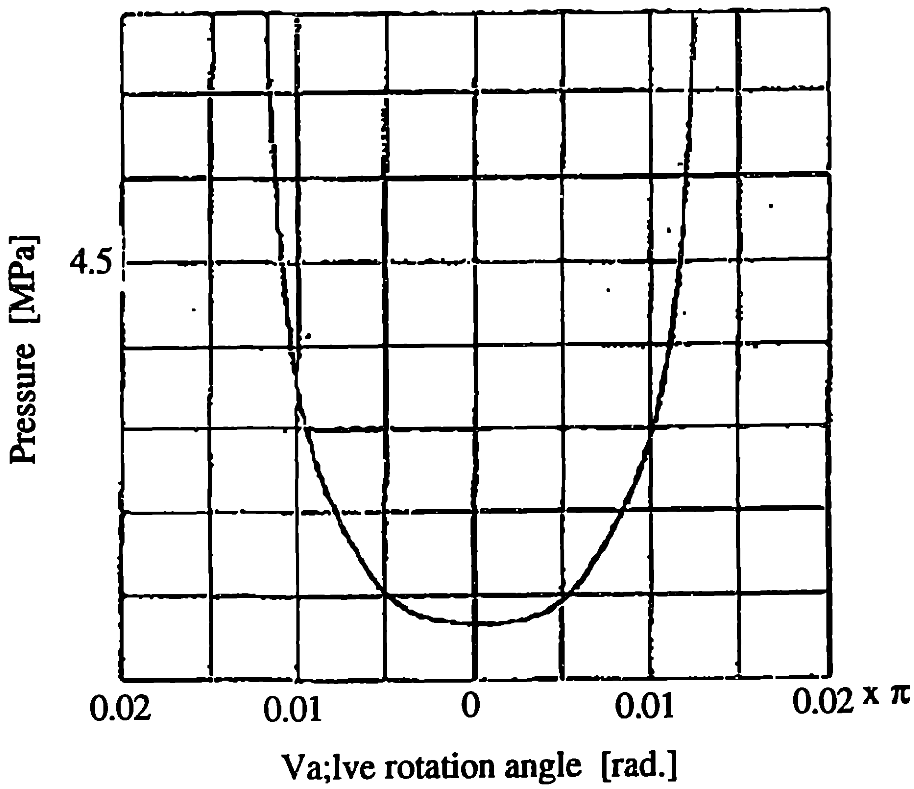

Figure 3.9: Simulation results of the pressure control valve

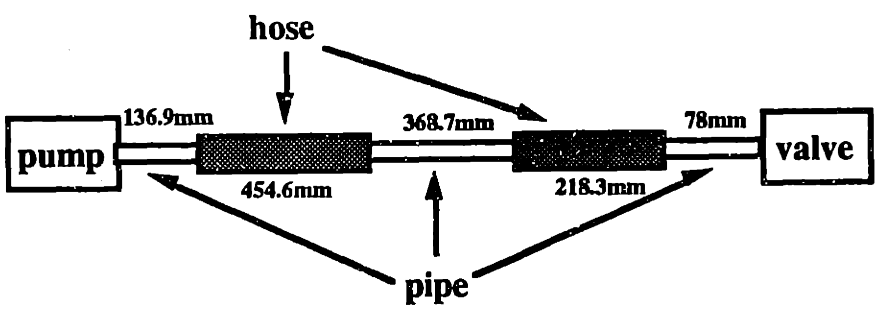

Figure 3.10: Schematic diagram of the hydraulic line

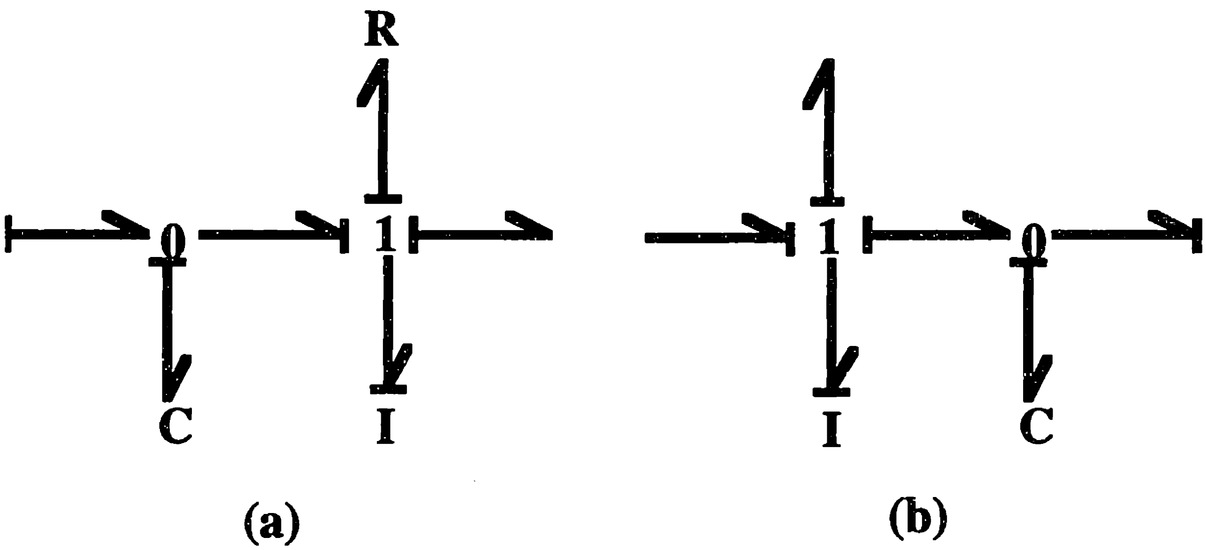

Figure 3.11: Two types of pipe model

- Mass of the oil in a hose is included in a mass of the oil in a pipe.
- Compressibility of the oil in a hose is included in the hose expandability.
- Pressure drop associated with a hose is included in the pipe resistance.

There are two possible types of a pipe model ; they are shown in Figure 3.11. Type (a) in Figure 3.11 is applied if the flow is imposed with power inflow and the pressure is detected by power outflow. Type (b) is applied if pressure is imposed with power flow and flow is detected by the power outflow.

In this system, type (a) is preferable because, from the previous section in this chapter, it is noted that the pump is a flow source and the control valve gives the pressure as its output. A bond graph of the hydraulic line is shown in Figure 3.12, where

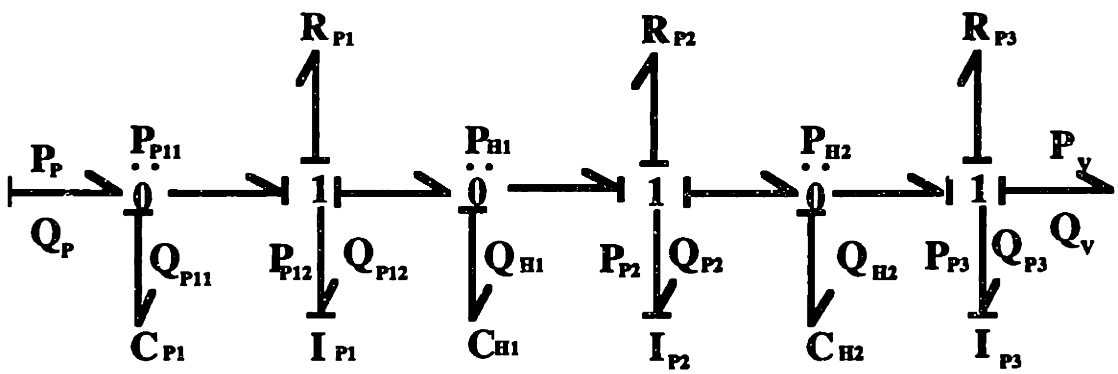

Figure 3.12: A bond graph of the hydraulic line

P_P is pressure at the pump outlet port

Q_P is flow rte from the pump

$R_{pn}$is resistance associated with the n-th pipe

$C_{pn}$is capacitance associated with the n-th pipe

I_{pn} is inertance associated with the n-th pipe

$C_{Hn}$is capacitance associated with the n-th hose

Q_R is flow rate into the right cylinder

Q_L is flow rate into the left cylinder

P_a is ambient pressure

Q_a is flow rate into the tank

x is spool displacement that modulates the orifice resistance

Approximation of the lumped parameters are derived as follows.

For the pipe resistance, Hagen-Poiseuille equation can be applied because the Reynolds number is 873.7 that means there is laminar flow in the pipe. Then, we obtain:

$$P_{in} - P_{out} = \frac{128\mu l}{\pi d^4} Q \tag{3.10}$$

For the pipe inertance, considering force balance, we obtain:

$$\frac{dv}{dt} A\rho l = A(P_{in} - P_{out}) \tag{3.11}$$

For the pipe capacitance, assuming that the pressure in the pipe is equal, w obtain:

$$\frac{Al}{K}\frac{dP}{dt} = Q_{in} - Q_{out} \tag{3.12}$$

For the hose capacitance, assuming linear relationship between pressure and flow, we obtain:

$$kl\frac{dP}{dt} = Q_{in} - Q_{out} \tag{3.13}$$

Therefore, parameters are calculated by following formulas.

$$I_p = \frac{\rho l}{A} \tag{3.14}$$

$$C_p = \frac{Al}{K} \tag{3.15}$$

$$R_p = \frac{128\mu l}{\pi d^4} \tag{3.16}$$

$$C_H = \frac{1}{kl} \tag{3.17}$$

Here,

A is a section area of the pipe 7.85×10^{-5} $[m^2]$

ρ is oil density 0.83×10^3 $[kg/m^3]$

l is pipe length

k is hose expandability $1.6 \times 10^9 [N/m^2]$

μ is oil viscosity 0.95×10^{-2} $[Nsec./m^2]$

d is pipe diameter 10 $[mm]$

K is oil bulk modulus 3.67×10^{-12} $[m^4/N]$

The constitu˙˙ve equations are:

$$\frac{d}{dt}P_{p11} = \frac{1}{C_{p1}}Q_{p11} \quad (3.18)$$

$$\frac{d}{dt}Q_{p12} = \frac{1}{I_{p1}}P_{p12} \quad (3.19)$$

$$\frac{d}{dt}P_{H1} = \frac{1}{C_{H1}}Q_{H1} \quad (3.20)$$

$$\frac{d}{dt}Q_{p2} = \frac{1}{I_{p2}}P_{p2} \quad (3.21)$$

$$\frac{d}{dt}P_{H2} = \frac{1}{C_{H2}}Q_{H2} \quad (3.22)$$

$$\frac{d}{dt}Q_{p3} = \frac{1}{I_3}P_{p3} \quad (3.23)$$

The junction equations are:

$$Q_{p11} = Q_P - Q_{p12} \quad (3.24)$$

$$P_{p12} = P_{p11} - P_{H1} - R_{p1}Q_{p12} \quad (3.25)$$

$$Q_{H1} = Q_{p12} - Q_{p2} \quad (3.26)$$

$$P_{p2} = P_{H1} - P_{H2} - R_{p2}Q_{p2} \quad (3.27)$$

$$Q_{H2} = Q_{p2} - Q_{p3} \quad (3.28)$$

$$P_{p3} = P_{H2} - (R_{p3} + R_V)Q_{p3} \quad (3.29)$$

The state space equations are written in matrix form $\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu}$ because the hydraulic line system is linear.

$$\frac{d}{dt}\begin{bmatrix} P_{p11} \\ Q_{p12} \\ P_{H1} \\ Q_{p2} \\ P_{H2} \\ Q_{p3} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{C_{p1}} & 0 & 0 & 0 & 0 \\ \frac{1}{I_{p1}} & -\frac{R_{p1}}{I_{p1}} & -\frac{1}{I_{p1}} & 0 & 0 & 0 \\ 0 & \frac{1}{C_{H1}} & 0 & -\frac{1}{C_{H1}} & 0 & 0 \\ 0 & 0 & \frac{1}{I_{p2}} & -\frac{R_{p2}}{I_{p2}} & -\frac{1}{I_{p2}} & 0 \\ 0 & 0 & 0 & \frac{1}{C_{H2}} & 0 & -\frac{1}{C_{H2}} \\ 0 & 0 & 0 & 0 & \frac{1}{I_{p3}} & -\frac{R_{p3}+R_V}{I_{p3}} \end{bmatrix} \begin{bmatrix} P_{p11} \\ Q_{p12} \\ P_{H1} \\ Q_{p2} \\ P_{H2} \\ Q_{p3} \end{bmatrix} + \begin{bmatrix} \frac{1}{C_{p1}} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} Q_P \tag{3.30}$$

The eigenvalues of the **A** matrix can tell the frequencies the system can show. The strength of each frequency mode also can be estimated by its left eigenvectors with the initial condition.

