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ELECTROMAGNETIC AND DYNAMIC ANALYSIS OF SOLENOID ACTUATOR TO REDUCE THE CLOSING TIME

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ABSTRACT

Solenoid has a coil that surrounded a moving ferrous plunger. Solenoid actuators are used in many fields, especially in aviation and automotive. The physical outcome of the solenoid actuator is the plunger motion. In order to determine the required time to start motion, a solenoid actuator is selected, modeled and analyzed. Electromagnetic and dynamic analyses were conducted with different material types using ANSYS Electronics software. Also, one of the analyses was validated with experiment. As a result of the analyses, the effect of material selection on the dynamic behavior of the solenoid is modelled. This paper covers the electromagnetic systems in order to achieve a fast closing time to improve the dynamic performance of a solenoid valve.

INTRODUCTION

Solenoid actuator is an electromagnetic actuator that can convert electrical energy to mechanical energy. Solenoid actuators are used in a wide range of industrial applications, process control systems applications, including control of on-off systems, plant control loops, calibration equipment, and test set-ups. They are also used in aerospace industry, because of their small size and reliable operation. Solenoid valves can be used as the feeding system of a mono-propellant thruster [Haq , 2017]. The solenoid actuator is used in aeronautical applications such as the operation of the valves with high durability and harsh environmental conditions. These actuators subject to high vibration from the aircraft engines and a high g-forces [Narayanswamy , 2012].

Solenoids are also used in the release mechanisms of rockets. It is essential to identify the inherent delay in the system after the actuator is activated in order to hit the target accurately. Targeting and separation systems work consecutively while accounting for this release delay in the system. Solenoid actuators are used to brake the shaft of actuator motor in lock mechanisms for release the ammunition [Kumar , 2017]. Hitting the right target would require precise timing, and hence separation time has to be clearly identified. The timing is effected by the actuator's dynamic properties, which depend on

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the electromagnetic properties of the solenoid actuator. In this study, electromagnetic and dynamic analyses of a solenoid actuator are performed and the effect of material and mechanical parameters on the motion model is examined. The aim of this study is to reduce the closng thme of the actuator by using different material types.

METHOD

In literature, solenoid actuator analyses studies concentrate on the effect of mechanical properties. Lequesne [Lequesne , 1990] studied how different permanent magnet materials affect the dynamics of the solenoids. In our study different soft magnetic material combinations were simulated and their effect on dynamic behavior is studied.

In order to perform the electromagnetic analysis of the solenoid actuator, magnetic hysteresis and permeability of the solenoid actuator's parts should be known. These parameters can be obtained from B-H curve of the related material, which is available in literature [Brauer , 2014].

An off-the-shelf solenoid was cut into its two halves and modeled using a computer aided design (CAD) software. The cut solenoid actuator along with its model is shown in Figure 1.

