Current Control and Mover Design Method for Thrust Characteristics Improvement of Linear Synchronous Motor with Half-Wave-Rectified Self-Excitation

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(Manuscript received Jan. 4, 2021, revised July 23, 2021)
J-STAGE Advance published date: Sept. 10, 2021

This paper presents a current control and mover design method for a linear synchronous motor with half-wave-rectified self-excitation to improve its thrust characteristics. First, we propose the current control method to improve the ratio of thrust to current in a maximum thrust/current control for this linear synchronous motor. Experiments are then performed to demonstrate that the proposed current control method is effective at increasing thrust and that the current and input power required to drive this linear motor can be reduced. Next, we propose a new mover that applies the principle of half-wave-rectified self-excitation to the mover with a multi-flux barrier structure. We design the structure of the proposed mover using finite element method. As a result, it is experimentally shown that the thrust density of this linear synchronous motor with the newly designed mover is approximately 30% higher than that of the previously fabricated mover.

Keywords: linear synchronous motor, half-wave-rectified, self-excitation, variable magnetic field, maximum thrust per ampere, multi-flux barrier

1. Introduction

Linear motors have been widely used in industry applications such as linear conveyor, transfer, and transport systems (1 2). The systems using linear motors have the merits of a free layout, high acceleration and deceleration, high speed, clean system, and high positioning accuracy. In particular, a permanent magnet (PM) type linear synchronous motor (LSM) is mainly used as the driving source for these systems. However, the PMLSM has some drawbacks, such as an expensive rare earth PM and the copper loss caused by the d-axis current during the field weakening operation.

As linear motors without the PM, there are the linear induction motor (LIM) (3 4), linear switched reluctance motor (LSRM) (5 7), linear synchronous reluctance motor (LSRM) (8 9), and so on. Many kinds of researches and developments are carried out to improve the characteristics and put into practical use of these linear motors. On the other hand, the LSM with half-wave-rectified self-excitation (HRSELSM) has been proposed in a bid to apply to conveyor, transfer, and transport systems (10 11). In the HRSELSM, the field winding of a mover is short-circuited through a diode, and the armature winding of the stator is a conventional three-phase winding. The HRSELSM requires no DC power supply or the PM for field excitation and has distinctive merits, such as a simple and robust structure, low cost, and variable magnetic flux. In the previous studies, a verification of the driving principle was carried out using an experimental machine (10), an asymmetrically-shaped mover was designed to reduce the thrust ripple, and a simulation model using a circuit simulator was built to confirm the operation characteristics (11). Moreover, a current control method was proposed to achieve a wide range of speeds and high-power operations (12). However, the maximum thrust/current (MTPA) control proposed in Ref. (12) is a control method, in which an excitation current component for inducing an electromotive force in the field winding is a constant value and the generated thrust is not always the maximum for the same armature current. Also, the HRSELSM has not been designed on the premise of applying MTPA control. Therefore, the thrust of the HRSELSM can be further improved by examining the control and design methods.

In this study, we first propose a new current control method that improves the ratio of the thrust to the armature current in the MTPA control for the HRSELSM. The usefulness of the proposed current control method is investigated by performing experiments. Next, the HRSELSM is designed when the new MTPA control is applied. In this study, we propose a mover with a multi-flux barrier structure (8) to improve the thrust density of the HRSELSM. The structure of the multi-flux barrier, which provides adequate inductance values, can adjust the distribution of the excitation current component and the d-axis direct current component (12) in the new MTPA control so that the thrust characteristics of the HRSELSM is...
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optimized. We design the structure of the proposed mover using the finite element method (FEM). The thrust density of the HRSELM with the newly designed mover is compared with that of the previously fabricated asymmetrically-shaped mover, and we verify the usefulness of the newly designed mover structure. Finally, an experimental machine is built and experimental results are described.