When the resistance $R_V = 0$, which means the end of the line is open to the air, the eigenvalues and left eigenvectors are:

Eigenvalues:

$$\begin{aligned} \lambda_{11} &= -1.8276 + 1.0151 \times 10^4 i \\ \lambda_{12} &= -1.8276 - 1.0151 \times 10^4 i \\ \lambda_{13} &= -1.8332 + 3.5258 \times 10^2 i \\ \lambda_{14} &= -1.8332 - 3.5258 \times 10^2 i \\ \lambda_{15} &= -1.8327 + 1.3661 \times 10^3 i \\ \lambda_{16} &= -1.8327 - 1.3661 \times 10^3 i \end{aligned}$$

Left eigenvectors:

$w11$	$w12$	$w13$
$4.97e-01+3.09e-06i$	$-1.36e+06+7.32e+09i$	$-4.98e-01-3.09e-06i$
$4.97e-01-3.09e-06i$	$-1.36e+06-7.32e+09i$	$-4.98e-01+3.09e-06i$
$-2.81e-03-2.54e-08i$	$7.50e+03-1.44e+06i$	$-6.99e-01-6.29e-06i$
$-2.81e-03+2.54e-08i$	$7.50e+03+1.44e+06i$	$-6.99e-01+6.29e-06i$
$3.78e-04-2.39e-08i$	$-9.58e+02+7.49e+05i$	$9.23e-02-5.84e-06i$
$3.78e-04+2.39e-08i$	$-9.58e+02-7.49e+05i$	$9.23e-02+5.84e-06i$
$w14$	$w15$	$w16$
$5.53e+03-2.95e+07i$	$7.56e-04+5.56e-09i$	$-1.75e+01+9.31e+04i$
$5.53e+03+2.95e+07i$	$7.56e-04-5.56e-09i$	$-1.75e+01-9.31e+04i$
$5.02e+06-9.65e+08i$	$-6.26e-02-8.14e-07i$	$1.15e+06-2.22e+08i$
$5.02e+06+9.65e+08i$	$-6.26e-02+8.14e-07i$	$1.15e+06+2.22e+08i$
$-6.31e+05+4.94e+08i$	$-4.95e-01+3.18e-05i$	$5.79e+05-4.53e+08i$
$-6.31e+05-4.94e+08i$	$-4.95e-01-3.18e-05i$	$5.79e+05+4.53e+08i$

Assuming that the flow rate Q_{p3} is given as an initial condition like $[0,0,0,0,0,10]$, the product of left eigenvector and initial condition is:

$$\begin{bmatrix} -1.7553\times 10^2+9.3176\times 10^5 i \\ -1.7555\times 10^2-9.3176\times 10^5 i \\ 1.1571\times 10^7-2.2214\times 10^9 i \\ 1.1571\times 10^7+2.2214\times 10^9 i \\ 5.7931\times 10^6-4.5364\times 10^9 i \\ 5.7931\times 10^6+4.5364\times 10^9 i \end{bmatrix}$$

Similarly, when $R_V = 2\times 10^9$, which represents the case the control valve at the end of the line is almost closed, the eigenvalues and left eigenvect rs are:

Eigenvalues:

$$\begin{aligned} \lambda_{21} &= -1.8276+1.0151\times 10^4 i \\ \lambda_{22} &= -1.8276-1.0151\times 10^4 i \\ \lambda_{23} &= -2.7472\times 10^2+6.2765\times 10^2 i \\ \lambda_{24} &= -2.7472\times 10^2-6.2765\times 10^2 i \\ \lambda_{25} &= -3.1470\times 10^2 \\ \lambda_{26} &= -1.5704\times 10^3 \end{aligned}$$

Table 3.1: Parameters of pipe

pipe #	l $[m]$	I $[kg/m^4]$	R $[Nsec/m^5]$	C $[m^5/N]$
1	1.369×10^{-1}	1.45×10^6	5.30×10^6	6.72×10^{-15}
2	3.687×10^{-1}	3.90×10^6	1.43×10^7	1.81×10^{-14}
3	7.8×10^{-2}	8.24×10^5	3.02×10^6	3.83×10^{-15}

Left eigenvectors:

$w21$	$w22$	$w23$
$-2.34e-01-4.39e-01i$	$6.46e+09-3.44e+09i$	$2.34e-01+4.40e-01i$
$-2.34e-01+4.39e-01i$	$6.46e+09+3.44e+09i$	$2.34e-01-4.40e-01i$
$2.65e-03+1.22e-03i$	$-2.17e+06+1.92e+06i$	$6.59e-01+3.02e-01i$
$2.65e-03-1.22e-03i$	$-2.17e+06-1.92e+06i$	$6.59e-01-3.02e-01i$
$7.21e-03-1.85e-15i$	$-3.29e+06-3.17e-06i$	$1.79e+00-4.54e-13i$
$-4.16e-04+1.77e-16i$	$9.47e+05+9.15e-07i$	$-1.05e-01+4.26e-14i$
$w24$	$w25$	$w26$
$-2.60e+07+1.38e+07i$	$-3.53e-04-6.68e-04i$	$8.76e+04-2.2564e+04i$
$-2.60e+07-1.38e+07i$	$-3.53e-04+6.68e-04i$	$8.76e+04+2.2563e+04i$
$-1.45e+09+1.29e+09i$	$-1.95e-02-8.65e-01i$	$1.45e+08+4.5953e+08i$
$-1.45e+09-1.29e+09i$	$-1.95e-02+8.65e-01i$	$1.45e+08-4.5953e+08i$
$-2.21e+09-2.13e-03i$	$1.41+1.53e-12i$	$-8.33e+08-9.2639e-04i$
$6.51e+08+6.16e-04i$	$-8.66e-01-4.46e-13i$	$1.25e+09+2.7020e-04i$

Assuming the same initial condition as before, the product of left eigenvector and initial condition is obtained:

$$\begin{bmatrix} 8.7685 \times 10^5 - 2.2564 \times 10^5 i \\ 8.7685 \times 10^5 + 2.2564 \times 10^5 i \\ 1.4508 \times 10^9 + 4.5953 \times 10^9 i \\ 1.4508 \times 10^9 - 4.5953 \times 10^9 i \\ -8.3330 \times 10^9 - 9.2639 \times 10^{-3} i \\ 1.2593 \times 10^{10} + 2.7020 \times 10^{-3} i \end{bmatrix}$$

Thus, the third eigenvalue λ_{n3} and the fourth eigenvalue λ_{n4} dominate the oscillation in both cases. The frequencies observed in these cases are 56.1 $[Hz]$ for the first case and 99.9 $[Hz]$ for the second case.

The parameters used in this analysis are listed in Table 3.1 and 3.2.

Table 3.2: Parameters of hose

hose #	l $[m]$	C $[m^5/N]$
1	4.546×10^{-1}	1.67×10^{-12}
2	2.183×10^{-1}	8.0×10^{-13}

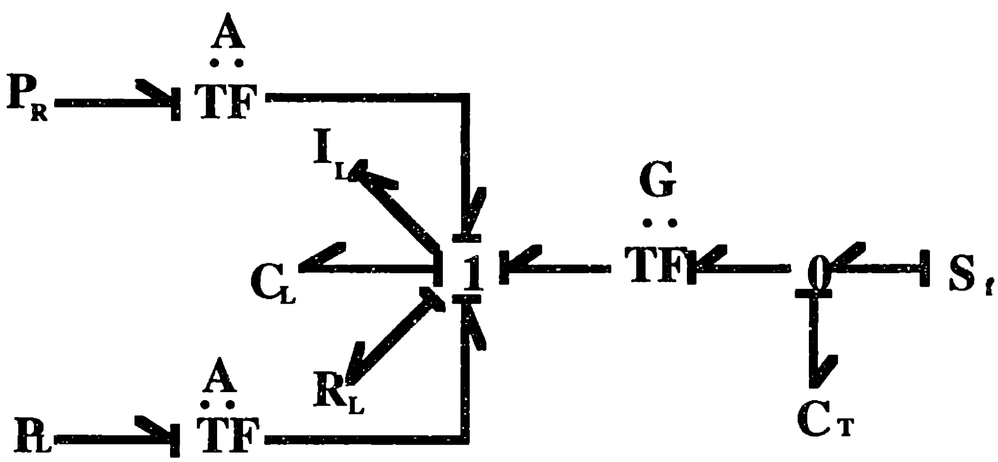

Figure 3.13: A bond graph of the power cylinder

3.5 Power cylinder

The power cylinder consists of a right cylinder, a left cylinder, a piston, a rack bar, and oil seals. The rack bar is connected to the front wheels by linkage, and the load including the tire mass and linkage friction is imposed on the lack bar. The piston attached rack bar converts the pressure from the control valve to the rack force. The driver's steering torque is also converted into the rack force by the rack and pinion gear. A corresponding bond graph is shown in Figure 3.13.

The constitutive equations are:

$$\frac{d}{dt}\dot{X} = fracl I_L\{A(P_R - P_L) + G\tau_T - F_{CL} - R_L\dot{X} \quad (3.31)$$

$$\frac{d}{dt}F_{CL} = fracl C_L\dot{X} \quad (3.32)$$

$$\frac{d}{dt}\tau_T = fracl C_L(\omega_{S2} - G\dot{X}) \quad (3.33)$$

Here,

P_R is pressure at the right side cylinder

P_L is pressure at the left side cylinder

A is piston area 1×10^{-3} $[m^2]$

C_T torsion bar spring constant 92.8 $[Nm/rad.]$

G is gear ratio 127.7 $[m/rad.]$

C_L is capacitance of the load 1×10^{-6} $[m/N]$

I_L is mass of the load 50 $[kg]$

R_L is resistance of the load $2.72 \times 10^4 [Nsec./m]$

$\omega_{S2}$is steering angular velocity as input.

τ_T is steering torque.

F_{CL}load force associated with the load capacitance.

$\dot{X}$ rack velocity.

The damping ratio of this subsystem is $\zeta = 1.92$. The subsystem is over damped and does not oscillate.

3.6 Summary

Each subsystem of the power steering system has been modeled properly.

Ideal pump with a constant rotation speed is described as a flow source, and even though there is internal leakage in the pump, flow is considered as the output.

The rotary pressure control valve is described as a four-way valve. To determine the causality of its bond graph, the objective of the valve is considered. In our case, the pressure changes according to the valve displacement. Thus, the pressure is considered as an output of the valve.

The Hydraulic line is described as the combination of capacitance, inertance, and resistance. The model of the pipe used in the hydraulic line can take two types. Proper type should be determined by considering the input and output relationship. The damped natural frequency of this subsystem changes according to the value of the resistance that connects to the end of the line.

The power cylinder subsystem also contains capacitance and inertance so that the subsystem could show some oscillation. However, in our case, the damping ratio is larger than one; oscillation can not be observed.

Chapter 4

Complete System Model & Results

4.1 Introduction

Numerical simulation is very useful to investigate the non-linear system behavior. It is also useful if the system has a lot of parameters, or to change only one parameter is impossible experimentally. In these cases, numerical simulation can help determine the effect of each parameter, and examine the system behavior. In this chapter, numerical simulation is used to analyze the pressure vibration behavior of the power steering system. Linearization of the non-linear system is tried after finding the vibration condition to analyze the system behavior by using linear analysis methods.

4.2 Whole system model

The model of the power steering system considered is assembled from the models of the sub-units described in the previous chapter. A bond graph of the total system is shown in Figure 4.1. Symbols used in this bond graph are the same as those explained in chapter 3.

