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A Dynamic Performance Evaluation of Fueling Machine Heavy Water Supply System with PID Controller

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Abstract

The dynamic performance of the Fueling Machine (F/M) Heavy Water (D_2O) supply system for Wolsong Nuclear Power Plant (NPP) Unit 1 was evaluated using Modular Modeling System (MMS) computer code. The analyses were performed for selected parameters to identify a dominant contributor to the dynamic behavior of common header pressure during the supply mode changes. The results show that the position change rate of series valve is one of the most dominant factors that affect a common header pressure performance. The set pressure change rates of supply and magazine also result in a dominant effect on the dynamic performance of common header pressure. The results also show that the common bleed valve goes to the full closed position regardless of the parameter variations during the supply mode changes. The introduction of a lower position limit in the common bleed valve is effective without any adverse effect on the system performance in avoiding the full closure of the valve during the supply mode changes.

1. Introduction

The F/M D_2O supply system regulates the pressure of D_2O to two F/M D_2O system valve stations at a selected mode of three supply pressure modes. The existing control system of the F/M D_2O supply system for Wolsong NPP Unit 1 is based on an analog cascaded proportional-integral-differential (PID) control. A PID controller is a hardware module used widely in the control system to control the process parameter to the target value. The analog control system has many electronic devices and requires much effort to set up the system during the system calibration. The recent development of the digital control technology draws much interest in system design and maintenance. In addition, a digital controller has much flexibility in changing the control logic. To alleviate the effort during system operation and maintenance and to improve the system performance, a new digital control system can be an option to replace the existing analog control system of the F/M D_2O supply system for Wolsong NPP Unit 1. The F/M D_2O supply system of Wolsong NPP Units 2, 3 and 4 already adopted digital PID controls.

The operating experience has shown that the large overshoot of common header pressure sometimes challenges the pressure setpoint of system relief valve installed to protect the system overpressure and may cause a heavy water leakage. However, it is quite difficult to identify the dominant factor that affects the common header pressure behavior during the on-line system operation and maintenance.

The operating experience has also shown that the common bleed valve in the F/M D_2O supply system goes to the full closed position during the either direction supply pressure mode change during one pump operation. This undesirable valve performance is experienced in both existing analog type and the digital control of the F/M D_2O supply systems. The full closed state in the common bleed valve may give a damage to its valve seat and is not desirable during the system operation. To resolve the problem, it needs much effort in the F/M D_2O supply system parameter settings during the on-line system operation and maintenance.

The various analyses with selected parameter variations were performed to identify a parameter causing a dominant effect on the dynamic behavior of common header pressure. The identified parameter will help minimize the common header pressure peak. The analyses also were performed to find a proper parameter setting to minimize or prevent the full closure of the common bleed valve. In addition, introduction of a lower position limit in the common bleed valve was analyzed as one of the means to prevent the full closure of the common bleed valve. The off-line dynamic evaluation of the F/M D_2O supply system will be useful to relieve system operators' burdens during the on-line system operation. And the quantitative results will also provide a starting point in the new control system parameter settings.

2. Analysis Method

2.1 System Description

The F/M D_2O supply system regulates the pressure of D_2O to two F/M D_2O system valve stations at a selected mode of three supply pressure modes (HIGH, MEDIUM, and LOW). The F/M D_2O system valve stations regulate the D_2O flow to maintain the required F/M pressure in various modes of operation at a mode of four magazine pressure modes (HIGH, INTERMEDIATE, PARK, and LOW) which is interfaced with the F/M D_2O supply pressure mode.

The D_2O is drawn from the primary heat transport system storage tank through the positive displacement pumps (PDPs). During normal operation, only one pump is in use, the second pump acting as a standby. Each pumping circuit is identical and each pump can provide a minimum flow of 72 gpm at pressures of up to 2700 psig. The relief valves are installed around the pump to limit pump output pressure to 2700 psig (18.62 MPa (g)).

The interconnection line from the two pumps serves as the take-off point for the line to the common bleed valve. The series and load shunt valves in each subsystem perform the basic pressure control function for the D_2O supply to each of two fueling machines. The common bleed valve serves as a decoupling mechanism between two-subsystem output supplies so that a major disturbance in one subsystem will not seriously affect the other. The common and load shunt valves bypass the excess D_2O to the pump inlet through bypass cooler.

Three automatic pressure controllers are provided for the F/M D_2O supply system. One is for the common bleed valve control and the others are for the series and load shunt valves control of each D_2O supply channel. Each controller functions independently to maintain its associated system output pressure. The setpoints for each controller are set independently, either manually on the control console subpanel or automatically by the fuel handling system control computer.

Pressure control is achieved by simultaneously adjusting the series and load shunt valves so as to produce a pressure division chain somewhat analogous to a potentiometer in electrical circuitry. The series valve acts as a throttling valve, passing a little more flow than that drawn by the load (F/M D_2O system), and reducing the pressure to the appropriate level. The load shunt valve acts as a bleed valve to drain the portion of the flow not required by the load, and to ensure that the output pressure stays at preset value regardless of routine fluctuations of the load flow.

Provision is also included for regulation of the common header pressure. The common bleed valve is controlled to hold the common header pressure at a preset value. This serves as a decoupling mechanism between two outputs supplies so that a major disturbance in one system will not seriously affect the other, and so that stability of control is not seriously impaired by interactions between two systems. It is also helpful to attenuate the disturbances imposed upon the system when the second pump in the system is started or stopped.

The F/M D_2O system regulates the pressure and flow of D_2O supplied to the F/M head and its hydraulic actuators. The F/M D_2O supply system supplies D_2O at one of three pressure levels. The D_2O from the supply system reaches the F/M via its valve station and a catenary system, which is a set of hoses to allow the F/M movement necessary to complete its tasks. At the valve station the D_2O supply splits in two: one line for the actuator control circuit and the other for magazine control circuit. The magazine circuit controls the pressure and temperature conditions in the F/M Head magazine while the actuator circuit controls ram actuation, feelers, retractors, stops and seals supply. The actuator circuit is referenced to magazine pressure via the magazine pressure sense line. A pneumatically actuated control valve located in the magazine return line controls the magazine pressure. The associated pressure controller sets up the desired pressure condition with a feedback signal from the pressure transmitter in the magazine pressure.

