Improvement of the Damping Factor at Low Speed in Electrodynamic Suspension System for the JR Maglev

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Abstract. The electrodynamic suspension system (EDS) is one of the magnetic levitation system and has advantage of stable levitation without the gap control. However, the damping factor of the EDS system is not enough. Once the oscillation of the bogie occurs by the external disturbance, it does not converge immediately. The additional damper system is needed, so the damper coil system is installed. By the semi-active damper system, the levitation stability is improved. This paper discusses about superconducting Maglev system as application of the EDS system. Superconducting Maglev has been the magnetic levitation system developed by Central Japan Railway Company and Railway Technical Research Institute. The operation speed of the train is $v = 120[\text{m/sec}]$. At low speed range such as $v = 60-80[\text{m/sec}]$, the damping factor is smaller than that of the normal operation $v = 120[\text{m/sec}]$, and it is difficult to keep the stable levitation. In this paper, running simulation when the bogie passes large displacement at low speed is undertaken, and the improved switching method for the semi-active damper system at low speed and large displacement is discussed. From the results, to increase the period that the damper coil works. The damping factor becomes larger, and the bogie keeps the levitation.

1. Introduction

Electrodynamic suspension system (EDS) is used for levitation and guidance of the high speed magnetically levitation system [1]. The principle of the EDS system is electromagnetic induction, and this system has the advantage of stable levitation without gap control. However, results of numerical simulations show that the damping factor of the EDS system is small. Once the vertical oscillation of the bogie occurs by the external disturbance, it does not converge immediately [2]. Thus, the additional damper system is needed. To increase the damping factor of the EDS system against the oscillation of the bogie, the damper coil system is installed. And, the semi-active damper system improves the levitation stability [3]. As the typical application of the EDS system, superconducting Maglev system developed by Central Japan Railway Company and Railway Technical Research Institute is studied [2][4]. We propose the damper coil system for the superconducting Maglev system to increase the stability for the levitation and guidance.

The average operation of the train is $v = 120[\text{m/sec}]$. At low speed range such as $v = 60-80[\text{m/sec}]$, the damping factor becomes smaller, and the oscillation of the bogie becomes larger than that of $v = 120[\text{m/sec}]$ because the influence of the levitation coil resistance becomes large. It is difficult to keep the stable levitation. Although the bogie does not run at low speed range stationary, it is important to research the levitation stability. In this paper, running simulation of the bogie at low speed and large
2. Analysis method

2.1. EDS system and the damper coil

Figure 1 shows the EDS system of superconducting Maglev, and Table 1 shows specifications of the superconducting Maglev system [5][6]. In superconducting Maglev, the oscillation of the cabin is decreased by air springs and dampers between the cabin and the bogie. But, the damping factor by the EDS system itself is not large. By improving the damping factor of the EDS system, the improvement of the oscillation of the bogie is discussed.

The Linear Synchronous Motor (LSM) is used for propulsion of the bogie and EDS system is used for levitation and guidance. Combined these two systems, it is possible to levitate the bogie for 100[mm] and move to the running direction at \( v = 150[\text{m/sec}] \) [4]. The levitation force is generated by the Superconducting coil (SC coil) attached to the bogie. The eight-figure null-flux connection is used for the levitation coil on the ground. When the bogie passes the front of the levitation coil, the levitation force is generated [7].

![Figure 1. The EDS system of superconducting Maglev](image)

Table 1. Specifications of the superconducting Maglev system

|                         |                         |                         |                         |                         |
|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| **Bogie**               | **Superconducting coil**| **Levitation coil**     |                         |                         |
| Mass                    | Electromotive force     | Height                  | Height                  | Height                  |
|                         |                         | 2.00 \( \times 10^4 \) [kg] | 700 [kA]                | 0.34 [m]                |
| Height                  |                         | 0.90[m]                 | 0.50 [m]                | 0.35 [m]                |
| Width                   |                         | 5.40[m]                 | 0.963 [m]               | 0.35 [m]                |
| Depth                   |                         | 2.98[m]                 | 1.35 [m]                | 0.45 [m]                |
The current induced in the levitation coils is calculated. The EDS system has an air-coil system and modelled as electric circuits. The mutual inductance between the SC coils and levitation coils is calculated by from the position of these coils. And the electric circuit equations are given, and it is solved by the numerical analysis. The electromagnetic forces are calculated by the virtual displacement method. The motion of the bogie is calculated from the motion equations. By putting these electromagnetic forces into the motion equations, the transient motion of the bogie is given. Runge-Kutta method is used to solve these differential equations [8].

