Modeling and Validation of an Electrically Controlled Hydraulic Power Assist Pump

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1 Introduction

1.1 General introduction
In automobiles, steering wheel, gears, linkages, and other components are used to control the direction of a vehicle’s motion. Because of inertia of the car and friction between the front tires and the road, especially in parking, effort is required to turn the steering wheel. To reduce the effort required, the wheel is connected through a system of gears to components that position the front tires. The gears give the driver a mechanical advantage, i.e., they multiply the force he applies, but they also increase the distance through which he must turn the steering wheel in order to turn the tires a given angle. Various types of gear assemblies, none with any decisive advantages over the others, are used, although most manufacturers prefer a rack-and-pinion system. In faster, heavier cars the amount of force required to turn the tires can be very large. [Columbia Encyclopedia]

Over the years, power steering has become a standard equipment item on many automobiles. The demand for this system has caused power steering to be installed on over 90% of all domestic new car production. Most common systems require a power steering pump attached to the engine and driven by a belt, a pressure hose assembly, and a return line. Also, a control valve is incorporated somewhere in the hydraulic circuit. All systems are constructed so that the car can be steered manually when the engine is not running or if any failure occurs in the power source. Most power steering pumps contain a flow control valve, which limits fluid flow to the power cylinder to about eight liters per minute, and a relief valve which limits pressure according to system demands. [Suspension and Steering Systems]

Market demand for energy efficient power steering systems has in recent years resulted in development of several new concepts. Better fuel economy and steering “feel” are some of the many reasons that have motivated development engineers to design several power steering systems. Other reasons for development of different power steering concepts can be found to be larger or smaller vehicle platforms, specific power associated with hydraulic and electric drives, and packaging issues. Power assist does not only improve comfort by reducing the steering torque, but also improves driving safety because of the more precise steering. The expectations of the steering system with respect to the precision and the adequate reaction have to be fulfilled in the same way as a proper sensitive feedback of the actual driving condition.

1.2 Objective
This study focuses on the pump of the power steering system. Since the power steering pump on most cars today runs constantly, pumping fluid all the time, it wastes horsepower. This wasted power translates into wasted fuel. To improve energy efficiency of the steering system the standard hydraulic pump can be equipped with an EVO (electrical variable orifice) valve, so that a driving situation dependent flow is generated. This so-called EVO pump has the following advantages.

- It provides assist as needed which only depends on design.
- It improves fuel consumption by reducing the flow and pressure within the steering system depending on the needed assist.
- It reduces parking efforts by speed dependent assist.
In the New Vehicle Dynamics Technology (NVDT) group of Ford Motor Company in Cologne (Germany) a new steering system is developed which is called Semi Active Steering (SAS). Semi Active Steering is a low cost and low weight system providing a progressive steering wheel angle dependent steering ratio. It offers the most indirect steering ratio on center while it becomes more direct near to the lock position. The benefits of this steering system are a high steering agility for the driver, reduced steering angle efforts for comfort parking and maneuvering as well as better handling and a high precision due to neutral behavior at high speed on center.

The power assist for this steering system has to be adapted to the current (steering wheel angle dependent) steering ratio. Thus, the hydraulic power assist is realized as a controlled Hydraulic Power Assist Steering (cHPAS), which in contrast to standard cHPAS systems (which are only speed dependent) is steering wheel angle dependent. Thus the power assist for the SAS system uses steering wheel angle and speed sensors as well as engine revolution in order to calculate the current steering ratio and the current required hydraulic flow and power support.

The goal of this study is to investigate the behavior of a pump for the SAS system. The pump is a High Displacement (HD) pump which is equipped with an EVO valve. For the sake of comparison and to have a reference also the standard pump is taken into account. The internally used name for the standard pump is the 14 pump. Throughout this report this name is used to refer to the standard pump. The EVO pump has to be installed in a test vehicle and has to be put into operation to be able to do experiments. Therefore the necessary hardware connections need to be set up in a proper way. Unfortunately, after all preparations for building in the EVO pump, it seemed to be not possible to have the EVO pump built in in the test vehicle within the time period of this study. This is because of problems of the supplier in the scheduling of experiments with the pump. Therefore the model of the EVO pump is made by means of measurements that are done on a test bed at the supplier. Also for the standard pump the model is created by means of test bed measurements. Both models are validated by comparing simulation results with the measurement data.

1.3 Overview
Section 2 presents some background information which is necessary to understand this report. First basic information on rack and pinion steering is given to make this report also understandable for readers who are not familiar with vehicle steering systems. Then in more detail power assisted steering is explained and general information on rotary-vane pumps is given. At the end of section 2 the EVO pump, which is the main subject of this report, is explained in detail. In section 3 the problem formulation is presented. First the background of the project where this study is part of, is given. Then the aims and objectives of this study are explained in detail. The setup of the test vehicle is explained in section 4. Also, the hardware specifications for building in the EVO pump are given. Section 5 explains the experiments on the test bed and the modeling of the standard pump and the EVO pump. Both models are validated in section 6. In section 7 some conclusions are presented and some recommendations are given.
2 Background

2.1 Rack-and-pinion steering

Rack-and-pinion steering is quickly becoming the most common type of steering on cars, small trucks and Sports Utility Vehicles (SUVs). It is actually a pretty simple mechanism. A rack-and-pinion gear set is enclosed in a metal tube, with each end of the rack protruding from the tube (see Figure 2.1). A rod, called a tie rod, connects to each end of the rack. The pinion gear is attached to the steering shaft. When you turn the steering wheel, the gear spins, moving the rack. The tie rod at each end of the rack connects to the steering arm on the spindle. The rack-and-pinion gear set does two things: It converts the rotational motion of the steering wheel into the linear motion needed to turn the wheels. It provides a gear reduction, making it easier to turn the wheels. [HowStuffworks]

![Figure 2.1: Rack-and-pinion steering](HowStuffworks)

When the rack-and-pinion is in a power-steering system, the rack has a slightly different design. Part of the rack contains a cylinder with a piston in the middle, see Figure 2.2. The piston is connected to the rack. There are two fluid ports, one on either side of the piston. Supplying higher-pressure fluid to one side of the piston forces the piston to move, which in turn moves the rack, providing the power assist. [HowStuffworks]

![Figure 2.2: Power rack-and-pinion](HowStuffworks)
2.2 Power steering

There are a couple of key components in power steering in addition to the rack-and-pinion, see Figure 2.3. The pump and the torsion bar valve are discussed in the following two paragraphs.