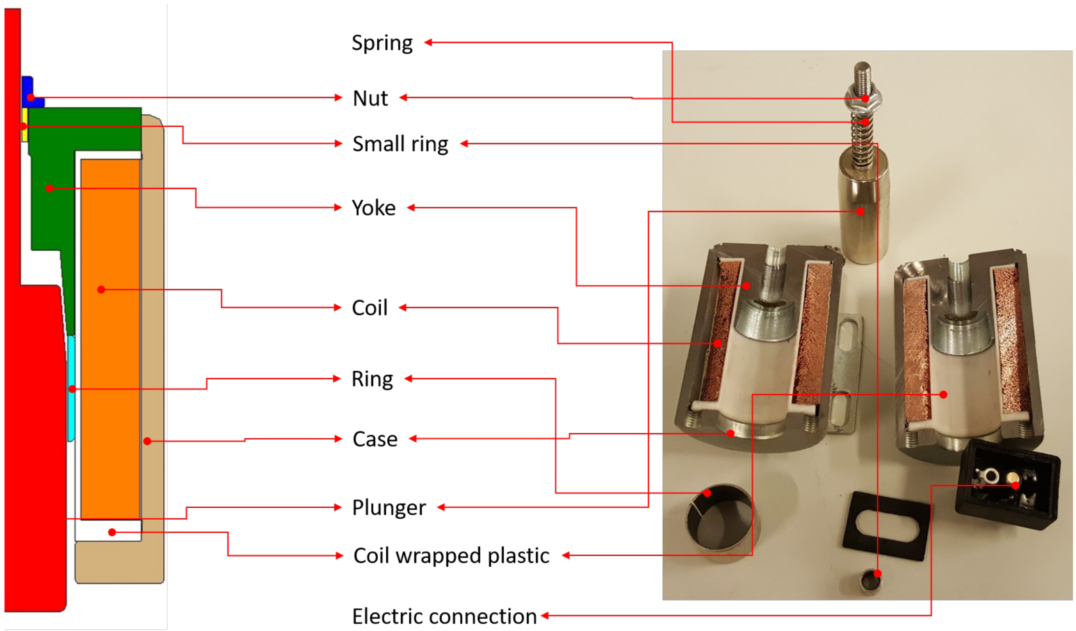

Figure 1: The cross section model of solenoid actuator and off-the-shelf solenoid.

Brauner[Brauer , 2014] describes basic criteria to design and provides methods to use for analyses of the solenoid actuators. Electromagnetic actuators are operated by the applied current that produces magnetic fields, which move the plunger to the desired position.

There are many parameters that effect the opening time of the actuator, such as the number of coil turns, size of the coil, magnitude of the actuation force, electrical and magnetic field density of the solenoid [Kamis and Yuksel, 2004]. In this study most of these parameters are kept constant and material type is change to find the opening time of the actuator.

Solenoid actuators have two subsystems, which are electromagnetic and mechanical; in combination they effect the dynamic behavior. Opening motion of the solenoid actuator is difficult to model in transient due to complex and nonlinear behaviour of the subsystems.

The motion can be divide into three regions depending on the state of the plunger. These are magnetic charging, motion, and target position.

Magnetic charging: In this region, current starts to increase with the applied voltage. Magnetic field forms due to the current passing through the coil. The magnitude of the magnetic force increases in time, but in this region it is not enough to move the plunger.

Motion: When the motion starts, current continues to raise with an increased slope. As the air gap decreases, the magnetic force acting on the plunger increases exponentially. Close to the end of the motion, the speed of the plunger peaks, which in return increases the effect of eddy current on the solenoid that cause the current to drop close to the target position.

Target position: In this final position, the plunger's motion is limited physically which cause a sudden stop. Eddy current effect disappears and the current continues to increase until it reaches a steady state value.

The motion steps of the solenoid actuator is shown in Figure 2.