The pump model has a flow source because of its constant angular velocity and is connected to the hydraulic-line model so that the pump supplies the flow to the line. The other end of the line is connected to the valve model, and flow goes into the valve from the line. The valve resistance determines the cylinder pressure P_R and P_L according to the valve rotation angle. The cylinder pressures are converted into the rack force by a transformer that represents the piston area. The steering torque

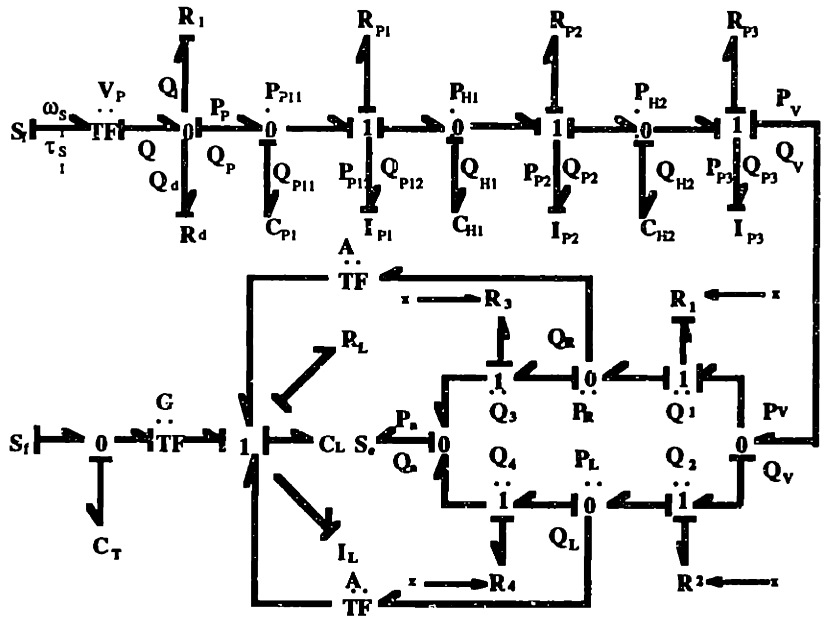

Figure 4.1: A bond graph of the power steering system

associated with the torsion bar twisted angle is also converted into the rack force by a transformer that represents the gear ratio. These forces move the rack bar and, as a result, the front wheels move against the load.

The total system can be described by the ninth order non-linear equation because the bond graph shows nine energy storage elements with integral causalities. The state space equations can take the form $\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u})$.

Here, the nine states are:

$$\mathbf{x} = \begin{bmatrix} \text{pressure at pump outlet port} \\ \text{flow rate of pipe \# 1} \\ \text{pressure at hose \# 1} \\ \text{flow rate of pipe \# 2} \\ \text{pressure at hose \# 2} \\ \text{flow rate of pipe \# 3} \\ \text{rack bar velocity} \\ \text{load spring force} \\ \text{torsion bar torque} \end{bmatrix}$$

, and the inputs are:

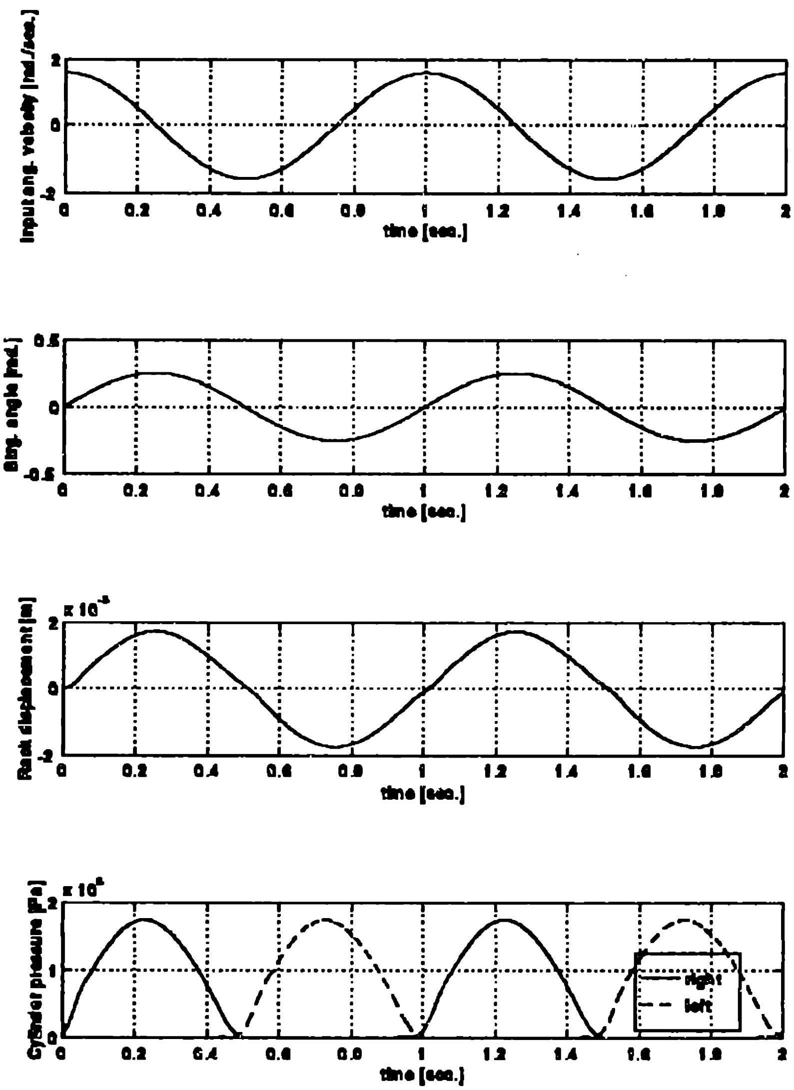

Figure 4.2: Simulation result of the power steering system: sinusoidal input

$$\mathbf{u} = \begin{bmatrix} \text{pump output flow rate} \\ \text{steering wheel angular velocity} \end{bmatrix}$$

To verify the feasibility of the whole model, a simulation was held under the simple condition. The simulation result of this model is shown in Figure 4.2.

Here, the steerig wheel angular velocity is given as the input; it is $\frac{\pi}{2} sin\ 2\pi t$. The pump angular velocity is 52.4 [rad./sec.].

As shown in Figure 4.2, the rack bar moves according to the steering angle. The right cylinder pressure and left cylinder pressure also changes with the steering angle to move the rack bar against the load. The model simulates the real system behavior.

4.3 Simulation

In the experiment, a triangular input was given as the steering angle. This is equivalent to the square input of the steering angular velocity. In this simulation, a square input is used as the second flow source ω_{S2}. Results of the simulation are shown in Figure 4.3. The corresponding experimental data is shown in Figure 4.4.

The simulation shows the pressure vibration at the valve inlet port, which is also observed in the experimental data. There is a discrepancy at the starting point of the vibration between the simulation and the experimental data. In the simulation, the vibration starts after the pressure peak, on the other hand, the vibration of the experiment starts before the pressure peak. However, the frequency of the vibration simulation has shown is 110 [Hz], and this is close enough to the frequency obtained from the experiment, that is 92 [Hz]. Therefore, this model of the power steering system is regarded as a sufficient model to investigate the pressure vibration behavior.

4.4 Analysis

Linearizing non-linear systems makes it possible to apply numerous linear analysis methods that will produce information on the behavior of non-linear systems. Therefore, linearization is applied to analyze the vibration behavior. The linearizaton method applied in this section is based on the expanding the non-linear function into a Taylor series about the operating point and take only the linear term into the consideration.

The constitutive equations associated with the control valve contain the non-

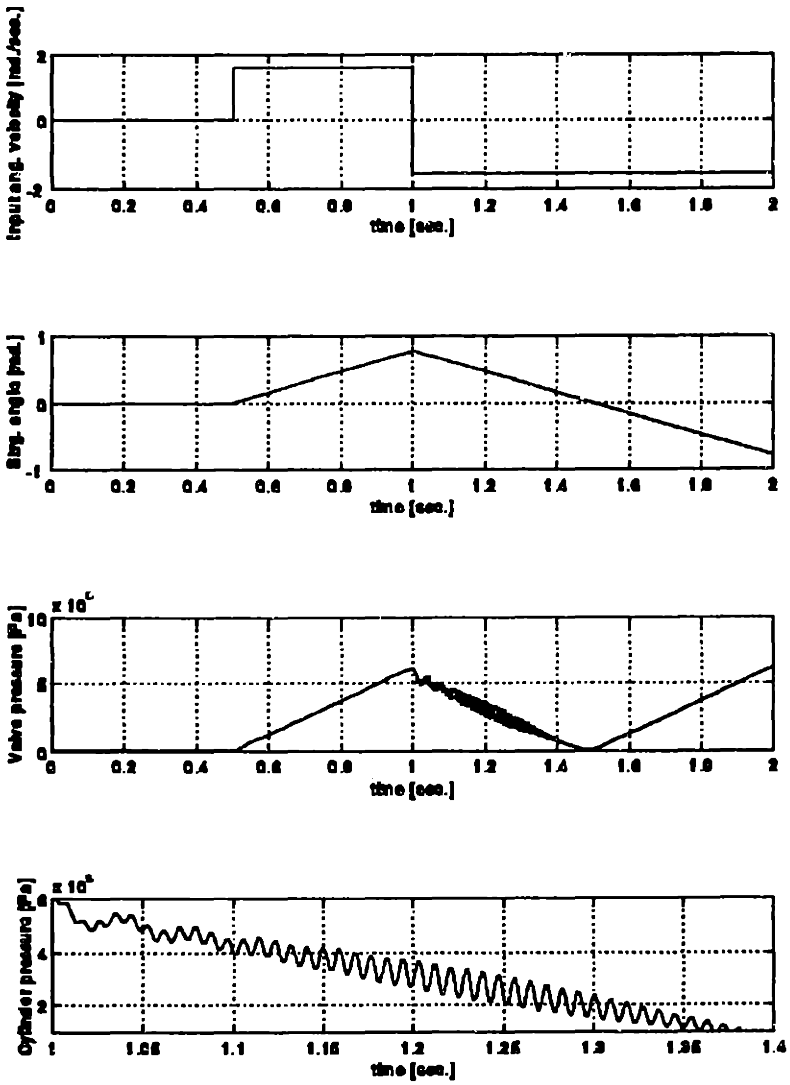

Figure 4.3: Simulation result of pressure vibration: triangular input

linearity. The expressions for the pressures as the output of the control valve are:

$$P_R = \frac{\rho}{2}\left(\frac{Q_3}{A_3}\right)^2 \tag{4.1}$$

$$P_L = \frac{\rho}{2}\left(\frac{Q_4}{A_4}\right)^2 \tag{4.2}$$

$$P_P = \frac{\rho}{2}\left(\frac{Q_2}{A_2}\right)^2 + \frac{\rho}{2}\left(\frac{Q_4}{A_4}\right)^2 \tag{4.3}$$

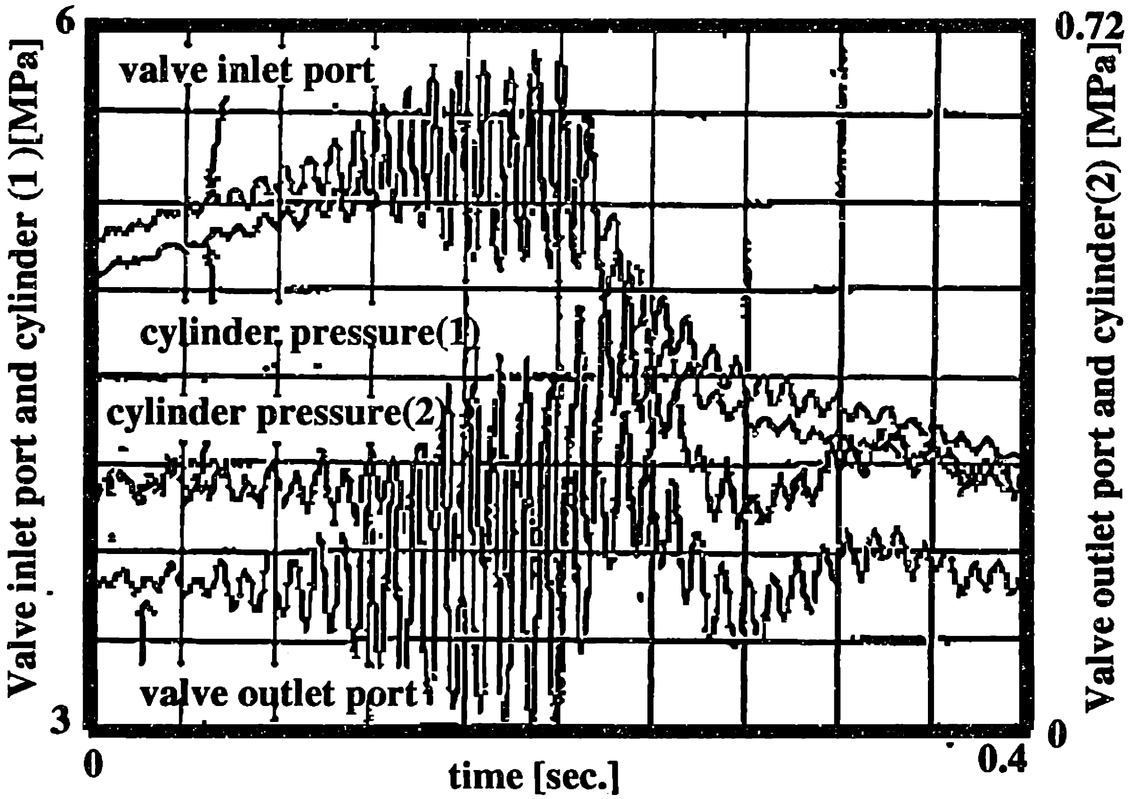

Figure 4.4: Experimental data of pressure vibration

where

$$
\begin{aligned}
A_1 &= l_V(b + r\theta) \\
A_2 &= l_V(b - r\theta) \\
A_3 &= l_V(b - r\theta) \\
A_4 &= l_V(b + r\theta) \\
Q_V &= Q_1 + Q_2 \\
Q_3 &= Q_1 - Q_C \\
Q_4 &= Q_2 + Q_C
\end{aligned}
$$

The symbols represent:

ρ is oil density.

