Chapter 8: Valve Design

Objectives

The objectives for this chapter are as follows:

• Introduce the concept of summation of forces, needed in valve design

• Learn what the actuator force, the spring force, the Bernoulli (flow) force, and the two friction forces are.

• Discuss the two types of friction forces, mechanical and viscous.

• Determine how each of these forces affect the spool and poppet valves.

• Obtain an understanding of how the forces must be taken into account in valve design.

• Learn how the actuator force is measured and calculated using FEA.

• Discover the difference between the free length and the compressed length of the spring.

• Walk through the steps of the poppet and spool valve in operation.

Introduction

In this chapter, the concept of the summation of the forces which act on the valves, is presented. Each of the forces and how it affects both the poppet and spool valves are discussed. In addition, the reader is given an understanding of some of the factors which need to be considered in designing the valve.
Summation of Forces

Valve design is based on the summation of forces acting on the valve. An example of the summation of forces, is the force you exert on the chair you are sitting on due to your weight. The chair exerts an equal and opposite force on you. If it didn’t, you would fall through the chair.

The summation of forces shows that $F_w + F_c = 0$. Since $F_w$ points down, it is considered negative. Therefore, the summation of forces for the man on the chair is $-F_w + F_c = 0$. To show that the system is balanced (the chair supports the man), the equation can be written $F_w = F_c$. (Note, the arrow represents the direction the force is acting).

Spool Valve Design

Unfortunately, in valve design, defining an exact quantity, (like your weight) for all the forces involved is nearly impossible, because many of the forces are immeasurable. Some of the forces that must be considered are, the actuator force, spring force, flow force and friction force. The location of the forces, in reference to the parts of a valve are shown in the following diagram. The symbol representing each force as well as a brief definition is given. These forces are discussed in detail in the sections which follow.
De-Energized

Energized

\( F_s \) = spring force
\( F_M \) = magnetic actuator force
\( F_{MR} \) = residual magnetic force
\( F_{FP} \) = friction force acting on the surface between the tube subassembly and the plunger
\( F_{VP} \) = friction (or viscous) force due to the oil between the plunger and guide tube
\( F_{FF} \) = flow force or Bernoulli force
\( F_{FS} \) = friction force related to the spool
\( F_{VS} \) = friction (or viscous) force due to the oil between the spool and the cage
Actuator Force

The actuator force is the first of the forces to consider. Either the flat face or the conical face actuator is selected over the linear proportional actuator, for two reasons. The cost for the flat face and the conical is lower than the proportional. In addition, the magnetic force versus the stroke characteristic for these two armatures is desirable for solenoid valves. This point will become more apparent as we discuss the interaction of all the forces later in this chapter.

In previous chapters, we learned that the magnetic force for the flat face and conical face actuator changes as the air gap changes. We also learned that the magnetic force was dependant on the current flowing through the coil. Recall the typical graph of the flat face armature shown below.

![Graph showing force versus air gap for a flat face actuator.](image)

The force versus the air gap can be measured by connecting a force measuring device known as a load cell (similar devices are used in bathroom scales) to the plunger. The plunger is moved from zero air gap to a distance or air gap which exceeds the required stroke. The stroke, or air gap of the 08 size valve is typically 0.065 in. and 0.095 in for the 10 size. As the plunger is moved, the force is graphed against the distance traveled.

HydraForce uses another method of determining the magnetic force of an actuator. A computer program named MAXWELL uses Finite Element Analysis (FEA). It can solve complex mathematical equations to find the force by breaking the components (coil, frame, plunger etc.) into tiny pieces. The program calculates the magnetic force through the tiny pieces of each part, as well as the air surrounding it. It then reassembles the pieces to determine the force of the entire actuator.
Spring Force

Another factor to consider is the spring force. The spring force, like the magnetic force, is not fixed. It varies due to the amount it is compressed and is defined by the following relation:

\[ F = K (FL - X) \]

where:  
- \( F \) = force measured in lbs
- \( K \) = spring rate measured in lbs/inch
- \( FL \) = free length of spring measured in inches
- \( X \) = compressed length of spring measured in inches

Note that the spring rate is a physical constant of the spring. It describes the amount the force can change with a change in compression (distance). The free length of the spring is the length of the spring when uncompressed.

