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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 mechanicals 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.

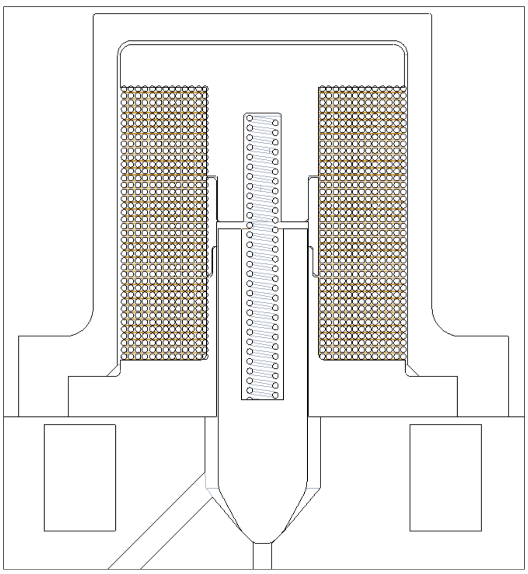


Fig.1 Solenoid valve concept

1. PHASE I (CCONCEPT)

The desires of design from customers are termed as VoCs (voice of the customer) and should be converted into 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.

Requirement	Specification limits
Operating Pressure	620 to 690 KPA (90 to 100 psig)
Proof Pressure	1206.6 KPA (175 psig)
Ultimate Pressure	2068.6 KPA (300 psig)
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	10 mΩ Max. to aircraft structure and 2.5 mΩ between any non-moving parts of the equipment

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

2. 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).

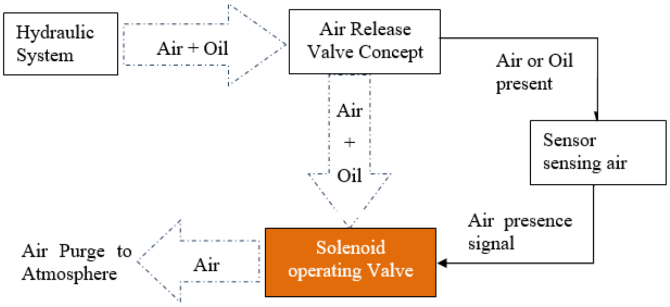


Fig.2 Solenoid valve within Air Release System [20] [21]

3. 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)

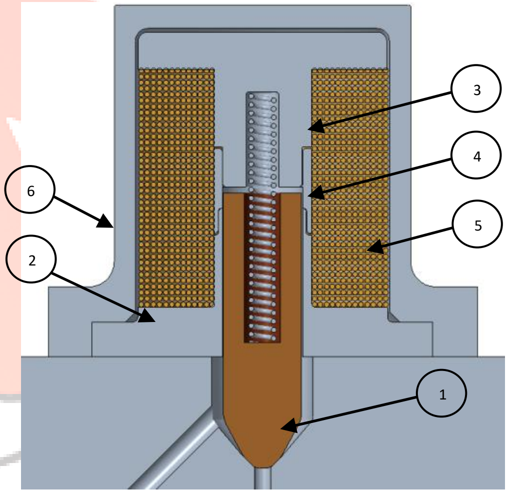


Fig.3 Solenoid valve section view

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.

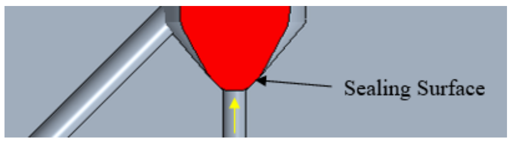


Fig.4 Solenoid valve closed condition

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.

