

# Flux Router in Solenoid Actuator for Aerospace Application

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**Abstract**—Solenoid is an electromagnetically operated actuator. A typical application of solenoid is to operate valves in aircraft engine under harsh environmental conditions and high endurance requirements. Under these circumstances usage of higher hardness materials for spindle becomes unavoidable. Unfortunately these materials exhibit magnetic susceptibility. This cause higher flux leakage and reduces the efficacy of the solenoid. Solenoid having very high force to weight ratio over a range of stroke with limited envelope is much appreciated for aerospace and space applications. A novel method of introducing flux router (a nonmagnetic component) at an appropriate location in the solenoid geometry in order to divert the unused magneto motive force (MMF) into working air gap is discussed in this paper. Numerical simulations based on finite element methods is used for performance comparison of conventional and proposed solenoid keeping same applied MMF and simulation parameters for various flux router geometries. This analysis considers worst case solenoid geometry and it also includes method of modeling the practical nonidealities that exists due to manufacturing and assembly process. This analysis also provides input for refinement of solenoid part dimensions and tolerance stack up.

**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 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 into the solenoid when the coil windings are energized and thus create 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 stroke 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].

## II. DESCRIPTION OF PROBLEM

There exists a need, where it is required to generate larger force over medium and longer driving paths or strokes. 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 field carrying paths. Interrupter is made of nonmagnetic material steel. 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 typical example with reference to Fig. 1; considering a valve with three ports consisting of Inlet, control and vent port, the solenoid is energized to 'open' or 'close' the valve controlling the fluid flow from one port to another. In the de-energized condition; the inlet port is connected to control with vent port closed and in the

energized condition; the control port is connect to vent port with inlet port closed. In the design of the valve, typically the valve seat, poppet and the spindle are designed in such a

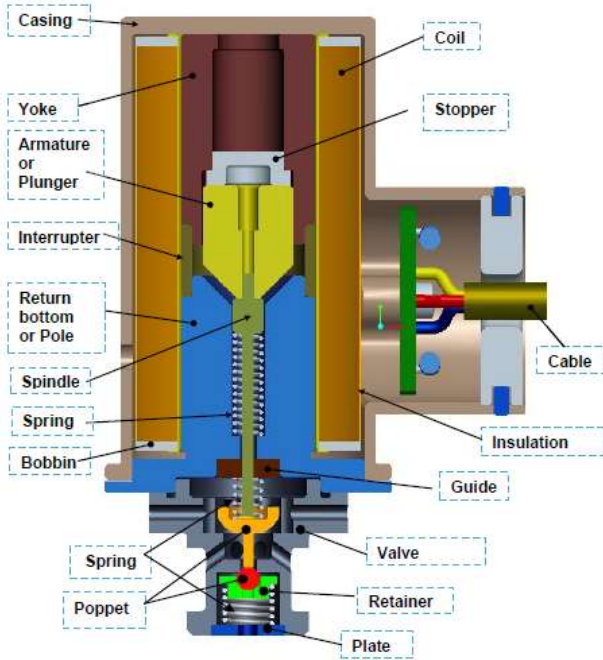


Figure 1. Typical push type solenoid

way to increase the life expectancy of the product. In such cases the materials of seat, poppet and Spindle are selected in such a way that the Brinell hardness number (BHN) of poppet is higher than seat and Brinell hardness of spindle is higher than poppet. For example seat is with corrosion resistant steel (CRES) 300 series (150BHN), poppet is with CRES 440 (269BHN) and Spindle is of 17-4PH CH900 (375BHN) [3].

Considering the above example of valve assembly, the spindle is further extended into solenoid. Spindle is either location clearance or press fitted into armature. In order to meet the life expectancy of the product spindles with higher BHN are considered. The solenoid with the normal configuration, the force generated in the practical example would be reduced as CRES17-4PH CH900 is susceptible to magnetic flux. Fig. 3 shows BH characteristics of 17-4 PH. A typical configuration of solenoid with spindle of material CRES 17-4PH CH900 is shown in Fig. 1. The reduction of nonuseful flux becomes very important in the case where solenoid has to generate force at a fixed volume over medium and longer driving paths or mechanical displacements or strokes.

