EFFECT OF VARYING AIRGAP LENGTH ON PERFORMANCE OF LINEAR AND NON LINEAR ELECTROMECHANICAL RELAYS

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Abstract

     This work studies the effect of varying air-gap length on performance and behavior of electromechanical relays. When the air-gap length changed due to mechanical movement producing from air or liquid pressure in pneumatic or hydraulic system, respectively therefore; the magnetic reluctance is change, that is the inductive properties be effected and as a result of that, the switching value of voltage and current are changed drastically in electromechanical relays. It can be controlled on the min. and maximum value for air pressure in a pneumatic system by controlling on the minimum and maximum value corresponding to voltage and current in the system relay. Two models of transducers are used in this study; the first is variable reluctance displacement transducer studies the intensity of magnetic field lines in 2-D, the intensity of magnetic field vectors and summation of magnetic field intensity contours estimated. The magnetic force is determined with air- gap length changing from (0.8 to 0.2) cm, gradually. Second model is variable differential reluctance transducer. The same results obtained in first model are determined in second model with two cases, armature in mid-way and armature shifted to right side by (0.4) cm. The magnetic force is determined along the line of axisymmetric and in Y direction of armature location. The results show from ANSYS 5.3 and MATLAB - 7 - simulation, the magnetic field increases with decreases of air-gap length in first model and for the second model the magnetic field concentrated in mid - way armature position and increase in the side where the air - gap length reduced and reduced in the side where the air – gap length increasing.

Keywords: Electromechanical relays; air – gap length; magnetic force, reluctance; magnetic field lines; vectors; Ferromagnetic, ANSYS and MATLAB simulation**.**

تأثير تغيير طول الفجوة الهوائية على أداء المرحلات الكهروميكانيكية الخطية واللاخطية

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الخلاصة

     الفجوة أن تغيير طول هذا البحث يدرس تاثير تغييرطول الفجوة الهوائية على أداء وتصرف المرحلات الكهروميكانيكية. نتيجة لحركة ميكانيكية ناجمة من ضغط الهواء أو السائل في المنظومة الهوائية أو الهيدروليكية على الترتيب ، لذلك تتغير المعاوقة في ملف المرحل الكهروميكانيكي المغناطيسية التي بدورها تؤثر على الخواص الحثية وكنتيجة لذلك تتغير قيمة الفولتية والتيار

بشكل ملحوظ. يمكن السيطرة على قيمة الدنيا والعليا لضغط الهواء في منظومة معينة عن طريق السيطرة على القيمة الدنيا والعليا في ملف المرحل. هنالك موديلين من المتحسسات أستخدمت في هذه الدراسة،الأول هو متحسس معاوقة للتياروالفولتية المناظرة لها متغييرالطول بأطوال مختلفة للفجوة والذي تم فيه حساب شدة خطوط الفيض المغناطيسي ذات البعدين، شدة المجال المغناطيسي كمتجهات، وشدة المجال المغناطيسي على أساس تدرج الألوان أضافة الى حساب قوة المجال وبعض المواصفات ذات العلاقة.أن القوة المغناطسية حددت نتيجة لتغير الفجوة من (٠.٠٨الى٠.٢) سم تدريجيا.الموديل الثاني هومتحسس معاوقة تفاضيلي الطريق بين الملفيين ومرة أخرى أزيح الى اليمين بمقدار (٠.٢)سم. لقد التغييروبموقعين مختلفين للجزء المتحرك مرة في منتصف تم حساب نفس الخواص في الموديل الثاني أضافة الى حساب قوة المجال المغناطيسي على طول خط التناظر الأفقي وعموديا في الأصدار ٥.٣ و بأستخدام ANSYS الحاصلة من المحاكاة بمساعدة برنامج المحاكاة . منطقة الفجوة الهوائية. أظهرت النتائج الحزمة البرمجية مختبر المصفوفات الأصدار السابع للموديل الأول أن قوة المجال المغناطيسي تزداد مع نقصان طول الفجوه أظهرت النتائج أن قوة المجال المغناطيسي تتمركز قرب الجزء المتحرك للمرحل وتزداد في الهوائية أما بالنسبة الموديل الثاني، فقد الجهة التي يقل فيها طول الفجوة الهوائية وتقل بالمقابل في الجهة التي يزداد فيها طول الفجوة

Nomenclature

Symbols	Definitions	Units
A	The cross sectional area of flux path	cm^2
B	Magnetic flux density	Tesla or (Wb / m^2)
D	Damping coefficient	-
F_{em}	The electromagnetic force	N
F_{load}	The pneumatic force	N
F_a	The mechanical load	N
H	Magnetic field intensity	A / m
L	The total of winding inductance in coil	H
l	The total length of the flux path	cm
M	Mass of the moving part	g
N	Number of Turns	Turn
R	Radius	cm
S	Surface arc length	cm
T	The Maxwell stress tensor	-
t	Switching time	sec.
V	Supply voltage	Volt
v	Armature velocity	m /sec.
x	Air – gap distance	cm
Λ	Magnetic reluctance	(Amp.Turn) / Wb
μ_r	Relative magnetic permeability	H / m
μ_0	Free space absolute permeability	$(4\Pi * 10^{-7})$ H / m
Ψ	Magnetic flux linkage	Wb. Turn
Φ	Magnetic flux	Wb

Introduction

The relay is a device for amplifying, attenuating modifying, or passing (**ON/OFF**) signals. Relays can be classified to electric, electronic, pneumatic, hydraulic, balanced beam differential or optical and they may have many different functions such as over current, over voltage, differential protection and electro-mechanic contactor after occurs a disturbance like trip, fault or D.C clock signal [Holman, 1997]. The contactor is a switching device, which connects (ON) or isolates (OFF) a load from the supply. The

mechanical contactor requires an operating movement and operated by tenderization of the magnetic spring carrying the contacts. The most common traditional form of relay is the electromechanical relay, which utilizes an electromagnetic coil, to move a plunger or an armature for open or close electrical contacts. The transducers can be adjusted by electromechanical motion produced from electrical signal air or liquid pressure in electrical, electronic, pneumatic or hydraulic systems.

The mechanical motion may be design in different forms such as armature and spring motion. Eelectromagnetic relay designed to switch (**ON / OFF**)**;** like in circuit breakers in all types and pressure valves. Application like large force is applied to a member, which moves a relatively short distance through the conversion of electrical energy into optimum mechanical work from magnetic attraction. The electromagnetic relay must have three features, which are compact electromagnetic, high speed and light weight. The magnetic circuit consists of a core made of a ferromagnetic material, with a coil of several number of wound on it. The coil acts as a source of magneto motive force, which drives the magnetic flux through a magnetic circuit. The presence of air - gap causes large increase reluctance and corresponding decrease in the flux, a small variation in air - gap results, a measurable change in inductive properties. Most of the inductive transducers are based on these principles [Doebelin, 1992]. The effect of alternating current in a distribution coil on magnetic flux density has been analyzed and discussed. It provides a theoretical basis for selecting the reasonable technology parameters [Wang, and Cui, 2005]. For apparatus with two stable positions of the moving part dynamics of opening and closing is of interest, in this case the duration of the process to be simulated is short, most often of order of milliseconds. For devices with continuous motion, although the dynamics determines the normal region of the devices on the period of the mechanical oscillation and the simulation should cover several periods [Ando and Ishikawa, 2001].

In presence of a linear material properties, this leads straight forward to the expression of the Maxwell stress tensor as well as to that of classical formulae obtained by the virtual work principle, thus making the link between them obvious [Ren, 2001].

The present paper, deals with a linear and non – linear relays and different models using, ANSYS Vol. 5.3 [ANSYS, 2002] and MATLAB Vol.7, simulations [Math Works, 2006] in electromichanical couple relays will be presented together with methods for analysis to the problem.

Mathematical Models

Numerical solution is performed by finite element approach using ANSYS program Vol. 5.3**.** Two models of transducers are studied. The central magnetic flux path is shown in **Figure 1**, which represents the first model, consists of four elements, which are a variable air - gap, ferromagnetic core in the semicircle shape ring (stationary part), coil, and ferromagnetic plate (armature), which is the moving part. The magnetic reluctance of the core in this model is dependent on varying air – gap length. The magnetic flux path is shown in **Figure 2,** which represents the second model consists of an armature, moving part between two identical cores separated by a fixed distance of (0.4) cm. The armature moves in the air - gap in response to a mechanical force. This movement alters the magnetic reluctance of cores that is altering their inductive properties. The second model arrangement overcomes the criterion of non-linearity in first model. The direction of magnetic flux lines, in two models, can be determined by using right hand screw rule [www.sayed.com].

