

Study of the Influence of Mechanical Parameters on the Behavior and Response of Electromagnetic Servo Relay (ESR)

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Abstract: The Relay is widely used in civil, industrial and military equipment. The Relay is considered to be one of the indispensable actuators for electric power and control flying objects and systems. Relays reliability strongly influences the system reliability.

The mathematical model of the servo is introduced including the electrical, magnetic and dynamic parts.

Simulations, using Matlab and Simulink, were performed. An improvement to the mathematical model has been carried through simulation which reflected on the results gained. Results of the effect and influence of magnetic materials and some important mechanical parameters like stiffness, viscosity, and copper insulator thickness, on the dynamic performance of the servo were presented. The results can lead to improving the servo performance and get the right design of parameters and right choice of materials.

Key Words: Relays, Electromagnetic Relay, Pulse Width Modulation, Relay Dynamics

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1. Introduction

Electro Magnetic Servo Relays have been widely used in civil, industrial and military equipments, and it has been considered to be one of the indispensable actuators for electric power and control systems.

The Relay is an important actuator for electric power and control systems. Its reliability strongly influences the system reliability [1],[2].

Many relays use an electromagnet to operate a switching mechanism mechanically [3].

One of the special relay types used in control systems is called Electromagnetic Servo Relay (ESR) utilizing Pulse Width Modulation (PWM).

The PWM is a well known technique and has very wide applications in power supplies and communications.

The actuator of a relay is a kind of a linear electromagnetic solenoid, especially push/pull type. Due to its simplicity, high reliability, and low cost, the solenoid actuator is widely used as an industrial apparatus for automobile application, pneumatic valves, electric relays, and switches. [4].

The principle of construction and operation of this type of servos is the electromechanical relay, which is well known and there are many literatures available about it.

Electromagnetic servos are generally reliable and simple in design, structure. There are many types of them, the simplest one in structure, is the so called pulse width modulating electromagnetic servo. It consists of two coils wound

around two ferrite cores to form the right and left sides of the magnetic circuit (the stator part). These two sides are separated by an air gap. The moving part is a ferrite type core moving to the side of the energized coil. The two coils are connected to the drive circuit which energizes one coil at a time with a DC voltage of say 26 volts. When the servo is at rest, the moving part stands at the mid position by the effect of the spring stiffness. [5]

2. Concept of Operation

The structure of the PWMES is shown in Fig. (1). When supplying one of the coils with the DC voltage, the force will be created and the moving part will move and stick to that side. When supplying the other side with the voltage the moving part will move to the second side. The movement of the moving part between both sides is performed with the help of the spring. To avoid the sticking of the ferrite materials, the air gaps are isolated by nonmagnetic materials (copper sheet of 0.05 – 0.20 mm for example). This type of motion is a none linear behavior.

The movement in control and dynamic systems wants to be proportional to the error. The control signal is generated according to the error signal.

For control purposes the movement of the armature is controlled by supplying the left and right coils with DC voltage utilizing the Pulse Width Modulation (PWM).

