Texas A&M University

Graduate Term Project: Analysis of Solenoid Valve -Applying MEEN 634 Principles

Term Project

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Dynamics and Modeling of Mechatronic Systems -MEEN 667

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OBJECTIVE

The main goal of this report is to analyze a solenoid valve using the principles discussed during the Dynamics and Modeling of Mechatronic Systems course. This report presents an overview of the common applications of these actuators. It also explains the working principles and slight variations currently used by the industry. The report then goes into the full dynamics and modeling of the solenoid valve's electromechanical system. It analyzes the valve's magnetic circuit as well as its interactions with the electromechanical model. The report ends with an overall conclusion of the analysis.

SIGNIFICANCE

Solenoid valves play a huge role in today's engineering world. They are meant to convert electrical energy into mechanical energy. The structure is composed of a valve body attached to a case that hosts the solenoid and all the required cabling.

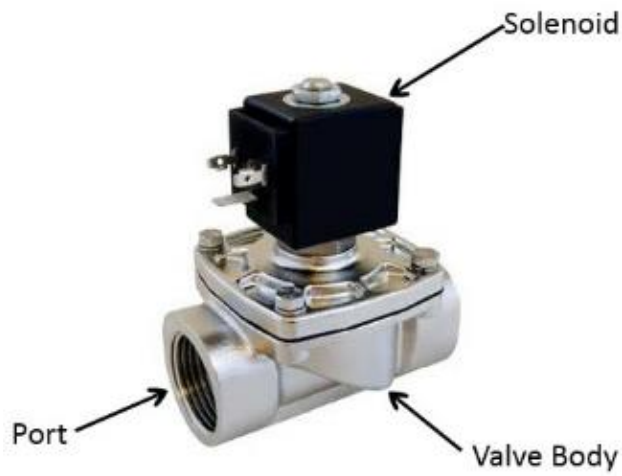

Figure 1: Solenoid Valve [1]

Solenoid valves allow for autonomous control of fluid flow within a system. The fluid that flows through the system could be a liquid or a gas. The solenoid controls the valve, by passing a current through it, that consequently produces an electromagnetic field. If the valve is connected to a controller, it can be operated remotely by a computer without the need for engineers to physically open and close these valves. Solenoid valves make systems run safely and efficiently.

The significance of these solenoid valves can be seen in the wide variety of systems that make use of these actuators. A clear example of its implementation can be found in commercial refrigeration systems[2]. At least one solenoid valve is present in the hot gas defrost line, to control the flow of hot refrigerant into the evaporator during the defrost cycle. When the moisture in the air condenses on the tubes of the evaporator, it will freeze and cause a build up of ice. To ensure efficient operation, this must be removed. So, a solenoid valve is used to send hot refrigerant from the compressor, through the evaporator instead of the condenser. Once the defrost has completed. The solenoid valve closes, and the system continues as normal, in cooling mode.

Another common field where these solenoid valves are necessary is for industrial applications. These valves can be used to precisely control the flow & mixing of fluids. I.e., to pour a perfect amount of soda into a bottle on a production line. Or to detect and prevent leaks. If a sensor detects a leak from the pipe work, then the controller will tell the solenoid valve to close that part of the production line off. Preventing product waste and keeping equipment protected.

WORKING PRINCIPLES & ELECTROMAGNETIC-MECHANICAL INTERACTIONS

To understand the interactions occurring at the valve's mechanical, electrical, and magnetic subsystems; a more in-depth analysis of the actuator's components is presented in figure 2. [3]

- **Coil windings:** A series of turns of wire wrapped around a ferromagnetic material i.e.,(steel). The coil has a hollow part where a plunger is found. The movement of the plunger inside this coil is controlled by a spring.
- **Plunger of a solenoid valve:** When the solenoid coil is magnetized and produces a magnetic field, the plunger moves up or down. It is cylindrical in shape and usually made of steel. The plunger moves up or down when the solenoid coil is energized and produces a magnetic field. This movement controls the media in the valve allowing the fluid to pass, block or restrict the amount that passes through. The plunger also has a seal that closes the holes.
- **Solenoid Coil:** As current flows through the valve, the cylindrical solenoid coil of wire serves as a current-carrying coil, acting as a magnet. It is usually round and hollow, is made of metal and houses the coil windings. It holds the coil wire in place and magnetizes to move the plunger.
- **Lead Wires:** Current from the power supply flows to the valve through the lead wires. When power is off, the current flow stops.
- **Solenoid Spring:** The tension required to keep the plunger in place is provided by the solenoid spring. When the current in the coil stops flowing, residual magnetism may cause the plunger to become stuck up or down the sleeve in which it moves. When current stops flowing, the spring returns the plunger to its original position. It also keeps the plunger from falling down the tube because of gravity.
- **Orifice:** Connects both input & output ports. The spring and the current flowing through the valve control the movement of the plunger or piston, which controls the opening of the hole. The sensor detects the process by which the valve passes through the inlet. As the sensor detects that fluid is not needed, it shuts off the current flow to the valve. The valve loses power supply, and the plunger or piston goes down and closes the hole. This stops the flow of fluid from the inlet to the outlet ports.