This equation can be extended to valve design in the following manner. The spring is installed in the valve with some initial compression at the maximum air gap. This is done to balance the flow force and because it is impractical to have a spring which begins at zero compression. Since the plunger cannot be made perfectly every time (exactly the same length), it is better to initially compress the spring slightly so the force is more predictable. In addition, in order for the spring to return the valve back from the energized position, it needs a “high” force when the valve is energized. To accomplish this, the spring must be installed with some force, or it has to have a high rate (large change in force for a small deflection). Springs with high rates tend to take up more space because the wire has to be stiffer (therefore thicker) to make the spring stiffer. If the wire is too thin, the spring might break.

When the coil is energized (power applied), the plunger begins to move, compressing the spring and therefore increasing the spring force. The following graph represents this relationship.
Chapter 8: Valve Design

The graph above describes the spring force in a valve. The variables are defined as:

\[ F_S = K (IC + (AG_{MAX} - AG_{CUR})) \]

\[ IC = \text{This is equal to the free length minus the initial compressed length (see diagram below)} \]

\[ AG_{MAX} = \text{Maximum air gap or the maximum distance between the armature and the pole piece.} \]

\[ AG_{CUR} = \text{Air gap or distance that the plunger is currently at, relative to the pole piece.} \]

The following diagram shows a spring at free length and one installed in a valve.
Bernoulli (flow) Force

The Bernoulli Force is a force which acts on the spool. It is caused by the acceleration of the oil as it flows from a larger passage through a smaller one. To clarify this concept, let’s first take a look at fluid flowing through a pipe in the diagram below. The diagram shows the inside diameter of the pipe is reduced along the length of it. Assume that the flow or quantity of oil moving through the pipe is fixed.

\[ A_1 = \text{initial tube diameter} \]
\[ A_2 = \text{reduced tube diameter} \]
\[ Q = \text{amount of flow} \]
\[ P_1 = \text{pressure measured in the } A_1 \text{ portion of the tube} \]
\[ P_2 = \text{pressure measured in the } A_2 \text{ portion of the tube} \]

As stated, the flow rate for the oil running through the pipe is fixed. The same amount of fluid passes through \( A_1 \) as it does through \( A_2 \). Therefore, in order to fit through the smaller area, it must speed up (accelerate). To do this, energy must be expended. The loss of energy can be measured by the decrease in pressure between \( P_1 \) and \( P_2 \). In this example, \( P_1 \) is greater than \( P_2 \). The difference between the two pressures measured in the tube is known as the \textit{pressure drop}.

Similar to the flow through a tube, acceleration of fluid and decreased pressure occurs as the fluid passes through the valve. The following diagram shows a typical cross section of a spool valve. We are specifically looking at the flow of oil as it goes into the cage, past the spool and back out.

In this example, as with the pipe, when the fluid goes from a larger area through a
smaller one, there is a drop in pressure. The difference in pressure is shown by the small arrows ($P_2$) acting on the spool. The larger arrows ($P_1$) indicate a higher pressure. Since pressure is force divided by area (measured in lbs / in$^2$ or psi), or force is equal to pressure multiplied by area, it can be shown that the flow force is pushing up on the valve.

As noted in the diagram, $P_1 > P_2$ and in general pressure = force / area, or force = pressure x area.

Since the area of the spool exposed to the pressure is equal on both sides of the spool, then the force due to the pressure $P_1$ is greater than the force due to $P_2$. This concept can be further shown below.

$$P_1 > P_2 \text{ then:}$$

$$F_1 = P_1 \times A > F_2 = P_2 \times A$$

Therefore, there is a force acting to close off the flow through the cross holes. As these holes close and the force pushes on the spool, the force increases because the difference in pressure increases. This increase in force continues until the limit of the system delivering the oil (the pump) reaches its pressure relief setting. When the force begins to decrease, it continues to push on the spool until it is closed. The following graph represents the typical trend of the flow force vs. the stroke of the spool (the stroke is the same as the plunger air gap).