2.2 Analysis Model and Assumptions

The MMS computer code has been widely utilized in evaluating the coupled responses of process systems and the associated control systems. The MMS computer code has a capability to evaluate the thermal hydraulic responses of process systems and to simulate a various control systems including a PID controller.

The F/M D_2O supply system and the part of the magazine pressure control circuit of the F/M D_2O control system are modeled for MMS code simulation. Figure 1 shows the modeled process system boundary. The Figure 2 shows the corresponding MMS computer code model. The positive displacement pump is modeled as a flow boundary. The flow boundary is to supply a minimum of 72 gpm of heavy water. The several piping sections upstream and downstream of each valve are neglected because their associated pressure losses are below 1 psid. The interconnection line between the two subsystems is also neglected because its pressure drop is about 3 psid. The pressure losses of other resistant devices such as check valves and filters are included in the piping pressure loss for simplicity.

The valve station model includes the flow path to the fueling machine magazines. This model allows the valve station boundary to follow the magazine pressure that is controlled by the F/M D_2O control system. The magazine pressure serves as a pressure boundary during the supply system mode change. The exit boundaries of common bleed and load shunt valves are modeled as a pressure boundary of 70 psig. This is consistent with the actual pressure experienced in the low pressure return line system.

All the valves have a pneumatic actuator and an associated controller. The series valve control is based on a open loop control with multiple preset valve positions depending on supply pressure mode and the others are based on a PID control with a feedback from the associated process variable. Each series valve receives position demand signal from the supply pressure control block. The common bleed, load shunt and magazine pressure control valves receive each position demand signal from the associated PID controller. The control code block supplies the required process variable, setpoint, and other control strategy to the controllers. Figure 3 shows the valve data based on the Wolsong NPP Unit 1. The used time constants of pneumatic actuators were 4.0, 4.5 and 1.0 sec for the common bleed valve, the series and load shunt valves and the magazine pressure control valves respectively.

The dynamic behaviors were evaluated only during the change between HIGH and MEDIUM supply modes because the common header pressure behavior is dominant during these mode changes. The set pressures and series valve target positions at each supply mode are shown in Table 1. Table 2 shows the major control system parameters.

3. Results and Discussion

3.1 Pump Supply Flow

The effect of the pump supply flow on common header pressure behavior needs to be investigated because of the following points.

(1) The operating experience has shown that the common bleed valve in the F/M D_2O supply system goes to the full closed state during the either direction pressure mode change between HIGH and MEDIUM supply modes during one pump operation. This is concerned with the valve controllability. The flow rate through the common bleed valve is typically about 24 % of the series valve.

(2) The D_2O supply pump has a capability of providing a minimum flow of 72 gpm at pressure of up to 2700 psig. The actual flow, however, is not measurable because there is no flow measurement device. The operating data shows indirectly that the supplied flow is a little above 72 gpm.

Analyses were performed four pump supply flow conditions: 95%, 100%, 110%, and 120% design flow of 72 gpm. The HIGH to MEDIUM supply mode change is initiated at the beginning and completes at about 50 sec. The MEDIUM to HIGH supply mode change is initiated at 150 sec after the stabilization.

Figures 4 through 6 show the common bleed valve position, common header pressure, and supply pressure for various pump supply flow conditions during the supply mode change. Figure 4 shows that the common bleed valve goes to the full closed position over all the analyzed flow conditions and that the pump supply flow affects the steady state valve position. Figure 5 shows the common header pressure behavior. The larger pump supply flow shows the larger pressure peak in the common header pressure during the either direction mode change while it gives the smaller pressure dip during the mode change. Figure 6 shows the supply pressure behavior for the pump supply flow conditions. The supply pressure behavior is little affected by the pump supply flow because the extra flow is bled through the load shunt valves.

3.2 Series Valve Position Change Rate

A preset open loop control to the target position is employed to the series valve. The series valve position decreases (closing) during the HIGH to MEDIUM mode change but increases (opening) during the MEDIUM to HIGH mode change. The series valve position demand is changed at a preset rate. Figures 7 through 11 shows the results for five valve position change rates. The results show that the series valve position change rate is one of the most dominant parameters that affect a common header pressure performance.

Figure 7 shows that the pressure dip always occurs at the first stage of the transient over the analyzed position change rates of the series valve. During the HIGH to MEDIUM mode change, the common header pressure drops at the initial stage of the transient because of the increased flow rate through the series valve. At this stage the flow rate through the series valve increases in spite of the valve closing because of the increase in the applied pressure drop across the valve. The increase in the flow rate across the valve is much more due to the increase in the applied pressure drop than the decrease in the flow rate due to the valve closing. The flow rate is more sensitive to the increase in the applied pressure drop across the valve than the decrease in the valve closing in the higher valve position at which the existing pressure drop is quite small. The common header pressure begins to recover below a position at which the series valve is closed enough to give a dominant effect on the flow rate through the valve. Figure 8 shows the flow rate through the series valve for various position change rate of the series valve.

During the MEDIUM to HIGH mode change, the common header pressure also drops at the initial stage of the transient because of the increased flow rate through the series valve. At this stage the flow rate through the series valve increases because the valve opening dominates over the decrease in the applied pressure drop while the series valve is in the lower position. The flow rate is more sensitive to the valve opening in the lower position because of large pressure drop across the valve as shown in Figure 8. The common header pressure begins to recover above a position at which the series valve is opened enough for the flow rate to be more sensitive to the decrease in the applied pressure drop at the given pressure drop across the valve.

Figure 7 shows that the higher change rate gives the first less pressure dip and the second larger pressure peak during the HIGH to MEDIUM mode change and the reverse results during the MEDIUM to HIGH mode change. Figure 7 also shows that the transient completion time is getting shorter during the HIGH to MEDIUM mode change while nearly the same during the second MEDIUM to HIGH mode change as the position change rate of the series valve increases. The results indicate nearly the same behavior over the first stage of the transient regardless of the position change rates of the series valve. However, the behavior is getting different below a certain position of the series valve. This means that the common header pressure and the transient completion time are mainly governed by the series valve change rate rather than the supply and magazine pressure change in the lower valve position range. This can account for the nearly same transient completion time during the MEDIUM to HIGH mode change. At the first stage the initial series valve position is quite low and its change more affects the common header pressure than the supply pressure change does.