Model of each transducer in **Figures 1 - a and 2 - a** are analyzed as a two dimension axisymmetric model. For given clock pulse and current in first model **Figure 3 - a**, the two dimensions flux lines contour, magnitude of flux density contour, flux density as vectors. Magnetic force, energy input, winding inductance, current per turn, and flux linkage will be presented for (0.8, 0.6, 0.4, and 0.2) cm of air – gap varying length, gradually. For given clock pulse and current in second model **Figure 3 - b**, the two dimension flux lines contour, magnitude of flux density contour, flux density as vectors. Magnetic force, energy input, winding inductance, current per turn, and flux linkage will be presented for two positions of the plate armature, the first is in the center between two cores and the second is shifted to the right side by (0.2) cm and not shifted to the left side due to axisymmetry model around Y axis. **Figures 1- b** and **2 - b** illustrate the electrical series equivalent circuits for variable reluctance displacement and series – parallel axisymmetric variable differential reluctance modelss, respectively.

There are several assumptions are made to simplify the solution of two models such as:

1- All material properties (resistively and permeability) are linear. Typical hysteresis curve (loop) in magnetic circuits is shown in Fig. (4), which represents the relation between magnetic flux and current. The magnetic materials have important role in effecting on (B – H) curve configuration. The electric and magnetic properties of ferromagnetic materials are described by the resistively of the material and the non- linear relationship of the flux density, B and the magnetic field strength, H.

2- The air - gap is modeled so that the quadrilateral is possible.

3- The magnetic force is calculated by virtual work and Maxwell stress tensor methods.

5- No saturation in iron occurs due to the small magnetic flux produced from the coil current.

6- The external flux leakage is negligible, which means that the magnetic flux lines will act parallel to the core surface.

If assume the air-gap length is zero the equation of magnetic circuit can be expressed as [Zhang and Cui, 2002]:

$$\text{m. m. f} = \text{magnetic flux} * \text{reluctance} = \phi * \Lambda \tag{1}$$

Such that the magnetic reluctance limits the magnetic flux path in magnetic circuit. If the magneto motive force in terms of current and number of turns, the magnetic flux can be expressed as:

$$\Phi = N. I / \Lambda \qquad \text{that gives,} \quad \Lambda = l / (\mu_o \, \mu_r. A) \tag{2}$$

The mechanical motion equation formed if, the armature is displaced a distance dl at the air-gap due to the magnetic field force acting on it, the magneto static energy must be equal the input mechanical work done for two dimensions X and Y axis forces :

$$dW_m = F.dl = F_x.dx + F_y.dy \tag{3 - a}$$

While, the mechanical work done would be in three dimensions X, Y and Z axis forces:

$$dW_m = F.dl = F_x.dx + F_y.dy + F_z.dz \tag{3 - b}$$

This work is done by supply voltage V volt at the expense of energy in the magnetic field such that the following energy balance is maintained that the magneto static energy change plus the mechanical work done equal to work done by the supply voltage V. the change in the magnetic energy , changing the air – gap length. The magneto static energy is:

$$W_m = \frac{1}{2}L.I^2 = \frac{1}{2}i\Psi = \frac{1}{2}\Lambda.\phi^2 \qquad (4\text{-}a)$$

The stored energy in air - gap is:

$$W_{air\,gap} = \frac{1}{2}BH.Al_{gap} \qquad (4\text{-}b)$$

Omitting the heat losses $I^2.r_{coil}$ associated with coil resistance in the equivalent circuit of a certain system. In the basis of the balance of the forces acting on the moving part:

$$M.\frac{d^2x}{dt^2} + D.\frac{dx}{dt} = F_{em} - F_{load} \qquad (5)$$

To reduce the order of derivatives in the force equation (5), the latter is split into two equations [Edward and Michael, 2001].

And the velocity is: $v = \dfrac{dx}{dt}$ (6)

The property of self inductance is a particular form of electromagnetic induction. Self inductance is defined as the induction of a voltage in a current – carrying wire when the current in the wire itself is changing. It can be seen that the number of turns in the coil will have an effect on the amount of voltage that is induced into the circuit, i.e., increasing the number of turns or the rate of change of magnetic flux increases the amount of induced voltage. There are several methods can be represented the total winding self inductance in the coil:

$$L = \frac{N\phi}{i} = \frac{\psi}{i} = \frac{N^2}{\Lambda} = N^2.\frac{\mu_0.\mu_r A}{x} = \frac{k}{x} \qquad (7)$$

The steady state equation is:

$$\frac{k}{2}.\frac{i^2}{x^2} = F_a + k.(\xi - x) \qquad (8)$$

The dynamic equations are:

The applied voltage in electrical circuit is depending on coil induced voltage and drop voltage on coil resistance: $V = r.i + e$ (9)

$$f_a = M\frac{d^2x}{dt^2} + k(x - \xi) + D\frac{dx}{dt} - f_{em} \qquad (10)$$

The induced voltage in the relay coil can be calculated:

$$e = \frac{d\Psi}{dt} = L.\frac{di}{dt} + i.\frac{dL}{dx}.\frac{dx}{dt} = \frac{k}{x}.\frac{di}{dt} - k.\frac{i}{x^2}.\frac{dx}{dt} \qquad (11)$$

There exist two distinct families of electromagnetic force formulae. The ones belonging to the first family are based on the Maxwell stress tensor while the other ones from the application of the virtual work principle. According to the virtual work method, considers the rate of the change of the total co-energy against the virtual displacement:

$$F_{em} = \frac{\partial W_c(x)}{\partial x} \qquad (12)$$

According to Maxwell's stress tensor method, from the energy density of the fields there is a momentum density one can show that:

$$F_{em} = \oint_s \frac{1}{\mu_0}[(B.n)B - \frac{1}{2}B^2 n].ds \tag{13}$$

The Maxwell's stress tensor T is a circle integral of:

$$T = \oint_s R.\frac{1}{\mu_0}[(B.n)B - \frac{1}{2}B^2 n].ds \tag{14}$$

Where, n is the number of nodes on surface.

3 - Results And Discussion

1: Variable Reluctance Displacement Transducer

Fig. **5-a** represents the finite element mesh model of the first type. The number of the finite elements for each case at (0.8, 0.6, 0.4, and 0.2) cm of air - gap length are (3238, 3235, 3231, and 3228), respectively. The results are obtained for the transducer from **Figure 1** with the following data: supply voltage is (12) V; coil resistance r_{coil} is (8) Ω; number of turns is (400); mass of the moving part is (35) g., damping coefficient is (25), cross section area of (0.785) cm2 and current density of (127. 388 * 10 ⁻⁶) A / m2. The following results consist of two parts, which are qualitative results and quantitative results [ANSYS Program, 2002]:

A-   Qualitative Results: **Figures. 5 -b, 5-c and 5-d)** illustrate the 2-D flux lines contour, magnitude of flux intensity contour, and flux intensity as vectors at (0.8) cm air - gap length. The maximum flux, flux intensity, and flux intensity vectors in these figures are (0.0576, 0.119976, and 0.119034), respectively. **Figures. 6-a, 6-b, and 6- c** show the 2-D flux lines contour, magnitude of flux intensity contour, flux intensity as vectors at 0.6 cm air gap length. The maximum flux, flux intensity, and flux intensity vectors in these figs are (0.0577, 0.120289, and 0.11928), respectively. Flux intensity, and flux intensity vectors in these figs are (0.0578, 0.120124, and 0.119186), respectively. **Figures. 7-a, 7-b, and 7- c** indicate the 2-D flux lines contour, magnitude of flux intensity contour, flux intensity as vectors at (0.4) cm air - gap length. The maximum flux, flux intensity, and flux intensity vectors in these figs are (0.0578, 0.120124, and 0.119186), respectively. **Figures.8-a,8-b, and 8-c** show the 2-D flux lines contour, magnitude of flux intensity contour, flux intensity as vectors at (0.2) cm air-gap length. The maximum flux, flux intensity, and flux intensity vectors in these figures. are (0.058, 0.12047, and 0.119386), respectively. These results indicate increasing of the flux, while increasing and then decreasing of the flux intensity magnitude and increasing of the flux intensity vectors with the decreasing of the air - gap length from (0.8 - 0.2) cm.

