Sensorless Control System of Superconducting Maglev

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Abstract

In this paper, we propose both driving and lateral sensorless control system using the Electromotive Force (EMF). The main purpose of these controls is reduction of the construction cost and running cost.

With driving sensorless control, we can omit the cross-inductive radio system that we have to lay along the guideway accurately. The principal of the driving control system using the EMF and the experimental results at the speed of 0km/h to 400km/h in the Yamanashi Maglev Test Line are reported in this paper. The new method of estimating the initial phase at the stopping point that can't be estimated from EMF is proposed too.

With lateral sensorless control, we can reduce the running cost. Lateral control enhances the lateral guidance forces and the lateral dumping forces. Enhancing the lateral guidance forces allows the Maglev train to land stably at the low speed. With this effect we can reduce the running cost of the tier. Enhancing the lateral dumping forces improves the riding comfort. The concept of the lateral control with the deviation of both side EMF and the results of the running test are reported.

1. Introduction

In the Yamanashi Maglev Test Line, the location of the train is detected with the inductive radio system. The inductive radio system is very reliable and accurate. On the other hand the cost of construction and maintenance of the inductive radio system is very expensive, because we have to lay the cross inductive cable along the guideway accurately and set up the detecting system of train's location in each power conversion station.

In this paper, we propose both driving and lateral sensorless control system using the Electromotive Force (EMF) in order to reduce the construction cost and running cost. With these control systems, Inductive radio system can be omitted.

First, we propose the driving control system using the EMF. We have already proposed a new detecting system of train's location using the Electromotive Force (EMF) [1]. In this system, phase can be estimated from EMF, and then speed and location of the train can be detected from the phase. The principal of the driving control system using the EMF and the experimental results in the Yamanashi Maglev Test Line are reported.

Second, we propose the new method of estimating the initial phase at the stopping point. Needless to say, EMF is not generated at the stopping point, therefore some other method to estimate the initial phase is needed. The new method of estimating the initial phase at the stopping point and the experimental results are reported.

Third, we propose a new lateral control system using the deviation of both sides EMF. If the train moves to the right side propulsion coil, EMF of the right side propulsion coil increases and that of the left side decreases. Therefore deviation of the lateral direction can be estimated from the deviation of the both side EMF. The purpose of this control is enhancing the lateral guidance forces and the lateral dumping forces. Enhancing the lateral guidance forces allows the Maglev train to land stably at the low speed. With this effect we can reduce the running cost of the tier. Enhancing the lateral dumping forces improves the riding comfort. The concept of the lateral control and the results of the running test are reported.

2. Driving control with EMF

2.1 Driving control system with EMF

Fig.1 shows the block diagram of EMF observer control system.

In the velocity control part, in order to follow the velocity reference V*, the current reference I* is calculated at Y(s) that consists of the PI controller.

In the phase synchronous control part, the input phase θ estimated by the EMF observer is taken into G(s) at interval of 5ms. G(s) is a compensation computing part using PLL that can follow the changes of speed and acceleration.

In the current control part, the deflection of current reference I* and current I is indemnified and the inverter output-voltage V* is calculated. The EMF is observed with EMF observer and compensates the output-voltage V*.

The EMF phase is computed as below. The deviation $\Delta\theta$ is calculated from d-q axis EMF ($\Delta\theta = \tan^{-1}(Zq/Zd)$), then the EMF phase θ can be get from adding $\Delta\theta$ to the base phase θ^*.

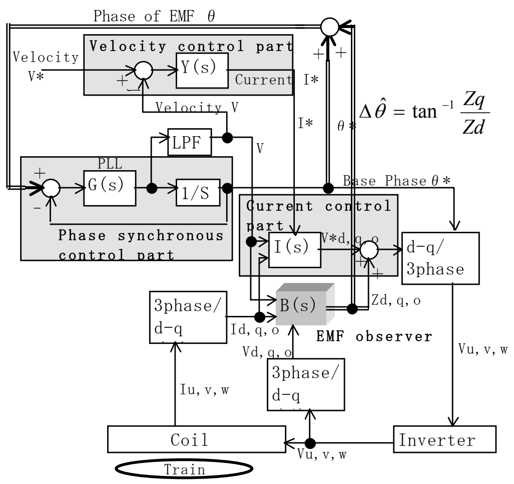

Fig.1 The block diagram of EMF observer control system

2.2 The result of the running test with EMF

From the result of the running tests, EMF phase can be estimated accurately. The d-axis current is controlled according to the reference current of inverter and the q-axis current is controlled to 0[A]. We confirm that the driving control with EMF has good characteristic.

