Electromagnetic Modeling of a Novel Linear Oscillating Actuator

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Single-phase linear oscillating actuators (LOAs) produce short-stroke reciprocating motion, and, thus, have many applications. Feasible pole/tooth number combinations for single-phase tubular moving-magnet LOAs are identified and results from a study on a 2-pole LOA equipped with an E-cored stator, and quasi-Halbach magnetized and radially magnetized magnets, respectively, are presented. It is shown that a quasi-Halbach magnetized LOA, in which the magnets are mounted on a ferromagnetic support tube, results in the best electromagnetic performance. Finally, its predicted thrust force characteristic is validated by measurements on a prototype actuator.

***Index Terms*—Halbach, linear motor, moving magnet, oscillating actuator, tubular motor.**

I. Introduction

LINEAR OSCILLATORY ACTUATORS (LOAs) are usually single-phase and provide sustained short-stroke reciprocating motion (mover displacement normally less than 1 pole-pitch) at a controlled frequency and amplitude. They are being employed extensively in applications such as pumps, compressors, and vibrators. In order to achieve a high power density and efficiency, and zero radial force, most LOAs have a tubular structure and employ high energy permanent magnets (PMs). In [1], a linear oscillating actuator was developed to drive an artificial heart. The mover is comprised of two axially magnetized permanent magnets sandwiched between three iron pole-pieces, while the stator had an annular winding housed in a C-shaped stator core, the armature displacement being ± 14 mm when the winding was excited with ac current. The tubular LOA topology reported in [2] had a radially magnetized permanent magnet mover, an annular iron core being used for the inner stator to complete the magnetic flux path. This LOA topology was later commercialized and utilized in household refrigerator compressors [3], and an efficiency of $\geq 92\%$ was reported.

In this paper, alternative design concepts for single-phase PM tubular moving-magnet LOAs are reviewed, and possible pole/tooth number combinations identified. The performance of a tubular LOA equipped with a Halbach magnetized and a radially magnetized mover, respectively, and an E-cored stator, is then predicted by axisymmetric finite element analysis. Finally, the predicted thrust force characteristic of the Halbach magnetized LOA is validated by measurements on a prototype actuator.

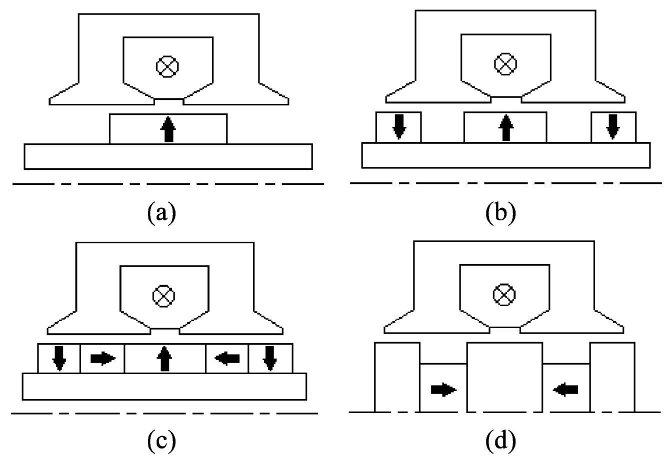

Fig. 1. Schematics of tubular C-cored PM LOAs.

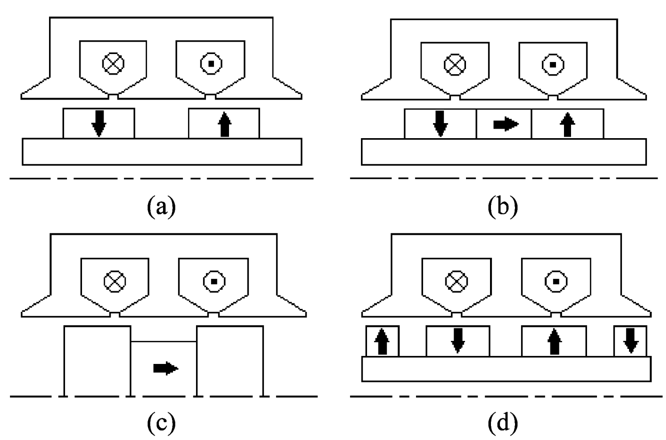

Fig. 2. Schematics of tubular E-cored PM LOAs.