### III. PROPOSED TOPOLOGY

#### A. Description of the Proposed Topology

The proposed topology of the solenoid employs a flux router fixed to armature and resting on spindle as shown in the Fig. 2. The flux router is a double cylinder extrusion made of nonmagnetic material which can be either metal or nonmetal. The heights of the two cylinders are fixed so as to optimize the magnetic flux path in the working gap. The

diameters of the cylinders are determined such that the smaller cylinder can get fitted into armature and the bigger cylinder can rest on the spindle without causing any friction

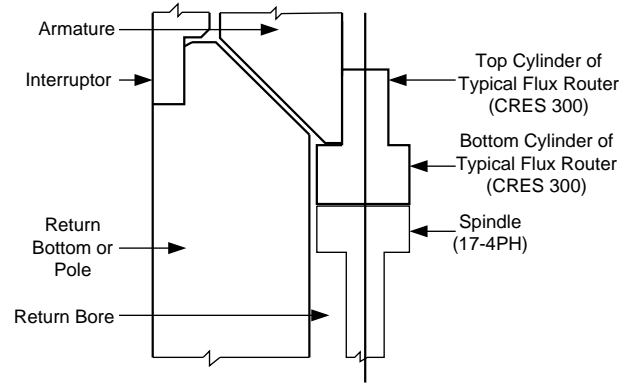


Figure 2. Proposed flux router configuration

with the return bottom as shown in Fig. 2. The proposed flux router is assembled such that when the armature is away from return bottom; bottom cylinder of the flux router is partially inside the return bore. Proposed topology consists of flux router as shown in Fig. 2 made-up of nonmagnetic CRES 300 series steel, keeping the height of the bottom cylinder up to 1.5 to 2 times the stroke length for comparison with conventional solenoid configuration.

#### B. Permeance calculations

Permeance  $P$  of the flux path is given by equation (1),

$$P = \mu \times S / l. \quad (1)$$

Where,  $\mu$  is permeability of medium,  $S$  is the cross section area of the medium, normal to flux path and  $l$  is the length of the flux path.

Magnetic flux leakage coefficient  $\nu(sl)$  as a function of stroke is given by equation (2),

$$\nu(sl) = P_t(sl) / P_w(sl). \quad (2)$$

Where,  $sl$  is stroke,  $P_t(sl)$  is permeance of all paths,  $P_w(sl)$  is permeance of useful path i.e. working air gap.

With reference to Fig. 4,  $P_{t1}(sl)$  for solenoid configuration without flux router is given by equation (3).

$$P_{t1}(sl) = P_w(sl) + P_f(sl) + P_c(sl) + P_s(sl) \quad (3)$$

$P_{t2}(sl)$  for solenoid configuration with flux router is given by equation (4).

$$P_{t2}(sl) = P_w(sl) + P_f(sl) + P_c(sl) \quad (4)$$

It is to be noted that,  $P_s(sl)$  corresponds to permeance of flux path through flux router for the solenoid configurations with flux router. It doesn't form part of  $P_{l2}(sl)$  as  $\mu$  of

