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Magnetic Damping Forces in Figure-Eight-Shaped Null-Flux Coil Suspension Systems

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Abstract – This paper discusses magnetic damping forces in figure-eight-shaped null-flux coil suspension systems, focusing on the Holloman maglev rocket system. The paper also discusses simulating the damping plate, which is attached to the superconducting magnet by two short-circuited loop coils interacting with the figure-eight-shaped null-flux coils in the guideway. Closed-form formulas for the magnetic damping coefficient as functions of heave-and-sway displacements are derived by using a dynamic circuit model. These formulas are useful for dynamic stability studies.

I. INTRODUCTION

The figure-eight-shaped null-flux coil suspension system has been widely used for many different maglev configurations, including the Japanese MLU system, several U.S. system concepts, and, more recently, the U.S. Air Force's Holloman maglev rocket sled system [1] (Fig. 1). The major advantage of this system is that it can provide very high lift-to-drag ratios (i.e., very high suspension efficiency). An important question is whether such a null-flux suspension system can produce sufficient magnetic damping forces to stabilize the rocket sled at hypersonic speeds. In fact, such magnetic damping forces are equally important to any electrodynamic suspension (EDS) maglev system [2], [3]. The dynamic stability of a maglev system cannot be predicted without knowing the magnetic damping forces.

This paper analyzes the magnetic damping forces resulting from the interaction between the figure-eight-shaped null-flux coil guideway and the damping plate by simulating the damping plate with two conducting loops. Thus, one can derive a simple relation for the magnetic damping force and therefore gain insight into the physics associated with the system design. In particular, the damping coefficient is expressed in terms of heave and sway displacements, which can be very useful for studying dynamic stability.

II. THE MODEL

A double-loop-shaped eddy current pattern is induced in the damping plate by the figure-eight-shaped null-flux guideway coils, suggesting that one may simplify the analysis of the damping problem by simulating the damping plate with two conducting loops (Fig. 2). Thus, one can use a dynamic circuit model in which the damping forces are determined in terms of circuit parameters and thus avoid using a complicated field analysis model [4], [5]. Following the conventional notation used in the maglev community, we

Fig. 1 Cross-sectional view of Holloman maglev rocket sled

Fig. 2 Damping plate simulated by two damping loops (only one magnet illustrated)

specify x as the direction of longitudinal motion, y as the direction of sway or lateral motion, and z as the direction of heave or vertical motion, as shown in Fig. 2, where the subscripts gu , gl , du , dl , and s refer to the upper and lower guideway loops, upper and lower damping loops, and the superconducting magnet (SCM), respectively. Assuming a constant magnet current, I_s , one obtains four voltage equations for the system:

$$i_{gu}R_{gu} + \frac{d\phi_{gu,g}}{dt} + \frac{d\phi_{gu,d}}{dt} + \frac{d\phi_{gu,s}}{dt} = 0, \quad (1)$$

$$i_{gl}R_{gl} + \frac{d\phi_{gl,g}}{dt} + \frac{d\phi_{gl,d}}{dt} + \frac{d\phi_{gl,s}}{dt} = 0, \quad (2)$$

$$i_{du}R_{du} + \frac{d\phi_{du,d}}{dt} + \frac{d\phi_{du,g}}{dt} = 0, \text{ and} \quad (3)$$

$$i_{dl}R_{dl} + \frac{d\phi_{dl,d}}{dt} + \frac{d\phi_{dl,g}}{dt} = 0, \quad (4)$$

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where i is the current, R is the resistance, and ϕ is the flux linkage. The flux linkages in the null-flux coils and the damping coils are divided into several groups, according to their generating sources. The terms $\phi_{gu,g}$ and $\phi_{gl,g}$ are the flux linkages of the upper and lower loops of the null-flux coil with the self-inductances and the mutual inductances from neighboring guideway coils. Similarly, $\phi_{gu,d}$ and $\phi_{gl,d}$ are the flux linkages with the damping loops, $\phi_{gu,s}$ and $\phi_{gl,s}$ are the flux linkages with the SCM, $\phi_{du,d}$ and $\phi_{dl,d}$ are the flux linkages of the upper and lower damping loops with their self-inductances and the mutual inductances between the damping loops, and $\phi_{du,g}$ and $\phi_{dl,g}$ represent the flux linkages with all null-flux guideway coils.