Therefore, the transients complete nearly at the same time regardless of the position change rate because the supply and magazine pressure change dominates near the transient completion time and is little affected by the position change rate of the series valve as shown in Figure 9. The level of common header pressure dip and peak and transient completion time is well accounted for by the fact that the larger position change rate of the series valve gives the faster attainment to a position at which the valve position change effect is dominant or not dominant.

Figure 9 shows that the supply and magazine pressure behavior is little affected by the position change rate of the series valve. This means that the supply and magazine pressures are well controlled by the load shunt and the magazine pressure control valves.

Figure 10 shows that the larger series valve position change rate does not lead to the full closure of the common bleed valve during the first HIGH to MEDIUM mode change. The larger change rate, however, leads to the full closure of the common bleed valve during the second MEDIUM to HIGH mode change. This contradictory result gives the difficulty in choosing the appropriate position change rate of the series valve to avoid the full closure of the common bleed valve. Therefore, the series valve position change rate needs to be selected considering the two factors: the common bleed valve closure and the pressure peak.

Figure 11 shows that the common header pressure behavior with the common bleed valve position limited at 10 % to avoid the full closure. The result shows that the common header pressure is similar to that of no lower position limit. The lower position limits of the common bleed valve produces slightly larger pressures dip than that without position limit. The slightly lower common header pressure reduces the flow rate through the series valve, which results in the controlled condition of the supply target pressure. The other parameters showed nearly the same behavior as that of no lower position limit. This indicates that the lower position limit is effective to prevent the full closure of the common bleed valve during the mode change.

3.3 Supply and Magazine Set Pressures Change Rate

The supply flow to the valve station is desirable to be maintained constant during the mode change. This is achieved by setting the same change rate for the supply and the magazine set pressures. Figure 12 shows the common header pressure behavior for the various change rates of the supply and magazine set pressures. The larger change rate shows the first larger pressure dip and the smaller pressure peak during the HIGH to MEDIUM mode change and the reverse during the MEDIUM to HIGH mode change. The pressure peak during the first mode change is much larger than that during the second mode change. The results also show that the set pressure change rate (resultantly supply pressure) dominates in the higher position rather than the lower position of the series valve from the point of common header pressure behavior. In the higher valve position, the flow rate through the valve is more sensitive to the increase in the applied pressure drop than the valve position change. Therefore, the more flow rate through the valve brings the larger decrease in the common header pressure. The larger change rate of set pressure turns out to be suitable to minimize the common header pressure peak.

Figure 13 shows that the change rate of set pressures governs supply and magazine pressure behaviors during the mode change. The four upper lines are supply pressures and the four lower lines are magazine pressures. The slower change rate shows a pressure perturbation during the mode change. This is considered mainly due to the large proportional gain of the load shunt valve controller at the associated set pressure change rate. Figure 14 shows that the common bleed valve closures happen regardless of the set pressure change rates.

3.4 Common Bleed Valve Time Constant and Pressure Controller Gain

The common header pressure peak is critical in the system overpressure protection. To identify another factors to minimize the pressure peak, some analyses were performed for the actuator time constants and the pressure controller gain of the common bleed valve.

Figure 15 shows that the smaller time constant gives the smaller pressure peak and dip. This is because the smaller time constant gives the faster response to the valve position demand. Figure 16 shows the pressure peak behavior for the proportional gain. The smaller PB means the larger proportional gain. The larger proportional gain shows the smaller pressure peak. This means that the proportional gain can be one of the controllable factors in minimizing the common header pressure peak.

4. Conclusion

The dynamic performance of the F/M D_2O supply system for Wolsong NPP Unit 1 was evaluated using MMS computer code. From the study, the following conclusions are obtained:

(1) The pump supply flow affects only the steady state position of the common bleed valve and the common header pressure peak.

(2) The common header pressure behavior is mainly governed by the position change rate of series valve and the set pressure change rates of supply and magazine.

(3) The common bleed valve full closure during the mode change occurs regardless of the parameter settings: pump supply flow, series valve change rate, and supply and magazine set pressure change rates.

(4) The behavior of the supply and magazine pressures is mainly governed by the set pressure change rates.

(5) The lower position limit in the common bleed valve is one of the means to avoid the full closure of the valve without adversely affecting the system performance.

(6) The smaller valve time constant and the larger controller proportional gain in the common bleed valve gives the smaller pressure peak and the pressure dip during the mode change.

The full closure of the common bleed valve can be avoided by placing a lower position limit without adverse effect on the system performance. Another important thing to be considered is that the common header pressure peak is critical in the system overpressure protection. The proper selection of actuator time constant and the pressure controller gain of the common bleed valve minimizes the common header pressure peak. The suitable selection of the series valve change rate also helps minimize the common header pressure peak. Further study will focus on the analysis of a dual mode in common header pressure to minimize the pressure peak, which is to lower the common header set pressure at the lower supply pressure modes.

Acknowledgement

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References

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[2] Guy Borden and P. G. Friedmann, Control Valves: Practical Guides for Measurement and Control, Instrument Society of America, 1998.

[3] F. M. White, Fluid Mechanics, McGraw-Hill, Inc., 1979.

Table 1. Supply and Magazine Set Pressures and Series Valve Position (Base Case)

Mode	Set Pressure (psig)			Series Valve Position (% opening)
	Common	Supply	Magazine	
HIGH	2,450	2,300	1,650	87.5
MEDIUM		1,100	450	56.0

Table 2. PID Controller Settings (Base Case)

Parameter	Common Valve	Load Shunt Valve	Magazine Control Valve
Proportional Gain (%/MPa)	4.167	3.846	6.25
Integral Gain (%/MPa/sec)	1.389	0.916	5.952
Setpoint Change Rate (MPa/sec)	N/A	± 0.2	± 0.2
Control Zone (MPa)	0	0	0
1) Series valve position change rate = ±1% /sec. 2) Differential gain in PID controller is not applied.			

