Unified Coil Solenoid Actuator for Aerospace Application

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***Abstract*- Solenoid is an electromagnetically operated actuator. One of the typical applications of solenoid is to operate valves in aircraft engine under harsh environmental conditions and high endurance requirements. Solenoid coil is wound around an insulator (e.g. PTFE / Polyimide/ Nomex etc) which is generally called as bobbin. Classical bobbin construction reduces the available window area for the coil winding. This successively reduces the number of turns that can be accommodated in the reduced window area. MMF (Magneto Motive Force) is the product of the number of turns and the magnitude of the coil current. Due to reduction in the MMF, the magnetic field strength of the solenoid reduces and the force generated by the solenoid gets decreased. The proposed topology of the solenoid eliminates the bobbin for reducing the size of solenoid coils or in other words more window area is available against the classical bobbin designs. The proposed method aims at generating higher force for the constrained size or generating the same force with less size and weight of the solenoid.**

***Keywords*—solenoid, actuator, aerospace, finite element methods.**

I. INTRODUCTION

Solenoid is an electromagnetic device which produces magnetic field when current is passed through its coil windings. The term solenoid refers to a variety of transducer devices that convert electrical energy into kinetic energy. A basic solenoid structure consists of an electromagnetically inductive coil which is wound around a movable armature. In general, a solenoid's armature is also widely known as plunger and it is usually made from ferromagnetic materials like soft iron. The armature provides mechanical force for certain mechanisms which is proportional to the change in inductance of the coil with respect to the armature's position and current flowing through the coil. The applied force will always move the armature in a direction that increases the coil's inductance. Basically, the armature will move inside the solenoid when the coil windings are energized and thus create a linear motion. Solenoid generally creates linear motion which is very unique due to its force – stroke characteristics. The force varies according to the stroke length which provides a wide range of energy band for the solenoid to operate. The range of energy band allows selection for the user to operate the solenoid with optimum performance and efficiency. Classically, there are two types of armature topologies, flat and conical. The flat-type solenoid generally provides large force in a range where the displacement or stroke is small. Whereas the cone-type solenoid provides approximately flat-curve force characteristics regardless of the displacement as compared to flat face solenoid, this makes the conical solenoid effective in usage with a medium driving path (stroke). Solenoid can be push type or pull type depending on the application requirement. The angle of armature cone is decided based on the force and the stoke requirements for typical application to optimize the weight of the solenoid. Armature cone is decided based on the index number for the typical application. Index number (i) is defined as the ratio of square root of the load force (lbf) to stroke (in) [1]. The relation between index number and armature cone angle; based on weight economy, is developed from practical experience [1].

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II. DESCRIPTION OF PROBLEM

There exists a need, where it is required to generate larger force over the mechanical displacements or strokes for the constrained physical size of the solenoid. Typical Solenoid consists of armature, return, yoke, interrupter, case, spring, spindle and coil as illustrated in Fig. 1. Armature, return, yoke and case are made of soft magnetic material, such as SAE 1006 low carbon steel (LCS). These parts are the main magnetic flux carrying paths. Interrupter is made of nonmagnetic material steel to direct flux in the working gap . Coil is wound around bobbin, bobbin is made of insulated material PTFE or Polyimide or Nomex. Spindle is made of 17-4PH (Precipitation Hardening) attached to the armature, spindle transfers the electromagnetic force produced by solenoid to valve. Spring is made of 17-7PH material; spring pushes the armature to its normal position when solenoid is de-energized. To quote one of such example from engine and

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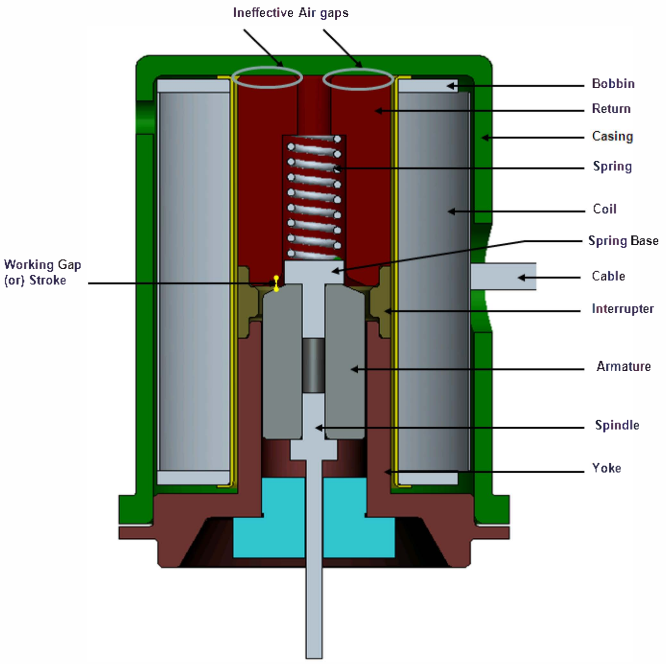


