Chapter 9: Internally Compensated Flow Control

Objectives

- Learn about the restrictive internally compensated flow controls.
- Learn about priority bypass internally compensated flow controls.
- Discover how a priority bypass flow control can be made into a restrictive type.
- Learn how the flow force affects the compensation characteristic.
- Learn about the reverse flow check valve built into one of the restrictive style valves.

Introduction

In this chapter we will learn about the proportional flow control valves that are internally compensated. That is, there is a compensating element or spool/spring combination that is built into these valves. This combination works similar to the one in the EC10-30 and EC10-40 which are described in the previous chapter. The operation, construction and function of both restrictive and priority/bypass type internally compensated proportional flow controls will be presented in this chapter.
PV72-20

The PV72-20 is a direct acting, internally compensated, normally closed, proportional flow control. The normally open version is the PV72-21. The valves are virtually identical except for the metering spool. The difference between a normally open and normally closed metering spool will be discussed in the PV70-30 section. The performance, forces acting on the valve, components and operation are described in the following sections.

HydraForce offers restrictive type, internally compensated flow controls in several cavity sizes. However, the PV72-20 is unique because it is the only valve in the range that is a 2-ported valve. In order to accomplish this function in other cavity sizes, one of the three ports in the PV70/76-30 style valves would be blocked. This will be further explained in the section describing the PV70-30. The PV72-20 is a two way valve designed specifically for restrictive flow control (which is a 2-way function). This implies that the valve was optimized for maximum flow handling capability.
Construction of PV72-20

The drawing below shows an enlarged view of the hydraulic components of the PV72-20. There are a few interesting features that are common to all the internally compensated flow controls. First, as expected, there are two spools. This is because the metering spool of the PV72-33 has been combined with the compensating spool of the EC12-30 into one valve.

All of the hydraulic components described below have been heat treated. This provides a hard surface for wear resistance. The compensating spool, which rides inside the cage, has a ground outer surface and a honed inner diameter. The cage itself is also honed. The outer surface of the metering spool guide is ground, as is the metering spool. The inside surface, where the metering spool rides, is honed. These processes are done to allow a close fit between the parts to minimize the leakage from the inlet (port 1) to the tank (port 2).

There are two other features worth noting in the construction of the internally compensated flow controls. The first is that the metering spool guide floats in the assembly. This is to reduce the mechanical friction between the guide and compensating spool. If it did not float, it may rub on one side of the compensating spool rather than being centered. The last feature to note is the contoured edge of the compensating spool which minimizes the affects of flow forces. Without it the maximum flow may be limited to a lower value.
Performance of PV72-20

Two primary characteristic graphs are presented in this section: the flow vs. current performance and the pressure compensation characteristic. The first graph shown below is the flow vs. current characteristic. The inlet pressure at port 1 was 3500 psi and the load pressure down stream of port 2 of the PV72-20 was 3000 psi. A current regulated electronic driver with the dither frequency set to 100 Hz was used to drive the current across the coil.

![Flow vs. Current Graph]

The graph above shows that the hysteresis is less than 6%. The flow range is 0 to 16 gpm. Saturation of the flow occurs at 1.5 amp or 100% of the rated current. Note that for the PV72-20 and PV72-21 the maximum control current is also the saturation current. For these two valves this value is 1500 mAmp for a 12V coil.
The graph below defines the compensation characteristic. Notice that the curves are flat or horizontal. This implies that regardless of a change in the upstream or downstream pressure, the flow remains constant based on the current applied. This is true as long as the difference in pressure between the inlet and outlet is above the compensation spring value, or approximately 245 psi. This is indicated by the bend in the curves where the flow characteristic changes from flat to a steep decrease in flow to zero.

The following schematic depicts the hydraulic circuit used to develop the graph. The flow and pressure was recorded using an x-y plotter. The inlet pressure (RV1) was set to 3500 psi and the flow is set to one of the levels shown on the graph. The load relief valve (RV2) was initially set to the minimum setting. This gives the largest differential between P1 and P2. The setting of RV2 is slowly increased thus decreasing the difference between P1 and P2 until the flow and pressure go to zero.
Forces on PV72-20

Shown below is the cross section of the PV72-20. The forces acting on the components are also labeled on the drawing. The direction the arrowheads face indicates the direction in which the force is acting. The spring forces $F_{S1}$ and $F_{S2}$, like all the compression springs, oppose the movement of the components in the valve. In this valve these are the armature and compensating spool, respectively. Also, a description of each force is provided below.