B-   Quantitative Results: **Figures. 9 - a & 9 - b** show the behavior of magnetic force along the line of x symmetric and along y - axis at the armature position; respectively. The first curve shows that the maximum magnitude of this force is between the (3.576 and 4.2) cm, which means at the armature position. The second curve indicates that the maximum magnitude of the magnetic force is at the air - gap positions and the force at the upper air - gap is greater than at the lower one. The behavior of magnetic force produced by virtual work and Maxwell stress tensor method, energy input,

winding inductance, current per turn, and flux linkage with the air - gap length are summarized and tabulate in **Table 1.** The results indicate strong increasing in force by the two method used with the decreasing in the air gap length, while a small increasing in the energy input, winding inductance, and flux linkage with the decreasing in the air- gap length, and the fluctuating mode produced in the current per turn behavior. The results conclude that the variable- reluctance transducers are based on the change in the reluctance of the magnetic flux path. This type of transducer finds application particularly in acceleration measurements and it can be constructed to be suitable for sensing displacement as well as velocities. The total reluctance of the magnetic circuit is the sum of the individual magnetic reluctances:

$$\Lambda_{total} = \Lambda_G + \Lambda_C + \Lambda_L + \Lambda_A \qquad (15)$$

Where: $\Lambda_G, \Lambda_C, \Lambda_L$ and Λ_A are the magnetic reluctances of the air - gap, core, coil and armature (moving part).

$$Or, \Lambda_{total} = \frac{2.dl}{\mu_\circ r^2 \pi} + \frac{R_{core}}{\mu_C \mu_\circ r^2} + \frac{R_{coil}}{2\mu_\circ r^2} + \frac{R_{armature}}{\mu_A \mu_\circ r.t} \qquad (16)$$

The total length of the flux path in air - gap is changing as non – linear and from two side of gaps (2.dl). The cross section area of the flux path in air - gap is represented as circle area (πr^2). The flux path length of the core is taken as circle circumstances (πR) and the cross section area is (πr^2). The flux path length of the coil is ($\pi R/2$) and the cross section area is constant (πr^2). The length of the flux path in the armature is (2R) and the cross section area is (2r.t), where t is the thickness of the armature. Despite of this non-linearity criterion, these types of transducers have applications in several areas, such as electromagnetic force measurements. In force measurement, the change in inductance can be made to be measure of the magnitude of the applied force. **Figure 10-a** illustrates MATLAB simulation for variable reluctance displacement transducer, **Fig. 10 - b** show mechanical and electrical forces versus time offset, **Figure 10 - c** shows air – gap length versus time offset and **Figure 10 - d** shows armature current versus time offset [Math Works, 2006]. The relative permeability for all three sections, which are air – gap, cast iron core and armature in first model are (1, 1100 and 2000) H / m, respectively.

Error in force calculation using two methods, which are Maxwell stress tenser represents an electrical force in nine directions and virtual work represents mechanical force in two directions, is coming from the fundamentals physic for each method, although Maxwell stress tenser method gives more accurate in results than virtual work. It's evident from **Figure 10 – d** the operating current varies between (0.45 – 0.55) Amp, which represents the actual operating current for switching (**ON / OFF**) states.

        Figure 11-a represents the finite element mesh model of the second type. The number of the finite elements for each armature positions at the mid – point and right are (535 and 531), respectively. The results are obtained for the transducer from **Figure** (2) with the following data: supply voltage is (12)V ; coil resistance r_{coil} is (10) Ω; number of turns is (600) for two coils; mass of the moving part is

(25) g., damping coefficient is (20) and cross section area of (0.785) cm2 and current density of (127. 388 $* 10^{-6}$) A / m2.. The following results consist of two parts, which are qualitative results and quantitative results[ANSYS Program, 2002].:.

A - <u>Qualitative Results</u>: **Figures. 11 - b, 11 - c and 11- d**, illustrate the 2-D flux lines contour, magnitude of flux intensity contour, and flux intensity as vectors at the first armature position. **Figures. 12 - b, 12-c and 12-d** illustrate the 2-D flux lines contour, magnitude of flux intensity contour, and flux intensity as vectors at the second armature position. These results indicate increasing of the flux, while decreasing of the flux intensity magnitude and decreasing the flux intensity vectors with the changing of the armature position at the center position and shifting by (0.2) cm to right side and not shifting to left side due to axi symmetric model.

B - <u>Quantitative Results</u>: **Figures. 13 - a & 13 - b** show the behavior of magnetic force along the line of x symmetric and along y - axis at the armature position respectively. The first curve shows that the maximum magnitude of this force is between (1.35 and 2.561) N, which means at the armature position. The second curve indicates that the maximum magnitude of the magnetic force is at the air gap positions and that the force at the upper air gap is greater than that at the lower one. The energy input, winding inductance, and flux linkage with the armature position change variable differential reluctance transducer are summarized and tabulate in **Table 2**. The relative permeability for all four sections, which are air – gap, cast iron core, coil and armature in second model are (1, 1100, 2000 and 3000) H / m, respectively. Error in force calculation using two methods, which are Maxwell stress tenser represents an electrical force in nine directions and virtual work represents mechanical force in two directions, is coming from the fundamentals physic for each method, although Maxwell stress tenser method gives more accurate in results then virtual work. MATLAB simulation for variable differential reluctance transducer can be repeated for same procedure and tests except the inductive properties and criterion of varying air gap length, depending on mathematical equations starting from Eq.(7) to Eq.(12). In case two the iron core is located in mid - way between the E - shaped frames. The flux generated by primary coil depends on the magnetic reluctance of the magnetic path, the main reluctance being the air - gap. Any motion of core increases the air - gap on one side and decreases the air gap on the other side, thus causing reluctance to change, in accordance with the principles explained above, and thereby including more voltage on one of the coils than on the other. Motion in the other direction reverses the action with (180°) phase shift occurring at null. The output voltage can be modified, depending on the requirement in signal processing by means of rectification, or filtering. In general, variable reluctance transducers have a small range and are used in specialized applications such as pressure transducers. Magnetic forces imposed on the armature are quit large and this severely limits their application. However, the armature can be constructed as a diaphragm, which is suitable for air - pressure measurements.

Conclusions

1- This study allows fast multiple analyses for a certain supply voltage and external circuit parameters, which can be especially useful at the stages of electromechanic relay design and manufacturing.

2- The results show from ANSYS and MATLAB simulation for second model, the magnetic force concentrated in mid - way location armature and magnetic force increase in the side, where the air - gap length reduced by (0.2) cm and finally, reduced in the side, where the air-gap length increased by shifting the armature location to the right side by (0.2) cm.

3- The mechanical motion change the air- gap length, which changes the reluctance of the magnetic circuit and then the inductive properties will be changed. The maximum and minimum motion can be controlled by maximum and minimum (switching voltage and current) magnitude setting.

4- Material properties like (resistively, which increases with increasing temperature degree and magnetic permeability) and dimensions geometry for different parts of relay can be affected on the magnetic properties such as the magnetic force, flux linkage and then on the response time offset. The performing procedures on the two models can be generalized for the other types of transducers.

5- The results show from simulation for first model, the magnetic flux density increases with decreasing in air- gap length. Also, magnetic field intensity concentrate near coil location and decrease as far as from coil position, as shown from ANSYS simulation, the colures density grading from red, yellow, green and blue, for two models.

6- Increasing air - gap length with time offset for linear and non – linear transducers can be discussed or proved due to the cyclic maintenance and crashing the external surface area of the moving contacts (due to arc or spark effect) to increase the operating life time, that is the performance, behavior, magnetic force, inductive properties and efficiency of the electromechanical relays will be decreased and demagnetized.

7- The running time for ANSYS simulation in two models (linear and non – linear) is approximately ten minutes, which dependents mathematically on finite element method FEM for (2 – D) model, while the running time for MATLAB simulation in two models (linear and non – linear) is approximately four minutes, which dependents mathematically on ordinary differential equations like (ODE 23 and ODE 45).

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Table 1: The energy input, winding inductance and flux linkage with armature position change in first model.

Air - gap Length (cm)	Force (N) Virtual Work $10^2 *$	Force(N) Maxwell Stress Tenser $10^2 *$	Energy Input (J) $*10^{-3}$	Winding Inductance (H) $10^{-3} *$	Switching Current (Amp.)	Flux Linkage (Wb. Turn) $10^{-4} *$
0.8	0. 30546	0. 30617	0. 509591	2.100452094	22. 0276453	1.1567029
0.6	0. 36323	0. 36414	0. 5102544	2.103181693	22. 0277407	1.1582085
0.4	0. 44228	0. 44352	0. 5110568	2.106498103	22. 0276953	1.1600324
0.2	0. 56572	0. 7101	0. 5120542	2.110600753	22. 0277407	1.1622941

Table 2: The energy input, winding inductance and flux linkage with the armature position change in second model.