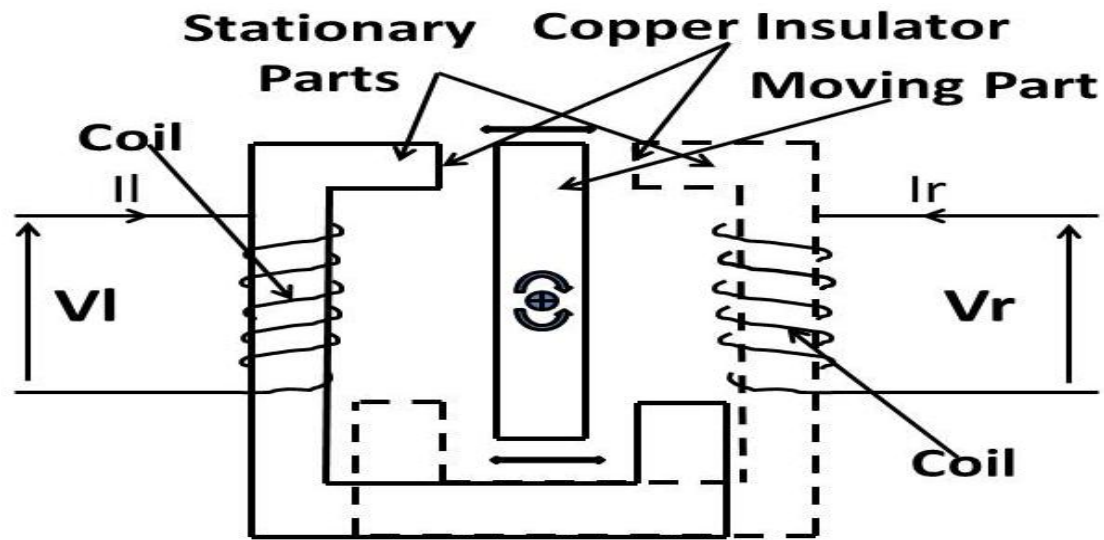


Fig.(1) The main parts of the Electromagnetic servo

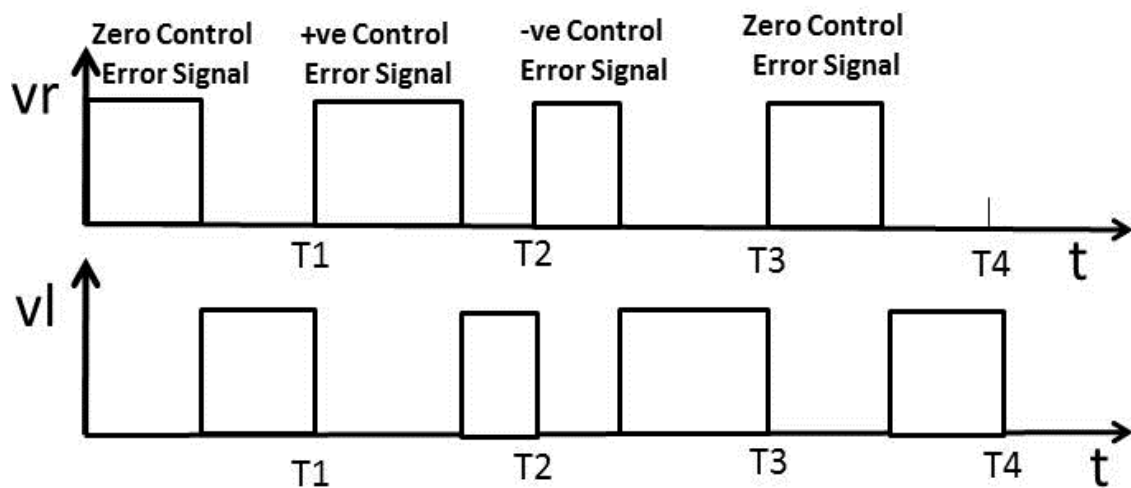


Fig.(2) Pulse Width Modulation

The cycle of the driving voltage period is divided into equal switching intervals (regular sampling) of width. As shown in Fig. (2), voltages of left and right coils width are modulated according to the control signal. This will cause the left and right positioning intervals to be proportional to the control signal. The PWM details are out of the scope of this paper [4].

3. Mathematical Model

The mathematical model will cover the main parts of the servo. These parts are the coils, the magnetic circuit and the moving parts. The model will deal with the final equations and the detailed equations are available in the references. :[6],[7],[8]

3.1. Mathematical model of coils

The coils can be represented by resistor R , inductor L and the number of turns N .

The subscripts l, r, m and a, whenever mentioned here, denote the left, right, mid, and air gap parts respectively. The relationship between the current (I) passing through the coil and the applied voltage (V) is: [6],[7],[8]

$$V_l = R_{cl} I + L_{cl} dI/dt \quad \dots (1)$$

$$V_r = R_{cr} I + L_{cr} dI/dt \quad \dots (2)$$

Where; R_c is the resistance of the coil [Ω], L_c is the inductance of the coil [H]

Note that L is a function to the magnetic circuit permanence which in term functions to the air gap dimension and the position of the moving part. The relation of finding L is,

$$L_{cl} = N_l \Phi_l / I_l \quad \dots (3)$$

$$L_{cr} = N_r \Phi_r / I_r \quad \dots (4)$$

Where; N_l and N_r are the number of turns of left and right coils respectively, Φ_l and Φ_r are the total magnetic flux [Wb] of left and right coils, I is the current [Amp]

3.2. Mathematical model of the magnetic circuit:

The magnetic circuit consists of right, left and mid parts. The right and left parts form the fixed or stationary part of the servo. The moving part in the mid is connected directly to the control surface. The total reluctance (S) seen from the right and left parts of the magnetic circuit is; [2],[6]

$$S = l / (\mu_o \mu_r a) \quad \dots (5)$$

Where l in (m) is the magnetic circuit length, μ_o is the absolute magnetic permeability, μ_r is the magnetic relative permeability and a is the cross section area in (m^2). [2],[6]

$$S_{rt} = S_r + S_{ar} + ((S_{al} + S_l) S_m / (S_{al} + S_l + S_m)) \dots (6)$$

$$S_{lt} = S_l + S_{al} + ((S_{ar} + S_r) S_m / (S_{ar} + S_r + S_m)) \dots (7)$$

The flux Φ in (Wb) and the flux density B in (T) of the magnetic circuit parts and their mutual effects depend on the m.m.f. and the reluctance of the magnetic circuit.

$$\Phi_{rt} = \Phi_r - \Phi_{rl} \quad \dots (8)$$

$$\Phi_{lt} = \Phi_l - \Phi_{lr} \quad \dots (9)$$

$$B_{al} = \Phi_{lt} / A_{al} \quad \dots (10)$$

$$B_{ar} = \Phi_{rt} / A_{ar} \quad \dots (11)$$

$$B_m = \Phi_m / A_m \quad \dots (12)$$

The force F in (N) and the torque T_g in (N.m) generated on the moving part are;

$$F_t = F_r - F_l \quad \dots (13)$$

$$T_g = F_t b \quad \dots (14)$$

Where; F_t is the total force in (N) and b is the arm connected to the moving part in (m).

3.3. Mathematical model of the dynamic system:

The dynamic system includes all the forces and torques connected to the moving mechanical parts which are the spring stiffness torsion torque (T_s), inertia torque (T_j), friction torque (T_f), and applied torque (T_a) if exists. [7],[8],[9]

$$T_g = T_s + T_j + T_f + T_a \quad \dots (15)$$

$$T_g = J \ddot{\alpha} \quad \dots (16)$$

Where α is the angle of the moving parts including plunger and J is the moment of inertia of moving parts ($Kg \cdot m^2$)

4- System Simulation and Modeling

Simulation, using MATLAB and Simulink, was performed. In addition to the blocks of initial parameters and condition, there are three other main blocks.