$l_V$is orifice groove length.

r is valve body radius.

θ is valve rotation angle.

b is the length of the valve underlap at the neutral position.

$A_i$is the area of the each valve orifice.

$Q_i$is the flow rate that goes through each valve orifice.

Q_V is the flow rate from the hydraulic line.

Q_C is the flow rate according to the piston velocity.

From the above equations, each flow rate is descried as a function of Q_P and Q_C.

$$Q_1 = \frac{Q_P + Q_C}{2} \tag{4.4}$$

$$Q_2 = \frac{Q_P - Q_C}{2} \tag{4.5}$$

$$Q_3 = \frac{Q_P - Q_C}{2} \tag{4.6}$$

$$Q_4 = \frac{Q_P + Q_C}{2} \tag{4.7}$$

Substituting these equations into the expressions for the pressures, they can be rewritten as:

$$P_R = \frac{\rho}{2l_V^2(b - r\theta)^2}\left(\frac{Q_P - Q_C}{2}\right)^2 \tag{4.8}$$

$$P_L = \frac{\rho}{2l_V^2(b + r\theta)^2}\left(\frac{Q_P + Q_C}{2}\right)^2 \tag{4.9}$$

$$\begin{aligned} P_P &= \frac{\rho}{2l_V^2(b-r\theta)^2}\left(\frac{Q_P-Q_C}{2}\right)^2 \\ &+\frac{\rho}{2l_V^2(b+r\theta)^2}\left(\frac{Q_P+Q_C}{2}\right)^2 \end{aligned} \tag{4.10}$$

Applying Taylor's expansion method, we obtain:

$$\begin{aligned} P_R &\approx \left.\frac{\partial P_R}{\partial \theta}\right|_{\theta_0,Q_{P0},Q_{C0}} \delta\theta + \left.\frac{\partial P_R}{\partial Q_P}\right|_{\theta_0,Q_{P0},Q_{C0}} \delta Q_P + \left.\frac{\partial P_R}{\partial Q_C}\right|_{\theta_0,Q_{P0},Q_{C0}} \delta Q_C \\ P_L &\approx \left.\frac{\partial P_L}{\partial \theta}\right|_{\theta_0,Q_{P0},Q_{C0}} \delta\theta + \left.\frac{\partial P_L}{\partial Q_P}\right|_{\theta_0,Q_{P0},Q_{C0}} \delta Q_P + \left.\frac{\partial P_L}{\partial Q_C}\right|_{\theta_0,Q_{P0},Q_{C0}} \delta Q_C \\ P_P &\approx \left.\frac{\partial P_P}{\partial \theta}\right|_{\theta_0,Q_{P0},Q_{C0}} \delta\theta + \left.\frac{\partial P_P}{\partial Q_P}\right|_{\theta_0,Q_{P0},Q_{C0}} \delta Q_P + \left.\frac{\partial P_P}{\partial Q_C}\right|_{\theta_0,Q_{P0},Q_{C0}} \delta Q_C \end{aligned}$$

Thus,

$$P_R = C_{r1}\delta\theta + C_{r2}\delta Q_P + C_{r3}Q_C \tag{4.11}$$

$$P_L = C_{l1}\delta\theta + C_{l2}\delta Q_P + C_{l3}Q_C \tag{4.12}$$

$$P_P = C_{p1}\delta\theta + C_{p2}\delta Q_P + C_{p3}Q_C \tag{4.13}$$

Here,

$$C_{r1} = \frac{\rho}{2l_V^2(b-r\theta_0)^3}\left(\frac{Q_{P0}-Q_{C0}}{2}\right)^2 \tag{4.14}$$

$$C_{r2} = \frac{\rho}{2l_V^2(b-r\theta_0)^2}\left(\frac{Q_{P0}-Q_{C0}}{2}\right) \tag{4.15}$$

$$C_{r3} = -\frac{\rho}{2l_V^2(b-r\theta_0)^2}\left(\frac{Q_{P0}-Q_{C0}}{2}\right) \tag{4.16}$$

$$C_{l1} = -\frac{\rho}{2l_V^2(b+r\theta_0)^3}\left(\frac{Q_{P0}+Q_{C0}}{2}\right)^2 \tag{4.17}$$

$$C_{l2} = \frac{\rho}{2l_V^2(b+r\theta_0)^2}\left(\frac{Q_{P0}+Q_{C0}}{2}\right) \tag{4.18}$$

$$C_{l3} = \frac{\rho}{2l_V^2(b+r\theta_0)^2}\left(\frac{Q_{P0}+Q_{C0}}{2}\right) \tag{4.19}$$

$$C_{p1} = C_{r1} + C_{l1} \tag{4.20}$$

$$C_{p2} = C_{r2} + C_{l2} \tag{4.21}$$

$$C_{p3} = C_{r3} + C_{l3} \tag{4.22}$$

Linearized state space equations can be written in matrix form:

$$\frac{d\underline{x}}{dt} = A\underline{x} + B\underline{u} \tag{4.23}$$

where,

$$\underline{x} = \begin{bmatrix} P_{p11} \\ Q_{p12} \\ P_{H1} \\ Q_{p2} \\ P_{H2} \\ Q_{p3} \\ \dot{X} \\ F_{CL} \\ \tau_T \end{bmatrix}, \quad \underline{u} = \begin{bmatrix} Q_0 \\ \frac{C_{p1} r \theta_0 + C_{p2} Q_{P0} + C_{p3} Q_{C0}}{I_{P3}} \\ \frac{A(C_{r1} - C_{l1})\theta_0 + (C_{r2} - C_{l2}) Q_{P0} + (C_{r3} - C_{l3}) Q_{C0}}{I_L} \\ \theta \end{bmatrix}$$

$$A = \begin{bmatrix} 0 & -\frac{1}{C_{p1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{I_{p1}} & -\frac{R_{p1}}{I_{p1}} & -\frac{1}{I_{p1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{C_{H1}} & 0 & -\frac{1}{C_{H1}} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{I_{p2}} & -\frac{R_{p2}}{I_{p2}} & -\frac{1}{I_{p2}} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{C_{H2}} & 0 & -\frac{1}{C_{H2}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{I_{p3}} & -\frac{C_{P2}+R_{p3}}{I_{p3}} & -\frac{C_{P3}A}{I_{p3}} & 0 & \frac{C_{p1} r C_T}{I_{p3}} \\ 0 & 0 & 0 & 0 & 0 & \frac{A(C_{r2}-C_{l2})}{I_L} & \frac{A^2(C_{r3}-C_{l3}-R_L)}{I_L} & -\frac{1}{I_L} & \frac{G+A(C_{r1}-C_{l1}) r C_T}{I_L} \\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{C_{I_L}} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\frac{G}{C_T} & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{1}{C_{P1}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & \frac{1}{C_T} \end{bmatrix}$$

As the operating point, the starting point of the vibration is chosen. They are:

$$\theta_0 = 2.6 \times 10^{-2} \; [rad.]$$

$$Q_{p0} = 1 \times 10^{-4} \; [m^3/sec.]$$
$$Q_{C0} = 0 \; [m^3/sec.]$$

Eigenvalues of the matrix A show the frequencies of the oscillation of the system. The eigenvalues about the operating point are:

$$\begin{aligned}
\lambda_1 &= -1.8276 + 1.0151 \times 10^4 i \\
\lambda_2 &= -1.8276 - 1.0151 \times 10^4 i \\
\lambda_3 &= -2.2793 \times 10^3 \\
\lambda_4 &= -1.7066 \times 10^2 + 6.9552 \times 10^2 i \\
\lambda_5 &= -1.7066 \times 10^2 - 6.9552 \times 10^2 i \\
\lambda_6 &= -7.4293 \times 10^2 \\
\lambda_7 &= -6.8751 \times 10^1 + 1.9253 \times 10^2 i \\
\lambda_8 &= -6.8751 \times 10^1 - 1.9253 \times 10^2 i \\
\lambda_9 &= 0
\end{aligned}$$

The frequency of each mode of this system is 1615 [Hz] from λ_1 and λ_2, 110 [Hz] from λ_4 and λ_5, and 30.7 [Hz] from λ_7 and λ_8. Therefore, contribution of $lambda_4$ and $lambda_5$ to the vibration is recognized. If the damping ratio of this frequency increases, the pressure vibration can be reduced. Reducing the natural frequency of this mode also can be useful to reduce the vibration; if the damping ratio is the same, small natural frequency shows a small damped natural frequency.

Comparing the eigenvalues of the whole system with hydraulic line that has resistance on its end, it is noticed that the first two frequencies of the whole system are quite close to those of the hydraulic line. This is plausible because the first 6×6 cofactor of the whole system A matrix is almost same as the A matrix of the hydraulic line. This means except the resistance of the control valve, adding other sub-units after the hydraulic line does not affect the oscillation frequencies very much.

There are at least two ways to change the eigenvalues of the A matrix in our case. One way is changing the dynamics characteristic of the hydraulic line. Another way is changing the resistance of the valve so that the dominant damped natural frequency changes. The first case is shown in Figure 4.5. Here, to change the dynamics characteristic of the hydraulic line, pipe resistance is increased by 100 times so that the damping ratio increases. As a result, the vibration reduced. The case of increasing the stiffness of the hose is shown in Figure 4.6 The hose stiffness is increased by 10000 times. The vibration is also decreased.

The second case is shown in Figure 4.7. To reduce the valve resistance, the flow rate has to be increased since the necessary pressure to move the rack bar against the load is fixed. This case also shows the vibration is reduced.

4.5 Summary

The whole model of the power steering system can simulate the pressure vibration observed in the experimental data. The vibration frequency is mainly dominated by the dynamics of the hydraulic line, and the frequency observed is determined by the valve resistance and dynamics characteristic of the hydraulic line. Therefore, the vibration can be reduced by changing the specification of the hydraulic line, for example the length of the pipe or stiffness of the hose. Increasing the pump flow rate also has an effect on the vibration reduction.