![Figure 2.3: Power steering][1]

2.2.1 Pump

The hydraulic power for the steering is provided by a rotary-vane pump, see Figure 2.4. This pump is driven by the car's engine via a belt and pulley. It contains a set of retractable vanes that spin inside an oval chamber. As the vanes spin, they pull hydraulic fluid from the return line at low pressure and force it into the outlet at high pressure. The amount of flow provided by the pump depends on the car's engine speed. The pump must be designed to provide adequate flow when the engine is idling. As a result, the pump moves much more fluid than necessary when the engine is running at faster speeds. The pump contains a pressure-relief valve to make sure that the pressure does not get too high, especially at high engine speeds when so much fluid is being pumped.

![Figure 2.4: Rotary-vane pump][2]
2.2.2 **Torsion bar valve**

A power-steering system should assist the driver only when he is exerting force on the steering wheel (such as when starting a turn). When the driver is not exerting force (such as when driving in a straight line), the system shouldn't provide any assist. The device that senses the force on the steering wheel is called the torsion bar valve. The key to the torsion bar valve is a torsion bar, a thin rod of metal that twists when torque is applied to it. When the steering wheel is not being turned, both hydraulic lines provide the same amount of pressure to the steering gear. But if the spool valve is turned one way or the other, ports open up to provide high-pressure fluid to the appropriate line. It turns out that this type of power-steering system is pretty inefficient. [HowStuffWorks]

2.3 **Rotary-vane pumps**

In the automobile industry the rotary-vane pump is the standard used pump for hydraulic or electro-hydraulic power steering systems. In this type, the vane or vanes, which may be in the form of blades, cooperate with a cam to draw fluid into and force it from the pump chamber. These pumps may be made with vanes in either the rotor or stator and with radial hydraulic forces on the rotor balanced or unbalanced. The vane-in-rotor pumps may be made with constant or variable displacement pumping elements.

Figure 2.5 a) shows a vane-in-rotor pump. Because the rotor is shifted from the center, the vanes pull hydraulic fluid from the low-pressure chamber and force it into the high-pressure chamber. This method leads to a continuing force on the rotor, caused by the high pressure compartment, which eventually reduces the period of operation. To prevent this problem, nowadays the pumps’ stator has an elliptic shape which makes the pump to have two opposite low pressure and high pressure compartments, see Figure 2.5 b). Since the two pair of low-pressure and high-pressure compartments are situated symmetrical, the pressure forces that work on the rotor balance each other. This means that they have almost no influence on the bearings, which also means that a higher pressure can be created.

![Figure 2.5: Rotary-vane pumps [Stoll 1992]](image_url)
Most rotary-vane pumps as in Figure 2.5 are constant displacement pumps. This means that they give a constant flow per rotation, which results in a proportional growth of the flow rate with increasing pump speed. This is a great disadvantage. Because of the constant flow per rotation, the pump is not always working efficiently and therefore wastes power. This power translates into wasted fuel. A good example for the loss in power is the straight trip on the highway. Since on a straight track with high speed there is almost no steering done, a power assist is not necessary. This means that the pump generates a flow that is not necessary and therefore it wastes power. [Stoll 1992]

The flow that is generated by a constant pump can be described with the following equation

\[ Q = V \cdot n \]  \hspace{1cm} (2.1)

where \( Q \) is the flow rate, \( V \) is the geometrical flow volume and \( n \) is the pump speed. Since the geometrical flow volume has a fixed value, the flow rate increases proportionally with the pump speed. The pump design however (most important the pump valve) limits the flow to its nominal flow rate. The flow that exceeds the nominal flow rate is led back to the tank through the return line.

Many pumps however are designed to have a digressive nominal flow rate. This means that at high pump speed the nominal flow rate is decreasing. The reason for this choice in design is that a high pump speed is often achieved with a high vehicle speed. Thus, the flow rate and therefore the assist force is decreased, which makes steering more stable at high speeds. The disadvantage is that sometimes a high pump speed is achieved with a relatively low vehicle speed.

The demanded flow rate for the power assist is controlled by a mechanical valve that adjust the required steering effort as described in paragraph 2.2. In the next paragraph an electrically controlled valve is described.
2.4 Variable power assist

2.4.1 Drawbacks of mechanical steering valves

In earlier systems, a mechanical steering valve has been relied upon as the direction control valve for determining the degree of communication between the steering pressure and the hydraulic motor. This type of system has a number of limitations. For one thing, the mechanical steering valve has inherent in its operation a certain amount of backlash or a dead band in which, although the vehicle steering wheel may be turned, no power assist is provided. In addition, with mechanical valves, rapid turning of the steering wheel results in hydraulic shock loading of the mechanical and hydraulic components of the steering system. In addition, since the steering valves are mechanical rotary hydraulic control valves, their operational characteristics are not easily changeable so that it is difficult to tailor their characteristics to a particular vehicle, and the same valve may not be easily adaptable from one vehicle to a different type of vehicle. [Wenzel et al. 1996]

2.4.2 Variable assist power steering

A variable assist power steering system for a motor vehicle has an electronically controlled working pressure valve which addresses these problems. The working pressure valve is provided for reducing the source pressure to a hydraulic working pressure in a working pressure line and is actuable by an electrical signal input to increase the working pressure in response to steering by a driver of the vehicle. A controller generates electrical signals to actuate the working pressure valve. With this system, the working pressure valve operates so as to relieve the source pressure to the relief pressure when no working pressure is required and only to increase it insofar as necessary, according to vehicle status such as vehicle speed and/or engine speed. This uses engine power efficiently, since no pressure is being generated when it is not needed and when it is needed, only the amount needed is generated. [Wenzel et al. 1996]

2.4.3 EVO Pump

The pump that is used in this study is a variable assist power steering pump from the company Visteon. It consists of a constant flow pump which is enhanced with an EVO valve. The EVO system changes steering effort by regulating fluid flow from the power steering pump. Because of the EVO valve the flow rate can be made dependent on the vehicle status. During parking maneuvers, the actuator provides high pump flow for easier steering effort while at highway speeds, the actuator reduces flow in proportion to vehicle speed for improved highway feel and stability. This is an effort of the EVO valve, the pump itself is a constant flow pump which means that it gives the same flow rate independently from the engine speed. The EVO system can be tuned to precise system performance specifications.

Figures 2.8 and 2.9 show a schematic representation and a sketch of the EVO pump. The EVO pump always gives a minimum flow $Q_0$ through the offset as shown in both figures. Parallel to this constant offset there is the EVO valve. Depending on the current that is put on the valve the flow rate $Q_{EVO}$ increases and so does the total flow $Q_{P0}$, which is the sum of $Q_0$ and $Q_{EVO}$. The flow control valve bypasses excess flow from the pump whereas the pressure relief valve opens to relief the pressure should the pressure of the output become to great.
Section 2: Background

Figure 2.7: Hydraulic circuit of the EVO pump

Figure 2.8: Sketch of the EVO valve
3 Problem Formulation

3.1 Project background
This study is part of a project where a new steering system, Semi Active Steering (SAS), is developed. Semi Active Steering is a system that provides a progressive steering wheel angle dependent steering ratio. It offers the most indirect steering ratio on center while it gets more direct near the lock position. As part of the project the power assist has to be adapted to the current (steering wheel angle dependent) steering ratio.

