**High-Pressure, High Flowrate & High-Speed Pilot Operated Solenoid Valve Design**

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Abstract

This article proposes design approaches to reduce the duration pilot operated solenoid valve duty cycle duration. Summarize problem with duration. In this study we iterated different assembly configurations to find the optimal balance between solenoid power, actuation chamber volume, pilot orifice and adjusting orifice to increase valve opening and closing speed. We observed that reducing actuation chamber volume reduces the opening time of the main orifice and optimizing adjusting orifice area reduces the main orifice closing time. This could reduce the number of valves used for regulator applications and reduce development time and cost.

Keywords: pilot operated solenoid valve, high-speed, high flowrate, high-pressure

Introduction

Solenoid valves are used to control fluid flow in the industry. They operate by turning magnetic force into linear motion using a coil and a ferromagnetic armature. Typical industrial applications use 18-watt, 24 volt and 0.75 ampere coils to energize the armature. Furthermore, designs should take fluid compatibility into account. Solenoid valve designs for oxidizer must use oxygen compatible metals and sealing elements, whereas solenoid valve designs for petrochemical or other solvent chemical must prefer chemical compatible sealing elements.

The key design criteria for the safe operation of these valves are response time, flow rate and operating pressure. Precise control of these valves is critical in terms of the full duty cycle, i.e., fully opening the valve from a closed state and closing it from fully opened state. Precise control of these valves allows them to be used in cold gas thrusters and bang-bang gas regulators for aerospace applications.

In this study we iterated different assembly configurations to find the optimal balance between solenoid power, actuation chamber volume, pilot orifice and adjusting orifice to increase valve opening and closing speed. We first modeled the flow characteristics of the existing pilot operated solenoid valve by measuring valve opening and closing timings from solenoid power on and off signals.

Working Principles

Above is the equation for force applied on iron armature (plunger) where; V is the voltage applied, is permeability of the iron armature, is permeability of air, is the resistance per unit length of the wire, is the inside radius of coil, is the center radius of coil, l is coil length, and x is the armature displacement. (Paul H. Schimpf)

As seen above solenoid force F is inversely proportional to stroke (armature displacement). The focus of this study is to design an aerospace grade solenoid valve thus, power consumption is a design criterion to reduce. Therefore, a minimal stroke of 0.3 mm (about 0.01 in) was preferred. On the other hand, reducing stroke reduces flow restriction area thus limiting maximum flow rate.

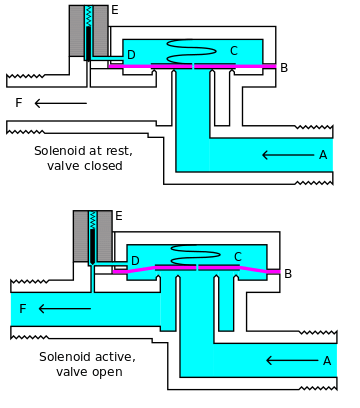
The equation above shows the relation between stroke h, and flow restriction area . Flow restriction area of plunger stroke is approximated by the side surface area of an upright cylinder. D represents the diameter of the orifice. Ideally flow should be restricted at the orifice thus the orifice surface area should be smaller than . The orifice surface area is calculated using the formula below:

To restrict flow at the orifice the following condition must be met:

Solenoid armature stroke must be greater than one fourth of orifice diameter as seen above. Design of orifice diameter must satisfy solenoid force balance and pressure balance.

Above is the equation for mass flow rate for an ideal compressible gas where; is the mass flow rate, A is the area of flow restricting surface, is the upstream gas pressure, is the upstream gas temperature, is the specific heat ratio, R is the gas constant, M is the Mach Number of the flow. Upstream pressure and temperature are dependent variables because the solenoid valve must operate in different regimes. Specific heat ratio and gas constant can only be controlled by restricting fluid type. For the two reasons above mass flow rate requirements are met by controlling the only independent variable flow restriction area.

Solenoid valve mass flow rate for gases is approximated using the ideal compressible gas assumption. Mass flow rate is proportional to the orifice, flow restriction, surface area. This relation increases the power requirements dramatically for high pressure and/or high flowrate applications. To break the direct relation between solenoid power and valve mass flow, pilot operated, two stage, solenoid valves were developed. The principal idea of pilot operated solenoid valve is to use the pressure of the upstream gas as the main actuating force rather than the solenoid force. This is achieved by carefully designing an actuation chamber to leverage pressure differences.



A- Input side  
B- Main Plunger  
C- Actuation chamber  
D- Pilot Orifice  
E- Electromechanical Solenoid  
F- Output side

G- Adjusting Orifice

H- Main Orifice

Figure 1 Pilot Operated Solenoid Valve Principles [1]

Actuation Chamber Inlet and Outlet

There are two flow restriction surfaces that dictate how the valve operates: pilot orifice (D) and adjusting orifice (G). Pilot orifice acts like the orifice of a single stage solenoid valve. Surface area of pilot orifice dictates how fast the actuation chamber is discharged. The designer should find a balance between pilot orifice area, solenoid power required to actuate the solenoid and adjusting orifice area.