Fig.1 Typical pull type solenoid

airframe pneumatic valves; the requirements of higher mechanical load appear in scenarios where the solenoid is used to operate a pneumatic ball poppet valve in a highly vibrating environment driving to higher g-forces. The high g-forces demand for higher mechanical load. The design becomes critical when the opposing mechanical load on the solenoid is severe under the constrained weight and size.

Classical bobbin construction reduces the available window area for the coil winding. This successively reduces the number of turns that can be accommodated in the reduced window area. MMF (Magneto Motive Force) is the product of the number of turns and the magnitude of the coil current. Due to reduction in the MMF, the magnetic field strength of the solenoid reduces and the force generated by the solenoid gets decreased. The proposed method aims at generating higher force for the constrained size or generating the same force with less size and weight of the solenoid.

The proposed method contemplates reducing the size of solenoid valve coils by eliminating the bobbin. For a solenoid coil formed from helically wound wire, the strength of the magnetic field is directly proportional to the number of turns of wire in the coil and the magnitude of the current drawn by the coil. Elimination of the bobbin allows a reduction in the solenoid coil diameter and a corresponding reduction in the diameter of the coil winding wire without reducing the magnetic field strength. The solenoid coil volume is a function of the square of the diameter of the wire forming the coil. While, the magnitude of the current drawn by the solenoid coil is a function of the diameter of the coil wire raised to the fourth power. Accordingly, reduction of the wire diameter should allow a significant reduction in the size of the coil and the amount of power required to energize the coil. Alternately, a unified coil having the same size as a conventional coil wound upon a bobbin would produce a stronger field for the same amount of electric current.

III. Proposed Topology

A. *Proposed Solenoid Coil Construction*

The proposed topology of the solenoid eliminates the bobbin for reducing the size of solenoid coils or in other words more window area is available against the classical bobbin designs. For the discussed solenoid design 20% more window area is available as shown in Fig. 2. Insulation (e.g. polyimide) coated barrel assembly and inner case surface that is coming in contact with the solenoid coil is utilized as insulation. Moreover the change in the return part configuration that will be acting as one of the bobbin flange along with the yoke flange on the other end. This proposed construction is shown in Fig.3. The flanges provided by return and yoke keep the coil in shape during winding, assembly and operation. Another advantage of utilizing the yoke and return parts as flanges is the shifting of the unavoidable ineffective air gaps in the assembly. This improves the magnetic efficiency of the solenoid by 3% in the said construction. The shifted unavoidable ineffective air gap as highlighted in Fig. 3; causes less MMF drop than the earlier case as shown in Fig. 1.

B. *Description of the Proposed Topology*

Return, interrupter and yoke assembly that is further referred as barrel, is coated with the insulating material. Moreover the inner surface of the case that is coming in contact with the coil is also coated with the insulating material. One such insulating material is polyimide that is

