DESIGN OF SOLENOID OPERATING VALVE APPLYING DESIGN FOR SIX SIGMA METHODOLOGY

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Abstract—Solenoid valves are Electromechanical valve in which electric current is passed through the conducting wire and the current flowing through conductive wire wound generates EMF within the wound axis and surrounding area, hey and due to generated magnetic flux drives the mechanical part called as plunger. Use of Electro mechanics all units is in different valve's, mechanical relays and electrical contactor. Solenoid coils are rated to operate from 12 V to 32 C DC and 110 V to 230 V AC systems with the power consumption ranging from 8 to 28 W. The solenoids made up of movable steel or iron slug called armature or plunger and wound of electromechanically inductive coil. The plunger movement is used to control fluid flow or the fluid flow direction. Selecting the proper valve for hydraulic system plays an important role in reducing the energy requirement and thus the operating cost. Various types of valves are used for an on/off control adjustment of the flow rate through the system, avoidance of back flow and pressure relief at safety devices. One of the most widely used valves is solenoid valve. The primary use of solenoid valve is to regulate the flow rate based on controlling electric power. Solenoid valves are also used as on/off valves in number of applications. The basic objective of this research is to achieve robustness in designing of solenoid valve for pull-in current CTQ using DFSS methodology.

Keywords—Solenoid Valve, Robust Design, Critical to Quality, Sensitivity Analysis, DFSS Methodology.

1. INTRODUCTION

The solenoid valves are mechanical structures comprising of the manifold and the sealing parts which are movable linearly or rotationally, perpendicular to the direction of fluid flow. These valves are utilized to regulate or to control flow of fluid. Solenoid valve is a made up of two important and basic functional units: 1. A solenoid with its core (electromagnet) 2. Manifold body containing one or more orifices. Besides that, the power used by solenoid valves become important as it comprises to total power consumption and in the application like aerospace the available power from system remains extremely low and solenoid needs to be designed to function in available electric power. Solenoid coils need more current only during activation, called the Pull-In current, to pull the plunger into the solenoid. However, when solenoid gets actuated, the coil of solenoid needs approximately 33% of its nominal current, termed as hold current, to maintain plunger in the hold position. Solenoid coils operating with even minor current steadily raise the temperature in the coil because of higher power dissipation. When the plunger movement gets detected, the stable condition current can be lower to hold current value to reduce power dissipation in the solenoid. The objective of this research work is to achieve robustness in designing of solenoid valve for pull in current CTQ using DFSS methodology.

Conventional Six Sigma or the DMAIC approach have some limitations, it can upgrade current products and services to a level which are capable, but the overall product or service performance may be limited by design. With the aim of improvement in this limitation, design for Six Sigma (DFSS) approach is advised as it comprises a complete range of product and service design, beginning with the voice of customer (VOC) up to the ending by product or service launch.
engineering CTQs, quantifiable functional requirements that can be measured and that will satisfy the VoCs. Identifying CTQs early in the design process clarifies design drivers that satisfy the VoCs and identifies the design risk early.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Pressure</td>
<td>620 to 690 KPA (90 to 100 psig)</td>
</tr>
<tr>
<td>Proof Pressure</td>
<td>1206.6 KPA (175 psig)</td>
</tr>
<tr>
<td>Ultimate Pressure</td>
<td>2068.6 KPA (300 psig)</td>
</tr>
</tbody>
</table>
| Temperature Requirement | Ambient temperature operation range = -55°C to +85°C  
Ambient temperature survivability range = -55°C to +85°C  
Fluid temperature range = -55°C to +85°C  
Bleed air temperature range = N/A |
| Leakage | Externally leakage: zero  
Internal leakage: zero  
Reverse leakage: N/A |
| Maximum dry weight | ≤ 0.091 kg (0.2 lbs) |
| Altitude | -1000 to +50000 ft |
| Endurance requirement | 25,000 closed to open to close cycles |
| Reliability | 80,000 cycles |
| Electrical Bonding | Max. to aircraft structure and 2.5 mΩ between any non-moving parts of the equipment |

### CTQs Table

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
<th>LS</th>
<th>US</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical bonding resistance (mΩ)</td>
<td>DC resistance between equipment case and aircraft structure ≤ 10 mΩ</td>
<td>10</td>
<td>0.300</td>
<td></td>
</tr>
<tr>
<td>Power consumption (Watt)</td>
<td>Overall power consumption by solenoid valve should be ≤ 12 W</td>
<td>6</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Pull-In current (mA)</td>
<td>This is drill down CTQ and should be ≤ 600 mA</td>
<td>300</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Endurance (Cycles)</td>
<td>Valve shall complete, 25k cycles without structural /performance degradation</td>
<td>25k</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air and fluid leakage (ml)</td>
<td>Zero air leakage at all operating conditions</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Max weight (kg)</td>
<td>Valve shall not exceed the weight of 0.091 kg</td>
<td>0.09</td>
<td>0.085</td>
<td></td>
</tr>
<tr>
<td>MTBF (cycles)</td>
<td>Minimum MTBF of 80k cycles under the environmental conditions specified</td>
<td>80k</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### PHASE II (DEFINITION)

This valve is designed to allow air to release in the atmosphere and holds fluid back in the system. Functional requirement is to have system to purge dissolved air from hydraulic system pressurised at operating pressure 620 -680 KPA (90 - 100 psig).

### PHASE III (DESIGN)

3.1 Construction (Modelling)

The concept model valve is shown in the below figure. It comprises of the following important components as shown in below figures.

