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Research Article

OPTIMIZING THE STRUCTURE OF A KIND OF SOLENOID VALVE AND IMPROVING ITS PERFORMANCE

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ABSTRACT
In this paper, in order to improve the performance of a solenoid valve, the nonlinear simulation of the valve this consists of electrical, mechanical and magnetic parts is created in MATLAB. Then, to optimize the design, the optimization method of genetic algorithm is used. The optimization can be done through determining variable parameters. The matter of great importance is that the dynamic optimization is used in this design, which leads to more realistic and more accurate results. In this paper, three cases are considered, and the force exerted on the plunger and plunger displacement in all cases is compared to the initial design. The simulation results show that the valve can perform better through implementing small changes in some parameters of solenoid valve.

Keywords*: *Nonlinear Modeling of Solenoid Valve, Plunger, Coil Current, Optimization, Genetic Algorithm, Dynamic Optimization

INTRODUCTION
Fast-acting solenoids are finding increasingly more new industrial applications and the demand for electronically controlled magnetic linear actuators is expanding rapidly, particularly in the automotive industry. These solenoids are found in a variety of sizes, configurations, and load requirements as the use of electronics increases to replace conventional hydraulics and mechanical systems with modern mechatronics. They are utilized as fuel injectors, exhaust gas recirculation (EGR) and transmission control solenoids, fuel pumps, compressor solenoids, speed-sensitive steering system solenoids, active suspension systems, air bag deployment, etc. From the armature design point of view, linear solenoids are divided into four families of solenoid actuator geometries, solenoids with disk, plunger, conical, and ball armatures. Plunger type solenoid is shown in figure 1. The fabricated solenoid valve is presented in figure 2.

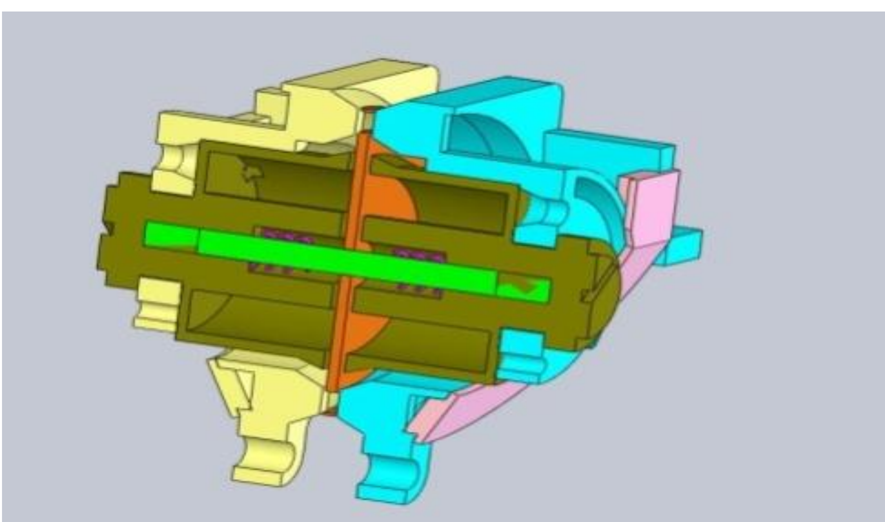

Figure 1: Fabricated Solenoid Servovalve

Figure 2: Fabricated Solenoid Coil

According to the descriptions, if the valve is used in a sensitive place such as in the missile, its performance becomes extremely important, and an error or a delay in its performance leads to mistakes in missile control.

Accordingly, this paper examines the performance of the valve and improvement of its performance.

Mathematical Modeling

Typically, a solenoid is designed to have a specific holding force at air gap closure and a pickup force that must be developed at the maximum air gap extension.

The cylindrical solenoid is shown by **Error! Reference source not found.**. In operation, the frame is fixed and the plunger connects to the mechanical load to be displaced. **A** thin, nonmagnetic bushing offers a low-friction guide for the plunger.

The bushing wall thickness is maintained as small as possible, since it acts as an air gap requiring mmf but not contributing to the developed force.