In equations (1) and (2), the third terms represent the voltage induced in the null-flux loops by the eddy current in the damping loops, which can be neglected. The fourth terms, which represent the voltages induced in the null-flux coils by the longitudinal motion of the SCMs, are the dominant terms. With a good approximation, one can express the flux linkages to the upper and the lower loops of the null-flux coil by a group of SCMs in terms of fundamental waves in the longitudinal direction. The amplitudes of the waves are determined by the product of the SCM current and the mutual inductances; that is,

$$\phi_{gu,s} = I_s M_{gu,s}(y,z) \cos \beta x \quad \text{and} \quad (5)$$

$$\phi_{gl,s} = I_s M_{gl,s}(y,z) \cos \beta x, \quad (6)$$

where $M_{gu,s}(y,z)$ and $M_{gl,s}(y,z)$, the mutual inductances between the SCM and the upper or lower loops of the null-flux coil, are functions of the vertical and lateral displacements. They are calculated at the position where the two coils are aligned in the longitudinal direction. The term $\beta_x (= \pi/\tau_x)$ is a wave number, and τ_x is pole pitch of the SCMs. The currents induced in the upper and lower loops of the null-flux coil are identical but have opposite signs ($i_g = i_{gu} = -i_{gl}$), and the resistance of the null-flux coil is much smaller than its reactance, $R_g \ll X_g$. Therefore, one can solve for the current flowing in the null-flux coil from (1), (2), (5), and (6) as

$$i_g = \frac{1}{2} I_s \frac{(M_{gl,s} - M_{gu,s})}{L_g} \cos(\omega_x x), \quad (7)$$

where ω_x is the radial frequency relating to the longitudinal motion only, and L_g is the equivalent self inductance of the null-flux loops, which includes all effects from its neighboring null-flux loops. Assuming that one SCM (and its associated damping loops) covers three null-flux coils, the total flux linkages to the upper and lower damping loops by three consecutive null-flux coils can be obtained as

$$\phi_{du,g} = i_{g-1} M_{du,gu-1} + i_g M_{du,gu} + i_{g+1} M_{du,gu+1}, \quad \text{and} \quad (8)$$

$$\phi_{dl,g} = -i_{g-1} M_{dl,gl-1} - i_g M_{dl,gl} - i_{g+1} M_{dl,gl+1}, \quad (9)$$

where i_{g-1} , i_g , and i_{g+1} are the currents flowing in the first, second, and third null-flux coils facing the SCM, and $M_{du,gu-1}$, $M_{du,gu}$, and $M_{du,gu+1}$ are the mutual inductances between the damping loop and the first, second, and third upper null-flux loops, respectively. Note that the coupling effect between the upper and lower damping loop is also neglected. With a harmonic approximation, the currents induced in three consecutive guideway coils are expected to be delayed by one-third of a time period; similarly, the mutual inductance terms are supposed to be delayed by one-third of a pole pitch. Thus, one can show that (8) and (9) have a traveling wave form referred to the guideway:

$$\phi_{dg} = \phi_{du,gu} = -\phi_{dl,gl} = \frac{3}{2} I_{gm} M_{dg} \cos(\omega_x t - \beta_x x), \quad (10)$$

where I_{gm} is the maximum value of the current in a null-flux coil given by (7). Equation (10) indicates that the flux linkage to the damping loop travels along the guideway with the same speed as the damping plate (simulated by loops) attached to the SCMs. In other words, there is no relative motion in the longitudinal direction between the damping plate or loop and the magnetic fields produced by the null-flux guideway coils. Consequently, one can now deal with the damping currents described by equations (3) and (4) without considering the motion in the x -direction. The total power dissipated in the two damping loops is expressed as