1. Plunger (Magnetic)
2. Bobbin Lower (Magnetic)
3. Bobbin Upper (Magnetic)
4. Tube (Non-Magnetic)
5. Solenoid Coil (Conductive)
6. Shell (Magnetic)
7. Spring (Non-Magnetic)

#### 3.2 Working of the valve

**Installed Condition:** The valve is normally closed in the installed condition as shown in below figure. The fluoro-silicone seal on the plunger, seals the air and fluid from hydraulic system due to spring force being exerted on plunger from backside.

**Open Condition:** When solenoid coil gets electrical power signal as air is present in hydraulic system, solenoid coil generates EMF and that EMF forces plunger to move against spring. The movement of plunger allows air to flow from hydraulic system into the atmosphere as shown by yellow arrows.

![Fig.2 Solenoid valve within Air Release System][20][21]

![Fig.3 Solenoid valve section view][3]

![Fig.4 Solenoid valve closed condition][4]
3.3 Orifice Sizing
The diameter of the orifice can be determined using the formula:

\[ d = \sqrt{\frac{C_v}{19}} \]

As \( C_v \) here is unknown it can be determined using the general relation to find the flow occurring through the orifice which is,

\[ Q = C_v X \sqrt{\frac{\Delta P}{SG}} \]

As air would be the fluid in this specific valve which would be functioning in an aircraft the equation used here has a different relation between flow and \( C_v \)\(^{[1]}\).

\[ Q = \frac{1360}{60} C_v \sqrt{\frac{\Delta P \times P_1}{SG \times T_1}} \]

Where,
- \( d \) = Diameter of orifice
- \( Q \) = Flow rate, SCFM
- \( \Delta P \) = Pressure difference, psig
- \( P_1 \) = Upstream absolute static pressure, psig
- \( SG \) = Specific Gravity
- \( T_1 \) = Temperature, Rankine
- \( C_v \) = Valve – Flow coefficient

3.4 Plunger lift Calculations
Plunger lift is the length required for the plunger to travel from its set position to allow the desired flow through the opening.

\[ \text{Fluid flow area} = \pi (r + R) S \]

3.5 Spring Design
The spring used in the poppet or poppet type Solenoid valve is the helical compression spring which resists a compressive force. The main objective of spring design is to obtain a spring which will be reasonably economical for given application, will fit into the available space and will give satisfactory performance.

As the loads and constraints are known depending on which the suitable spring was selected from the Lee Springs Handbook of material S302 [16].
3.6 Current required by Solenoid at Pull-In mode
Force balance equation at the solenoid plunger pressure separating line can be given as:

\[ F_{\text{pull}} - in = F_s + F_r - F_p \]

Where,
- \( F_{\text{pull}} - in \) = Force required for Pull In of plunger
- \( F_s \) = Spring Force at installed condition is that Finstalled
- \( F_r \) = Force due to frictional resistance
- \( F_p \) = Pressure force on sealing surface

Magnetic Flux Density required to generate Pull In force can be given by,

\[ B = \sqrt{\frac{F_{\text{pull}} - in \times 2 \times \mu_0}{Ae}} \]

Where,
- \( B \) = Magnetic Flux
- \( \mu_0 \) = Permeability of air
- \( Ae \) = Sealing area

Also, relation of magnetic flux and conductive coil carrying current is given by,

\[ N I = \frac{B X ge}{\eta X \mu_0} \]

Where,
- \( N \) = No. of turns
- \( I \) = Current required
- \( ge \) = air gap length in inches
- \( \eta \) = Efficiency

Deriving equation further gives required current at Pull-In mode as,

\[ I = \frac{B X ge}{N X \mu_0 X \eta} \]

Deriving equation further gives current required at Pull-In mode as,

\[ I_{\text{pull}} - in = \sqrt{\frac{(F_{\text{pull}} - in \times 2 \times \mu_0)}{\pi X (D_b^2 - D_p^2) / 4 X \mu_0 X \eta X N}} \times ge \]

Where,
- \( N \) = No. of turns
- \( I \) = Current required
- \( B \) = Magnetic flux
- \( ge \) = air gap length in inches
- \( \eta \) = Efficiency
- \( \mu_0 \) = Permeability of air
- \( D_b \) = Bobbin outer diameter
- \( D_p \) = Bobbin inner diameter

Now, used Monte-Carlo Analysis to decide design space means to finalise tolerances for all parameters.

The certainty of meeting the current required at Pull-In mode requirement within the range of 254 mA to 100 mA.
4. PHASE IV (VALIDATION)

Verification and validation, in engineering or quality management systems, is the act of reviewing, inspecting, or testing, in order to establish and document that product, service or system meets regulatory or technical standards. It includes conducting an experimental testing on a Solenoid valve with proper testing setup, to extract current required by solenoid valve at Pull-In mode. After applying required pressure and temperature parameter on a solenoid valve via flowing media. Measuring actual current taken, power consumption and conducting validation trial by operating valve for specified number of cycles to prove endurance. Then observing performance of valve & valve components and its comparison with results obtained through robust design approach.

5. CONCLUSION

DFSS is an approach to design or redesigning a new product and/or service for a commercial market, with miserably high process Sigma for performance from day one. The objective of DFSS is to produce such new product and/or services to market with the progression of performance of roughly 4.5 Sigma or better, for each customer requirement. This implies an ability to understand the customer needs and to design and implement the new offering with the reliability of delivery before launch rather than after!

The valve design including concept designing, sizing and completed design project execution were carried out with the DFSS approach. The whole process has been followed right from identifying the CTQ’s to verifying whether the proposed design meets the requirements.

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