

Simulation-Based Experiments in Hydraulic Motor Speed Control

By Daniel W. Williams, Ph.D.

Milwaukee School of Engineering



Sponsored by NFPA



Grant Dated 4 November 2021

Table of Contents

1.	List of Symbols	3
2.	Introduction	4
3.	Fluid Power System Under Consideration	5
4.	Circuit Analysis Example	7
5.	Simulated Experiments	9
5.1	Exercise: Motor Speed Control – <u>Valve</u> Actuation	11
	Procedure	11
5.2	Exercise: Motor Speed Control – <u>Pump</u> Actuation	13
	Procedure	13
6.	Sample Results	15
6.1	Valve-Actuated Test Results	15
6.2	Pump-Actuated Test Results	16
6.3	Follow-up Circuit Analysis Examples	17
7.	Summary	18
8.	Appendix – Default Model Parameters (MATLAB Scripts).....	19

1. List of Symbols

Symbol	Units	Description
C_{Lm}	$\text{in}^3/\text{s}/\text{psi}$	Motor leakage coefficient
D_p, D_m	in^3/rev	Pump and motor volumetric displacements, respectively
K_v	$\text{in}^3/\text{s}/(\text{psi})^{1/2}$	Various valve and leakage coefficients
N_p, N_m	rpm	Pump and motor shaft speeds, respectively
$P_A, P_B, \text{ or } P_{mi}$	psi	Valve work port pressure (A or B) equal to the motor inlet pressure
$P_{mo} \text{ or } P_T$	psi	Motor outlet pressure equal to the return pressure due to filtering, etc.
P_s	psi	System pressure at the pump outlet
P_v	psi	Valve supply pressure downstream of the sequence valve
ΔP_m	psi	Motor pressure differential associated with the load torque
ΔP_{pL}	psi	Directional control valve (DCV) powered land pressure differential
ΔP_{sv}	psi	Sequence valve pressure differential
Q_{mo}	in^3/s	Motor outlet flow that returns to the reservoir
Q_p	in^3/s	Net flow delivered by the variable displacement pump
$Q_{pL} = Q_{mi}$	in^3/s	Motor inlet flow equal to the flow across the powered land of the DCV
Q_{Lp}, Q_{Lm}	in^3/s	Pump and motor leakage flows, respectively
T_L	in·lb	Motor load torque
V_p, V_{rv}, V_{dcv}	V	Control signals for the pump, relief valve and DCV, respectively
η_{vp}, η_{vm}	—	Volumetric efficiencies of the pump and motor, respectively
η_{Tm}	—	Mechanical (torsional) efficiency of the motor

2. Introduction

The intent in preparing this document is to guide the reader in using the accompanying MATLAB files (Simulink models and associated parameter scripts) to run simulation-based experiments on a model of a hydraulic motor speed control circuit. The hydraulic circuit under consideration represents one configuration of the fluid power test stands located in MSOE's Motion Control Lab. This lab facility is used for the required course in automatic control systems.

With the social-distancing constraints associated with the COVID-19 pandemic, students were afforded only minimal time in the physical lab. In response to this reality, simulation-based experiments were used to give the students an opportunity to conduct the full laboratory exercises on their personal computers. The simulation model of the physical setup provided a sufficient degree of realism for the students to experience many of the issues normally associated with the equivalent physical lab, albeit without the sights and sounds of the real machinery.

For example, for the hydraulic motor speed control lab all the system settings including pump speed, pump displacement, and relieve valve setting, must be established for the simulated system to operate as intended. Then for the experimental procedure, the motor load is adjusted, and the resulting speed and other steady-state data are observed on system readouts. The process and results accurately mimic those of the physical version of the exercises.

With the return to "normal" laboratory attendance, the students resumed doing the experiments on physical systems. However, the simulated experiments are still used for some labs to give the students an opportunity to preview the lab procedure virtually to enhance their preparation for the physical lab. This helps to mitigate time constraints that often come into play. We also can assign simulated labs to students having excused absences from the physical lab sessions.

It is the hope of the author to enable other fluid power instructors in academia and/or industry the ability to assign such simulation-based experiments to their students along with, if desired, associated circuit analyses. The simulation model provided is fully parameterized to allow complete modification of the circuit operational details.

Software Requirement: As of this writing, the provided Simulink models require version MATLAB 2021b (or newer?) and its associated Simulink license.

Support: A cursory knowledge of Simulink is assumed for users of the provided materials. Consult the Simulink OnRamp tutorial by Mathworks if an introduction to the software is required. Otherwise, if you have any problems with running the models, please contact this author at williamsd@msoe.edu. I will attempt to provide start-up assistance as time allows.

3. Fluid Power System Under Consideration

The provided simulation model is based on the rotary configuration of the fluid power test stands located in MSOE's Motion Control Laboratory. Figure 1 contains a schematic of the modeled hydraulic system.

