Effect of Ferromagnetic Core Material Types on Solenoid Actuator Performances

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تأثير نوع مادة القلب الفيرومغناطيسية على أداء المعجل اللولبي

الخلاصة

بهدف ادخال تأثير خصائص الفيض المغناطيسي على تحليل مسائل الفيض, تم استخدام طريقة التحليل الغير خطي باستخدام واحدة من تقنية التحليل العددي بهدف اكمال التحليل. في هذا البحث تم استخدام طريقة تحليل العنصر المحدد الثلاثي الابعاد لدراسة المعجل اللولبي. تم استخدام نوعين من المواد الفيرومغناطيسية في التحليل، الاول معدن الفيروكوبلت والثاني حديد السلكون حيث يتم ادخال منحني B-H لكلا المعدنين في الحل الرقمي التكراري. اظهرت النتائج زيادة في قوة عضو الانتاج (المنتج) عند استخدام الفيرو كوبلت بالمقارنة مع حديد السليكون حيث تكون قيمة النفاذية النسبية قيمة عالية بالاعتماد على خصائص المعدن المستخدم.

Abstract

In order to introduce the effects of magnetic field characteristics (B-H) relationship in magnetic field problems analysis, nonlinear method of analysis by using some sort of numerical technique need to complete the analysis. In this work, three dimension finite element analysis is used for solenoid actuator studying. Two types of ferromagnetic, Ferro cobalt and silicon iron used where B-H curves for both materials are introduced in the iterative numerical solution. The results appears the increasing of armature force when the relative permittivity of the material exhibit large value depending on the characteristic of the material used in the solution.

1-Introduction

The solenoid actuators is an electromagnetic devices which able to transform electrical power input to mechanical movement and provide linear motion over short displacement with non-contacting translation force. These devices are presently used as mechanical switching component in different industrial applications such as automobile, aircraft, pneumatic valves, electrical relay and switches,...etc. The devices construction are simply, rugged with high reliability, low cost, and ability to convert electromagnetic energy into mechanical energy in order to perform the required work [1] . The promising properties of actuators such as high energy densities with large strokes and fast response which cause to the increasing of actuators necessities in smart devices where control applications are developed. In order to study actuators performance, different methods of analysis are used for studying these types of electrical machines devices. Fast action solenoid actuator with electromagnetic model is described using general method to obtain electromagnetic model [2], the dynamic analysis technique has been extended to simulate the performance and consist in computing magnetic curves. Finite element method analysis showing the magnetic flux distribution and density according to the position of the armature using governing equations [3]. Direct model is proposed where this model has particular application for large class of stress dependent models based on the employment of general effective field with time varying mechanical loads taken into account [4]. A new formulas obtained for mutual inductance and magnetic forces by using complete elliptical integrals of first and second kind. The Human's Lambda function with well behaved integral solved numerically [5]. A three dimensional analytical model based on formal resolution of Maxwell's equations of actuator is compared with three dimensional finite element analysis where good agreement between the two methods is satisfied [6]. In this work, the nonlinear behavior of core material magnetic properties are taken into consideration in the analysis taken at first time Ferro cobalt metal for the solenoid core and armature into consideration using three dimension finite element method FEM. This solution requires accurate knowledge of material property and geometric parameters. The performances for magnetic field are shown and compared with the results obtained for silicon iron core where high relative permeability is considered for this types of ferromagnetic materials.

2-Actuator model and Mathematical representation

The solenoid actuator consist from fixed iron core for magnetic field path and armature (plunger) moving axially within the core to perform confident mechanical stroke. The magnetic field produced by using rounded excitation copper coil composed by number of turns and the coil supplies from d-c constant current supply.

Due to the necessity of more accuracy, the process of solenoid analysis in order to determine the distribution of magnetic field in the structure under consideration, based on the solution of Maxwell's equations. Finite element method is a numerical technique that appropriate for this purpose. It permit the field solution to be obtained for nonhomogeneous, anisotropic, or nonlinear material. This method used in a wide region for solving magnetic field problems where the partial differential equations for the model domain are solved by discretising the equations in their space dimension. These equations are Maxwell's equations in differential form [5]:

$$\nabla \times H = J_s + J_e + J_v \tag{1}$$

$$\nabla \times E = \frac{\partial B}{\partial t} \tag{2}$$

$$\nabla \cdot B = 0 \tag{3}$$

$$\nabla \cdot D = \rho \tag{4}$$

For this work where the model materials are saturable types without permanent magnets, the constitutive relation for the magnetic fields is:

$$B = \mu H \tag{5}$$

The discretisation is approved out over small region of tetrahedral shape with 10 nodes, this process results in matrix equations concerning the input at the cubic nodes to the output at the same nodes. The equations of the smaller sub region are summed node by node resulting in global matrix equations in order to compute magnetic vector potential A in each node. Finite element matrices is resulting depending on variational principles, where field problem is solves by means of an integral approach. Starting from magnetic field which explain by a differential equations defined in a domain where a appropriate functional is built, so that its minimum corresponds to the solution of the field problem, which is when the field equations and the boundary conditions have been matched. This functional is just called variational in these matrix exist for both linear and nonlinear material behavior as well as static and transient response. The basic equation to be solved is in the form of [6]:

$$[N]\{A\} + [R]\{A\} = \{J\} \qquad (6)$$

The basic magnetic analysis results include magnetic field density and magnetic field intensity as well as armature force. The flux density in the first derived result from the curl of magnetic vector potential [7]:

$$\{B\} = \nabla \times [N]^T\{A\} \qquad (7)$$

Then magnetic field intensity is computed from flux density where the permeability is obtained from the interpolation of B-H curve of the actuator material:

$$\{H\} = \{B\}/\mu \qquad (8)$$

Since the solenoid actuator is a conservation system, the mechanical forces that take effect can be determine by means of the principle of the energy conservation. Magnetic forces on ferromagnetic armature are computed by using magnetic vector potential A in the nodes of each element. Maxwell stress tensor theory is used to calculate the net actuating force on the armature [8]. The actuating force is the vector sum of the normal Maxwell force. This force is computed by rapid computation of the electromagnetic forces acting on the moving object within electromagnetic field [9]. Via this method the forces is computed by performing the calculations on the surface air material elements which have non-zero face loading specified. The calculations is done by using volume integral on armature surface:

$$F_e^{mx} = -\int_{vol}\{T^{mx}\}\,dvol$$

Also, by making use of virtual work method, the armature forces can be computed by derivative the energy versus the displacement of the moving part. This computation is done by summing the force acting on a layer of the air material element surrounding the armature in the defined direction:

$$F_v = \int_{vol}\{B\}^T\left\{\frac{\partial H}{\partial v}\right\}d(vol) + \int_{vol}\left[\int \{B\}^T\,dH\right]\frac{\partial}{\partial V}d(vol) \qquad (9)$$

The virtual displacement of each node coordinate take three dimensions and the integration is performed for all element volume. Field intensity is taken with respect to

the displacement which depend on the direction of the force. This method for force computing is called element shape virtual work force method.

The magnetic flux circuit through the armature, stationary iron yoke, and the airgap between them. Magnetic energy density stored in the actuator material can be evaluated depending on flux density and intensity inside each element. For this work, where stationary magnetic field, the energy is constant and given by [10]:

$$W_m = \frac{1}{2}\int_v H \cdot B\,dv \qquad (10)$$

The value $\frac{1}{2}$ appears because B and H represent the maximum value of flux density and field intensity. Magnetic coenergy can be computed as:

$$W_m' = \int_v H \cdot B \, dv - W_m \quad (11)$$

3-Implementation of computer programming

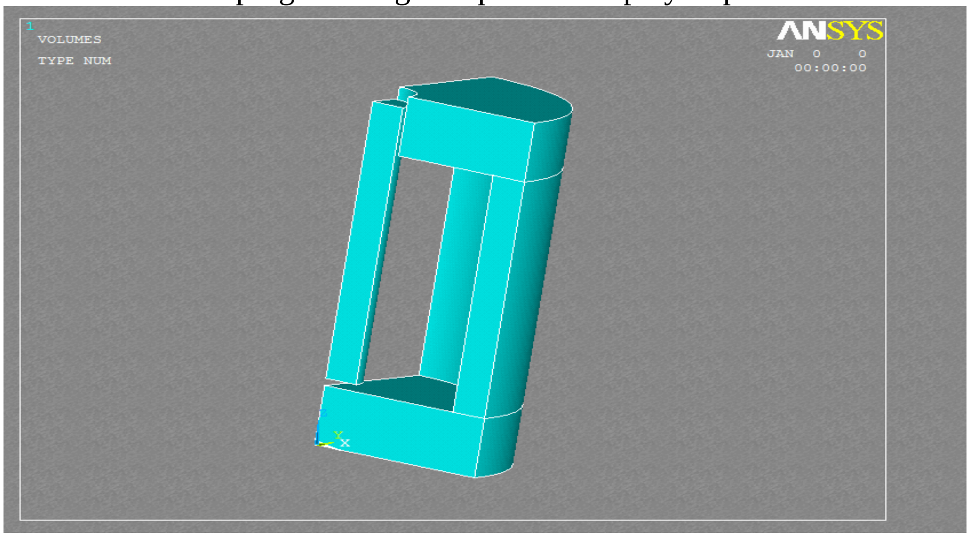
Programming of actuator model depend on the geometry dimension of actuator and the type of material of model parts, with respect to excitation coil measurement and the current inside the winding. The geometry details of actuator model is shown in table 1 where the core (yoke) is cylindrical shape and the same as for the armature. The magnetic field path encountered by the flux consists of the outer shell, the armature position, the front and back airgap. Because the back airgap is determined by the armature position, the overall effective reluctance is position dependent. Therefore, the total flux flowing through the magnetic circuit depends on the applied magnetomotive force as well as the position of the armature. In order to reduce the computing time and to depicted the distribution of magnetic field parameters interior the model, only quarter part of the actuator (angle from 0 to 90^0)are built and taken into the solution.