3.1.1 Semi Active Steering
In most commonly used steering mechanisms, the transmission ratio between the rotational movement of the steering wheel and that of the steered wheels remains basically constant over the entire steering range. In other words, there is a linear relationship between the angle of rotation $\alpha$ of the steering wheel and the steering angle $\beta$ of the steered wheels. In terms of operation of the vehicle, however, a variable ratio is generally desirable. When the transmission ratio of a neutral steering position for travel straight ahead decreases with rotation of the steering wheel to the right or left up to steering stop, this is referred to as a progressive steering mechanism. The SAS system consists of such a progressive steering mechanism which is called Wandfluh gear.

3.1.2 Power Assist for SAS
The power assist for this steering system has to be adapted to the current steering ratio. Thus, the hydraulic power assist is realized as a controlled HPAS (Hydraulic Power Assisted Steering), which in contrast to standard controlled HPAS systems is steering wheel angle dependent. The standard cHPAS system is speed dependent. Thus the SAS system uses steering wheel angle and speed sensors as well as engine revolution in order to calculate the current steering ratio and the current required hydraulic flow and power support.

3.2 Aims and objectives
The overall aim of the project is to use experiments to generate a rigorous assessment of the pump in the controlled Hydraulic Power Assist Steering (cHPAS) system. The pump is a High Displacement pump (HD pump), which is equipped with an EVO valve such that it can regulate the fluid flow from the pump as described in paragraph 2.4.3. To be able to install the EVO pump in the test vehicle, the hardware connections are set up and the dSpace system is made operational to do experiments and read out the desired parameters. Due to scheduling problems of the supplier, data from test bed experiments is used for modeling the pump instead of data from the test vehicle. The model is used to make a so-called inverter that controls the current that is needed to generate the desired flow rate. The desired flow rate itself needs also to be controlled. Therefore some desired flow rate generators, which are assigned as boost curves, are proposed. Finally the model is validated by comparing simulation results with experimental data.

The objectives of the project are thus to:

1) Put the EVO Pump into operation in a test vehicle and install the dSpace system.
2) Use experimental data to create a model of the EVO pump in Simulink
3) Design an inverter for the EVO pump and propose some boost curves.
4) Validate the model.
4 Test vehicle experiments

4.1 Experimental setup

For the experiments a test vehicle is used of the type Ford Mondeo with a 2.0 l gasoline engine and a manual gear. The test vehicle is equipped with the SAS system as described in paragraph 3.1.1. It is also equipped with a measuring setup which consists of a dSpace system that is built in in the trunk of the vehicle and sensors to acquire the desired parameters. The measured parameters are listed in Table 4.1. The hardware connections for the l4 pump are already installed and are available in the test vehicle. For reading out the desired parameters the dSpace controller needs to be adjusted. In the next paragraphs the functions of the sensors that are used for the measurements are explained.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Parameter</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>swt</td>
<td>steering wheel torque</td>
<td>[Nm]</td>
</tr>
<tr>
<td>swa</td>
<td>steering wheel angle</td>
<td>[°]</td>
</tr>
<tr>
<td>sws</td>
<td>steering wheel speed</td>
<td>[°/s]</td>
</tr>
<tr>
<td>ltr</td>
<td>left tie rod force</td>
<td>[N]</td>
</tr>
<tr>
<td>rtr</td>
<td>right tie rod force</td>
<td>[N]</td>
</tr>
<tr>
<td>pp</td>
<td>pressure behind pump</td>
<td>[bar]</td>
</tr>
<tr>
<td>pl</td>
<td>pressure actuating cylinder left</td>
<td>[bar]</td>
</tr>
<tr>
<td>pr</td>
<td>pressure actuating cylinder right</td>
<td>[bar]</td>
</tr>
<tr>
<td>po</td>
<td>pressure oil conservator</td>
<td>[bar]</td>
</tr>
<tr>
<td>To</td>
<td>temperature oil conservator</td>
<td>[°C]</td>
</tr>
</tbody>
</table>

4.1.1 Sensors

To measure the steering wheel angle, steering wheel speed and the steering wheel torque, the original steering wheel is replaced by a Measurement Steering Wheel (MSW). To be able to determine the direction in which the steering wheel is turned the incremental drum creates two signals that are 90° phase shifted. Torque values are acquired using a specially designed measuring body equipped with strain gauges. Torque applied to the steering wheel is transferred directly through the measuring body and into the steering shaft. The steering speed is calculated externally by differentiating the angle signal. Specifications for the MSW are available in Table B.2 in appendix B.

In the test vehicle there are also four pressure sensors built in. There is a sensor to measure the supply pressure, which is installed directly after the output of the hydraulic pump. A sensor for measuring the pressure of the excess flow is installed at the return line. The pressures of the actuating cylinder are measured in the connecting line between the torsion bar valve and the actuating cylinder. Two load cells that are implemented between the rack and the tie rods measure the tie rod forces. For this purpose the rods are shortened to be able to place the load cells. A temperature sensor in the excess flow line of the oil reservoir measures the temperature of the hydraulic oil. A flow rate sensor in the output of the pump measures the flow rate.
4.1.2 Measuring system

Autobox is a hardware environment for using a dSpace real-time system for in-vehicle control experiments. It provides space for modular dSpace hardware. The Autobox is installed in the trunk of the test car. It is connected to a notebook via link boards to control the experiments from the passenger seat using ControlDesk. For the power of the Autobox a battery is installed which is loaded by the generator of the car. Also, a measurement amplifier is installed which is connected between the sensors in the car and the Autobox.

The Autobox consists of a digital-analog card, an analog-digital card, a CAN Bus card and a PCMCIA card. The analog-digital card is for reading the signals from the sensors that are installed in the test car. The digital-analog card can be used to send the output signal from a controller to the pump. The CAN Bus card is connected with the Auto CAN Bus. The Auto CAN Bus is the information system of the car which controls the parameters that are already measured in the car. This connection makes it possible to use the signals from the car that are already available. To be able to control and read the signals there is a notebook available that is connected to the Autobox by the PCMCIA card. In Appendix A the wiring diagram is shown.

4.2 Experiments

To be able to compare the EVO pump to the I4 pump, the experiments are also carried out for the I4 pump which is already built in in the test vehicle. When the experiments with the standard pump are completed, the I4 pump is replaced by the EVO pump. This replacement makes it necessary to adjust the hardware connections and the settings of the dSpace system.

