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THRUST CALCULATION OF LINEAR OSCILLATORY ACTUATOR USING PERMEANCE ANALYSIS METHOD

M. Norhisam[1], F. Azhar[2], H. Hashim[1], M.Nirei[3], H.Wakiwaka[4] and Abdul Razak J.[5]

[1]Jabatan Kejuruteraan Elektrik dan Elektronik,
Fakulti Kejuruteraan, Universiti Putra Malaysia, 43400 UPM Serdang

[2]Fakulti Kejuruteraan Elektrik,
Universiti Teknikal Malaysia,
Beg Berkunci 1752, Pejabat Pos Durian Tunggal, 76109 Durian Tunggal, Melaka

[3]Nagano National College of Technology
716 Tokuma Nagano, 381-8550, Japan

[4]Faculty of Engineering,
Shinshu University, 4-17-1, Wakasato, Nagano, 380-8553 Japan

[5]Malaysian Palm Oil Board (MPOB),
No. 6, Persiaran Institusi, Bandar Baru Bangi, 43000 Kajang, Selangor

(norhisam@eng.upm.edu.my)

RINGKASAN : *Pada awal penemuannya, motor linear banyak digunakan dalam sistem pengangkutan. Kebelakangan ini, motor linear dicipta bagi menggantikan sistem yang menggunakan motor putar dan pengubah untuk menghasilkan gerakan linear. Dengan menggunakan motor linear, prestasi sistem akan meningkat oleh kerana had mekanikal telah dihapuskan. Ini membawa kepada ketepatan, pecutan dan halaju bahagian bergerak yang lebih tinggi. Aktuator Pengayun Linear (LOA) adalah salah satu daripada aplikasi linear motor. Ianya boleh digunakan di dalam pelbagai aplikasi seperti mesin penggetar dan mesin ulang alik pantas. Terdapat dua teknik yang boleh digunakan untuk mengira daya tujahan LOA iaitu 'Finite Element Method' (FEM) dan 'Permeance Analysis Method' (PAM). Di dalam kertas kerja ini, daya tujahan LOA telah dikira menggunakan teknik PAM. Keputusan daripada teknik PAM telah dibandingkan dengan keputusan daripada FEM dan ujikaji.*

ABSTRACT : In the past, linear motors were used in transportation systems. Currently, linear motors replace a system using a rotating motor and a transmission to realize a linear movement. By using linear motors, the performances can be increased considerably since the mechanical limitations are removed. This leads to a better precision, higher acceleration and higher speed of the moving part. Linear Oscillatory Actuator (LOA) is one of the linear motor applications that can be applied in various applications such as shaker machines and rapid motion machines.The two techniques used to calculate the thrust of LOA are Finite Elements Method (FEM) and Permeance Analysis Method (PAM). In this paper, the thrust of LOA was calculated using PAM. The result from PAM was compared with FEM and further verified experimentally.

KEYWORDS : Linear Oscillatory Actuator, thrust calculation, Permeance Analysis Method.

INTRODUCTION

Finite Elements Method (FEM) and Permeance Analysis Method (PAM) are two techniques commonly used to calculate the thrust of LOA (Hirata *et al.,* 1992). FEM makes it possible to obtain the magnetic forces and other characteristics of electromagnetic equipment with high degree of accuracy because it gives an approximation of the magnetic flux distribution on a microscopic scale. However, FEM requires the minutely subdivided meshes in order to improve its analytical accuracy and cannot be directly applied to the analysis of large-sized models owing to a huge Central Processing Unit (CPU) and memory capacities of computers (Hirata *et al.,* 1992 ; Delforge *et al.,* 1995).