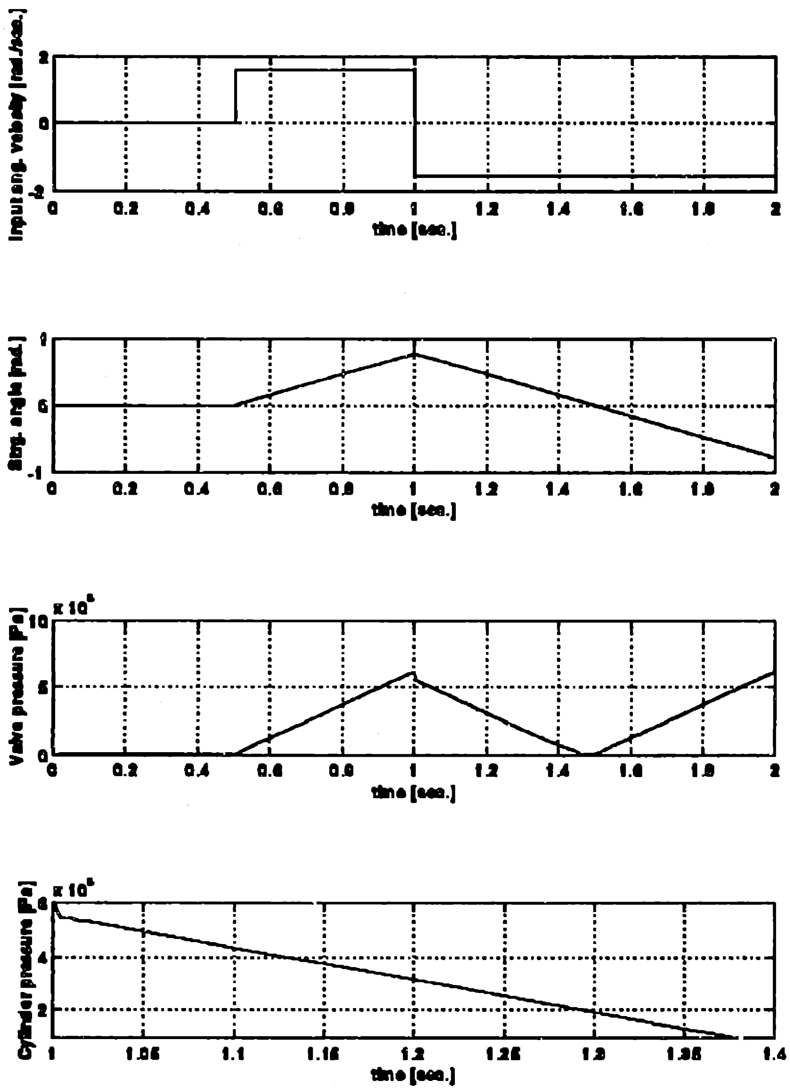

Figure 4.5: Simulation results: Increasing hydraulic line resistance

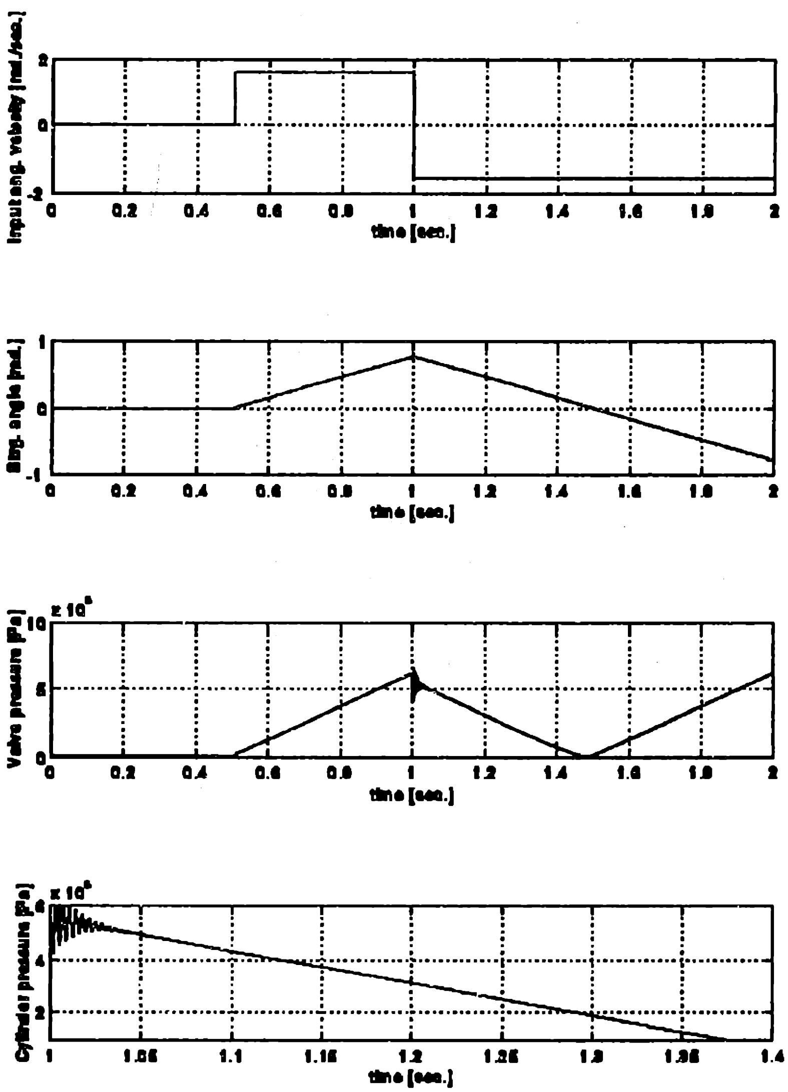

Figure 4.6: Simulation results: Reducing hydraulic capacitance

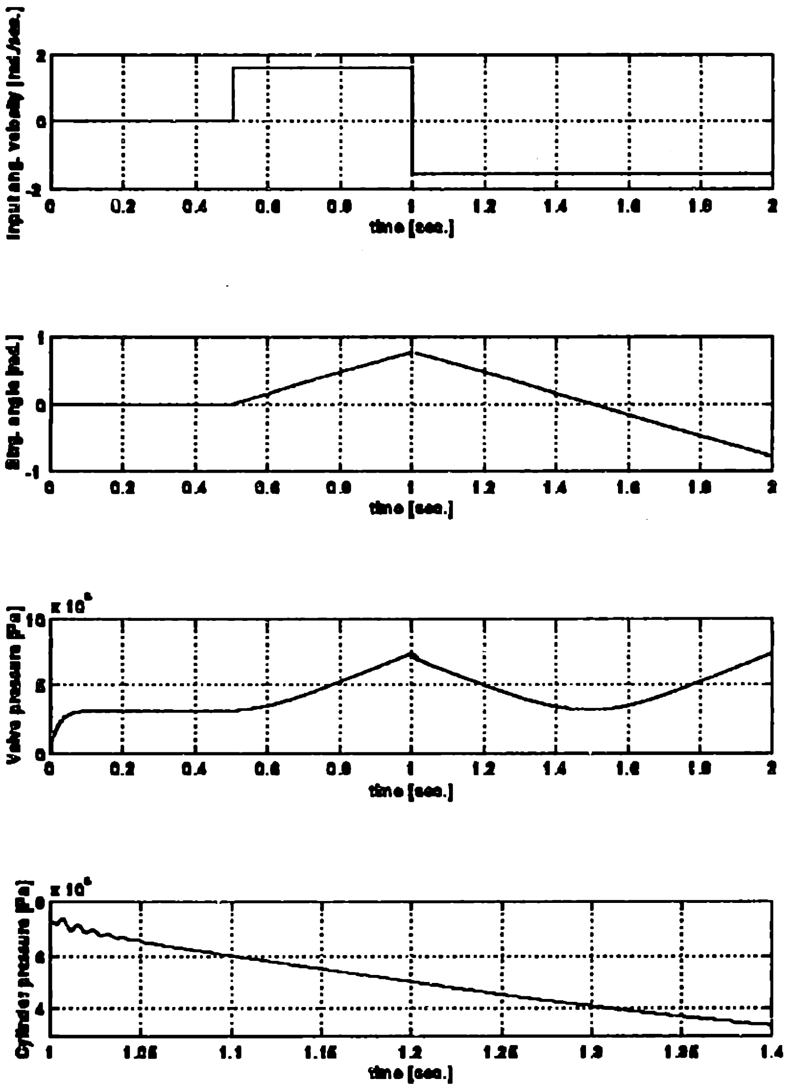

Figure 4.7: Simulation results: Increasing flow rate into the control valve

Chapter 5
Conclusions & Recommendations

The purpose of this thesis work was to understand the dynamics of the power steering system and to provide an efficient method to reduce the pressure vibration of the system. During this research, the bond graph method was used for modeling the power steering system, and numerical simulations were performed. Each component of the power steering system was modeled using the bond graph method. When several choices for the causality of the model were encountered, the proper causality assignment was determined by considering the function of the component(s) in question. Thus, the pump was modeled as a flow source and the valve was assumed to supply the pressure to the other components interacting with the valve. It turns out that this modeling decision implies the existence of an algebraic loop. Such algebraic loops were solved by hand and before the simulation was held. The hydraulic line was modeled as a combination of the pipe inertance, pipe resistance, pipe capacitance, and hose capacitance.

Non-linear dynamic equations were derived from the bond graph model, and the model feasibility was verified by conducting numerical simulations using a mathematical software, Matlab and Simulink. These simulations show that the pressure vibration occurred in the same way as seen in the experimental results. Therefore, the model developed in this work can be applied for prediction of the pressure vibration of a given power steering system. This model can be used to estimate the probability of vibration occurrence before the prototype model is made. However, there are some uncertainties about the simulation. System load condition basically varies according to the road condition and a vehicle weight. It also changes depend on the front tire characteristics.

A linear model was also developed based on the nonlinear model. The system state equations were linearized around an operating point in order to analyze the vibration behavior of the power steering system. The method used is the Taylor series expansion. The linearized state space equations indicated that the dynamics of the hydraulic line affects the vibration frequency of the total system. Eigenvalues of the system revealed that one pair of complex eigenvalues of the system dominated the pressure vibration. From this point of view, two ways to reduce the vibration are suggested. One is to reduce the resistance of the pressure control valve, in other words, increase the supply flow rate of the supply line to the valve. Another way is to change the dynamic characteristic of the hydraulic line. Using the mathematical model, the proper specification of the hydraulic line can be found. In our case, the pipe resistance or the hose stiffness need to be increased. Increasing the flow rate was also worked well, however, in reality it requires the larger pump and much power so that they may not be desirable. To use this linearized model for reducing the vibration, the operating point must be found. Therefore, the linearized model makes it possible to predict the system vibration. It also helps in finding a proper combination of the pipes and hoses characteristics once the vibration is observed. Once the operating point is found, the linearized model is much faster to simulate than the non-linear model in determining the system behavior.

Although these two models can describe the dynamic behavior of the power steering system sufficiently, there is some discrepancy between the experimental result and simulation result. The vibration frequency of the simulation is a little higher than the experimental data. The vibration starting point of the simulation is after the pressure peak, although the experimental data shows the vibration before the peak. These discrepancies can be from the simplification and estimation of the characteristic of the hydraulic line. In this thesis, some simplifications were assumed. The compressibility of the oil in the cylinder and hose resistance were neglected. The edge shape of the pressure control valve is simplified. The effect of the tubing between the control valve and cylinder is neglected. For further research, these factors should be considered to improve the feasibility of the vibration prediction .