Armature Position	Force (N) Virtual Work $10^2 *$	Force (N) Maxwell Stress Tenser $10^2 *$	Energy Input (J) $10^{-3} *$	Winding Inductance (H) $10^{-3} *$	Switching Current (Amp.)	Flux Linkage (Wb.Turn) $10^{-6} *$
Mid-Way	0. 50352	0. 48924	2. 52006	5. 0401284	0.9	8. 400244
(0. 2) cm Shifting to Right	0. 22721	0. 22480	2. 76194	5. 5238866	0.9	9. 206477
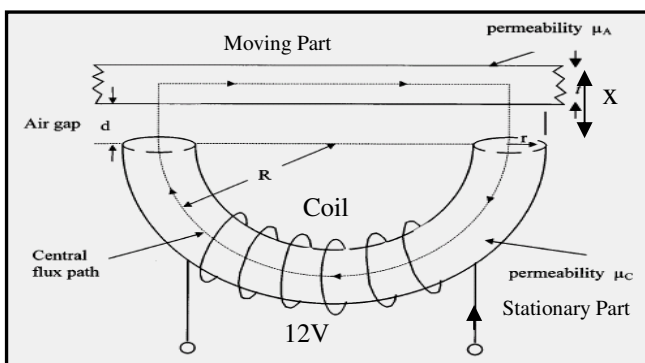
Fig. 1-a: Single coil, variable reluctance displacement transducer.
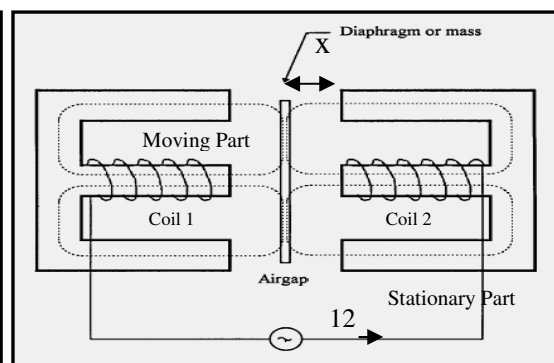
Fig. 2 - a: Two coils variable differential reluctance transducer.
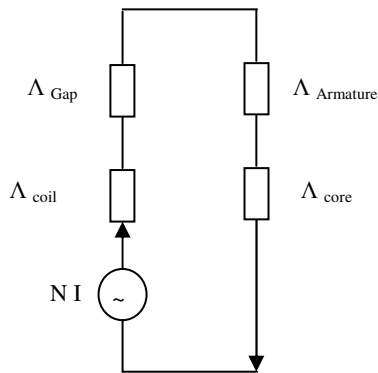
Fig.1- b: Electrical series equivalent circuit for variable reluctance displacement model.
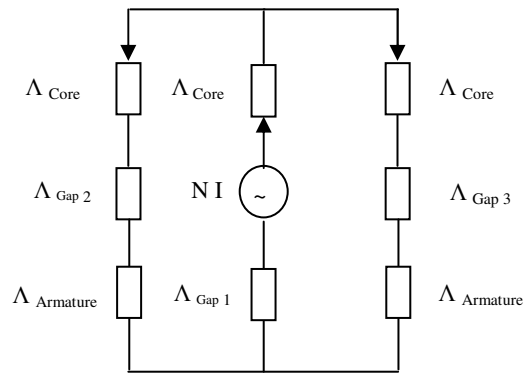
Fig.2- b: Electrical series – parallel equivalent circuit for axisymmetric variable differential model.
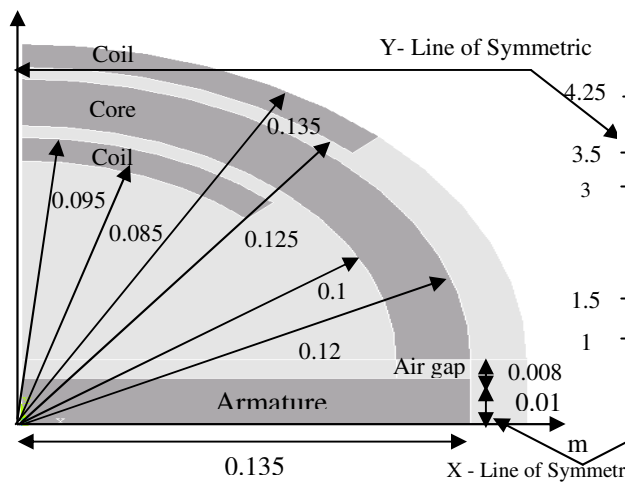
Fig. 3-a: 2-D axisymmetric model for first model.
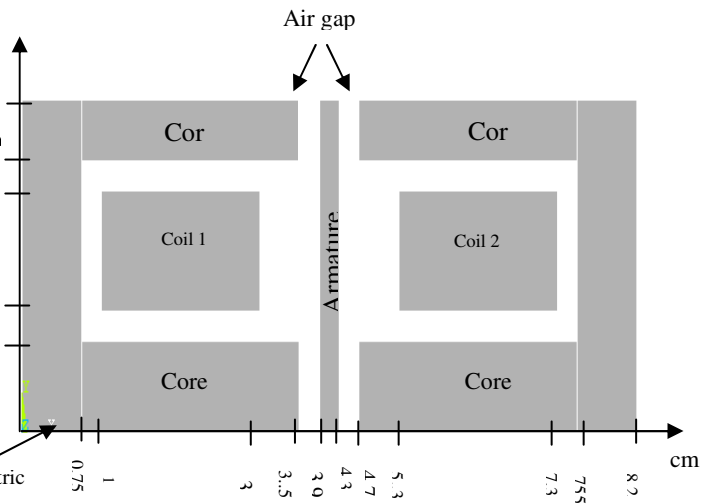
Fig. 3-b: 2-D axisymmetric model for second model.
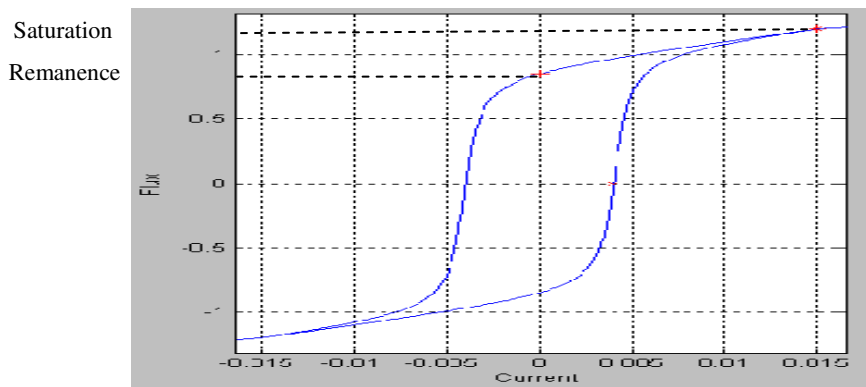
Fig. (4): Typical Hysteresis curve in magnetic circuits
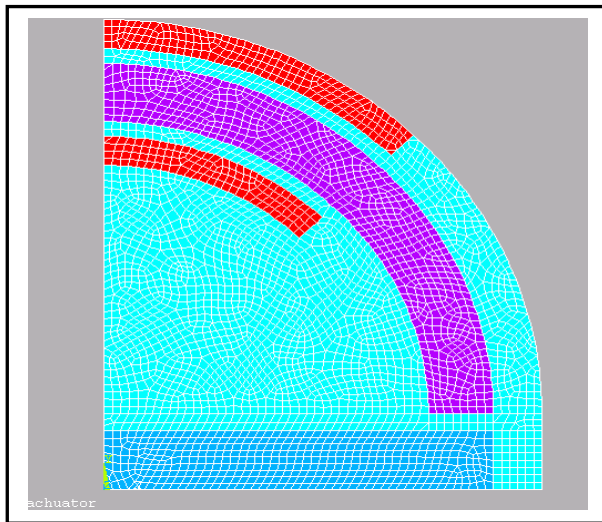
Fig. 5 - a:Shows the finite element model in first model.
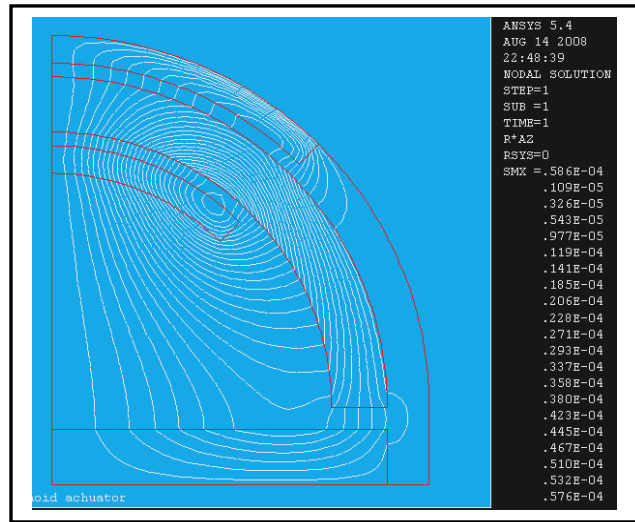
Fig. 5 - b: Shows the magnetic flux lines.
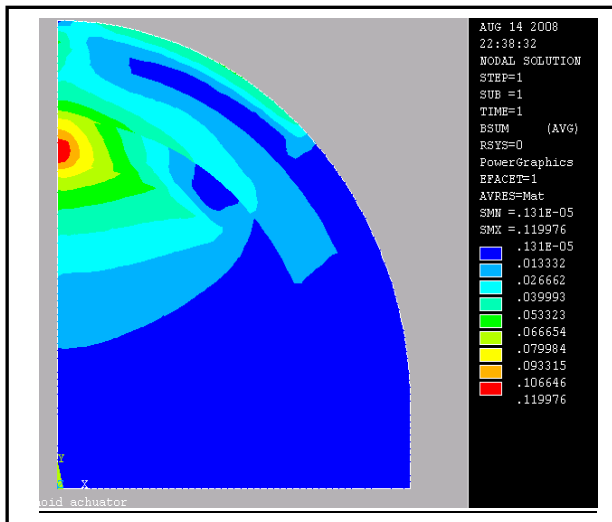
Fig. 5 - c: Show the magnetic field intensity summation contours.
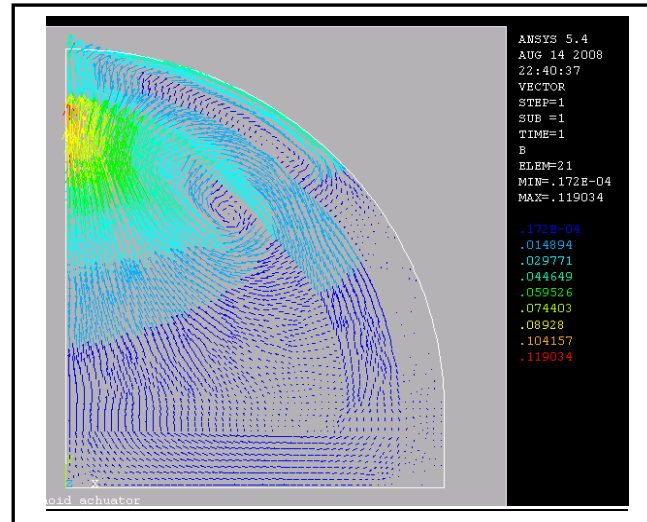
Fig. 5 - d: Show the magnetic field intensity vectors at air - gap of (0. 8) cm length.
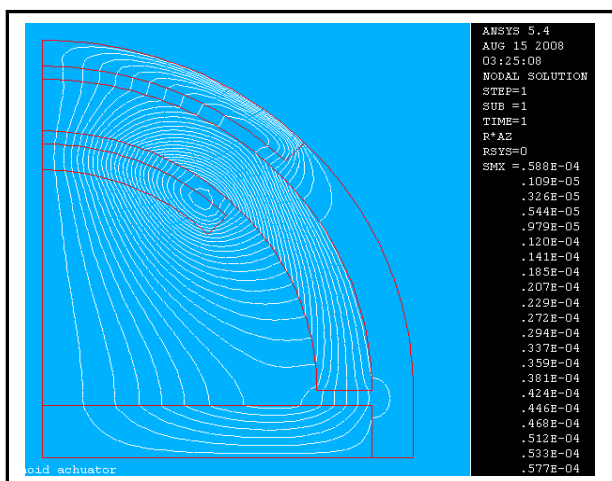
Fig. (6 - a): Show the magnetic flux lines.
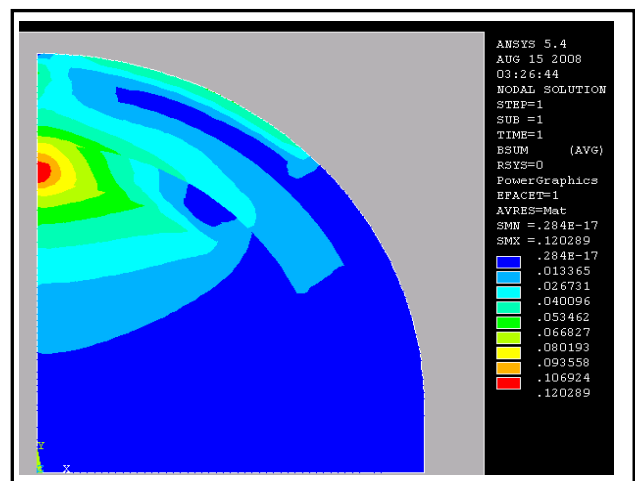
Fig. (6 - b): Show the magnetic field intensity summation contours.
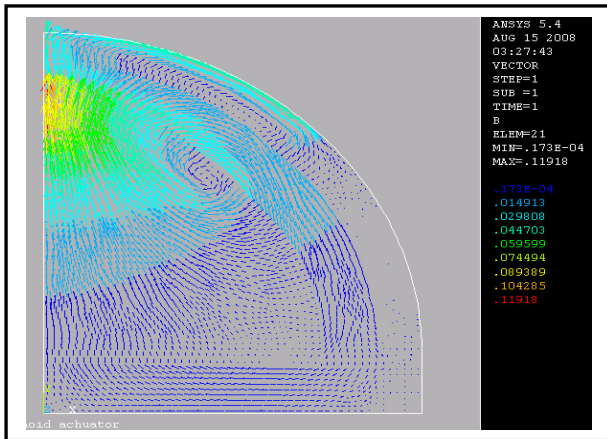
Fig. 6 - c: Shows magnetic field intensity vectors at air - gap of (0. 6) cm length.
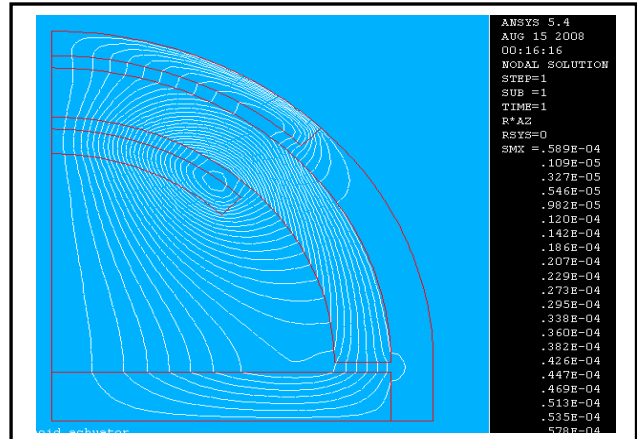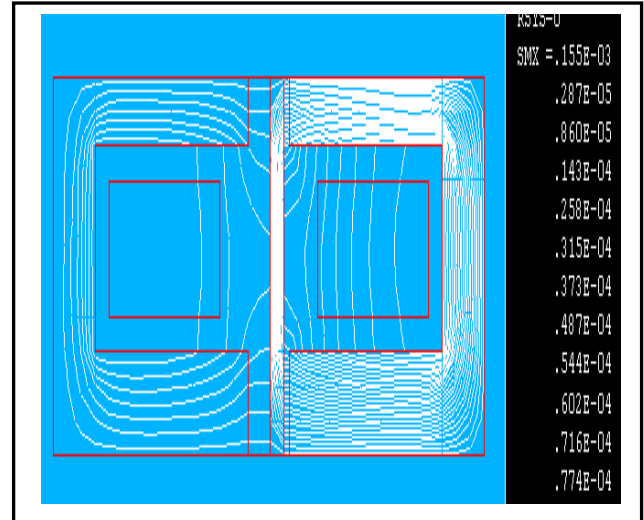