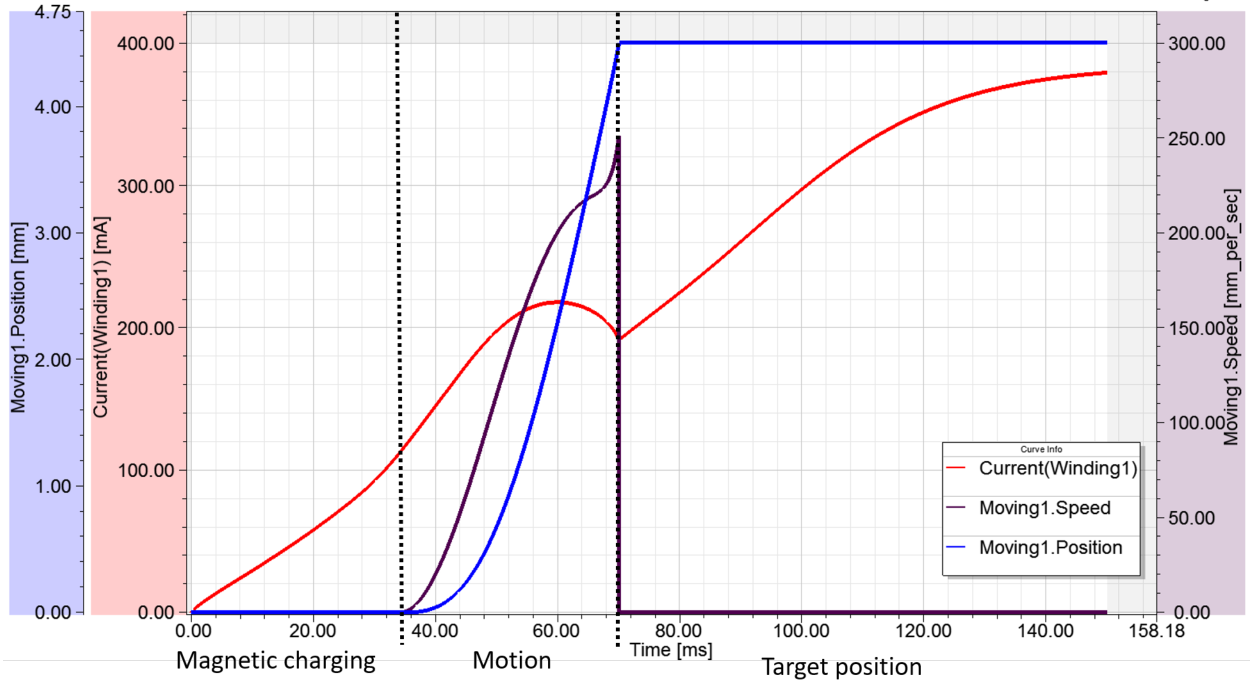

Figure 2: Behavior of typical solenoid

Electromagnetic Subsystem

Electrical aspect of the electromagnetic subsystem of the solenoid actuator consists of the coil. When the temperature change is ignored, the resistance of the coil can be calculated simply as:

$$R = \frac{\rho N(r_{orc} + r_{irc})}{r_{wire}^2}$$

where ρ is resistivity of copper coil, N is number of coil turns, r_{orc} and r_{irc} are outer and inner radius of the coil, respectively, r_{wire} is the copper wire radius. The lower the resistance, the faster and more current can be applied to the coil. High current causes acceleration of motion.

Magnetic aspect of the electromagnetic subsystem of the solenoid actuator is consisting of a magnetic circuit which is comprised of at least one closed path containing a magnetic flux. The magnetic subsystem can be written as shown in below:

$$\phi = \frac{NI}{R_z}$$

$$F_{mag} = \frac{\phi^2}{2\mu_0 \pi r^2}$$

where ϕ is the total magnetic flux, I is the current, R_z is reluctance of solenoid, F_{mag} is electromagnetic force, μ_0 is magnetic permeability of air, and r is the radius of plunger.The reluctance method is a way of using Amperes law to solve for magnetic field and magnetic flux of solenoid. Magnetic flux prefers to the path through high permeability materials such as some soft magnetic materials. If the path has an air gap, the magnetic circuit follows the smallest of the air gap way.

Mechanic Subsystem

The mechanic subsystem consists of the plunger and spring, which can be modeled as a single degree of freedom mass-spring-damper system. The equation of motion is given as:

$$ma + \zeta v + kx = F_{mag}$$

where m is the mass of the plunger, a is plunger's acceleration, ζ is the damping ratio of the system, v is the velocity of the plunger, k is spring's stiffness constant, and x is plunger's displacement. a, v, x, and F_{mag} are the functions of time. The effect of gravity is ignored because the system is modeled horizontally.

ANALYSIS AND EXPERIMENTS

Solenoid actuator's characteristics are determined for the transient finite element analysis (FEA). These are resistance of the coil, supplied voltage, mass of the moving part, spring's stiffness constant, and material parameters of the plunger. According to these parameters, analysis was completed with the ANSYS Electronics software. The FEA is repeated with many materials with unique B-H curves. The purpose of the analyses was to determine the material combination that provides the shortest duration of actuator opening time.

Electromagnetic Parameters

The magnetic field and force are determined by current and number of coil turns, NI. Ampere's law states that current produces the magnetic field. The system is supplied with DC voltage and current rises according to the properties of the coil, such as resistance and number of coil turns. In some coils the current rises very quickly because the resistance of these coils is quite low. If the low-resistance coil and the slow magnetizing material is combined, then the current reaches the steady state before the motion is completed. Often the current does not reach the steady state value before the plunger completes its motion. In all experiments, 24 VDC was applied to the solenoid. The coil resistance is 62.4 ohms and it is measured by FLUKE 179 True RMS Multimater. Manufacturer supplied the number of turns information which is 3627.