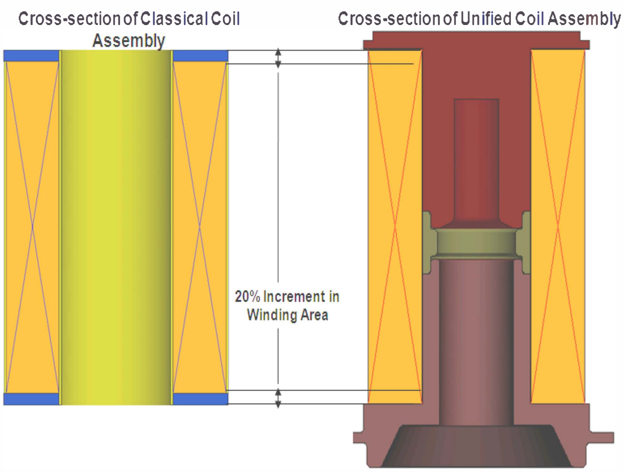


Fig. 2 Comparison of classical bobbin Vs unified coil construction

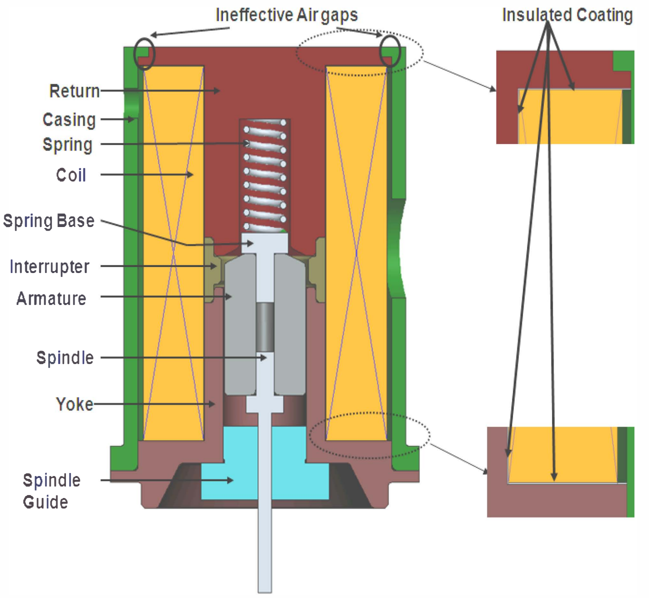


Fig. 3 Proposed Topology

250^{o}C temperature class insulation material as classified by NEMA (National Electrical Manufacturers Association). Due its very high insulation resistance and dielectric strength of the order of 4kV/mil; only 0.002in thick coating is sufficient. The change in the return part configuration that will be acting as one of the bobbin flange along with the yoke flange on the other end reduces the part count. These flanges provided by return and yoke keep the coil in shape during winding, assembly and operation. Thus, the proposed unified coil solenoid doesn't need any temporary or permanent guides or fixtures. In the proposed concept the unavoidable ineffective air gap between case and return is shifted and the shifted air gap drops less MMF. Construction differentiators can be seen in Fig. 3 and Fig. 2 as compared to Fig. 1. Another advantage of utilizing the yoke and return parts as flanges is the shifting of the unavoidable ineffective air gaps in the assembly improves the magnetic efficiency and successively adds to the increment in the force to weight ratio of the solenoid.

C. Design and Analysis

Solenoid internal part dimensions and windings are designed by following steps of the design flow chart as shown in Fig. 5 to meet the specifications described in Table I. Design output after following the flow chart is verified for mechanical position tolerances, stack up and optimized. 3D static model is created with inputs from mechanical fits, position and part tolerances. Infolytica MAGNET® tool is used for numerical simulations based on finite element methods. Model is refined by incorporating asymmetric air gaps at the part assemblies and plating thicknesses of individual components.