The first block is the electric power supplies which consist of voltage supplies V_l and V_r (10 V DC each), coil resistance R (20 Ohm), and Coil reluctance L (10 mH). The reluctance is considered here a constant value, actually it is a nonlinear value, its value depends mainly on the magnetic material

of the cores, magnetic value, and moving armature position see Fig.(3) [5].

$$\frac{I(s)}{V(s)} = \frac{K_v}{T_v s + 1} \quad (17)$$

Equation (17) is the transfer function of the electric circuits, where $K_v = 1/R$ and $T_v = L / R$ (sec).

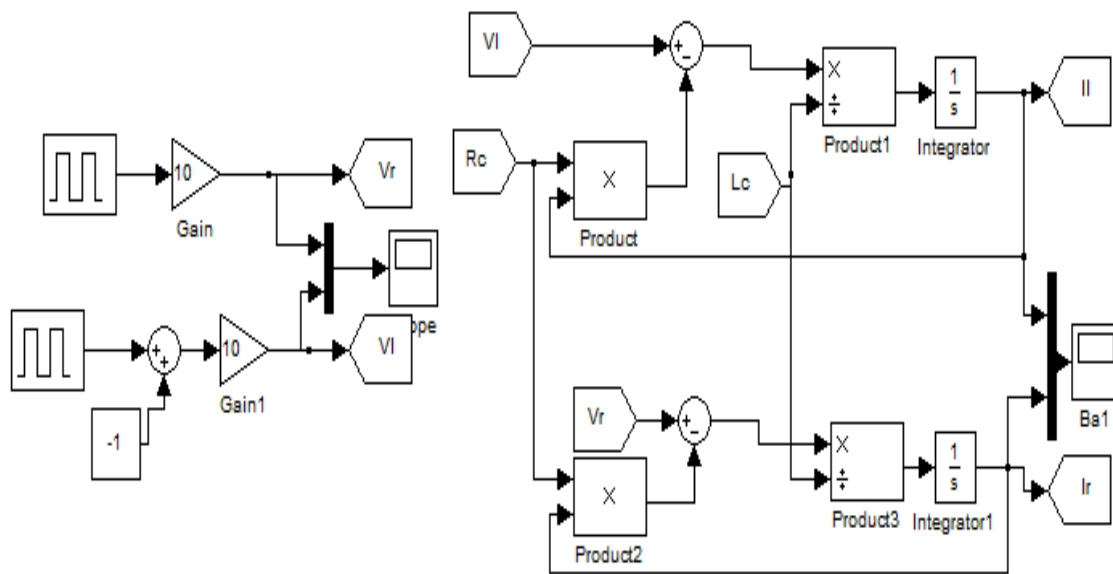


Fig.(3) Electric Circuit Simulation

The second block is the two side magnetic circuits in which the magnetic strength (NI) depends on the number of coil turns and the magnetic circuit length l in (m). The main parameters are magnetic flux density (B), total flux (Φ) and the attraction force (or torque) of moving armature (T_g) which are functions of the electric current(I),

magnetic material(μ_r) and the moving armature position (α). In Matlab function blocks of all the magnetic relations mentioned in the equations above are calculated. The B-H curve of five different magnetic materials was implemented in look-up tables. See Fig.(4) and Fig.(5).

