# List of Symbols

|  |  |  |
| --- | --- | --- |
| **Symbol** | **Units** | **Description** |
| CLm | in3/s/psi | Motor leakage coefficient |
| Dp, Dm | in3/rev | Pump and motor volumetric displacements, respectively |
| Kv | in3/s/(psi)1/2 | Various valve and leakage coefficients |
| Np, Nm | rpm | Pump and motor shaft speeds, respectively |
| PA, PB, or Pmi | psi | Valve work port pressure (A or B) equal to the motor inlet pressure |
| Pmo or PT | psi | Motor outlet pressure equal to the return pressure due to filtering, etc. |
| Ps | psi | System pressure at the pump outlet |
| Pv | psi | Valve supply pressure downstream of the sequence valve |
| ΔPm | psi | Motor pressure differential associated with the load torque |
| ΔPpL | psi | Directional control valve (DCV) powered land pressure differential |
| ΔPsv | psi | Sequence valve pressure differential |
| Qmo | in3/s | Motor outlet flow that returns to the reservoir |
| Qp | in3/s | Net flow delivered by the variable displacement pump |
| QpL = Qmi | in3/s | Motor inlet flow equal to the flow across the powered land of the DCV |
| QLp, QLm | in3/s | Pump and motor leakage flows, respectively |
| TL | in⋅lb | Motor load torque |
| vp, vrv, vdcv | V | Control signals for the pump, relief valve and DCV, respectively |
| ηvp, ηvm | — | Volumetric efficiencies of the pump and motor, respectively |
| ηTm | — | Mechanical (torsional) efficiency of the motor |

# 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.

Diagram, schematic

Description automatically generated

**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.

|  |  |  |
| --- | --- | --- |
| **Item** | **Description** | **Default Model Parameters** |
| A | **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. | Displacement, Dp,max = 1.70 in3/rev  The actual displacement is Dp = (vp/5) Dp,max, where vp is the 0-5V pump command signal  Volumetric Efficiency, ηvp = 95%  Leakage Coefficient, KvLp = 0.005 (in3/s)/(psi)1/2  Maximum Speed, Np,max = 1200 rpm |
| B | **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. | Threshold Pressure, PSV = 350 psi  Flow coefficient, Kvsv = 10 (in3/s)/(psi)1/2 |
| C | **Pressure Relief Valve**  In place to set operating pressure and to protect the system from excessive pressures. | Cracking Pressure, PRV = 550\*vrv, where vrv is the 0-5V relief valve command signal  Flow coefficient, Kvrv = 10 (in3/s)/(psi)1/2 |
| D | **Directional Control Valve**  A switch in the model allows the selection of this valve (default) or a user-defined option. | Metering Curve (X-Y lookup table) interpolated to obtain Kvdcv  X (voltages): [ -10 0.34 8 9.64 10 ] (V)  Y (valve coefficients): [ 0 0 1.1 1.2 1.2 ] (in3/s)/(psi)1/2) |
| E | **Hydraulic Motor**  The load pump circuit is not explicitly modeled. Rather the load pump torque (ideal) is directly set in the simulation model. | Displacement, Dm = 1.5 in3/rev  Torque Efficiency, ηTm = 96%  Leakage Coefficient, CLm = 0.0005 (in3/s)/(psi)  Load Torque, TL = adjustable; opposing  The load torque cannot drive the motor backwards due to its resistive nature from back pressure which depends on positive motor speed. |
| - | Return Pressures | Tank port pressure for all returning fluid: PT = 30 psi |
| **Table 1**. Modeled motor circuit components and default model parameters. | | |

# Circuit Analysis Example

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

Ps = 1249 psi Pv = 896 psi Pmi = 510 psi Pmo = PT = 30 psi

Np = 1200 rpm vp = 2.5V vrv = 2.5V vdcv = 6.0V TL = 110 in-lb

**NOTE:** In the following analysis, the pressure-flow relationship for valve coefficients is the empirical one based on the orifice equation: Q = KvΔ, from which the pressure differentials are obtained:

ΔP = (Q/Kv)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:

Ps = PT + ΔPm + ΔPpL + ΔPsv

The breakdown of these pressure differentials follows:

**Return pressure**, PT (given): PT = 30 psi

**Motor differential pressure**, ΔPm:

ΔPm = 2π⋅TL /(ηTm⋅Dm) = 2π(110)/(0.96)(1.5) ΔPm = 480 psi

**Motor inlet pressure**, Pmi:

Pmi = PT + ΔPm = 30 + 480 Pmi = 510 psi ✓

**Valve differential pressure of the powered land**, ΔPpL (requires flow computation):

Motor inlet flow, Qmi (ideal flow plus leakage):

Qmi = Dm⋅Nm/60 + CLm⋅Pmi = (1.5)(629.4)/60 + (0.0005)(510) Qmi = 16.0 in3/s

DCV flow coefficient, Kvdcv (for vdcv = 6.0V, by interpolation):

Kvdcv = 0 + (1.1-0)(6.0-0.34)/(8.0-0.34) Kvdcv = 0.8128 in3/s)/(psi)1/2

ΔPpL = (Qmi/Kvdcv)2 = (16.0/0.8128)2 ΔPpL = 387 psi

**Valve supply pressure**, Pv:

Pv = PT + ΔPm + ΔPpL = 30 + 480 + 387 Pv = 897 psi ✓

**Sequence valve differential pressure**, ΔPsv:

ΔPsv = PSV + (Qmi/Kvsv)2 = 350 + (16.0/10)2 ΔPsv = 353 psi

**Pump outlet (system) pressure**, Ps:

Ps = PT + ΔPm + ΔPpL + ΔPsv = 30 + 480 + 387 + 353 Pv = 1250 psi ✓

Figure 2 contains a screen shot of the simulation model under the steady-state operating conditions analyzed in the preceding example. For this condition, the model was run in its open-loop control mode. A manual switch in the model allows it to be configured for closed loop control as well and, under that mode, a second switch is used to opt for P or PI control. A third manual switch allows for the selection of a second directional control valve with user-defined flow properties.

Diagram

Description automatically generated

**Figure 2**. Valve-controlled simulation model under the conditions portrayed in the analysis example.

# 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.

Graphical user interface

Description automatically generated

**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.

|  |  |  |
| --- | --- | --- |
| **Course / Topic** | **Experiment** | **Outcomes** |
| Automatic Controls | Motor Speed Control – Valve Actuation  (existing exercise) | Comparison of open loop control to closed loop P and PI controls. Students observe:   * 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 | Opportunity for the students to see how changing the actuation can affect the disturbance sensitivity of a system. Students observe:   * that the motor speed is relatively impervious to load until the system reaches pressure and/or flow saturation |
| Fluid Power Circuits | Valve Metering | Comparison of the flow characteristics of two valves with different dead zones (overlap) and sizing (flow capacity).   * 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 | Comparison of the efficiency of driving a motor via an open-circuit versus a closed-circuit configuration   * 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 | REQUIRES MODIFICATION TO THE TOP-LEVEL MODEL.   * 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.
* 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 that 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: FPTS\_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)
  + 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.

# 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.

## 5.1 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 | | | | | | | | |



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

## 5.2 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 | | |



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

## 5.3 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 ⇒ 6.635 gpm x (231/60) in3/s/gpm = *K*vp

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

*K*vp = 0.77 in3/s/(psi)0.5

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

*η*vm = =

*η*vm = 0.89 = 89% 

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

*T*L =*η*Tm π⋅Δ*P*m ⇒ 80 in-lb = *η*Tm π⋅(386.5 psi – 30 psi)

*η*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 in-lb *P*v = 1488 psi *P*T = 30 psi

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

*T*L =*η*Tm π⋅Δ*P*m ⇒ 182 = 0.94π(*P*mi – 30) ⇒ *P*mi = 841 psi

*Q*mi = *K*vp ⇒ *Q*mi = 0.77 ⇒ *Q*mi = 19.59 in3/s

*Q*mi = *η* ⇒ 19.59 = ⇒ *N*m = 697 rpm

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