Fig. 7 - a: Shows the magnetic flux lines.
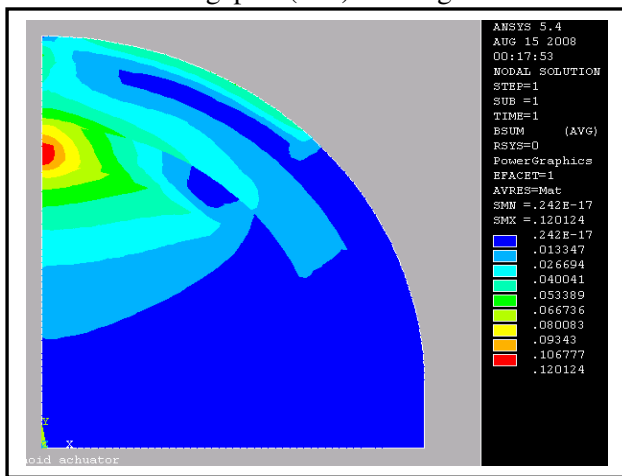
Fig. 7 - b: Shows magnetic field intensity
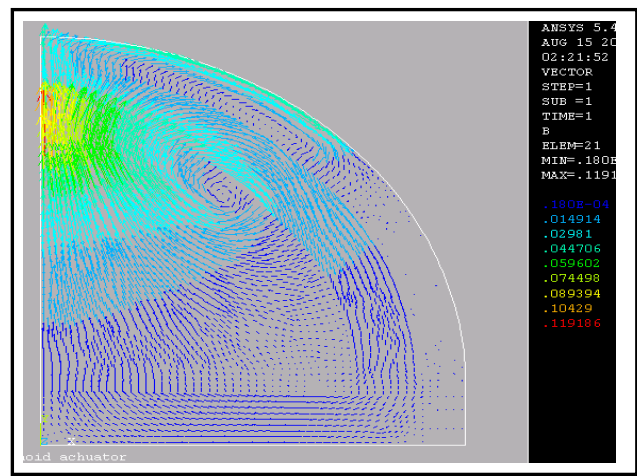
Fig. 7 - c: Shows magnetic field intensity as
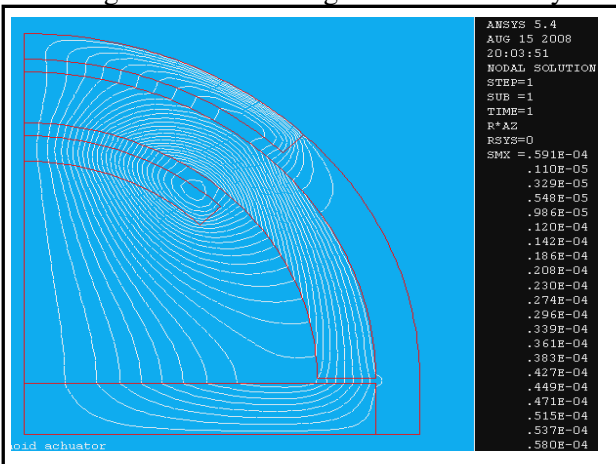
Fig. 8 - a: Shows the magnetic flux lines.
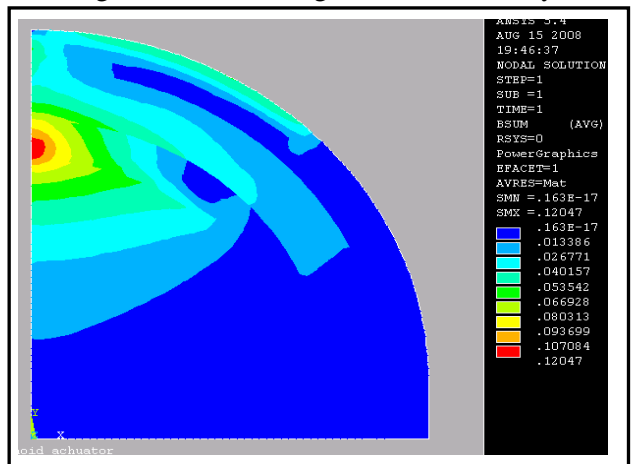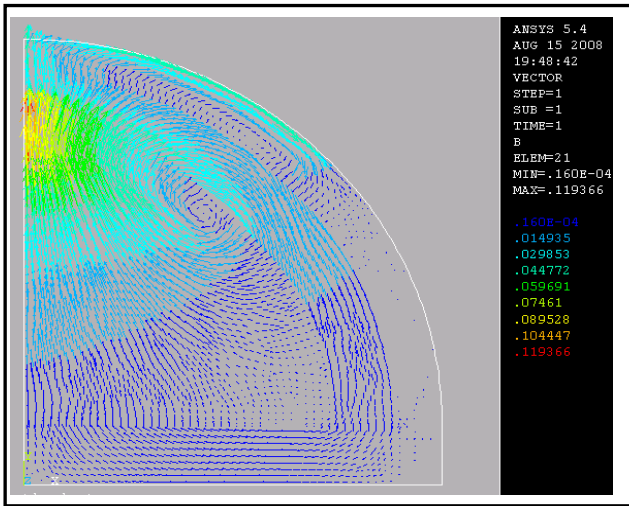
Fig. 8 - c: Shows magnetic field intensity vectors at air - gap (0. 2) cm length.
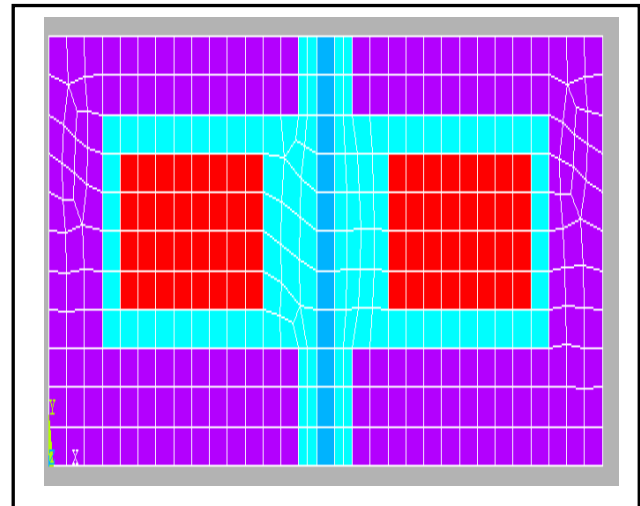
Fig. 11 - a: Shows the finite element model in second model.
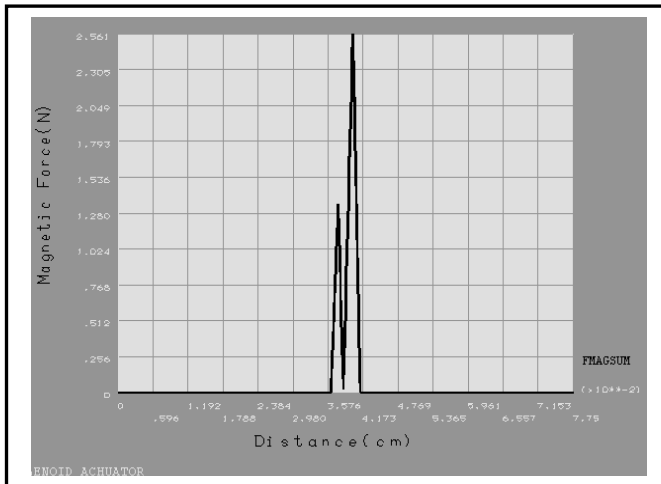
Fig. 9 - a: Shows the behavior of magnetic force in first case of (0.8) cm a long line of x symmetric, in item (3-1).
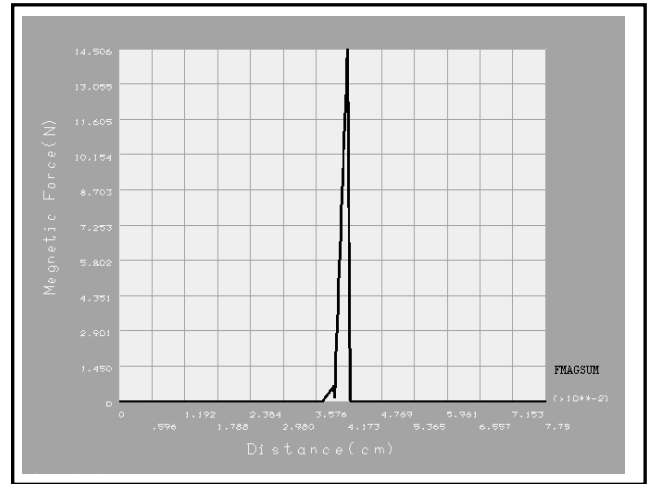
Fig. 9 - b: Shows the behavior of magnetic force in second case a long of y axis, in item (3 - 1).
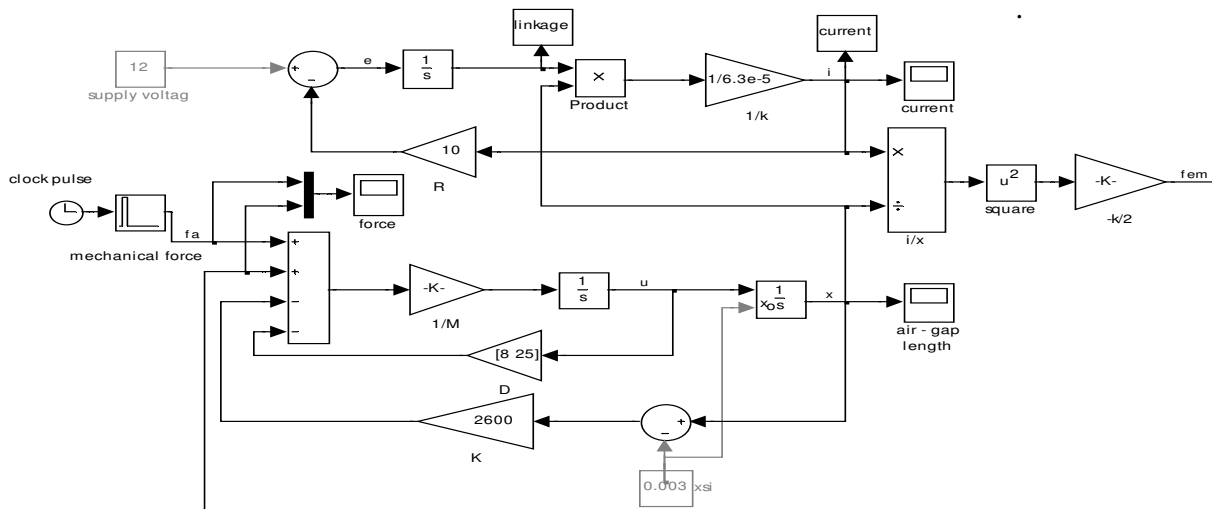
Fig. 10 - a: MATLAB simulation for variable reluctance displacement transducer.
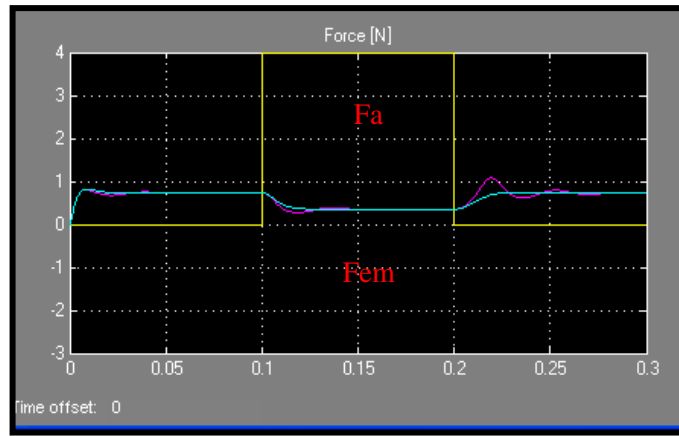
Fig. 10 – b: Shows effect of mechanical and electromagnetic forces versus time offset for first model.
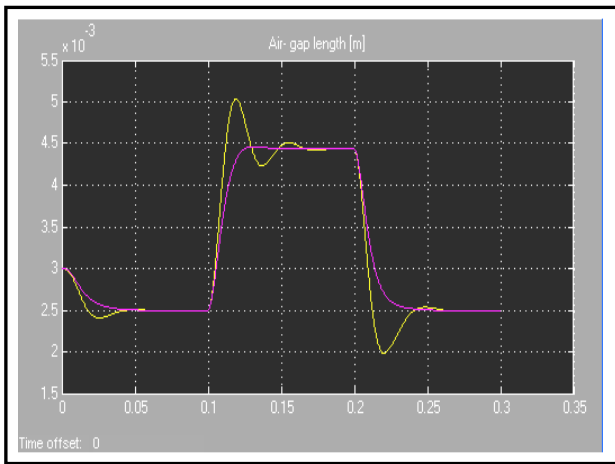
Fig. (10 - c): Shows effect of varying air gap length versus time offset for first model.
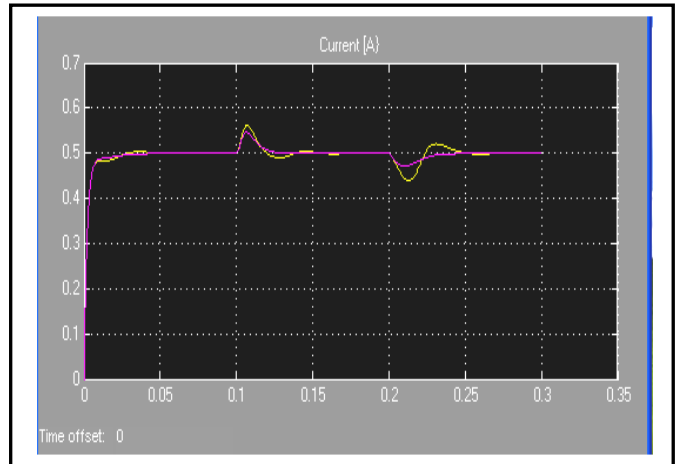
Fig. (10 - d): Shows effect of switching current versus time offset for first model.
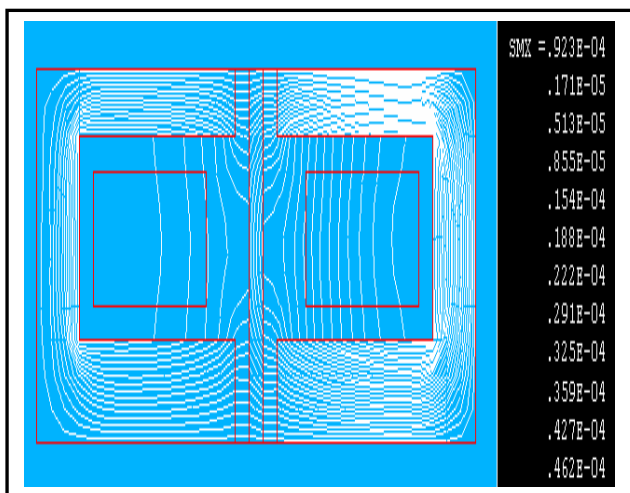
Fig. 11 - b: Shows magnetic flux lines in second model.
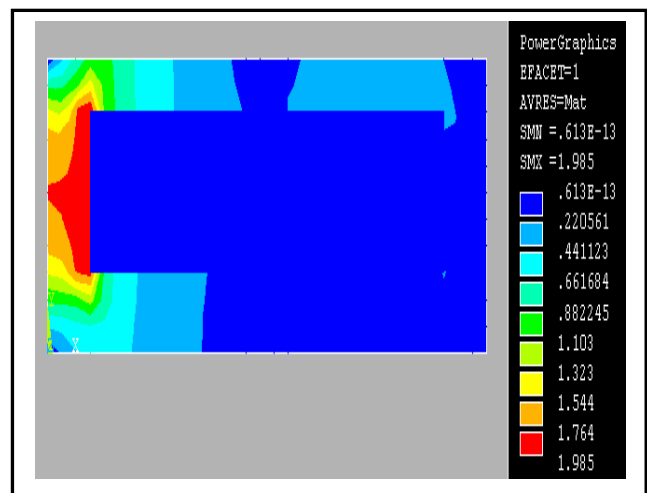
Fig. 11 - c: Shows magnetic field intensity summation contours.
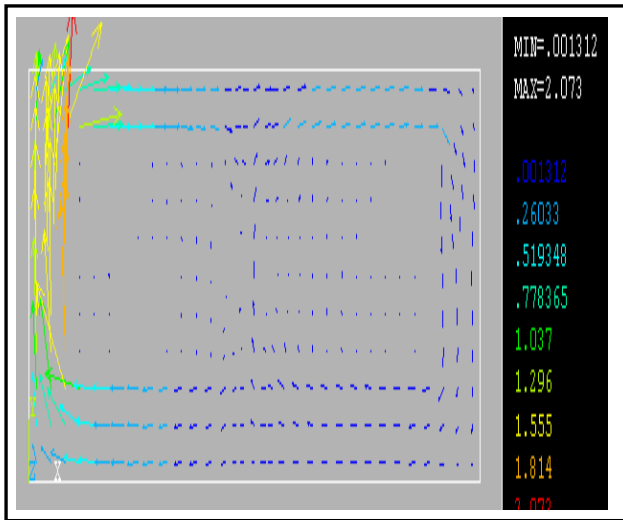
Fig. 11 - d: Shows magnetic field intensity vectors when armature at the mid - way.