The adjusting orifice area determines how fast the upstream fluid fills actuation chamber. If the adjusting orifice area is bigger than the pilot orifice area, the pilot operated solenoid valve will require a higher pressure differential to operate. For aerospace applications a low-pressure differential is preferred; thus, adjusting orifice area is a critical design parameter.

Actuation Chamber

Actuation chamber volume is critical for high-speed high flow rate pilot operated solenoid valves and dictates how much gas needs to be discharged from or filled into the actuation chamber to push the main plunger. Ideally, a negligible actuation chamber volume is desirable. Unfortunately, the range of motion of the pilot and the main plunger and the volume occupied by compression springs in the assembly only slightly increases actuation chamber volume which, limits how fast the main orifice of the pilot operated solenoid valve can open and close.

Diagram

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Figure 2Valve States [2]

As seen in the figure above valve opening, is divided into 3 steps. In this design the main plunger is PEAK plastic and is the main sealing material. The outlet body, the pilot plunger, and the plunger body are 304 stainless steel for oxygen compatibility.

The main plunger force balance is presented below where is the compression spring force, , and are the forces applied by the actuation chamber and the upstream pipe section and downstream pipe section pressure respectively.

Graphical user interface, application

Description automatically generated

Figure 3 Main Plunger Force Balance

The pilot plunger force balance is presented below where is the compression spring force, is the solenoid electromagnetic force, , and are the forces applied by the actuation chamber and the downstream pipe section pressure respectively.

Graphical user interface, application

Description automatically generated

Figure 4Pilot Plunger Force Balance

In the initial state (a) the actuation chamber pressure is equal to the upstream pipe section pressure and the downstream pipe pressure is lower than the upstream pipe section pressure. Net forces the pilot plunger to press against the main plunger and seals the pilot orifice.

In state b, the pilot is pulled by overcoming the spring and the pressure forces on the pilot plunger. The pilot orifice is opened and the fluid in actuation chamber start to discharge to the downstream pipe section.

In state c, the increase in downstream pipe section pressure and the decrease in the actuation chamber pressure are observed. However, for the main plunger to move the actuation chamber pressure must fall below a critical threshold. In addition to the fluid discharge, fluid flows from upstream pipe section to actuation chamber through the adjusting orifice and pressurizes the actuation chamber. For the actuation chamber pressure to fall below the critical limit, the adjusting orifice mass flow rate must be smaller than the pilot orifice mass flow rate.

In state (d), the actuation chamber pressure fell below the critical threshold and main plunger retracted. This opens the main orifice and high flowrate is achieved. The upstream pipe section pressure starts to tip off at this point to a level determined by the mass flow rate. The downstream pipe section pressure approaches to upstream pipe section pressure. Pressure difference between the upstream and the downstream pipe sections are determined by the mass flow rate.

Computational Model

Our model is constructed to observe the performance of the design under steady upstream and downstream pressure. It is assumed that there is an infinite upstream and downstream reservoir. The upstream reservoir pressure is set to 400Bar, and the downstream reservoir pressure is set to 1Bar. The pilot operated solenoid valve is connected to the upstream and the downstream reservoirs via the upstream pipe section and the downstream pipe section respectively. These pipe sections are critical for modeling because they simulate the plumbing the end user would use. Both pipe sections have a 15mm, ~0.6 inch, inside diameter and have a length of 250 mm, ~9.85 inches. Upstream pipe section inlet surface area is restricted by the pipe diameter itself and is equal to 176.7 mm2, 0.27 square inches. The downstream pipe section is modeled to have a nozzle that discharges gas to the downstream reservoir to emulate other flow restricting components in plumbing. Nozzle orifice diameter is selected as 9mm and the area is 63.6mm2, ~0.1 square inches.

In the initial state upstream reservoir, upstream pipe section and the actuation chamber are at 400 Bars and 273 K. The downstream pipe section and the downstream reservoir are at 1 Bar and 273 K.

A full simulation cycle is first opening the valve and obtaining steady mass flow then, closing the valve and waiting for the system to get back to equilibrium. At ms, the pilot plunger is retracted completely and at ms the pilot plunger seals the pilot orifice. The total simulation time is 6ms and timestep for the simulation is .

Thermodynamics

Nitrogen gas is selected as the working fluid in this model. Mass flow rates for the upstream pipe section inlet, the adjusting orifice, the pilot orifice, the main orifice and the downstream pipe section nozzle are computed using the equation for mass flow rate of ideal gases. First, Mach number is computed and limited to 1 since if the flow is choked in a converging nozzle, it cannot accelerate further than Mach 1. The total gas intake and releases for all control volumes are computed individually and put through a polytropic process. For this study the polytropic index is taken as 1.1 assuming that high velocity flow causes effective heat transfer with the valve body. Gas flowing through control volumes creates pressure changes that result in a change in net force applied on the main plunger. The main lunger acceleration is computed using this net force. The plunger position for next iteration is computed and another polytropic process is applied on the actuation chamber, with the expansion or contraction in volume by the main plunger movement.