2. LSM with Half-wave-rectified Self-excitation

2.1 Structure of HRSELM

Figure 1 shows the principle figure of the HRSELM, where \( \tau \) is the pole pitch, \( x \) is the mover position, and \( v_x \) is the mover velocity. The HRSELM consists of a mover whose field winding is short-circuited through a diode D and a stator with conventional three-phase armature windings. The position where the q-axis coincides with the stator a-phase winding axis is \( x = 0 \).

2.2 Principle of Self-excitation and Thrust Generation

Figures 2 and 3 show a dq-axis model of the HRSELM and the waveforms of current, flux, and thrust, respectively. Here, \( e_d \) and \( e_q \) are the dq-axis voltages, \( i_d \) and \( i_q \) are the dq-axis currents, \( \lambda_d \) and \( \lambda_q \) are the dq-axis flux linkages, \( M_{fd} \) is the field winding flux linkage, \( W_d \) and \( W_q \) are the stator dq-axis windings, \( L_{sd} \) is the field winding self-inductance, \( M_{fd} \) is the mutual inductance between \( W_q \) and the field winding, and \( F \) is the thrust. The following dq-axis currents are supplied to the stator dq-axis windings:

\[
i_d = \sqrt{3} I_d \sin \frac{\pi}{\tau} + \sqrt{3} I_q \cos \frac{\pi}{3} \tag{1}
\]

\[
i_q = \sqrt{3} I_q \cos \frac{\pi}{3} \tag{2}
\]

The first term in the equation for \( i_d \) is the excitation current component with \( A_f(t) \), where \( A_f(t) \) is a triangular wave function with an effective value of \( I_f \) and a bias angular frequency \( \omega_b \). \( I_f \) is the d-axis direct current component for generating the reluctance thrust and \( I_t \) is the thrust current component. To obtain the dq-axis currents in (1), the following three-phase currents are supplied to the armature windings:

\[
i_a = \{ A_f(t) + \sqrt{3} I_f \sin \frac{\pi}{\tau} \} \cos \frac{\pi}{3} + \sqrt{3} I_q \cos \frac{\pi}{3} \]

\[
i_b = \{ A_f(t) + \sqrt{3} I_q \sin \frac{\pi}{3} \} \cos \frac{\pi}{3} + \sqrt{3} I_q \cos \frac{\pi}{3} \]

\[
i_c = \{ A_f(t) + \sqrt{3} I_q \sin \frac{\pi}{3} \} \cos \frac{\pi}{3} + \sqrt{3} I_q \cos \frac{\pi}{3} \]

The waveform of \( i_d \) is a triangular wave with a DC offset as shown in Fig. 3, and the flux linkage \( M_{fd} i_d \) pulsating at \( \omega_b \) is generated on the mover d-axis. The field current \( i_{fd} \) is induced in the field winding by this magnetomotive force to keep the maximum value of the flux. The field winding flux linkage \( \lambda_{fd} \) is the sum of \( M_{fd} i_d \) provided by the stator excitation current and \( L_{sd} i_{fd} \) by the field current. Consequently, the following flux linkages are generated on the dq-axis windings, and \( \lambda_{dq} \) is kept constant if the time constant of the field winding is sufficiently large.

\[
\lambda_d = L_d i_d + M_{fd} i_d \]

\[
\lambda_q = L_q i_q \]

\[
\lambda_{dq} = M_{sd} i_d + L_{sd} i_d \]

\[
F_{avg} = \frac{\pi}{\tau} \left\{ \sqrt{3} \left( 1 - \sigma \right) L_d I_d I_t + 3 \left( L_d - L_q \right) M_{fd} I_t \right\} \tag{5}
\]

where \( \sigma \) is the leakage coefficient and is defined as

\[
\sigma = 1 - \frac{M_{sd}^2}{L_d L_{sd}} \tag{6}
\]

The first term in (5) is the average thrust generated by the
principle of half-wave-rectified self-excitation and the second term represents the reluctance thrust.

