PERFORMANCE ANALYSIS OF THE COMBINED EDS MAGLEV
PROPULSION, LEVITATION, AND GUIDANCE SYSTEM

by

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ABSTRACT

An analysis of the Japanese maglev system which uses only one set of coils in the guideway for combined levitation, propulsion, and guidance functions is presented in this paper. This preliminary study, using the dynamic circuit approach, indicates that the system is very promising.

INTRODUCTION

The updated Japanese electrodynamic suspension (EDS) maglev system invented by Fujiiwara et al. (1-3) uses a combined propulsion and null-flux suspension concept in which two rows of figure-eight-shaped null-flux coils mounted on the side walls of the guideway are cross-connected. These coils interact with null-flux coils on the guideway to generate propulsion, null-flux levitation, and null-flux guidance forces. The concept has many potential advantages over existing EDS maglev systems. In particular, it requires only one set of guideway coils to perform the three functions. This concept may greatly reduce guideway costs.

To date, insufficient attention has been given to the system to determine if it really works and has good performance. In this paper, the dynamic circuit approach is used to investigate the system and predict its performance. The use of the dynamic circuit theory in combination with numerical analysis to deal with the null-flux EDS maglev system was discussed in previous papers (4-6). This paper emphasizes the combined performance of propulsion, levitation, and guidance and studies the coupling effects among the three functions. Simple closed-form formulas of the magnetic forces are obtained in the paper on the basis of a harmonic approximation. To prove the concept and obtain physical insight, only four equation are considered. However, to ensure that the analysis is accurate, a numerical approach is also applied to the lateral and vertical motions. The paper consists of six parts: introduction, the model, propulsion force, levitation force, guidance force, and conclusions.

THE MODEL

To study the combined propulsion, levitation, and guidance system, it is necessary to consider a complete motor section (an energized guideway block). In a long-stator propulsion system, the energized block length is generally longer than that of the vehicle magnet system. One may divide the block length into two sections: one that couples with the magnet system of the vehicle and another that comprises the balance of the block. By letting \( n_b \) be the total number of poles in the block, \( n_p \) be the number of poles that couple with the vehicle magnet system, and \( t \) be the pole pitch of the vehicle magnet system, one can express the length of the energized block and the length of the vehicle magnet system in terms of \( n_b \) and \( n_p \), respectively. In a three-phase systems, each pole interacts with three figure-eight-shaped guideway coils that belong to different phases. Figure 1 is a sketch of the combined propulsion, levitation, and guidance system, in which two rows of figure-eight-shaped coils on opposite sides (only one side is shown) are cross-connected to form a null-flux guidance system, and the coils in the same row are connected in series to form three-phase propulsion windings. Thus, the three functions of propulsion, levitation, and guidance are expected to be achieved with one set of figure-eight-shaped guideway coils.

As discussed in reference (4), a figure-eight-shaped coil interacting with an SCM can be represented by an equivalent circuit having two branches connected in parallel. Each branch has a resistance \( R \), a self-inductance \( L \), and an induced voltage \( E \). At the equilibrium (or null-flux) position, there is no circulating current or magnetic force because the induced voltages in each branch are equal. A circulating current flows through the branches and a null-flux force is generated if a vertical offset between the SCM and the null-flux coil exists. Similarly, two cross-connected figure-eight-shaped coils can be represented by a circuit containing four branches connected in parallel, each of which represents a single loop of the figure-eight-shaped coils (4). Null-flux lift and guidance forces are generated when circulating currents exist. By applying the information provided in reference (4), one can represent one phase of the combined system shown in Fig. 1 by an equivalent circuit, as shown in Fig. 2, where \( R \) and \( L_0 \) are the resistance and the equivalent inductance of a loop of the figure-eight-shaped coil and \( E_i \) is the voltage induced in the loop. The term \( E_i \) is also called the armature voltage or induced voltage. The terms \( n_b \) and \( n_p \) are used to modify the circuit for phase representation. The equivalent circuit consists of two parts: the left part, representing the figure-eight-shaped coils per phase that couple with the magnet system of the vehicle, and the right part, representing the remaining guideway coils per phase that do not couple with the magnet system of the vehicle.
of $I_1$, $I_2$, $I_3$, and $I_4$ is the phase current that produces propulsion force, and the differences between $I_1$ and $I_2$ and between $I_3$ and $I_4$ generate null-flux lift. The null-flux guidance force is generated from the current difference between the sum of $I_1$ and $I_2$ and the sum of $I_3$ and $I_4$.