PAM uses magnetic equivalent circuit approach that consists of permeance network development which is representative of the studied magnetic circuit (Delforge *et al.,* 1995). By using this technique, it is necessary to assume the magnetic path of the motor as a whole, and in particular the analytical results are conspicuously influenced by the assumption of the fringing magnetic flux distribution of the air gap (Hirata *et al.,* 1992). In order to build an accurate permeance network, the modeling computing time need to be minimized, whilst maintaining a topology that is able to give an accurate result (Delforge *et al.,* 1995). On top of that, by implementing the PAM technique, the effect of dimension of LOA structure to the thrust value can be easily evaluated (Tsutomu *et al.,* 2005). In this paper, the thrust of LOA has been calculated using PAM and further verified with FEM and experimental results. A good correlation was obtained using these three methods.

MAGNETIC EQUIVALENT CIRCUIT OF LOA

Structure and Parameters of LOA

The structure and parameters of LOA (Figure 1) consist of stator and mover parts. The coils are embedded inside the stator yoke to form the stator part. The coils are used to provide the external magnetic fields that will generate the attracting and repulsive forces (Norhisam *et al.,* 2006). The permanent magnets are combined with the moving yoke and attached to the shaft to form the mover part. The magnetization of the permanent magnet is in the stroke direction. This type of LOA, referred to as slot type LOA, comprises of a magnetic circuit that can provide a high value of thrust (Tsutomu *et al.,* 2005).

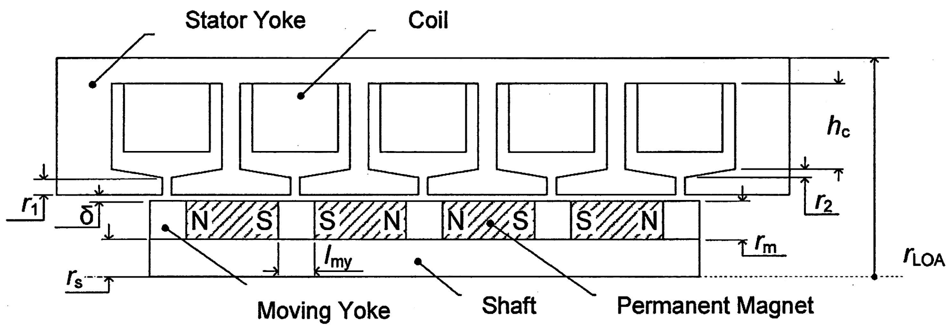


Figure 1. *Structure of LOA*

The parameter of LOA structure has been optimised using FEM for high thrust of LOA performance (Norhisam *et al.,* 2006). The dimension of LOA structure has been determined based on the optimisation work to determine the permeance value. Table 1 shows the dimension of LOA structure.

Table 1. Dimension of elements in LOA (Norhisam *et al.,* 2006)

Elements	Dimension (mm)
Shaft radius, r_s	3.5
Permanent magnet thickness, r_m	4.5
Height of taper, r_1	2.0
Thickness of taper, r_2	1.0
Length of taper, l_g	1.5
Height of coil, h_c	10.0
Width of coil, W_c	18.0
Air gap, δ	0.5
Length of permanent magnet, l_m	7.5
Total radius of LOA, r_{LOA}	24.5