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Appendix A

Simulation Files

A.1 Main Program

```
function [ret,x0,str,ts,xts]=ps\_03p\_sim(t,x,u,flag);
\%PS\_03P\_SIM is the M-file description of the SIMULINK system named PS\_03P\_SIM.
\% PS\_03P\_SIM has a the following characteristics:
\% 10 continuous states
\% 0 discrete states
\% 0 outputs
\% 0 inputs
\% does not have direct feedthrough
\% 1 sample times
\%
\% The block-diagram can be displayed by typing: PS_03P_SIM.
\%
\% SYS=PS_03P_SIM(T,X,U,FLAG) returns depending on FLAG certain
\% system values given time point, T, current state vector, X,
\% and input vector, U.
\% FLAG is used to indicate the type of output to be returned in SYS.
\%
\% Setting FLAG=1 causes PS_03P_SIM to return state derivatives, FLAG=2
\% discrete states, FLAG=3 system outputs and FLAG=4 next sample
\% time. For more information and other options see SFUNC.
\%
\% Calling PS_03P_SIM with a FLAG of zero:
\% [SIZES]=PS_03P_SIM([],[],[],0),  returns a vector, SIZES, which
\% contains the sizes of the state vector and other parameters.
\% SIZES(1) number of states
\% SIZES(2) number of discrete states
\% SIZES(3) number of outputs
\% SIZES(4) number of inputs
\% SIZES(5) number of roots (currently unsupported)
\% SIZES(6) direct feedthrough flag
\% SIZES(7) number of sample times
\%
\% For the definition of other parameters in SIZES, see SFUNC.
\% See also, TRIM, LINMOD, LINSIM, EULER, RK23, RK45, ADAMS, GEAR.

\% Note: This M-file is only used for saving graphical information;
\%       after the model is loaded into memory an internal model
\%       representation is used.

\% the system will take on the name of this mfile:
sys = mfilename;
new_system(sys)
simver(1.3)
if (0 == (nargin + nargout))
     set_param(sys,'Location',[26,81,605,828])
     open_system(sys)
end;
set_param(sys,'algorithm',     'Gear')
```

```
set_param(sys,'Start time',    '0.0')
set_param(sys,'Stop time',     '2')
set_param(sys,'Min step size', '1e-6')
set_param(sys,'Max step size', '1e-3')
set_param(sys,'Relative error','1e-8')
set_param(sys,'Return vars',   '')


\%    Subsystem  'valve'.

new_system([sys,'/','valve'])
set_param([sys,'/','valve'],'Location',[305,358,789,757])

add_block('built-in/Note',[sys,'/','valve/PL'])
set_param([sys,'/','valve/PL'],...
'position',[405,190,410,195])

add_block('built-in/Note',[sys,'/','valve/PR'])
set_param([sys,'/','valve/PR'],...
'position',[405,145,410,150])

add_block('built-in/Note',[sys,'/','valve/Pv'])
set_param([sys,'/','valve/Pv'],...
'position',[405,100,410,105])

add_block('built-in/Note',[sys,'/','valve/A2'])
set_param([sys,'/','valve/A2'],...
'position',[80,225,85,230])

add_block('built-in/Note',[sys,'/','valve/A1'])
set_param([sys,'/','valve/A1'],...
'position',[75,185,80,190])

add_block('built-in/Note',[sys,'/','valve/QR'])
set_param([sys,'/','valve/QR'],...
'position',[75,105,80,110])

add_block('built-in/Note',[sys,'/','valve/Qp'])
set_param([sys,'/','valve/Qp'],...
'position',[80,70,85,75])

add_block('built-in/Demux',[sys,'/','valve/Demux1'])
set_param([sys,'/','valve/Demux1'],...
'outputs','3',...
'position',[305,86,340,224])

add_block('built-in/MATLAB Fcn',[sys,'/','valve/valve_31_fn'])
set_param([sys,'/','valve/valve_31_fn'],...
'MATLAB Fcn','valve_31_fn',...
'Output Width','3',...
'position',[205,134,265,176])

add_block('built-in/Mux',[sys,'/','valve/valve input'])
set_param([sys,'/','valve/valve input'],...
'inputs','5',...
'position',[145,48,175,262])

add_block('built-in/Inport',[sys,'/','valve/in_1'])
set_param([sys,'/','valve/in_1'],...
'position',[95,65,115,85])

add_block('built-in/Outport',[sys,'/','valve/out_1'])
set_param([sys,'/','valve/out_1'],...
'position',[375,100,395,120])
```

```
add_block('built-in/Inport',[sys,'/','valve/in_2'])
set_param([sys,'/','valve/in_2'],...
'Port','2',...
'position',[95,105,115,125])

add_block('built-in/Outport',[sys,'/','valve/out_2'])
set_param([sys,'/','valve/out_2'],...
'Port','2',...
'position',[375,145,395,165])

add_block('built-in/Inport',[sys,'/','valve/in_4'])
set_param([sys,'/','valve/in_4'],...
'Port','4',...
'position',[95,185,115,205])

add_block('built-in/Outport',[sys,'/','valve/out_3'])
set_param([sys,'/','valve/out_3'],...
'Port','3',...
'position',[375,190,395,210])

add_block('built-in/Inport',[sys,'/','valve/in_5'])
set_param([sys,'/','valve/in_5'],...
'Port','5',...
'position',[95,225,115,245])

add_block('built-in/Note',[sys,'/','valve/QL:'])
set_param([sys,'/','valve/QL:'],...
'position',[25,145,30,150])

add_block('built-in/Inport',[sys,'/','valve/in_3'])
set_param([sys,'/','valve/in_3'],...
'Port','3',...
'position',[95,145,115,165])
add_line([sys,'/','valve'],[120,235;140,235])
add_line([sys,'/','valve'],[345,200;370,200])
add_line([sys,'/','valve'],[120,195;140,195])
add_line([sys,'/','valve'],[345,155;370,155])
add_line([sys,'/','valve'],[120,115;140,115])
add_line([sys,'/','valve'],[345,110;370,110])
add_line([sys,'/','valve'],[120,75;140,75])
add_line([sys,'/','valve'],[180,155;200,155])
add_line([sys,'/','valve'],[270,155;300,155])
add_line([sys,'/','valve'],[120,155;140,155])


\%    Finished composite block 'valve'.

set_param([sys,'/','valve'],...
'position',[225,116,255,254])

add_block('built-in/Scope',[sys,'/','Scope'])
set_param([sys,'/','Scope'],...
'Vgain','10000000.000000',...
'Hgain','2.000000',...
'Vmax','20000000.000000',...
'Hmax','2.000000',...
'Window',[654,255,907,406])
open_system([sys,'/','Scope'])
set_param([sys,'/','Scope'],...
'position',[370,45,400,75])


\%    Subsystem  'perfect hose and pipe'.
```

```
new_system([sys,'/','perfect hose and pipe'])
set_param([sys,'/','perfect hose and pipe'],'Location',[161,177,765,513])

add_block('built-in/Note',[sys,'/','perfect hose and pipe/pump pressure out'])
set_param([sys,'/','perfect hose and pipe/pump pressure out'],...
'position',[514,266,519,271])

add_block('built-in/Note',[sys,'/','perfect hose and pipe/pump flow in'])
set_param([sys,'/','perfect hose and pipe/pump flow in'],...
'position',[45,25,50,30])

add_block('built-in/Inport',[sys,'/','perfect hose and pipe/in_2'])
set_param([sys,'/','perfect hose and pipe/in_2'],...
'Port','2',...
'position',[35,220,55,240])

add_block('built-in/Outport',[sys,'/','perfect hose and pipe/out_1'])
set_param([sys,'/','perfect hose and pipe/out_1'],...
'position',[550,230,570,250])

add_block('built-in/Outport',[sys,'/','perfect hose and pipe/out_2'])
set_param([sys,'/','perfect hose and pipe/out_2'],...
'Port','2',...
'position',[560,95,580,115])

add_block('built-in/Inport',[sys,'/','perfect hose and pipe/in_1'])
set_param([sys,'/','perfect hose and pipe/in_1'],...
'position',[35,60,55,80])


\%    Subsystem  ['perfect hose and pipe/pipe_2',13,'(1jinction)'].

new_system([sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)']])
set_param([sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)']],'Location',[41,544,438,731])

add_block('built-in/Gain',[sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)/I1']])
set_param([sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)/I1']],...
'Gain','1/(3.9e6)',...
'position',[200,67,225,93])

add_block('built-in/Note',[sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)/dQ//dt']])
set_param([sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)/dQ//dt']],...
'position',[240,45,245,50])

add_block('built-in/Integrator',[sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)/int1']])
set_param([sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)/int1']],...
'position',[250,70,270,90])

add_block('built-in/Note',[sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)/Q']])
set_param([sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)/Q']],...
'position',[345,75,350,80])

add_block('built-in/Note',[sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)/Pp']])
set_param([sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)/Pp']],...
'position',[70,33,75,38])

add_block('built-in/Note',[sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)/P out']])
set_param([sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)/P out']],...
'position',[60,105,65,110])

add_block('built-in/Outport',[sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)/out_1']])
set_param([sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)/out_1']],...
'position',[310,70,330,90])
```

```
add_block('built-in/Sum',[sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)/1J-1']])
set_param([sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)/1J-1']],...
'inputs','+--',...
'position',[145,62,165,98])

add_block('built-in/Inport',[sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)/in_1']])
set_param([sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)/in_1']],...
'position',[95,35,115,55])

add_block('built-in/Inport',[sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)/in_2']])
set_param([sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)/in_2']],...
'Port','2',...
'position',[55,70,75,90])

add_block('built-in/Gain',[sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)/R1']])
set_param([sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)/R1']],...
'orientation',2,...
'Gain','1.43e7',...
'position',[205,117,230,143])
add_line([sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)']],[170,80;195,80])
add_line([sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)']],[230,80;245,80])
add_line([sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)']],[120,45;140,70])
add_line([sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)']],[80,80;140,80])
add_line([sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)']],[275,80;305,80])
add_line([sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)']],[285,80;285,130;235,130])
add_line([sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)']],[200,130;120,130;120,90;140,90])


\%    Finished composite block ['perfect hose and pipe/pipe_2',13,'(1jinction)'].

set_param([sys,'/',['perfect hose and pipe/pipe_2',13,'(1jinction)']],...
'position',[280,72,310,123])


\%    Subsystem  ['perfect hose and pipe/hose_1',13,'(0junction)'].

new_system([sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)']])
set_param([sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)']],'Location',[67,454,388,658])

add_block('built-in/Inport',[sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)/in_1']])
set_param([sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)/in_1']],...
'position',[45,45,65,65])

add_block('built-in/Inport',[sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)/in_2']])
set_param([sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)/in_2']],...
'Port','2',...
'position',[45,90,65,110])

add_block('built-in/Outport',[sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)/out_1']])
set_param([sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)/out_1']],...
'position',[245,70,265,90])

add_block('built-in/Sum',[sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)/0J-1']])
set_param([sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)/0J-1']],...
'inputs','+-',...
'position',[95,70,115,90])

add_block('built-in/Integrator',[sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)/int2']])
set_param([sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)/int2']],...
'position',[145,70,165,90])

add_block('built-in/Note',[sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)/V']])
set_param([sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)/V']],...
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'position',[180,50,185,55])

add_block('built-in/Gain',[sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)/Chi']])
set_param([sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)/Chi']],...
'Gain','1/(1.67e-12+1.81e-14)',...
'position',[200,67,225,93])

add_block('built-in/Note',[sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)/P']])
set_param([sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)/P']],...
'position',[295,65,300,70])

add_block('built-in/Note',[sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)/Q in']])
set_param([sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)/Q in']],...
'position',[50,15,55,20])

add_block('built-in/Note',[sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)/Q out']])
set_param([sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)/Q out']],...
'position',[50,130,55,135])
add_line([sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)']],[120,80;140,80])
add_line([sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)']],[170,80;195,80])
add_line([sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)']],[70,55;90,75])
add_line([sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)']],[230,80;240,80])
add_line([sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)']],[70,100;90,85])


\%     Finished composite block ['perfect hose and pipe/hose_1',13,'(0junction)'].

set_param([sys,'/',['perfect hose and pipe/hose_1',13,'(0junction)']],...
'position',[165,57,195,108])


\%     Subsystem  ['perfect hose and pipe/pipe_3',13,'(1jinction)'].

new_system([sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)']])
set_param([sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)']],'Location',[221,583,762,792])

add_block('built-in/Note',[sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/Q']])
set_param([sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/Q']],...
'position',[295,25,300,30])

add_block('built-in/Note',[sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/dQ//dt']])
set_param([sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/dQ//dt']],...
'position',[230,20,235,25])

add_block('built-in/Inport',[sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/in_2']])
set_param([sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/in_2']],...
'Port','2',...
'position',[25,120,45,140])

add_block('built-in/Integrator',[sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/int2']])
set_param([sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/int2']],...
'position',[255,40,275,60])

add_block('built-in/Gain',[sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/I3']])
set_param([sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/I3']],...
'Gain','1/8.24e5',...
'position',[200,37,225,63])

add_block('built-in/Sum',[sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/1J-2']])
set_param([sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/1J-2']],...
'inputs','+--',...
'position',[155,32,175,68])

add_block('built-in/Gain',[sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/R1']])
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set_param([sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/R1']],...
'orientation',2,...
'Gain','3.02e7',...
'position',[200,82,225,108])

add_block('built-in/Inport',[sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/in_1']])
set_param([sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/in_1']],...
'position',[25,30,45,50])

add_block('built-in/Note',[sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/Ph2']])
set_param([sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/Ph2']],...
'position',[30,8,35,13])

add_block('built-in/Note',[sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/Pv']])
set_param([sys,'/',['perfect hose and pipo/pipe_3',13,'(1jinction)/Pv']],...
'position',[34,99,39,104])

add_block('built-in/Outport',[sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/cut_1']])
set_param([sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/out_1']],...
'position',[380,40,400,60])

add_block('built-in/Note',[sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/Qv']])
set_param([sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/Qv']],...
'position',[385,20,390,25])

add_block('built-in/Outport',[sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/out_2']])
set_param([sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/out_2']],...
'Port','2',...
'position',[380,115,400,135])

add_block('built-in/Note',[sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/Qp3']])
set_param([sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)/Qp3']],...
'position',[385,90,390,95])
add_line([sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)']],[280,50;375,50])
add_line([sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)']],[295,50;295,95;230,95])
add_line([sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)']],[50,40;150,40])
add_line([sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)']],[195,95;122,95;122,60;150,60])
add_line([sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)']],[230,50;250,50])
add_line([sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)']],[180,50;195,50])
add_line([sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)']],[50,130;95,130;95,50;150,50])
add_line([sys,'/',['perfect hose and pipe/pipe_3',13,'(1jinction)']],[335,50;335,125;375,125])


\%     Finished composite block ['perfect hose and pipe/pipe_3',13,'(1jinction)'].

set_param([sys,'/',['perfect hose and pipe/pipo_3',13,'(1jinction)']],...
'position',[500,92,530,143])


\%     Subsystem  ['perfect hose and pipe/hose_2',13,'(0junction)'].

new_system([sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)']])
set_param([sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)']],'Location',[117,443,537,615])

add_block('built-in/Sum',[sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)/0J-2']])
set_param([sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)/0J-2']],...
'inputs','+-',...
'position',[145,60,165,80])

add_block('built-in/Integrator',[sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)/int4']])
set_param([sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)/int4']],...
'position',[190,60,210,80])

add_block('built-in/Note',[sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)/V2']])
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set_param([sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)/V2']],...
'position',[225,40,230,45])

add_block('built-in/Inport',[sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)/in_1']])
set_param([sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)/in_1']],...
'position',[95,30,115,50])

add_block('built-in/Inport',[sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)/in_2']])
set_param([sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)/in_2']],...
'Port','2',...
'position',[95,90,115,110])

add_block('built-in/Note',[sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)/Q in']])
set_param([sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)/Q in']],...
'position',[105,5,110,10])

add_block('built-in/Note',[sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)/Q out']])
set_param([sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)/Q out']],...
'position',[105,130,110,135])

add_block('built-in/Gain',[sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)/Ch2']])
set_param([sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)/Ch2']],...
'Gain','1/(8e-13+3.83e-15)',...
'position',[250,57,275,83])

add_block('built-in/Outport',[sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)/out_1']])
set_param([sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)/out_1']],...
'position',[300,60,320,80])

add_block('built-in/Note',[sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)/P']])
set_param([sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)/P']],...
'position',[340,60,345,65])
add_line([sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)']],[170,70;185,70])
add_line([sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)']],[215,70;245,70])
add_line([sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)']],[120,40;140,65])
add_line([sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)']],[280,70;295,70])
add_line([sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)']],[120,100;140,75])


\%    Finished composite block ['perfect hose and pipe/hose_2',13,'(0junction)'].

set_param([sys,'/',['perfect hose and pipe/hose_2',13,'(0junction)']],...
'position',[375,87,405,138])

add_block('built-in/Note',[sys,'/','perfect hose and pipe/valve pressure in'])
set_param([sys,'/','perfect hose and pipe/valve pressure in'],...
'position',[56,259,61,264])

add_block('built-in/Note',[sys,'/','perfect hose and pipe/valve flow out'])
set_param([sys,'/','perfect hose and pipe/valve flow out'],...
'position',[550,62,555,67])


\%    Subsystem  ['perfect hose and pipe/pipe_1',13,'(1jinction)'].

new_system([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)']])
set_param([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)']],'Location',[32,479,573,688])

add_block('built-in/Outport',[sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/out_2']])
set_param([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/out_2']],...
'Port','2',...
'position',[490,160,510,180])

add_block('built-in/Inport',[sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/in_2']])
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set_param([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/in_2']],...
'Port','2',...
'position',[45,100,65,120])

add_block('built-in/Sum',[sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/1J-1']])
set_param([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/1J-1']],...
'inputs','+-',...
'position',[130,37,150,73])

add_block('built-in/Integrator',[sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/int1']])
set_param([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/int1']],...
'position',[175,45,195,65])

add_block('built-in/Gain',[sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/Cp1']])
set_param([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/Cp1']],...
'Gain','1/6.72e-15',...
'position',[220,42,245,68])

add_block('built-in/Note',[sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/dQ//dt']])
set_param([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/dQ//dt']],...
'position',[165,20,170,25])

add_block('built-in/Outport',[sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/out_1']])
set_param([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/out_1']],...
'position',[485,55,505,75])

add_block('built-in/Integrator',[sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/int2']])
set_param([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/int2']],...
'position',[420,55,440,75])

add_block('built-in/Gain',[sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/I1']])
set_param([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/I1']],...
'Gain','1/1.45e6',...
'position',[365,52,390,78])

add_block('built-in/Sum',[sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/1J-2']])
set_param([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/1J-2']],...
'inputs','+--',...
'position',[320,47,340,83])

add_block('built-in/Gain',[sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/R1']])
set_param([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/R1']],...
'orientation',2,...
'Gain','5.3e6',...
'position',[365,97,390,123])

add_block('built-in/Note',[sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/Q']])
set_param([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/Q']],...
'position',[460,35,465,40])

add_block('built-in/Note',[sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/P out']])
set_param([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/P out']],...
'position',[55,150,60,155])

add_block('built-in/Inport',[sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/in_1']])
set_param([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/in_1']],...
'position',[45,35,65,55])

add_block('built-in/Note',[sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/Qp']])
set_param([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)/Qp']],...
'position',[50,13,55,18])
add_line([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)']],[250,55;315,55])
add_line([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)']],[260,55;260,170;485,170])
add_line([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)']],[445,65;480,65])
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add_line([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)']],[460,65;460,110;395,110])
add_line([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)']],[460,110;460,155;102,155;102,65;125,65])
add_line([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)']],[360,110;287,110;287,75;315,75])
add_line([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)']],[70,110;275,110;275,65;315,65])
add_line([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)']],[395,65;415,65])
add_line([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)']],[345,65;360,65])
add_line([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)']],[200,55;215,55])
add_line([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)']],[155,55;170,55])
add_line([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)']],[70,45;125,45])


\%    Finished composite block ['perfect hose and pipe/pipe_1',13,'(1jinction)'].

set_param([sys,'/',['perfect hose and pipe/pipe_1',13,'(1jinction)']],...
'position',[85,57,115,108])
add_line([sys,'/','perfect hose and pipe'],[120,95;120,240;545,240])
add_line([sys,'/','perfect hose and pipe'],[60,70;80,70])
add_line([sys,'/','perfect hose and pipe'],[120,70;160,70])
add_line([sys,'/','perfect hose and pipe'],[200,85;235,85;235,160;50,160;50,95;80,95])
add_line([sys,'/','perfect hose and pipe'],[235,85;275,85])
add_line([sys,'/','perfect hose and pipe'],[315,100;370,100])
add_line([sys,'/','perfect hose and pipe'],[335,100;335,180;151,180;151,95;160,95])
add_line([sys,'/','perfect hose and pipe'],[410,115;451,115;451,190;256,190;256,110;275,110])
add_line([sys,'/','perfect hose and pipe'],[450,115;450,105;495,105])
add_line([sys,'/','perfect hose and pipe'],[535,130;551,130;551,205;361,205;361,125;370,125])
add_line([sys,'/','perfect hose and pipe'],[60,230;455,230;455,130;495,130])
add_line([sys,'/','perfect hose and pipe'],[535,105;555,105])


\%    Finished composite block 'perfect hose and pipe'.

set_param([sys,'/','perfect hose and pipe'],...
'position',[110,57,140,108])


\%    Subsystem  'pump ok'.

new_system([sys,'/','pump ok'])
set_param([sys,'/','pump ok'],'Location',[154,409,671,785])

add_block('built-in/Constant',[sys,'/',['pump ok/pump angular',13,'velocity']])
set_param([sys,'/',['pump ok/pump angular',13,'velocity']],...
'Value','2*pi*500/60',...
'position',[175,145,195,165])

add_block('built-in/MATLAB Fcn',[sys,'/','pump ok/pump2_fn'])
set_param([sys,'/','pump ok/pump2_fn'],...
'MATLAB Fcn','pump2_fn',...
'Output Width','1',...
'position',[360,183,420,217])

add_block('built-in/Mux',[sys,'/','pump ok/Mux'])
set_param([sys,'/','pump ok/Mux'],...
'inputs','2',...
'position',[305,172,335,223])

add_block('built-in/Gain',[sys,'/','pump ok/Vp'])
set_param([sys,'/','pump ok/Vp'],...
'Gain','13e-6/(2*pi)',...
'position',[250,142,275,168])

add_block('built-in/Outport',[sys,'/','pump ok/out_1'])
set_param([sys,'/','pump ok/out_1'],...
'position',[450,190,470,210])
```