The following diagram shows the flow through the spool in various stages.
When the spool is in position 1, the plunger is at the full open air gap position. At position 2, the coil has been energized and the spool begins to move. As previously stated, when the spool begins to close off the holes, the force builds. The force continues to increase until the system pressure is reached. Point 3 represents the flow force when the plunger and spool are fully shifted. In this case, there is no flow and therefore no flow force.
Flow Forces acting on SV10-40

As shown in the force diagram of the SV10-40 at the beginning of the chapter, the flow force can act in either direction. This is due to the fact that the oil switches flow paths when the coil is energized or de-energized. The diagrams shown below indicate how the flow goes through the valve during different positions of the stroke.

Position 1 (the de-energized position) shows flow going from port 3 to port 2 and from port 4 to port 1. (The port and its number are simply a designation for the passage.) When flow is going in these directions, the flow force tends to act in the same direction as the magnetic force. In position 3 (the energized position), flow goes from port 3 to port 4 and from port 2 to port 1. When the flow travels through the valve in this direction, the flow force is acting in the same direction as the spring force. Position 2 shows the spool in the transition position. This stage is neither fully de-energized nor energized. In this stage, the flow is traveling in all directions and therefore no flow force is acting on the valve. Note that when the spool allows fluid to pass through other ports in the transition position, it is referred to as an open in transition spool or a negative lap spool. When the spool does not allow fluid to pass in the transition state it is referred to as a closed in transition spool, or positive lap.
Friction Forces

Two types of friction force exists, as shown in the diagram. The mechanical friction force is due to the surface of the parts rubbing against one another. The viscous force is due to the parts moving through the oil. The following section describes each force in more detail.

Mechanical Friction

Most people have experienced friction by rubbing two objects together, such as a brick across sandpaper. Friction force, or resistance to movement is created by this rough surface and is opposite to the movement of the plunger. This force is small compared to the spring force, armature force or flow force, and is difficult to measure.

The following diagram is an enlarged view of the plunger in contact with the guide tube. The magnified view shows extreme jagged peaks and valleys on the surface. This surface roughness (peaks and valleys) is measured in micro inches (µ in.) which is equivalent to 0.000001 inches or 1 in. / 1000000. The surface finish of the plunger is typically 125 µ in. (0.000125 in.) or less. The surface finish of the guide tube is less than 46 µ in. The cage and spool have polished surfaces with a surface finish of less than 10 µ in.

As a practical example, the size of these peaks and valleys can be compared to a sheet of paper. One sheet of paper is typically 0.005 inches thick. This measures fifty times greater than the highest peak on the plunger surface. It would seem that since the peaks and valleys are so small that they are not significant. However, all forces must be taken into account. The magnetic force developed by some of the solenoid valves is only a few pounds. Therefore, the combination of the spring force, flow force and the friction force may be too great to be overcome by the magnetic force.
Viscous Force

The second type of friction force, the viscous force, can be described by use of an example. When drying dishes, have you ever noticed that when pulling two very smooth plates apart they stick together slightly? This sticking together is a viscous force. The force specifically at work between the two plates and the water is an adhesive force. Adhesive forces exist between two unlike substances such as a plate and water or a spool and oil. Another type of viscous force is the cohesive force. This is the force which pulls water together to form a drop. These two forces work together opposing the movement of the spool and plunger.