Where:
- $F_M$ = Magnetic force
- $F_{S1}$ = Metering spool spring force
- $F_P$ = Compensator spool pressure force
- $F_{S2}$ = Compensation spool spring force

As with the non-compensated proportional valves presented in Chapter 8, the consideration of friction and viscous damping forces have been omitted because these forces are typically much smaller.

The magnetic force and the spring force acting on the metering spool are the same as those defined in Chapter 8. As for the spring and pressure force acting on the compensator spool, the forces defined for the EC10-30 are similar. All four of these forces will be briefly reviewed in the following section.
The metering spool spring force and the actuator magnetic force are briefly viewed in the graph below.

![Graph showing force balance between spring and magnetic forces](image)

A = Position of armature closest to pole piece
B = Position of armature furthest from pole piece

The spring force is dependent on the stiffness of the spring and how much the spring is compressed. The magnetic force is dependent on the amount of current applied to the coil, but not on the position of the armature. This implies that the force balance equation for the metering spool is \( F_M = F_S \). In other words, the magnetic force is balanced by the spring force, or, for each current level which creates a given level of magnetic force, there is an equal and opposite spring force.

The other two forces of concern in the PV72-20 are the compensator spring force and pressure force acting on the compensation spool. The compensator spool is shown below with the direction these forces act, as well as the area on which the pressure acts.

![Diagram showing compensator forces](image)

Where:

- \( A_{EC} \) = Area affected by pressure
- \( F_{S2} \) = Compensator spring force
- \( F_{P1} \) = Force due to the inlet pressure acting on \( A_{EC} \)
- \( F_{P2} \) = Force due to the load pressure acting on \( A_{EC} \)

As with the compensator spools in previous chapters, the force balance equation is \( F_S = F_{P1} - F_{P2} \). Again, this equation shows that the spool will not move or compensate for changes in load pressure until the difference between the two pressure forces exceeds the spring force.
Operation of PV72-20

The operation of the PV72-20 is similar to the PV70-33-E. The function of the valve is to give a constant flow for a given current level regardless of the load pressure. The first drawing to the left shows the metering spool in the neutral position. In this case the current has not been applied to the coil. Notice that the compensator spool has moved to block off the cage holes at port 2. This occurs because there is no load pressure to oppose the force created by the inlet pressure.

The next diagram shows that the metering spool has opened or uncovered some of the cross holes in the guide. Notice however that the compensating spool has moved back to the neutral position. This occurred because the pressure drop (difference between the inlet and load) is less than 240 psi or less than the compensating value.
The diagram to the right shows that the compensating spool has moved to restrict the flow of oil to the load. As expected, this happened because the pressure drop across the inlet and outlet has exceeded the compensating spring value.

In the next two drawings shown below, the metering spool has moved even further to allow more flow. The difference between the two diagrams is the position of the compensating spool. The diagram to the left shows the compensating spool moved down further, opening more of the cage cross hole compared to the drawing on the right. The opening of the cage cross holes created by the edge of the compensating spool is less because the load downstream is less than the one to the left. This illustrates that the operation of the PV72-20 is the same as the PFR70-33-E. That is, if the load decreases, the compensating spool moves to assure the flow rate is maintained.
PV70-30

The PV70-30 is a normally closed, internally compensated, proportional flow control valve. The operation of this valve is similar to the PFR70-33-F described in Chapter 8, however it is one cartridge rather than two. The cross section of the valve is shown below. The normally open version, PV70-31, is shown on the following page. The difference between the two is the metering spool. The comparison of these two spools is also shown on the following page. Both the PV70-30 and PV70-31 can be used as either a restrictive type flow control or a priority/bypass style. These valves can be used as restrictive type flow controls by blocking port 2. The performance difference between the 2-way mode and 3-way mode, as well as forces acting on the components and operation of the PV70-30, are presented in the following sections.
Performance of PV70-30

The graphs below represent the performance of the PV70-30. The first graph is the flow vs. current characteristic when the valve is used as a restrictive type flow control. Recall that at a restrictive type flow control is a two port device with an inlet and a regulated work port. The load pressure was held at 3000 psi while the current was varied in the graph below. Also, the dither frequency was set to 110Hz.

The graph above shows that the regulated flow range of the PV70-30A when used as a restrictive flow control is 0 to 8.5 gpm. The threshold current is 20% and the saturation current is 95% of the maximum current. The hysteresis is 6%.
The next graph shows the flow vs. current characteristic of the PV70-30A when used as a 3-port priority/bypass flow control valve. As with the previous graph, the load pressure was 3000 psi and the dither frequency was 110Hz while the current was varied.