3. The new method of estimating initial phase of the starting point

In this section, we propose the new method of estimating initial phase of the starting point. Needless to say, the phase of EMF cannot be estimated at 0 speed. Therefore we have to employ the new method of estimating initial phase as below.

First we send electric current of the constant frequency into the propulsion coil at which the train stops. Then the thrust synchronized in the frequency of electric current occurs in the superconductivity coil (SCM) on the train, and the initial position phase can be estimated by measuring this thrust change. Now θ is expressed phase of current, ϕ is expressed phase of stopping position and then the thrust is in proportion to $I \times \cos(\theta - \phi)$. The maximum SCM thrust is equivalent to the phase ϕ of the stopping position(Fig.2).

From the experimental result, we can estimate the initial phase within the deviation of 30deg.

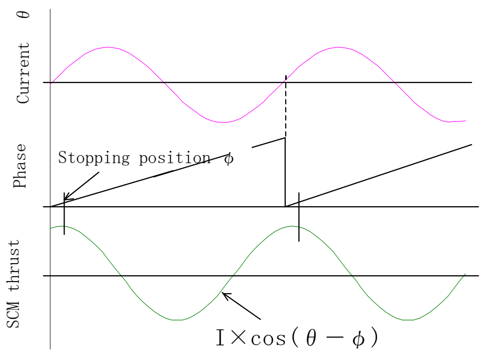

Fig.2 The new method of estimating initial phase

4. Lateral control with EMF

In this section, we propose the lateral control system with EMF. The purpose of this control is enhancing the lateral guidance forces and the lateral dumping forces. Enhancing the lateral guidance forces allows the Maglev train to levitate and land stably at the low speed. With this effect we can reduce the running cost of the tier. Enhancing the lateral dumping forces improves the riding comfort.

4.1 Principle of the estimating lateral displacement with EMF

Fig.3 shows the concept figure of the lateral control with EMF. If the vehicle moves to the right, the EMF of the right side increases and that of the left side decreases. EMF is inverse proportion to distance between SCM and propulsion coil (equ (1)). Therefore lateral displacement ΔY can be led is as the following(equ(2)).

$$1/Y0^2 : 1/(Y0+\Delta Y)^2 = V0 : (V0+\Delta V) \cdots (1)$$

$$\Delta Y = \sqrt{V0/(V0+\Delta V)} \times Y0 - Y0 \cdots\cdots (2)$$

ΔV: deviation of the both side EMF

ΔY: lateral displacement

V0: theoretical value of EMF according to the speed

Y0: length between center of the guideway and propulsion coil

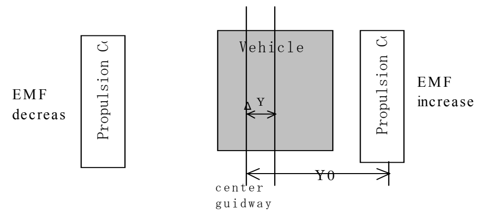

Fig.3 The concept figure of the lateral control with EMF

4.2 Principle of the lateral control with EMF

The method of controlling lateral displacement is as the following. The equation of lateral motion of the vehicle is led equ (3).

$$M(dy/dt)^2 + D \cdot y = Fy \cdots\cdots (3)$$

M: weight of the vehicle Y: lateral displacement

D: lateral guidance coefficient

Fy: lateral electromagnetic force by the lateral current

The change of the lateral guidance force coefficient according to levitation height and lateral displacement is ignored, and then lateral electromagnetic force is simplified in the equ (4).