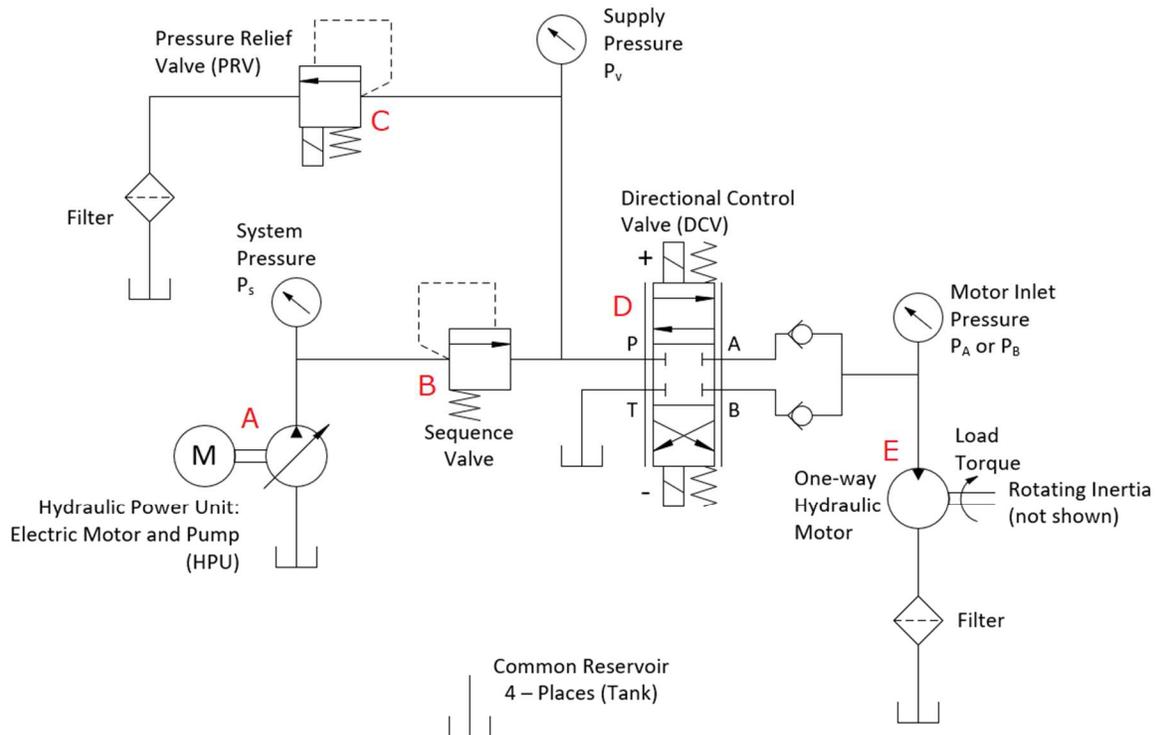


Figure 1. Hydraulic test circuit used for the motor speed control experiments.

As is common in preliminary circuit design analysis, the elements of the physical system associated with line losses and boundary conditions are not included in the simulation model. As such, the simulated circuit pressures are associated with the restrictions modeled in the various valving and the motor load torque as well as the boundary condition of return flow restriction representing the combined effect of the reservoir and filtering. The sample circuit analysis provided in the next section illustrates this.

The major components identified by the red-letter annotations in Figure 1 are described in Table 1 below, along with their model parameters set per the first MATLAB script (`HydMtrCtrlSys_paramsV1.m`). As mentioned above, these parameters are accessible to the reader for full adaptation of the system within the constraints of the provided circuit topology. Within the Simulink model environment, the remaining operational parameters are adjusted as part of the experimental procedure.

Experiments in Hydraulic Motor Speed Control

Item	Description	Default Model Parameters
A	<p>Electrohydraulic Pump The load on the electric motor is not modeled. Rather the electric motor is assumed to be operating at the set speed independent of the pump load.</p>	<p>Displacement, $D_{p,max} = 1.70 \text{ in}^3/\text{rev}$ The actual displacement is $D_p = (v_p/5) D_{p,max}$, where v_p is the 0-5V pump command signal Volumetric Efficiency, $\eta_{vp} = 95\%$ Leakage Coefficient, $K_{vLp} = 0.005 \text{ (in}^3/\text{s)/(\psi)}^{1/2}$ Maximum Speed, $N_{p,max} = 1200 \text{ rpm}$</p>
B	<p>Sequence Valve This valve is in place to generate the required backpressure at the pump outlet. The pump requires this minimum stand-by pressure for its internal controls.</p>	<p>Threshold Pressure, $PSV = 350 \text{ psi}$ Flow coefficient, $K_{vsv} = 10 \text{ (in}^3/\text{s)/(\psi)}^{1/2}$</p>
C	<p>Pressure Relief Valve In place to set operating pressure and to protect the system from excessive pressures.</p>	<p>Cracking Pressure, $PRV = 550 * v_{rv}$, where v_{rv} is the 0-5V relief valve command signal Flow coefficient, $K_{vrv} = 10 \text{ (in}^3/\text{s)/(\psi)}^{1/2}$</p>
D	<p>Directional Control Valve A switch in the model allows the selection of this valve (default) or a user-defined option.</p>	<p>Metering Curve (X-Y lookup table) interpolated to obtain K_{vdcv} X (voltages): [-10 0.34 8 9.64 10] (V) Y (valve coefficients): [0 0 1.1 1.2 1.2] $\text{(in}^3/\text{s)/(\psi)}^{1/2}$</p>
E	<p>Hydraulic Motor The load pump circuit is not explicitly modeled. Rather the load pump torque (ideal) is directly set in the simulation model.</p>	<p>Displacement, $D_m = 1.5 \text{ in}^3/\text{rev}$ Torque Efficiency, $\eta_{Tm} = 96\%$ Leakage Coefficient, $C_{Lm} = 0.0005 \text{ (in}^3/\text{s)/(\psi)}$ Load Torque, $T_L = \text{adjustable; opposing}$ The load torque cannot drive the motor backwards due to its resistive nature from back pressure which depends on positive motor speed.</p>
-	Return Pressures	Tank port pressure for all returning fluid: $P_T = 30 \text{ psi}$

Table 1. Modeled motor circuit components and default model parameters.