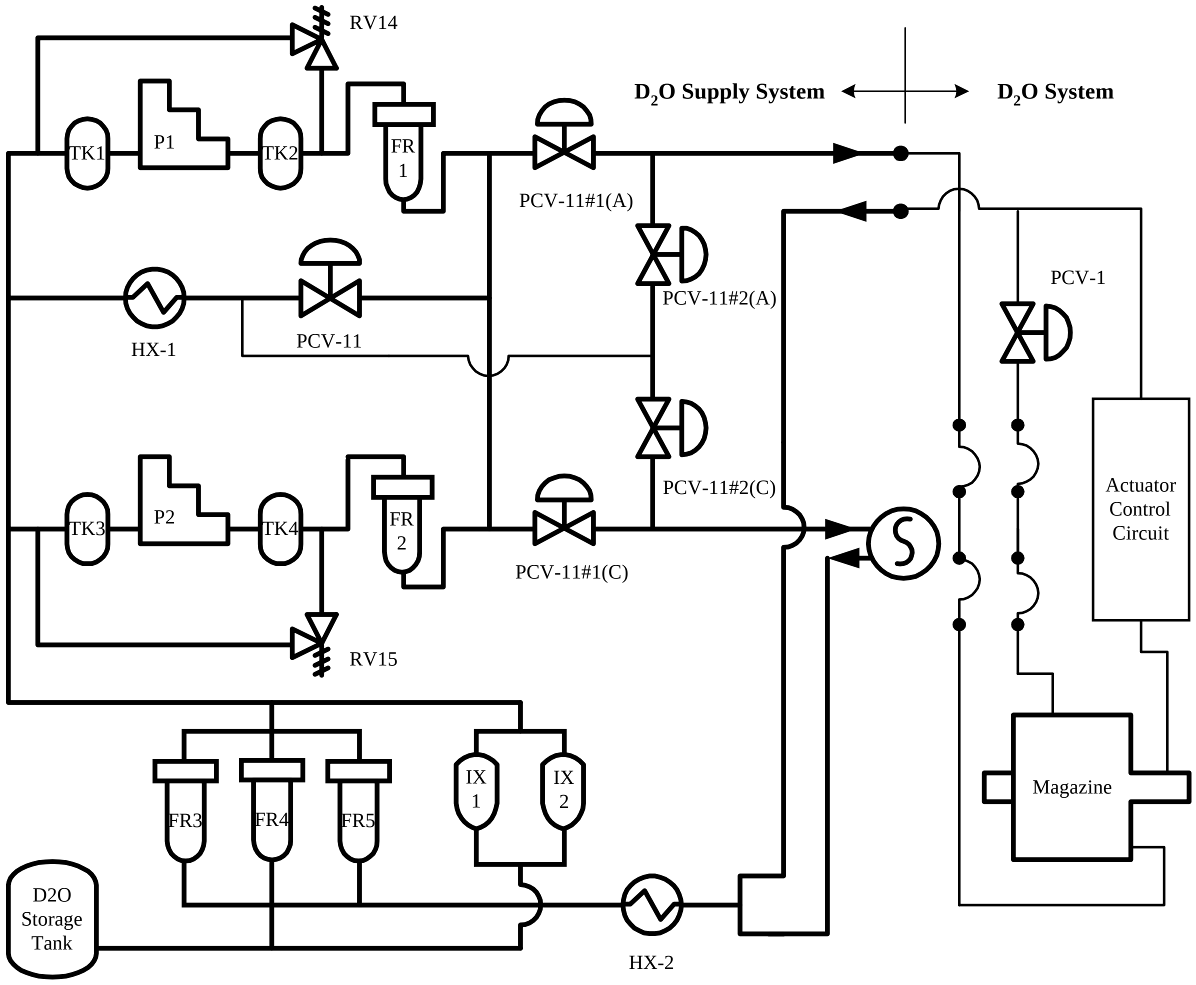

Figure 1. Schematic of F/M D_2O Supply System and D_2O System

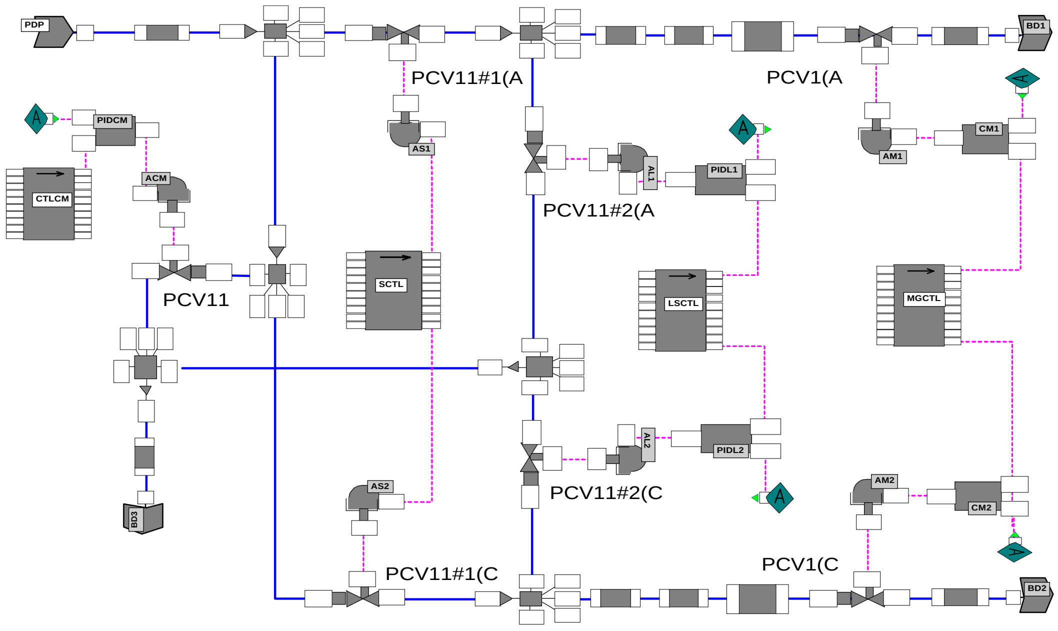

Figure 2. MMS Model for F/M D_2O Supply System

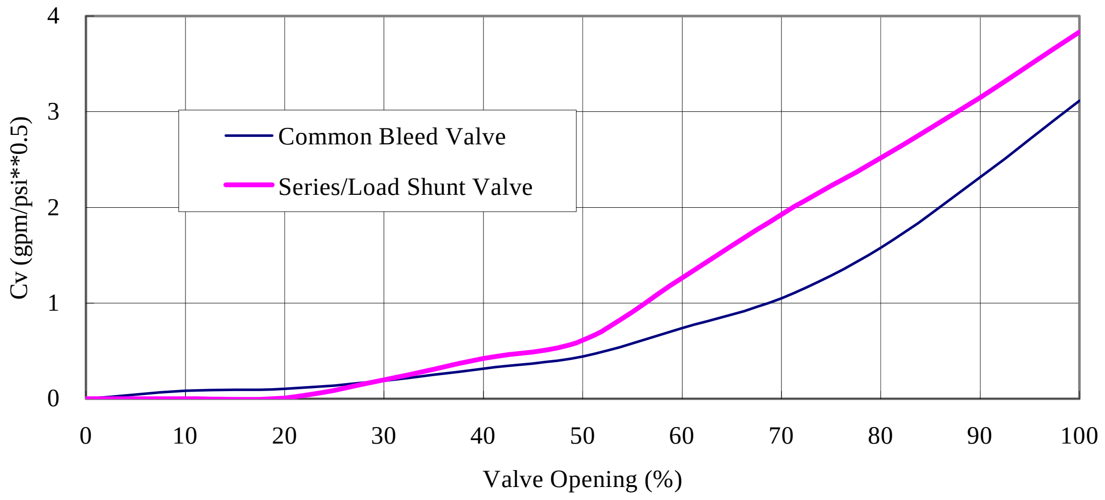

Figure 3. Valve Flow Coefficient

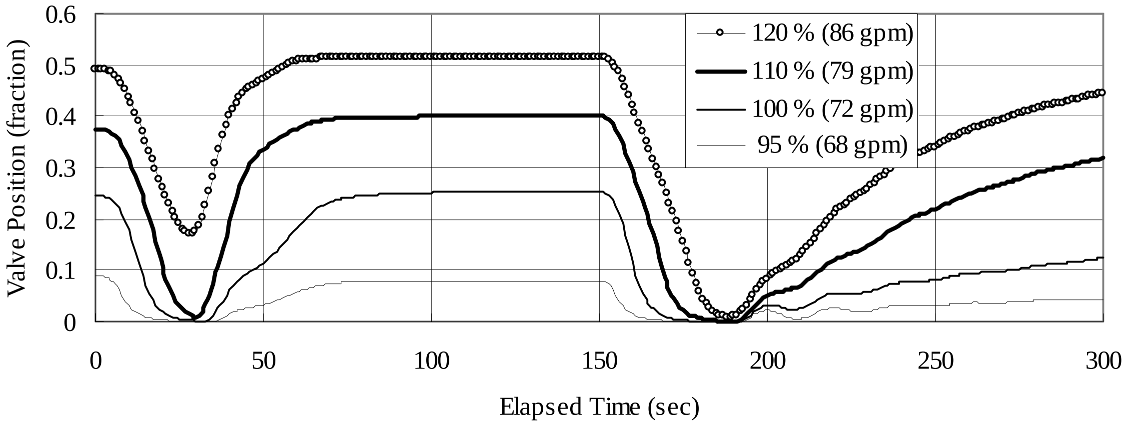