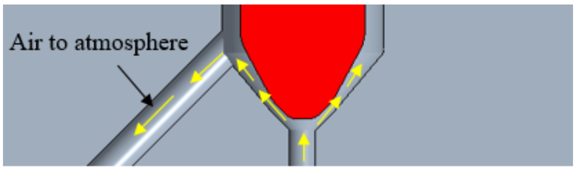


Fig.5 Solenoid valve open condition

3.3 Orifice Sizing

The diameter of the orifice can be determined using the formula:

$$d = \sqrt{\frac{Cv}{19}}$$

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

$$Q = Cv\ X \sqrt{\frac{\triangle P}{SG}}$$

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 Cv[1].

$$Q = \frac{1360}{60} Cv \sqrt{\frac{\triangle P\ X\ P1}{SG\ X\ T1}}$$

Where,

d = Diameter of orifice
Q = Flow rate, SCFM
△P = Pressure difference, psig
P1 = Upstream absolute static pressure, psig
SG = Specific Gravity
T1 = Temperature, Rankine
Cv = Valve – Flow coefficient

Orifice Sizing

Requirement	Symbol	Value	unit	comments
Minimum flow required through orifice	m1	0.09	lb/min	
Maximum flow required through orifice	m2	0.12	lb/min	
Mean mass flow rate	m	0.11	lb/min	
Density of air		1.20	kg/m^3	
		0.07	lb/ft^3	1 kg/m^3 = 0.06242796 lb/ft^3
		13.35	ft^3/lb	
Air Flow rate	Q	1.47	SCFM	Mean mass flow rate X 13.35 ft^3/lb
		88.11	SCFH	SCFH X 60
Pressure difference	ΔP	85.00	psig	
Temperature	T	70.00	°F	
		530.67	R	F + 460.67 = Rankine
Upstream absolute static pressure,	P1	99.69	psig	
Factor Y	Y	1.00		Y = 1 for sunsonic flow
specific gravity (Air)	SG	1.00		Gas specific gravity is 1
Valve Flow Coeffienet	Cv	0.016		((Q/1360)(sqrt(T1/(ΔP*P1))))
Diameter of Orifice	d	0.029	Inch	Sqrt(Cv/19)

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.

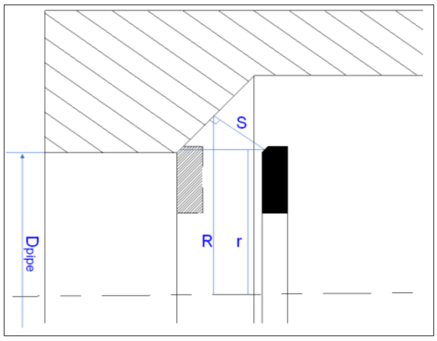


Fig.6 Surface area of opening during plunger travel

The fluid flow area of the opening that the plunger shift has created in the valve geometry is calculated by,

Fluid flow area = π (r + R) S

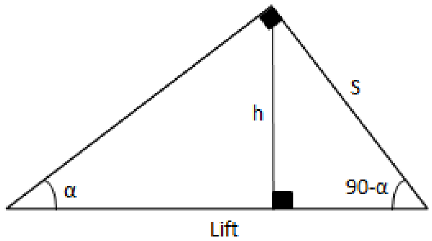


Fig.7 Lift calculation Diagram

Lift Calculations

Increment	Lift	s = L sin α	h = s X sin(90-α)	R2 = r2 + h	Flow Area = πX (R1 + R2) X S
0	0	0	0	0.034	0
1	0.001	0.0007	0.0005	0.0345	0.000152
2	0.002	0.0014	0.001	0.035	0.000307
3	0.003	0.0021	0.0015	0.0355	0.000463
4	0.004	0.0028	0.002	0.036	0.000622
5	0.00425	0.0030	0.002125	0.036125	0.000662
6	0.0045	0.0032	0.00225	0.03625	0.000702
7	0.00475	0.0034	0.002375	0.036375	0.000743
8	0.005	0.0035	0.0025	0.0365	0.000783

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.