Also, the effective value of the armature current \( I \) is given as the following equation (12).

\[
I = \sqrt{I_f^2 + \frac{1}{2}I_r^2 + I^2}
\]

(7)

3. MTPA Control for HRSELSM

In the previously proposed current control method (12), \( I_f \) for obtaining the reluctance thrust is controlled so that the generated thrust is maximized in the same armature current under the condition that the excitation current component \( I_f \) is a constant value. In this study, we investigate the MTPA control that maximizes the thrust under the same armature current by controlling not only \( I_f \) but also \( I_r \).

3.1 Principle of MTPA for HRSELSM

Figure 4 shows the average thrust \( F_{avg} \) calculated using (5) for various values of \( I_f \) and \( I_r \) at a rated current \( I = 4 \text{ A} \). To calculate \( F_{avg} \), we used the rated current and motor parameters of the experimental machine (11). These parameters are shown in Table 1. As shown in Fig. 4, it is confirmed that there is a point where \( F_{avg} \) is maximized under a constant armature current condition. The method of controlling both \( I_f \) and \( I_r \) to operate at the thrust maximum point is the MTPA control for the HRSELSM proposed in this study.

\( I_f \) and \( I_r \) for realizing the MTPA control are as shown in Fig. 5. \( I_f \) and \( I_r \) change according to \( I \). In the previously proposed current control method, only \( I_r \) was controlled while \( I_f \) was always a constant value. On the contrary, the proposed MTPA control for the HRSELSM in this study controls both \( I_f \) and \( I_r \) to truly maximize the thrust under the same armature current condition. The \( F_{avg} \) in (5) is represented by \( I_f \), \( I_r \), and \( I \) using (7). And the proposed MTPA control is realized by controlling according to \( I_f \) and \( I_r \) obtained from the following equations:

\[
\frac{\partial F_{avg}(I, I_f, I_r)}{\partial I_f} = 0
\]

\[
\frac{\partial F_{avg}(I, I_f, I_r)}{\partial I_r} = 0
\]

(8)

However, solving these simultaneous equations is complicated. Therefore, \( I_f \) and \( I_r \) for the MTPA control are derived using the steepest descent method.

3.2 Experimental Verification of Effectiveness of MTPA Control for HRSELSM

To verify the effectiveness of the proposed MTPA control for the HRSELSM experimentally, the driving circuit and control system were built as shown in Fig. 6. The driving circuit consists of a conventional three-phase PWM inverter system. For the control system, s-BOX (MIS Corporation) equipped with a DSP TMS320C6713 is used. A-phase and B-phase signals from the position sensor attached to the experimental machine are counted using an up/down counter, and that value is taken into the DSP to calculate the mover position \( x \). The actual
mover velocity $v_x$ is calculated from $x$. The $q$-axis current command $i_{q*}$ is calculated using the PI control. The command values of $I_f$ and $I_r$ are derived through the MTPA control using $i_{q*}$. In the MTPA control, the command values $I_f^*$ and $I_r^*$ are determined by the following equations according to the algorithm of the steepest descent method with a search target as $F_{avg}$.

$$
I_{f(i+1)} = I_f(i) + \alpha \left( \frac{\partial F_{avg}}{\partial I_f} \right)_{I_f=I_f(i), I_r=I_r(i)}, \quad i = 0, 1, 2, \ldots, n
$$

and

$$
I_{r(i+1)} = I_r(i) + \alpha \left( \frac{\partial F_{avg}}{\partial I_r} \right)_{I_f=I_f(i), I_r=I_r(i)}
$$

where $n$ and $\alpha$ are the repeat count and learning coefficient for the steepest descent method, respectively. $I_f^*$ is calculated from (1) using the $i_{q*}$ obtained PI control. The last values of $I_f$ and $I_r$ obtained by the steepest descent method are the command values $I_f^*$ and $I_r^*$. In the experiments, the values of $n$ and $\alpha$ were 6 and 0.07, respectively. In addition, the initial value of both $I_f(0)$ and $I_r(0)$ was zero. The $d$-axis current command $i_{d*}$ is calculated through (1) using $I_f^*$, $I_r^*$, and $\omega_b$ from the host computer. After the $dq$-axis command currents $i_{d*}$ and $i_{q*}$ are converted to the three-phase command current $I_{d*}$, $I_{q*}$, and $I_{r*}$, the three-phase command currents are output from the D/A converter. The above calculation in the DSP is performed every 10 kHz. The PWM signals for the IGBT control of the PWM inverter are generated by comparing the actual currents from the current sensor with the command currents.