II. Pole and Tooth Number Combinations

Fig. 1 shows the cross sections of four tubular PM LOAs equipped with a C-shaped stator core. The movers differ from each other in terms of the number of poles, the magnetization, and the disposition of the magnets. The homopolar design in Fig. 1(a) [2] has only one radially magnetized ring magnet, but, although being very simple, it suffers from significant leakage flux. The mover in Fig. 1(b) has three radially magnetized ring magnets of alternate polarity, while the mover in Fig. 1(c) is a quasi-Halbach array consisting of five ring magnets, of which three are radially magnetized and two are axially magnetized [4]. Because the flux density which remains on the inner bore of a Halbach array is so small, the magnets may be mounted on a nonmagnetic or ferromagnetic support tube. The mover shown in Fig. 1(d) [1] has two axially magnetized ring magnets which are sandwiched between three ferromagnetic pole-pieces. Although their operating principles are identical, their specific thrust force capability and force/moving-mass ratio vary, given identical overall dimensions and winding ampere-turns.

Fig. 2 shows cross sections of 4 tubular PM LOAs equipped with an E-shaped stator core, and the two stator winding

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TABLE I
POSSIBLE POLE AND TOOTH NUMBER COMBINATIONS

Stator tooth number, N_t	Mover pole number, N_p
2	1, 3
3	2, 4
4	3, 5
5	4, 6
…	…

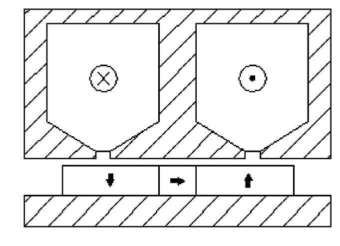

Fig. 3. Schematic of 2-pole, E-core LOA.

comprising coils connected in anti-series, as indicated. The 2-pole mover in Fig. 2(a) has two radially magnetized, surface-mounted ring magnets, and the 2-pole magnetized Halbach mover in Fig. 2(b) has 3 ring magnets, two being radially magnetized and one being axially magnetized, whilst the 2-pole mover in Fig. 2(c) has an axially magnetized magnet sandwiched between ferromagnetic pole-pieces. The 4-pole mover in Fig. 2(d) has 4 radially magnetized ring magnets (a quasi-Halbach mover is also possible), the axial length of the two end magnet being approximately half that of the inner ones. Again, for a given volume envelope and thermal constraint, the performance of the 4 LOAs shown in Fig. 2 will vary.

A common feature of all the foregoing moving-magnet LOAs is that the stator tooth number N_t and the mover pole number N_p differ by 1, i.e.,

$$|N_t - N_p| = 1. \tag{1}$$

Table I includes all possible combinations of N_t and N_p which satisfy (1). It should also be noted that significant variations on the LOA topologies shown in Figs. 1 and 2 are possible. For example, some may have stationary inner back-iron to reduce moving mass [2], the stators may be slotless to eliminate cogging force.

III. COMPARISON OF 2-POLE, E-CORE LOAS

Fig. 3 shows the 2-pole, E-core LOA under investigation, which will quantify the benefits of including the axially magnetized ring magnet and mounting the magnets on a ferromagnetic support tube. The stator core material is a soft magnetic composite (SMC), other relevant parameters being listed in Table II.

Fig. 4(a) shows the open-circuit field distribution when the quasi-Halbach magnetized magnets are mounted on a ferromagnetic support tube and the mover is at its central rest position.