Magnetic permeability depends on the material. The symbol of permeability is μ which is found by multiplying by relative permeability(μ_r) and air permeability ($\mu_0 = 12.5E - 7H/m$). Materials with high magnetic permeability are called soft magnetic materials. The most common soft magnetic alloys are steels which have relative permeability above 2000. Permeability is given with the relationship between magnetic field strength, $\mathbf{H}$, and magnetic flux density.

$$\mathbf{B} = \mu\mathbf{H} = \mu_r\mu_0\mathbf{H}$$

$\mathbf{H}$ cannot be defined with a single value for the whole solenoid. Every point on the solenoid actuator that is analyzed has a different value. To find the magnetic flux density, magnetic field strength is multiplied by the permeability of the material at that specific point. In most cases, the relative permeability is nonlinear which can be seen from the $\mathbf{B}$-$\mathbf{H}$ curves of the materials. In this study, the material for the plunger is 430F stainless steel. The $\mathbf{B}$-$\mathbf{H}$ curve of the material is given in Figure 3.

Mechanical Parameters

The mass of the plunger used in this study is measured as 90 grams. The spring of the system is used to move the plunger back to its starting position. Spring's stiffness constant is experimentally

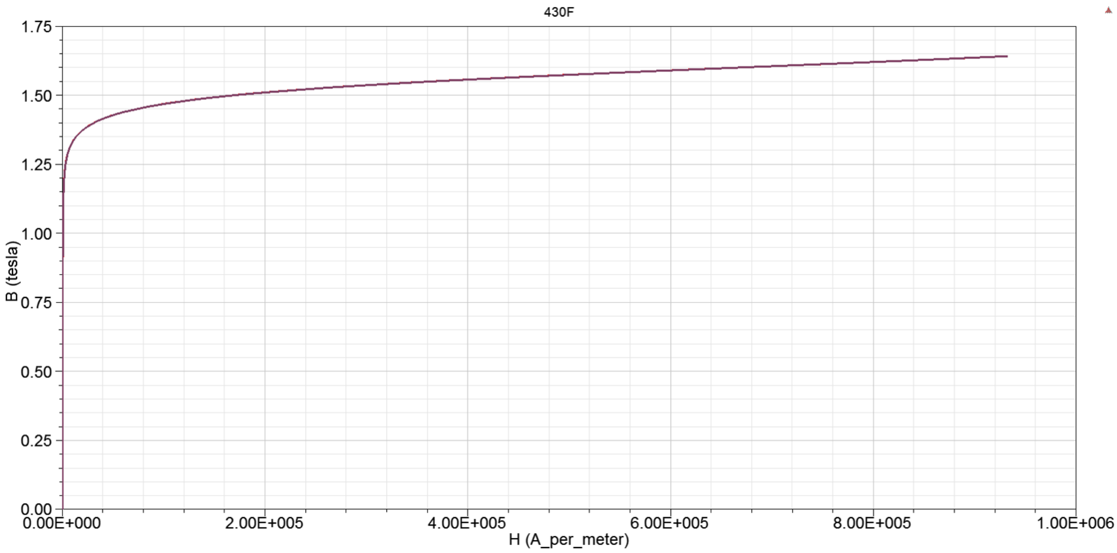

Figure 3: B-H curve of 430F steel[Brauer , 2014]

determined for analysis. Experimental set-up to determine the constant is shown in Figure 4. An OptoForce HEX-70-CE-2000N 6-axis force/torque sensor was fixed next to a linear stage that carries the solenoid actuator. Spring is initially pre-compressed inside the bobbin attached to the plunger. The plunger is moved with 0.25 mm displacements pushing against the force sensor and measurements are recorded. The results are shown in Figure 5. A line is fit to the data and the slope is calculated as 463 N/m which is the spring constant.