To examine the thrust obtained by the proposed MTPA control, we measured the static thrust at various values of $I_f$ and $I_r$. Figure 7 shows the measured results of the average static thrust $F_{avg}$ at $I = 2$, 3, and 4 A. The static thrust according to the mover position was measured using a compression-type load cell. $F_{avg}$ is the average value of measured static thrust. The bias frequency command $\omega_b$ was set to 50 Hz, and the DC link voltage of the inverter was 280 V. The plots in Fig. 7 are the measured results and are complemented using a piecewise linear function. Figure 7 also shows the $F_{avg}$ obtained using the MTPA control. As shown in Fig. 7, it is confirmed that the $F_{avg}$ obtained using the MTPA control can obtain almost the maximum point of $F_{avg}$ when changes depending on $I_f$ and $I_r$. Therefore, the $I_f$ and $I_r$ values to realize the MTPA control can be calculated by the control scheme using the steepest descent method proposed in this study. It is considered that the reason for the deviation of the $F_{avg}$ obtained using the MTPA control from the thrust maximum point with an increase in $I$ is owing to the change in the $dq$-axis inductances because of the magnetic saturation.

Figure 8 shows the measured results of the armature current $I_f$ and input power $P_{in}$ at various values of $v_x$ with no load in the previous current control method with constant $I_f = 1.4$ A and the proposed MTPA control method. The bias frequency command $\omega_b$ was set to 50 Hz. Figure 9 shows the current command values $I_{f*}$, $I_{r*}$, and $I_{q*}$ calculated in the control system. In the previous current control method, $I_{f*}$ and $I_{r*}$ are significantly lower than $I_f^*$ at different values of $v_x$, as shown in Fig. 9. The armature current $I$ given by (7) is almost dominated by $I_f$. Therefore, the value of $I$ in the previous current control method hardly changes with the change in $v_x$, as shown in Fig. 8. On the other hand, in the proposed MTPA control, $I_f$ is also controlled so that $I$ is minimized with respect to $v_x$, as shown in Fig. 9. Therefore, $I$ in the proposed MTPA control is reduced by approximately 40 to 60% compared to that in the
previous current control method, as shown in Fig. 8. It is also confirmed that $P_{in}$ is reduced by approximately 60 to 90% compared to the previous current control method because the copper loss reduces as $I$ decreases.

Figure 10 shows the measured waveforms of the field current $i_{fd}$ at $v_s = 0.5 \text{ m/s}$ in Figs. 8 and 9. As shown in Fig. 10, the amplitude of $i_{fd}$ in the proposed MTPA control is lower than that in the previous current control method. Figure 11 shows the measured results of the effective value of $i_{fd}$ at various values of $v_s$ with no load. The values on the vertical axis in Fig. 11 are the root mean square values obtained from the field current waveform. As shown in Fig. 11, the effective values of $i_{fd}$ in the proposed MTPA control are reduced compared to those in the previous current control method because $I_f$ is controlled with respect to $v_s$. Therefore, the proposed MTPA control can also be expected to reduce the copper loss caused by the field current.

From the above results, the ratio of the thrust to the armature current can be improved using the MTPA control for the HRSELM proposed in this study. It can be expected to improve the thrust and efficiency compared to the previous current control method. In addition, the proposed MTPA control method can be applied to rotating machines\cite{13,14}, which have the same excitation principle for the field winding as the HRSELM.

4. Mover Design for High Thrust Density

To improve the thrust density by increasing the reluctance thrust, we newly use a shape of the mover iron core with a multi-flux barrier structure for the HRSELM. The structure of the multi-flux barrier, which provides adequate inductance values, can adjust the distribution of the excitation current component $I_f$ and the d-axis direct component $I_r$ in the proposed MTPA control so that the thrust characteristic of the HRSELM is optimized. The structure of the mover is designed using the FEM. In this study, we design only the mover and use the stator of the experimental machine fabricated during a previous study\cite{11}. Table 2 shows the design parameters of HRSELM.