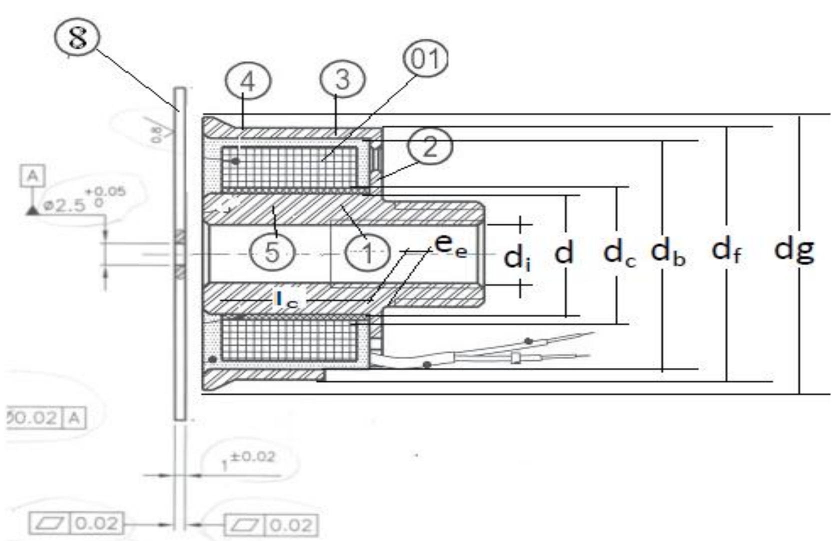

Figure 3: Cylindrical Solenoid, Physical Model

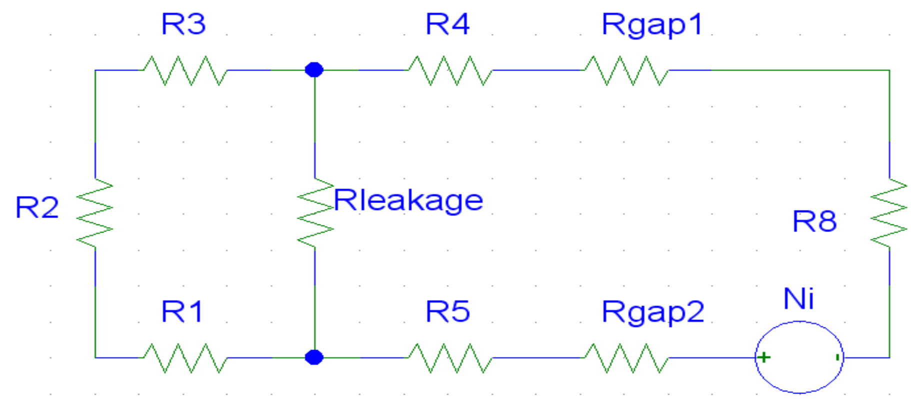

Figure 4: Schematic of Magnetic Circuit

The magneto motive force (mmf) is the line integral of the time-varying magnetic field intensity, H, that is (Cathey, 2001):

$$\oint H.dl = H_{magnet} l_{magnet} + H_{core} l_{core} + H_{gap} l_{gap} + H_{leakage} l_{leakage} = 0$$

Referring to **Error! Reference source not found.**, the total mmf is equal to:

$$N\,i = \sum H_i\, l_i = \sum \frac{l_i B_i}{\mu_{equal}}$$

$$N\,i = \phi_c\,(R_{gap1} + R_{gap2} + \sum R_i) + \phi_{leakage} R_{leakage}$$

$$= \frac{\phi_c}{\mu_0 \mu_c} \sum \frac{L_i}{A_i} + \phi_c R_{gap} + \phi_{leakage} R_{leakage}$$

For calculating magnet resistance, length and area of flux path must be obtained. For example for L_3/A_3 and for plunger L_8/A_8:

$$\frac{L_3}{A_3} = \frac{l_c + l_e/2}{(\pi/4)(d_f{}^2 - d_b{}^2)}$$

$$\frac{L_8}{A_8} = \frac{1}{2\pi t \mu_0 \mu_c} \ln \frac{(d_f + d_b)}{(d + d_i)}$$

t is plunger thickness, (label 8), and other parameters are found in **Error! Reference source not found.**. The air gap and leakage permeance are equal to:

$$\rho_{gap} = \frac{1}{R_{gap}} = \mu_0 \left[\frac{A_{gap}}{\delta_{gap}} + 0.52\, p_{gap} + 0.616\,\delta_{gap} \right]$$

$$\rho_l = \frac{1}{R_{leakage}} = \mu_0 \left(\frac{0.5(d_b + d_c)\frac{l_c}{2}}{0.5(d_b - d)} \right)$$