$$P_d = 2P_{dl} = 2P_{du} = |i_d|^2 R_d = \frac{9}{4} \frac{R_d v_z^2}{R_d^2 + X_d^2} \left[\frac{\partial}{\partial z} (I_{gm} M_{dg}) \right]^2, \quad (11)$$

where v_z is the speed associated with vertical motion, and R_d and X_d are the resistance and reactance of the damping loops. The two damping loops are assumed to be identical. Letting $v_{zc} = R_d/(\beta_z L_d)$, where β_z is the vertical wave number, equation (11) can be further simplified as

$$P_d = \frac{9}{16\pi^2} \frac{v_z^2}{v_z^2 + v_{zc}^2} F(y,z) I_s^2 R_d, \quad (12)$$

where $F(y,z)$ is a non-dimensional coupling function, depending on the geometry of the null-flux coils and the damping loops:

$$F(y,z) = \left\{ \frac{\tau_z}{L_d L_g} \frac{\partial}{\partial z} [(M_{gu,s} - M_{gl,s}) M_{dg}] \right\}^2. \quad (13)$$

Finally, one obtains the damping coefficient, C_d , associated with the vertical or heave motion from equation (12) as

$$C_d = \frac{P_d}{v_z^2} = \frac{9}{16\pi^2} \frac{1}{v_z^2 + v_{zc}^2} F(y,z) I_s^2 R_d. \quad (14)$$

One can derive similar relations for the damping coefficient for the lateral motion. This topic will not be discussed here.

III. RESULTS AND DISCUSSION

The power dissipation in the damping loops has three factors, as shown in equation (12). The first factor is related to the motion, which scales the power from zero to one as the speed varies from zero to infinity. The second factor is associated with the coupling between the guideway coils and the damping plate, and the last term has the form of resistive power dissipation. The relationships developed in equations (13) and (14) are illustrated in Figs. 3-5, where the following parameters are assumed: a 0.36-m by 0.17-m SCM with an excitation of 500-kA turns, 0.25-m by 0.12-m null-flux loops, 0.45-m by 0.12-m damping loops; a mean air gap between the SCM and the null-flux coil of 7-cm; and a gap between the damping loop and the null-flux coil of 4 cm (y_0).

The dependence of the coupling function, F , on the vertical and lateral displacements is shown in Fig. 3, where one can see that F peaks at vertical null-flux position ($z=0$) and decreases as the vertical displacement increases in either direction. This implies that the power dissipated in the damping loops reaches a maximum value at a vertical null-flux position, although the currents flowing in the null-flux coils vanish at this position, simply because the damping power is proportional to the change of the currents in the null-flux coils. As expected, the coupling function F decreases as the lateral air gap, y , increases.

For a given speed, v_z , the dependence of the damping coefficient, C_d , on the vertical and lateral displacements is determined by the coupling function F , as shown in Fig. 4, where one can see that several hundred kilograms per second per SCM can be achieved for the Holloman system, depending on the heave and sway displacements. The damping coefficient C_d approaches a peak at the vertical null-flux position, one that is similar to the peak shown in Fig. 3. However, note that C_d decreases with vertical speed, as shown in Fig. 5.

Fig. 3 Coupling function vs. vertical displacement with lateral displacement as a parameter

Fig. 4 Damping coefficient vs. vertical displacement with lateral displacement as a parameter at $V_z = V_{zc} = 2.1$ m/s

Fig. 5 Damping coefficient as a function of vertical speed ratio, V_z/V_{zc} , with lateral displacement as a parameter at vertical equilibrium (vertical null-flux position)

IV. CONCLUSIONS

The magnetic damping forces associated with heave-and-sway motions of the Holloman maglev sled were studied by simulating the damping plate with two damping loops. Simple closed-form formulas for the damping coefficient are obtained in terms of a dynamic circuit model. These relations can be very useful for dynamic stability studies.

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