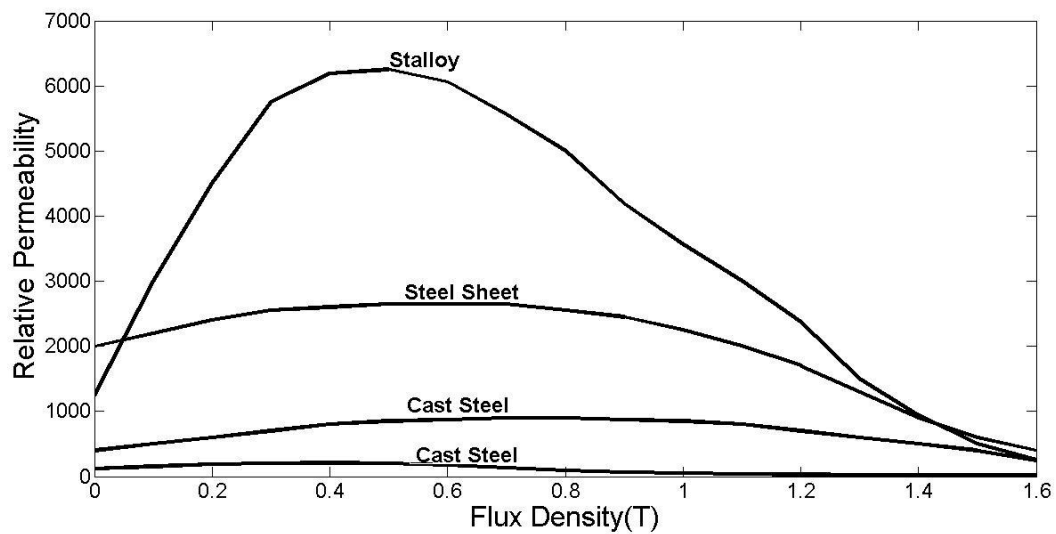


Fig. (4) Variation of relative permeability with flux density

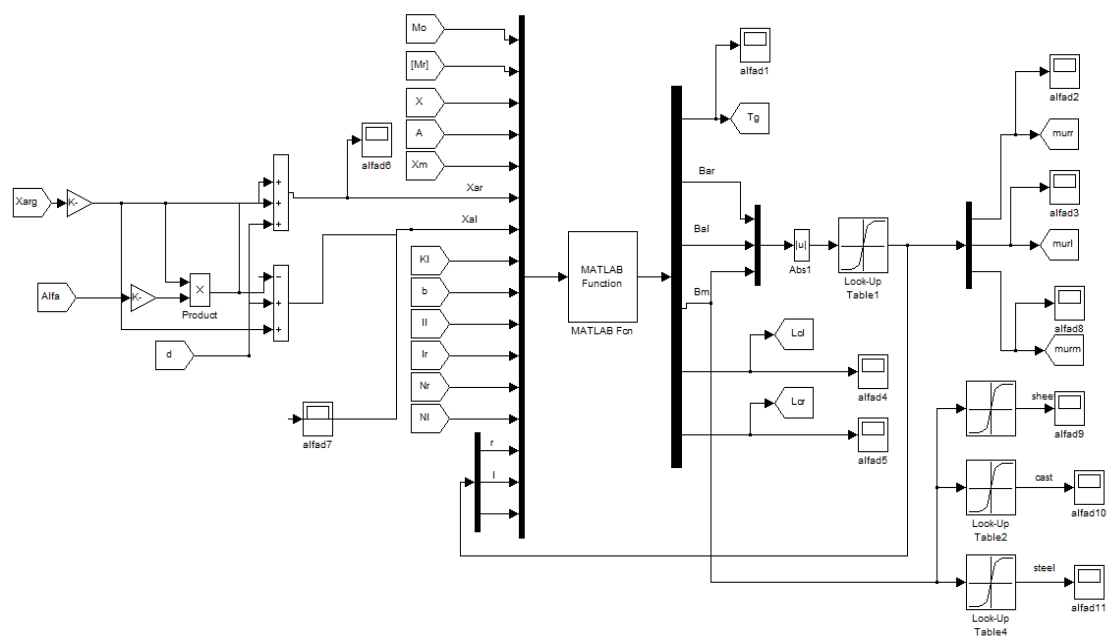


Fig.(5) Magnetic Circuit Simulation

The third block is the dynamic block. The attraction force and torque (T_g), viscosity torque (T_v), and stiffness torques (T_s) are calculated. The main parameters are the angular acceleration $\ddot{\alpha}$ of the moving parts, magnetic torque generated (T_g) moving parts inertia (J)

and the time response of the armature translation from side to side. [5],[6],[7] In Matlab function Dynamic relations are calculated. When the moving part reaches the maximum deflection angle α (13 Degrees in our model) then it will stick to the stator

An improvement to the mathematical model has been carried through simulation which reflected on the results gained. It is specified that when the displacement of armature is equal to the

length of work air gap, the direction of acceleration is contrary; the velocity becomes zero and then changes direction. See Fig.(6).

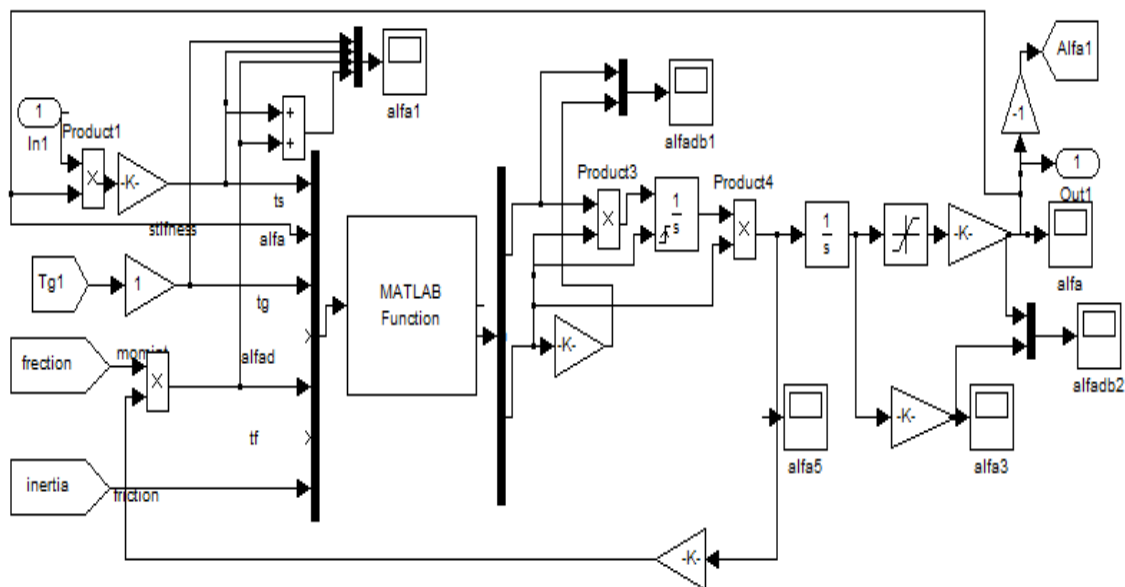


Fig.(6) Simulation of Relay Dynamic

5. Results

The results have been presented according to a sample of ESR used to move and control an aerodynamic surface in a flying object. The ESR has the following parameters:

For Electric Circuit:

$V_l=V_r=10$ V square voltage with 10 Hz,
 $R_l=R_r=25\Omega$, $L_l=L_r=10\text{mH}$,
 $N_l=N_r=1500$.