Fig.12 - a: Shows the magnetic flux lines
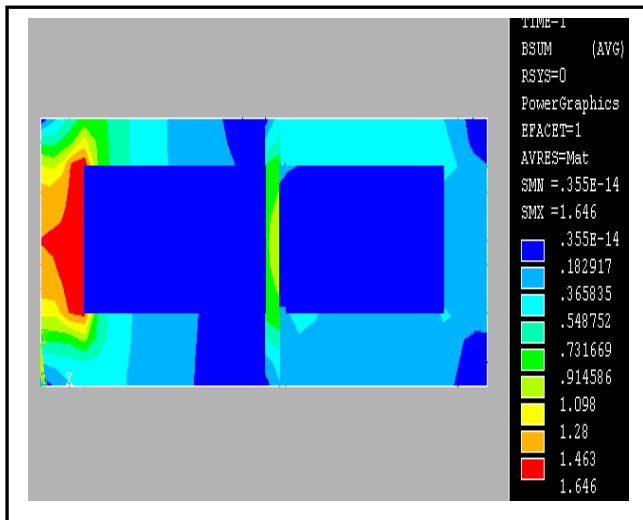
Fig. 12 - b: Shows magnetic field intensity summation contours when the position of armature is shifted by (0.2) cm to the right side.
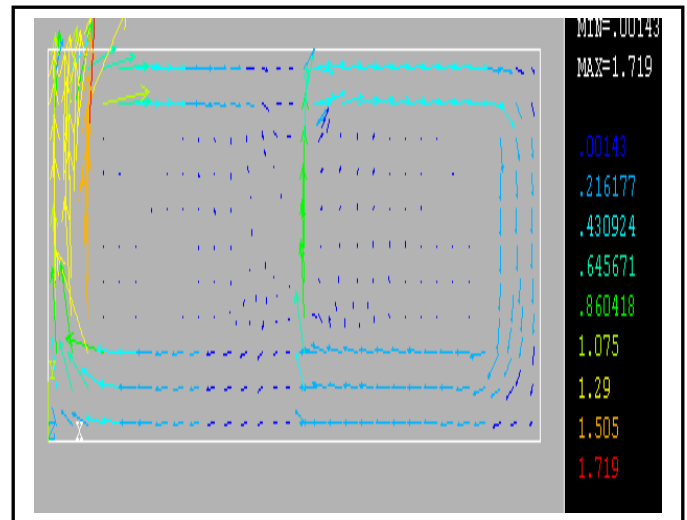
Fig. 12 - c: Shows the magnetic field intensity vectors when the position of armature is shifted by (0. 2) cm to the right side.
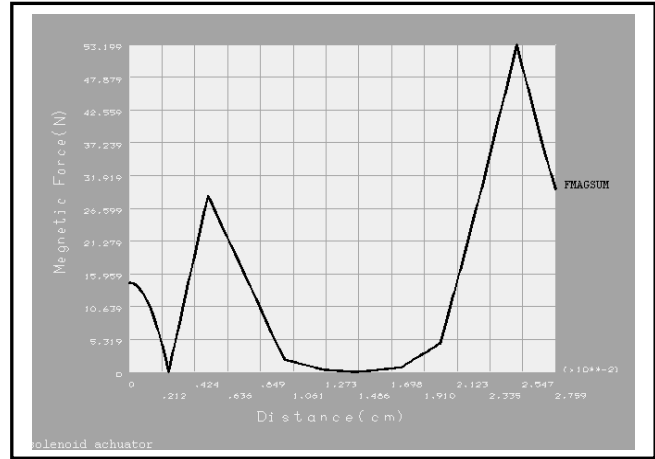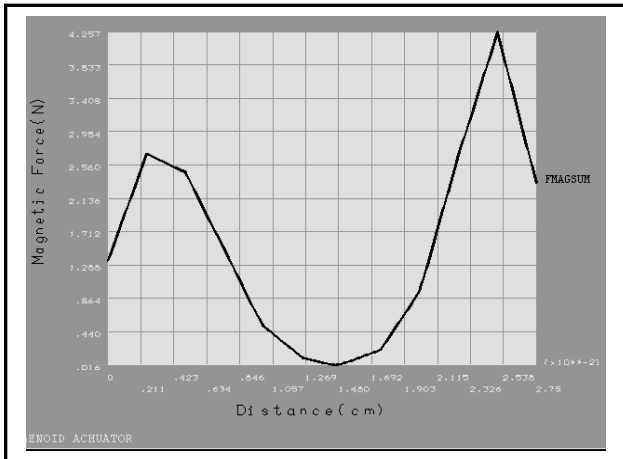
Fig. 13 -a: Shows the behavior of magnetic force in first case a long x symmetric at mid - way between two cores starting from the bottom, in tem (3-2).