The following diagram represents the spool moving through oil. The enlarged view shows three layers of oil and the surfaces of the spool and cage. The first and third layers represent the oil which adheres to the surface of the valve. The second layer represents the oil which coheres or joins the other two layers together. This layer will be stretched as the parts begin to move. Eventually, the magnetic force overcomes the strength of the cohesive force, and the bonds between the molecules in layer two break. The bonds immediately reattach to the next adjacent molecule and are again broken by the magnetic force. This continues throughout the movement of the parts.
Summary of Forces

The following graph summarizes the forces and shows how they interact. Notice that the spring is drawn on the negative side of the axis. This shows that the force acts opposite the magnetic force as shown in the flow force diagram at the beginning of the chapter.

\[ F_M > F_S + F_{VP} + F_{FP} + F_{VS} + F_{FS} \]

and

\[ F_S > F_{FF} + F_{VS} + F_{FS} + F_{VP} + F_{FP} \]

These factors indicate which parameters affect the performance of the valve. The factors can be adjusted to vary the performance for certain applications. For example, let’s take a look at the performance specifications for an SV10-31 valve.

- Maximum operating flow: 6 gpm
- Maximum operating pressure: 3000 psi
- Maximum leakage: 10 in³ / min
- Allowable voltage range: ± 15% nominal (nominal voltage is the ideal voltage which a system is designed to)
To extend the performance of this valve for a particular application the forces need to be adjusted. For example, assume a higher operating flow is required. If the flow is increased, the pressure drop increases and the flow force increases. When this occurs, the spring force must increase so that it is still greater than the flow and friction force combined. If the spring force is increased, the magnetic force also must be increased. As we learned in previous chapters, if more magnetic force is required, more current is needed. When more current is needed, the voltage range must be limited to ensure that the coil can still draw sufficient current at the lower operating voltage. It can be clearly seen that there are many factors affecting performance. Trade-offs exist when choosing which performance factors to increase.

**Spool Valve Operation**

Now that we’ve described how the forces exerted on the valve affect it, let’s discuss how the valve actually operates. Assume that the fluid is passing through the valve as shown in the following diagram.

When the coil is energized, the plunger is attracted to the pole piece (or plug in, the pull style armature). The armature pulls on the spool. As the two parts move, the magnetic force has to overcome the friction forces and the spring force. Initially, the flow force assists the magnetic force because it is acting in the same direction. As shown in the flow force section, this force switches directions as the spool passes through transition. When the flow is rerouted, the flow force acts against the magnetic force. During the final third of travel, the plunger must overcome the spring force, friction forces and flow forces combined. When the armature hits the plug, the valve is in the energized position, or *pull in* has occurred. The term pull in is from the action of the armature pulling the spool into position.

When the power to the coil is turned off, the spring pushes against the armature. The spring force must overcome the residual magnetic force. It must also overcome both mechanical and viscous friction forces. Recall that these forces oppose the movement of the parts regardless of the direction of travel. During the first one third of the spool travel, the flow assists the spring. When the flow switches directions, the spring must overcome flow force as well as the others. Once the spool shoulder hits against the cage, the spool and armature are considered to be in the de-energized position. The action of these parts returning to this position is known as *drop out*. 
Poppet Valve

The following diagram shows an SV08-21 normally open, pilot operated, poppet valve. As in the spool valve shown at the beginning of the chapter, there are various forces acting on the parts.

\[
\begin{align*}
F_S &= \text{spring force} \\
F_M &= \text{magnetic actuator force} \\
F_{MR} &= \text{residual magnetic force} \\
F_{FP} &= \text{friction force acting on the surface between the tube subassembly and the plunger} \\
F_{VP} &= \text{friction (or viscous) force due to the oil between the plunger and guide tube} \\
F_{VT} &= \text{viscous force acting on the poppet} \\
F_{FT} &= \text{mechanical friction force acting on the poppet} \\
F_{PP} &= \text{pressure force acting on the pilot pin} \\
F_{PT} &= \text{pressure force acting on the poppet}
\end{align*}
\]

The friction force, spring force and magnetic force are basically the same as those discussed with the spool valve, with the exception of the pressure force acting on the pilot pin.
Pressure Force Acting on a Poppet

In the diagram of the SV08-21 shown to the right, the valve is shown in the de-energized state. The poppet is opened, which allows flow to pass from one port to another. Assume that the oil is flowing through the valve, as shown in the diagram.