4.1 Analytical Model of HRSELM with Multi-flux Barrier Mover

Figure 12 shows the analytical model of the HRSELM with the multi-flux barrier mover (three iron layers). For the iron core shape of the multi-flux barrier mover, we use a reluctance equalization structure\cite{8}. The ratio of the total width of the iron layers to that of the flux barriers is 2 : 1. The spaces of the flux barriers have field windings for half-wave-rectified self-excitation. In addition, there is a slit of width $w_s$ between the segments of the mover. The iron core material for the mover design is the commonly used magnetic steel sheet 35A300.

The structure of the mover is designed by calculating the thrust density and normal force for different numbers of iron layers and slit width $w_s$. Table 3 shows the dimensions of the iron layer, flux barrier width, and number of turns of the field winding for each number of iron layers. A $\phi$ 0.8 mm copper

| Item                        | Value          |
|-----------------------------|----------------|
| Stator length               | 1990 mm        |
| Stack height                | 50 mm          |
| Air gap                     | 0.6 mm         |
| Rated voltage               | 200 V          |
| Number of turns of stator winding | 85 turn/pole phase |
| Windings                    | Double layer distribution pitch |

Table 2. Design parameters of the HRSELM

![Fig. 9. Current command values calculated in the control system at various velocities in the previous current control method with constant $I_f = 1.4$ A (Const. $I_f = 1.4$ A) and the proposed MTPA control method](image)

![Fig. 10. Measured results of the field current waveform at $v_s = 0.5 \text{ m/s}$ in the previous current control method with constant $I_f = 1.4$ A (Const. $I_f = 1.4$ A) and the proposed MTPA control method](image)

![Fig. 11. Measured results of the effective value of the field current at various velocities in the previous current control method with constant $I_f = 1.4$ A (Const. $I_f = 1.4$ A) and the proposed MTPA control method](image)

![Fig. 12. Analytical model of the HRSELM with the multi-flux barrier mover (three iron layers)](image)
wire is used for the field winding. Because the coil space factor of the previously fabricated asymmetrically-shaped mover and other linear motors is approximately 50%, the coil space factor of the field winding of the newly designed mover is set to 50%. The thrust density is given by the ratio of the average thrust to volume. The volume is defined as a hexahedron of width \(w_m\), height \(h_m\), and depth \(d_m\), as shown in Fig. 13. Here, \(w_m\) is the width including coils on both ends of the mover, \(h_m\) is the sum of the height of the stator and mover core and the air gap length, and \(d_m\) is the sum of the iron core stack height and length of the coil end. The width of the coils on both the ends for \(d_m\) is equal to the width of the field windings contained in the flux barriers. The length of the coil end for \(d_m\) is calculated assuming that the inner diameter of the bent portion is 5 mm. The depth is calculated for both the stator and mover, and the longer one becomes \(d_m\).

4.2 Analytical Method The thrust and normal force characteristics were calculated by a two-dimensional nonlinear magnetic field analysis using the FEM. The FEM software JMAG-Designer 18.1, produced by JSOL Corporation, is used for the magnetic field analysis. The analysis is performed using the analytical model with a stator length of approximately 2 m created based on Tables 2 and 3 and Fig. 12. The number of elements in the FEM analysis model is approximately 100,000. The magnetic field analysis for characteristic calculation is performed at the mover position at 1 mm intervals, and the currents are supplied using the current source. Before calculating the thrust and normal force characteristics, \(L_d\), \(L_q\), \(M_{fd}\), and \(M_{fd}\) for deriving the command currents for the proposed MTPA control are calculated through magnetic field analysis using the analytical model.