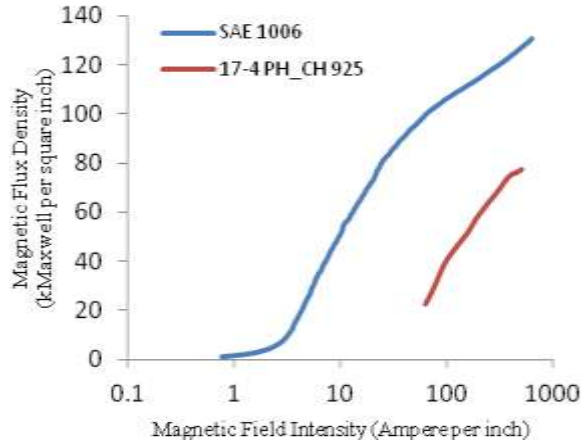
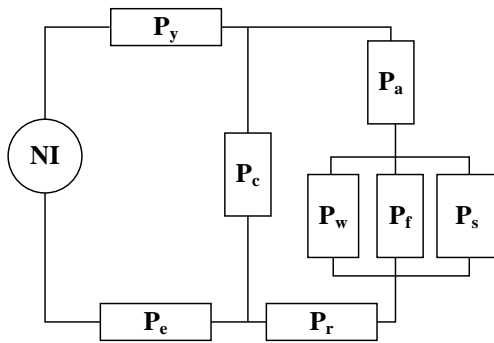


Figure 3. BH characteristics of SAE 1006 & 17-4 PH



Where,

- $P_y$  – Permeance of yoke
- $P_e$  – Permeance of case
- $P_r$  – Permeance of return
- $P_c$  – Permeance of coil
- $P_a$  – Permeance of armature
- $P_w$  – Permeance of working air gap
- $P_f$  – Permeance of fringe
- $P_s$  – Permeance of spindle

Figure 4. Solenoid magnetic circuit

flux router material is approximately 150 times lower than spindle material. Substituting equation (3) and (4) in equation (2) is observed that  $v(sl)$  in solenoids with flux router configuration is far less than solenoid without flux router. For the typical design presented in this paper  $v(sl)$  for solenoid without flux router configuration is 2.59 and for the solenoid with flux router is 1.46.

### C. Design and Analysis

Solenoid internal part dimensions and windings are designed by following 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<sup>®</sup> 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. Modeling and simulations is useful in finding effect of various flux router configurations on force to weight ratio.

3D static models of solenoid configuration with flux router and without flux router 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. 3 are applied to armature, yoke, return bottom and case. Magnetic properties of 17-4PH as shown in Fig. 3 are applied to spindle. CRES 304, relative permeability of 1.008 is applied for flux router, interrupter and stopper. Working air gap, air voids, fitment air gaps and plating thickness are applied with air properties. 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 1915 turns and 285mA is applied as per design. All the simulation conditions stated above and inputs are kept constant for analyzing solenoid configuration with flux router and solenoid configuration without flux router.

Post processed results from 3D Finite Element Analysis (FEA) are compared for electromagnetic performance parameters such as force and working gap field density. The field density plots of solenoid with one such shape of flux router and conventional solenoid are compared as shown in Fig. 6 and Fig. 7. Magnetic flux density arrow plots of solenoid with flux router and conventional solenoid is shown in Fig. 7 (a) and Fig. 7(b) respectively. It is evident from Fig. 7(b) that the magnetic flux flows through spindle and enters in the radial direction inside the return bottom causing increment in the side load adding to frictional force. Fig. 7 (a) configuration clearly shows that most of the magnetic flux from armature to return bottom is in the working gap as compared to configuration shown in Fig. 7(b), it causes reduction in leakage coefficient. This reduces side load on armature and increment in the useful force. Fig. 8 shows the magnetic field density line plots of solenoid with one typical flux router shape and conventional solenoid.

TABLE I SPECIFICATIONS OF THE SOLENOID ACTUATOR

Parameter	Quantity	Unit
Nominal input voltage	28	V dc
Pull in current	285	mA
Ambient temperature	150	°C
Duty	100	%
Load force at mid stroke	3.0	lbf
Mechanical displacement or stroke	0.05	in



Length of solenoid envelope	1.94	in
Diameter of solenoid envelope	1.04	in
Mass of armature assembly	0.013	lb
Weight of solenoid assembly	0.315	lb

These magnetic field density graphs are plotted over the working gap zone marked by line a-b. Working gap flux density is as highlighted in the balloon marked in the Fig. 8. It is observed from the Fig. 8 that there is higher magnetic field density in the working gap for the solenoid configuration with flux router. Fig. 9 depicts the various other possible flux router concepts such as circular, conical and flat and the effect of their usage on solenoid force stroke characteristics.