4.2.1 I4 Pump

The I4 pump is a vane pump with a constant flow rate which is proportional to the pump speed. It has a nominal flow rate of 8.25 l/min and a geometrical flow volume of 14 cm³ per revolution. The flow rate of the pump depends mainly on the pump speed, which is related to the measured engine speed by a constant ratio. It is not possible with the current experimental setup to change the supply pressure to several desired pressures, so it is not possible to investigate the supply pressure dependency on the flow rate. This means that for modeling the standard pump only the flow rate $Q$ and the engine speed $n$ need to be measured. The flow rate $Q$ is measured by means of the flow rate sensor. The engine speed is available from the Auto CAN Bus and can be read out by the CAN Bus card. Since this parameter is not already measured, a setup is made in the dSpace controller to be able to read out this parameter.

Figure 4.1 a) shows the measured flow rate as a function of the pump speed. It looks like the flow rate has two different paths, one for the increasing pump speed and a different one on the way back. At first thought one would think that there is hysteresis in the pump, but this is not the case. The Auto CAN Bus that transfers the measured engine speed has a certain delay in transferring the data of the engine speed to the CAN Bus of the Auto Box. This means that if the engine speed is changed fast, the engine speed data is delayed a certain time while the delay of the measured flow is not. To obtain the right information, the engine speed must be changed slowly to cancel the delay as much as possible. This gives the right plot of the flow rate as function of the pump speed in Figure 4.1 b).
Section 4: Test vehicle experiments

Figure 4.1: a) Flow rate measurement with delayed engine speed signal, b) Flow rate measurement with almost no delay in engine speed signal

The plot shows no flow measurements for pump speeds below 800 rpm. This is because the test car has an idle speed around 800 rpm and therefore it is not possible to keep the engine running below that value. One way to obtain measurements in that region is from a test bed. On a test bed the pump has no connection to the vehicle. In Figure 4.2 a) an example of test bed measurements of another pump, which is quite similar, is shown.

Figure 4.2: a) Example of test bed measurements, b) Polynomial fit (black) to the measurements (gray)

To create a good model without the noise of the measurements, a polynomial is fitted to the measurements. The point \( (n, Q) = (0, 0) \) is added to the polynomial fit to include the region below 800 rpm in model. In Figure 4.2 b) the model is represented with the black line while the gray line shows the measurements.

With the measurements it is possible to directly model the pump in Simulink. This is done by means of the look-up table block. A look-up table approximates a one-dimensional function using a selected look-up method. This means that for each measured engine speed the measured flow rate is given. For engine speeds that are not measured, an approximated flow rate is calculated from the measured flow rates. To be able to use the data in Simulink in the look-up table block, the data has to be prepared in a certain way. The input, which in this case
Section 4: Test vehicle experiments

is the pump speed, should be sorted in ascending order and may not contain two or more equal values.

4.2.2 EVO Pump

For the EVO pump, test bed measurements are available for two values for the current, one for the maximum current (PWM = 100%) and one for the minimum current (PWM = 0%), see Figure 4.3.

The test bed measurements are used to model the EVO pump in Simulink. Since the flow rate is now not only dependent on the pump speed but also on the current, a 2D look-up table is used. The 2D look-up table has two inputs, the pump speed and the current, and one output, the flow rate. Instead of a polynomial fit of the measurements, the measurements themselves are used for the model of the EVO pump. Therefore the 2D look-up table block is not able to give a good extrapolation of the flow for higher pump speeds. Therefore the measurements data is extrapolated in Matlab manually by using the average value of a fixed number of the last measurement points. Also, the point \((n, Q, I) = (0, 0, 1)\) is added to have a right starting point. The 2D look-up table in Simulink automatically carries out the interpolation and extrapolation of the current. All the interpolations and extrapolations that are carried out by the 2D look-up table are linear.

![Figure 4.3: Test bed measurements for the EVO pump](image)

Figure 4.3 shows the model of the EVO pump with some interpolation of the current and an extrapolation for the pump speed.

To control the EVO pump the model has to be inverted to create an inverter that can give a PWM (Pulse Width Modulation) signal as an output for the desired flow and pump speed as inputs. The model can only be inverted for the points where data for the PWM signal is available. In Figure 4.4 for example, the point \((1000, 18)\) has no value for the PWM signal and therefore cannot be inverted. The value will be NaN (Not a Number), which is not accepted in a look-up table. To solve this problem, the inverter is divided in two parts. The first part is between 0 and 560 rpm. Since all the currents are almost on the same curve, which means that the flow rate is not dependent on the PWM signal, the controller is set to create zero current to use as less energy as possible. The second part of the model is from 560 rpm until 7000 rpm. For this part of the pump speed, the model where the flow rate is between 8 and 20 l/min is inverted to give a PWM signal. This inverted data is put in a 2D look-up table to acts as an inverter for the EVO pump, see Figure 4.5.
The desired flow rate $Q_{\text{des}}$ depends on the specifications for the boost curve. A boost curve shows the assist force for the steering system as function of the steering wheel torque. To create this assist force a certain desired flow is demanded. A boost curve depends mainly on the specifications of the car and it can be varied to create a certain assist behavior for the car. The boost curve can give a high assist force for comfortable driving or it can give low assist force for sportier behavior.
4.3 Hardware setup for the EVO pump

To build in the EVO pump the specifications of the EVO pump have to be compared with the available experimental setup.

4.3.1 EVO Pump Specifications

The EVO pump is limited in the voltages and current in the following way. The maximum voltage and current that can be connected to the pump are 18 VDC and 1.2 ADC respectively. The solenoid can be connected very easily since there are only two connections, one for the ground and one for the PWM signal. A PWM circuit works by making a square wave with a variable on-to-off ratio; the average on time may be varied from 0 to 100 percent. In this manner, a variable amount of power is transferred to the load [Barr 2001]. The PWM signal for the pump has to be a square wave with a frequency of 250 Herz. The duty cycle, which is the ratio of on time to total time, must be between 5% and 95% (5% gives the maximum flow and 95% gives the minimum flow). The ideal amplitude of the PWM signal is at 13.5 V.

4.3.2 DS4002 Timing and Digital I/O Board

In the Autobox that is available in the test vehicle there are several boards available with different functions. The DS4002 Timing and Digital I/O Board provides a 32-bit digital I/O unit that can be used to observe input lines (switches, sensors) or control output lines (relays, displays). Its most relevant function for the EVO pump is that it provides a timing I/O unit with 8 channels for either capturing digital signals or generating arbitrarily pulse patterns.