To determine the currents flowing in each branch, one can use the Thévenin equivalent circuit technique to simplify Fig. 2. Thus, a simple equivalent circuit model for the combined system is formed, as shown in Fig. 3, where $E_{ph}$ and $X_{ph}$ are the resistance and reactance for each equivalent phase and where $E_{ph}$ and $V_{ph}$ are the induced and applied phase voltages, respectively. They are

$$R_{ph} = \frac{1}{4} n_b R,$$  \hspace{1cm} (1)

$$x_{ph} = \frac{1}{4} n_b x_0,$$  \hspace{1cm} (2)

$$E_{ph} = \frac{n_b}{4} (E_1 + E_2 + E_3 + E_4),$$  \hspace{1cm} (3)

where $x_0 = \omega (L + M_{12} - M_{al})$ and $x_0 = \omega (L \cdot M_{12} - M_{ab})$, of which $M_{12}$ is the mutual inductance between the upper and lower loops and $M_{ab}$ is the mutual inductance between the two longitudinal neighboring loops that belong to different phases. It should be noted that $M_{12}$ and $M_{ab}$ are negative because the two loops are in parallel. It is important to note that $E_1$, $E_2$, $E_3$, and $E_4$ are in phase, although their amplitudes may be different because the two cross-connected figure-eight-shaped coils experience the same SCM phase as vehicle moves forward. Thus, one can conclude from Eq. (3) that $E_{ph}$ is in phase with $E_1$, $E_2$, $E_3$, and $E_4$. By assuming the applied voltage $V_{ph}$ as a reference phasor, one can introduce a power angle $\delta$ by which the induced voltage $E_{ph}$ lags $V_{ph}$. Thus, Eq. (3) may be rewritten as

$$E_{ph} = E_{ph} \cdot e^{j \delta} = \frac{n_b}{4} (E_1 + E_2 + E_3 + E_4) \cdot e^{j \delta}.$$  \hspace{1cm} (4)

The root mean square (rms) value of the induced voltage may also be expressed in terms of the mutual inductance between the moving SCM and the loop coil:

$$E_i = \frac{1}{\sqrt{2}} \omega M_{si} \quad i = 1, 4.$$  \hspace{1cm} (5)

The flux linking the figure-eight-shaped coils lags the induced voltage by $90^\circ$. Dividing the flux by the SCM current (which is assumed to be constant), one can express the mutual inductances and their derivatives in phasor notation as:

$$M_{si} = -j M_{sl} e^{j \delta},$$  \hspace{1cm} (6)

$$\frac{d M_{si}}{d \phi} = \beta M_{sl} e^{j \delta},$$  \hspace{1cm} (7)

$$\frac{d M_{si}}{d \phi} = -j M_{sl} e^{j \delta},$$  \hspace{1cm} (8)

$$\frac{d M_{si}}{d \phi} = j M_{sl} e^{j \delta},$$  \hspace{1cm} (9)

where $\beta = \frac{\pi}{2}$ and $M_{sl} (i = 1, 4)$ are functions of $\phi$ and $\delta$, depending upon vertical and lateral motions, as shown in Fig. 4.

The currents flowing in each branch of the circuit are then determined from Figs. 3 and 4 as follows:

$$I_{ph} = \frac{V_{ph} - E_{ph}}{R_{ph} + j x_{ph}},$$  \hspace{1cm} (10)

$$I_1 = \frac{I_{ph}}{4} \left( (E_3 + E_4) \cdot (E_2 - E_1) + E_1 \cdot E_2 \right) + \frac{E_2 \cdot E_1}{2(R + j x_0)},$$  \hspace{1cm} (11)

$$I_2 = \frac{I_{ph}}{4} \left( (E_3 + E_4) \cdot (E_2 - E_1) + E_2 \cdot E_1 \right) + \frac{E_2 \cdot E_1}{2(R + j x_0)},$$  \hspace{1cm} (12)

$$I_3 = \frac{I_{ph}}{4} \left( (E_3 + E_4) \cdot (E_2 - E_1) + E_2 \cdot E_1 \right) + \frac{E_2 \cdot E_1}{2(R + j x_0)},$$  \hspace{1cm} (13)

$$I_4 = \frac{I_{ph}}{4} \left( (E_3 + E_4) \cdot (E_2 - E_1) + E_2 \cdot E_1 \right) + \frac{E_2 \cdot E_1}{2(R + j x_0)}.$$  \hspace{1cm} (14)