Predicted force-position characteristics are shown in Fig. 5, the net force being equal to the total force minus the cogging force, while the variation of the per-turn flux-linkage with the mover position is shown in Fig. 6. As can be seen, the magnitude of the cogging force is relatively small (~10% of maximum

TABLE II
PARAMETERS OF 2-POLE, E-CORE LOA

Overall axial length, $2\tau_a$	41 mm
Axial length of radial ring magnets, τ_{p1}	13 mm
Axial length of axial ring magnet, τ_{p2}	5 mm
Outer radius, R_o	32 mm
Mover radius, R_m	11 mm
Air-gap length, g	1 mm
Magnet radial thickness, h_m	4 mm
Magnet remanence, B_r	1.2 T
Number of turns per coil, N	343

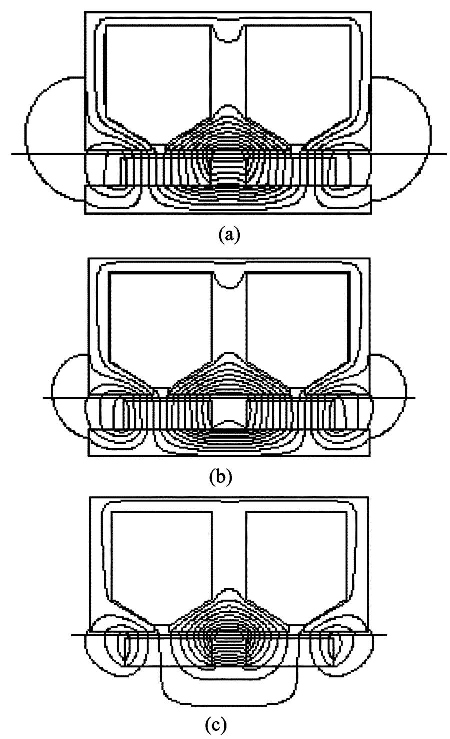

Fig. 4. Open-circuit field distributions. (a) Quasi-Halbach magnetized, with back-iron. (b) Radially magnetized, with back-iron. (c) Quasi-Halbach magnetized, without back-iron.

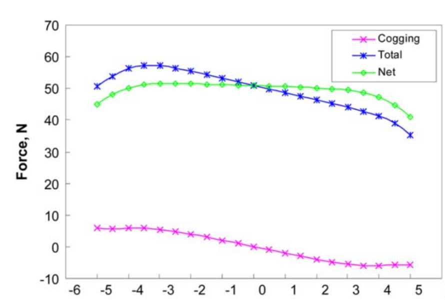

Fig. 5. Thrust force characteristics of LOA shown in Fig. 4(a).

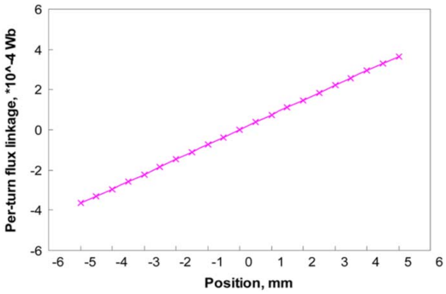

Fig. 6. Flux-linkage characteristic of LOA shown in Fig. 4(a).

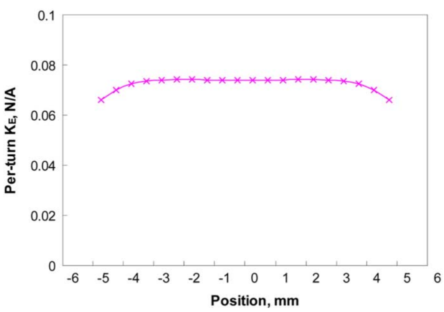

Fig. 7. Back-EMF coefficient of LOA shown in Fig. 4(a).

force at the rated current of 2 A), due to the relatively small slot openings. Thus, the thrust force is relatively constant over the stroke of ± 5 mm. As will be seen, the per-turn flux-linkage, ϕ, increases linearly as the mover is displaced from its rest position. Thus, for a constant mover velocity, v, the back-EMF coefficient, K_E, is given by,

$$E = -\frac{\Delta \varphi}{\Delta t} = -\frac{\Delta \varphi}{\Delta x}\frac{\Delta x}{\Delta t} = -K_E v \tag{2}$$

and, therefore, the force coefficient is almost constant, Fig. 7.