Outer core diameter	63.5 mm
Inner core diameter	50 mm
Armature diameter	13.5 mm
Actuator height	68 mm
Excitation coil outer diameter	45 mm
Excitation coil inner diameter	14 mm
Coil turns number	1000
Excitation current	1 Amp

Table 1 : solenoid actuator data tabe.

By making use table data , the program start from defined parameter data and starting with core creating using three dimension cylindrical shape plotting. The same procedure is done for plotting armature and excitation coil. Figure 1 show three dimension plotting of the respective model. After that each part of the solenoid material must be defined in order to take the non linearity of material B-H curve. Current value is taken constant during the solution. By using computer-aid design, the model is built step-by-step. The important second

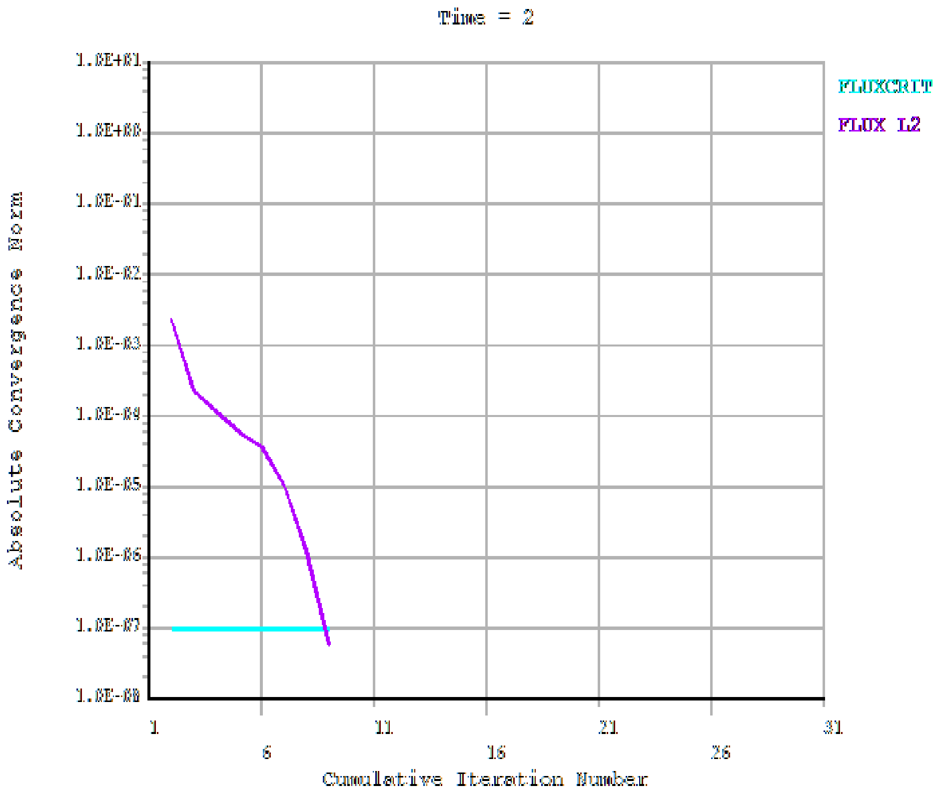
step is to define the type of material for each part of the model, and then meshing the model to a large number of tetrahedral shape element. The number of elements after meshing the whole model is 22224 element. Material property curve is put in the form of flux density values versus field intensity values and then converted to spline fit curve of permeability μ versus $|B|^2$. The shape of element depend on the type of solution, in this program tetrahedral shape with ten nodes are defined. Due to the nonlinear behavior of solenoid material then Newton-Raphson solution procedure is used to solve the matrices equations. The solution is consider to be converged when specified convergence criteria are met. Convergence criterion is specifying a value and a tolerance for that value and so that the tolerance value defined the convergence criterion. In this program, the convergence track can be plotted graphically via its graphical solution tracking feature. The FEM programming is depend on step by step solution.



