The Independent Control of Thrust and Levitation Forces with a Third Order Harmonics Injection Method for TFLIM

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Keywords

Combined lift and thrust, Third order harmonic injection, Transverse flux machine

Abstract

A non-contacting steel plate conveyance system using the Transverse Flux Linear Induction Motor (TFLIM) is studied and a combined control principle of levitation and thrust for TFLIM is proposed. TFLIM characteristics are calculated both for the levitation and thrust forces acting on the secondary steel plate with a third order harmonic current injection scheme, on the basis of a three-dimensional electromagnetic field analyzing program (J-MAG Studio). This scheme is considered for the drive system, and then it is possible to control thrust and levitation forces independently of each other.

1 Introduction

The iron and steel industries of developed countries are trying to shift their production from mass-produced conventional steel plates into high quality and value-added products. The non-contacting product conveyance system is expected as a practical mean to realize such objective in these industries and has been studied with various aspects. ([1], [2])

The transverse flux linear induction motor (TFLIM) has a different structure from the conventional LIM as shown in Fig.1. Because of its large pole piece and primary flux path through the secondary iron vertically to the direction of its motion, TFLIM can generate high levitation force and is considered to fit to application to the conveyance system, where steel plate makes up its secondary and the combined principle of levitation and thrust can be used [3]. A third order harmonic current injection scheme for its excitation current is proposed and studied for the drive system, because the levitation force varies lineally with the effective value of primary current, but the thrust force depends only on the amplitude of fundamental component in the primary current. So, it is possible to regulate two forces independently of each other. And using this method, its maximum primary current value can be kept invariant, so it is serve the purpose of using the capacity of the inverter for its control to the maximum. Therefore, levitation and thrust forces can be controlled independently for an actuator of non-contacting conveyance system using TFLIM with third order harmonic current.

2 TFLIM with Iron Secondary

2.1 LIM with Iron Secondary

In the conveyance system studied here, the steel plate makes up the secondary of TFLIM. It means TFLIM has an iron secondary. Generally in LIM with iron secondary, the effect of eddy current in the secondary is relatively less than electromagnetic force acting between the primary and the secondary. Then TFLIM in this conveyance system can generate large attractive force to the steel plate in even high slip frequency.

2.2 The Difference of TF Type and Conventional (Longitudinal Flux) Type

In TFLIM the flux path lies in the plane vertical to the direction of its motion as shown in Fig.1 [4]. While in the conventional LIM, the flux path lies in the plane parallel to the motion of the primary as shown in Fig. 2.

Because of this difference, the path of magnetic flux in the secondary is relatively short in TFLIM [5]. The pole piece of the primary of TFLIM has a relatively large area, and less influenced by magnetic saturation due to skin effect in the secondary.

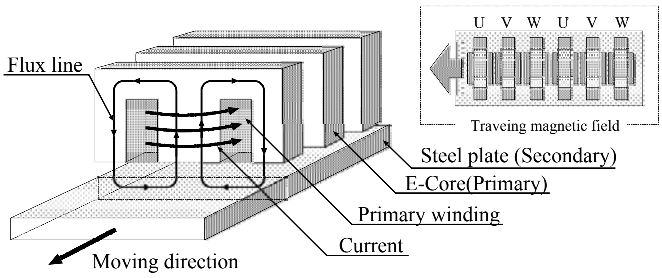

Fig. 1 Flux line of Transverse Flux type LIM

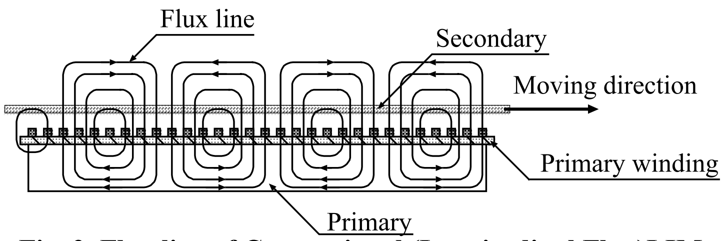

Fig. 2 Flux line of Conventional (Longitudinal Flux)LIM

3 Model TFLIM for Conveyance System

3.1 TFLIM Model

The photograph of a model TFLIM is shown in Fig. 3. The dimension of this model is given in Fig. 4, which shows a half of the model because of the structural symmetry to x-axis. TFLIM characteristics are calculated with a general-purpose three-dimensional electromagnetic field analyzing program (J-MAG Studio) using finite element method (FEM). The calculation mesh using in this analysis is shown in Fig. 5.