The hysteresis and threshold current are the same as the previous graph. However, the saturation current is 90% of the maximum control current. Note that for the PV70-30 and the PV70-31, the maximum control current corresponds to the saturation current when the valve is used as a two port restrictive type valve. That is, when the valve is a 3-way bypass style, the flow saturates at a lower current. The saturation current is 1250mA for the 2-way mode and 1200mA for the 3-way mode. This is less than the 1500 mA given for the PV72-20. A further explanation of the maximum allowed current for the proportional flow controls will be given in Chapter 14.
The following graphs represent the compensation characteristic. The first one shows the compensation characteristic for the PV70-30A when it is used as a two-port restrictive type valve. The test schematic used to develop these curves is also shown below the graph. It is similar to that of the one used for the PV72-20.

The relief valve used to simulate the load, RV\textsubscript{REG}, is initially set to the lowest possible setting. This would cause the difference between P\textsubscript{REG} and P\textsubscript{IN} to be approximately 3500 psi. This is indicated by the pressure recorded to the far right of the graph. The setting of RV\textsubscript{REG} is increased until the flow at FL\textsubscript{REG} is reduced to zero. This is because there is insufficient pressure to overcome the setting of RV\textsubscript{REG}. The droop shown in the top curve from 8.00 gpm to 6.5 gpm will be explained further in the operation section.

![Graph showing regulated flow vs. pressure drop](image-url)
The next graph is the compensation characteristic for the priority/bypass function of the PV70-30A. The difference between this and the previous schematic is the additional load relief valve RVBY, connected to port 2. The graph below shows how the regulated flow varies with a change in pressure. The left side shows how well the desired regulated flow is maintained, while the pressure in the bypass line changes. The right side shows the change in regulated flow due to varying pressure in the regulated line.

![Regulated Flow vs. Pressure Drop Graph]

### Regulated Flow vs. Pressure Drop

**Pressure (bar)**
- 37.9
- 30.3
- 22.7
- 15.1
- 7.6

**Flow (lpm)**
- 276
- 138
- 0
- 138
- 276

**Flow (gpm)**
- 0
- 2
- 4
- 6
- 8

**Pressure (psi)**
- 4000
- 2000
- 104% of maximum current
- 32% of maximum current
- 56% of maximum current
- 80% of maximum current

Change in Bypass Pressure
(P\textsubscript{by} > P\textsubscript{reg})

Change in Regulated Pressure
(P\textsubscript{by} < P\textsubscript{reg})

![Schematic Diagram]
Forces of PV70-30

The diagram below shows the cross section of the PV70-30A and the forces acting on the components. Notice that these are all similar to the ones described for the PV70-20 except for the flow force and damping force indicated on the compensation spool. For a description of all other forces except the flow force and damping force, refer to the PV72-20. The damping force and flow force are described in previous chapters.

Where:
- $F_M$ = Magnetic force
- $F_{S1}$ = Metering spool spring force
- $F_{P1}$ = Inlet port pressure force
- $F_{P2}$ = Bypass port pressure force
- $F_F$ = Flow force
- $F_{S2}$ = Compensator spring force
Forces acting on Compensating Spool

The diagram on the previous page shows a cross-section of the compensating spool and cage. The forces acting on the spool are labeled. As with the compensating spool in the PV72-20, there is a spring force and a pressure differential force. A third force shown is the flow force. A full description of the flow force was presented in the previous chapter. The flow force is noted here in order to describe why the compensation curve is not flat, or droops. This is when the current applied is greater than 65% of I_MAX. As with the other compensating spools, its position relies on the compensator spring force being balanced by the pressure force or F_S2 = F_P1 - F_P2. However, the flow force can also influence the position of the compensating spool. In most compensators, the flow force is not as large as the other two and therefore is omitted for simplicity. In the case of the PV70-30, where HydraForce tried to maximize the available regulated flow, the flow force is almost as large as the other two forces. Notice that the flow force acts on the spool where oil exits at both port 2 and port 3. In other words, there is a flow force acting on the spool when oil flows through the regulated port and the bypass port. The force balance equation is F_S2 = (F_P1 - F_P2) + F_f. This equation shows that as the flow force increases, the compensator spring will need to increase. Recall that the spring force is determined by how much it is compressed. When the compensator spool moves, the compensator spring is compressed. Thus balancing the flow force. As this occurs, the compensating spool closes off the cage cross holes at port 2, thus restricting or reducing the flow expected. This is shown on the graph as droop.
Operation of PV70-30

In this section, various operating modes of the PV70-30 will be described. The first diagram shows that the plunger/pushpin is pushing down on the metering spool because current is applied to the coil. As with the PV72-20, the compensating spool is actively metering the flow at the regulated port. Also, notice that the excess flow is being bypassed through port 2.