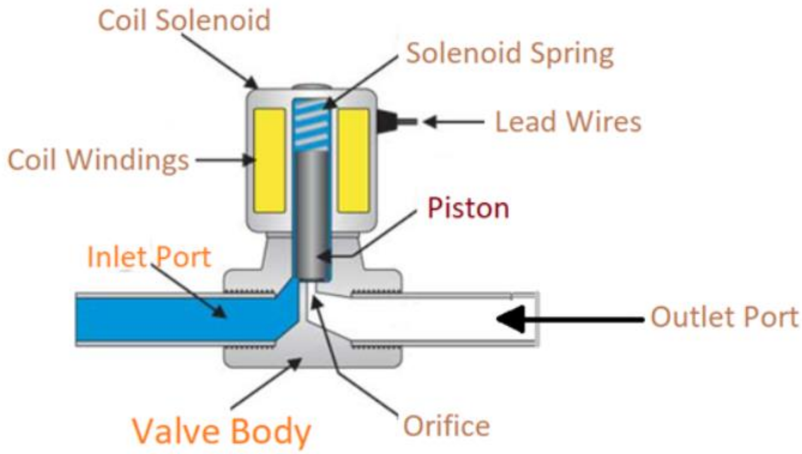

Figure 2: Schematic of a Solenoid Valve [3]

There are a few variations in how the valve operates depending on the required capacity and the pressure it's working with. Directly operated valves are the most widely used kind of operated valves [2]. When you pass an electrical current through a coil, it generates an electromagnetic field. This magnetic field is used to control the valve. There are two types of valves: normally open and normally closed.

Let's start by presenting the working principle of the normally closed type first. Inside the valve the armature can be found. The solenoid is placed over this and surrounds the armature, so that it's at the center of the magnetic field. The previously introduced solenoid spring pushes the plunger down in a normally closed type of valve. Because the plunger is pushed by the spring, it will sit in the down position to close the valve indefinitely. But if the coil receives an electrical current then it will generate an electromagnetic field. This magnetic field passes through the plunger and causes it to move upwards against the spring. Consequently, opening the valve. At the center of the coil, the magnetic field lines are the most compact and therefore the strongest. Therefore, we place the plunger in the center. Once the electrical current is stopped, then the magnetic field disappears, and the spring will force the plunger down again to close the valve.

In the case of normally open valves. The coil is again sitting around the armature, but this time the spring pushes the plunger in an upwards position so that the valve is always open, unless the solenoid coil is powered on.

In this design, if a current is passed through the coil in the opposite direction, it again creates an electromagnetic field, but this time the electromagnetic field pushes the plunger instead of pulling it. When the plunger is pushed. It will close the valve and stop the flow of fluid in the system. When the electrical current is stopped, the spring will then force the plunger back to the upwards position and open the valve again. In this design the direction of the current flowing in the coil is what determines whether the coil produces a pulling or pushing force on the plunger.

DESIGN & MODELING BASED ON DYNAMICS & ELECTROMAGNETICS PRINCIPLES

The solenoid can be implemented as an electrodynamic device for many electrical and mechanical parts. It behaves like a magnet to implement the effect of electricity upon motion It encapsulate a plunger or armature, which provides rectilinear motion. [4]

Solenoids can be mathematically modelled as electromagnetic circuits in addition to the related mechanical circuits, with one or several electrical inputs used to imply the interactions between currents in coil conductors and their corresponding magnetic fields.

The lumped electromechanical systems have two parts:

- The electrical part of the solenoid coil can be modeled as a combination of resistor and inductor elements in series
- The mechanical subsystem of the solenoid is represented as a mass model with a single conservative node.