Equations (11) to (14) show that each current contains three terms: the first term associated with the applied voltage, the second term dealing with the lateral motion, and the third term due to vertical motion. Subtracting Eq. (12) from Eq. (11) and Eq. (14) from Eq. (13), one obtains the currents circulating in the figure-eight-shaped coils as:

$$I_1 - I_2 = \frac{E_2 \cdot E_1}{(R + j x_0)}.$$  \hspace{1cm} (15)

$$I_3 - I_4 = \frac{E_2 \cdot E_1}{(R + j x_0)}.$$  \hspace{1cm} (16)

These internal circulating currents depend upon the vertical displacement to produce null-flux lift, and they are basically...
not affected by the propulsion and guidance currents. By adding Eqs. (11) to (14), one obtains the propulsion current, \( I_{ph} \), resulting from the applied voltage. This implies that the propulsion force is not affected by the levitation and guidance currents. Similarly, one can also show that the null-flux guidance current is independent of the propulsion and levitation currents:

\[
(I_1 + I_2) - (I_3 + I_4) = \frac{(E_3 + E_4) - (E_2 + E_1)}{2(R + j\omega) + X_{ph}}.
\]  

(17)

The lateral displacement generates the voltage difference between the figure-eight-shaped coils on the two sides and produces the null-flux guidance force. It can be concluded from the above relations that the propulsion, levitation, and guidance currents of the combined system are independent. However, it will be shown that small force couplings do exist among the three functions and they do not follow the null-flux principle.

### THE PROPULSION FORCE

The propulsion force can be readily determined from the equivalent circuit shown in Figs. 2 and 3. The total complex power, \( S \), delivered to the combined system is

\[
S = P + jQ = V_{ph}I_{ph}^*.
\]  

(18)

where the real power is

\[
P = 3Re[V_{ph}I_{ph}^*] = 3 \left( V_{ph}^2 - E_{ph}E_{ph}\cos\delta \right) + x_{ph}E_{ph}\sin\delta
\]

(19)

and the reactive power is

\[
Q = 3Im[V_{ph}I_{ph}^*] = 3 \left( V_{ph}^2 - E_{ph}E_{ph}\cos\delta \right) - x_{ph}E_{ph}\sin\delta
\]

(20)

The power factor of the combined system can be determined from Eqs. (19) and (20). Because the resistance of the system is much smaller than the reactance, it is a good approximation to neglect the resistance \( R \). Thus, the real power absorbed from the electric power system is also the power delivered to the load. The converted mechanical power can then be obtained from Eq. (19):

\[
P = Re \left( E_{ph}I_{ph}^* \right) = 3 \left( \frac{E_{1} + E_{2} + E_{3} + E_{4}}{\sin\delta} \right) x_c.
\]  

(21)

Equation (21) shows that the propulsion power of the combined system is given by the sum of the four individual linear motors, which have the induced voltages of \( E_1 \), \( E_2 \), \( E_3 \), and \( E_4 \), respectively. The propulsion power is independent of internal circulating currents that generate null-flux levitation and guidance forces. Finally, the propulsion force is obtained in terms of the mutual inductances from Eqs. (5) and (21)

\[
F_p = \frac{P}{V} = \frac{3 \left( M_{31} + M_{32} + M_{33} + M_{34} \right)}{v} \frac{V_{ph}I_{ph}^*}{\sin\delta}
\]

(22)

The simple relation shown in Eq. (22) relates the propulsion force of the combined system to the system parameters. It is important to note from Eq. (22) that for a given vehicle speed \( v \), the propulsion force depends upon several major factors—namely, the length of the vehicle magnet system to the length of the energized block, the sum of the coupling coefficients between vehicle magnets and the guideway coils, the applied voltage, and the current flowing in the superconducting coils.

Figures 5 and 6 show the dependence of the coupling coefficients on the vertical and lateral displacement, respectively. The sum of the four coupling coefficients is rather insensitive to the lateral and vertical motions of the vehicle. (It is about 1.4% for the system given in Table 1.) Maximum thrust is obtained at a load angle of 90°. By assuming a vehicle speed of 500 km/h (139 m/s), a magnet current of 700 kA, and a load angle of 30°, one obtains the following relation:

\[
F_p = 75 \frac{V_{ph}}{V_{nb}} = 75 \frac{V_{ph}}{V_{nb}} n_{m/nb}
\]

If one assumes a required propulsion force of 200 kN, the required phase voltage is 2.7 kV for \( n_{m/nb} = 1 \), 5.3 kV for \( n_{m/nb} = 0.5 \), and 10.7 kV for \( n_{m/nb} = 0.25 \). This implies that the energized block length should be selected around 100 m for a vehicle having 20- to 30-m-long magnet system in order to keep the applied phase voltage within 10 kV.