Figure 2 and 3 show the configuration of the damper coil and position and shape of the damper coil. Table 2 shows the specification of the damper coil. The damper coil is set in front of the SC coil of the bogie [8]. The damper coil current is induced by the levitation coil of the guideway, and the damping force is generated against the transition of the levitation force. In superconducting Maglev, the eddy current is generated in the magnetic shield of the bogie and affects the oscillation of the bogie. But in this paper, to improve the damping factor of EDS system, the eddy current is not considered.

Table 2. Specification of the damper coil

| Parameter          | Value         |
|--------------------|---------------|
| Mass               | 10.31 [kg]    |
| Turn               | 2 [turn]      |
| Resistivity        | $2.655 \times 10^{-8}$ [Ω·m] |
| Upper coil position| 0.28 [m]      |
| Lower coil position| -0.13 [m]     |
| Distance from SC coil | 0.085 [m]  |
| Pitch              | 1.35 [m]      |

2.2. Semi-active damper system

The damper coil current is delayed by its self-inductance against the oscillation of the bogie. Thus, there are the periods that the damper coil increases the oscillation of the bogie. To solve this problem, the semi-active damper system is introduced. The damper coils are switched according to the oscillation velocity of the bogie and the magnetic force generated by the damper coils [6].

Table 3 shows the switching method of the semi-active damper system. $P_{zld}$ and $P_{pld}$ is power of the vertical motion and the pitching motion. When the switch is ON, the damper coils are short circuited, and OFF, resistances $R_s = 0.06$[Ω] are inserted to the circuits. The power of vertical motion is defined as eq(1). $F_{zld}$ is vertical force, and $v_z$ is vertical velocity.

$$P_{zld} = F_{zld} \cdot v_z$$ (1)

Also, the power of pitching motion is defined as eq(2). $T_{pld}$ is pitching torque, and $\omega_p$ is pitching angular.
\[ P_{pld} = T_{pld} \cdot \omega_p \]  \hspace{1cm} (2)

**Table 3.** Switching method

| Condition       | Switch |
|-----------------|--------|
| \( P_{zld} + P_{pld} > 0 \) | OFF    |
| \( P_{zld} + P_{pld} < 0 \) | ON     |

3. Results

Running simulation of the bogie is undertaken when the bogie passes the displacement of the guideway. When the bogie passes the vertical displacement, vertical and pitching oscillation occurs. Figure 4 shows analysis model with vertical displacement of the guideway. The bogie moves at \( v = 60 \) or \( 80 \) [m/sec] and passes the displacement \( z_{step} = 0.07 \) [m] at the time \( t = 0.6 \) [sec].

![Analysis model with vertical displacement of the guideway](image)

**Figure 4.** Analysis model with vertical displacement of the guideway

Figure 5 shows the vertical oscillation and the pitching oscillation without the damper coil at \( v = 60 \) [m/sec]. From Figure 5, the vertical oscillation without the damper coil at low speed does not converge because the damping factor in this case is small. The oscillation at \( v = 60 \) [m/sec] becomes larger than that at \( v = 80 \) [m/sec]. The bogie does not keep the levitation at \( v = 60 \) [m/sec] within 10 [sec]. The pitching oscillation also does not converge. At \( v = 60 \) [m/sec], the oscillation becomes large so much around \( t = 4.0 \) [sec]. The oscillation at \( v = 80 \) [m/sec] also does not become smaller, and the levitation is unstable.

![Running simulation without damper coils](image)

**Figure 5.** Running simulation without damper coils
Figure 6 shows the vertical oscillation and the pitching oscillation with the semi-active damper system. The vertical oscillation at $v = 60$ or $80$[m/sec] becomes smaller. The oscillation at $v = 80$[m/sec] converges. However, the pitching oscillation at $v = 60$[m/sec] becomes large around $t = 6.0$[sec], and the bogie does not keep the levitation. The vertical displacement $z_{\text{step}} = 0.07$[m] is as twice large as the initial position. So, the damping force becomes unstable in this case. Especially, at $v = 60$[m/sec], the amplitude of the oscillation becomes large. Therefore, the bogie does not keep the levitation.

Figure 7 shows the transition of the switching at $v = 60$ or $80$[m/sec] and $z_{\text{step}} = 0.07$[m]. The count of switching at $v = 60$[m/sec] is more than that at $v = 80$[m/sec]. So, at $v = 60$[m/sec], the periods that the switch is ON is shorter than at $v = 80$[m/sec]. To increase the damping factor, the semi-active damper system is installed. However, the damping factor at low speed is still not enough. Therefore, the bogie does not keep the stable levitation at $v = 60$[m/sec].