With the DS4002, a PWM signal can be generated. The PWM signal period \( T_p \) (\( =T_{\text{high}}+T_{\text{low}} \)) can be specified for each PWM signal individually, see Figure 4.7. Depending on the number of channels of the timing I/O unit that is used for the application, \( T_p \) can be in the range as presented in Table 4.2.

<table>
<thead>
<tr>
<th>Channels used</th>
<th>( T_p ) min</th>
<th>( T_p ) max</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.2 ( \mu )S</td>
<td>107 s</td>
</tr>
<tr>
<td>8</td>
<td>8 ( \mu )S</td>
<td>107 s</td>
</tr>
</tbody>
</table>

Also the duty cycle can be specified. The following illustration shows how the duty cycle \( d \) (\( =T_{\text{high}}/T_p \)) is defined. The available duty cycle range is 0 ... 1 (0 ... 100%).

![Figure 4.7: PWM signal](image-url)
In Table B.1 in Appendix B the mapping between the RTI block and the corresponding pins used to provide I-phase PWM signals is shown. The timing I/O unit has a maximum output current of ±75 mA per channel and a voltage range between 0 and 5 V. From the EVO pump specifications in paragraph 4.3.1 it is clear that this is not enough to power the EVO pump.

4.4 Flow curves

There are two options to power the EVO pump. The first option is with the so-called PWM signal as described before. This is a direct connection from the DS4002 card of the Autobox to the EVO pump. The power that is created by the Autobox is not enough for the EVO pump. Therefore some additional amplifiers need to be installed which will cause a certain delay in the signal. The second option is by sending the PWM signal to the pump via the Vehicle CAN. This means that the signal has to be generated by the CAN of the Autobox and is sent via the Vehicle CAN to the ECU of the pump.

The ECU of the EVO pump is programmed for 4 modes. Each mode generates a flowcurve with a PWM signal between 0 and 100 percent. This signal stands for the amount of flow that is requested from the pump. The first three modes (0,1 and 2) are already programmed by the supplier Visteon and are therefore fixed. The fourth mode is a free mode, which can be programmed manually. This last mode is used as an input to define some desired flowcurves. The flowcurves determine together with the valve design of the pump the boost curves. Since the valve design is fixed, the flowcurves are directly related to the boost curves.

The numbers of boost curves that can be designed are infinite. A few basic flowcurves are created in Simulink. The first one is with minimum steering assist, which means minimum flow. Generating a PWM signal with a constant value of zero can create this minimum flow. The second flowcurve is the one with maximum steering assist. This is generated in the same way as the first flowcurve but with a constant PWM signal with a value of 100. The third flowcurve gives a variable flow, which can be assigned manually by means of a slider that goes from zero until 100. The fourth flowcurve is the curve that will generate the same power assist as for the standard pump, see Figure 4.8. All these flowcurves can be treated as submodes for the fourth mode.

In practice one could imagine that these submodes could be used as steering assist options in a vehicle. One could for example switch between a low steering assist to a very high steering assist. In this implementation also the change between two submodes should be considered. It could lead to very dangerous situations when there is an instant change in the steering assist while someone is driving. To avoid this dangerous situation the abrupt change in steering assist between two submodes can be smoothened or the change between two submodes can be allowed only for driving straight (steering wheel angle = 0°). Since this implementation is not part of this study, no further attention will be paid to it.
4.5 Supplier problems

During the preparations to build in the EVO pump, it has become clear that it is not possible to stick to the planned schedule. The EVO pump cannot be built in the test vehicle as planned in first instance, because the pump has to be tested on the test bed first. Because this will take more time than planned it will also take more time before the pump is available to be built in the test vehicle.

Therefore another approach is used. The measurements from the test bed will be carried out for several pumps including the 14 pump and the EVO pump. The measurements that are carried out at the test bed are better than the earlier test bed measurements, because more parameters are taken into account. With the available data from the measurements it will be possible to make a better model for the standard pump as well as for the EVO pump.
5 Modeling

The engine provides the pump with a torque which makes the pump rotate with a certain speed. Due to this rotation, the pump generates a flow with a certain supply pressure. Tubes between the pump and the cylinder, which provides the assist force, create a loss in pressure. There is no loss in flow because it is a closed system with no leakages. In Figure 5.1 the complete power assist system is shown in a scheme.

5.1 I4 pump

The I4 pump model has two inputs and two outputs, just like the test bed measurements. This means that two 2D look-up tables can be used to model the pump.

5.1.1 Test bed experiments for the I4 pump

The test bed measurements for the standard pump are carried out in the following way. For a set of constant supply pressures the pump speed is increased from 100 till 6000 rpm. The supply pressures are chosen to be 2, 5, 7, 10, 50, 60 and 83 bar. The last one is the maximum pressure which opens the pressure relief valve to prevent damage to the pump because of a too high pressure. Because of the way the test bed was setup, it is not possible to measure the flow at this pressure. Therefore the data at 83 bar cannot be used directly in the pump model. However, this information can be used to limit the pump model to a maximum of 83 bar.

To prevent the influence of temperature change on the viscosity of the fluid in the pump and therefore on the flow rate, the fluid temperature is kept constant at 50°C ± 5°C. The test bed measurements are carried out with a sampling frequency of 10 kHz, because there are also some other parameters measured which demand this high frequency. The pump torque and the flow rate are measured, but also the input signals (supply pressure and pump speed).
5.1.2 Postprocessing the 14 pump data

The parameters \( n, p, Q \) and \( T \) are downsampled 100 times in Matlab from 10 kHz to 100 Hz. The measurements, especially the pressures, contain a lot of noise, see Figure 5.2 a). To have a good representation of the pump, the model may not contain this noise and needs to be filtered. A simple averaging filter is used which uses a certain number of points to calculate the average. The \texttt{filtfilt} function in Matlab is used. The advantage of a high value for the number of averaging points is that the curves are very smooth and most distortions are canceled. The disadvantage is that important details, which in this case is the characteristic slope change around 800 rpm, are also smoothened out. To eliminate this disadvantage, the data is filtered with two different values for the number of averaging points. For the first part (the first 1000 samples) of the curves, the data is filtered with 50 averaging points while for the second part 200 averaging points are used to get a smooth curve. To have a smooth transition where the second filter starts, the filters are set up to have a certain overlap in calculating the average around that point. This creates the filtered data as in Figure 5.2 b).

![Figure 5.2: a) Noisy measurement data, b) Filtered data](image)

The experiments with different desired pressures do not all have measurements at the same points for the pump speed. With the interpolation function \texttt{interp1} in Matlab the pump speed is interpolated for pump speeds from 0 till 6000 rpm with a step of 1 rpm, see Table 5.1

The calculated flow rates for the interpolated values for the pump speed, together with the pump speed points and the constant pressures can be used for the 2D look-up tables in Simulink. As inputs there are the \( n \)-vector which consists of values from 0 to 6000 with steps of 1 rpm ( \([0 1 2 \ldots 6000]\) ) and the \( p \)-vector \([2 5 7 10 50 60]\). These two vectors have the 6001x6 matrix \([Q(0:6000,2) \ Q(0:6000,5) \ldots \ Q(0:6000,60)]\) as output for the 2D look-up table. For the pump torque the same procedure can be carried out.