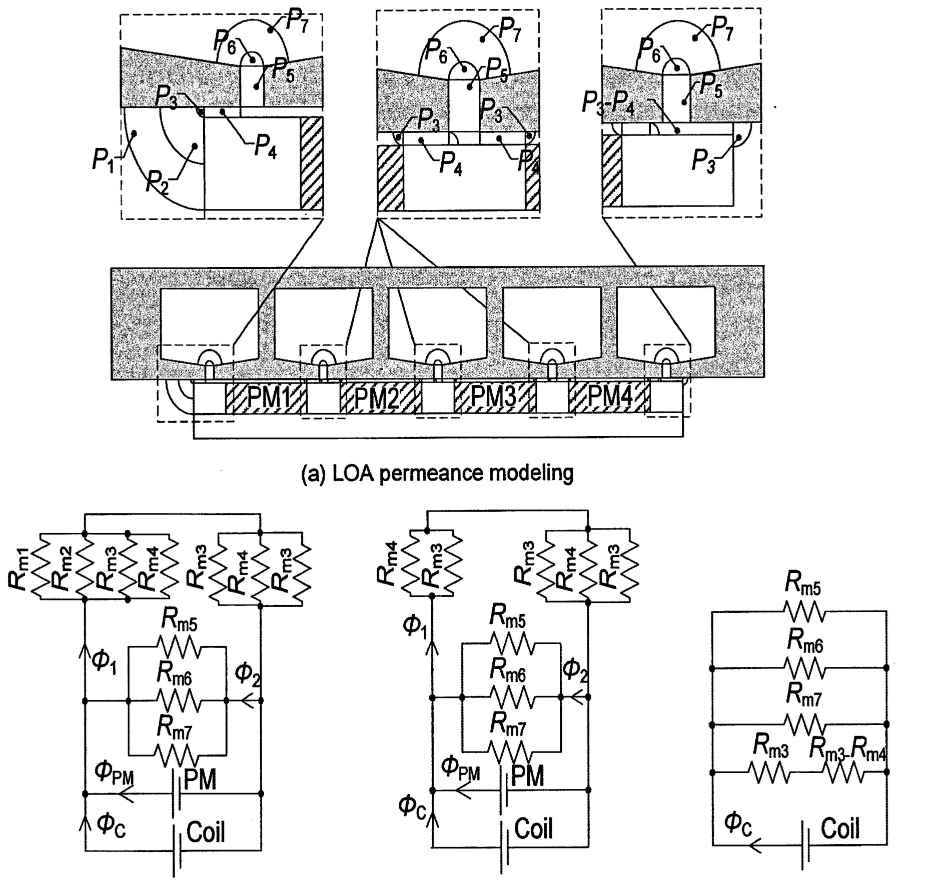
Permeance and Magnetic Equivalent Circuit of LOA

The permeance model was built depending on the estimated magnetic flux path at the air gap with the following assumptions:

1) The permeability of the yoke is regarded as infinity.
2) The leakage flux is disregarded.

The yoke of LOA is made of SS400 type material. Based on the specification of the material, it is 300 times more permeable than air. This causes the value of magnetic resistance inside the yoke to be 300 times lower compared with air. This condition will make most of the flux produced by the LOA to flow inside the yoke due to the lower magnetic resistance. Therefore, if the assumption factors are considered, the calculation result will only deviate about 0.3 %.

The magnetic equivalent circuit of LOA was developed based on the permeance model of LOA. Considering the permeance model of LOA at $x = 0$ mm (Figure 2 (a)), the magnetic equivalent circuits at $x = 0$ mm are shown in Figures 2 (b)-(c). The magnetic equivalent circuit of LOA was constructed by considering left end coil, middle coil and right end coil. In this paper, only permeance model at $x = 0$ mm will be discussed and is shown in Figure 2.



(a) LOA permeance modeling

(b) Magnetic equivalent circuit for left end coil

(c) Magnetic equivalent circuit for middle coil

(d) Magnetic equivalent circuit for right end coil

Figure 2. *Permeance model of LOA of 0 displacement ($x = 0$ mm)*

The permeance value can be calculated using equation (1), provided the shape of the permeance is square.

$$P = \frac{\mu_o a}{l} \tag{1}$$

where P is the permeance value (H), μ_o is the air permeability (H/m), a is the air gap area (m^2) and l is the air gap length (m). For other permeance shapes, other permeance equations (2-8) can be used (Figure 3) (Zhu *et al.,* 2006).