To calculate the thrust characteristics of the HRSELSM accurately, it is necessary to perform an electric and magnetic coupled analysis. In this case, it is necessary to execute the analysis step time according to the bias frequency, and it takes a lot of time to calculate the thrust and normal force characteristics once. Therefore, in this study, we do not perform the electric and magnetic coupled analysis to reduce the computational time by referring to the previous design method for the HRSELSM. In this instance, the field current induced by the d-axis current based on the principle of half-wave-rectified self-excitation cannot be calculated directly. Therefore, an equivalent DC electricity that generates the same flux linkage as \(L_{fd}\) obtained by half-wave-rectified self-excitation is supplied to the field winding, and the analysis is performed. Here, the equivalent DC electricity \(I_{fd}\), ignoring the field winding resistance for simplicity, is given as follows:

\[
I_{fd} = \frac{3}{2\sqrt{2}} \frac{M_{fd}}{L_{fd}} I_f 
\]  

In the analysis for the design of the mover, the values of \(I_f\) and \(I_{fd}\) are given by the proposed MTPA control. However, \(I_f\) is limited so that the current density of the field winding given by (12) does not exceed 5 A/m².

4.3 Analytical Results Figure 14 shows the analytical results of the effects of the number of iron layers on the thrust density and the normal force at \(w_s = 0 \text{ mm}\) and the rated current \(I = 4 \text{ A}\). Although it is confirmed that the thrust density increases with an increase in the number of iron layers, there is approximately no difference in the thrust density between the number of iron layers three, four, and five. Meanwhile, the normal forces of the number of iron layers two and three are approximately the same value. The normal forces of the number of iron layers four and five are 10 to 14% higher than those of iron layers two and three. From these analytical results, the number of iron layers is determined to be three in consideration of the thrust density, normal force, and ease of fabrication.

Figure 15 shows the analytical results of the thrust density when the slit width \(w_s\) is changed from 1 mm to 5 mm at the rated current \(I = 4 \text{ A}\). In this analysis, the number of iron layers is three. Because \(L_q\) decreases with an increase in \(w_s\), the reluctance thrust is expected to increase. However, if \(w_s\) becomes too large, \(L_d\) decreases. In this case, not only the reluctance thrust but also the thrust based on the principle of half-wave rectified self-excitation decreases. As shown in Fig. 15, it is found that the thrust density increases with an increase in \(w_s\) and becomes a maximum value at \(w_s = 3 \text{ mm}\). The thrust density decreases when \(w_s\) exceeds 3 mm. There is almost no difference between the thrust densities at \(w_s = 4 \text{ mm}\) and \(5 \text{ mm}\), but the thrust density at \(w_s = 5 \text{ mm}\) is slightly higher than that at \(w_s = 4 \text{ mm}\). Because the value of \((1 - \sigma)L_d\) in (5) is almost the same at \(w_s = 4 \text{ mm}\) and \(5 \text{ mm}\),
the thrust generated by the principle of half-wave-rectified self-excitation is almost equal for both values of \(ws\). On the other hand, it is confirmed that the value of \((L_d-L_q)\) at \(ws = 5\) mm is greater than that at \(ws = 4\) mm from the analytical results. It is considered that the result shown in Fig. 15 is obtained because the reluctance thrust can be used more effectively when \(ws = 5\) mm. From this analytical result, \(ws\) is determined to be 3 mm to improve the thrust density.

Figure 16 compares the dimensions of the iron core of the previously fabricated asymmetrically-shaped mover and that of the newly designed multi-flux barrier mover. The height of the previously fabricated asymmetrically-shaped mover shown in Fig. 16(a) is 54 mm, while that of the newly designed multi-flux barrier mover shown in Fig. 16(b) is 30 mm. The newly designed multi-flux barrier mover can make the structure flatter.