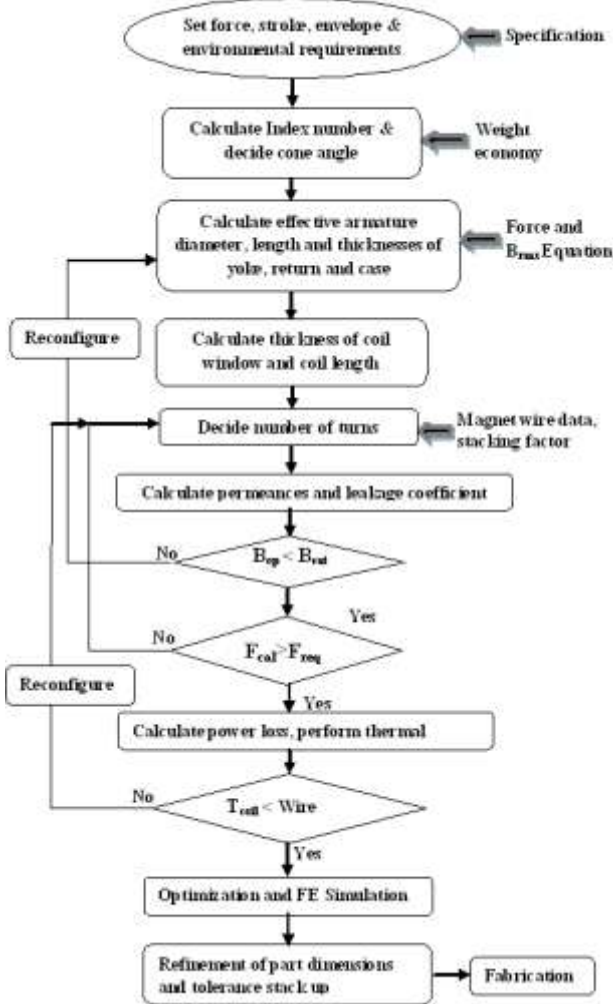


Figure 5. Solenoid design flow chart

#### D. Discussion- Design for Manufacturability

Benefits of usage of flux router in solenoid configuration are detailed in above sections however, fixing of flux router to armature needs careful 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 armature leading to 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. armature 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.