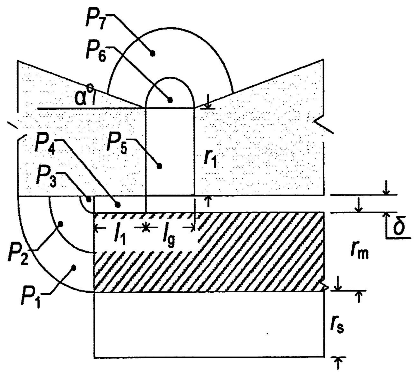


Figure 3. *Typical air-gap permeance*

$$P_1 = 2\mu_o(2r_s + r_m + \delta)\ln(1 + \frac{r_m}{r_m + \delta}) \tag{2}$$

$$P_2 = 2\mu_o(2r_s + 1/2r_m + \delta)\ln(1 + \frac{r_m}{2\delta}) \tag{3}$$

$$P_3 = 1.04\mu_o\pi(r_s + r_m + \delta/2) \tag{4}$$

$$P_4 = \frac{4\mu_o l_1}{\pi\left(\frac{2r_s + 2r_m}{\delta} + 1\right)} \tag{5}$$

$$P_5 = \frac{4\mu_o l_g}{\pi\left(\frac{2r_s + 2r_m + 2\delta}{r_1} + 1\right)} \tag{6}$$

$$P_6 = 1.63\mu_o(r_s + r_m + \delta + r_1 + l_g / 4) \tag{7}$$

$$P_7 = \frac{2.2\pi\mu_o}{\pi - 2\alpha}(r_s + r_m + \delta + r_1 + 3/2l_g \sin\alpha) \tag{8}$$

Thus, the total equivalent permeance for magnetic equivalent circuit of left end coil, P_{T1}, middle coil, P_{T2} and right end coil, P_{T3} are as equations (9) to (11).

$$P_{T1} = \frac{(P_1 + P_2 + P_3 + P_4)(2P_3 + P_4)}{P_1 + P_2 + 3P_3 + 4P_4} + (P_5 + P_6 + P_7) \tag{9}$$

$$P_{T2} = \frac{(2P_3 + P_4)(P_3 + P_4)}{3P_3 + 2P_4} + (P_5 + P_6 + P_7) \tag{10}$$

$$P_{T3} = \frac{(P_3)(P_3 - P_4)}{2P_3 - P_4} + (P_5 + P_6 + P_7) \tag{11}$$

The characteristics of a permanent magnet are represented by its demagnetization curve. It is essential to know the demagnetization curve of a permanent magnet in order to estimate the operating point of a permanent magnet. The operating point of a permanent magnet will provide the information about the value of magnetic flux produced per unit area by a permanent magnet, (B_k) at certain value of permeance total (P_T). Consider the demagnetization curve of a permanent magnet and the permeance line; as shown in Figure 4, the intersection point between these two lines is known as operating point or K point. At this point, the value of B_k can be obtained. With fixed permanent magnet parameter such as permeance magnetic flux density of B_r and coercive force of H_c, the operating point of the permanent magnet is solely depends on the slope of the permeance line. The slope of the permeance line is determined by the $\alpha°$ angle and can be calculated using equation (12). Thus, general equation to calculate the B_k, is as equation (13).

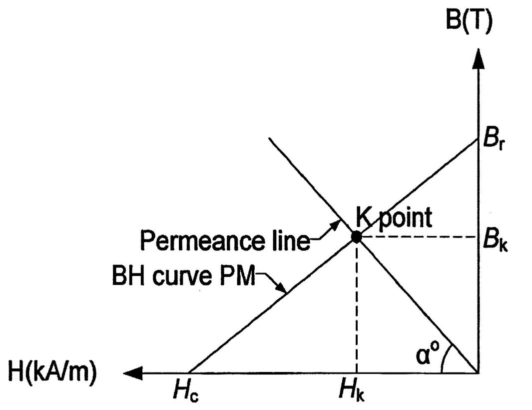


Figure 4. *Magnetic flux density of permanent magnet (PM) at operating point*

$$\tan\alpha = P_T \frac{H_c l_m}{B_r A_m} \tag{12}$$

$$B_K = \frac{P_T H_c^2 l_m B_r}{B_r^2 A_m + P_T H_c^2 l_m} \tag{13}$$

where α is the permeance line slope, P_T is the total permeance (H), H_c is the coercive force (kA/m), l_m is the length of a permanent magnet (m), B_r is the remanent flux density (T), A_m is the area of permanent magnet (m^2) and B_k is the magnetic flux density of PM at operating point (T).