Figure 4. Common Bleed Valve Position vs. Pump Supply Flow

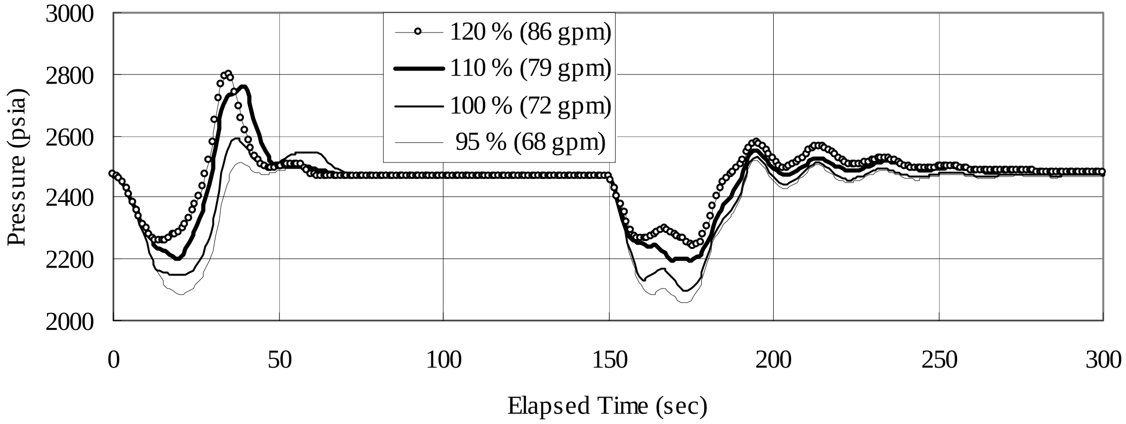

Figure 5. Common Header Pressure vs. Pump Supply Flow

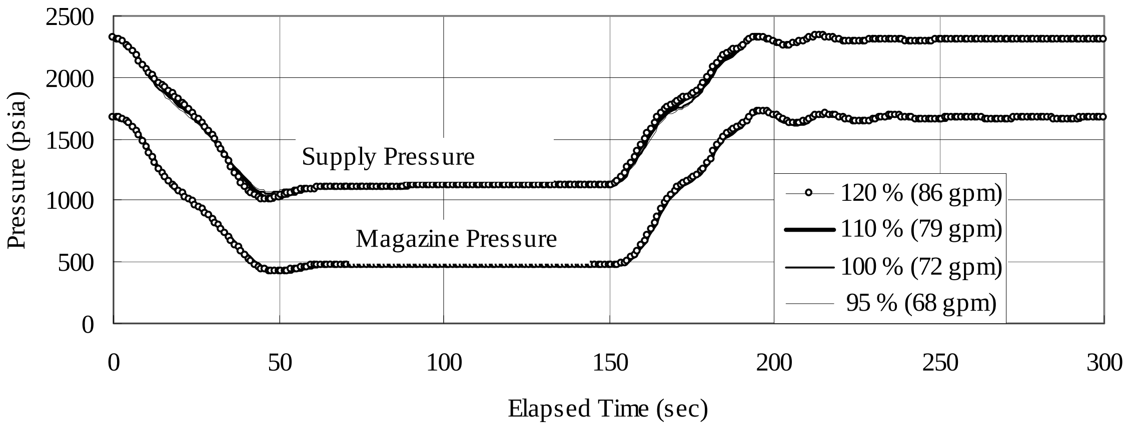

Figure 6. Supply and Magazine Pressures vs. Pump Supply Flow

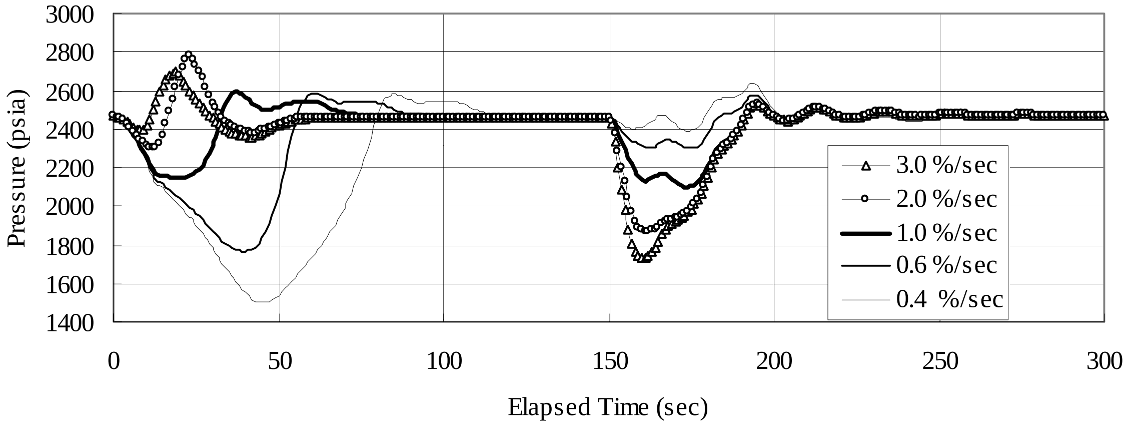

Figure 7. Common Header Pressure vs. Series Valve Position Change Rate

