

Cogging Force Reduction of Two-Phase Linear Hybrid Stepping Motor

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This paper presents a $\pi/4$ -multiple-coupled two-phase linear hybrid stepping motor (LHSM) that has two windings per phase, one of which shares the other phase winding. The proposed motor shows a unique ability to deliver low cogging force without any complex control scheme or additional power electronics hardware in microstepping control. An analytical and experimental comparison between conventional $\pi/2$ - and $\pi/4$ -multiple-coupled LHSM confirms the effectiveness of the proposed design.

Index Terms—Linear hybrid stepping motors, low cogging force, $\pi/4$ -multiple-coupled LHSM.

I. INTRODUCTION

LINEAR hybrid stepping motors (LHSMs) consist of a permanent-magnet (PM) mover with excitation coils and a platen with many teeth [1]. Most are designed as two-phase synchronous reluctance motor [Fig. 1] as this keeps the power electronics circuits are relatively simple and operated in the open loop with microstepping where the phase currents are controlled in sinusoidal fashion [2]. The mover has three poles per phase and the teeth at one pole of one phase are offset by $1/4$ -tooth-pitch with respect to those of the other phase. Thus, it has the permeances with $\pi/2$ pitch difference and it can be called a $\pi/2$ -coupled LHSM. Due to its hybrid topology, LHSMs have higher force and require much simpler drive/control than any other position-controlled servo motors. Despite its attractive features, the conventional $\pi/2$ -coupled LHSM has the multiples of fourth times harmonic reluctance force from excitation current and cogging force from space harmonic of permeance [2]. Recently, a cogging force compensation strategy for LHSM has been investigated [2], [3] but this effort is so complex that it increases the overhead on the controller, making it lose the simplicity of LHSM drive.

This paper presents a specific type of LHSM, namely, a $\pi/4$ -multiple-coupled two-phase LHSM. All the magnetic poles [Fig. 2] have the permeances with $\pi/4$ -multiple pitch difference, $\theta - (n\pi)/(4)$, according to the toothed surface alignment between mover and platen. The proposed motor shows a unique ability to deliver very low detent force without any particular complex control scheme and can be easily applicable in open-loop microstepping control requiring no additional power electronics hardware. An analytical and experimental comparison between conventional and $\pi/4$ -multiple-coupled LHSM is evaluated to confirm the effectiveness of the proposed design.

II. ANALYSIS OF COGGING FORCE OF PROPOSED LHSM

Fig. 1 shows the schematic view of conventional $\pi/2$ -coupled LHSM. Each phase with three single-poles has an N -turn phase winding at the center pole which is directly connected to the electric source terminal and the toothed surface alignment of two phases is arranged in displacement by $\pi/2$.

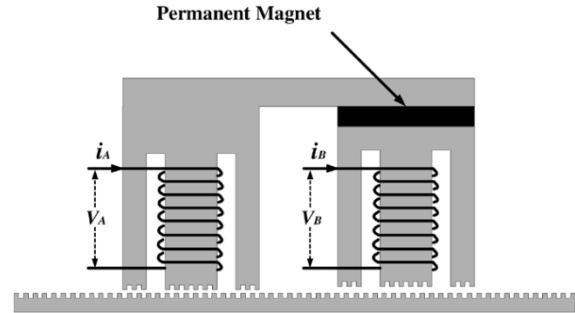


Fig. 1. Schematic view of conventional $\pi/2$ -coupled LHSM.

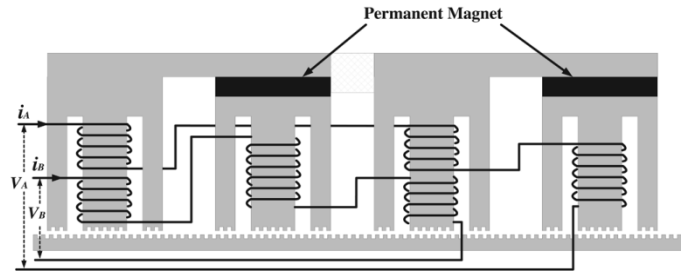


Fig. 2. Structure of proposed $\pi/4$ -multiple-coupled LHSM.