Similar to the flow through tubing, there is a pressure drop as oil flows past the poppet and cage seat. This pressure pushes up on the poppet, holding it in place.

When the valve is energized, the oil flows through the bleeder hole and pressurizes all the surfaces of the poppet. This is shown in the diagram to the left.

This pressure force acting on the poppet assists the valve when the coil is energized.

Although there is pressure acting on all parts of the valve, the pressure which acts on the pilot pin directly affects the ability of the valve to open. The following diagram shows the areas of pressure while the pin is sitting on the seat and the coil is energized.
As the diagram below illustrates, there is high pressure around the pilot pin, except for the small area which sits on the seat and is exposed to low pressure. This small area exposed to low pressure creates a force imbalance which is equal to:

\[ F_{pp} = \text{high pressure} \times \text{seat area} \]

The following graph shows the forces acting on the poppet valve when it moves from the de-energized to the energized position. The equations show the balance of forces:

\[ F_M > F_{FS} + F_{FP} + F_{VP} + F_{VT} + F_{FT} + F_{PP} \]
As in the spool valve, the forces shown on the previous graph are balanced, to obtain the best performance of the valve. Again, trade-offs exist between the available magnetic force due to the temperature and voltage range, and the other forces acting on the valve. The factor which most often influences the poppet valve performance is the pressure force acting on the pilot pin. The friction forces remain basically unchanged, even when flow or pressure changes. However, if pressure increases the force \( F_{pp} \), the spring must compensate. When the spring force is increased, the magnetic force must also increase.

**Pilot Operated Poppet Valve Operation**

We have discussed the features of the poppet valve as well as the forces exerted on it. We will now take a look at how this valve works. As described in previous chapters, the coil is energized, which causes the plunger to be attracted to the pole piece. The plunger pushes on the push pin, which in turn pushes on the pilot pin. The parts begin to move, compressing the spring and pushing down on the poppet. When the poppet finally reaches the seat, the parts stop moving. At this point the valve is considered to be in its energized state. Another way of stating this is that *pull-in* has occurred. The forces which the armature force must overcome during pull-in are, the spring force, mechanical and viscous friction forces and the pressure force acting on the poppet. When the valve is in the energized position, fluid gets behind the poppet and around the pilot pin creating the pressure force on the pilot pin.

When the coil is de-energized (power turned off), the term *drop-out* is used to describe it. In order for the valve to drop out or return to its initial state, the spring must overcome the residual magnetism between the plunger and the pole piece. The spring force must also be larger than the pressure force acting on the pilot pin, as well as the friction forces. Once the spring overcomes these forces, the oil behind the poppet and in the tube drains through the seat, relieving the pressure force acting on the poppet. Fluid drains faster than it fills because the bleeder hole is smaller than the seat. The spring continues to push on the push pin until it is back in its original de-energized position.

**Valve Response Time**

Response time is a measurement of how quickly a valve shifts fully from the de-energized state to the energized state or from the energized state back to the de-energized state. Simply put, it is the time it takes the valve to turn on or off. Response time is typically measured in units of milliseconds. A millisecond, ms for short, is 0.001 second or 1 second / 1000. The device typically used to measure response time is an oscilloscope. This device is able to measure fast changes in voltage from sources such as electronic pressure sensors or the current applied to a solenoid coil. The following graph is a typical example of a response time test recorded on an oscilloscope.
The solid curve on the graph shown above is a typical trace or graph recorded when current is applied to a coil as well as when the current is turned off on an SV08-24. The dashed curve on the graph above shows how the pressure changes as the spool opens and closes. The points defined on the graph are as follows:

\[ P_1 = \text{steady state pressure when spool is opened (coil energized)} \]
\[ P_2 = \text{steady state pressure when spool is closed (coil de-energized)} \]
\[ I_1 = \text{current level where the plunger begins to move} \]
\[ I_2 = \text{current level when the plunger has stopped moving} \]
\[ I_3 = \text{steady state system current} \]