4- Results

The electromagnetic analysis for calculating magnetic vector potential and consequently flux density in all solenoid parts be carried out simultaneously by nonlinear three dimensional FEM. Actuator model was designed via FEM software and the model meshed to 45690 tetrahedral shape elements with ten nodes. The solution was performed for two cases according to the materials type. First solution is approved for Ferro cobalt where B-H curve is show in Appendix B. The nonlinear solution convergence is depicted in figure 2 where the absolute convergence value start with 10^{-3} at the first iteration and arrive at 10^{-7} at the final iteration and the total number of solution iterations is 9.

The results obtained from FEM solution for Ferro cobalt material solenoid actuator are magnetic field quantities. Magnetic field density distribution inside all model parts is shown in figure 3. Field density value varied from 0.002152 to 4.007 Tesla anywhere inside solenoid



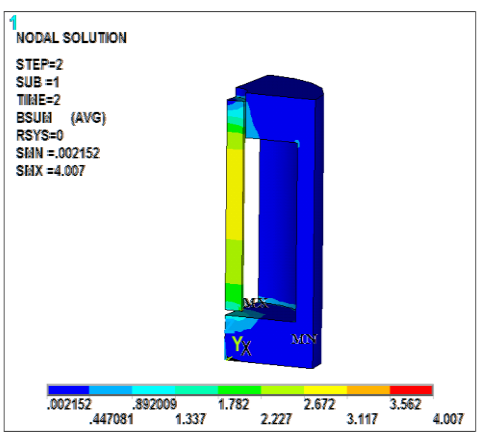


Figure 3: Flux density distribution for Ferro cobalt solenoid (nodal results).

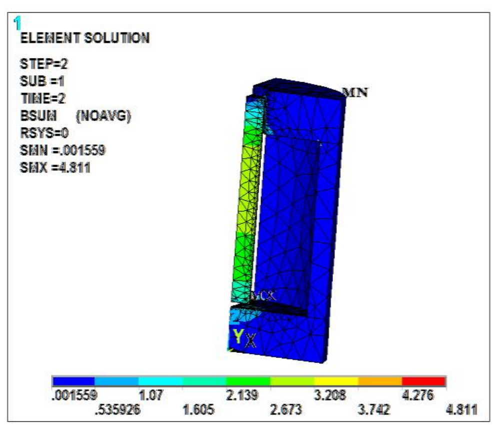


Figure 4: Flux density distribution for Ferro cobalt solenoid (elements results).

armature. This variation is due to the model construction and the effect of excitation coil position surrounding and nearby the armature body. The flux density plotting depend on display the solution results as a continuous contours element boundaries for the selected nodes and

elements. Various element results depend upon the recalculated method and the selected location and the contours are determined by linear interpolation within each element from nodal values, which are averaged at a node whenever two or more elements connect to the same node. Another technique for plotting magnetic parameters by displaying the solution results as element contours discontinuous across element boundaries for the chosen elements. The discontinuity between contours of adjacent elements is an indication of the gradient across elements. Figure 4 depicted flux density plotting by making use of elements solution results.
The flux density change from 0.001559 to 4.811 Tesla and the concentration of flux is inside solenoid armature which give an matching the results with that obtain for nodal solution.

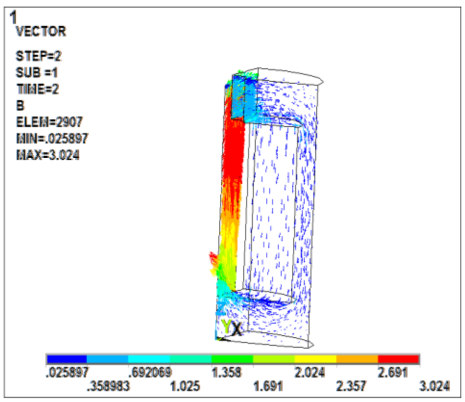


Figure 5: Flux density distribution for Ferro cobalt solenoid (vector plotting).

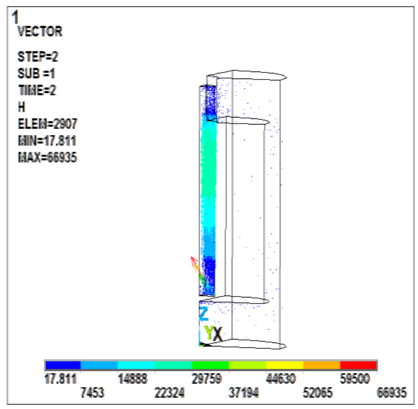
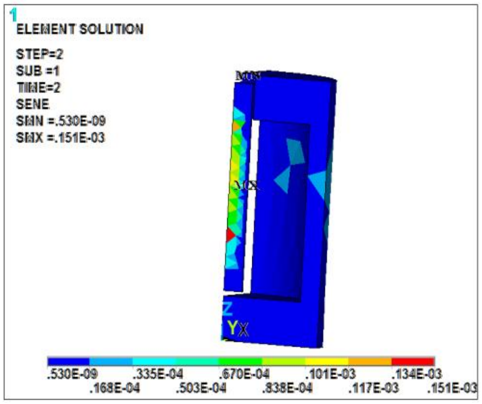


Figure 6: Field intensity distribution for Ferro cobalt solenoid (vector plotting).