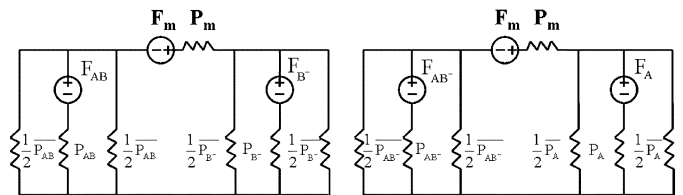


Fig. 3. Magnetic equivalent circuit corresponding to Fig. 2.

Fig. 2 shows the structure of proposed $\pi/4$ -multiple-coupled LHSM in which each $1/\sqrt{2}N$ -turn phase coil is compounded in one magnetic pole. The each compound winding is wound to the opposite direction of main winding and enhances the force-producing characteristics. To analyze the thrust characteristics of $\pi/4$ -multiple-coupled LHSM, assuming the relative permeability of iron core is much larger than that of air gap, the equivalent magnetic circuit of Fig. 2 can be represented as shown in Fig. 3. The individual pole in Fig. 2 corresponds to each permeance branch in Fig. 3. F_m and P_m represent the electromagnetic force and permeance of PM, respectively.

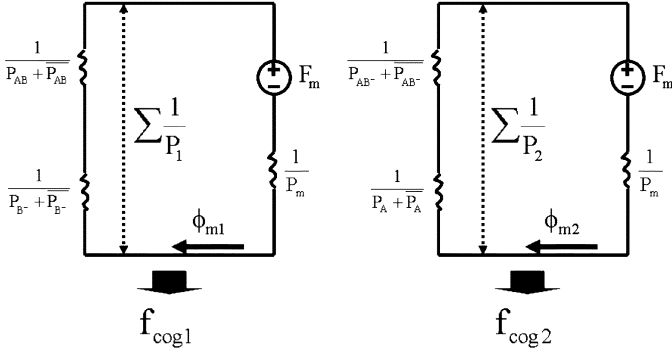


Fig. 4. Simplified magnetic equivalent circuit of $\pi/4$ -multiple-coupled LHSM.

Neglecting high order harmonic components, the permeance in each branch is given by

$$P_{AB} = P_o + \sum_{n=1}^5 P_n \cos n \left(\theta - \frac{\pi}{4} \right) \quad (1)$$

$$\overline{P}_{AB} = P_o + \sum_{n=1}^5 P_n \cos n \left(\theta - \frac{\pi}{4} - \pi \right) \quad (2)$$

$$P_{B-} = P_o + \sum_{n=1}^5 P_n \cos n \left(\theta - \frac{\pi}{2} \right) \quad (3)$$

$$\overline{P}_{B-} = P_o + \sum_{n=1}^5 P_n \cos n \left(\theta - \frac{\pi}{2} - \pi \right) \quad (4)$$

$$P_{AB-} = P_o + \sum_{n=1}^5 P_n \cos n \left(\theta + \frac{\pi}{4} \right) \quad (5)$$

$$\overline{P}_{AB-} = P_o + \sum_{n=1}^5 P_n \cos n \left(\theta + \frac{\pi}{4} - \pi \right) \quad (6)$$

$$P_A = P_o + \sum_{n=1}^5 P_n \cos n(\theta - \pi) \quad (7)$$

$$\overline{P}_A = P_o + \sum_{n=1}^5 P_n \cos n(\theta) \quad (8)$$

$$\theta = \frac{2\pi}{p_t} x \quad (9)$$

where p_t is the pole pitch and x indicates the mover position.

The electromagnetic force of each winding is given as

$$F_{AB} = \frac{N}{\sqrt{2}} (i_A + i_B) \quad (10)$$

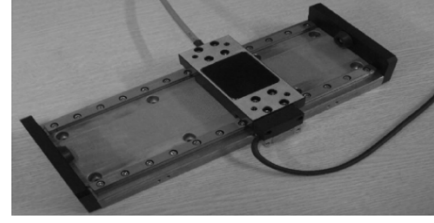
$$F_{B-} = -N \cdot i_B \quad (11)$$

$$F_{AB-} = \frac{N}{\sqrt{2}} (i_A - i_B) \quad (12)$$

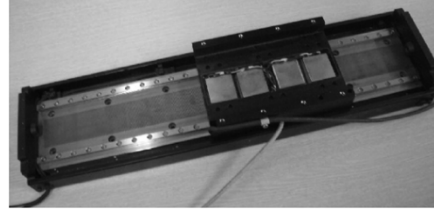
$$F_A = N \cdot i_A \quad (13)$$

Selecting the $1/\sqrt{2}$ N -turn in compound winding, it can be seen from (10)–(13) that the forces by individual phases are equal in magnitude and this could lead to the constant force production.