Time elapsed from when current is:
\[ t_1 = \text{first applied to when plunger stops moving} \]
\[ t_2 = \text{first applied to when pressure reaches 10\% of } P_2 \]
\[ t_3 = \text{turned off to when the pressure is 20-30psi above } P_1 \]
\[ t_4 = \text{turned off to when the pressure reaches 90\% of } P_2 \]

The illustration which follows, shows a typical schematic for testing the valve response time. (Refer to the appendix for further clarification on the symbol designations).
**Pressure Defined**

When no current is applied, the SV08-24 is normally closed and the pressure seen at the pressure gage or transducer is 3000 psi. \( P_2 \). When the coil is energized, the spool opens and the pressure falls. The pressure measured at the transducer is the pressure drop due to the oil flowing through the valve. \( P_1 \).

**Current Defined**

In chapter three we discussed how current flowing through the solenoid coil induces a magnetic field. To expand on this concept, as a magnetic part moves though a coil of wire, it induces a current. In the case of a coil which has current flowing through it, the induced current flows in the opposite direction of the current which is applied to the coil. Recall the diagram of the pole piece and plunger inside a solenoid coil.

![Diagram of Plunger and Pole Piece](image)

Shown below is the pull in portion of the current response graph.
From points one to two, the current in the solenoid is building. The time required for this to occur is based on the inductance of the coil. The inductance basically describes the amount of time required for the current to flow through the solenoid coil. This time is based on the number of turns and the resistance of the coil. When the current reaches point two, the magnetic force is strong enough to overcome all the other forces previously discussed. The plunger begins to move at this point. The time between points two and three shows a decrease in the current because the plunger movement forces current backwards or against the direction of the applied current. At point three, the current begins to build because the plunger has stopped moving. The current continues to build as if the plunger were never there. The current reaches a steady or constant level at point four based on the system voltage and resistance of the coil. (Recall Ohm’s law $I = \frac{V}{R}$.)

The drop out end of the trace begins at point five. At this point the current goes from ON to OFF at point six. This occurs when the switch connecting the solenoid and power supply is opened.

### Time Described

The times defined in the valve response graph are based on a combination of the current and pressure traces. The times described by $t_1$ and $t_3$ are times which HydraForce uses to determine the response of their solenoid valves. Those described by $t_2$ and $t_4$ represent the times currently proposed by the NFPA (National Fluid Power Society) to describe the response time of a valve. There are pros and cons to using each of these times which are described in the following section.

$t_1$ = This time is the most exact of all four times because it relates directly to the movement of the plunger. This is described in the previous section, on the description of the current.

$t_2$ and $t_4$ = These times are not always as good as $t_1$ and $t_3$. The shape of the pressure graph is not only determined by how quickly the valve opens, but also by how the rest of the system is connected. For example, if the system is stiff because the connections are made with hard tubing, the response time recorded may be faster. If the system is soft because the connections are made with hoses, the time recorded may be longer. Another reason for this may be that other valves (such as relief valves) must react during the test.
t₁ = This time is less dependent on the rest of the system (as t₂ and t₄ are). Testing shows that regardless of the compliance (stiffness) of the system the initial rise in pressure takes the same amount of time. The downside of using this time is that the spool may be only be partially shifted and the pressure may still begin to rise. This means that the spool and plunger may still be moving after this time

**Parameters Affecting Response Time**

All the forces described in the previous sections affect the response time. For example, to decrease the pull-in response of an SV10-20, normally open pilot operated poppet valve, the air gap could be decreased. By reducing the air gap, the initial magnetic force when the current is turned on, is higher. A graph of the force versus the varying air gap is shown below. Point one represents the air gap of the standard valve. Point two is the air gap of the valve with the faster opening time.

The following graph shows that the pressure drop through the valve increases when the air gap is decreased.