<table>
<thead>
<tr>
<th>( n ) (rpm)</th>
<th>( p )</th>
<th>( Q(n,p) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:6000</td>
<td>2</td>
<td>( Q(0:6000,2) )</td>
</tr>
<tr>
<td>0:6000</td>
<td>5</td>
<td>( Q(0:6000,5) )</td>
</tr>
<tr>
<td>0:6000</td>
<td>7</td>
<td>( Q(0:6000,7) )</td>
</tr>
<tr>
<td>0:6000</td>
<td>10</td>
<td>( Q(0:6000,10) )</td>
</tr>
<tr>
<td>0:6000</td>
<td>50</td>
<td>( Q(0:6000,50) )</td>
</tr>
<tr>
<td>0:6000</td>
<td>60</td>
<td>( Q(0:6000,60) )</td>
</tr>
</tbody>
</table>
5.1.3 Improved 14 pump model

In the model for the 14 pump the flow rate is dependent on the pump speed and the supply pressure. The supply pressure is assumed to be kept constant during the experiments and therefore the desired values are used for the model. The plots of the measured pressures in Figure 5.3 show that the pressures are not constant at all times. Therefore the assumption that the pressures are constant somehow effects the pump model in a negative way. Since the real measured pressures are available, the model can be improved by using the measured values.

![Figure 5.3: Measured supply pressures for the 14 pump](image)

When the real pressure values are used instead of the desired ones, each set of measurements for a desired pressure can be seen as measurements for a lot of independent coordinates in the \((n, p, Q)\)-space and \((n, p, T)\)-space. With the six sets for the desired pressures, there are a lot of points in the 3 dimensional spaces \((n, p, Q)\) and \((n, p, T)\). With the function \texttt{griddata} it is possible to fit a surface through all these points and to interpolate for intermediate pump speed and pressure values to get a value for the flow rate \(Q\) and pump torque \(T\). The function \texttt{griddata} can only interpolate from the measured data but it does not extrapolate. Therefore the points for which the look-up table is created should be within the boundaries of the measured values. If the look-up table consists of values outside the range of the measurement data it will return for those point the value \texttt{NaN} which is not accepted in the look-up table block in Simulink. When the look-up table is clean from \texttt{NaN} values, the look-up table block in Simulink will use those values to extrapolate for out of range values.

The surface in the 3 dimensional space is extended to the \(n = 0\) line by adding a vector of zeros for the flow rate and the pump torque for a vector with pressures from 0 till 60 bar. This means that for all pressures at \(n = 0\) the flow rate and pump torque are zero. The 3 dimensional surface that presents the look-up table for the pump model is shown in Figure 5.4. The look-up table for the pump torque is shown in Figure 5.5.
Section 5: Modeling

Figure 5.4: Look-up table for the flow rate $Q$

Figure 5.5: Look-up table for the pump torque $T$
Both look-up tables are used to model the 14 pump in Simulink. In Figure 5.6 some simulation results are presented to have a better understanding of the model. The $n-Q$-plot shows that from 0 till 800 rpm there is a linear increase in flow rate with respect to the pump speed which is almost not dependent on pressure. This part matches with (2.1) where the flow rate is shown to be linearly dependent with the pump speed. From 800 rpm to 6000 rpm the flow rate seems to increase with the pressure. This is an unexpected result since the flow rate was expected to keep its maximum flow rate of 8.25 l/min. In the $p-Q$-plot the increase in flow rate is plotted for increasing pressure at constant pump speeds. The increasing slope for higher pump speeds can be understood by looking at the $n-Q$-plot.

\[ T = \frac{V \cdot \Delta p}{2\pi}, \text{with } \Delta p = p_{\text{tank}} - p_{\text{supply}} \quad (5.1) \]

The pump torque in the $n-T$-plot shows an almost constant value as function of the pump speed. In the $p-T$-plot this results in a torque increase which is almost independent on pump speed and increases linearly with the pressure. In (5.1) the pump torque $T$ shows a linear relationship with the difference pressure $\Delta p$. Since for the pump $\Delta p$ is the difference pressure between the tank pressure and the supply pressure and the tank pressure has a constant value that is equal to the atmosphere pressure, the torque $T$ has a linear relation with the supply pressure and is not dependent on the pump speed. This theory confirms that the pump behavior as described by the model is correct.

Figure 5.6: Simulation results
5.2 EVO pump

The model of the EVO pump is quite similar to the I4 pump. The difference here is that there is an extra input, which is the PWM signal from the electrical controller.

5.2.1 Test bed experiments for the EVO pump

The test bed experiments for the EVO pump are carried out almost in the same way as for the I4 pump. The pump speed is increased from 100 to 6000 rpm for a set of constant supply pressures which vary between 5 and 50 bar. For pressures higher than 50 bar, the pump speed is increased from 100 to only 2500 rpm, because the pump is a prototype and has to be handled carefully. The experiments for all sets of desired supply pressures are carried out with PWM signals that vary between 0 and 100 percent. Table 5.2 presents the combinations of parameters for the experiments. Cells that contain an X represent experiments for which the data is not available (yet) because of a delay in the delivery. During the experiments, the flow rate, the pump torque, the supply pressure and the pump speed are measured.

<table>
<thead>
<tr>
<th>PWM signal [%]</th>
<th>Pressure [bar]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5  7  8.5 10  20 30 40 50 60 80</td>
</tr>
<tr>
<td>20</td>
<td>5  X  X 10  20 30  X 50 60 80</td>
</tr>
<tr>
<td>40</td>
<td>X  X  8.5 10  20 30 40  X 60 80</td>
</tr>
<tr>
<td>60</td>
<td>X  7  8.5 10  20 30 40 50 60 80</td>
</tr>
<tr>
<td>80</td>
<td>5  7  8.5 10  20 30 40 50  X 80</td>
</tr>
<tr>
<td>100</td>
<td>5  7  8.5 10  20 30 40 50 60 80</td>
</tr>
</tbody>
</table>

5.2.2 Postprocessing the EVO pump data

The extra parameter $I$ creates much more experiments with the EVO pump and therefore much more measurement data. To keep the calculation times in Matlab acceptable the data is downsampled 1000 times instead of the 100 times for the I4 pump. For filtering the data the same filter and method is used as in paragraph 5.1.2 for the I4 pump.