Based on equation (13), the value of B_k for each permanent magnet is determined by the permeance total. Depending on the direction of magnetic flux and permeance model, each permanent magnet of LOA is having different value of permeance total, P_T, as shown in equations (9 to 11). Thus, each permanent magnet having different value of B_k, can be calculated using equations (14 to 16).

$$B_{KPM1} = \frac{\left[\begin{array}{l}(P_1+P_2+P_3+P_4)(2P_3+P_4)\\+(P_5+P_6+P_7)(P_1+P_2+3P_3+4P_4)\end{array}\right]H_c^{\,2} l_m B_r}{(P_1+P_2+3P_3+4P_4)B_r^{\,2} A_m + \left[\begin{array}{l}(P_1+P_2+P_3+P_4)(2P_3+P_4)\\+(P_5+P_6+P_7)(P_1+P_2+3P_3+4P_4)\end{array}\right]H_c^{\,2} l_m} \tag{14}$$

$$\begin{aligned} B_{KPM2} &= \frac{\left[\begin{array}{l}(2P_3+P_4)(P_3+P_4)\\+(P_5+P_6+P_7)(3P_3+2P_4)\end{array}\right]H_c^{\,2} l_m B_r}{(3P_3+2P_4)B_r^{\,2} A_m + \left[\begin{array}{l}(2P_3+P_4)(P_3+P_4)\\+(P_5+P_6+P_7)(3P_3+2P_4)\end{array}\right]H_c^{\,2} l_m} \\ &= B_{KPM3} \\ &= B_{KPM4} \end{aligned} \tag{15}$$

$$B_{KPM4} = \frac{\left[\dfrac{(P_3)(P_3-P_4)}{2P_3-P_4}+(P_5+P_6+P_7)\right]H_c^{\,2} l_m B_r}{B_r^{\,2} A_m + \left[\dfrac{(P_3)(P_3-P_4)}{2P_3-P_4}+(P_5+P_6+P_7)\right]H_c^{\,2} l_m} \tag{16}$$

where B_{KPM1} is the operating magnetic flux density of PM1 (T), B_{KPM2} is the operating magnetic flux density of PM2 (T), B_{KPM3} is the operating magnetic flux density of PM3 (T) and B_{KPM4} is the operating magnetic flux density of PM4 (T).

Thrust Calculation of LOA

Each displacement of LOA gives different value of permeance total, P_T of each permanent magnet due to the variation of the magnetic flux flow direction. It leads to variation of B_k values of each permanent magnet along its displacement shaft. However, in this paper, only the values of permeance total, P_T and B_k at displacement of $x = 0$ mm will be highlighted. These values will be used to calculate the magnetic energy of LOA, W_m, produced by each permanent magnet. The magnetic energy of LOA, W_m, can be calculated using equation 17.

$$\begin{aligned} W_m &= NI\,(\Phi_{PM}+\Phi_c) \\ &= NI\,(B_k A_m + NIP_T) \end{aligned} \tag{17}$$

where W_m is the magnetic energy (J), Φ_{PM} is the permanent magnet magnetic flux (Wb), Φ_C is the coil magnetic flux (Wb), NI is the coil magneto motive force (A), B_k is the magnetic flux density at operating point of permanent magnet (T), A_m is the cross area of permanent magnet (m^2) and P_T is the permeance total for every magnetic equivalent circuit (H).

