Armature Reaction Effect and Inductance of Moving Coil Linear Oscillatory Actuator with Unbalanced Magnetic Circuit

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***Abstract*—The unbalanced reciprocating force due to armature reaction field decreases the advantage of moving coil LOA, such as a high degree of linearity and controllability in the force and motion control. This paper firstly describes the coil inductance, the deviation of flux density, and the unbalanced reciprocation force, which are derived from the permeance model of motor. Secondly, the analytical method is verified using 2D finite element method and tests. Finally, the dynamic simulation algorithm considering the armature reaction and variable inductance is proposed and confirmed through the experiments.**

***Index Terms*—Armature reaction field, inductance, moving coil LOA, permeance model, unbalanced force.**

I. INTRODUCTION

A MOVING coil linear motor is used in many applications where rapid, controlled motion and/or high-frequency vibration of devices is required, such as the disk storage device of computer, the compressor of a refrigerator and the vibration generator [1]–[3]. The stroke-length may go up to 2 m, and the maximum speed is in the range of 5 to 10 m/s with oscillating frequency as high as 15 kHz. Therefore, linear motors may be considered as variable speed drivers of precise controller with stroke-length and reversal periods during the reciprocating motion.

A moving coil linear oscillatory actuator (LOA) consists of permanent magnets as the stator, a coil-wrapped nonmagnetic structure and an iron core as a pathway for magnetic flux. The variation of mover position and the consequent changes of coil flux path affect the coil inductance because of unbalanced magnetic circuit [4]. Furthermore, the armature field shifts and distorts the airgap flux density distribution due to the magnet alone by a certain amount, which causes the unbalanced reciprocating force [5]. The effect of armature current in a moving coil linear motor is similar to that in DC and synchronous machines and is known as “armature reaction” or “push/pull” effect. The variation of the coil inductance and thrust with displacement of the actuator decreases the advantage of moving coil linear motor, such as a high degree of linearity and controllability in the force and motion.

In this paper, the coil inductance as a function of mover position is derived from the permeance model of motor. Thus, the deviation of airgap flux density and the variation of thrust with displacement of actuator are predicted and verified using the 2D finite element method and tests. Secondly, the paper describes the unbalanced reciprocation force. Finally, the dynamic simulation algorithm considering the armature reaction effect and variable inductance is proposed and confirmed through the experiments.

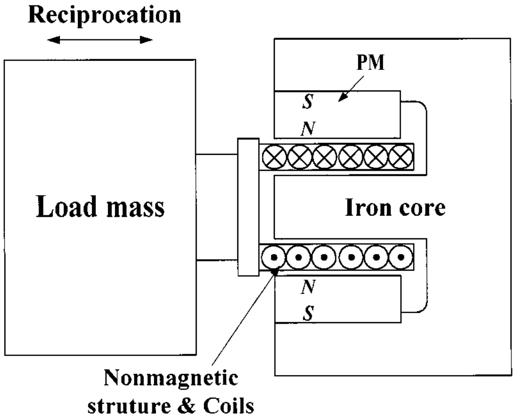

Fig. 1. Moving coil linear oscillatory actuator.

II. ANALYSIS OF COIL INDUCTANCE AND ARMATURE REACTION EFFECTS

A. Moving Coil Linear Oscillatory Actuator

With the introduction of high-energy product rare-earth cobalt magnets and especially NdFeB magnets, the moving coil motor with high power are being developed. The moving coil LOA shown in Fig. 1, consists of the NdFeB permanent magnets as the stator produced magnetic field, a coil-wrapped nonmagnetic rectangular bobbin structure, and an iron core as a pathway for magnetic flux. If the coil is fed with alternating current, an oscillating force is produced to the mover connected to the load mass. The stator topology with surface-mounted PM provides high gap flux density and at the same time avoid the demagnetization effect and therefore was chosen in the design [5], [6].

B. Permeance Model

The basis of the analysis of the LOA with unbalanced magnetic circuit is the permeance model. Fig. 2 illustrates the location of the airgap flux $\Phi_g$and the fringing flux $\Phi_f$in a LOA.