Flux density results can displays as vectors for selected nodes or elements and vector magnitude as show in figure 5 depending on the defined item either node or element centrode depending on what item is displayed. The vector direction clearly shown in the figure where its direction is clockwise depending on the direction of the current in the excitation coil. The field intensity diffusion within the model depending on the instantaneous relative permeability. Figure 6 show field intensity vector appear as arrows at the element centrode taken the value from 17.811 to 66935 A/m and its maximum value in the air-gap of the model.

Magnetic energy stored in actuator model is computed for both yoke and armature which represent the active elements that stored this energy. This energy vary from $0.530*10^{-9}$ to $0.151*10^{-3}$ joule as show in figure 7 and the total energy for the yoke is $0.68884*10^{-1}$ joule, also, armature energy $0.45042*10^{-2}$ joule. The summation of total energy $0.73388*10^{-1}$ joule. This value of energy represent the amount of work required to drive the ferromagnetic material through its hysteresis loop.
The main function for solenoid actuator design is to produce force in the Z-direction in order to perform a certain previously defined option. From the programming results, the force produced the air elements surrounding the armature can be displayed. As depicted in figure 8, the minimum force value which appear in dark blue color is 0.025897 Newton and maximum force 3.025 Newton . the summation of magnetic force for the armature by using Maxwell stress tensor in the longitudel direction is 69 Newton, at the same, the force is computed by using virtual work

where the force value is 68.5 Newton. The co-energy stored in the active elements is computed by using equation (11) is 0.97127 joule. Also, the stored magnetic energy in Ferro core and armature is computed with total value of 0.60562 joule. This stored energy value is consider to be big value due to the large instantaneous relative permeability of Ferro cobalt material.



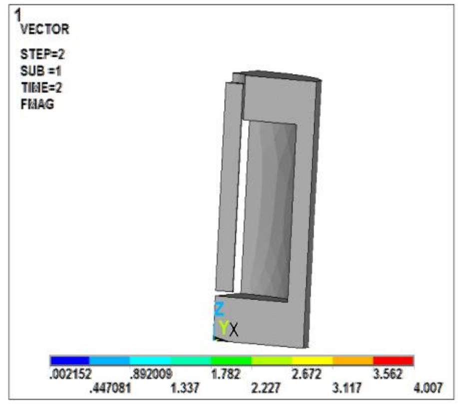


Figure 7: Magnetic energy distribution in actuator model.

Figure 8: Armature force produced In Z-direction

The second material type that taken into the solution is silicon iron core and armature where it is B-H curve is shown in Appendix c. this type of magnetic material has the lest relative permeability in the family of materials. Iterative solution start with absolute convergence value 1.0^{-3} and reduce to 1.0^{-7} taken 21 iterations to reach the convergence of the solution as show in figure 9.

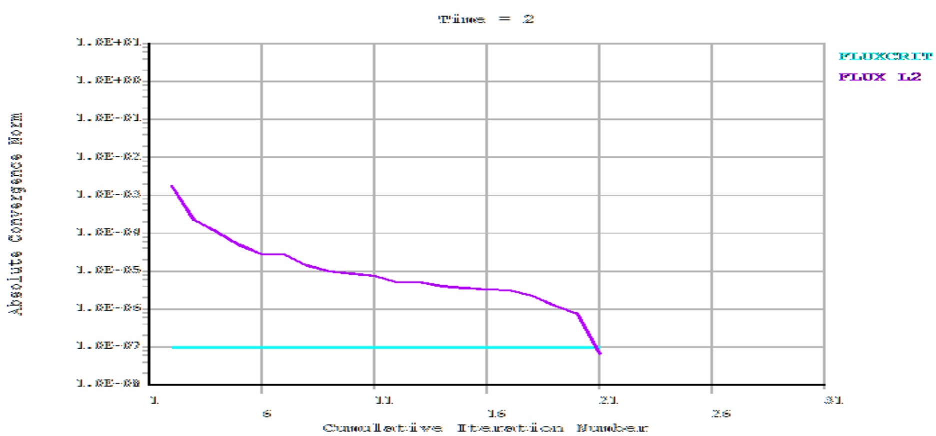


Figure 9: Nonlinear solution iteration convergence for silicon iron.

