Position Feedback Control of Permanent Magnet Type Tubular Linear Synchronous Motor for Vertical Transportation

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Abstract

A tubular linear synchronous motor with permanent magnets in a mover is studied as a hardware of the distribution network system. Conventional elevator system, which is driven with cables, is not suitable for long distance vertical transportation because of the weight of cables and their mechanical oscillations. The proposed system, which is able to drive without cables, can overcome the above-mentioned difficulty. Stable drive without position feedback has been realized with an experimental machine in a preceding study. It was, however, weak against disturbance. This paper proposes a method, which makes it possible to accelerate or decelerate arbitrarily and to guarantee stability against disturbance by using position feedback signal.

Key words: linear synchronous motor, position control, permanent magnet, vertical transport.

1 Introduction

Research and development of a “cableless” elevator system that does not have cables are required, and a permanent magnet type tubular linear synchronous motor has been applied [1]. The merits of this system are as follows:

- It is easy to manufacture owing to its symmetrical structure,
- it is easy to construct because this system consists of many units, and
- tubular coil produces large thrust per unit volume, in general.

We have already designed an experimental machine analytically, we realized smooth and stable drive without position feedback. But driving at high speed caused step out phenomenon in an experiment. It had no tolerance to disturbance and could not realize arbitrary acceleration and deceleration. The next step is to realize arbitrary acceleration and deceleration, and to control position of the mover with high accuracy.

In this paper, physical structure of the system will be described at first. The control scheme of the mover position will be explained. Finally, simulation results are shown after discussing exciting current waveform and stability of suspension.

2 Structure of Tubular LSM

The structure of a tubular vertical LSM is illustrated in Fig. 1. The stator coils are intermittently disposed in the vertical direction. This study premises three-phase alternating non-sinusoidal drive, since one cannot obtain constant thrust when an ordinary three-phase alternating sinusoidal current is applied to the armature. One unit of armature coils consists of 3 coils. The experimental machine dealt in this study has 3 units, i.e., 9 coils. Between each unit, same phase armature coils are series-connected.

The mover has two permanent magnets and they are magnetized in the inverse direction each other. Permanent magnets in the mover are approximately modeled as a single loop of current for simplifying the analysis. The
mover is mechanically guided because of lack of horizontal stability. In this paper, a halfway point between two magnets is defined as the position of the mover.

The unit concerned with the mover and its upper and lower ones are taken into consideration, whereas other units are neglected in the calculation. The length of one period is equal to 3 coil pitches, but the study of one coil pitch is enough for the symmetric structure.

3 Position Control

3.1 Control Method

Fig. 2 shows the block diagram of position feedback control with current controller. I-PD control is adopted for position controller, and I-P control for current controller.

Transfer characteristic from reference thrust, $F_{\text{ref}}$, to reference current, $I_{\text{ref}}$, is non-linear, and that from real current, $I_{\text{rea}}$, to generated thrust, $F_{\text{rea}}$, is also non-linear. The relation between former and latter ones can approximately be taken as inverse transformation, when the time delay of current control is small enough. Then, the whole system can be regarded as 3-order plant based on the approximated 1-order controlled current source. This approximation will contribute to setting parameter values of controller with ease.

Lookup table shown in Fig. 1 holds the data of armature current value of each phase needed to generate 1 N at each mover position. By referring the mover position, armature current value of each phase needed at that time is obtained, and its multiplication with the required thrust gives the armature current value of each phase needed at that time.

3.2 Exciting Current Waveform

Exciting current of each phase to generate 1 N thrust at each position of the mover is not unique. From the viewpoint of running cost and generation of heat, we determined waveforms of armature currents by minimizing energy consumption.

Fig. 3 shows the calculated result of minimization by sequential quadratic programming-NLPQL [2]. The value of resistance of each phase is set to 0.096 $\Omega$ when calculating. When each phase has a DC power supply individually, this waveform is optimal. If a three-phase inverter is used, however, as the power supply, this pattern is of no use because the summation of current of each phase is needed to be zero. Fig. 4 shows the result of minimization under the constraint that the summation of the total current is always zero.

The excitation pattern made here is held in aforesaid

![Fig. 2. Block diagram of position feedback control with current controller.](image1)

![Fig. 3. Optimal current waveform without constraint of summation of each phase.](image2)
lookup table.

### 3.3 Stability ofSuspension

The current waveforms described in the foregoing section can generate required thrust at each position of the mover, however, the stability in practice is not guaranteed. Fig. 5 and Fig. 6 show the contour lines of positive area of the effective thrust margin obtained by subtracting the thrust required to support mover’s own weight, i.e., 6.9 kgf from the real thrust when the current waveforms described in the foregoing section are applied to this system.

The circumference, i.e., the coast of the islands, is the equilibrium position. The upper side of the area is the stable suspension area and the lower one is the unstable area. The diagonal straight line is the suspension-goal line. The figures show that the both exciting patterns have both stable and unstable positions. So if you control position of the mover without position feedback, some other current waveforms that make the islands under the diagonal straight line at all target positions should be used. Fig. 7 shows an example of such a waveform, and the contour lines is shown in Fig. 8.

However you can expect that the position feedback control stabilize the suspension at all position. In addition, simple waveform would be easy to handle. Therefore, we have decided to use the waveform like Fig. 3 or Fig. 4, which is not taken account of stability of suspension.

### 4 Simulation Results

We tested the effect of proposed method by simulation. All the dimension used in the simulation is given in Fig. 1. The mover’s own weight is set to 0.69 kg, and the residual magnetic flux of each permanent magnet in the mover is set to 1.25 T. The characteristic of power supply is approximately regarded as the first-order delay, and its time constant is set to 0.05 sec. Controller parameters are determined by Kessler standard form [3]. Step disturbance of 1 N, i.e., 14.5% of mover’s own weight, is given at t=5.5 sec. The waveform shown in Fig. 4 is used as exciting current waveform.
The result in Fig. 9 tells us that position of the mover is well following target position. Fig. 10 shows the response of the armature voltage and speed electromotive force. The speed electromotive force can be ignored in the speed range of experimental machine dealt in this paper. But when driving speed is high enough not able to ignore the effect of speed electromotive force, feedforward compensation to power supply would be needed to improve control characteristic. It is estimated that maximum speed electromotive force is about 2.5 mV for 0.01 m/s constant speed. In other words, the speed electromotive force will be 1 V, when the speed is 4 m/s.

Fig. 11 shows the experimental bench. We are now trying to verify the efficiency of proposed method experimentally. Fig. 12 shows the driving circuit of experimental bench.

5 Conclusions

A tubular linear synchronous motor with permanent magnets in a mover has been studied to realize long distance vertical transportation. A method to control position of the mover has been proposed, and the performance of the feedback control has been verified in this paper.

I-PD control has been applied to position control, and I-P control to the current control. To avoid the difficulty in determining controller parameters derived from non-linear transfer characteristic, the whole system has been approximately regarded as 3-order plant. We have decided to apply the waveform which does not include the open-loop stability of suspension to current waveform.

References