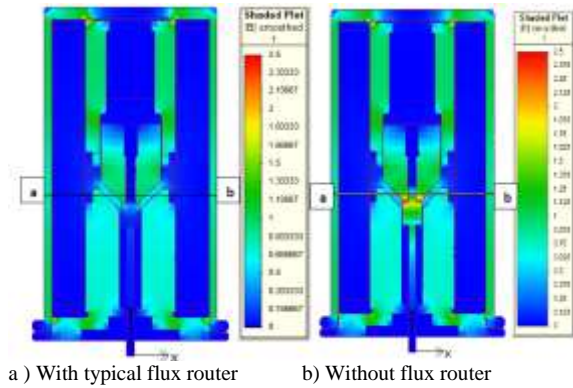


Figure 6. Magnetic field density plot

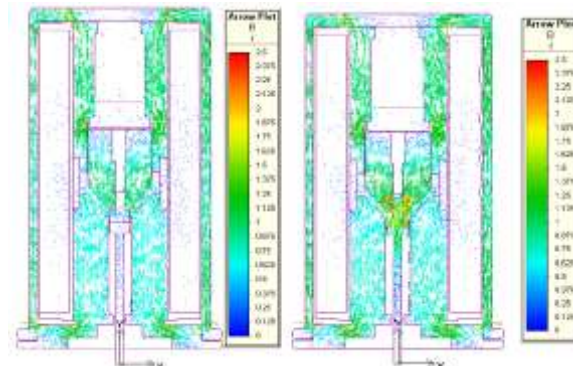


Figure 7. Magnetic field density arrow plots

#### IV. CONCLUSION

Proposed flux router concept has wide applicability for various solenoid types as illustrated in introduction section of this paper, as it is a unique way of shifting nonuseful MMF drop to useful MMF. It is evident for the Fig. 9 an outcome of this analysis that, with usage of flux router, increment of 10% – 40% in mechanical force generated from solenoid is achievable. Flux router geometry optimization can be done for solenoid force - stroke curve shaping as per the application.

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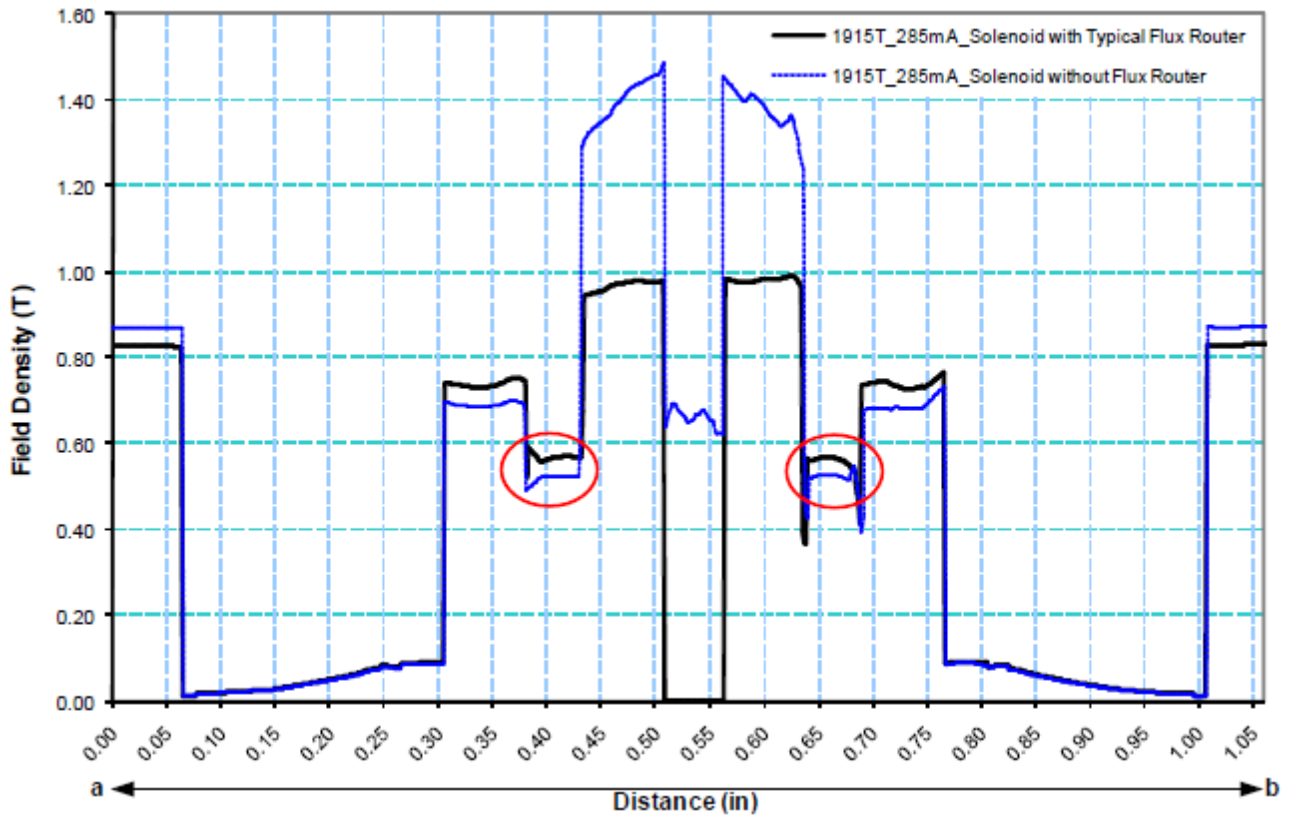