For Magnetic Circuit:

Left and Right parts are identical with a length=5cm, Moving part length=3 cm, Cross section area of all magnetic parts including the air-gap= $4 \times 10^{-5} \text{ m}^2$, Leakage factor of coils=0.9, Air-gap length=0.5 cm, Isolated sheet thickness=50 μm .

Mechanical Parameters: $J=0.000003$
 Kg m^2 , $\alpha_{\text{max}}=13$ deg., Stiffness=
 0.0014 N/deg.

Viscosity= 0.001 N/(Deg^2),

These mechanical dimensions made the movement of the armature limited mechanically by an angle equal to 13 degrees around the mid position.

5.1. Influence of Magnetic Material Type

Fig.(4) shows the Variation of relative permeability with flux density for different types of metals (Stalloy, Sheet Steel, Cast Steel, and Cast Iron). The main changes are the relative permeability verses flux density curve.

The influence of the core material type on generated torque and on moving part time response is shown in Fig.(7) and Fig.(8) respectively.

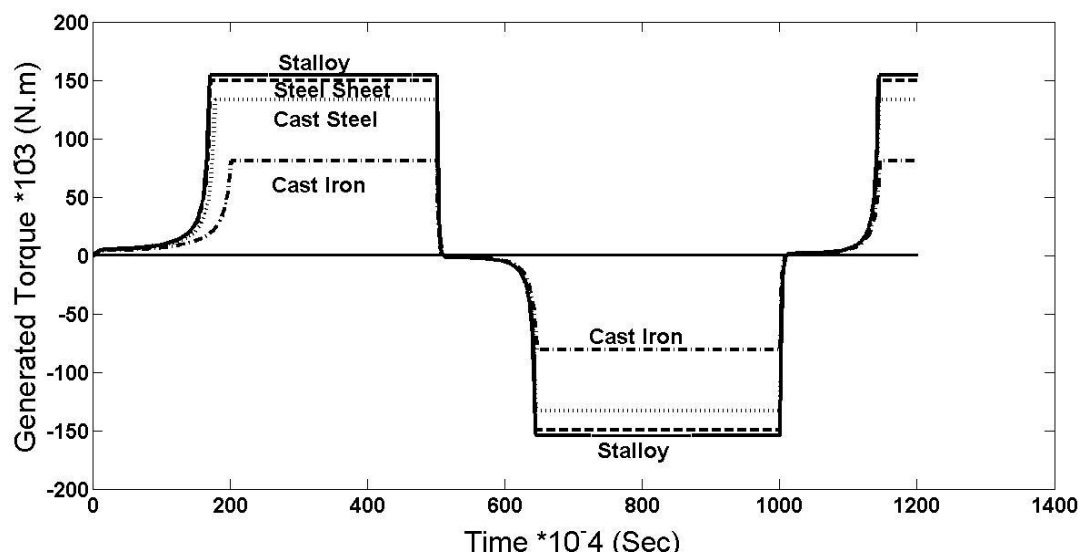


Fig. (7) Generated torque on moving part for different cores materials

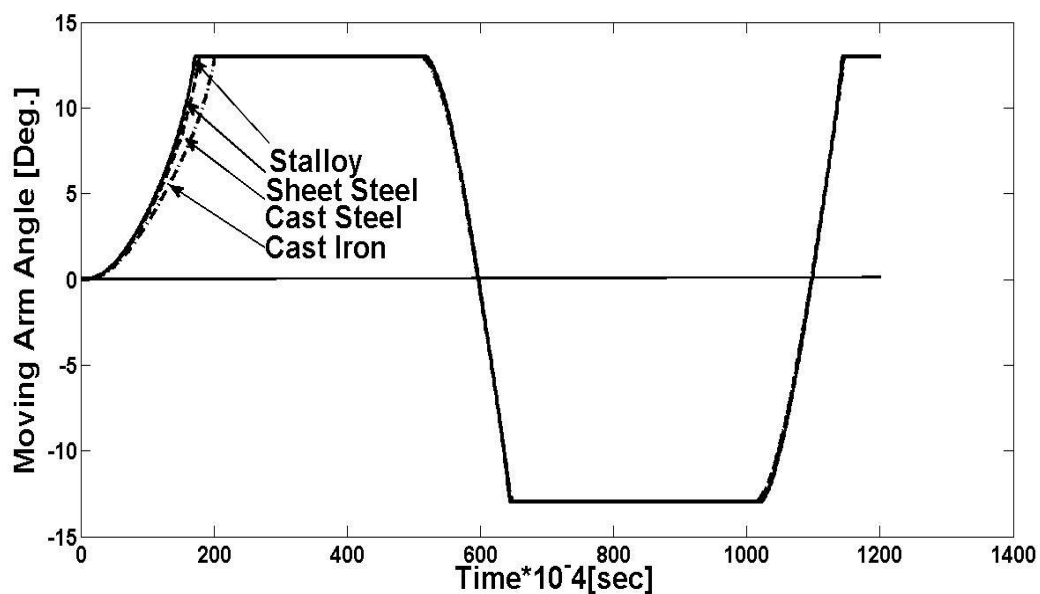


Fig.(8) Moving part angular response behavior for different core materials

Figures show that the permeability of ferrite parts increases the generated torque and the rise time of the response of the moving part decreases which leads to improving the behavior of the relay. Note that the maximum permeability used here for Stalloy is about 6600, for some nickel-iron alloys, the permeability

may be as high as 100000. In applications in which there is an air-gap, the high permeable materials are not as effective as the permeability increase due to that fact, the total reluctance of the magnetic circuit is mainly due to air-gap (permeability equal to 1).