4. Circuit Analysis Example

The model predicts a motor speed of $N_m = 629.4$ rpm under the following conditions:

$$P_s = 1249 \text{ psi} \quad P_v = 896 \text{ psi} \quad P_{mi} = 510 \text{ psi} \quad P_{mo} = P_T = 30 \text{ psi}$$

$$N_p = 1200 \text{ rpm} \quad v_p = 2.5V \quad v_{rv} = 2.5V \quad v_{dcv} = 6.0V \quad T_L = 110 \text{ in-lb}$$

NOTE: In the following analysis, the pressure-flow relationship for valve coefficients is the empirical one based on the orifice equation: $Q = K_v \sqrt{\Delta P}$, from which the pressure differentials are obtained:

$$\Delta P = (Q/K_v)^2$$

A steady-state circuit loop analysis can be used to corroborate the pressure states while illustrating the algebraic relationships that are used in the Simulink model. Working in reverse through the circuit from the known return pressure boundary condition and using the resulting motor speed, the system pressure results from the constituent pressure differentials due to flow losses and the motor load torque:

$$P_s = P_T + \Delta P_m + \Delta P_{pL} + \Delta P_{sv}$$

The breakdown of these pressure differentials follows:

Return pressure, P_T (given):

$$\underline{P_T = 30 \text{ psi}}$$

Motor differential pressure, ΔP_m :

$$\Delta P_m = 2\pi \cdot T_L / (\eta_{Tm} \cdot D_m) = 2\pi(110)/(0.96)(1.5)$$

$$\underline{\Delta P_m = 480 \text{ psi}}$$

Motor inlet pressure, P_{mi} :

$$P_{mi} = P_T + \Delta P_m = 30 + 480$$

$$\underline{P_{mi} = 510 \text{ psi}} \checkmark$$

Valve differential pressure of the powered land, ΔP_{pL} (requires flow computation):

Motor inlet flow, Q_{mi} (ideal flow plus leakage):

$$Q_{mi} = D_m \cdot N_m / 60 + C_{Lm} \cdot P_{mi} = (1.5)(629.4)/60 + (0.0005)(510)$$

$$Q_{mi} = 16.0 \text{ in}^3/\text{s}$$

DCV flow coefficient, K_{vdcv} (for $v_{dcv} = 6.0V$, by interpolation):

$$K_{vdcv} = 0 + (1.1-0)(6.0-0.34)/(8.0-0.34)$$

$$K_{vdcv} = 0.8128 \text{ in}^3/\text{s}/(\text{psi})^{1/2}$$

$$\Delta P_{pL} = (Q_{mi}/K_{vdcv})^2 = (16.0/0.8128)^2$$

$$\underline{\Delta P_{pL} = 387 \text{ psi}}$$

Valve supply pressure, P_v :

$$P_v = P_T + \Delta P_m + \Delta P_{pL} = 30 + 480 + 387$$

$$\underline{P_v = 897 \text{ psi}} \checkmark$$

Sequence valve differential pressure, ΔP_{sv} :

$$\Delta P_{sv} = P_{sv} + (Q_{mi}/K_{vsv})^2 = 350 + (16.0/10)^2$$

$$\underline{\Delta P_{sv} = 353 \text{ psi}}$$

Pump outlet (system) pressure, P_s :

$$P_s = P_T + \Delta P_m + \Delta P_{pL} + \Delta P_{sv} = 30 + 480 + 387 + 353$$

$$\underline{P_s = 1250 \text{ psi}} \checkmark$$

5. Simulated Experiments

Just like the physical test stand, the simulation model of the hydraulic motor speed control circuit can regulate the motor speed either by modulating the command to the EH directional control valve (valve-controlled motion) or the command to the EH pump (pump-controlled motion). These two modes of speed control correspond roughly to the two types of hydrostatic drives used in mobile hydraulics, namely open circuit (valve-controlled) and closed circuit (pump controlled) hydrostatic drives.

With the implementation of closed loop control, a distinction must be made between the model depicted in Figure 2, which uses feedback to control the valve signal, and a second model that uses the feedback to control the pump displacement signal. Figure 3 shows the pump-controlled version of the simulation model. Both models employ the same physical fluid power system model. A quick study of the two models reveals that they differ simply in the choice of the active control feature being driven by the controller, the valve signal versus the pump signal.