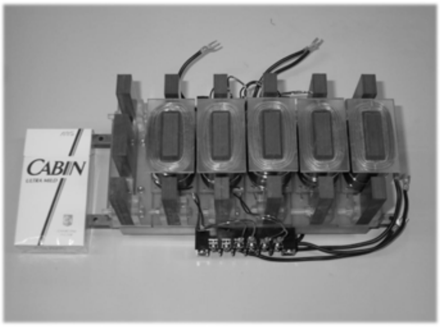

Fig. 3 TFLIM (experimental device)

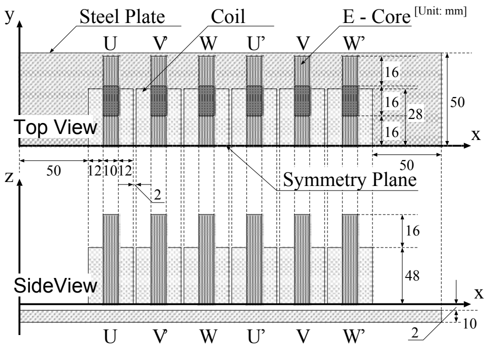

Fig. 4 Dimension of a model TFLIM

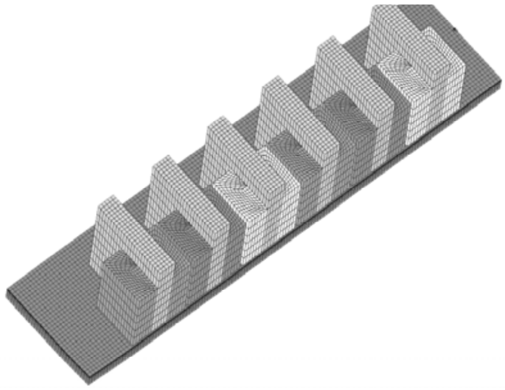

Fig. 5 Calculation mesh for FEM Analysis

3.2 TFLIM Design Parameters and its Operational Condition

The design parameters and operating conditions of TFLIM used for experiments are summarized in Table I for the following analysis.

The thrust and levitation force of TFLIM is calculated against the power supply frequency to its primary coil as shown in Fig. 6. The slip of TFLIM is supposed to 1, because the conveyance speed is about 1 m/s and far smaller than its synchronous speed in this system. The figure shows that the thrust force doesn't increase over 30Hz, and the levitation force decreases over 30Hz. So the frequency is set to 30Hz for further analysis.

Table I
Model TFLIM Parameters

Condition	Value
Turns of Coil	100 Turns
Maximum value of current	14.14 A
Frequency of power supply	30 Hz
Slip	1
Conductivity of Secondary	2560000 (1/ohm m)
Permitivity of Secondary	1000

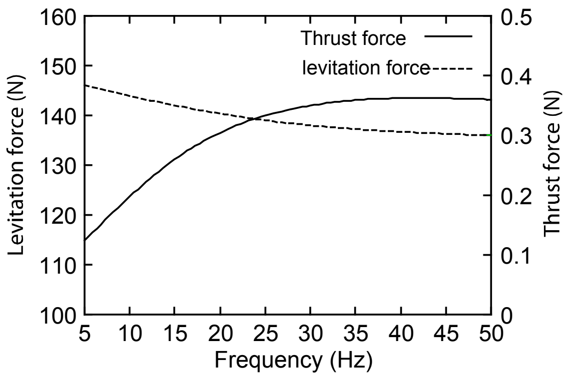

Fig. 6 Frequency of primary current vs. Force

4 Third Harmonic Current Injection

The third harmonic current is assumed to be injected into the three phase primary current of TFLIM. Defining the amplitude of fundamental current as A and the amplitude of third harmonic current as B, the balanced three phase primary currents are given as Eq. 1- Eq. 3, where ω is the angular frequency of the fundamental current.