Fig.13 -b: Shows the behavior of magnetic force in second case a long y axis at mid -way between two cores starting from the bottom, in item (3 - 2).
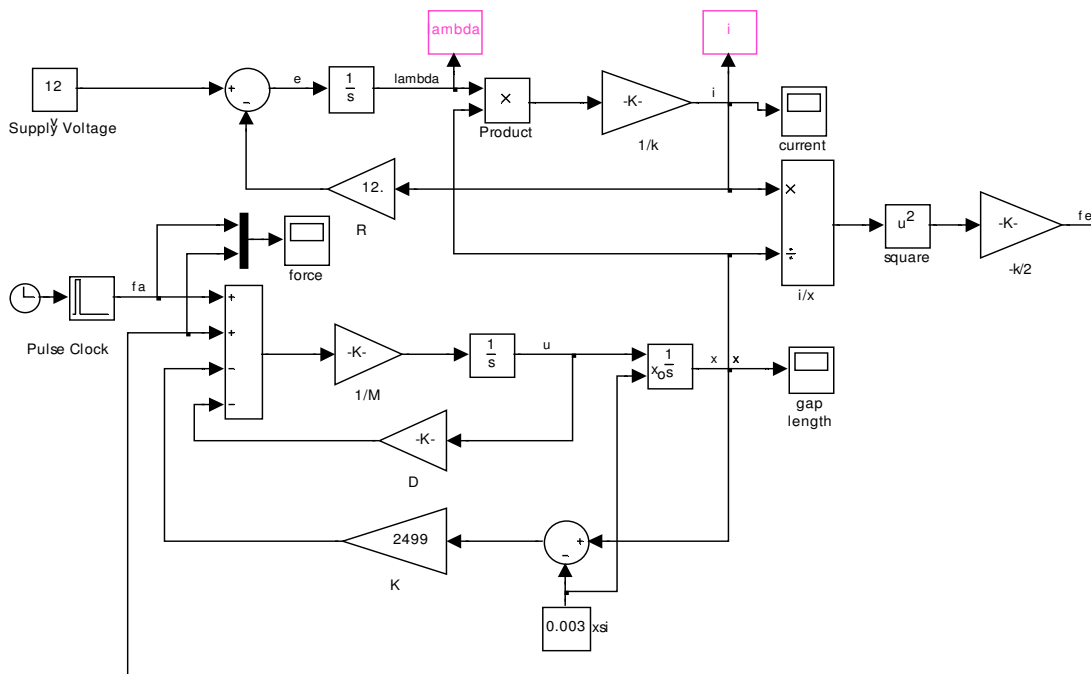