$$Fy = K_0 \cdot Iq \cdots\cdots (4)$$

K_0: lateral electromagnetic force coefficient

Iq: lateral current

In order to stabilize the lateral motion and improve the riding comfort, both lateral displacement Y and lateral velocity dY/dt are feedbacked to lateral current Iq. The equation of lateral current Iq is as follow.

$$Iq = -f1 \cdot y - f2 \cdot dy/dt \cdots\cdots (5)$$

Lateral guidance coefficient is enhanced by the feedback of lateral displacement Y and lateral dumping coefficient is enhanced by the feedback of lateral velocity dY/dt. Fig.4 shows the block diagram of vehicle guidance regulator led by equation (3)～(5).

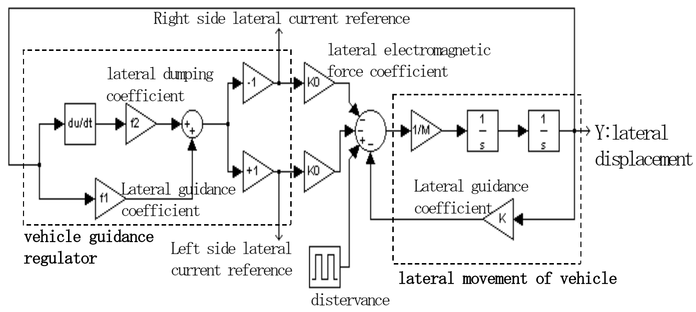

Fig.4 Block diagram of vehicle guidance regulator

4.3 Simulation result of the lateral control

Fig.5 shows the simulation result of the lateral movement of vehicle when the vehicle receives the lateral disturbance for 10s. With lateral control maximum lateral displacements are suppressed and settling time is short compared to without lateral control. In this simulation EMF contains random noise. We confirm that the lateral control is efficient for suppressing lateral movement.

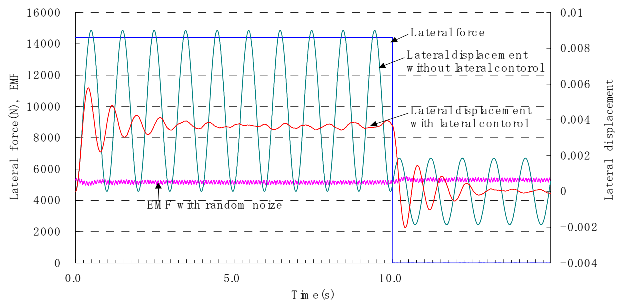

Fig.5 Simulation result of lateral control

4.4 Precision of the lateral displacement estimated with EMF

In the lateral control with EMF, lateral control characteristic depends on the precision of the lateral displacement estimated with EMF. When the 200A lateral current is flowed, the actual vehicle moves by 10mm in 400ms and the lateral displacement estimated with EMF shows approximately similar movement. From this result, lateral displacement estimated with EMF can be used in lateral control.

4.5 Improvement of the riding comfort by lateral control with EMF

The lateral guidance forces and the lateral dumping forces are enhanced by lateral control with EMF, therefore the riding comfort can be improved. We tested the improvement effect of the riding comfort when applying the lateral control with EMF at the curve section. The riding comfort level is improved when applying the lateral control.

5. Conclusions

In this paper we propose both driving and lateral sensorless control system with EMF.

Related to the driving sensorless control system, EMF phase can be estimated accurately and initial phase of the starting point can be estimated within the deviation of 30deg. The performance of the driving sensorless control with EMF is good and reliability of this control is very high, therefore this control system will be employed for commercial control system.

Related to the lateral sensorless control system, the lateral displacement can be estimated with EMF accurately. Therefore the performance of the lateral sensorless control with EMF is good and the riding comfort can be improved by enhancing the lateral dumping forces.

These driving and lateral sensorless control systems with EMF require no special facilities. In order to reduce the construction cost and enhance the riding comfort for the Maglev, these control systems will be very effective for commercial control system.

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References

[1] Koga, Shunsaku et al., “Self Control System of Superconducting Maglev Synchronized with the Phase of Electromotive Force,” Trans. IEE of Japan, Vol. 119-D, No. 6, June