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add_block('built-in/Inport',[sys,'/','pump ok/in_1'])
set_param([sys,'/','pump ok/in_1'],...
'position',[255,200,275,220])

add_block('built-in/Note',[sys,'/','pump ok/flow to tube'])
set_param([sys,'/','pump ok/flow to tube'],...
'position',[460,153,465,158])
add_line([sys,'/','pump ok'],[200,155;245,155])
add_line([sys,'/','pump ok'],[280,210;300,210])
add_line([sys,'/','pump ok'],[425,200;445,200])
add_line([sys,'/','pump ok'],[340,200;355,200])
add_line([sys,'/','pump ok'],[280,155;290,155;300,185])


\%    Finished composite block 'pump ok'.

set_param([sys,'/','pump ok'],...
'position',[30,45,60,95])

add_block('built-in/Clock',[sys,'/','Clock'])
set_param([sys,'/','Clock'],...
'position',[405,10,425,30])

add_block('built-in/To Workspace',[sys,'/','To Workspace3'])
set_param([sys,'/','To Workspace3'],...
'mat-name','t',...
'buffer','1e6',...
'position',[485,12,535,28])

add_block('built-in/Constant',[sys,'/','Constant'])
set_param([sys,'/','Constant'],...
'Value','6/6e4/4',...
'position',[295,8,350,32])

add_block('built-in/To Workspace',[sys,'/','To Workspace'])
set_param([sys,'/','To Workspace'],...
'mat-name','pv',...
'buffer','1e6',...
'position',[305,132,355,148])

add_block('built-in/To Workspace',[sys,'/','To Workspace6'])
set_param([sys,'/','To Workspace6'],...
'mat-name','pp',...
'buffer','1e6',...
'position',[205,52,255,68])

add_block('built-in/To Workspace',[sys,'/','To Workspace7'])
set_param([sys,'/','To Workspace7'],...
'mat-name','qp',...
'buffer','1e6',...
'position',[110,127,160,143])

add_block('built-in/To Workspace',[sys,'/','To Workspace8'])
set_param([sys,'/','To Workspace8'],...
'mat-name','x',...
'buffer','1e6',...
'position',[300,622,350,638])

add_block('built-in/Gain',[sys,'/',['load',13,'spring1']])
set_param([sys,'/',['load',13,'spring1']],...
'Gain','1e6',...
'position',[405,702,430,728])
```

```
add_block('built-in/Gain',[sys,'/','Friction'])
set_param([sys,'/','Friction'],...
'Gain','2.72e4',...
'position',[340,672,365,698])

add_block('built-in/Integrator',[sys,'/','dv//dt'])
set_param([sys,'/','dv//dt'],...
'orientation',2,...
'position',[275,525,295,545])

add_block('built-in/Gain',[sys,'/',['Load',13,' mass']])
set_param([sys,'/',['Load',13,' mass']],...
'orientation',2,...
'Gain','1/(50*1)',...
'position',[325,522,350,548])

add_block('built-in/Integrator',[sys,'/','dx//dt'])
set_param([sys,'/','dx//dt'],...
'orientation',2,...
'position',[190,525,210,545])

add_block('built-in/Note',[sys,'/','x'])
set_param([sys,'/','x'],...
'position',[238,572,243,577])

add_block('built-in/Note',[sys,'/','v'])
set_param([sys,'/','v'],...
'position',[308,547,313,552])

add_block('built-in/Note',[sys,'/','spring'])
set_param([sys,'/','spring'],...
'position',[513,587,518,592])

add_block('built-in/Note',[sys,'/','F'])
set_param([sys,'/','F'],...
'position',[403,497,408,502])

add_block('built-in/Note',[sys,'/','a'])
set_param([sys,'/','a'],...
'position',[353,502,358,507])

add_block('built-in/Note',[sys,'/','friction'])
set_param([sys,'/','friction'],...
'position',[468,602,473,607])

add_block('built-in/Gain',[sys,'/','piston area2'])
set_param([sys,'/','piston area2'],...
'orientation',2,...
'Gain','1e-3',...
'position',[180,465,210,495])

add_block('built-in/Gain',[sys,'/','TF Gear1'])
set_param([sys,'/','TF Gear1'],...
'Gain','127.7',...
'position',[415,352,440,378])

add_block('built-in/Sum',[sys,'/','Sum2'])
set_param([sys,'/','Sum2'],...
'inputs','+-',...
'position',[260,355,280,375])

add_block('built-in/Sum',[sys,'/','Sum1'])
set_param([sys,'/','Sum1'],...
'orientation',2,...
```

```
'inputs','++---',...
'position',[385,405,415,665])

add_block('built-in/Gain',[sys,'/','piston area1'])
set_param([sys,'/','piston area1'],...
'orientation',2,...
'Gain','1e-3',...
'position',[450,520,480,550])

add_block('built-in/Gain',[sys,'/','piston area'])
set_param([sys,'/','piston area'],...
'orientation',2,...
'Gain','1e-3',...
'position',[445,470,475,500])

add_block('built-in/To Workspace',[sys,'/','To Workspace1'])
set_param([sys,'/','To Workspace1'],...
'mat-name','pr',...
'buffer','1e6',...
'position',[415,132,465,148])

add_block('built-in/To Workspace',[sys,'/','To Workspace4'])
set_param([sys,'/','To Workspace4'],...
'mat-name','pl',...
'buffer','1e6',...
'position',[430,197,480,213])

add_block('built-in/Integrator',[sys,'/','Integrator'])
set_param([sys,'/','Integrator'],...
'position',[305,355,325,375])

add_block('built-in/Gain',[sys,'/','Gera1'])
set_param([sys,'/','Gera1'],...
'orientation',2,...
'Gain','127.7',...
'position',[205,412,230,438])

add_block('built-in/To Workspace',[sys,'/','To Workspace2'])
set_param([sys,'/','To Workspace2'],...
'mat-name','tm',...
'buffer','1e6',...
'position',[425,322,475,338])

add_block('built-in/Gain',[sys,'/','Gain'])
set_param([sys,'/','Gain'],...
'Gain','180/pi',...
'position',[370,252,395,278])

add_block('built-in/To Workspace',[sys,'/','To Workspace5'])
set_param([sys,'/','To Workspace5'],...
'mat-name','sita',...
'buffer','1e6',...
'position',[430,257,480,273])

add_block('built-in/Sine Wave',[sys,'/','Sine Wave'])
set_param([sys,'/','Sine Wave'],...
'amplitude','90/180*pi',...
'frequency','2*pi',...
'phase','3/2*pi',...
'sampletime','0',...
'position',[55,676,75,694])

add_block('built-in/Constant',[sys,'/','Constant1'])
set_param([sys,'/','Constant1'],...
```