Spring Design

Pressure Acting Diameter	0.068	in
Area Pressure Acting	0.0036	in^2
Proof Pressure (+5 psi tolerance during Testing)	172.5	psi
FOS	1.10	
Spring Force Required at Installed Length	0.689	lbf
Spring Compression Required	0.165	in
Spring Installed Length Calculated (Max)	0.426	in
Spring Installed Length Design	0.4165	in
Lift required (Max)	0.00425	inches
Spring working length (SOV open)	0.406	inches
Spring Force at working Length	0.77145	lbf

Lee Catalog

Outer dia	0.055	inch
Mean diameter (Dm)	0.045	inch
Solid Height	0.359	inch
Wire dia (dw)	0.01	inch
Spring Rate (Catalog)	4.17	lbf-in
Load at Solid height	0.967	lbf
Free length	0.591	inch

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:

$$Fpull - in = Fs + Fr - Fp$$

Where,
Fpull-in = Force required for Pull In of plunger
Fs = Spring Force at installed condition is that Finstalled
Fr = Force due to frictional resistance
Fp = Pressure force on sealing surface

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

$$B = \sqrt{\frac{Fpull - in\ X\ 2\ X\ \mu 0}{Ae}}$$

Where,
B = Magnetic Flux
μ0 = Permeability of air
Ae = Sealing area

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

$$NI = \frac{B\ X\ ge}{\eta\ X\ \mu 0}$$

Where,
N = No. of turns
I = Current required
ge = air gap length in inches
η = 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 –

$$Ipull - in = \frac{\sqrt{\left(\frac{Fpull-in\ X\ 2\ X\ \mu 0}{\pi\ X\ \frac{Db^2 - Dp^2}{4}}\right)}\ X\ ge}{\mu 0\ X\ \eta\ X\ N}$$

Where,
N = No. of turns
I = Current required
B = Magnetic flux
ge = air gap length in inches
η = Efficiency
μ0 = Permeability of air
Db = Bobbin outer diameter
Dp = Bobbin inner diameter

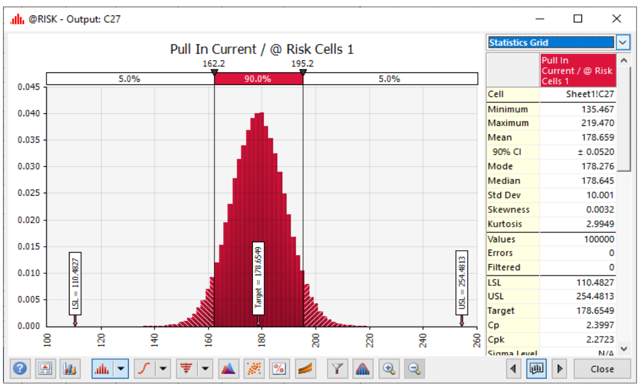
Acceleration Loads			
Componeents		Nominal	
Total	m	0.002	lbs
Plunger seal	m1	0.0003101	lbs
Spring	m2	0.0001114	lbs
Plunger	m3	0.0016289	lbs
Other Components	m4	0	Lbs
Design Acceleration	-	15	G
Acceleration Load	F_a	0.031	lbf
Pressure Resisting			
Parameters	Symbols	Nominal	Unit
Spring Force - at Installed Condition	F_{Spr}	0.670	lbf
Friction Force	F_{fr}	0	lbf
Pressure Acting Area	A.seat	0.0033	in^2
System Pressure	P_{ope}	175	psig
Force Pressure	F_p	0.282	lbf
FOS		1.1	-
Pull In Force Required	$F_{pull-in}$	0.457	lbf