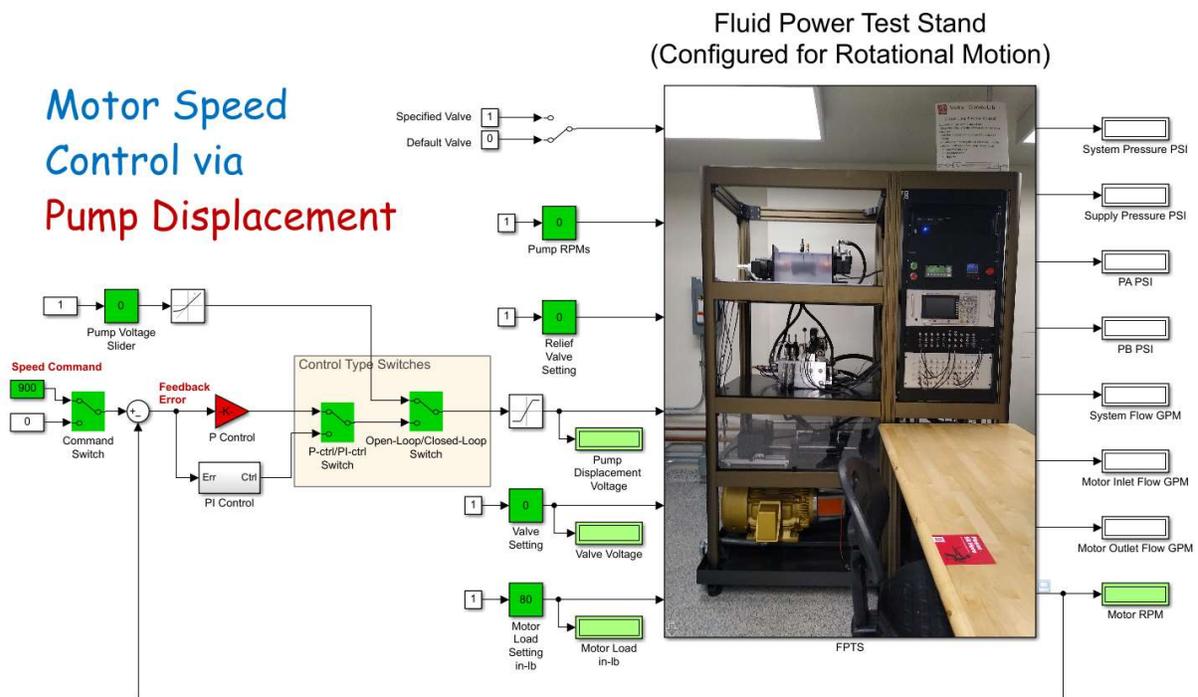


Figure 3. Pump-controlled simulation model that modulates motor speed via pump displacement.

The two forms of motor speed control depicted in Figures 2 and 3 provide the platforms for multiple potential experiments in fluid power and automatic controls. A few suggested experiments and analyses will be outlined here. Of these, some have already been the subject of our physical laboratory exercises (and simulated counterparts), and a few are now in planning stages for expanded utilization of the Motion Control Lab. Table 2 lists these existing and potential exercises for consideration. The procedure for the automatic controls experiments will be outlined in this document. The fluid power circuit experiments are relatively straightforward, and procedures are left to the reader to establish according to their preferences.

Experiments in Hydraulic Motor Speed Control

Course / Topic	Experiment	Outcomes
Automatic Controls	Motor Speed Control – Valve Actuation (existing exercise)	<p>Comparison of open loop control to closed loop P and PI controls. Students observe:</p> <ul style="list-style-type: none"> • progressively better performance as they progress from open loop to closed loop P and PI control • that P control requires an adjusted setpoint to achieve the target output speed because P control “requires an error to generate a signal” • that PI control can achieve zero steady-state error until the system saturates as the valve reaches its wide-open condition • the adverse effect of unmitigated “integrator windup” due to operating beyond saturation for some time without correcting the integrator signal
Automatic Controls	Motor Speed Control – Pump Actuation	<p>Opportunity for the students to see how changing the actuation can affect the disturbance sensitivity of a system. Students observe:</p> <ul style="list-style-type: none"> • that the motor speed is relatively impervious to load until the system reaches pressure and/or flow saturation
Fluid Power Circuits	Valve Metering	<p>Comparison of the flow characteristics of two valves with different dead zones (overlap) and sizing (flow capacity).</p> <ul style="list-style-type: none"> • Students record flow and pressure readings for various valve command voltages and generate metering curve(s) for the valve passages • Students experience the difference between overlapped and critically lapped valve spools
Fluid Power Circuits	Hydrostatic Drive Power Calculations	<p>Comparison of the efficiency of driving a motor via an open-circuit versus a closed-circuit configuration</p> <ul style="list-style-type: none"> • Students record circuit data for different motor loads under the two types of control actuation • Students calculate the component power consumption values and identify the fundamental differences in efficiency • Students ascertain how speed sensitivity is influenced by system configuration
Fluid Power Circuits	Fixed vs Variable Pump Drive Power	<p>REQUIRES MODIFICATION TO THE TOP-LEVEL MODEL.</p> <ul style="list-style-type: none"> • Students compare the motor speed performance efficiency of valve control using a fixed displacement pump versus a variable displacement pressure comp and/or load sense pump.

Table 2. Meaningful hydraulic motor speed control exercises.

5.1 Exercise: Motor Speed Control – Valve Actuation

The following instructions apply to the associated top-level Simulink model, the **Model**, provided in the MATLAB/Simulink file folder. The supporting protected model file is also required but cannot be opened. A MATLAB script, the **Script**, is used to initialize the model parameters. Both the **Model** and the **Script** may be customized at the discretion of the user. Use of modified versions of these files to extend their use and/or functionality is encouraged by the author but will not be supported as part of the delivered file package.