```
'Value','45/180*pi',...
'position',[95,540,115,560])

add_block('built-in/Derivative',[sys,'/','Derivative'])
set_param([sys,'/','Derivative'],...
'position',[90,500,120,520])


\%     Subsystem  'orifice ok'.

new_system([sys,'/','orifice ok'])
set_param([sys,'/','orifice ok'],'Location',[198,565,633,715])

add_block('built-in/Inport',[sys,'/','orifice ok/in_1'])
set_param([sys,'/','orifice ok/in_1'],...
'position',[15,60,35,80])

add_block('built-in/Demux',[sys,'/','orifice ok/Demux'])
set_param([sys,'/','orifice ok/Demux'],...
'outputs','2',...
'position',[140,28,175,112])

add_block('built-in/MATLAB Fcn',[sys,'/','orifice ok/orif_fn'])
set_param([sys,'/','orifice ok/orif_fn'],...
'MATLAB Fcn','orif_fn',...
'Output Width','2',...
'position',[55,53,115,87])

add_block('built-in/Outport',[sys,'/','orifice ok/out_1'])
set_param([sys,'/','orifice ok/out_1'],...
'position',[310,40,330,60])

add_block('built-in/Outport',[sys,'/','orifice ok/out_2'])
set_param([sys,'/','orifice ok/out_2'],...
'Port','2',...
'position',[310,80,330,100])

add_block('built-in/Gain',[sys,'/','orifice ok/Gain'])
set_param([sys,'/','orifice ok/Gain'],...
'Gain','4*0.6',...
'position',[215,37,290,63])

add_block('built-in/Gain',[sys,'/','orifice ok/Gain1'])
set_param([sys,'/','orifice ok/Gain1'],...
'Gain','4*0.6',...
'position',[215,78,285,102])
add_line([sys,'/','orifice ok'],[40,70;50,70])
add_line([sys,'/','orifice ok'],[120,70;135,70])
add_line([sys,'/','orifice ok'],[180,50;210,50])
add_line([sys,'/','orifice ok'],[295,50;305,50])
add_line([sys,'/','orifice ok'],[180,90;210,90])
add_line([sys,'/','orifice ok'],[290,90;305,90])


\%     Finished composite block 'orifice ok'.

set_param([sys,'/','orifice ok'],...
'position',[155,197,185,248])

add_block('built-in/Constant',[sys,'/','Constant2'])
set_param([sys,'/','Constant2'],...
'Value','2e-6',...
'position',[30,550,50,570])
```

```
add_block('built-in/Constant',[sys,'/','Constant3'])
set_param([sys,'/','Constant3'],...
'Value','0',...
'position',[30,600,50,620])

add_block('built-in/To Workspace',[sys,'/','To Workspace9'])
set_param([sys,'/','To Workspace9'],...
'mat-name','input',...
'buffer','1e6',...
'position',[255,297,305,313])

add_block('built-in/Sine Wave',[sys,'/','Sine Wave1'])
set_param([sys,'/','Sine Wave1'],...
'amplitude','120/180*pi',...
'frequency','2*pi',...
'position',[25,525,45,545])

add_block('built-in/Step Fcn',[sys,'/','Step Input1'])
set_param([sys,'/','Step Input1'],...
'After','-180/180*pi',...
'position',[90,380,110,400])

add_block('built-in/Step Fcn',[sys,'/','Step Input'])
set_param([sys,'/','Step Input'],...
'Time','0.5',...
'After','90/180*pi',...
'position',[90,300,110,320])

add_block('built-in/Sum',[sys,'/','Sum'])
set_param([sys,'/','Sum'],...
'position',[170,350,190,370])

add_block('built-in/Integrator',[sys,'/','Integrator1'])
set_param([sys,'/','Integrator1'],...
'orientation',2,...
'position',[165,275,185,295])

add_block('built-in/To Workspace',[sys,'/','To Workspace10'])
set_param([sys,'/','To Workspace10'],...
'orientation',2,...
'mat-name','sta',...
'buffer','1e6',...
'position',[50,272,100,288])
add_line(sys,[260,140;300,140])
add_line(sys,[430,20;480,20])
add_line(sys,[280,140;280,60;365,60])
add_line(sys,[400,265;425,265])
add_line(sys,[65,70;105,70])
add_line(sys,[145,95;175,95;175,135;220,135])
add_line(sys,[145,70;158,70;158,19;13,19;13,69;25,70])
add_line(sys,[275,140;275,110;180,110;180,50;85,50;85,95;105,95])
add_line(sys,[440,485;420,485])
add_line(sys,[445,535;420,535])
add_line(sys,[270,535;215,535])
add_line(sys,[320,535;300,535])
add_line(sys,[380,535;355,535])
add_line(sys,[248,535;248,480;215,480])
add_line(sys,[248,535;250,685;335,685])
add_line(sys,[370,685;470,685;470,635;420,635])
add_line(sys,[185,535;170,535:170,715;400,715])
add_line(sys,[435,715;500,715;500,585;420,585])
add_line(sys,[158,60;200,60])
add_line(sys,[65,70;80,70;80,135;105,135])
add_line(sys,[170,630;295,630])
```

```
add_line(sys,[285,365;300,365])
add_line(sys,[260,185;390,185;390,140;410,140])
add_line(sys,[260,230;390,230;390,205;425,205])
add_line(sys,[248,480;250,480;250,425;235,425])
add_line(sys,[445,365;480,365;480,435;420,435])
add_line(sys,[200,425;185,425;185,395;235,395;235,370;255,370])
add_line(sys,[330,365;330,265;365,265])
add_line(sys,[115,310;135,310;135,355;165,355])
add_line(sys,[115,390;135,390;135,365;165,365])
add_line(sys,[190,210;220,210])
add_line(sys,[190,235;220,235])
add_line(sys,[175,480;22,480;20,160;220,160])
add_line(sys,[20,185;220,185])
add_line(sys,[330,265;110,265;110,225;150,225])
add_line(sys,[390,185;537,185;537,484;480,485])
add_line(sys,[300,230;507,230;507,534;485,535])
add_line(sys,[195,360;255,360])
add_line(sys,[210,360;210,305;250,305])
add_line(sys,[330,365;410,365])
add_line(sys,[385,365;385,330;420,330])
add_line(sys,[215,305;215,285;190,285])
add_line(sys,[160,285;140,285;140,280;105,280])

drawnow

\% Return any arguments.
if (nargin | nargout)
\% Must use feval here to access system in memory
if (nargin > 3)
if (flag == 0)
eval(['[ret,x0,str,ts,xts]=',sys,'(t,x,u,flag);'])
else
eval(['ret =', sys,'(t,x,u,flag);'])
end
else
[ret,x0,str,ts,xts] = feval(sys);
end
else
drawnow \% Flash up the model and execute load callback
end
```

A.2 Orifice area calculation

```
function [A] = orif_fn(sita)

\% sita: relative angle betwieen mainshaft and valve body                    \%

\% A1: area of R1 orifice (if sita is positive, A1 becomes large)            \%
\% A2: area of R2 orifice (if sita is negative, A2 becomes large)            \%
fai = 71.5/180*pi;
L = 10e-3;
L1 = 3.28e-3;
L2 = 3.68e-3;
L3 = 4.075e-3;
b0 = (L3 - L2)/2;
h = (L2 - L1)/2 /tan(fai);
x0 = h/tan(fai);
x_lim = -(L2-L1)/2;

\%\%\%\%\%\%\%\%\% calculate A1 \%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%
```

```
dx = sita*10.5e-3;
x = dx+b0;
a = tan(pi/2 - fai);
xj = x_lim + 1e-10;
if x > x0
A(1) = L*sqrt(h^2+ x^2);
elseif x <= x0 & x > xj
xc = a*(a*x+h)/(a^2+1);
yc = -1/a*xc;
A(1) = L*sqrt(xc^2 +yc^2);
else
x_sub = xj;
xc = a*(a*x_sub+h)/(a^2+1);
yc = -1/a*xc;
A(1) = L*sqrt(xc^2 +yc^2)*exp(x-xj);
end

\%\%\%\%\%\%\%\%\%\% calculate A2 \%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%\%

dx = -sita*10.5e-3;
x = dx+b0;
a = tan(pi/2 - fai);

if x > x0
A(2) = L*sqrt(h^2+ x^2);
elseif x <= x0 & x > xj
xc = a*(a*x+h)/(a^2+1);
yc = -1/a*xc;
A(2) = L*sqrt(xc^2 +yc^2);
else
x_sub = xj;
xc = a*(a*x_sub+h)/(a^2+1);
yc = -1/a*xc;
A(2) = L*sqrt(xc^2 +yc^2)*exp(x-xj);
end

\% This is the end.
```

A.3 Pump simulation

```
function[Pp] = pump_fn(q)

\% This function is for pressure output so that it includes algebraic loop.

\% Pp is  pressure at the pomp outlet port.                              \%
\% Q0 is flow rate generated by vane rotation.                           \%
\% Qp is flow determined by the system.                                  \%

Pset = 8.0e6;       \% define relief pressure [MPa]
Rl = 3.03e15;       \% define coefficiant of reakage
Rd = 4.132e-8;       \% define coefficient of discharge

Q0 = q(1);
Qp = q(2);

dQ = Q0-Qp;
if Qp < 0
Pp = 0;

elseif Qp >= Q0 - sqrt(Pset/Rl)
```

```
Pp = Rl * dQ*abs(dQ);

else
Pp = Rl*dQ * (dQ + 2 * Rd * Pset)/(1 + 2 * Rl * Rd * dQ);
end
```

A.4 Valve simulation

```
function[op] = valve_fn(in)

\% Pp = op(1): pressure at inlet port                                    \%
\% QR = op(2): flow rate to right cylinder                               \%
\% QL = op(3): flow rate to left cylinder                                \%
\% Qa: flow rate to ambient area                                         \%

\% Qp: flow rate from inlet port                                         \%
\% PR: pressure at reight cylinder                                       \%
\% PL: pressure at left cylindr                                          \%
\% A1: area of R1 orifice (if A1 is small, left pressure is high)       \%
\% A2: area of R2 orifice (if A2 is small, right presure is high)       \%
\% A3: area of R3 orifice (A3 is small, if A1 is large)                 \%
\% A4: area of R4 orifice (A4 is small, if A2 is large)                 \%

rho = 0.83e3;      \% oil density [Kg/m^3]

Qp = in(1);
PR = in(2);
PL = in(3);
A1 = in(4);
A2 = in(5);
Pa = 0;
A3 = A2;
A4 = A1;

r1 = rho/(2*A1^2);
r2 = rho/(2*A2^2);
r3 = r2;
r4 = r1;

\%
\% calculation of Pp
\%



a = (1-r1/r2)^2;
b = 2*((1-r1/r2)*(r1/r2*PL - PR) - (1+r1/r2)*r1*Qp^2);
c = (PR + r1*Qp^2)^2 + r1^2/r2^2*PL^2 - 2*(PR - r1*Qp^2)*r1/r2*PL;
d = (b^2-4*a*c)^0.5;

if Qp == 0
Pp = PR + r1/(r1+r2)*(PL - PR);

elseif r1 == r2
Pp = -c/b;

else
sol1 = (-b+d)/(2*a);
sol2 = (-b-d)/(2*a);
```

```
if sol1 < sol2
Pp = sol2;
else
Pp = sol1;
end
end

\% flow calculation

Pr2 = Pp - PL;
Qr2 = sqrt(Pr2/r2);
Qr1 = Qp - Qr2;
Qr3 = sqrt((PR - Pa)/r3);
Qr4 = sqrt((PL - Pa)/r4);
QR = Qr1 - Qr3;
QL = Qr2 - Qr4;

op(1) = Pp;
op(2) = QR;
op(3) = QL;


end
```