Figure 17 shows the analytical results of the static thrust waveforms of the previously fabricated asymmetrically-shaped mover and the newly designed multi-flux barrier mover at \(I = 4\) A. From Fig. 17, the average values of static thrust in the previously fabricated and newly designed movers are 140 N and 115 N, respectively. The analytical results for the thrust density and normal force are shown in Fig. 18. The volumes of the analytical model of the HRSELSM for the previously fabricated and newly designed mover are \(2.46 \times 10^{-3}\) m\(^3\) and \(1.71 \times 10^{-3}\) m\(^3\), respectively. As shown in Fig. 18, the thrust density of the newly designed multi-flux barrier mover increases by approximately 20% compared with that of the previously fabricated mover, because the volume of the HRSELSM with the newly designed mover is lower than that with the previously fabricated mover. Also, it is confirmed that the normal force of the newly designed mover decreases by approximately 30% compared with the previous one. However, as shown in Fig. 17, the HRSELSM with the newly designed mover has a larger thrust ripple compared to the HRSELSM with the previously fabricated asymmetrically-shaped mover. Therefore, it is necessary to reduce the thrust ripple in the future.

Owing to the design of the multi-flux barrier mover applied the new MTPA control, the ratio of the thrust to the normal force is changed, and the thrust density increases. This result is considered that it is because the equivalent load angle of the operation is changed. The new MTPA control is effective in improving the equivalent load angle of the operation of the HRSELSM. Therefore, it is predicted that the ratio of the thrust to the normal force of the previous asymmetrically-shaped mover can also be improved by performing the design applied the new MTPA control.

**4.4 Experimental Results**

Figure 19 shows the iron core before lamination for one segment of the multi-flux barrier mover that was fabricated based on the design results. For the iron core material, although it is different from the material used in the design, a general structural rolled steel SS400 with a thickness of 0.8 mm is used because of its availability. In the iron core shown in Fig. 19, the iron layers are held by bridges with a width of 0.5 mm. We have confirmed by the analysis that bridges have almost no effect on the thrust characteristics. The appearance of the experimental machine
The calculation results of the electric and magnetic coupled analysis include the pulsating component caused by the bias frequency of 50 Hz; however, the analytical result in Fig. 21 shows a time-averaged value of the pulsating thrust caused by the bias frequency. From Fig. 21, the average value of both the measured and analytical results in the HRSELSM with the newly designed mover is 102 N. Also, the distribution of static thrust to $x$ is in good agreement with the measured and analytical results. From these results, it is confirmed that we can obtain the static thrust characteristics as designed. The measured average static thrust of the previously fabricated asymmetrically-shaped mover is 88 N. The measured volumes of the HRSELSM with the previously fabricated and newly designed movers are $2.93 \times 10^{-3} \text{m}^3$ and $2.52 \times 10^{-3} \text{m}^3$, respectively. Therefore, the thrust densities of the previously fabricated and newly designed movers are $30 \text{kN/m}^3$ and $40 \text{kN/m}^3$, respectively. It is confirmed that the thrust density of the newly designed mover increases by approximately 30% compared to that of the previously fabricated mover in the experiments.

5. Conclusion

This study proposed the new current control method that improved the ratio of thrust to armature current in MTPA control for the HRSELSM. By performing the experiments, it was confirmed that $I_f$ and $I_r$ for realizing the proposed MTPA control could be calculated using the steepest descent method, and the thrust maximum point could be obtained. Furthermore, it was confirmed that the ratio of thrust to armature current could be improved by the proposed MTPA control, and the copper loss could be reduced and the efficiency could be improved compared with the previous current control method. The proposed MTPA control could also be expected to reduce the copper loss caused by the field current. Next, we proposed the HRSELSM with the multi-flux barrier mover to improve the thrust density by optimizing the thrust characteristics when the new MTPA control was applied to the HRSELSM. We designed the structure of the multi-flux barrier mover using FEM. As a result, it was confirmed that the thrust density of the HRSELSM with the newly designed multi-flux mover increased by approximately 20% compared to that with the previously fabricated mover using FEM analysis. Furthermore, we fabricated the newly designed mover to verify the thrust characteristics by performing experiments. From the experimental results, it was confirmed that the thrust density of the HRSELSM with the newly designed mover increased by approximately 30% compared to that with the previously fabricated mover.

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