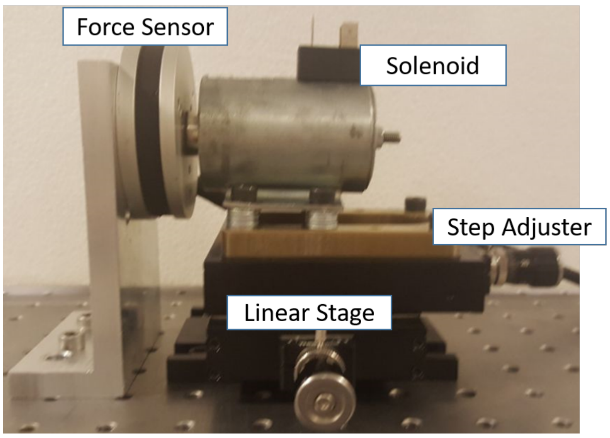

Figure 4: Spring constant experiment setup

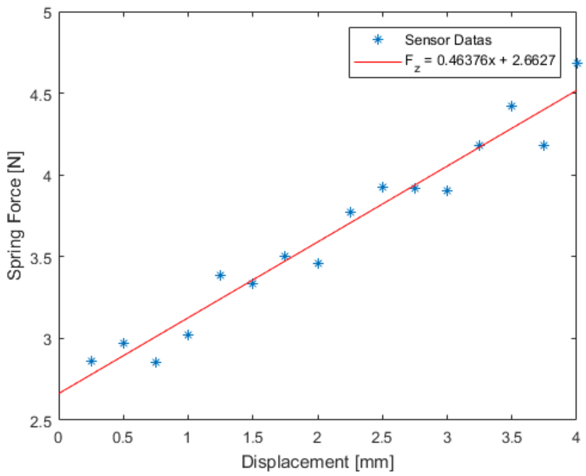

Figure 5: Experiment result

Finite Element Analysis and Experimental Validation

It is difficult to calculate the outcome of the solenoid analytically. Therefore, the operation of the solenoid actuator is examined using a finite element software. Some software are specialized to solve electromagnetism, such as ANSYS Electronics [ANSYS , 2011] which use Energy Conservation and Functional Minimization Method [Brauer , 2014]. ANSYS Electronics can solve static and transient behavior of a solenoid. In time-dependent analyses, magnetic field properties and motion behavior were obtained by applying direct current to the solenoid coil. The electromagnetic force is calculated by Maxwell stress tensor as shown below:

$$F_{mag} = \iint_S \left\{ \frac{1}{\mu_0}(\mathbf{B}\cdot\hat{\mathbf{n}})\mathbf{B} - \frac{1}{2\mu_0}\mathbf{B^2}\cdot\hat{\mathbf{n}} \right\} ds$$

where $\mathbf{B}$ is the magnetic flux density, $\hat{n}$ is a unit vector pointing out of the surface. In order to solve the magnetic fields in a solenoid, a finite element model of that solenoid should be developed. Finite element model has four components. These are meshed geometry, material, excitations, and boundary conditions. If the geometry is already drawn in a CAD software, finite element software can prepare the mesh model. The material is the most important factor forming the magnetic circuit by regulating magnetic permeability. Excitations may be related to the voltage and current supplied to the solenoid for magnetic fields. Boundary conditions must be defined. Once these parameters are defined, the FEA can be performed.

Electrical, magnetic and mechanical parameters are defined on software. An analysis model was prepared for transient solution. Magnetic field analysis of the solenoid actuator was performed using 2D axi-symmetric solver. Figure 6 shows right hand side of the solenoid model, the left boundary is specified with an odd symmetry condition. In the analysis, the solution time step was 50 microseconds.The magnetic flux is isolated from the other three surfaces. The magnetic flux and magnetic flux density when the solenoid actuator's plunger is at the target position are shown in Figure 6.