To calculate the cogging force, a simplified magnetic circuit is redrawn as in Fig. 4. From (1)–(8), it can be noticed that the phase difference of opposite-phase permeance is π and the sum of each odd number harmonic components is zero. Then, as-



(a)



(b)

Fig. 5. Photograph of prototype motor under test. (a) $\pi/2$ -coupled LHSM. (b) Proposed LHSM.

suming $P_o \gg P_2$ and $P_o \gg P_4$ [4], the permeances can be calculated as

$$\frac{1}{P_{AB} + \overline{P}_{AB}} \cong \frac{1}{4P_o^2} (2P_o - 2P_2 \sin 2\theta + 2P_4 \cos 4\theta) \quad (14)$$

$$\frac{1}{P_{B-} + \overline{P}_{B-}} \cong \frac{1}{4P_o^2} (2P_o + 2P_2 \cos 2\theta - 2P_4 \cos 4\theta) \quad (15)$$

$$\frac{1}{P_{A-B} + \overline{P}_{A-B}} \cong \frac{1}{4P_o^2} (2P_o + 2P_2 \sin 2\theta + 2P_4 \cos 4\theta) \quad (16)$$

$$\frac{1}{P_A + \overline{P}_A} \cong \frac{1}{4P_o^2} (2P_o - 2P_2 \cos 2\theta - 2P_4 \cos 4\theta). \quad (17)$$

The stored energy in the left-hand side of Fig. 4 can be

$$W_{m1} = \frac{1}{2} \phi_{m1}^2 \sum \frac{1}{P_1} = \frac{\phi_{m1}^2}{8P_o^2} (4P_o + 2P_2 \cos 2\theta - 2P_2 \sin 2\theta). \quad (18)$$

The energy of the other side can also be expressed as

$$\begin{aligned} W_{m2} &= \frac{1}{2} \phi_{m2}^2 \sum \frac{1}{P_2} \\ &= \frac{\phi_{m2}^2}{8P_o^2} (4P_o - 2P_2 \cos 2\theta + 2P_2 \sin 2\theta). \end{aligned} \quad (19)$$

The permeance of core branch can be neglected and the flux can be found as

$$\phi_m = \phi_{m1} \cong \phi_{m2} \cong F_m P_m. \quad (20)$$

The partial derivative is taken and the cogging force of each part is given by

$$f_{\text{cog1}} = -\frac{\partial W_{m1}}{\partial x} = \left(\frac{2\pi}{p_t} \right) \frac{\phi_m^2}{2P_o^2} (P_2 \sin 2\theta + P_2 \cos 2\theta)$$

$$f_{\text{cog2}} = -\frac{\partial W_{m2}}{\partial x} = \left(\frac{2\pi}{p_t} \right) \frac{\phi_m^2}{2P_o^2} (-P_2 \sin 2\theta - P_2 \cos 2\theta). \quad (21)$$

It is apparent from (21) that the resultant cogging force of proposed LHSM is inherently zero.

III. EXPERIMENTAL RESULTS

Two different 1-mm pole-pitch LHSM prototypes based on the above design structure have been built as shown in Fig. 5 and