5.2. Influence of Spring Plate Stiffness

Fig.(9) and Fig.(10) show the influence of spring plate stiffness on the behavior and response of both generated torque and Moving part angular position. The

values examined and simulated are the nominal value of the stiffness (0.29 N.m/Deg.) , 1.5 and 0.75 of the nominal value of the stiffness.

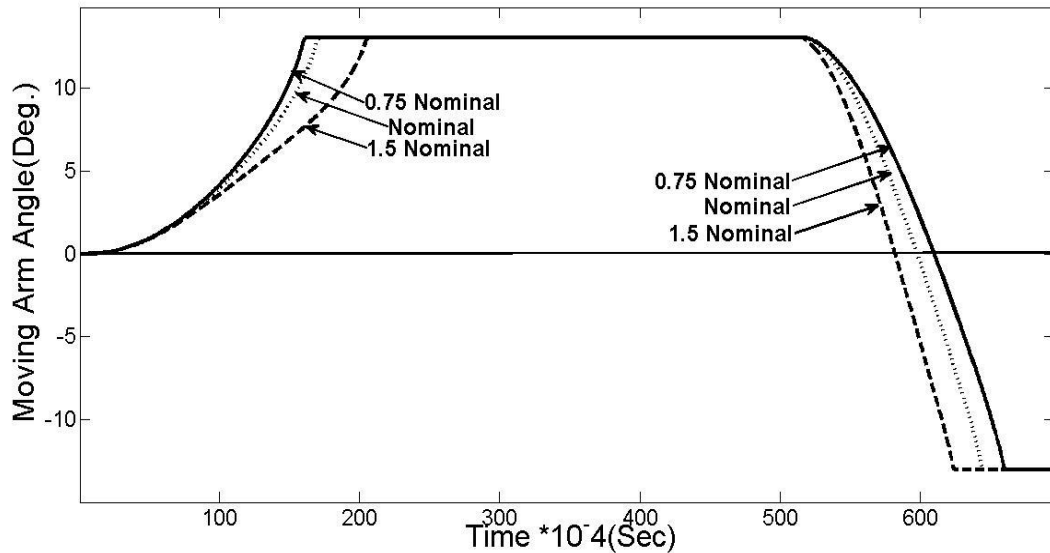


Fig.(9) Moving Part Angular behavior for different Stiffness values

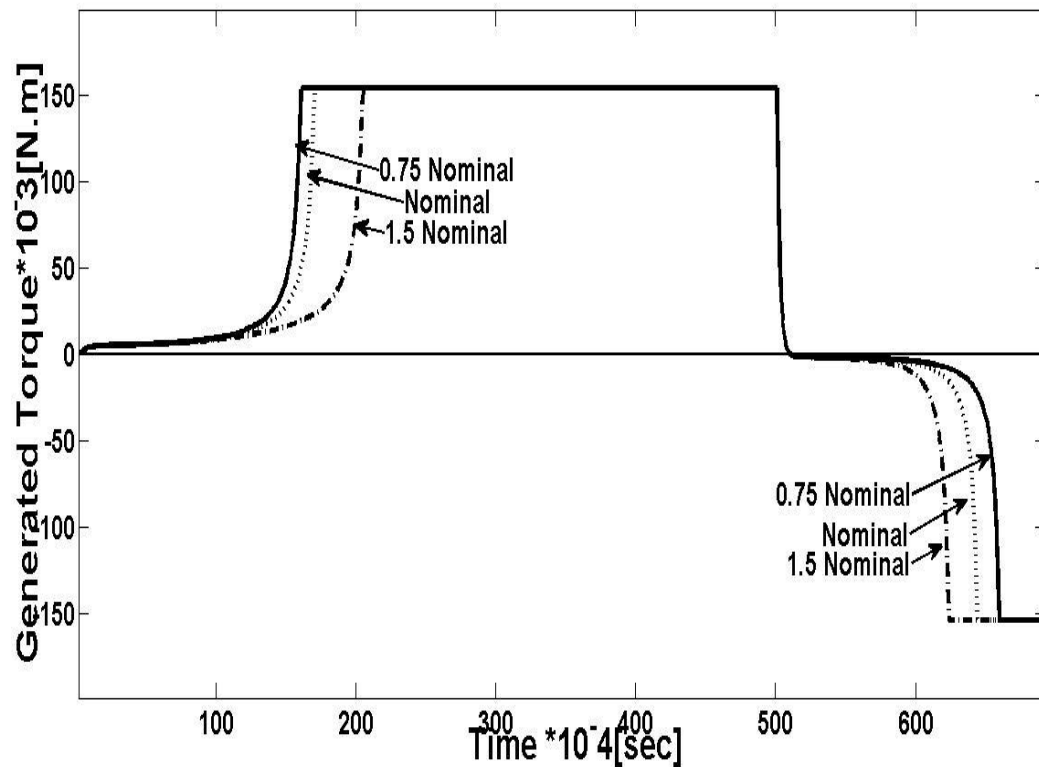


Fig.(10) Moving Part Generated torque for different Stiffness values

It is seen that, as the stiffness of the spring plate increased, the rise time of the response will decrease and improve the system response. This increment is limited by a situation in which the starting generated torque will not be able to reach the moving part to reach the maximum allowed angular position (13 degrees in our model). This means that the stiffness torque is high enough not to allow the generated torque to move the moving part to the end.