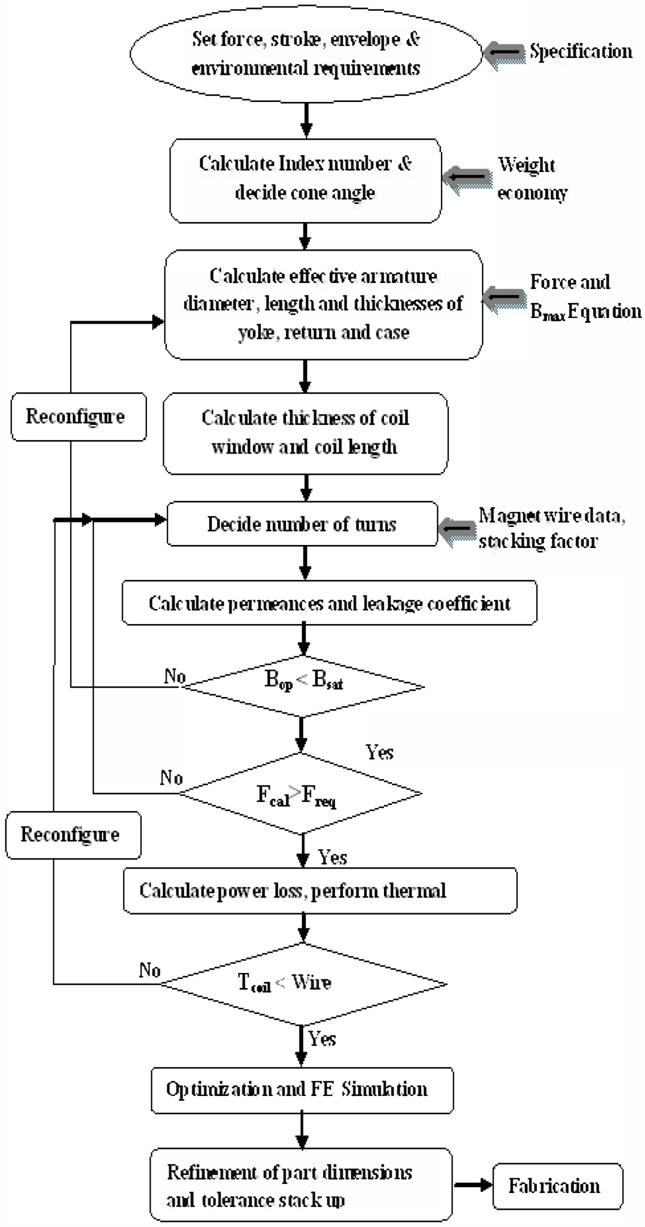


Fig. 4 Solenoid design flow chart

TABLE I

SPECIFICATIONS OF THE SOLENOID ACTUATOR

Parameter	Classical Bobbin/ Unified Coil	Unit
Nominal input voltage	28	V dc
Ambient temperature	150	°C
Duty	100	%
Load force at mid stroke	3.73	lbf
Mechanical displacement or stroke	0.030	in
Length of solenoid envelope	1.40	in
Diameter of solenoid envelope	1.04	in
Weight of solenoid assembly	0.315	lb

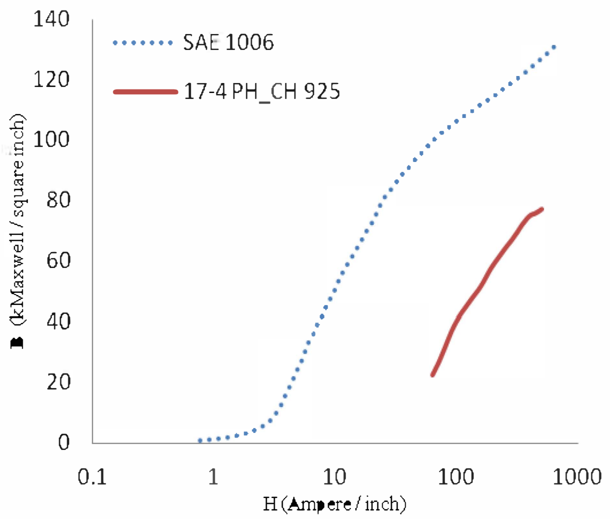
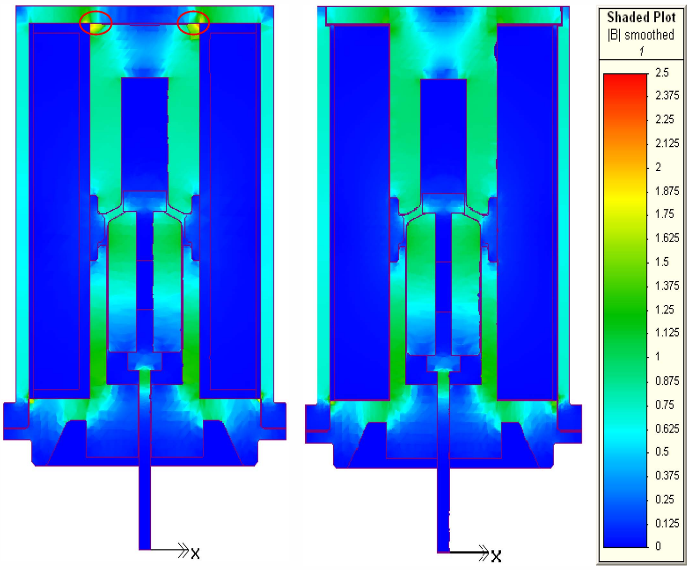