5.2.3 The EVO pump model

For modeling the EVO pump measured pressures are used and it would also be better to use measured values of the PWM signal. Because it is not possible to measure the PWM signal because of a lack of output channels, the desired values for the PWM signal are used. For all pressure values and PWM signal values $Q$ and $T$ are set to be equal to zero when $n = 0$. This means that whenever the pump is not running there is no flow rate and no pump torque.

With the use of measured pressures, pump speed, flow rate, pump torque and desired PWM signals, all the measurements create a lot of coordinates $(n, p, I, Q)$ and $(n, p, I, T)$ in a 4 dimensional space. The function \texttt{griddata3} in Matlab can fit a surface through all these points and interpolates for intermediate pump speed, pressure and PWM signal values to get a value for the flow rate and pump torque. Just as for the function \texttt{griddata} the function \texttt{griddata3} cannot extrapolate. This causes problems in using all the available data, because there are some measurements missing (see Table 5.2). Therefore the model can only be made with the data for the combinations of experiments with $p_{des} = 10, 20$ and 30 bar. Figure 5.7 and Figure 5.8 show respectively the look-up tables for the flow rate and pump torque in the $(n, p, Q)$-space and $(n, p, T)$-space for a few constant PWM signals.
Figure 5.7: Look-up table of the EVO pump for the flow rate $Q$

Figure 5.8: Look-up table of the EVO pump for the pump torque $T$ with a PWM signal of 0 percent.
In Figure 5.9 some simulation results are presented to give a better understanding of the model. These simulation results show the flow rate and torque as function of the pump speed and PWM signal for $p = 10, 20$ and $30$ bar.

As we also can see in the 3 dimensional plot in Figure 5.7, the flow rate for $I = 0$ with a pressure of 10 bar seems to be still very noisy. This is probably because the measurement for this combination of parameters contains much more noise than all the other measurements and therefore the model is not filtered enough to produce smooth results in the simulations. From the flow rate simulations, it is very clear that the flow rate does not have a linear relationship with the PWM signal. This means that if the EVO valve is opened with a certain factor, the flow is not increasing with the same factor. The torque simulations show a very fluctuating response so that it is hard to draw a conclusion. However, the torque seems to show a small increase with respect to the pump speed.

Figure 5.9: Simulations with the EVO pump model for $p = 10, 20$ and $30$ bar and $I = 0, 20, 40, 60, 80, 100$

Figure 5.10 shows 6 simulations where constant pump speeds of 2000,4000 and 6000 rpm are chosen and the flow rate and torque as function of the pressure and PWM signal are measured. Since the model is created by measurements between 10 and 30 bar one should focus only on that part. The pressures outside this range are not reliable and are only to indicate the trend of the plots in Figure 5.10. The plots show that the flow rate increases with the pressure in an almost linear manner. The torque also increases with the pressure in a linear manner. Just as for the I4 pump, the torque depends mostly on the pressure and seems not to depend on the PWM signal.
Figure 5.10: Simulations with the EVO pump model for \( n = 2000, 4000 \) and \( 6000 \) rpm and \( \theta = 0, 20, 40, 60, 80, 100 \)
6 Model validation

6.1 14 pump validation

To validate the pump models, the measurement results are compared with simulations. The model in Simulink can only be compared with the real measurements if the same inputs for the model and the measurements are used. Therefore the measurement data for the pressures and the pump speeds are used as inputs for the model so that the simulated flow rates and pump torques can be compared to the measured values, see Figure 6.1.

![Diagram of comparison scheme for validation of the 14 pump model](image)

Figure 6.1: Comparison scheme for validation of the 14 pump model

The simulations are carried out with the available data from the test bed measurements. The measurement sets with a desired pressure of 2, 5, 7, 10, 50 and 60 bar and increasing pump speeds are used. The simulated flow rate is compared with the measured flow rate in Figure 6.2. The simulated pump torque is compared with the measured pump torque in Figure 6.3.

![Comparison of simulated (gray) and measured (black) flow rates for various pressures](image)

Figure 6.2: Comparison of simulated (gray) and measured (black) flow rates for \( p_{des} = 2, 5, 7, 10, 50, 60 \)
Figure 6.2 shows over the whole range of pressures that the simulated flow rates are almost equal to the measured flow rates. For the simulation with $p_{\text{des}} = 2$ bar, the simulation shows a very fluctuating behavior near 6000 rpm. This is probably due to the fact that $p_{\text{des}} = 2$ bar is at the boundary of the data with which the model is created and therefore bad extrapolation is carried out. Besides this exception, the model gives good result for all the simulated flow rates.

![Graph showing simulated and measured flow rates for different pressures.]

Figure 6.3: Comparison of simulated (black) and measured (gray) pump torques for $p_{\text{des}} = 2, 5, 7, 10, 50, 60$

Figure 6.3 shows like in Figure 6.2 a very fluctuating simulation for $p_{\text{des}} = 2$ bar near 6000 rpm. The rest of the simulations for the pump torque show good behavior compared to the measured data.

Both the flow rate and pump torque comparisons with the real measurements indicate that the model for these values is quite reliable. For simulation with values that are not part of the look-up table data, interpolation and extrapolation is used. This means that with more measurement data, the look-up table can be made more reliable.

6.2 EVO pump validation

The validation of the EVO pump takes place in the same way as for the I4 pump. The extra parameter $f$ for the PWM signal is included in Figure 6.4.

In Figure 6.5 some simulation results are compared to the measurements. The simulations for the flow give good result with respect to the measurements. Just as for the I4 pump, the simulation which is closest to the boundary of the look-up table shows a fluctuating behavior near 6000 rpm. This behavior is probably explainable with the same reason as for the I4 pump. The simulated pump torques in Figure 6.5 give also good results.
Section 6: Model validation

Figure 6.4: Comparison scheme for validation of the EVO pump model

In Figure 6.6 and Figure 6.7 the same simulations are carried out for \( P_{\text{des}} = 20 \) bar and \( P_{\text{des}} = 30 \) bar. As mentioned before the look-up table is generated with the measurements for \( P_{\text{des}} = 10, 20 \) and \( 30 \) bar. Since this is a small range with not much data, the interpolations and extrapolations for other values is expected to be not very good. When the missing experimental data as described in Table 5.2 is available, the model can be improved by including this data in the model.
Section 6: Model validation

Flowrate simulations and measurements with $p_{des} = 20, 10, 40, 80$

Flowrate simulations and measurements with $p_{des} = 20, 10, 80, 100$

Torque simulation and measurement with $p_{des} = 20, 1 = 20$

Torque simulation and measurement with $p_{des} = 20, 1 = 80$

Figure 6.6: Comparison of simulated (black) and measured (gray) flow rate and pump torque for $p_{des} = 20$

Flowrate simulations and measurements with $p_{des} = 30, 1 = 40, 80$

Flowrate simulations and measurements with $p_{des} = 30, 1 = 20, 60, 100$

Torque simulation and measurement with $p_{des} = 30, 1 = 20$

Torque simulation and measurement with $p_{des} = 30, 1 = 80$

Figure 6.7: Comparison of simulated (black) and measured (gray) flow rate and pump torque for $p_{des} = 30$
7 Conclusions and recommendations

7.1 Conclusions
As part of a project where the standard steering assist needs to be replaced with a controllable one, an electrically controllable pump is investigated. This pump, which is called EVO pump, is a high displacement pump that is equipped with an EVO valve.