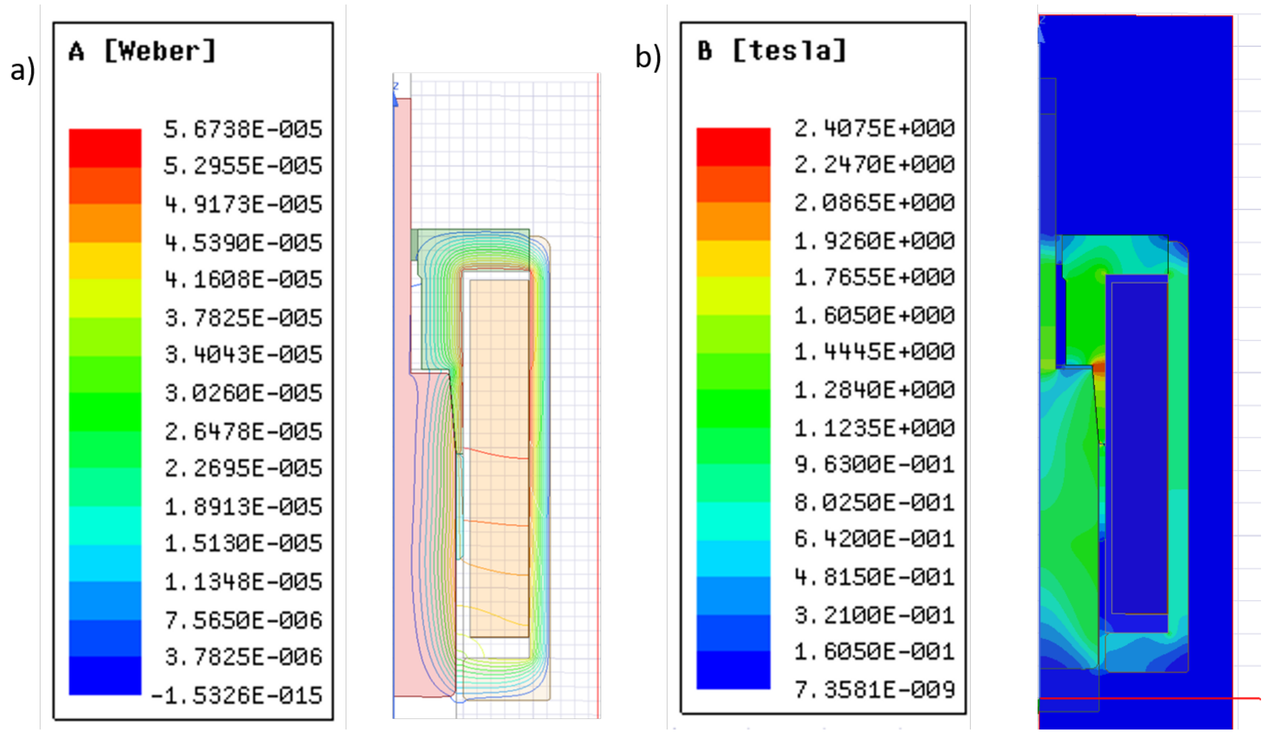

Figure 6: a) Magnetic flux b) Magnetic field density

Experiments are conducted to verify the results of the simulations. The block diagram showing the relation between the equipment used is shown in Figure 7. National Instruments cRio supply the operation voltage to the solenoid actuator. Voltage level is controlled by Labview program from control PC. The armature motion is limited to 4.5 millimeters to match the simulations. A high resolution rotary encoder is used to measure the linear position of the plunger. The linear motion of the plunger is converted to rotary motion with a capstan-rope system. Position encoder reads movement of the plunger and provide position data. The position data is read by Quanser Q8 and logged on PC with Simulink program. To prevent time and sample rate differences, NI cRio sends a synchronization pulse to Quanser Q8. This pulse is used for finding magnetic charging time which is the delay between the actuation signal and start of movement.