### THE LEVITATION FORCE

The levitation forces, \( F_L \), are obtained from Eqs. (1) to (14) as

\[
F_L = 3n_{m/nb}L \left( \sum_{i=1}^{4} \frac{\partial M_{bi}}{\partial z} \right) = F_{LL} + F_{LP} + F_{LG}.
\]  

(23)

The force consists of three components: \( F_{LL} \), resulting from the vertical offset and following the null-flux principle; \( F_{LP} \), resulting from the applied voltage; and \( F_{LG} \), resulting from the...
lateral displacement. The term $F_{LL}$, in terms of mutual inductances and their derivatives, is given by

$$F_{LL} = \frac{3}{2\sqrt{2}} n_m^2 \frac{V_{ph}\cos \delta - E_{ph}}{4x_{ph}} \left[ \frac{\partial M_{s1}}{\partial z} + \frac{\partial M_{s2}}{\partial z} + \frac{\partial M_{s3}}{\partial z} + \frac{\partial M_{s4}}{\partial z} \right]$$

(24)

For a vertical offset of $z \in (0, M_{s2} > M_{s1}, M_{s4} > M_{s3}$, the derivatives of $M_{s1}$ and $M_{s3}$ are positive and those of $M_{s2}$ and $M_{s4}$ are negative, but their amplitudes are in the same order as shown in Figs. (5) to (8). A positive null-flux lift is induced at a negative vertical offset independent of the lateral displacement.

The second term of the lift force, $F_{LP}$, is given by

$$F_{LP} = 3I_e n_m \frac{V_{ph}\cos \delta - E_{ph}}{4x_{ph}} \left[ \frac{\partial M_{s1}}{\partial z} + \frac{\partial M_{s2}}{\partial z} + \frac{\partial M_{s3}}{\partial z} + \frac{\partial M_{s4}}{\partial z} \right]$$

(25)

This term depends upon the propulsion current flowing through the power source. It is also a function of vertical offset. At zero vertical offset, the sum of the mutual derivatives, with respect to the vertical displacement, is always zero independent of the lateral displacement. In this case, $F_{LP}$ disappears independent of the propulsion current. Under normal operating conditions, a negative vertical offset always exists.

In this case, the sum of the mutual inductance derivatives (with respect to the vertical displacement) is positive, as shown in Figs. 7 and 8. It follows that $F_{LP} > 0$ for $V_{ph}\cos \delta > E_{ph}$, which represents a lagging internal power factor, and $F_{LP} < 0$ for $V_{ph}\cos \delta < E_{ph}$, which represents a leading internal power factor. This lift-force component can be also viewed as result of the edge effect between the upper and lower linear motors, which operate in parallel.

The third term of the lift force component, $F_{LG}$, is due to the vehicle lateral displacement

$$F_{LG} = \frac{3}{4\sqrt{2}} n_m^2 \left[ \left( M_{s3} + M_{s4} \right) - \left( M_{s1} + M_{s2} \right) \right]$$

(26)

$$\left[ \frac{\partial M_{s1}}{\partial z} + \frac{\partial M_{s2}}{\partial z} + \frac{\partial M_{s3}}{\partial z} + \frac{\partial M_{s4}}{\partial z} \right]$$

This term is very small because the derivatives of mutual inductances ($M_{s1}$ and $M_{s2}$, with respect to vertical displacement) have opposite signs, so do $M_{s3}$ and $M_{s4}$ as shown in Figs. (5) to (8). $F_{LG}$ may be positive or negative, depending upon the lateral displacement.