![Pressure-Drop-Graph](image-url)
Another way to decrease the time to actuate the valve is to increase the magneto-motive force (NI). NI can be increased by changing the winding used in the coil or by increasing the system voltage. This is typically accomplished by changing the winding. Both methods are known as hot shotting the coil. As the name implies, this process causes the coil to heat up due to the increase in voltage or decrease in resistance, which in turn draws more current or power. This method of decreasing the ON response time should only be used in applications where the coil is not on for long periods of time. If the coil gets too hot, the resistance increases and the current draw decreases. Therefore, there will be no increase in force.

As stated, one way to increase NI is to decrease the resistance. To accomplish this on a standard HydraForce product, the coil can simply be changed. For example, if the nominal system voltage is 12V, a 12V coil would be used. To hot shot the valve (coil), the coil could be replaced with a 10V coil. The 10V coil has a room temperature resistance of 4.8Ω and has 880 turns on the winding. The resistance of the 12V coil is 7.2Ω and has 1054 turns. The following comparison shows the NI of the 10V and the 12V coils when the available voltage is 12V:

<table>
<thead>
<tr>
<th></th>
<th>NI = 880 X 2.5 amp = 2200 NI</th>
</tr>
</thead>
<tbody>
<tr>
<td>10V coil</td>
<td>I = V/R</td>
</tr>
<tr>
<td></td>
<td>I = 12V / 4.8Ω</td>
</tr>
<tr>
<td></td>
<td>I = 2.5 Amp</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>NI = 1054 X 1.667 amp = 1760 NI</th>
</tr>
</thead>
<tbody>
<tr>
<td>12V coil</td>
<td>I = V/R</td>
</tr>
<tr>
<td></td>
<td>I = 12V / 7.2Ω</td>
</tr>
<tr>
<td></td>
<td>I = 1.667 Amp</td>
</tr>
</tbody>
</table>

By changing the coil, a 25% increase in force is obtained. Before hot shotting a coil, HydraForce should be contacted to determine if the application is suitable for this method of decreasing the ON response.

Decreasing the OFF response can be accomplished by increasing the spring force. This increase needs to be weighed against the flow and pressure to which the valve is subjected, as well as the available NI. Again, the NI is affected by the number of turns, system voltage, coil resistance, time that the coil is energized and ambient temperature.

HydraForce makes several valves which have response times lower than the standard product. These are denoted by a F in the model code. For example, a fast acting SV10-20 is model coded as an SV10-20F. This valve has both a smaller air gap (to decrease the on time) and a spring with higher force (to decrease off time). The response time of each is given in the following table.
Area where fracture could occur in a 12 size design

Conical Vs. Flat Face

The reasons for choosing either the conical or flat face over the other are based on the summation of forces. The main question is, how the other forces affect the valve. In the normally open pilot operated poppet valve, the forces opposing the pull in action are small, with the exception of the spring force. This force is large because it must overcome the pressure force acting on the pilot pin. For this reason, the flat face armature is used. Refer to chapter four for further comparison of the Force vs. Air gap characteristic.

The conical plunger is selected in the spool valve because it has a higher force than the flat face at the larger air gap. This higher force is required to overcome the flow forces acting on the valve.

Push vs. Pull

The choice between a push or pull style armature is based on the hydraulic function and strength of the valve. In 08 and 10 size spool valves the armature type is a pull style. This style allows for a variety of spool functions. However, a push style armature such as that used in the 12 size spool valves could also be used. The 12 size uses the push style because it is more robust than the “t” for this size valve. The flow force in the 12 size valves can be as high as 20 lbs compared to 8 lbs in the 10 size valves. Simply increasing the thickness of the parts would not be sufficient. The diagram below shows the area that would be weak in the 12 size if it used a “t” slot.