At low speed and large displacement, the bogie does not keep the stable levitation because the period of switch ON is short. To increases the damping factor, the switching method is improved. Table 4 and 5 show the switching method to extend switch ON period and the comparison of switching method.

From Table 3, with the conventional switching, when the sum of the power of the vertical motion and the pitching motion is positive, the switch is turned OFF, and when the sum is negative, the switch is turned ON. To extend the period that the damper coil works, the period of switch ON is extended.
about 20%. When both the power of vertical motion and the pitching motion is positive, the switch is turned OFF. Otherwise, the switch is turned ON.

**Table 4.** Switching method to extend switch ON period

| Condition            | Switch |
|----------------------|--------|
| $P_{zd} > 0$ and $P_{pl} > 0$ | OFF    |
| Else                 | ON     |

**Table 5.** The comparison of switching method

| $P_{zd}$ | $P_{pl}$ | Condition       | Conventional | Extend ON |
|----------|----------|-----------------|--------------|----------|
| +        | +        | All times       | OFF          | OFF      |
| +        | -        | $|P_{zd}| > |P_{pl}|$ | OFF          | ON       |
| -        | +        | $|P_{zd}| < |P_{pl}|$ | ON           | ON       |
| -        | -        | All times       | ON           | ON       |

Figure 8 and 9 show the vertical oscillation and the pitching oscillation, and the transition of the switching with the switching extended switched ON period. From Figure 8, the maximum amplitude of the oscillation with extended Switch ON period is a little smaller than that with conventional switching. Although the oscillation becomes small slowly, the bogie keeps the levitation. The pitching oscillation is like that with conventional switching until $t = 5.0[sec]$. However, $t > 5.0[sec]$, although the oscillation becomes large, it is not larger than that with conventional switching.

From Figure 9, the switching extended switched ON period is 21.2% lesser than that of conventional switching. Therefore, by improving the control method of the semi-active damper system, the levitation stability is improved.

**Figure 8.** Running simulation with switching extended switched ON period
To research the reason to keep the levitation with this switching, the difference of the damper coil displacement is discussed. Figure 10 shows the number of the damper coil. From the vertical oscillation and the pitching oscillation, the front damper coil displacement ($p = 1$) and the rear damper coil displacement ($p = 4$) are studied.

Figure 11 shows the damper coil displacement with extended switch ON period. The oscillation of the front damper coil displacement with extended switch ON period is not so large like that with conventional switching. The oscillation of the rear damper coil displacement is so large around $t = 3.0$[sec]. At $t > 3.0$[sec], the oscillation becomes large again. However, it is still smaller than that with conventional switching. So, by improving the switching method, the oscillation of the damper coil displacement becomes smaller.
Figure 12 and 13 show the damping force and the damper coil current with extended switched ON period.

The damping force with extended switched ON period is smaller than that with conventional switching overall. In particular, around $t = 6.0$[sec], the oscillation of the damping factor with extended switched ON period is not amplified more than that with conventional switching. So, the levitation becomes stable. From Figure 13, the damper coil current is similar to that with conventional switching. The oscillation of the bogie is not amplified so much. The damper coil current in this case does not increase.

From these results, by extending the period of switch ON, the damping factor is increased. The levitation of the bogie becomes stable.

4. Conclusion
In this paper, to increase the damping factor at low speed and large displacement, the improved switching method is undertaken. Without the damper coil, the vertical oscillation and the pitching oscillation do not converge because the damping factor of the EDS system is small. With semi-active damper system, the bogie does not keep the levitation. In this case, the periods of the switch ON of the damper coil is short. Therefore, the oscillation of the bogie becomes large, and the levitation still becomes unstable.

To increase the damping factor, the improved switching method is discussed. To extend the period that the damper coil works, the period of the switch ON is extended about 20%. By this switching method, the vertical oscillation becomes smaller than that with conventional switching. The pitching oscillation is amplified, but it is not so large. To show the reason, the front and the rear damper coil displacement is discussed. The oscillation of the front damper coil is not so large. The rear damper coil displacement becomes large, but it is smaller than that with conventional switching. And, the damping force and damper coil current are smaller than that with conventional switching. From these results, by extending the period of switch ON, the damping factor is increased. The levitation stability of the bogie becomes better than with conventional switching.
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