The same that for Ferro cobalt model, the flux density and intensity appears obvious reduction due to low instantaneous relative permeability value. Flux density value reduce to $0.841*10^{-3}$ whilst its maximum value is 2.203 Tesla as see in figures 10,11. At the same time field intensity minimum value is 6.695 A/m and maximum value 151608 A/m as show in figure 12 for nodal results. Field intensity inside the model is show in figure 13 by using elements results.

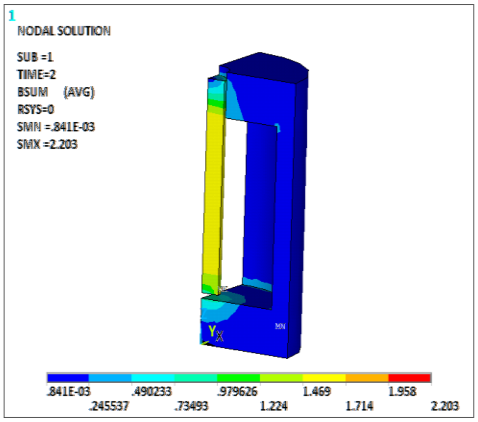


Figure 10: Flux density distribution for silicon iron solenoid (nodal results).

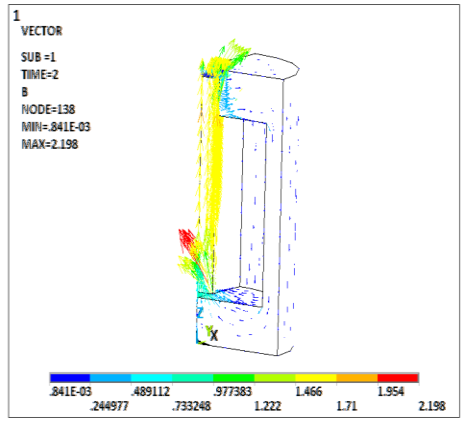


Figure 11: Flux density distribution for silicon iron solenoid (vector results).

The armature force for silicon iron used for constructed solenoid model is computed also using two types of force calculation methods. By using Maxwell stress tensor, the force value is 34.4 Newton and maximum value is 35 Newton. the force reduction is quite acceptable due to the low material relative permeability. The magnetic co-energy is 0.49945 joule and the stored energy is 0.01702 joule, this reduction is also owing to reduction in silicon relative permeability.

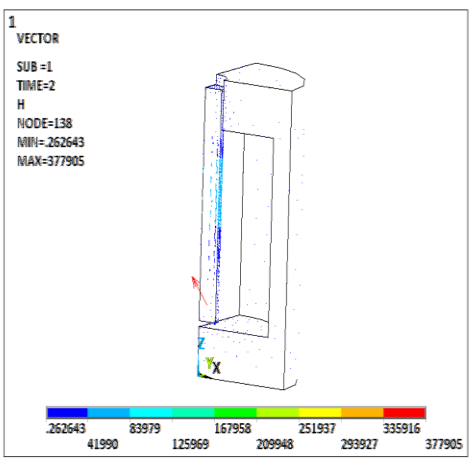


Figure 12: Field intensity distribution for silicon iron solenoid (vector results).