Where A_{gap} is gap area [m^2], p_{gap} is gap perimeter [m] and δ_{gap} is gap distance [m].
Finally, the force developed by the solenoid can be written as:

$$F_{sol} = \frac{-i^2 N^2}{2\mu_0 A_{gap}} \frac{1}{\left(\frac{1}{\mu_0 \mu_c} \times \sum \frac{L_i}{A_i} + \frac{x_0 + x}{\mu_0 A_{gap}} \right)^2}$$

The current i is produced by voltage terms appearing in the system voltage balance, will be identified as follows [A.M. Pawlak, 2007]:

$$V_s = V_c + V_e + V_r + V_{mag} \qquad (1)$$

where V_s is the source power, V_c is the power loss due to winding resistance, V_e is the eddy current loss, V_r is the due to rate of change in the stored magnetic energy (reactive power), and V_{mag} is the rate of energy conversion (electromagnetic power). In mechanical modeling, the plunger motion is usually restricted to one axis and is used in the dynamic analysis of solenoids, injectors, and linear actuators.

The sum of all forces acting on a body along the unconstrained portion of the *x* axis yields the accelerating force on the body.

The net mechanical accelerating force is the result of the magnetic, spring, and viscous forces acting on the moving body as follows:

$$F_{mech} = F_{mag} - F_{sp} - F_{vd} \qquad (2)$$

Where *Fmech* is the net mechanical accelerating force, *Fmag* is the magnetic force; *Fsp* is the total spring force, and *Fvd*is the viscous damping force.

$$F_{sp} = 2k(x_s - (g_{max} - g_{min})/2)$$

$$V_s = V_c + V_e + V_r + V_{mag}$$

Where g_{max} and g_{min} are determined with plunger limit. Combining Equation (1) and Equation $F_{mech} = F_{mag} - F_{sp} - F_{vd}$ (2) yields the overall system power balance:

$$P_s = P_c + P_e + P_r + P_{mech} + P_{sp} + P_{vd}$$

Genetic Algorithm

The mathematical modeling presented for dynamic optimization problem of the solenoid valve parameters is a complex nonlinear model which cannot be simply solved using analytical methods of optimization. In this paper, the method of genetic algorithm is used to optimize and obtain the solenoid valve parameters. It is a common method for using indiscrete and continuous variable optimization, and has a great capacity for wide spaces search.

Genetic algorithm is a simple and efficient method for optimizing mathematical models without any simplification, and there is no need to concern about the non-linearity of the objective functions of the problem and constraints associated with it.

Another advantage of this method is generating several similar good solutions instead of a single one. This allows the designer to adopt the best solutions to be implemented. The genetic algorithm is an optimization method based on biological evolution, natural selection and the possibility of longer lives for generations with higher fitness.

In this algorithm, variables and unknowns of the problem are defined as binary strings called genes, and putting the genes together, chromosome is composed, which is one of the possible solutions to the problem. First, a certain number of randomly generated chromosomes form the initial population.

Next, the fitness of each chromosome is evaluated according to the fitness function defined with the help of the objective function of the problem. Then, some chromosomes with higher fitness breed a new generation by producing new chromosomes and replacing chromosomes with less fitness in the current generation with the new ones.

By reiterating the fitness evaluation and producing a new generation, the search makes progress in a way to approach the desirable and optimized solution (Royer *et al.,* 2013).

The production of each generation is composed of four stages as follows (Davatgaran *et al.,* 2013):

a) ***Selection****:* Selection of some individuals as parents.

b) ***Crossover:*** In this step, each pair of parents should be mated and produce 2 new offspring. Therefore, each pair that is coded before should be combined with each other.

c) ***Mutation:*** In this step, by random changing one or more gene in a parent can produce new parent.

d) ***Elite:*** In this step, some outstanding individuals will be transferred directly to the next generation.

The flowchart of the proposed algorithm for improving the performance of solenoid valve is shown in Figure 5.