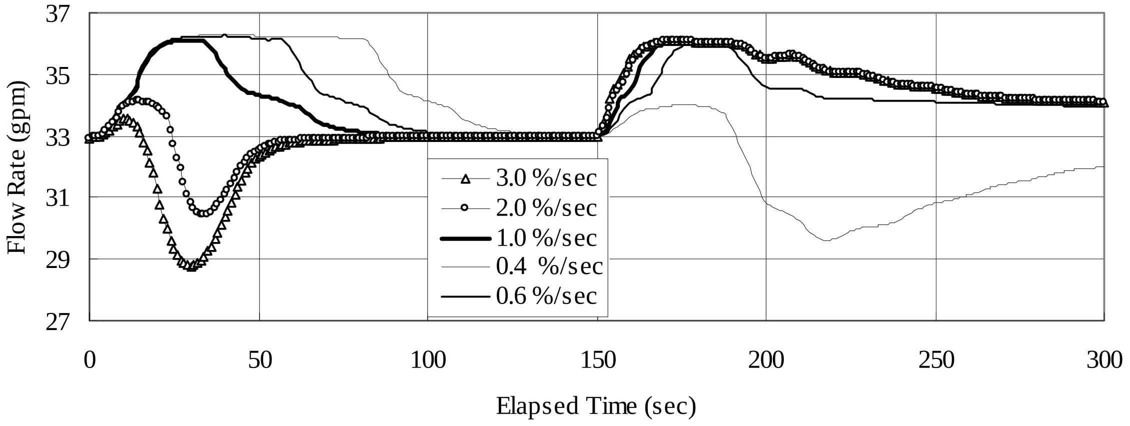

Figure 8. Flow Rate through Series Valve vs. Series Valve Position Change Rate

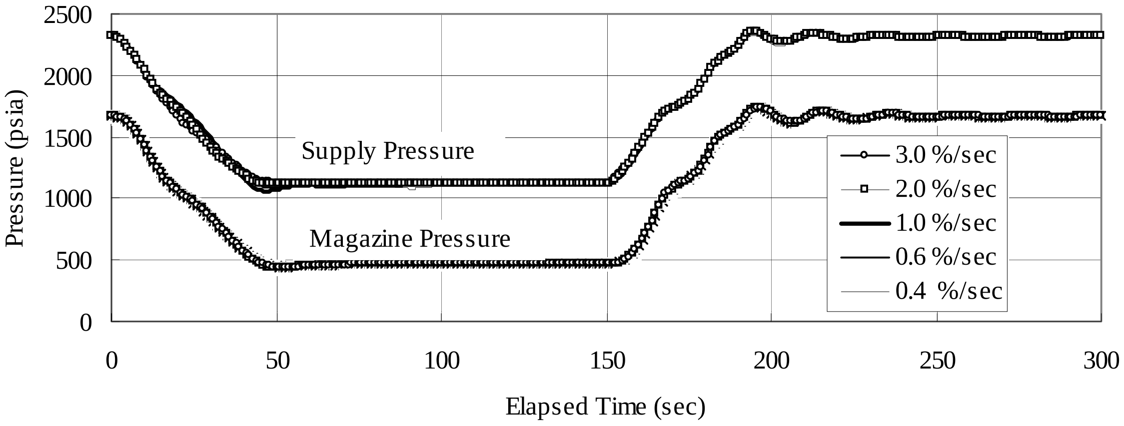

Figure 9. Supply and Magazine Pressures vs. Series Valve Position Change Rate

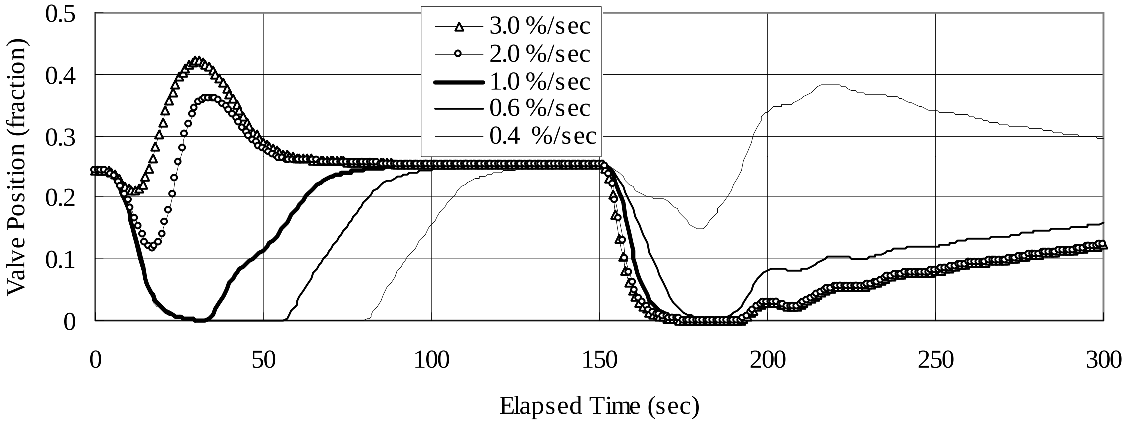