Thus, the total of magnetic energy of LOA at $x = 0$ mm was calculated using equation (18). The thrust of LOA was calculated using differentiation of total magnetic energy and as shown in equation (19).

$$
\begin{aligned}
W_{mTotal} = {} & NIH_C{}^2 l_m B_r A_m \left[\frac{\begin{bmatrix} (P_1+P_2+P_3+P_4)(2P_3+P_4) \\ +(P_5+P_6+P_7)(P_1+P_2+3P_3+4P_4) \end{bmatrix}}{\begin{bmatrix} (P_1+P_2+3P_3+4P_4)B_r{}^2 A_m \\ + \begin{bmatrix} (P_1+P_2+P_3+P_4)(2P_3+P_4) \\ +(P_5+P_6+P_7)(P_1+P_2+3P_3+4P_4) \end{bmatrix} H_c{}^2 l_m \end{bmatrix}} + \frac{3\begin{bmatrix} (2P_3+P_4)(P_3+P_4) \\ +(P_5+P_6+P_7)(3P_3+2P_4) \end{bmatrix}}{\begin{bmatrix} (3P_3+2P_4)B_r{}^2 A_m \\ + \begin{bmatrix} (2P_3+P_4)(P_3+P_4) \\ +(P_5+P_6+P_7)(3P_3+2P_4) \end{bmatrix} H_c{}^2 l_m \end{bmatrix}} \right] \\
& + NI^2 \begin{bmatrix} \dfrac{(P_1+P_2+P_3+P_4)(2P_3+P_4)}{P_1+P_2+3P_3+4P_4} \\ + \dfrac{3(2P_3+P_4)(P_3+P_4)}{3P_3+2P_4} + \dfrac{(P_3)(P_3-P_4)}{2P_3-P_4} \\ + (5P_5+5P_6+5P_7) \end{bmatrix}
\end{aligned}
\qquad (18)
$$

$$
F = \frac{\delta W_{mTotal}}{\delta x} \qquad (19)
$$

where W_{mTotal} is the total magnetic energy of LOA (J), F is the thrust of LOA (N) and x is the displacement of LOA (mm).

COMPARISON ON CALCULATION OUTPUT AND MEASUREMENT RESULT OF THRUST OF LOA

The thrust of LOA has been calculated using the PAM technique at every 1 mm of the shaft displacement and different value of magneto motive force (NI). The output of thrusts in term of its maximum values are shown in Table 2.

Table 2. Calculated maximum thrust of LOA

Magneto motive foce, NI (A/turns)	Max. thrust, *F* (N)
100	27.73
200	46.61
300	74.64
400	105.83
500	140.16
600	177.64
700	218.28
800	262.06
900	308.67
1000	353.79

In order to verify the calculation output, the result of FEM and experimental measurement were used as comparison. Figure 5 shows the comparison of the results between these three techniques and it can be seen that the profile of each thrust characteristics of LOA is similar for each result regardless of different techniques used. However, the thrust calculated using these three methods showed a slightly different value. For example, at NI of 100 A/turns, the thrust difference between PAM and FEM is 17.1 %, and the thrust difference between PAM and the measurement result is 14.1 %. At NI of 600 A/turns, the thrust difference between PAM and FEM was 16.7 %, and the thrust difference between PAM and the measurement result was 18.2 %.