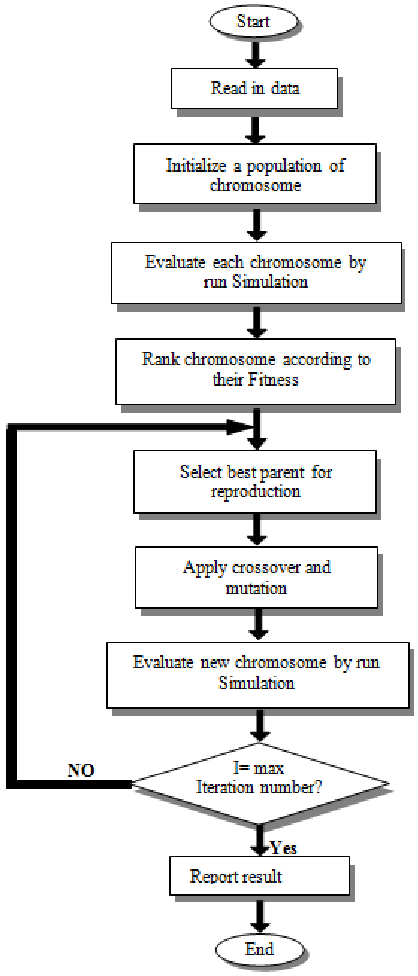

Figure 5: Flowchart GA for solenoid valve

Dynamic Simulation

In order to optimize the design of the solenoid valve, the whole system must be fully simulated, to see how performance of each parameter influences the structure of the solenoid valve. The system is fully implemented in MATLAB. In this simulation, the impact of all mechanical and electrical factors on the system is taking into account, to make the results of the simulation applicable. The simulation as a whole is given below. The simulation, as shown in Figure 6, illustrates the force exerted on the Plunger.

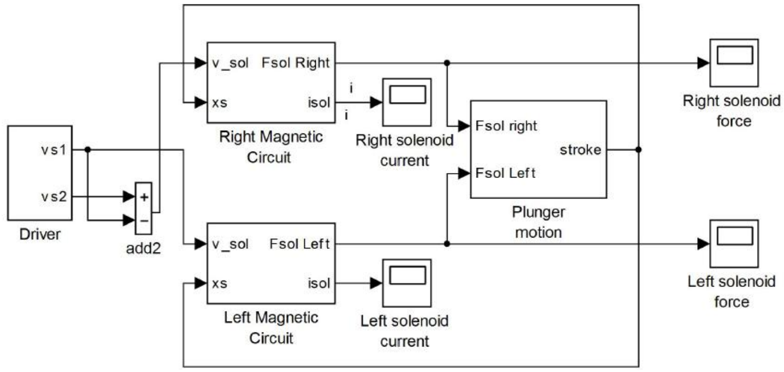

Figure 6: Block diagram of Simulation

RESULTS AND DISCUSSION

Results

To make it possible to perform the optimization in a dynamic way, the above simulation was used in the proposed algorithm. In order to fully implement this algorithm, it is very important to determine the parameters that can be changed, limits to parameters changes must also be identified. Knowing the limits of changes and the proposed algorithm, we can calculate the best values for these parameters. The great advantage of this procedure lies in the possibility of utilizing this algorithm for optimizing each system parameter just through identifying the variable parameters and their limitations. In this paper, we seek to optimize the force exerted on the plunger. This algorithm can also be used in other studies.

To optimize the solenoid valve, three cases have been considered:

First Case: In this case, just the internal dimensions of the core have been considered the variables.

Second Case: In this case, the internal dimensions of the core and the number of turns in the coil have been considered the variables.

Third Case: In this case, the permeability of the core, the number of turns in the coil and the internal dimensions of the core are intended the variables.

Fitness chart in all three cases, concerning the implementation of the proposed algorithm, is shown in Figure7.

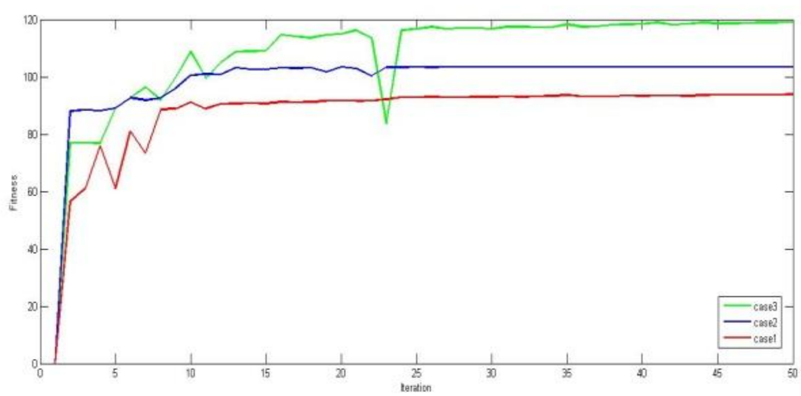

Figure 7: Fitness in all cases

In Table 1, the values for initial design parameters are compared to the obtained values for parameters, concerning the implementation of the proposed algorithm, in all cases.