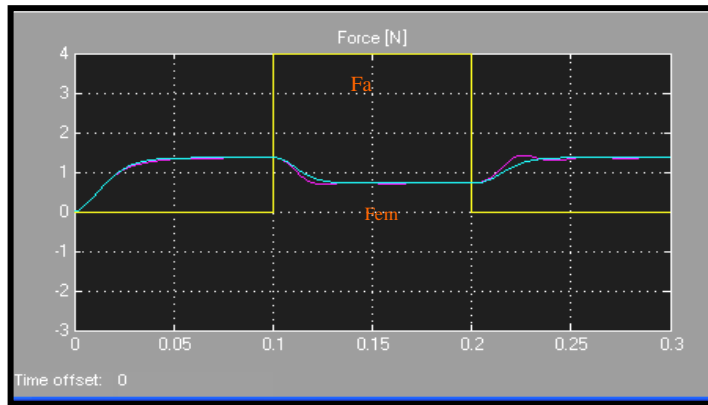Fig. 14-a: MATLAB simulation for variable differential reluctance transducer.

Fig. 14-b: Shows effect of mechanical and electromagnetic forces
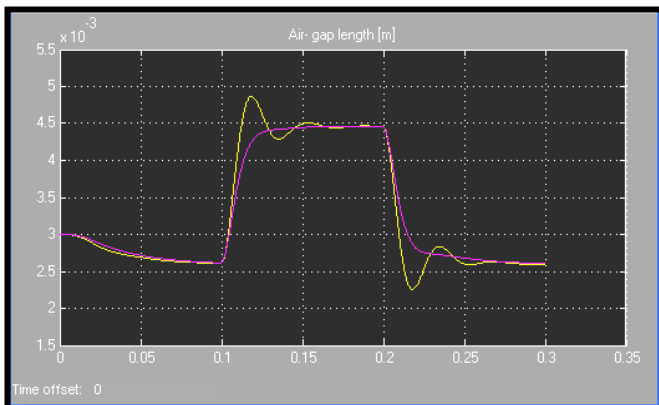versus time offset for second model.

Fig. 14-c: Shows effect of varying air – gap
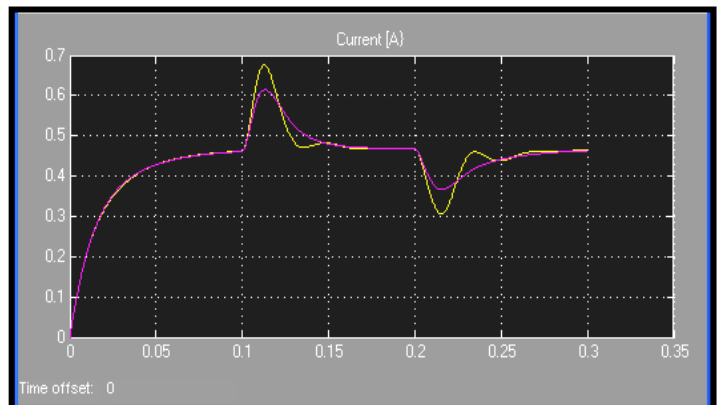length versus time offset for second model.

Fig. 14-d: Shows effect of switching current versus
time offset for second model.