Design Optimization

Reducing Actuation Chamber Volume

Reducing actuation chamber volume reduces main plunger response time. Original design closed actuation chamber volume is 3,675 mm3 and the open actuation chamber volume is 2,198 mm3. The new design has the following actuation chamber volumes for closed and open state respectively 1722 mm3 and 1037 mm3. The closed volume is reduced by 53% and the opened volume is reduced by 52%. The main plunger stroke was also reduced to 3 mm from 5.9 mm to facilitate the reduction in volume. The main plunger requires to travel a shorter distance thus opening and closing take less time.

The pilot and the main orifice dimensions were kept the same to isolate the effect of volume change in pilot operated solenoid valve response time.

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Figure 5Main Plunger Displacement

In the figure above pilot orifice is opened at and closed at , (t in ms). As seen in the figure, low volume design responded faster to pilot orifice opening. Original design fully opened in 0.557ms and closed shut in 1.684ms. The low volume design on however opened fully in 0.322ms and closed shut in 0.665ms. Valve opening time reduced by 42% and closing time is reduced by 60%. This reduction in response time is due to faster settling time for the actuation chamber pressure.

Diagram

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Figure 6Valve Opening Pressures

Figure above presents pressures at the opening phase of the pilot operated solenoid valve. In the original design, it takes 0.3ms for the action chamber pressure to drop to its minimum. In the low volume design, it only takes 0.24ms. The maximum force difference between and is applied at this moment where the main plunger has the top acceleration to open. The maximum flow rate from the upstream pipe section to the downstream pipe section in achieved at the dipping point (downward spike) of the upstream pipe section pressure. In the original design, it takes 0.457ms to reach the maximum flow rate. In the low volume design, it takes 0.308ms to reach the maximum flow rate.

Diagram

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Figure 7Upstream Pipe Section to Downstream Pipe Section Mass Flow Rate

In the figure above, the dipping point of upstream pipe section pressures are verified by the maximum mass flow rate achieved at the main orifice. Notice that both designs have a maximum steady flow rate of 4.807 kg/s. The response time improvement does not reduce the mass flow rate capability.

Diagram

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Figure 8Valve Closing Pressures

Figure above presents the pressures at the closing phase of the pilot operated solenoid valve. In the original design, it takes 3ms for the action chamber pressure to raise to the maximum upstream pressure. In the low volume design, it only takes 1.366ms. The downstream pipe section pressures settle in 1.938ms and 0.889ms for original and low volume design respectively. Notice that the actuation chamber pressures lag in behind the upstream pressures by a considerable amount. This is due to the expansion of the actuation chamber volume. The actuation chamber pressures settle after the downstream pipe section pressures. Adjusting the orifice surface area is the limiting factor for actuation chamber pressure settling time.

Orifice Optimized Design

Although low volume design reduced opening time by 42% and closing time by 60%, the valve closing duration (0.665ms) is more than the double of opening duration (0.322ms). For ideal PWM valve operation opening and closing time should be equal. Considering precise drilling capabilities on this scale, increasing adjusting orifice diameter from 0.3mm to 0.5mm yielded closer opening and closing durations. Orifice optimized design is an iteration on low volume design, thus they have the same actuation chamber volume and the same plunger range of motion.

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Figure 9Orifice Optimized Main Plunger Displacement

As seen in the figure above, the orifice optimized opening duration is 0.412ms and the closing time is 0.361ms. The closing time improved by 45% compared to the low volume design. However, there is a tradeoff for increasing the adjusting orifice area, the opening time is increased by 28% compared to low volume design. The main orifice opening is 15% slower than the closing time in the orifice optimized design. The orifice optimized design increased responsiveness of the pilot operated solenoid valve considering that closing the duration was more than double the opening duration in low volume design. Total of opening and closing duration for the original, low volume and the orifice optimized designs are 2.242ms, 0.983ms and 0.773ms respectively. The orifice optimized design reduced the total minimum cycle time by 65% and 21% for the original and the low volume design respectively.

Conclusion

We observed that reducing actuation chamber volume reduces the opening time of the main orifice and optimizing adjusting orifice area reduces the main orifice closing time with a small tradeoff for opening time. Reducing the total minimum cycle time by 65% gives the engineers greater control on flow systems. This could reduce the number of valves used for regulator applications and reduce development time and cost.

It should be noted that in this two-step design optimization, the pilot orifice was assumed to be opened instantaneously with the solenoid power signal. However, in real-life application an overhead for armature magnetization must be expected. Pilot orifice dynamics will be modeled in a future work for a more comprehensive pilot operated solenoid valve model.

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