$$I_u = A\sin\omega t + \underline{B\sin 3\omega t} \tag{1}$$

$$I_v = A\sin(\omega t - \frac{2\pi}{3}) + B\sin 3(\omega t - \frac{2\pi}{3}) \tag{2}$$

$$I_w = A\sin(\omega t + \frac{2\pi}{3}) + B\sin 3(\omega t + \frac{2\pi}{3}) \tag{3}$$

Equation Eq. 2 and Eq. 3 are transformed as follows;

$$I_v = A\sin(\omega t - \frac{2\pi}{3}) + \underline{B\sin 3\omega t} \tag{4}$$

$$I_w = A\sin(\omega t - \frac{2\pi}{3}) + \underline{B\sin 3\omega t} \tag{5}$$

The third harmonic component (underlined term) is inphase for three phase currents. This component works only for levitation force, because it doesn't contribute to the traveling magnetic field along the secondary iron plate of TFLIM. Then the thrust force depends on the amplitude of the fundamental component A alone. While the levitation force acting on the secondary plate is given as the Maxwell stress to the primary pole piece and is determined by the effective value of primary current.

Therefore, it is said that control thrust and levitation forces are controlled independently of each other.

5 The Calculation of Third Order Harmonic Ingredient

The capacity of the primary current controller, which regulates the thrust and levitation, is given by its maximum current. The relation between A and B is derived, keeping the maximum value of the primary current constant from this practical reason.

The maximum value of primary current I_{max} is given from Eq. 1 as follows;

$$\frac{dI}{dt} = A\omega\cos\omega t + 3B\omega\cos 3\omega t = 0$$

i.e.

$$A\cos\omega t + 12B\cos^3\omega t - 9B\cos\omega t = \cos\omega t(12B\cos^2\omega t + A - 9B) = 0$$

This equation's extreme values are as follows;

$$\omega t = \frac{\pi}{2}, \omega t = \cos^{-1} \pm\sqrt{\frac{-A+9B}{12B}}$$

Therefore,

When $A \geq 9B$:
$I_{max} = A - B$

When $A \leq 9B$:

$$I_{max} = A \sin \cdot \cos^{-1} \sqrt{\frac{-A+9B}{12B}} + B \sin 3 \cdot \cos^{-1} \sqrt{\frac{-A+9B}{12B}}$$

The optimum combination of A and B is studied under the condition to keep I_{max} constant. When I_{max} is set to 14.14A, the relation between A and B is shown by the bold curve of Fig. 7. The points given on the bold curve with coordinate value sets in Fig. 7, are chosen for the detailed analysis of TFLIM characteristics with properties explained in Table II.

Table II
Analysis Point

Case	A (A)	B (A)	Remark
1	15.91	1.77	Corner point in Fig. 7 of A=9B
2	16.33	2.72	Maximized the fundamental component
3	15.91	3.91	Different effective value from others
4	14.14	5.83	Same fundamental component with the base case
5	14.14	0	Base case, sine wave

Fig. 8 gives the waveform of case 2 with a bold curve. Its fundamental component is shown by a dotted line. The fine curve is a fundamental current with the same maximum value with the bold curve. The effect of the third harmonics injection is clearly illustrated in this figure.