Table 1: the obtained values for parameters in all cases

	d (mm)	db (mm)	lc (mm)	le (mm)	N	muc
Initial design	22	11.5	13	1	670	89.97
Case1	21	8.7	11.1	2.9	670	89.97
Case2	22.5	7.5	12.3	1.7	860	89.97
Case3	22.5	7.5	12.3	1.7	860	100

If the above changes are made to the design of a solenoid valve, the changes in the force exerted on the plunger and displacement of the plunger obtained with the applied voltage are as follows:

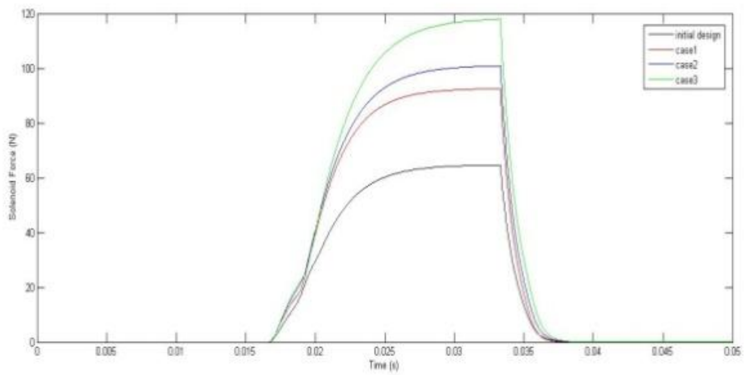

Figure 8: Solenoid Force in all cases

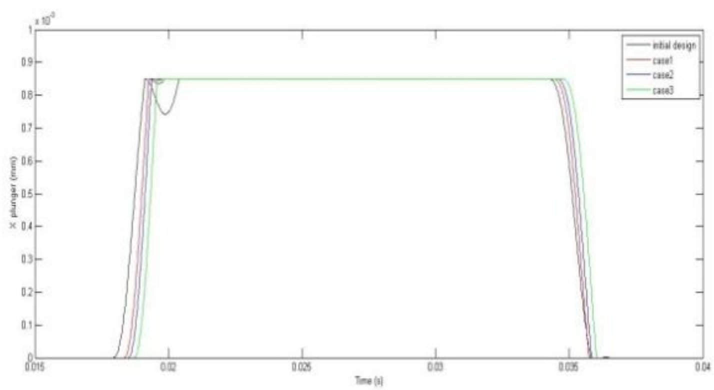

Figure 9: X plunger in all cases

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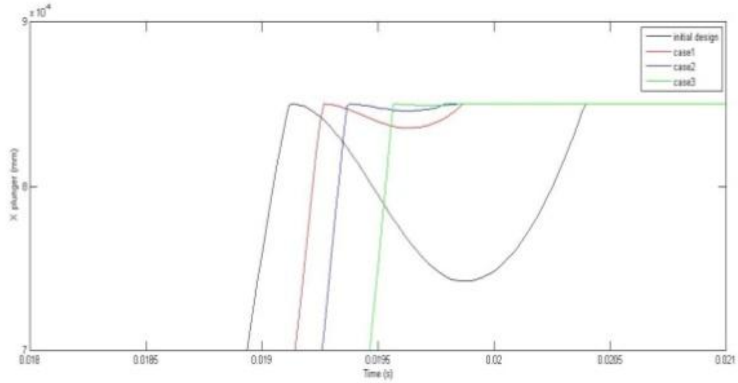

Figure 10: X plunger in all cases

Conclusion

The results clearly indicate that, without changing the input voltage, the force exerted on the plunger can be increased through a slight change in the electrical and mechanical parameters of the solenoid valve. It is also observed that the more improvements to the structure of the valve, the shorter the time of plunger displacement is, and displacement in unnecessary parts is prevented. In fact, it caused the system to become stable more quickly and the unwanted performances be prevented. Everything mentioned indicates the great importance of these optimizations. Moreover, the advantage of this algorithm lies in the possibility of optimization for each single parameter, which demonstrates the comprehensiveness of the proposed algorithm.

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