Figure 8. Magnetic field density line plot for the section a-b marked in Fig. 6

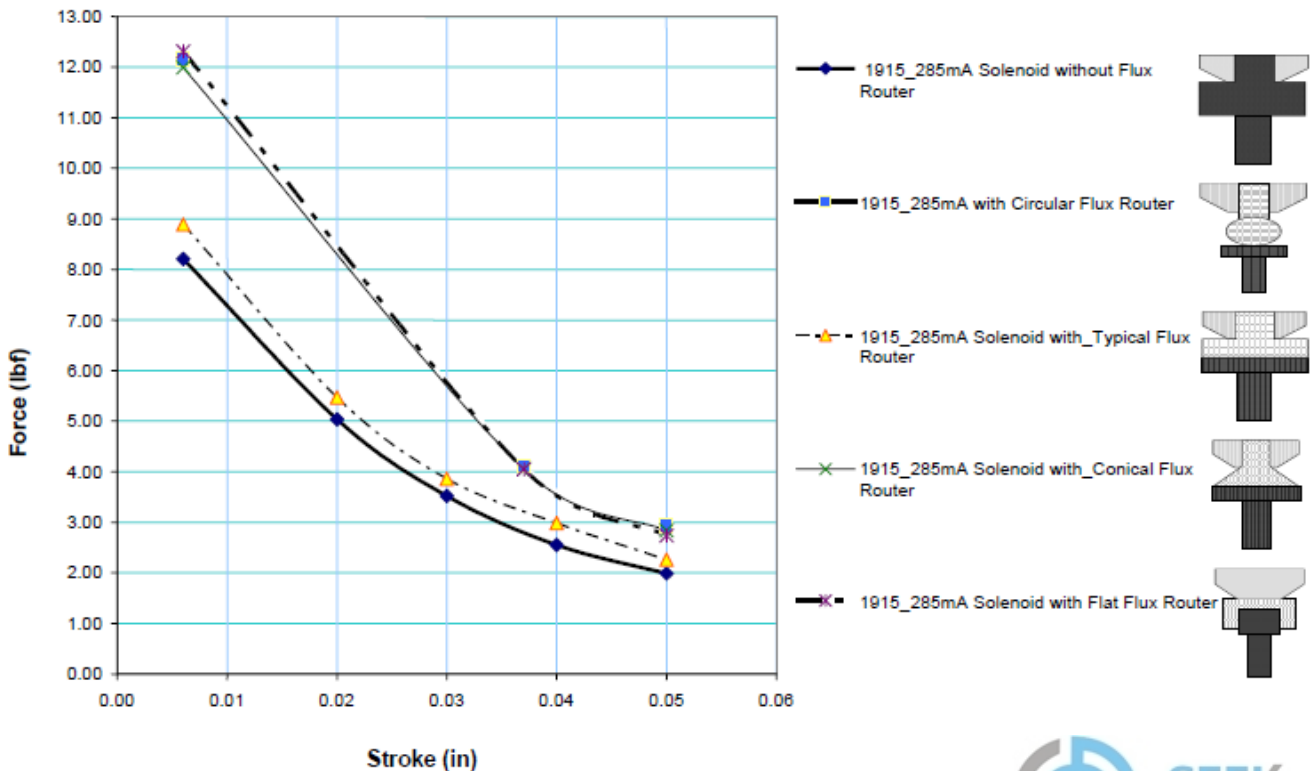


Figure 9. Force stroke comparison between different solenoid configurations with flux router and without it.