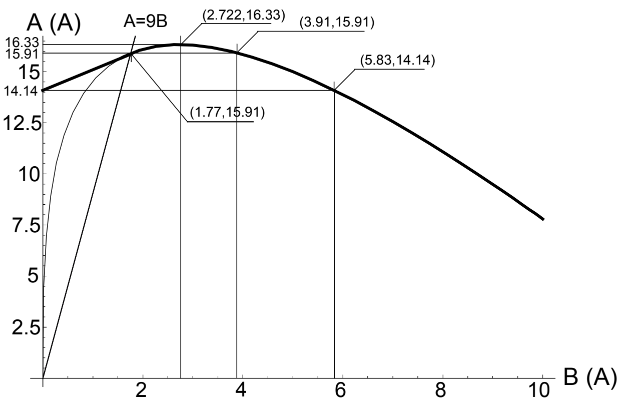

Fig. 8 Relation between *A* and *B* under the condition for I_{max}=14.14A

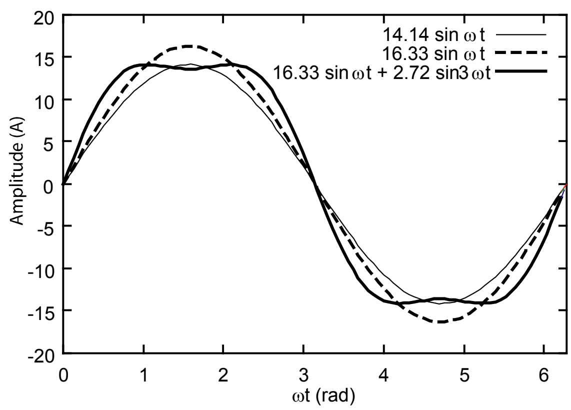

Fig. 8 Example Current Waveform (*A*=16.33A, *B*=2.72A)

6 Evaluation of Third Order Harmonic Injection

6.1 The Results of Analysis

The characteristics of TFLIM of 30Hz are calculated with on electromagnetic field analyzing program (J-MAG Studio) against various types of primary current defined in Table II. The waveform of levitation and thrust force is shown in Fig. 9 and Fig. 10 respectively. The levitation force fluctuates with the sixth harmonics of the supply frequency. Its average value depends on the amplitude of both fundamental current (*A*) and the third harmonic current (*B*). While, the thrust force fluctuates with the second harmonics of the supply frequency. Its average value depends only on the amplitude of fundamental current.

The amplitude of force are also evaluated by their density under pole pieces as defined by (6) and shown in Table IV. The dimension of primary magnet is given in Fig. 4. High force density for levitation shows that TFLIM is practically applicable to the conveyance system.

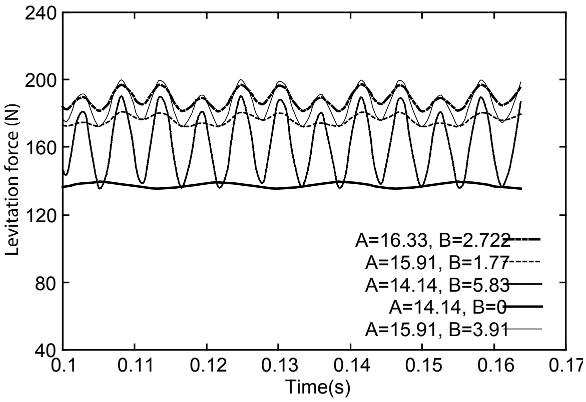

Fig. 9 Levitation Force

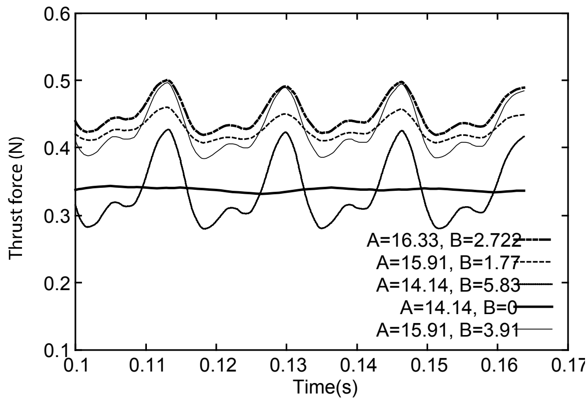

Fig. 10 Thrust Force

6.2 Effectiveness of Third Harmonic Injection

The influence of the third harmonic injection on the forces generated by TFLIM is summarized Table III, and the value of thrust and levitation force in this table is plotted in Fig. 11 and Fig. 12 respectively. As Fig. 11 and Fig. 12 show, the average value of levitation force varies lineally with the effective value of primary current, but the average value of thrust force depends only on the amplitude of fundamental component in the primary current clearly. It suggests that two forces are controlled independently of each other.