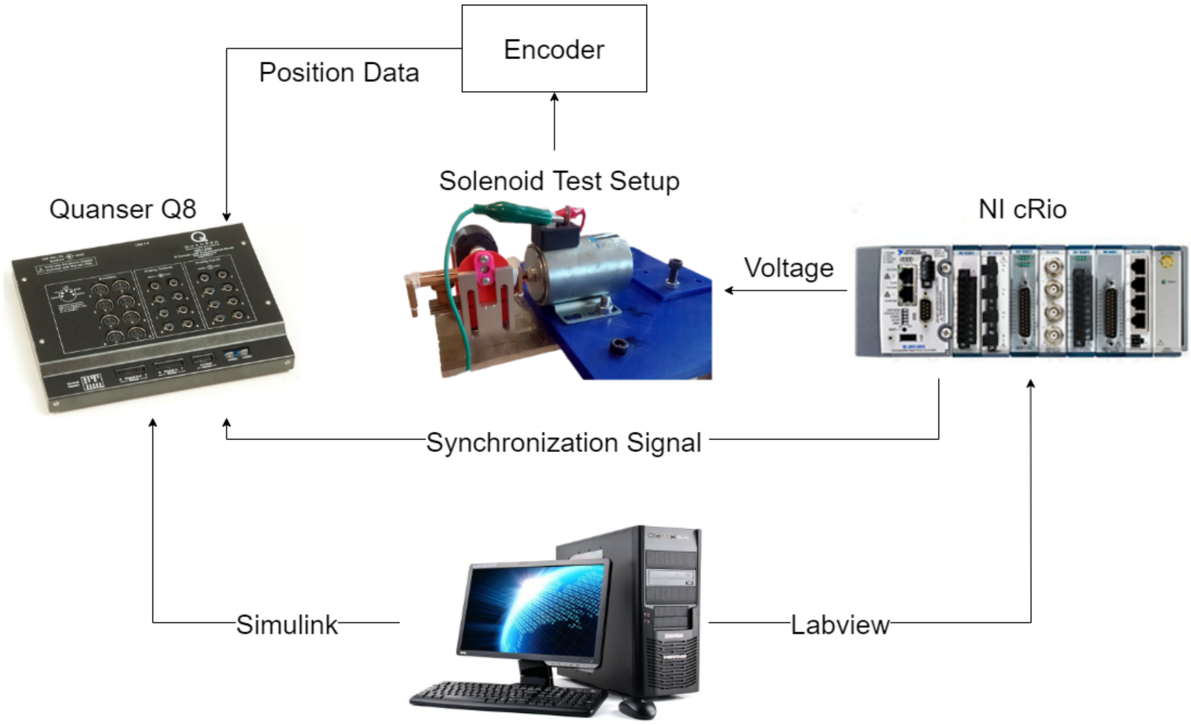

Figure 7: Experiment setup

The results of the experiment shows that the armature of the solenoid actuator start its motion 38 millisecond after the voltage is supplied to the system, and it takes about 32 milliseconds to reach its final target position. As shown in Figure 8, the motion of the tested solenoid actuator is matched with the simulation data.

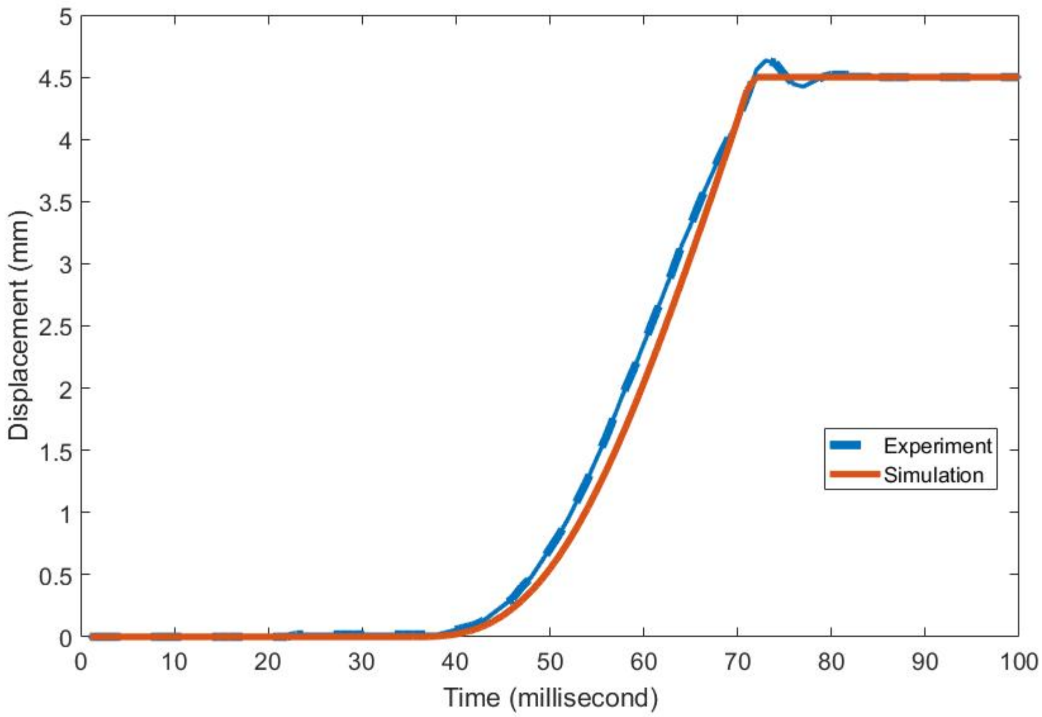

Figure 8: Comparison of the results between simulation and experiment

There is an oscillation where the plunger reaches the target position in the experiment. The reason is that the motion is defined as maximum 4.5 mm in the FEA environment and analyses are stopped when the target is reached. But in reality the plunger hits the target and oscillates before reaching stopping. The root-mean-square (RMS) error is calculated as 0.11 mm from applied voltage to reached the target position.