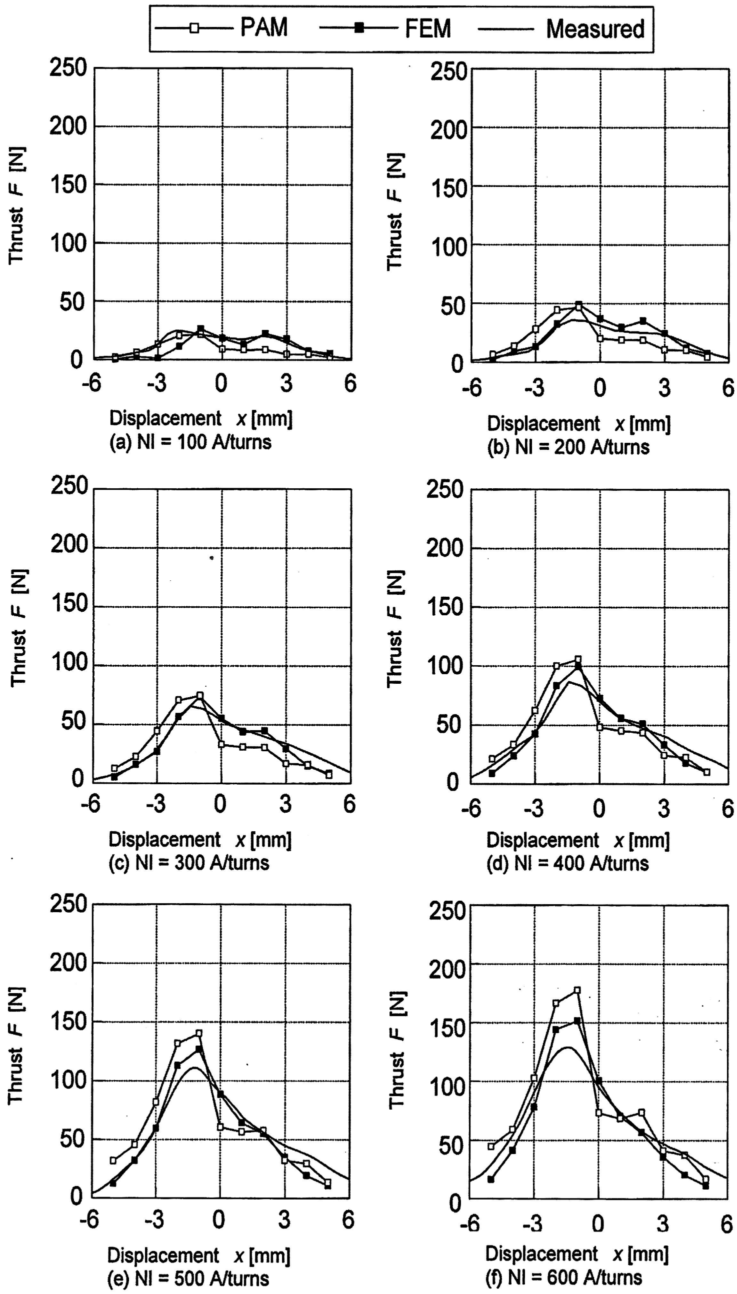


Figure 5. *Comparison of thrust of LOA between different method and NI*

CONCLUSION

This paper discussed the procedure to calculate the thrust of LOA by using the PAM technique. The sample of calculation output has been shown and verified by experimental and FEM results. Comparisons between the results proved the reliability of the equations derived for calculations of the thrust of LOA at different shaft displacement, x, as well as magneto motive force, NI.

REFERENCES

Delforge C. and Lemaire-Semail B. (1995). Induction machine modeling using Finite Element and Permeance Network Methods. *IEEE Trans. on Magnetics,* **31(3)** : pp 2092-2095.

Hirata K., Kagami Y., Yanosaka M., Ishihari Y. and Todaka T. (1992). Thrust calculation of linear pulse motors using a combined technique employing the Finite Element Method and the Permeance Analysis Method. *IEEE Trans. On Magnetics.* **28(2)** : pp 1394-1397.

Norhisam M., Alias K., R.N.Firdaus, Mahmod S., Mariun N. and Abdul Razak J. (2006). Comparison on thrust characteristic of linear oscillatory actuators. *First International Power and Energy Conference PECon, Putrajaya, Malaysia,* pp 470-475.

Tsutomu Mizuno, Masanori Kawai, Fumiaki Tsuchiya, Masashi Kosugi and Hajime Yamada. (2005). An examination for increasing the motor constant of a cylindrical moving magnet-type linear actuator. *IEEE Trans. on Magnetics.* **41(10)** : pp 3976 -3978.

Zhu Z.Q., Pang Y., Howe D., Iwasaki S., Deodhar R. and Pride A. (2005). Analysis of electromagnetic performance of flux-switching permanent-magnet machines by nonlinear adaptive lumped parameter magnetic circuit model. *IEEE Trans. on Magnetics.* **41(11)** : pp 4277-4287.