The delivered file package includes four files. The files used for this exercise are:

Model: VCM_Simulated_Mtr_Speed_Control.slx

Script: HydMtrCtrlSys_paramsV2.m

Protected Simulink model of the fluid power system: FPTS_VCMM_v3_21b.slxp

Procedure

- Run the specified **Script** to define the model parameter values (characterizes the model)
- Open the specified **Model**
- Run the model for the default run time (5 seconds) to verify it runs without errors
- When it stops, set the stop time to “inf” (so it runs indefinitely) and start the model again
- With the model running, double-click on the associated slider gain blocks (in green) and adjust
 - **Pump RPMs** to 1200
 - **Pump Displacement Voltage** until **System Flow GPM** reads about 7.5
 - **Relief Valve Setting** until **Supply Pressure PSI** (not system pressure) is about 1500

Side Note: Locate the two manual switches in the model that are in the shaded area labeled **Control Type Switches**. For the **Model** as received, these switches are set to use the **Valve Voltage Slider** to manually set the valve command for the open-loop speed test, so leave them “as is” for now. Later, for the closed-loop tests, you will select the other control options by double-clicking on these switches in turn for the P-control and PI-control tests, respectively.

- Open-loop speed test:
 - With the model still running, adjust the **Valve Voltage Slider** until **Motor RPM** reads approximately 900 (the precise value is not critical)
 - For the duration of this test, the valve voltage is kept constant while incrementally increasing the motor load torque using the associated slider block. At each steady-state operating condition, record the load torque, the motor speed, and the valve voltage. The latter is constant for this test but will be variable in the closed-loop control tests that follow. Starting with the minimum load:
 - Record the load torque, speed and voltage data at steady state
 - Using the **Motor Load Setting** slider, increase the load torque in approximately 20 in-lb increments, recording the same data at each load
 - Continue recording data for increasing loads until the recorded motor speed is below 700 rpm.
 - Quickly return the load torque to its minimum value and observe the response of the motor speed.
 - Use Excel or MATLAB to create two plots: speed vs load torque and valve voltage vs load torque. Load torque is the abscissa in both cases.

Experiments in Hydraulic Motor Speed Control

- Closed-loop speed test with proportional (P) control:
 - With the load restored to its minimum value, stop the model simulation.
 - Double-click on the right-most **Control Type** manual switch to activate the lower, closed-loop option for valve actuation. In this mode, the valve gets its voltage from either the P or the PI controller, depending on the status of the left-hand controller type switch.
 - With the switches set to connect the P-control output to the valve, start the simulation again.
 - With P-control, the voltage is set proportionally to the feedback error. Therefore, the system will not run at 900 rpm unless the feedback error is set artificially high to generate the required voltage. Mitigate this shortcoming by adjusting the **Speed Command** reference input from its 900-rpm default value to a higher value until the motor speed is about 900 rpm.
 - For the duration of this test, the **Speed Command** is kept constant while incrementally increasing the motor load torque using the associated slider block. At each steady-state operating condition, record the load torque, the motor speed, and the valve voltage. For this test, none of the recorded values will remain constant. Starting with the minimum load:
 - Record the load torque, speed, and voltage data at steady state
 - Increase the load torque in approximately 20 in-lb increments, recording the same data at each load
 - Continue recording data for increasing loads until the recorded motor speed falls below 700 rpm.
 - Quickly return the load torque to its minimum value and observe the response of the motor speed.
 - Add this new set of data to the two open-loop control data plots created previously so the performance of the two control types can be directly compared.
- Closed-loop speed test with proportional plus integral (PI) control:
 - With the load restored to its minimum value, stop the model simulation.
 - Double-click on the left-hand **Control Type** manual switch to activate the PI controller.
 - Set the **Speed Command** reference input back to 900 rpm.
 - With the switches set to connect the PI-control output to the valve, start the simulation again.
 - With PI-control, the voltage will be continually adjusted until the integral portion sees a zero steady-state error. This is why the reference input no longer has to be set artificially high. However, since it takes time for the integral control to make its adjustments, more time must be allowed for the system to reach steady state before data is collected.
 - For the duration of this test, the **Speed Command** is again kept constant while incrementally increasing the motor load torque using the associated slider block. At each steady-state operating condition, record the load torque, the motor speed, and the valve voltage. Starting with the minimum load:
 - Record the load torque, speed, and voltage data at steady state
 - Increase the load torque in approximately 20 in-lb increments, recording the same data at each load. If the preset limit in the load slider is reached, the range can be extended while the simulation is running by editing the constant input block connected to the slider to a multiplier higher than one. Then be sure to record the actual load from the display block, not the value set in the slider.
 - Continue recording data for increasing loads until the recorded steady-state motor speed falls below 700 rpm.

- Quickly return the load torque to its minimum value and observe the response of the motor speed. Now you should observe the motor running up to its top speed, not the set speed, because the integrator was continuing to “wind up” its signal while the actual signal was saturated at 10 V. This provides an opportunity to expose the students to integrator wind-up and discuss how it can be remedied in control system code. It may take a long time, but eventually the signal will integrate down below the saturation limit and the motor will return to its set reference speed.
- Once the system returns to the appropriate reference speed, stop the model. The model can now be closed if no further activity is desired.
- Add this new set of steady-state data to the two plots created previously to reveal the comparative performance of all three control types.

5.2 Exercise: Motor Speed Control – Pump Actuation

Like the previous exercise, the following instructions apply to an associated top-level Simulink model, the **Model**. For pump actuation a different model provided in the MATLAB/Simulink file folder is used. The supporting protected model file and the Script are also required. Again, except for the protected model, full customization is at the discretion of the user.