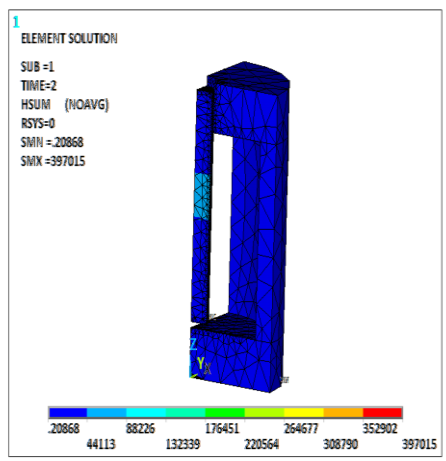


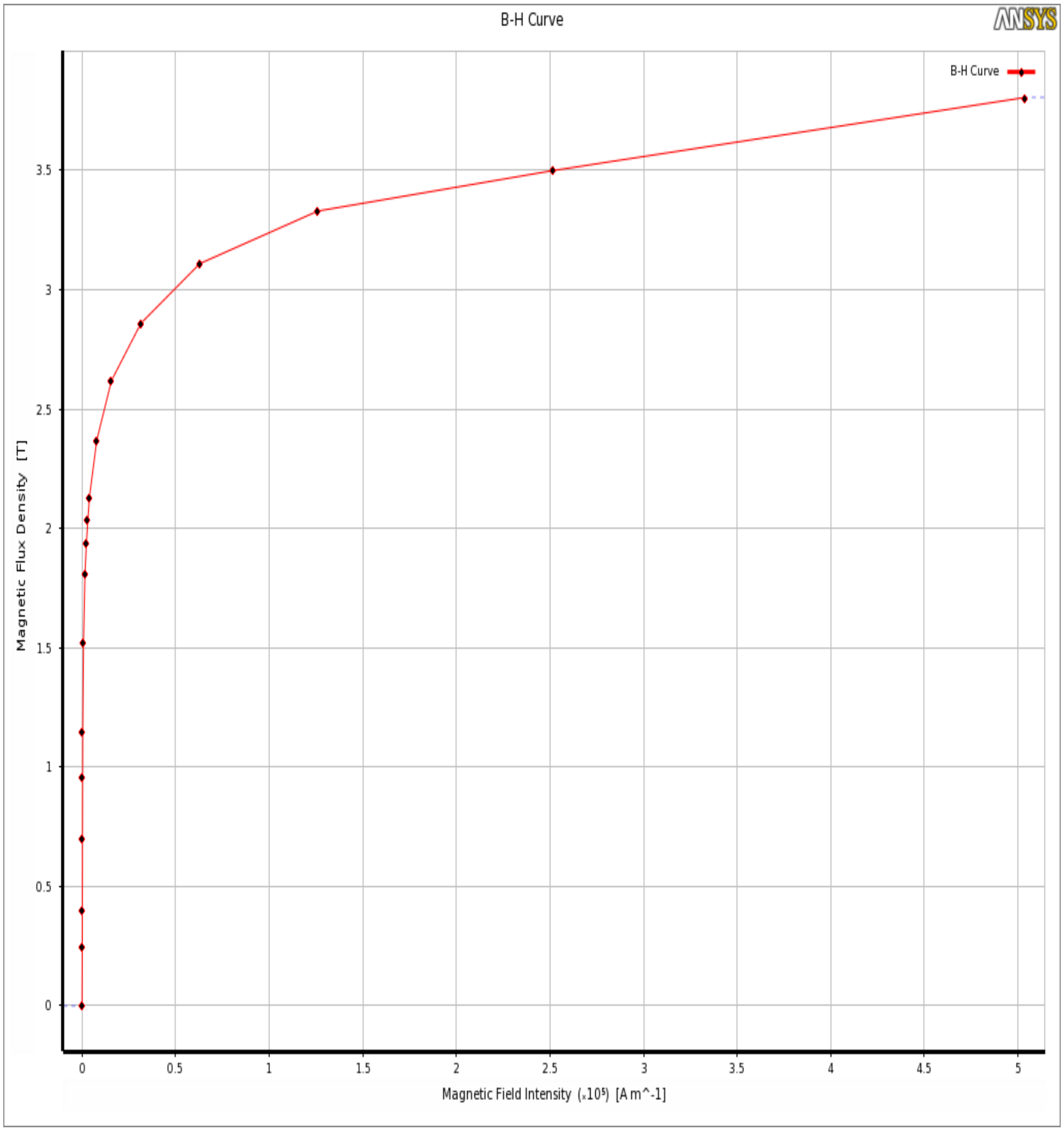
Figure 13: Field intensity distribution for silicon iron solenoid (element results).

5- Conclusions

In this paper the consequence of solenoid actuator magnetic material for yoke and armature is taken into consideration by using one of the accurate numerical analysis where the solenoid geometry and dimension material nonlinearities and driving conditions are modeled. The simulation with FEM plays an important function in verifying the performance of the actuator and its magnetic distribution. The results appears the increasing of flux density, intensity, and armature force. The proposed Ferro cobalt actuator can produce an increasing of force is nearby 50% for using Ferro cobalt metal instate of silicon iron while the excitation electrical power remain constant during the solution. Also, for Ferro cobalt solution, the convergence of nonlinear solution is approved at less number of iterations.