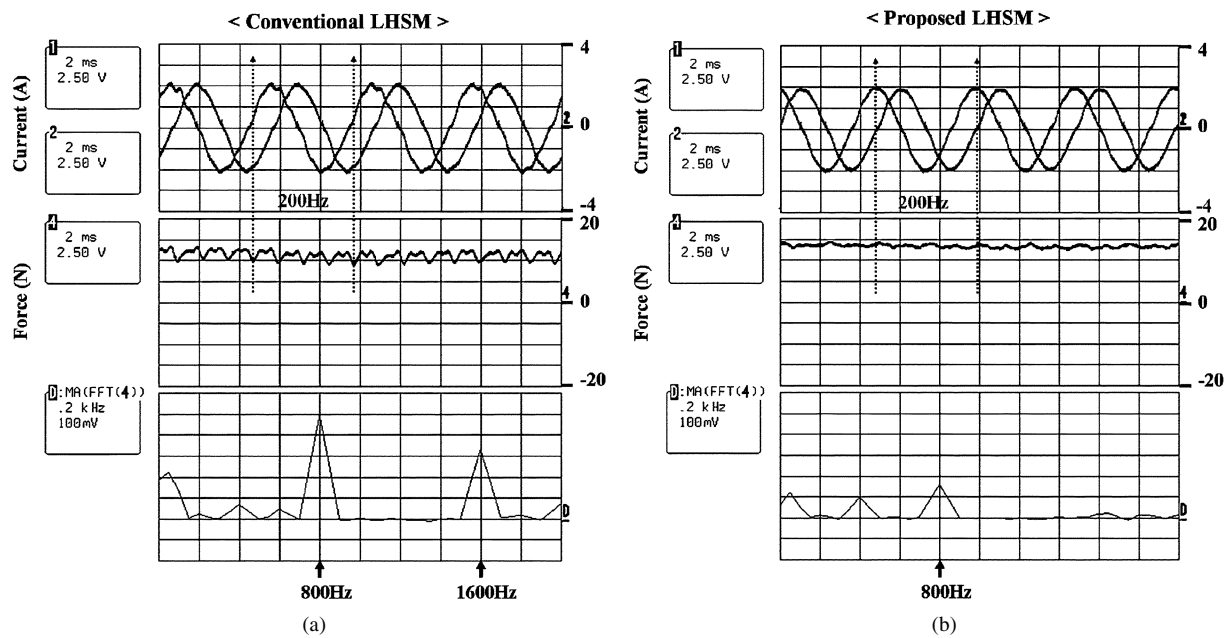


Fig. 6. Steady-state responses at 200 Hz speed. (a) Conventional LHSM. (b) Proposed LHSM.

TABLE I
COMPARISON OF COGGING FORCE OVER FREQUENCY RANGE

Harmonic Order	Cogging Force (N)	
	Conventional LHSM	Proposed LHSM
1 st	0.050	0.040
2 nd	0.115	0.178
3 rd	0.101	0.032
4 th	0.960	0.321
5 th	0.040	0.005
6 th	0.052	0.012
7 th	0.045	0.002
8 th	0.600	0.061
THD (%)	5.874	2.918

tested to verify the validity of the proposed idea. The mover of the proposed motor is almost twice as long as that of the conventional LHSM. The PWM inverter consists of 20 kHz switching modules and is controlled by the drive using a digital signal processor (DSP), TMS320VC33.

Fig. 6(a) shows the feedback currents, measured force, and fast Fourier transform analysis result of force of microstepping controlled $\pi/2$ -coupled LHSM when the motor speed is 200 Hz. The current waveform is nearly sinusoidal but it can be observed that the motor force has the multiples of fourth harmonic cogging force. Fig. 6(b) illustrates the proposed LHSM experimental result and the fourth harmonic force is strongly reduced by more than 60% without any complex control algorithm and additional hardware. The amplitude of eighth harmonic cogging force is also reduced significantly. In this test, the second har-

monic force of proposed motor is somewhat increased and this is due to the unbalanced force which is induced by the magnetic difference between two PMs since the proposed motor employs a dual PM topology.

The comparison results over frequency range are summarized in Table I. It may be noted that the total harmonic distortion (THD) of proposed LHSM is almost reduced by 50% compared to that of the conventional motor. It can be concluded that the proposed $\pi/4$ -multiple-coupled LHSM delivers the low cogging force of not losing the simplicity of drive.

IV. CONCLUSION

An improved design approach to reduce the cogging force in LHSM is proposed. The proposed motor shows a unique ability to deliver very low cogging force without any particular complex control scheme. An experimental comparison between conventional and proposed LHSM is evaluated.

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