The **Script** and protected model used for this exercise are the same as those used for the valve-actuated procedure. The top-level model is a new one. The required files are:

Model: PCM_Simulated_Mtr_Speed_Control.slx

Script: HydMtrCtrlSys_paramsV2.m

Protected Simulink model of the fluid power system: FPT5_VCMM_v3_21b.slxp

Side Notes:

1. Ensure that the two manual switches in the model that are in the shaded area labeled **Control Type Switches** are set for manual control of the pump displacement. This sets the model up for an open-loop speed test.
2. Procedures for P and PI control will not be outlined here; they follow logically from the preceding valve-actuation examples. Furthermore, the open-loop test will reveal a reduced sensitivity to load with pump-actuation making closed-loop control less necessary, at least with the constant efficiency parameters defined in the model parameter script. The reader may choose to explore those options with more generous leakage coefficients parameter values for the pump and motor (parameters with “leakage” in the name).

Procedure

- If not already done, run the specified **Script** to define the model parameter values
- Open the specified **Model**
- Run the model for the default run time (5 seconds) to verify it runs without errors
- When it stops, set the stop time to “inf” (so it runs indefinitely) and start the model again
- With the model running, double-click on the associated slider gain blocks (in green) and adjust
 - **Pump RPMs** to 1200
 - **Pump Voltage** until **System Flow GPM** reads about 7.5
 - **Relief Valve Setting** until **Supply Pressure PSI** (not system pressure) is about 1500
 - **Valve Voltage Slider** to its maximum value (10 V)

Experiments in Hydraulic Motor Speed Control

- Reduce Pump Voltage until **Motor RPM** reads approximately 900 (the precise value is not critical)
- Open-loop speed test:
 - For the duration of this test, the **Pump Displacement Voltage** is kept constant while incrementally increasing the motor load torque using the associated slider block. At each steady-state operating condition, record the load torque, the motor speed, and the pump voltage. The latter is constant for this test and is observed only to make that point. Starting with the minimum load:
 - Record the load torque, speed, and voltage data at steady state
 - Increase the load torque in approximately 20 in-lb increments, recording the same data at each load
 - Continue recording data for increasing loads until the recorded motor speed falls below 700 rpm.
 - Quickly return the load torque to its minimum value and observe the response of the motor speed.
 - Stop the model. The model can now be closed if no further activity is desired.
 - Use Excel or MATLAB to create a plot of speed vs load torque. You may also wish to make a plot comparing the open-loop valve-actuation results to these for the pump-actuation test.

6. Sample Results

A sampling of results from the preceding test procedures run with the specified model parameters are presented below. Following these, a sample of representative analyses that more deeply explore the fluid power aspects of the speed tests are provided to exemplify how the simulated testing can augment discussions and analysis activities associated with hydraulic motor circuits.

6.1 Valve-Actuated Test Results

Table 3 presents the data collected from the simulated valve-actuated tests. For the proportional control test, the setpoint was adjusted to 2040 rpm to achieve the desired motor speed (near 900 rpm). For comparison, the results are plotted in Figure 4 on the next page. The closed-loop controls perform better than open-loop control because of using feedback to continually adjust the valve signal.

Open-Loop Control			Closed-Loop P Control			Closed-Loop PI Control		
Valve Signal (V)	Load Torque (in-lb)	Motor Speed (rpm)	Valve Signal (V)	Load Torque (in-lb)	Motor Speed (rpm)	Valve Signal (V)	Load Torque (in-lb)	Motor Speed (rpm)
5.7	80	909	5.7	80	905	5.6	80	900
5.7	102	868	5.8	100	884	5.9	104	900
5.7	121	831	5.9	119	863	6.1	121	900
5.7	141	789	6.0	140	838	6.5	141	900
5.7	162	744	6.1	160	811	6.9	163	900
5.7	182	697	6.3	180	780	7.3	182	900
			6.5	201	745	7.7	199	900
			6.7	221	705	9.0	221	900
			6.9	242	657	10	240	843 ⁽¹⁾
						10	260 ⁽²⁾	738
						10	281 ⁽²⁾	616
⁽¹⁾ PI control accurately achieves the set speed until the valve become completely open; there is no longer any opportunity for adjustment of the system speed. ⁽²⁾ Loads above 250 can be achieved by changing the slider limits or simply changing the constant input to the slider to a multiplier higher than 1.								