<table>
<thead>
<tr>
<th>Voltage Applied</th>
<th>Response Time</th>
<th>SV10-20</th>
<th>SV10-20F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pull-in (ms)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.2</td>
<td>58</td>
<td>28</td>
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</tr>
<tr>
<td>12.0</td>
<td>40</td>
<td>24</td>
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</tr>
<tr>
<td>13.2</td>
<td>31</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>Dropout (ms)</td>
<td>32</td>
<td>17</td>
<td></td>
</tr>
</tbody>
</table>

(Note: A millisecond is 0.001 seconds or 1 second / 1000)

The graph above shows the effect of changing the air gap and the voltage (NI). As previously discussed, decreasing the airgap increases the force. The same is true if you increase the voltage. When the current is higher the voltage or current increases as well as the NI or magnetic force.
Chapter 8: Valve Design

Pull-In

Pull-in occurs when the armature has traveled fully through the air gap from the de-energized to the energized position. HydraForce has established values which are used in production, to ensure that the products will consistently pull in lower than a certain threshold current. The values tested in production for pull in are approximately 69% of the room temperature nominal current draw. The reason this pull in value is so high is to ensure the valve will actuate at 85% of nominal voltage, when used continuously in an ambient of 78°F (25°C). Additional continuous duty voltages required are discussed in Chapter 10. For a 12 V coil, these values are:

- 08, 80, 98 size: 840 mA
- 10, 12 (poppet valves), 16, 38, 58 size: 1140 mA
- 12 size (spool valves): 1850 mA

These values are for standard products. Customer specific products may be tested at other values.

Drop-Out

Drop out current is the amount of current that can still be applied to the coil when the valve shifts back to the neutral or de-energized position. HydraForce has established that valves must drop out above a current level equal to 5% of the nominal room temperature current draw. The values used in production are based on the 12V coil, and are as follows:

- 08, 80, 98 size: 60 mA
- 10, 12 (poppet valves), 16, 38, 58 size: 80 mA
- 12 size (spool valves): 130 mA

These values are for standard products. Customer specific products may be tested at other values.

HydraForce designs in the ability for the valves to continuously dropout over the life of the product. This is accomplished in two ways, one of which is to use strong springs. The second way is for the armature and pole piece surfaces to never come into full contact. In the push style, a small gap remains between these parts even when the coil is energized. In the pull style, the conical plug and plunger have slightly different angles. Therefore, when the coil is energized and these parts come in contact, only an edge comes into contact, not the entire surface. Both of these designs eliminate the possibility of a concept known as latching. Latching occurs when the residual magnetic force is greater than the spring force.
Summary

In this chapter the following concepts were presented:

• The term summation of forces.
• What the actuator force, spring force, flow force and friction forces are.
• The two types of friction forces were discussed, mechanical and viscous.
• How the various forces affect the poppet and spool valves.
• How to measure and calculate the forces.
• What the compressed and free lengths of the spring are.
• The operation of the spool and poppet valve.
• How the response time is measured.
• Parameters affecting valve performance and response time, such as:
  - amp turns, available voltage, spring force, pressure, flow
• The meaning of open and closed in transition.
• What pull in and drop out are.
• When a push or pull style armature is used.
Review Questions

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

1. List two ways to measure the actuator force. __________ / __________

2. True or False. The spring force is a fixed force. ______________________

3. True or False. The free length of the spring is its length when installed in the de-energized valve. ______________________

4. Does the spring force increase or decrease when the coil is energized? ______________________

5. What causes the Bernoulli force to occur? ______________________

6. When fluid passes from a larger area to a smaller area is there a rise or drop in pressure? ______________________

7. What do the port numbers on the valve designate? ______________________

8. What term is used when the spool allows fluid to pass through to other ports in the transition position? ______________________

9. What term is used when the spool does not allow fluid to pass through to other ports in the transition position? ______________________

10. Name the two types of friction forces discussed in the chapter. __________ / __________

11. What type of force pulls water together to form a drop? ______________________

12. Which area of the pilot pin is exposed to low pressure? ______________________

13. What term describes the de-energized coil? ______________________

14. What are the forces acting on the spool valve. ______________________

15. What is pull-in? ______________________

16. What is the surface finish of the cage? Of the spool? ______________________

17. Describe how the poppet valve pulls in. ______________________

18. What is the pressure force acting on the pilot pin? ______________________
Notes