Figure 9 shows the levitation force components as a function of displacement at a lateral offset of -4 cm. Clearly, $F_{LL}$ is dominant and $F_{LG}$ is negligible. The term $F_{LP}$ is small at a small vertical offset. In this computation, the required propulsion force is assumed to be 200 kN, SCM current is 700 kA, total number of vehicle SCMs is 40 (corresponding to $n_m=20$), and total energized block length is $n_b^L = 112$ m. Other detailed information is given in Table 1. As shown in Fig. 5, a vehicle of 60 to 70 metric tons vehicle can be levitated at a vertical offset of around 2 cm.
THE GUIDANCE FORCE

An approach similar to that described in the above section can be used to determine the guidance force. However, it should be noted that the guidance force depends upon two different air gaps, which requires the introduction of two coordinate systems. By letting \( y_0 \) be the equivalent air gap, the distance from the center of the SCM to the center of the figure-eight-shaped coil, one can define \( y_1 = y_0 + y \) and \( y_2 = y_0 - y \), as shown in Fig. 4. Therefore, the guidance force can be expressed as:

\[
F_G = 3n_m I_R C \left( I_1 \frac{\partial M_{41}}{\partial y_1} + I_2 \frac{\partial M_{42}}{\partial y_1} + I_3 \frac{\partial M_{43}}{\partial y_2} + I_4 \frac{\partial M_{44}}{\partial y_2} \right)
= \frac{F_{GG}}{F_{GP}} + F_{GL}, \tag{27}
\]

where \( F_{GG} \) denotes the guidance force resulting from the lateral offset. This term follows the null-flux principle and is a dominant part of the guidance force. It is given by

\[
F_{GG} = \frac{3}{4\sqrt{2}} n_m I_R C \left( \frac{[M_{34} + M_{44}] - [M_{34} + M_{44}]}{L_e} \right) \left( \frac{\partial M_{41}}{\partial y_1} + \frac{\partial M_{42}}{\partial y_1} + \frac{\partial M_{43}}{\partial y_2} + \frac{\partial M_{44}}{\partial y_2} \right), \tag{28}
\]

and \( F_{GP} \) is the guidance force component due to the propulsion current

\[
F_{GP} = 3I_n n_m \frac{V_p \cos \delta - E_{ph}}{4x_{ph}} \left( \frac{\partial M_{41}}{\partial y_1} + \frac{\partial M_{42}}{\partial y_1} + \frac{\partial M_{43}}{\partial y_2} + \frac{\partial M_{44}}{\partial y_2} \right). \tag{29}
\]

It should be noted that \( F_{GP} \) is an unstable force according to the data in Figs. 5, 6, 10, and 11, in which the sum of the mutual inductance derivatives, with respect to lateral displacement, is negative for a negative lateral offset. This implies that the force is negative for a lagging internal power factor \( V_p \cos \delta > E_{ph} \). (That is, a negative lateral displacement leads to a negative guidance force.) Because the propulsion motors operate in such a way that the vehicle SCMs are attracted by the air gap traveling wave with a load angle \( \delta \) between 0 to 90°. As the vehicle shifts to one side and the air gap of this side decreases, the attractive force increases naturally, as described by Eq. (29). The last term of the guidance force results from the vertical offset. It couples with the null-flux lift and is given by

\[
F_{GL} = \frac{3}{4\sqrt{2}} n_m I_R C \left( \frac{[M_{41} - M_{41}] + [M_{42} - M_{42}]}{L_e} \left( \frac{\partial M_{41}}{\partial y_1} + \frac{\partial M_{42}}{\partial y_1} + \frac{\partial M_{43}}{\partial y_2} + \frac{\partial M_{44}}{\partial y_2} \right) \right). \tag{30}
\]

One can use Figs. 5, 6, 10, and 11 to examine and better understand Eqs. (28) - (30). Figure 12 shows guidance force components plotted as a function of lateral displacement; one can see that \( F_{GP} \) is an unstable force, but it is negligible when compared with \( F_{GG} \) and \( F_{GL} \). The term \( F_{GG} \) is dominant, and \( F_{GL} \) is relatively small, depending upon vertical offset. The total guidance force for a vehicle having 40 SCMs \( (n_m = 20) \) is 159 kN for a 2-cm lateral offset, 241 kN for a 3-cm lateral offset, and 326 kN for a 4-cm lateral offset.

More detailed information concerning the numerical example used above is listed in Table 1, which provides some other predicted results, including phase voltage, current, power factor, and block length.
CONCLUSIONS

An analytical model, in combination with the numerical approach, has been developed for a combined maglev system proposed in Japan recently. Closed-form formulas of the propulsion, levitation, and guidance magnetic forces for the system are discussed. Preliminary results show that such a combined system can perform three functions of propulsion, levitation, and guidance with one set of figure-eight-shaped guideway coils. The coupling effects among three functions are small. The system seems to be promising and have many potential advantages. Further investigations, including system optimization and computer simulations, are necessary.

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