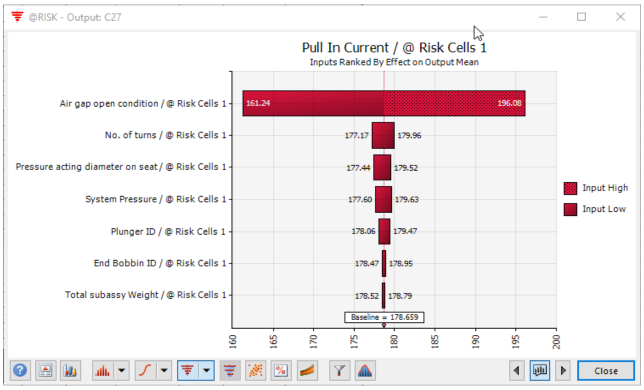
Solenoid Valve - Pull-in and Drop Out Calculations (Pool Type - Flat, Normally Closed Type)				
Parameters	Symbols	Spec	Nominal	Unit
Inputs				
Design Type	Pressure Resisting			
Pull In Force	$F_{pull-In}$		0.457	lbf
Air Gap - Open Condition	g_e		0.0090	in
Air Gap - Closed Condition	g_e		0.0000	in
absolute permeability=2*m_0	μ_0		72	-
End Bobbin ID	D_b		0.159	In
Plunger ID	D_p		0.065	In
Effective Area(End Bobbing and Plunger)	Ae		0.0166	in^2
Flux Density	Bf		44.45	K max/In^2
Permeability	μ_0		0.00319	-
Magnetic efficiency factor = 70% (Pull In)	h		0.70	-
Magnetic efficiency factor = 100% (Drop Out)	h		1.0	-
No. of Turns	N		1058	-
Magneto-Motive Force	MMF		179	amp-turns(A*T)
Resistance (-40F to 210F)	Ohm		25	Ohm
Output - Pull In				
Pull in Current	$I_{pull\ in}$	<300	169	mA
Pull in Voltage	$V_{pull\ in}$	<10	4.2	Volts
Output - Drop Out				
Drop Out Current	$I_{Drop\ Out}$		0	mA
Drop Out Voltage	$V_{Drop\ Out}$		0.0	Volts

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

Pull In & Drop out current & voltage Sensitivity Analysis											
Description	Symbol	@ Risk Cells 1	Units	Mean/Target	Distribution type	LSL	USL	Equal bilateral tolerance Tolerance	Std Deviation	Process Capability assumption	Typical Manufacturing Tolerances
Inputs											
Air gap open condition	g	0.00900	in	0.0090	Normal	0.006	0.012	0.003	0.00050	6 σ	
Air Gap - Closed Condition	g_c	0.001	in	0.001	Normal	0.0008	0.0012	0.0002	0.00003	6 σ	
End Bobbin ID	D_b	0.159	in	0.159	Normal	0.1589	0.1600	0.00055	0.00009	6 σ	
Plunger ID	D_p	0.065	in	0.065	Normal	0.0600	0.0700	0.005	0.00083	6 σ	
No. of turns	N	1033.000	Nos	1033.000	Normal	1008	1058	25	4.16667	6 σ	
Resistance (-40F to 210F)	Ohm	25.000	Ohm	25.000	Normal	18	32	7.08	1.18000	6 σ	
System Pressure	P_{ope}	85.000	psig	85.000	Normal	80	90	5	0.83333	6 σ	
Total subassy Weight	m	0.00205	lbs	0.00205	Normal	0.00195	0.00215	0.00010	0.00002	6 σ	5.0%
Friction Force	F_{fr}	0.000	lbf	0.000	Normal	0.0	0.0	0	0.00000	6 σ	5.0%
Pressure acting diameter on seat	d	0.06800	in	0.06800	Normal	0.0660	0.0700	0.002	0.00033	6 σ	
absolute permeability=2*m_0		72.000		72.000							
Permeability		0.003		0.00319							
Magnetic efficiency factor = 100% (Drop Out)		1.000		1.000							
Magnetic efficiency factor = 70% (Pull In)		0.700		0.700							
FOS		1.100		1.100							
Spring force	F_{Spr}	0.72150	lbf	0.72150	Normal	0.6590	0.7840				
Acceleration Load	F_a	0.0308	lbf	0.03076	Normal	0.01948	0.04306				
Pressure acting area	A	0.0036317	in^2	0.0036317	Normal	0.00342	0.00385	0.0002136	0.00004	6 σ	
Force due to Pressure	F_p	0.308693	lbf	0.308693	Normal	0.308	0.308				
Pull In Force	$F_{pull-in}$	0.4848	lbf	0.4848	Normal	0.406	0.567				
Outputs											
Pull In Current	$I_{pull\ in}$	178.655	mA	178.655	Normal	110.48	254.48	$I_{pull-in}$ = [illegible] *1000 mA			
Pull In Voltage	$V_{pull\ in}$	4.466	Volts	4.466	Normal	1.98	8.16				
Drop out Current	$I_{Drop\ Out}$	13.895	mA	13.895	Normal	10.31	17.81				
Drop out Voltage	$V_{Drop\ Out}$	0.347	Volts	0.347	Normal	0.18	0.57				
Outputs											
	$I_{pull\ in}$	$V_{pull\ in}$	$I_{Drop\ Out}$	$V_{Drop\ Out}$							
Mean	178.659	4.466	13.896	0.347							
Standard deviation	10.001	0.326	0.473	0.020							
Cpk Lower	2.272	2.539	2.526	2.685							
Cpk Upper	2.527	3.775	2.762	3.699							
Cpk	2.272	2.539	2.526	2.685							
DPM	0	0	0	0							