5.3. Influence of Moving parts Viscosity

Fig.(11) and Fig.(12) show the viscosity coefficient of moving part influence on the behavior and response on both Generated torque and Moving part angular position. The values examined and simulated here are the nominal value of the viscosity as a damping coefficient ($0.0001 \text{ N.m/(Deg./Sec)}$), 0.0 (ideal case) and 2.0 of the nominal value.

It is seen that, when the viscosity of the moving part decreases, the rise time of the response will decrease improving the system response.

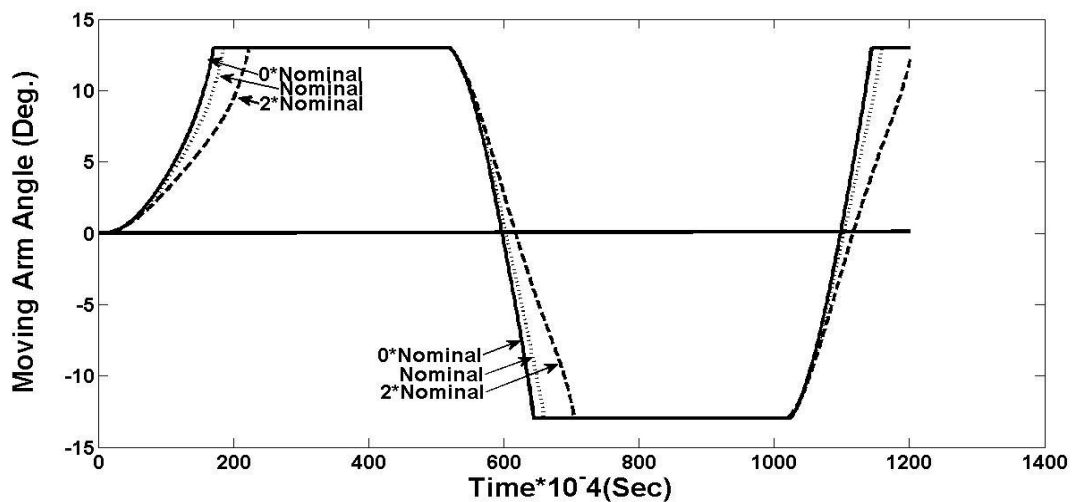


Fig.(11) Moving Part Angular behavior for different Viscosity values

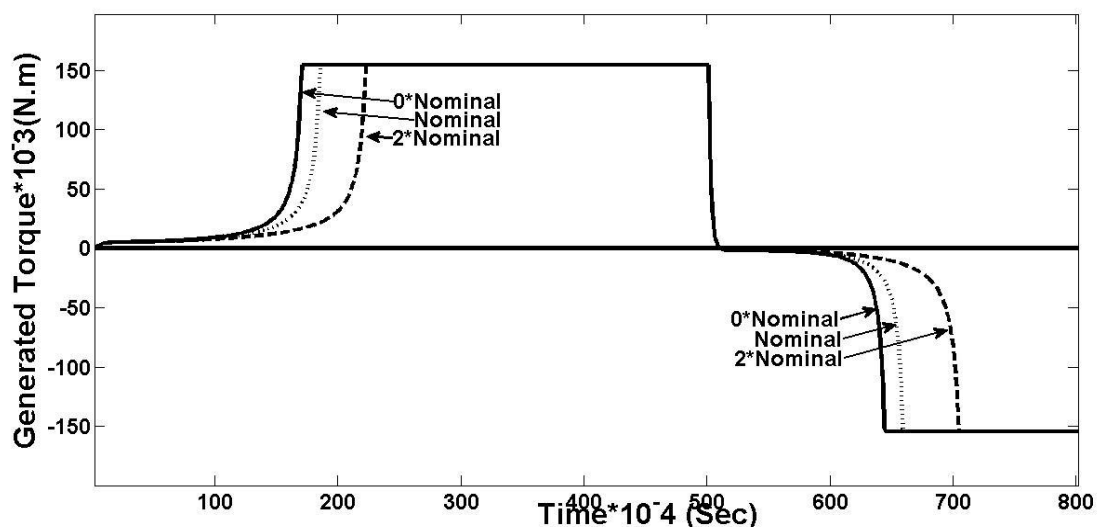


Fig.(12) Moving Part Generated torque for different Viscosity values

5.4 Influence of Copper Insulator

Fig.(13) and Fig.(14) show the effect of copper isolating sheet thickness on the moving part generated torque and moving part angular position response respectively. The values examined and simulated are the nominal value of copper thickness (0.5 mm) , 1.5 and 0.75

of the nominal value of the copper isolating thickness.