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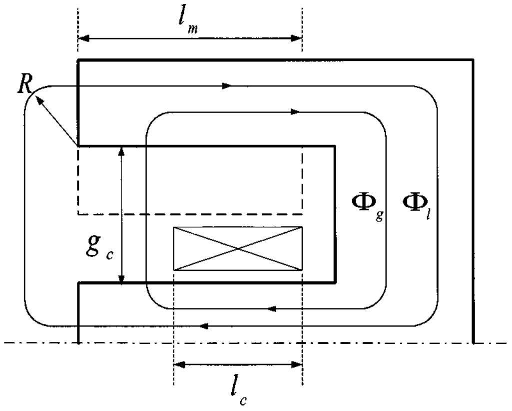


Fig. 2. Permeance model for inductance.

Leakage flux was neglected. The airgap permeance is expressed as;

$$P_g(x) = \frac{\mu_0 L_{st}(l_m + x)}{2g_C} \tag{1}$$

where
L_{st}: stack length,
l_m: permanent magnet length,
x: mover position,
g_c: magnetic airgap length as coils.
The fringing permeance is:

$$P_f = \int_0^R \frac{\mu_0 dA}{l} = \frac{\mu_0 L_{st}}{\pi} \ln\left(1 + \frac{\pi R}{g_C}\right) \tag{2}$$

where $dA = Ldr$, $l = g_c + \pi r$. In this equation, R, the extent that the fringing permeance extends up the sides of the blocks, is unknown and commonly chosen to be some multiple of the airgap length.

C. Coil Inductance

Through (1) and (2), coil inductance is:

$$L_C(x) = N^2(P_g + P_f) = \mu_0 N^2 L_{st} \cdot \left\{\frac{l_m + 2x}{2g_C} + \frac{1}{\pi}\ln\left(1 + \frac{\pi R}{g_C}\right)\right\} \tag{3}$$

where N: number of turns.

D. Armature Reaction Field

When the coil current is turned off, the magnet operates at the point “O” of the demagnetization curve shown in Fig. 3. When the coil current is turned on, the magnet operates at the point “P” or “Q” of the demagnetization curve according to the current direction. The deviation of airgap flux density derived by (3), is defined as;

$$\Delta B(x) = \frac{\mu_0 N^2 I}{l_m}\left\{\frac{l_m + 2x}{2g_C} + \frac{1}{\pi}\ln \cdot \left(1 + \frac{\pi(l_c - l_m - 2x)}{2g_C}\right)\right\} \tag{4}$$

where I: input current, l_c: coil length.

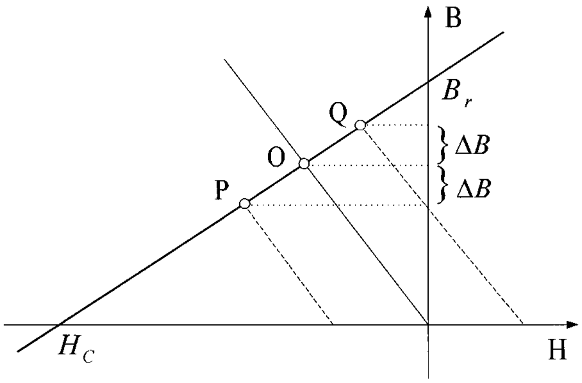


Fig. 3. Operating points due to armature reaction.

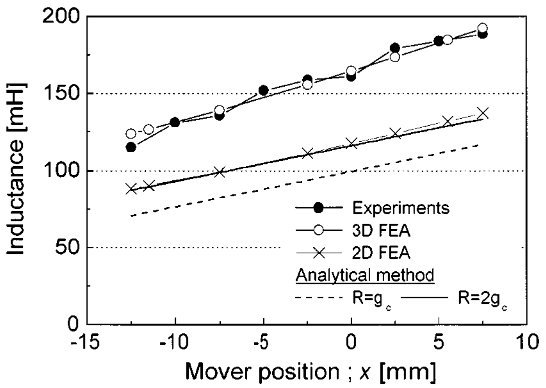


Fig. 4. Variable inductance of moving coil.

E. Push/Pull Coefficient

In accordance with the Lorentz law, the electromagnetic force resulting from the interaction of the coil current and the magnetic airgap field. If uni-axial motion is only considered, the developed force is expressed as:

$$F = 2B_g L_{st} N I \tag{5}$$

where $B_g = B_m + \Delta B$. B_m is the magnetic flux density due to only permanent magnet. The resultant unbalanced reciprocating force therefore is expressed as;

$$\Delta F = 2k_{pp} L_{st} N I^2 \tag{6}$$

where $k_{pp} = \Delta B / I$ is defined the push/pull coefficient.