Open-circuit flux distributions, with the mover at its central rest position, are shown in Fig. 4(b) when the mover does not have the axially magnetized magnet, and in Fig. 4(c) when the mover does not have ferromagnetic back-iron. Fig. 8 compares the predicted force, flux-linkage, and back-EMF coefficient characteristics of the three LOAs, from which the following observations can be made. (a) The quasi-Halbach magnetized LOA in which the magnets are mounted on a ferromagnetic support tube exhibits the best performance, because the central axially magnetized magnet provides the main flux return path between the two radially magnetized magnets. Together with the low reluctance of the ferromagnetic support tube, this enhances the air-gap flux density by $\sim$10%, Fig. 9. (b) Thus, the excitation force in the LOA with the quasi-Halbach magnetized mover is $\sim$9% higher than that of the LOA without the central axially magnetized magnet and approximately twice that of the LOA without the ferromagnetic support tube. (c) The shape of back-EMF coefficients in Fig. 8(c) is similar to that of the excitation force, Fig. 8(a). Hence, the reluctance force is negligible.

The magnet pole-ratio, α_p, defined as

$$\alpha_p = \frac{\tau_{p1}}{\tau_{p1} + \tau_{p2}} \tag{3}$$

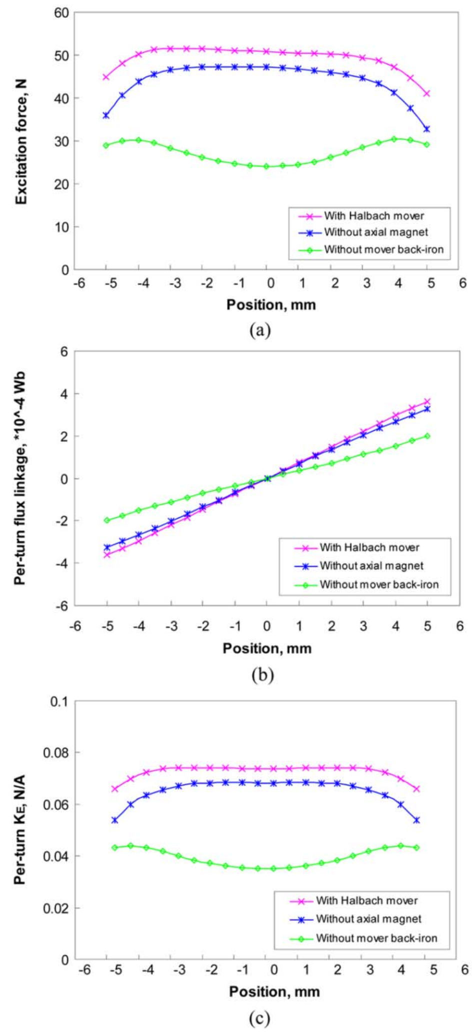

Fig. 8. Comparison of FE predicted electromagnetic performance. (a) Excitation force. (b) Flux-linkage. (c) Back-EMF coefficient.

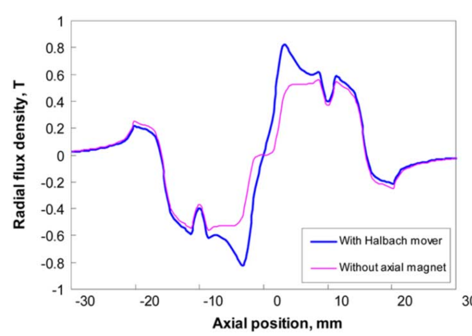

Fig. 9. Comparison of air-gap flux density distributions ($r = 11.625$ mm).

has a significant influence on the LOA performance. Hence, the pole-ratio has been optimized to achieve the maximum thrust force, using finite element analysis, while maintaining the other parameters fixed.