- For modeling the EVO pump as part of a power steering assist system, the first objective is to install the pump in a test vehicle. For this installation the EVO pump specifications are compared with the available experimental setup. To install the EVO pump there are two options. The first option is a direct connection from a board in Autobox (the DS4002 Timing and Digital I/O Board) to the pump, but since the board is not able to provide enough power to the EVO pump an amplifier would be necessary. This will cause a delay in the signal. The second option is to control the pump via the vehicle CAN. This means that the signal is generated by the CAN of the Autobox and is sent via the vehicle CAN to the ECU of the pump.

Unfortunately it seemed not to be possible to have the EVO pump installed in the test vehicle within the time period of this study. Therefore, test bed experiments are used to model the pump.

- The EVO pump is modeled by using the measurement data of test bed experiments. Also, the I4 pump is modeled to have a reference and for the sake of comparison. The models are made in Simulink by using look-up tables. For the I4 pump two 2D look-up tables are used with the pump speed and pressure as inputs and the flow rate and pump torque as outputs. For modeling the EVO pump two 3D look-up tables are used which are the same as the 2D look-up tables for the I4 pump but with an extra input for the PWM signal.

- For controlling the EVO pump, the model has to be inverted to create an inverter that can give a PWM signal as an output for the desired flow and pump speed as inputs. The desired flow rate depends on the specifications for the boost curve, which can be varied to create a certain assist behavior for the car. In this study some possible boost curves are described, including the boost curve that gives the assist behavior of the I4 pump. For the EVO pump in combination with a vehicle with the nonlinear steering gear (SAS), an intensive study is necessary to find the optimal boostcurve.

- The models of the I4 pump and the EVO pump are validated by comparing the measurements with simulations. The results of the simulations seem to match the measurements quite well. For the I4 pump the results where more satisfying than for the EVO pump. This is because for the I4 pump there are more measurements so that the model is more reliable than for the EVO pump. The lack of measurements for the EVO pump is due to delivery problems of the measurement data and because the EVO pump is a prototype and can only undertake measurements in a small range.
7.2 Recommendations

- For modeling the pumps, test bed measurements are used. The pumps however are for operation in vehicles, where (dynamical) influences from the steering system, the tubes, engine vibrations and many other components that are directly or indirectly connected to the pump are not considered. This means that the models represent only the pumps on the test bed and they do not represent the pumps in a vehicle.

- In paragraph 5.2.3 it is noticed that for the PWM signal the desired value is used in the model instead of measurement values. To improve the model and have a better representation of the pump behavior with respect to the change in PWM signal it is better to use the real measurement values instead of the desired values.

- During the test bed experiments the temperature is kept within the range of 50°C ± 5°C to cancel the influence of temperature of the fluid on the flow rates. When the pump is operating in a real vehicle the temperature of the fluid can have high variations which results in flow rate changes. It is therefore recommended to include the temperature in the set of varying parameters and to model the flow rate and torque also as function of the temperature.

- The models of the 14 pump and the EVOpump are created by means of look-up tables. The look-up table blocks in Simulink use measurement data to interpolate for intermediate values and to extrapolate for out of range values. By increasing the range and the number of measurements for different pressures and PWM signals, there is less need for interpolation or extrapolation which makes the models more reliable.

- The test bed measurements are filtered with a simple averaging filter to remove the noise from the measurements. The number of averaging points is chosen by trial and error. A systematic way for choosing the kind of filter can result in a better filtering with attention to small pump characteristics that may not be filtered away.
Appendix A: SAS Vehicle Instrumentation
Appendix B: Hardware Specifications

The following table shows the mapping between the RTI block and the corresponding pins used to provide 1-phase PWM signals.

Table B.1: pins for the PWM signal

<table>
<thead>
<tr>
<th>Related RTI Blocks</th>
<th>Channel</th>
<th>Connection pin</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS4002PWM1_OUT</td>
<td>Ch 1</td>
<td>P2 14</td>
<td>CH1</td>
</tr>
<tr>
<td></td>
<td>Ch 2</td>
<td>P2 47</td>
<td>CH2</td>
</tr>
<tr>
<td></td>
<td>Ch 3</td>
<td>P2 31</td>
<td>CH3</td>
</tr>
<tr>
<td></td>
<td>Ch 4</td>
<td>P2 15</td>
<td>CH4</td>
</tr>
<tr>
<td></td>
<td>Ch 5</td>
<td>P2 48</td>
<td>CH5</td>
</tr>
<tr>
<td></td>
<td>Ch 6</td>
<td>P2 16</td>
<td>CH6</td>
</tr>
<tr>
<td></td>
<td>Ch 7</td>
<td>P2 49</td>
<td>CH7</td>
</tr>
<tr>
<td></td>
<td>Ch 8</td>
<td>P2 33</td>
<td>CH8</td>
</tr>
</tbody>
</table>

For the steering angle and the steering torque both outputs, as described in Table B.2 are available in parallel. The analog output of the smaller measuring range will reach the point of saturation when the specified range is exceeded.

Table B.2: MSW specifications

<table>
<thead>
<tr>
<th>Measurement signal</th>
<th>Output Channel</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steering Angle</td>
<td>L1</td>
<td>1V = 125° range: 1250°</td>
</tr>
<tr>
<td></td>
<td>L2</td>
<td>1V = 20° range: 200°</td>
</tr>
<tr>
<td>Steering torque</td>
<td>M1</td>
<td>1V = 5 Nm range: 50 Nm</td>
</tr>
<tr>
<td></td>
<td>M2</td>
<td>1V = 1 Nm range: 10 Nm</td>
</tr>
<tr>
<td>Steering angle speed</td>
<td>TTL 0°</td>
<td>900 pulses/ rotation, max steering speed</td>
</tr>
<tr>
<td></td>
<td>TTL 90°</td>
<td>900 pulses/ rotation, max steering speed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9000°/sec</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000°/sec</td>
</tr>
</tbody>
</table>
References


Suspension and Steering Systems Operation. URL: www.autoshop-online.com/auto101/susp.html [Suspension and Steering Systems]