Parametric Analysis With Different Materials

After proving the correctness of the analysis with the experiment, parametric analyses were performed on the solenoid with different materials of plunger. Variables other than the material properties are kept constant, such as the spring's stiffness coefficient, supply voltage. Same time steps are used to repeat the analyses. The parameter modification has different effect on the motion characteristics of the actuator. Some of the results are given in Table 1.

Table 1: Analysis with magnetic materials at 24 V.

Plunger Material	Closed Time(ms)	Starting Time(ms)	Motion Time (ms)
50JN270	70,45	30,25	40,20
N30UHZ	15,25	0,4	14,85
NMX-S52	5,85	0,3	5,55
Stainless Steel 430F	70,1	37,9	32,2

The closing time is the time that passed from the start of the voltage supplied until the target is reached. The starting time is the time from when the voltage is applied until the plunger begins to move. The motion time is duration of the motion. The difference between these analyses are due to the tendency of the material to magnetize. Different materials can be used for different purposes. For example, the plunger's motion time must be very short for an injector mechanism, and the magnetic properties of the material should resemble that of NMX-S52 [Hitachi Metals , 2017]. But the motion time does not necessary to be very short for a lock mechanism. If the motion time is not important, it is necessary to choose the different parameters such as accessibility, machinability, or material cost.

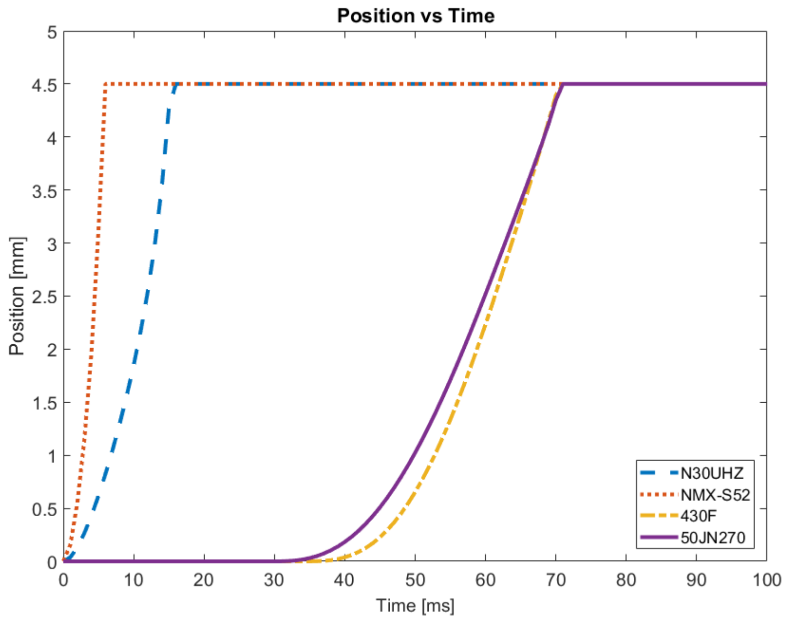

Figure 9: Analyses with 430F, NMX-S52, N30UHZ, and 50JN270 materials' position versus time graph

CONCLUSION

In this research, the effect of the plunger material on the motion of the solenoid actuator was investigated. The plunger's displacement is not known in advance as a function of time. The relationship of electromagnetic equations, electric circuit, and the equation of motion has enabled analysis of the solenoid actuator. Finite element method was applied using ANSYS Electronics. In this method, in order to well simulate the solenoid actuator's magnetic field, a simplified axially symmetric plane model is adopted. FEA is a powerful tool in considering not only the geometric and material non-linearities, but also the dynamic characteristic. Different materials can be used depending on the desired closing times. It is possible to reduce the movement of the releasing mechanism down to 6 milliseconds for 4.5 mm stroke. 430F steel was used as the plunger as the initial material. Once the analysis model is verified with initial material, the analyses of different materials are conducted and results are shown in Figure 9. In our study, the closing time is reduced by 92 percent compared with the initial material. Curves for current, speed, and plunger displacement characterize performance of solenoid actuators. The dynamic characteristics of the solenoid actuators were predicted in this study.

Acknowladgment

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