Table 3. Valve-actuated motor speed test data

Experiments in Hydraulic Motor Speed Control

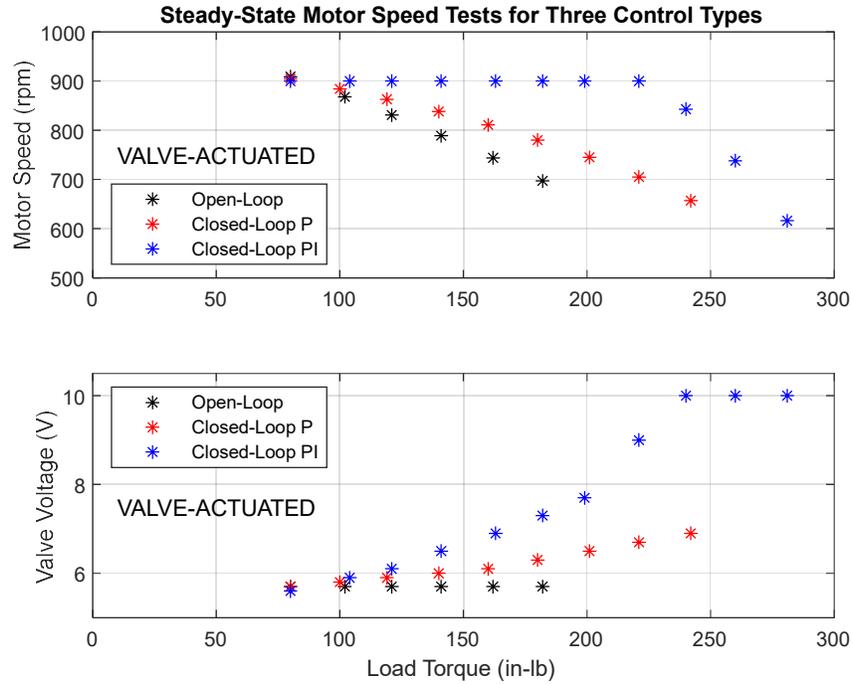


Figure 4. Comparison of control types under valve-actuated speed control.

6.2 Pump-Actuated Test Results

Table 4 presents the data collected from the simulated pump-actuated test. Only open-loop data is presented due to the lack of significant speed droop under load up to the point where the system power (pressure) is the limit. Figure 5 reveals the comparison of open-loop control performance under the two types of actuations.

Pump Signal (V)	Load Torque (in-lb)	Motor Speed (rpm)
3.95	80	902
3.95	111	902
3.95	141	902
3.95	172	901
3.95	201	901
3.95	230	901
3.95	260	758
3.95	291	571

Table 4. Pump-actuated open-loop motor speed control test data

Experiments in Hydraulic Motor Speed Control

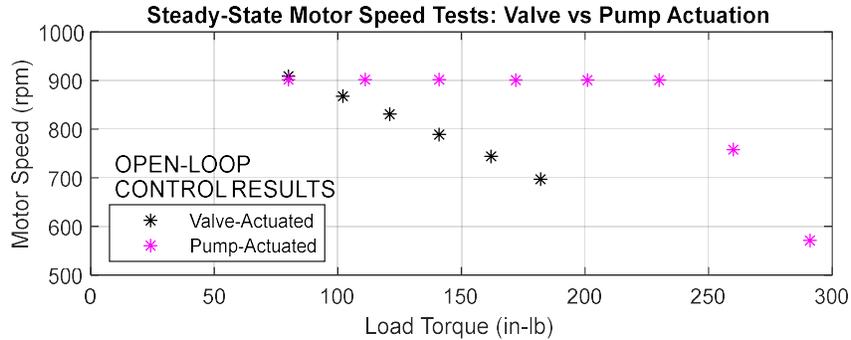


Figure 5. Comparison of open-loop speed control: valve-actuation vs. pump-actuation

6.3 Follow-up Circuit Analysis Examples

Example 1: Auxiliary data was collected during the open-loop valve-actuated experiment. Specifically, from the minimum load case recorded in Table 3, hydraulic circuit data was also collected:

Load torque: $T_L = 80$ in-lb Supply and work port pressures (psi): $P_V = 1488$ $P_A = 386.5$ $P_T = 30$

Motor inlet and outlet flows: $Q_{mi} = 6.635$ gpm $Q_{mo} = 5.905$ gpm

Test data such as this can be used with the known motor displacement to determine the valve flow coefficient and motor efficiencies. The same relationships used in the earlier circuit analysis example apply here. For example, the motor inlet flow is associated with the supply and work port A pressures:

$$Q_{mi} = K_{vp} \sqrt{P_V - P_A} \quad \Rightarrow \quad 6.635 \text{ gpm} \times (231/60) \text{ in}^3/\text{s}/\text{gpm} = K_{vp} \sqrt{1488 \text{ psi} - 386.5 \text{ psi}}$$

So, the powered land coefficient for the valve at the given voltage is

$$K_{vp} = 0.77 \text{ in}^3/\text{s}/(\text{psi})^{0.5}$$

The motor inlet and outlet flows provide the volumetric efficiency of the motor:

$$\eta_{vm} = \frac{Q_{mo}}{Q_{mi}} = \frac{5.905}{6.635}$$

$$\eta_{vm} = 0.89 = 89\%$$

Finally, the motor torque equation leads to the mechanical (torque) efficiency of the motor:

$$T_L = \eta_{Tm} \frac{D_m}{2\pi} \cdot \Delta P_m \quad \Rightarrow \quad 80 \text{ in-lb} = \eta_{Tm} \frac{1.5 \text{ in}^3/\text{rev}}{2\pi \text{ rad/rev}} \cdot (386.5 \text{ psi} - 30 \text{ psi})$$

$$\eta_{Tm} = 0.94 = 94\%$$

Of course, these parameters match those used in the model, but such an exercise could be assigned to the students to reinforce their understanding of the circuit.