Figure 10. Common Bleed Valve Position vs. Series Valve Position Change Rate

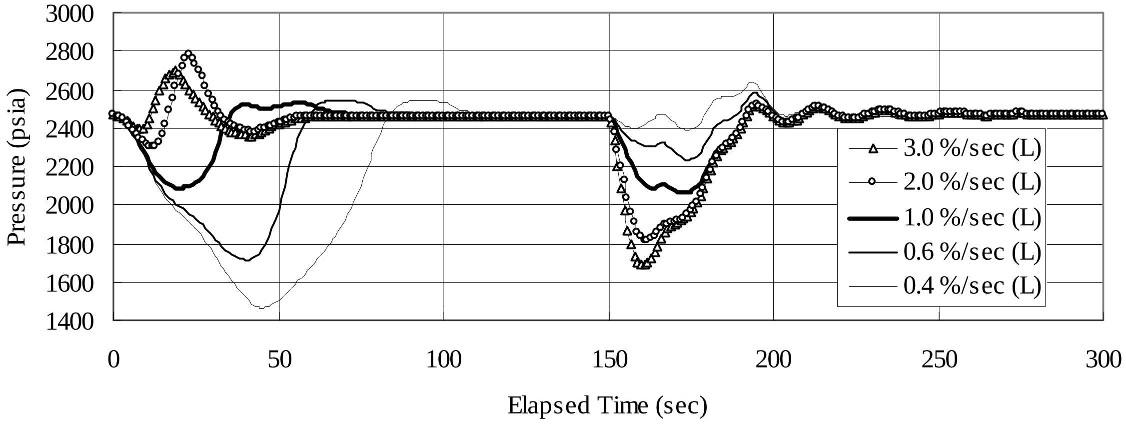

Figure 11. Common Header Pressure vs. Series Valve Position Change Rate
With Common Bleed Valve Position Limited at 10%

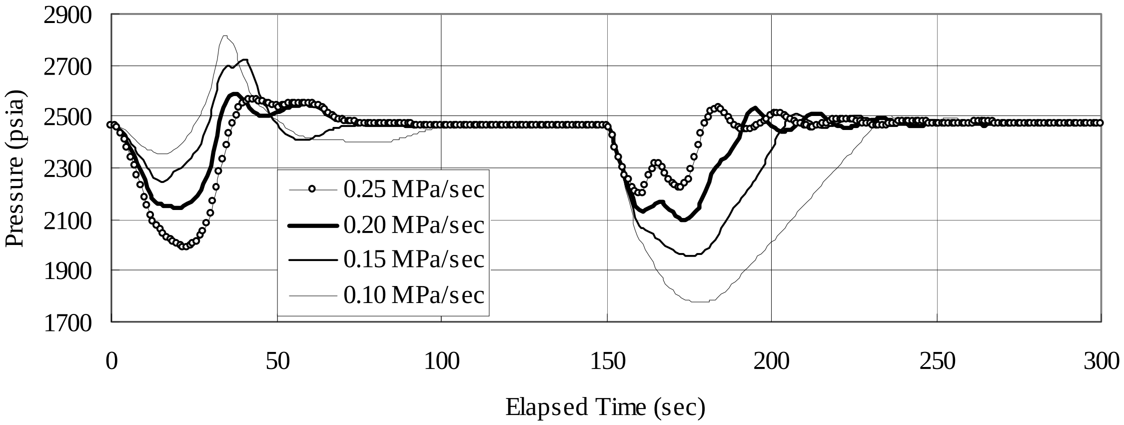

Figure 12. Common Header Pressure vs. Supply and Magazine Set Pressures Change Rate