Electromagnetic interactions and relations:

- When the electrical current passes through the coil, each section of wire generates a strong and uniform magnetic field inside the hollow of the solenoid. The strength of the magnetic field is proportional to the magnitude of the electric current in the coil and the iron core moves inside the casing of the solenoid.

Force-Energy relations:

- The solenoid gets energized with the required level of electrical energy using the lead wires. When current given to the coil is cut off, the mechanical parts push the plunger backward to its original position.

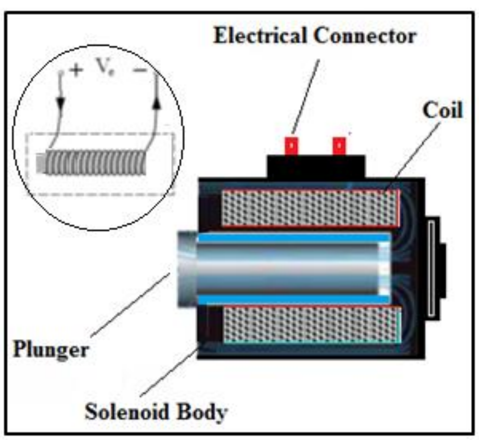

Figure 3. Schematic Diagram of the Solenoid [4]

The electromechanical model of the solenoid can split into electrical, magnetic, and mechanical subsystems. [4]

The voltage applied to the electrical part of the solenoid can be seen as input. The magnetic subsystem then generates magnetic force proportional to the electrical current in the coil. Finally, the magnetic force gets translated into displacement by the mechanical subsystem.

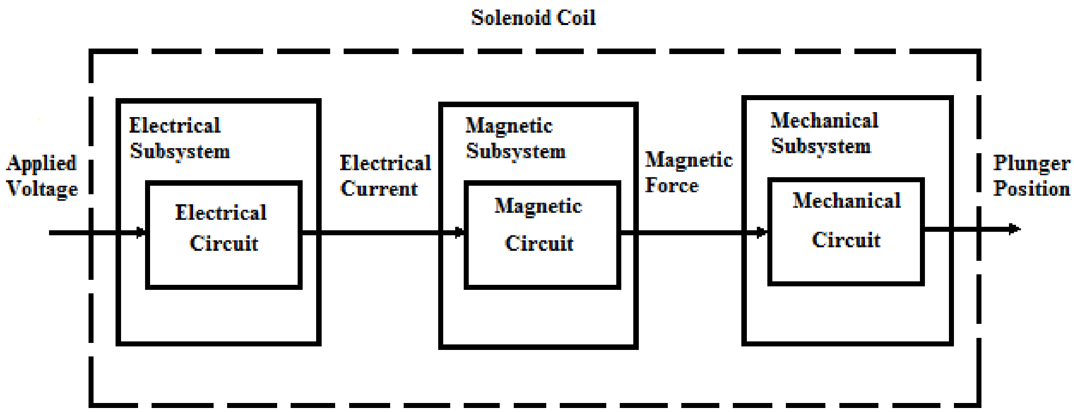

Figure 4. Electromechanical System [4]

Electrical Dynamics:

The electrical side of the system is modeled as series combination of inductance and resistance and can be considered as an *RL* circuit (seen figure 5).

Applying Kirchhoff's voltage law (*KVL*): voltage across the solenoid coil equals the sum of the voltages across the inductance and the resistance of the coil.

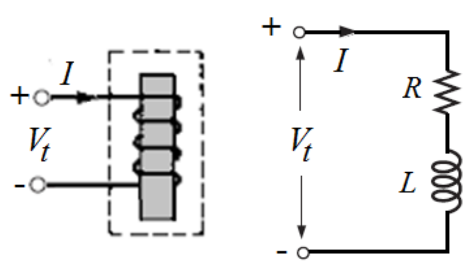

Figure 5. Lumped Electrical Subsystem - circuit [4]

$$V_t = V_R + V_L \quad \text{(Equation 1)}$$

Where:

- V_t = Total voltage applied to the solenoid coil (V)
- V_R = Voltage across the resistance of the solenoid coil (V)
- V_L = Voltage across the Inductance of the solenoid coil (V)
- $V_t =(L\, di(t)/dt)) + i(t)/R$ (Equation 2)

$$(L\, di(t)/dt)) + i(t)/R \ = V_R + V_L \quad \text{(Equation 3- Electrical EOM)}$$

When energizing the magnetic circuit of the solenoid with electrical energy, the magnetic force is set up in terms of the electrical current and it is applied into the plunger placed inside the core of the solenoid (see figure 6).