Example 2: The final open-loop data point will now be used in a complimentary analysis to illustrate the ability to predict motor speed. For that last load point, the recorded data was:

$$T_L = 182 \text{ in-lb} \quad P_v = 1488 \text{ psi} \quad P_T = 30 \text{ psi}$$

Under these conditions, and using the valve coefficient and motor efficiencies determined above,

$$T_L = \eta_{Tm} \frac{D_m}{2\pi} \cdot \Delta P_m \quad \Rightarrow \quad 182 = 0.94 \frac{1.5}{2\pi} (P_{mi} - 30) \quad \Rightarrow \quad \boxed{P_{mi} = 841 \text{ psi}}$$

$$Q_{mi} = K_{vp} \sqrt{P_v - P_A} \quad \Rightarrow \quad Q_{mi} = 0.77 \sqrt{1488 - 841} \quad \Rightarrow \quad \boxed{Q_{mi} = 19.59 \text{ in}^3/\text{s}}$$

$$Q_{mi} = \frac{1}{\eta_{vm}} \frac{D_m N_m}{60} \quad \Rightarrow \quad 19.59 = \frac{1}{0.89} \frac{1.5 N_m}{60} \quad \Rightarrow \quad \boxed{N_m = 697 \text{ rpm}}$$

These results match those observed in the system under that load condition.

7. Summary

The forgoing discussion and examples are intended to be used as presented and/or modified at the discretion of the reader to generate educational exercises employing simulated experiments and/or analysis activities related to the hydraulic motor circuit as presented. As an aid to developing such user-defined assignments for their students, a separate MS-Word document of the core sections of this document is provided and permission is granted for this document and the associated MATLAB and Simulink files to be used to spawn customized off-shoot assignments, with appropriate acknowledgments to the source.

If you find these resources to be valuable, the author would also welcome feedback on potential improvements and enhancements that might be appreciated in the future. By way of example, the other mode of operation of the test stands at MSOE is hydraulic cylinder position control. Simulated experiments in valve-controlled cylinders would be a logical extension to this present work.

8. Appendix – Default Model Parameters (MATLAB Scripts)

As delivered, most of the model parameters are defined in either of the two provided MATLAB scripts, giving the user full access to customizing the parametric characterization of the valve-controlled hydraulic motor system. The scripts are included here for convenience.

The first script:

```
% -----
% HydMtrCtrlSys_paramsV1.m
% Edited by D. Williams 19-May-2022
% -----

FluidProp = struct;
FluidProp.Air_0tol = 0.005;
FluidProp.BulkModulus_psi = 220000;
FluidProp.VaporPressure_psi = 0.5;

Motor = struct;
Motor.Displacement_in3 = 1.5;
Motor.VolumetricEff_0tol = 1;
Motor.TorqueEff_0tol = 0.96;
Motor.LeakageCoeff_in3perpsisec = 0.0005;
Motor.Inertia_inlbsec2 = 0.01;
Motor.Damping_inlbsec = 0;
Motor.InitialSpeed_rps = 0;

MotorInletVolume = struct;
MotorInletVolume.Init_psi = 50;
MotorInletVolume.Volume_in3 = 100;

MotorOutletVolume = struct;
MotorOutletVolume.Init_psi = 50;
MotorOutletVolume.Volume_in3 = 100;

Pump = struct;
Pump.MaxDisplacement_in3 = 1.7;
Pump.VolumetricEff_0tol = 0.95;
Pump.Max_rpm = 1200;
Pump.LeakageKv = 0.005;
Pump.SequencePressure_psi = 350;

ReturnPressure_psi = 30;

SupplyVolume = struct;
SupplyVolume.Init_psi = 50;
SupplyVolume.Volume_in3 = 100;

SystemVolume = struct;
SystemVolume.Init_psi = 50;
SystemVolume.Volume_in3 = 100;

% Metering curve for user-specified valve
Valve1 = struct;
Valve1.voltages = [-10 1.5 4 9 10];
Valve1.Kvs = [0 0 0.1 0.8 0.8];
```

Experiments in Hydraulic Motor Speed Control

The second script:

```
% -----  
% HydMtrCtrlSys_paramsV2.m  
% Edited by D. Williams 30-June-2022 (for efficiency calculations)  
% -----  
  
FluidProp = struct;  
FluidProp.Air_0tol = 0.005;  
FluidProp.BulkModulus_psi = 220000;  
FluidProp.VaporPressure_psi = 0.5;  
  
Motor = struct;  
Motor.Displacement_in3 = 1.5;  
Motor.VolumetricEff_0tol = 0.89;  
Motor.TorqueEff_0tol = 0.94;  
Motor.LeakageCoeff_in3perpsisec = 0.00;  
Motor.Inertia_inlbsec2 = 0.01;  
Motor.Damping_inlbsec = 0;  
Motor.InitialSpeed_rps = 0;  
  
MotorInletVolume = struct;  
MotorInletVolume.Init_psi = 50;  
MotorInletVolume.Volume_in3 = 100;  
  
MotorOutletVolume = struct;  
MotorOutletVolume.Init_psi = 50;  
MotorOutletVolume.Volume_in3 = 100;  
  
Pump = struct;  
Pump.MaxDisplacement_in3 = 1.7;  
Pump.VolumetricEff_0tol = 0.95;  
Pump.Max_rpm = 1200;  
Pump.LeakageKv = 0.005;  
Pump.SequencePressure_psi = 350;  
  
ReturnPressure_psi = 30;  
  
SupplyVolume = struct;  
SupplyVolume.Init_psi = 50;  
SupplyVolume.Volume_in3 = 100;  
  
SystemVolume = struct;  
SystemVolume.Init_psi = 50;  
SystemVolume.Volume_in3 = 100;  
  
% Metering curve for user-specified valve  
Valve1 = struct;  
Valve1.voltages = [-10 1.5 4 9 10];  
Valve1.Kvs = [0 0 0.1 0.8 0.8];
```