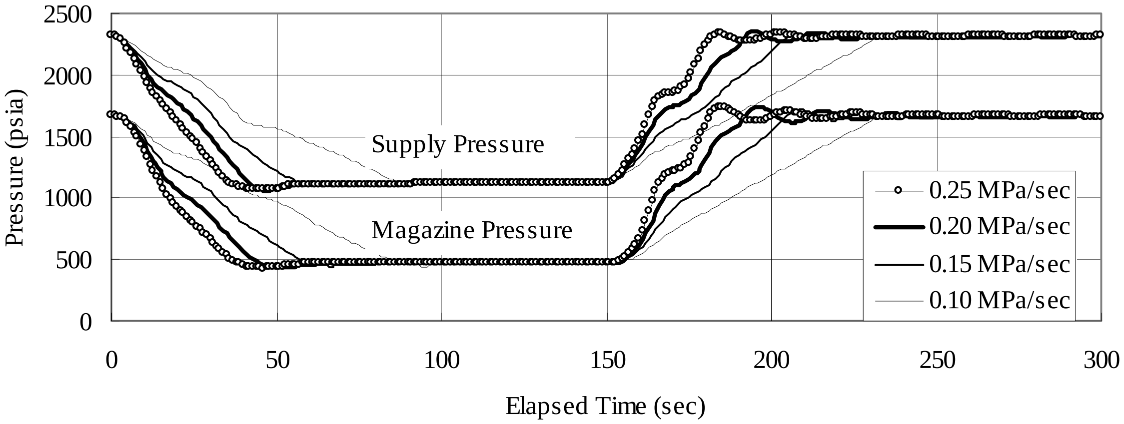

Figure 13. Supply and Magazine Pressure vs. Supply and Magazine Set Pressures Change Rate

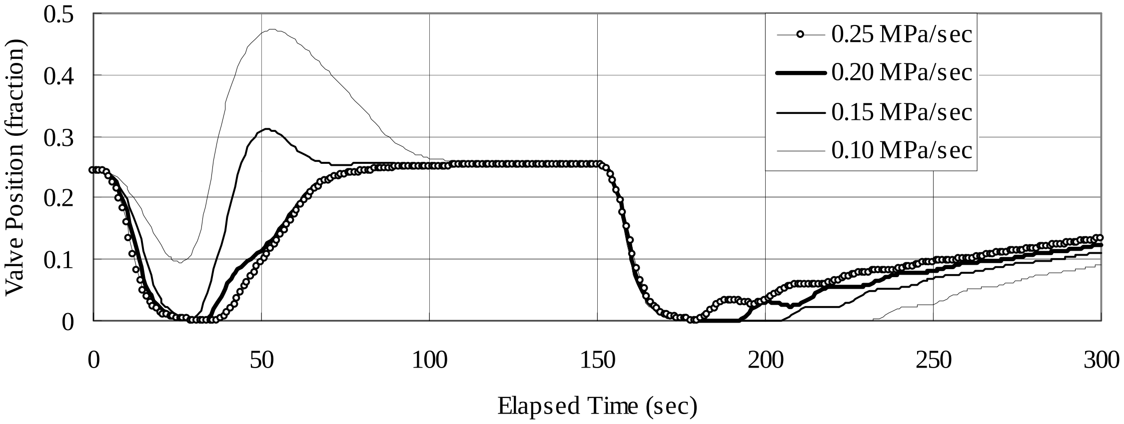

Figure 14. Common Bleed Valve Position vs. Supply and Magazine Set Pressures Change Rate

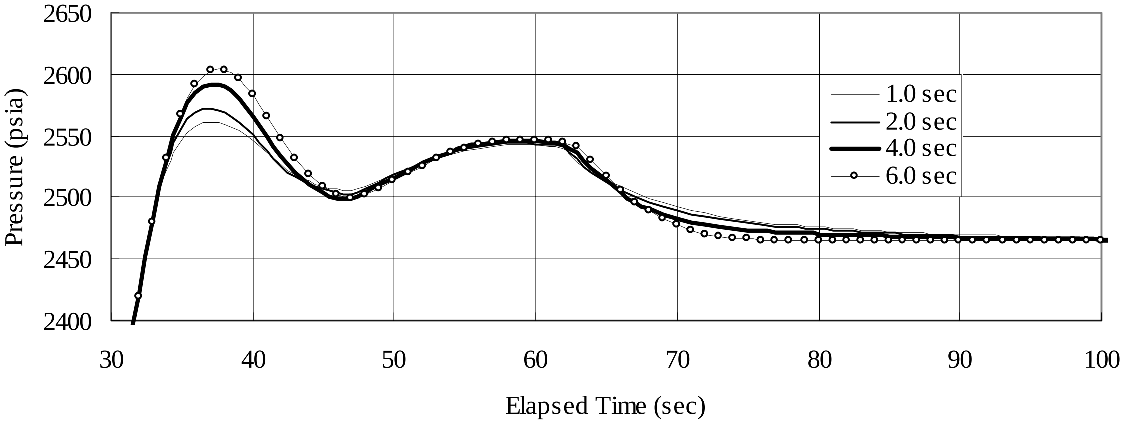

Figure 15. Common Header Pressure Peak vs. Common Valve Actuator Time Constant

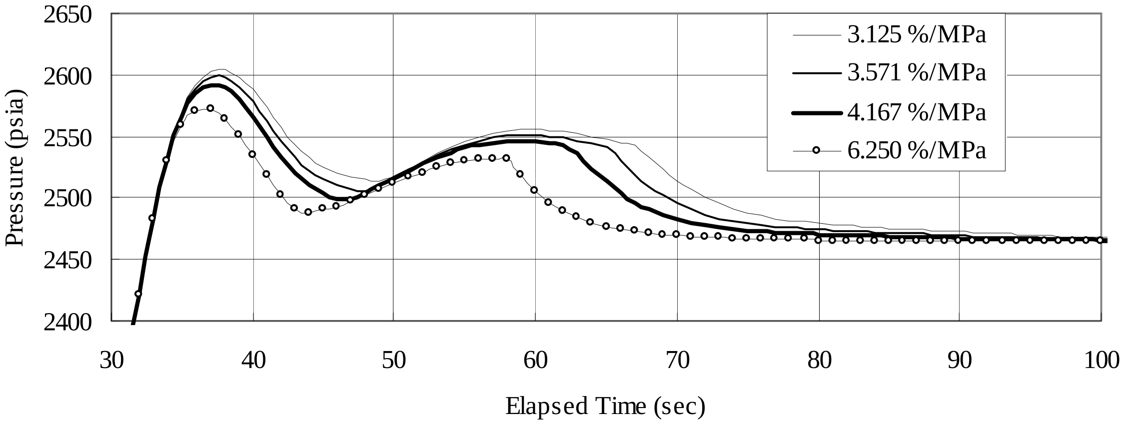

Figure 16. Common Header Pressure Peak vs. Common Bleed Proportional Gain