The certainty of meeting the current required at Pull-In mode requirement within the range of 254 mA to 100 mA.





Acceleration Loads					
Componeents		Nominal	Max	Min	
Total	m	0.002	0.00215292	0.000194788	lbs
Poppet	m1	0.0003101	0.000325605	2.94595E-05	lbs
Spring	m2	0.0001114	0.00011697	0.000010583	lbs
Plunger	m3	0.0016289	0.001710345	0.000154746	lbs
Other Components	m4	0	0	0	Lbs
Design Acceleration	-	15	20	10	G
Acceleration Load	F_a	0.031	0.043	0.002	lbf
Pressure Resisting					
Parameters	**Symbols**	**Nominal**	**Max**	**Min**	**Unit**
Spring Force - at Installed Condition	F_{Spr}	0.670	0.752	0.576	lbf
Friction Force	F_{fr}	0	0	0	lbf
Pressure Acting Area	A.seat	0.0033	0.0036	0.0031	in^2
System Pressure	P_{ope}	175	180	170	psig
Force Pressure	F_p	0.282	0.286	0.276	lbf
FOS		1.1			-
Pull In Force Required	$F_{pull-in}$	0.457	0.566	0.320	lbf
Pressure Assisting					
Parameters	**Symbols**	**Nominal**	**Max**	**Min**	**Unit**
System Pressure	P_{ope}	85	90	80	psig
Spring 2 Cracking Pressure	$P_{opeCrack}$	95	100	90	psig
Spring Force (2)	F_{Spr2}	0.315	0.358	0.276	lbf
Pull In Force Required	$F_{pull-in}$	0.347	0.394	0.304	lbf

Solenoid Valve - Pull-in and Drop Out Calculations (Pool Type - Flat, Normally Closed Type)						
Parameters	Symbols	Spec	Nominal	Max	Min	Unit
Inputs						
Design Type	Pressure Resisting					
Pull In Force	$F_{pull-In}$		0.457	0.566	0.320	lbf
Air Gap - Open Condition	g_e		0.0090	0.012	0.006	in
Air Gap - Closed Condition	g_e		0.0010	0.0012	0.0008	in
absolute permeability=2*m_0	μ_0		72			-
End Bobbin ID	D_b		0.159	0.16	0.1589	In
Plunger ID	D_p		0.065	0.070	0.065	In
Effective Area(End Bobbing and Plunger)	Ae		0.0166	0.0168	0.0160	in^2
Flux Density	Bf		44.45	49.27	37.98	K max/In^2
Permeability	μ_0		0.00319			-
Magnetic efficiency factor = 70% (Pull In)	h		0.70			-
Magnetic efficiency factor = 100% (Drop Out)	h		1.0			-
No. of Turns	N		1033	1058	1008	-
Magneto-Motive Force	MMF		179	265	102	amp-turns(A*T)
Resistance (-40F to 210F)	Ohm		25	32	18	Ohm
Output - Pull In						
Pull in Current	$I_{pull\ in}$	<300	173	254	100	mA
Pull in Voltage	$V_{pull\ in}$	<10	4.3	8.1	1.8	Volts
Output - Drop Out						
Drop Out Current	$I_{Drop\ Out}$		13	18	9	mA
Drop Out Voltage	$V_{Drop\ Out}$		0.3	0.6	0.2	Volts

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 set up, 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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