It is seen that the effect is clear at the starting of motion then the effect is not notable. Remember that its main function is to magnetically isolate the ferrite moving part and the ferrite stator in order not to stick together.

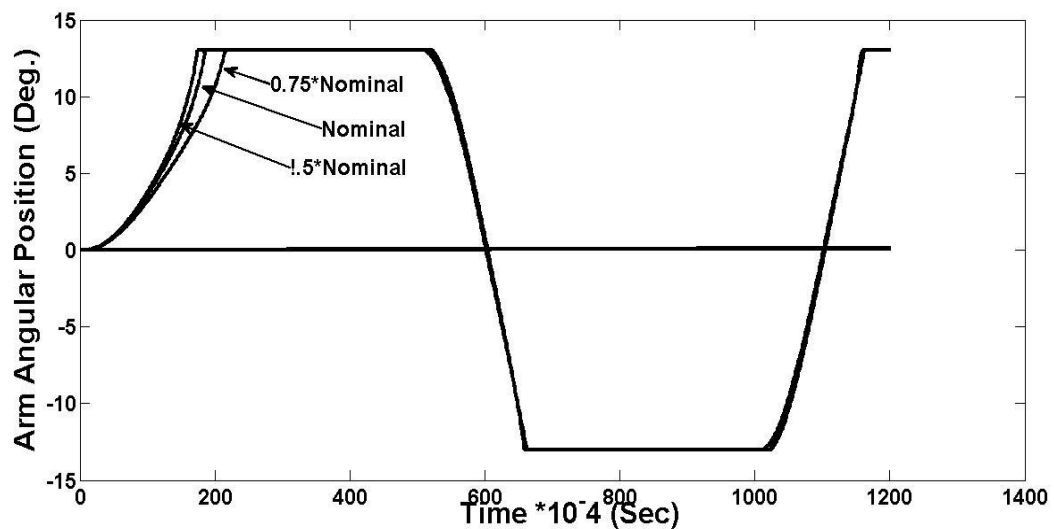


Fig.(13) Moving Part Angular position response for different Copper Insulating thickness

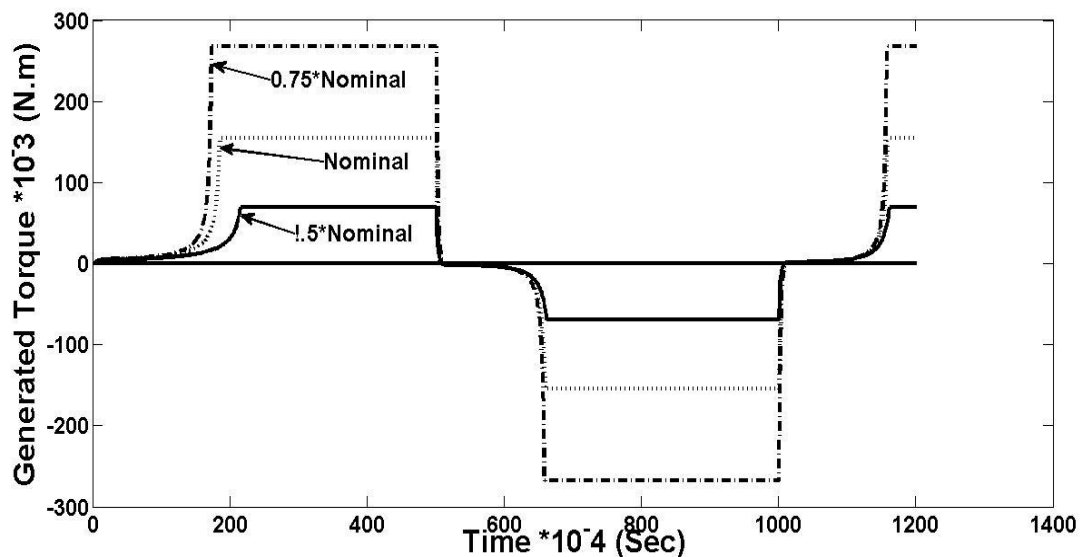


Fig.(14) Moving Part Generated torque for different Copper Insulating thickness

6. Conclusion

- 1- The Model shows the behavior and response of the relay in a way which can be used and extended to be a part of the complete control and regulated system.
- 2- The rise time of the response of the moving arm is about 10.3% of the total duration time of the pulse width. This effect is due to all electrical and mechanical influences. See Fig.(8).
- 3- It is essential to choose good magnetic materials like Stalloy or Nickel-Iron alloys. Results show that increasing the permeability will not result in a notable increase in the rise time of the response. Regarding the generated torque, it is seen that increasing the permeability 10 times will result in only 10% increase in the generated torque. See Fig.(7) and Fig.(8).
- 4- The influence of spring plate stiffness is notable on the dynamics of the system. A great care has to be taken in choosing the value. The value is to be as high as possible in order to make the system start easily and begin running. Increasing stiffness by 100% will result in 45% increase in rising time and only 0.5% in pulse width duration. See Fig.(9) and Fig.(10).
- 5- The viscosity parameter didn't show an unordinary note. As simple as it is, the value should be as minimum as possible. This is done by choosing proper ball-bearings and proper lubrication. Changing the viscosity 100% resulted in 11% change in rise time and 4% in pulse width duration. See Fig.(11) and Fig.(12).

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