The optimal value of α_p was determined to be 0.3. The thrust force profiles of the optimal $(\alpha_p = 0.3)$ and original $(\alpha_p = 0.72)$ designs are compared in Fig. 10(a). However, as will be seen, although the peak force of the optimal design is 74 N, $\sim$45% higher, at the rated current of 2 A, it now varies

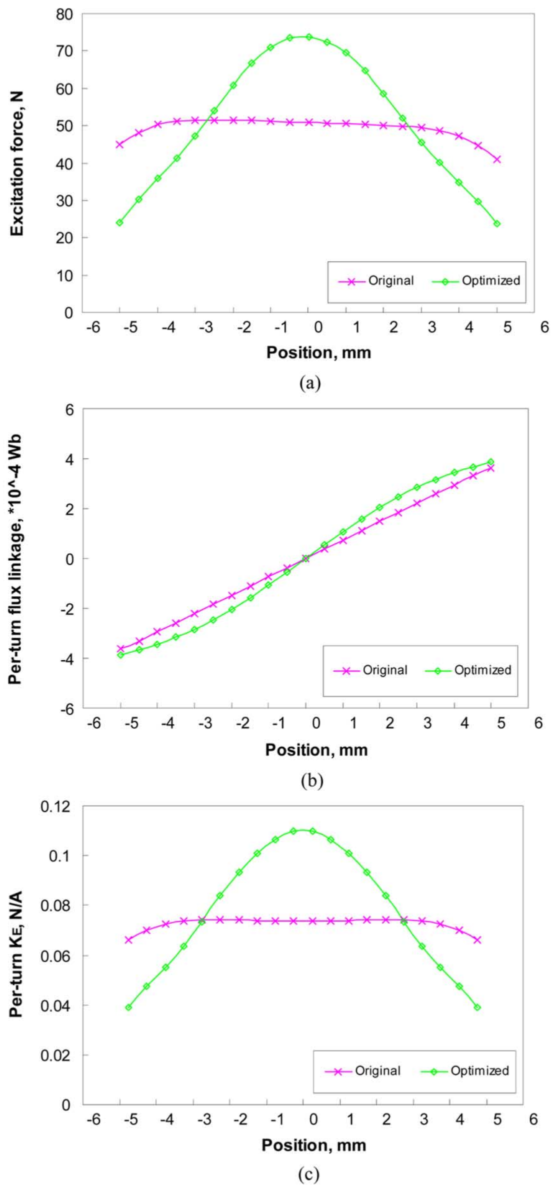

Fig. 10. Comparison of electromagnetic performance characteristics before and after optimization. (a) Excitation force. (b) Flux-linkage. (c) Back-EMF coefficient.

markedly over the stroke of ± 5 mm. Fig. 10(b) compares the per-turn flux-linkage/position characteristic of the original and optimized LOAs, the characteristic of the optimized LOA now being nonlinear. This is mainly due to the influence of saturation as the mover is displaced, which, in turn, causes the back-EMF and excitation force coefficient of the optimized LOA to vary widely, Fig. 10(c).

IV. Comparison With Measurements

In order to validate the FE predicted performance, measurements have been made on a prototype LOA equipped with quasi-Halbach magnetized mover, in which each radially magnetized

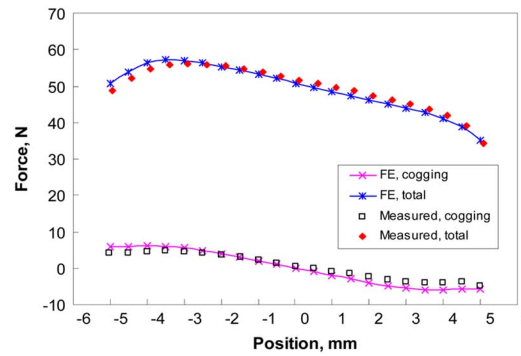

Fig. 11. Comparison of predicted and measured force-displacement characteristics.

ring magnet comprised of 8 sintered NdFeB magnet segments and whose design parameters are given in Table II. The measured static thrust force-displacement characteristic is compared with the predicted characteristic by FE analysis, for an excitation current of 2 A in Fig. 11. As will be seen, good agreement is achieved.

V. Conclusion

Feasible pole and tooth number combinations for single-phase tubular moving-magnet oscillating actuators have been identified, and it has been concluded that the stator tooth number N_t and the mover pole number N_p should differ by 1. A 2-pole LOA with a quasi-Halbach magnetized mover has been analyzed and its performance has been validated by measurements on a prototype LOA. The influence of the magnet pole-ratio, the axially magnetized magnet, and the magnetic properties of the support tube on the performance of the LOA has been quantified.

Acknowledgment

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