III. COMPARISONS WITH FINITE ELEMENT ANALYSIS AND TEST RESULTS

A. Variable Coil Inductance

The variation of mover position and the resulting changes of coil flux path affect the coil inductance because of the unbalanced magnetic circuit. The coil inductance therefore is a function of mover position, as shown in Fig. 4. The analytical results agree with the 2D FEA results at $R = 2g_c$.

B. Unbalanced Reciprocating Force

The armature reaction field increases or decreases the airgap flux density due to the magnet by a certain amount. When the current polarity is negative, the armature field pushes the magnet

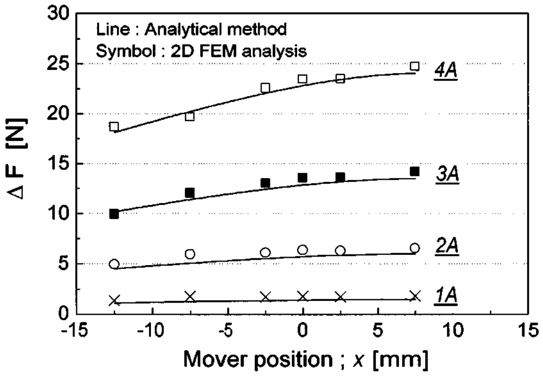


Fig. 5. Unbalanced reciprocating force.

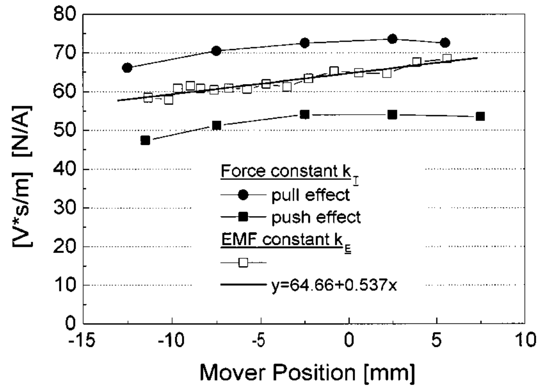


Fig. 6. EMF and force constant.

TABLE I
CIRCUIT PARAMETERS

Parameters		Values	[Unit]
Moving mass		23	[kg]
Coil resistance		5.8	[Ω]
Coil inductance		$2.31x + 0.116$	[H]
EMF & Force constant	Push effects	50	[N/A or Vs/m]
	Pull effects	70	[N/A or Vs/m]

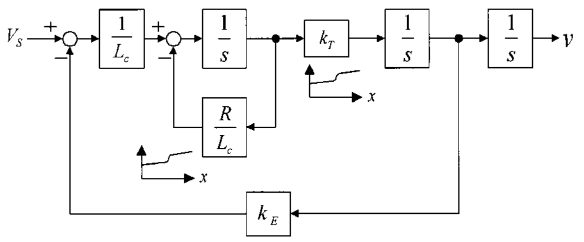


Fig. 7. Block diagram of moving coil LOA.