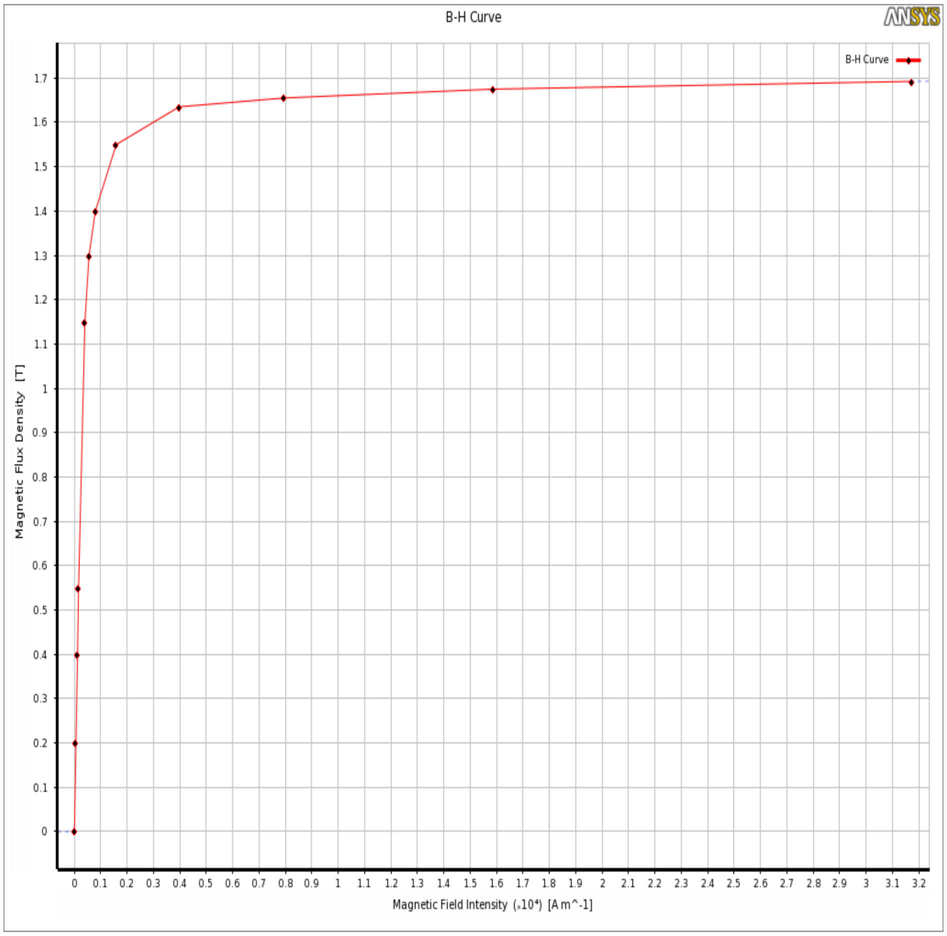
Appendix A

Ferro cobalt magnetic material characteristic B-H relationship [6].



Appendix B

Silicon iron magnetic material characteristic B-H relationship [6]



List of symbols

A	Magnetic vector potential
B	Magnetic flux density
F	Force
J	Current density
H	Field intensity
N	Shape function
W	Magnetic energy
v	Volume
μ	Permeability

6- References

[1]- Back-Ju Sung, Eun-Woong, and Jae-Gyu Lee, “A design method of solenoid actuator using empirical design coefficients and optimization technique,” Downloaded UTC from IEEE Transaction on Magnetics, page 279 to 284, Year 2007.

[2]- M.Piron and p. Sangha, “Rapid Computer-Aided Design Method for Fast-Action Solenoid Actuators,” Download UTC from IEEE Transaction on Magnetics, page 197 to 204, Year 1998.

[3]- B. J. Sung, and E. W. Lee "Optimal Design of High-speed Solenoid Actuator Using a Non-Magnetic Ring," Downloaded UTC from IEEE Transaction on Magnetics, page 2333 to 2338, Year 2011

[4]- D. Davino, A. Giustiniani, and C. Visone "Design and Test of a Stress-Dependant Compensator for Magnetostrictive Actuators," IEEE Transactions on Magnetics, Vol. 46, No. 2, page 3608 to 3616, February 2010.

[5]- Slobodan Babic and Frederic Sirois,"New Formules for Mutual Inductance and Axial Magnetic Force Between a Thin Wall Solenoid and a Thick Circular Coil of Rectangular Cross-Section," IEEE Transaction on Magnetics, Vol.47, No.8, page 2034 to 2044, August 2011.

[6-] ANSYS theory reference, release 12.1 2009 SAS, inc. all right reserved.

[7]- Jaewook Lee and Ercan M. Dede,"Simultaneous Design Optimization of Permanent Magnet, Coils, and Ferromagnetic Material in Actuators," IEEE Transactions of Magnetics, Vol. 47, No. 12, page 4712 to 4715, December 2011.

[8]- Dan Wu, Xiaodan Xie and Shunyan Zhou " Design of a Normal Stress Electromagnetic Fast Linear Actuator," IEEE Transactions on Magnetics, Vol. 46, No. 4, page 1007 to 1014, April 2010.

[9]- Nicola Bianchi, " Electrical Machine Analysis Using Finite Elements," book, Taylor & Francis Group, Year 2010.

[10]- Odle la Barriere and S. Hlioui, "Three-Dimensional Analysis Modeling of a Permanent-Magnet Linear Actuator With Circular Magnets," IEEE Transactions on Magnetics, Vol. 46, No. 9, page 3608 to 3616, September 2010.

[11]- QingHui and Perry Y. Li,"Self-Calibration of Push-Pull Solenoid Actuators in Electrohydraulic Valves," proceeding of IMECE'04, 2004 ASME International Mechanical Engineering Congress and RD&D Expo, California, USA, November 13-19, 2004