TABLE III
Average Value of Forces vs. Amplitudes of Currents

A (A)	*B* (A)	Effective value (A)	Thrust force (N)	Levitation force (N)
16.33	2.72	11.71	0.450	188.7
15.91	1.77	11.32	0.428	176.2
15.91	3.91	11.59	0.428	185.3
14.14	5.83	10.81	0.338	162.2
14.14	0.00	10.00	0.338	137.4

The amplitude of force are also evaluated by their density under pole pieces as defined by Eq. 6 and shown in Table IV. The dimension of primary magnet is given in Fig. 4. High force density for levitation shows that TFLIM is practically applicable to the conveyance system too.

$$Density = \frac{\text{The levitation force or thrust force}}{\text{The area of core faced its air gap}} [\text{N/m}^2] \quad (6)$$

TABLE IV
Density of Forces

A (A)	*B* (A)	Effective value (A)	Density of thrust force (N/m^2)	The density of levitation force (kN/m^2)
16.33	2.72	11.71	117.2	49.14
15.91	1.77	11.32	115.5	45.88
15.91	3.91	11.59	111.5	48.25
14.14	5.83	10.81	88.02	42.23
14.14	0.00	10.00	88.02	35.78

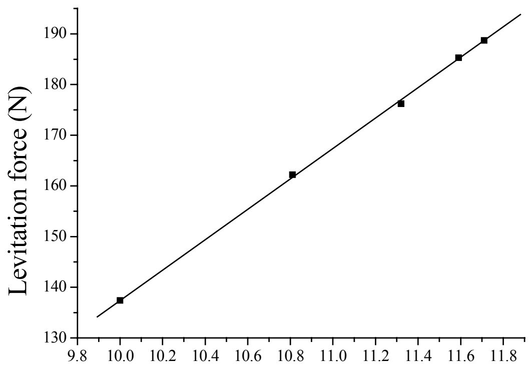

Fig. 11 Levitation Forces vs. Effective value of Currents

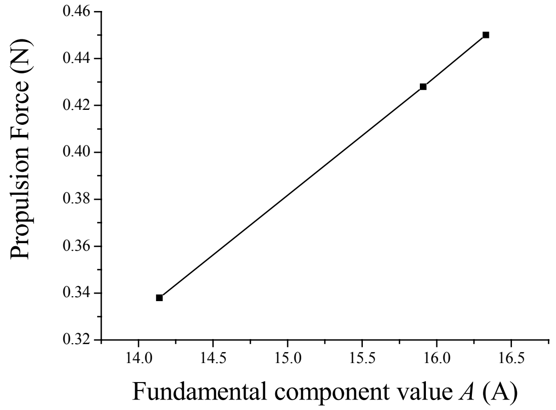

Fig. 12 Propulsion Forces vs. Fundamental Component value of Currents

7 Conclusion

It is clarified that the injection of the third harmonic ingredient into the primary current of TFLIM does not effect its propulsive force and only increases the amplitude of the levitation force. It is possible to regulate two forces independently of each other. Therefore, levitation and thrust forces can be controlled independently for an actuator of non-contacting conveyance system using TFLIM with third order harmonic current. And this method is very beneficial for the combined principle of levitation and thrust, because only TFLIM can be used for controlling thrust and levitation forces.

Moreover, by appropriate injection of the third harmonic ingredient into the primary current, the propulsive force and the levitation force of TFLIM can be increased nearly 30% respectively more than the sine wave excitation with the same maximum value of current. Hence, it is serve the purpose of using the capacity of the inverter for its control to the maximum.

Because the steel plate is thick and the conveyance speed is about 1 m/s in the practical system, large amplitude of the levitation force is needed more than the thrust force in the non-contacting steel plate conveyance system. For the realization of levitating conveyance system, improvement of the levitation performances is very important.

With the harmonics injection scheme, TFLIM with the combined lift and thrust principle is considered as a promising mean to realize a compact transfer unit for the steel plate in the non-contacting conveyance system.

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