This is the typical operation of the PV70-30. That is, a current level is selected causing the metering spool to move to a defined position. The compensating spool then moves in response to a change in pressure. This assures a constant pressure drop across the metering spool. The compensating spool of the PV70-30 begins to regulate at a differential pressure of 190 psi. The oil is flowing out of the regulated and bypass port. In order to achieve the maximum rated regulated flow given in the performance section, the inlet flow must be 10-20% greater.

The next diagram shows what occurs if the flow downstream of port 3 suddenly stops. This could happen if a cylinder reaches the end of its stroke. Notice the metering spool is still in the shifted position, as shown in the previous diagram. The compensating spool has moved back to its original at rest position, closing off the bypass port. The reason is related to the forces acting on the compensating spool. As noted in the previous section, the compensating spool moves in response to changes in the inlet pressure, outlet pressure, flow force and the spring force. Recall that the force balance equation is \( F_s = (P_{in} - P_{out}) A_{sp} + F_f \). When flow is stopped, because the load is no longer moving, the difference between \( P_{in} \) and \( P_{out} \) is zero. This implies that there is no force to balance the spring force. Therefore, the spring pushes the compensating spool until it stops on the cage. This in turn causes the bypass flow to go to zero and all the flow will then pass through the system relief.
The operation of the compensating spool closing off the bypass port will also occur with the EC10-40 when used with the PV70-33 as discussed in Chapter 8. If continuous flow is required to the bypass, regardless if the flow to the regulated port ceases, it is recommended to install a small orifice in parallel with the regulated load, as shown in the schematic below.

An 0.020 orifice is recommended to be used with the PV70-30, PV70-31 and PV70-33. An 0.031 orifice is recommended to be used with the PV72-30, PV76-30, PV72-31, PV76-31 and PV72-33. Alternatively, a relief valve could be installed in place of the parallel orifice. The setting of this relief valve should be lower than the setting of the system relief, but higher than the pressure required to move to load.
Damping Chamber Operation

Inside the priority/bypass internally compensated flow control valve is a damping chamber. The damping chamber is also the area that holds the compensating spool spring. This chamber dampens or slows the movement of the compensator. Its function is to prevent the spool from oscillating, which can occur due to fluctuations in the output of flow from the pump (known as **pump ripple**). The fluctuations in flow may also occur because of the stopping and starting movement of an actuator. This is caused by the mechanical friction of the piece of equipment in which the valve and actuator are installed.

When the compensator spool moves to regulate flow the damping chamber is in operation. As it moves, oil is pumped in and out of the damping chamber. When the compensating spool moves up, as shown in the left hand diagram below, oil is pushed out of the damping chamber. When the damping spool moves down, oil is drawn into the damping chamber as shown on the right.

The clearance between the compensating spool and guide determines the amount of damping. This clearance is balanced to allow the compensator to react to changes in load pressure, but to ignore small oscillations due to pump ripple.
Summary

In this chapter the following concepts were presented:

- The performance of restrictive style internally compensated flow controls.
- The performance of the priority/bypass internally compensated flow controls.
- The reason for droop in a compensation curve.
- Basic construction of an internally compensated flow control.
- How a priority/bypass flow control can become a restrictive style flow control.
- Bleed orifice requirements for no flow priority/regulated port such as at the end of a stroke condition.
Review Questions

Use the following review questions as a measure of your understanding of the chapter material. Answers are provided in the appendix.

1. What type of flow control is the PV72-20?

2. Which port of the PV70-30 is blocked to make it a restrictive type flow control?

3. What does the compensating spool do if the load pressure suddenly changes? Assume that the difference between the inlet pressure and load pressure is greater than the compensating pressure and the current remains constant.

4. What is the difference between the PV70-30 and PV70-31?

5. How many spools are inside the internally compensated flow controls?

6. True or False. Inside the internally compensated flow controls, the magnetic force is balanced by the metering spool spring force.

7. What purpose does the damping chamber serve?