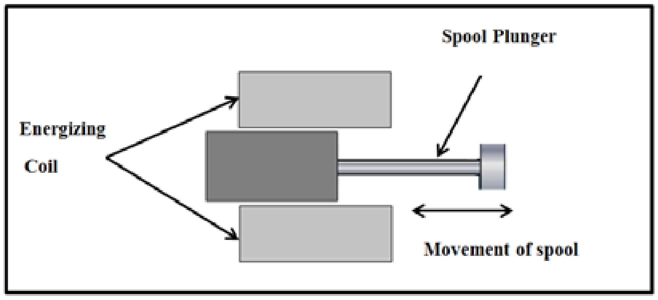

Figure 6. The Magnetic System of the Solenoid [4]

Using the co-energy conservation, a relation between the electrical and the mechanical dynamics can be derived.

The resulting magnetic force (F_m) of the coil depends on the distance travelled by the plunger (x) and the coil's electrical current $i(t)$; therefore, if we integrate the flux linkage with respect to current, we get (Equation 4) [4]:

$$F_m = \int_0^i \lambda(i,x)di = \frac{1}{2}L(x)i^2(t)$$

(Equation 4- Electromechanical relation)

λ= flux linkage (weber-turn)
L = the inductance of the coil (H)
$i(t)$ = coil's electrical current (A)

Mechanical Dynamics:

The mechanical subsystem is formed by the plunger along with the spring (see figure 7).

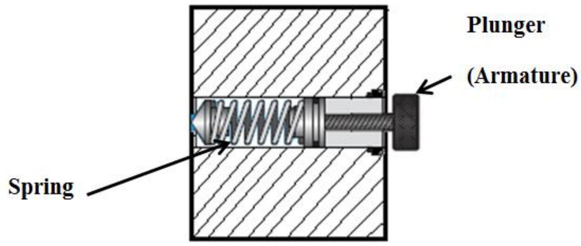

Figure 7. Spool Plunger of the Solenoid [4]

The mechanical system of the solenoid can me modeled as a typical mass- spring-damper system (see figure 8). The differential equation describing the motion of the spool in the solenoid is given by (Equation 5- Mechanical EOM) [4]:

$$m\ddot{x} + c\dot{x} + kx + F_f = F_m = k_c i(t)$$

m = plunger's mass (kg)
x = distance of the plunger (m)
kx= spring force (N)
c = damping coefficient
F_f = friction force (N)
F_m= magnetic force
k_c = coil force coefficient.

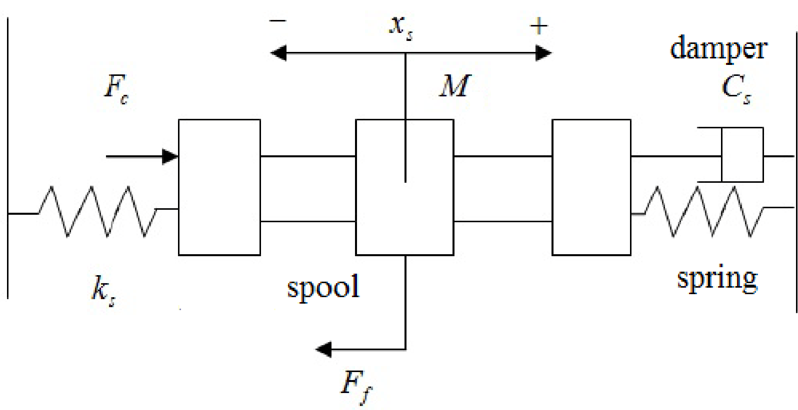

Figure 8. Mechanical Behavior of the Spool [4]

CONCLUSION

This project has covered a very detailed analysis of the design of solenoid valves. Such valves have proven to be present almost everywhere in today's world. Their application positively contributes to the overall efficiency and safety of multiple engineering systems. The significance of these actuators is the true reason behind the importance of understanding the working principles and electromechanical interactions behind these valves as well as the full dynamics and modeling of the solenoid's electromagnetic system. These actuators have proven to be truly useful tools in the world of systems' design & automation. These actuators could not be here today if it wasn't for the principles learned during the Dynamics and Modeling of Mechatronic Systems course.

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