Fig. 5 BH characteristics of SAE 1006 & 17-4 PH

3D static models of solenoid configuration with classical bobbin and unified coil for each stroke condition are solved. Mesh refinement is determined by inspection as well as by ensuring force and flux convergence with respect to an increase in element density. Practically tested magnetic properties of low carbon soft magnetic material SAE 1006 as shown in Fig. 4 are applied to armature, yoke, return bottom and case. Magnetic properties of 17-4PH as shown in Fig. 4 are applied to spindle. CRES 304, relative permeability of 1.008 is applied for interrupter and stopper. Working air gap, air voids, fitment air gaps and plating thickness are applied with air properties. Cylindrical air box surrounding the solenoid is modeled; air box is 10 times the size of the solenoid. Flux tangential boundary condition is set to the air box. Magnetic field outside of an air box in which the solenoid model is placed, is considered to be zero. MMF excitation of 2363 turns and 255mA is applied in case of with classical bobbin and MMF excitation of 2527 turns and 240mA is applied in case of unified coil as per design. All the simulation conditions stated above and inputs are kept constant for analyzing solenoid configuration with unified coil and solenoid with classical bobbin.

Post processed results from 3D Finite Element Analysis (FEA) are compared for electromagnetic performance parameters such as force and field density, flux penetration, area and mmf drop. The field density plots of solenoid with classical bobbin of solenoid and unified coil of solenoid shown in Fig. 6. Inherent air gap leakage flux is reduced in unified coil compared as with classical bobbin (red circled) as show in Fig. 6.From this magnetic field density plots the leakage flux at ineffective air gap is less in case of solenoid with unified coil compared with solenoid with classical



a) With classical bobbin b) With unified coil

Fig. 6 Magnetic field density plot

bobbin. Fig. 7 depicts the Force-Stroke characteristics for solenoid with classical bobbin and unified coil. These plots show that mechanical force generated from solenoid with unified coil is more than solenoid with classical bobbin. Hence the objective of obtaining high force density is achievable.

D. *Discussion- Design for Manufacturability*

Benefits of usage of unified coil in solenoid configuration are detailed in above sections however, fixing of return to the case needs careful process selection. There are various methods for fixing, of which the popular one is the interference or press fit between the parts. The selection of kind of fit and dimensioning is critical which would otherwise lead to high mechanical stresses at the interface and tends to crack the case and return flange leading to

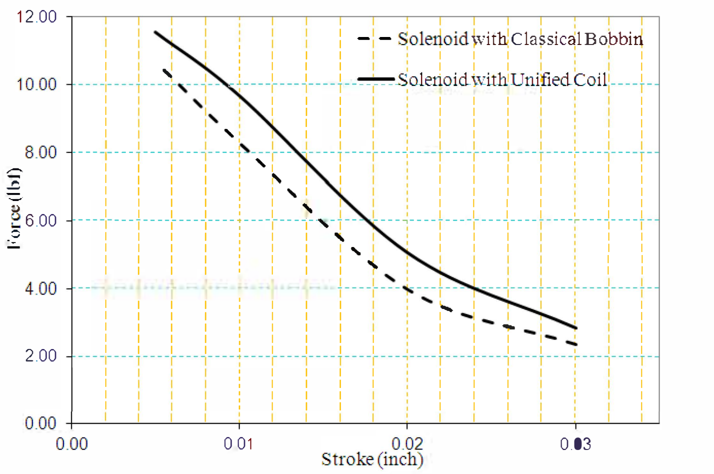


Fig. 7 Force stroke curves for classical bobbin and unified coil solenoid topologies

catastrophic failure. This method can be utilized in the assemblies which are sealed or isolated from the external atmosphere so as to avoid the corrosion of soft magnetic LCS. Plating on the soft magnetic LCS can be used to avoid corrosion for applications where the moving assembly is exposed to external atmosphere. Interference or press fit would not be a right option as it would peel or damage the plating on the soft magnetic LCS component, e.g. case and return interface in the present case. In such assemblies where they are exposed to external atmosphere it is a good option to either fuse the parts locally at the interface by electron-beam weld or braze the components with suitable filler material.

Polyimide insulation in liquid state can be used for coating on the barrel assembly but it will be special process. However fiber glass tape or polyimide tape wrapping around barrel is easy and efficient. Polyimide insulation or fiber glass insulation stamped washers can be used to provide insulation between coil and return and yoke flanges.

IV. CONCLUSION

Proposed solenoid with unified coil improves the coil window availability and also reduces leakage flux at inherent air gaps. By winding coil directly on the barrel improves the heat removal of coil. It is evident for the Fig. 7 an outcome of this analysis that, with usage of unified coil, increment of 20% – 25% in mechanical force generated from solenoid is achievable. With this method force density of the solenoid is increased; that is much in demand for aerospace application.

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