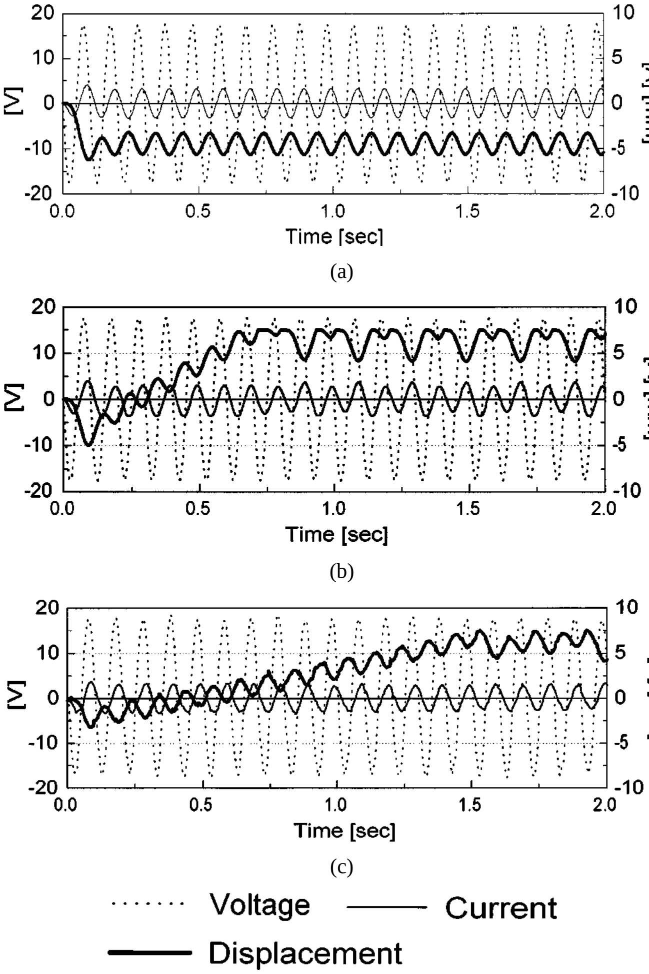


Fig. 8. Dynamic performance at (−) sine wave excitation (10 Hz); (a) simulation no considering armature reaction effects; (b) simulation considering armature reaction effects; (c) experiment.

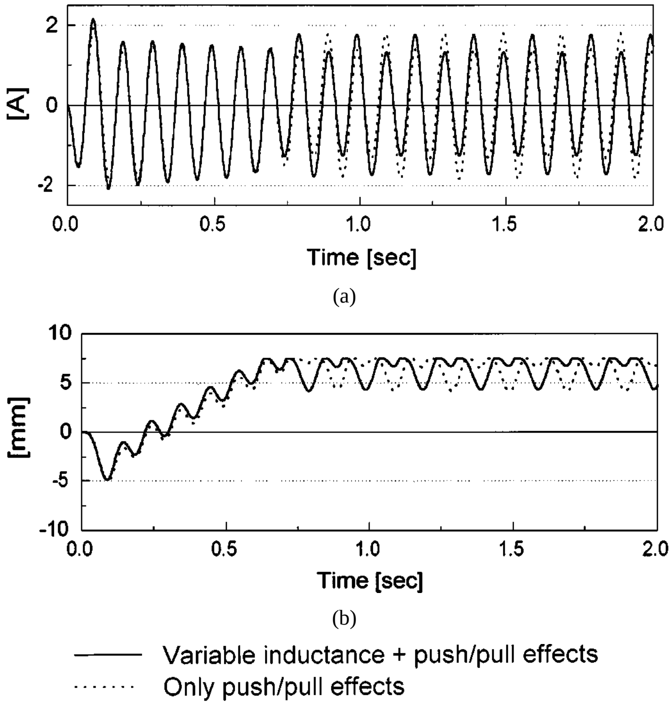
flux and therefore a small thrust force is produced. When the polarity is positive, a large force is produced. The developed force varies at reciprocation, which is bigger as the coil current increases and depends on the mover position, as shown in Fig. 5.

C. EMF and Force Constant

The EMF constant is directly determined through the induced voltage in armature coils at open circuit test. However, the force constant is derived through the static test, where moving members is fixed. Fig. 6 shows the EMF and force constants versus mover position. The EMF constant becomes small according as the coil moves to negative.

IV. DYNAMIC SIMULATION AND EXPERIMENTS

Armature reaction effects clearly appear in the dynamic performance. The voltage and motion equation of LOA system provides the dynamic simulation algorithm. The circuit parameters of LOA are summarized in Table I. Voltage source inverter-fed LOA without feedback control is modeled as shown in Fig. 7. The results of simulation and experiments are shown in Fig. 8. The simulation not to take the armature reaction effect into account is different from the test results. However, the numerical simulation considering with the push/pull effect shows a good agreement with the dynamic test result. Because of ignoring the friction, the long time is taken to the steady state in the experiment. Fig. 9 shows the simulation results considering the variable inductance and the armature reaction. The displacement laggs behind the waveform which is the result of modeling by constant inductance.



(a)

(b)

Fig. 9. Dynamic performance considering variable inductance (10 Hz); (a) current; (b) displacement.

V. CONCLUSION

The unbalanced reciprocating force and variable inductance decreases the advantage of moving coil LOA, such as a high degree of linearity and controllability in the force and motion control. The coil inductance and the unbalanced force derived from the permeance model, analytically were described. The coil inductance and the armature reaction effect is a function of mover position because of the unbalanced magnetic circuit. Consequently, the coil inductance and the force constant are variable circuit parameters. The dynamic simulation algorithm considering the armature reaction and variable inductance was proposed. Through the simulation results, the effects of armature reaction and variable inductance were convicted in the moving coil LOA with unbalanced magnetic circuit.

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