Computer Modeling and Experimental Verification of Figure-Eight-Shaped Null-Flux Coil Suspension System

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Abstract

This report discusses the computer modeling and experimental verification of the magnetic forces associated with a figure-eight-shaped null-flux coil suspension system. A set of computer codes called COILGDWY, were developed on the basis of the dynamic circuit model and verified by means of a laboratory model. The experimental verification was conducted with a rotating PVC drum, the surface of which held various types of figure-eight-shaped null-flux coils that interacted with a stationary permanent magnet. The transient and dynamic magnetic forces between the stationary magnet and the rotating conducting coils were measured and compared with results obtained from the computer model. Good agreement between the experimental results and computer simulations was obtained. The computer model can also be used to calculate magnetic forces in a large-scale magnetic-levitation system.

1 Review of Coil-Type Maglev Guideways

The electrodynamic suspension (EDS) magnetic-levitation (maglev) system utilizes the repulsive magnetic force generated from the interaction between vehicle-borne magnets, usually superconducting magnets (SCMs), and the eddy currents induced in the guideway conductors. Various types of guideway conductors have been developed for EDS maglev systems. Two typical guideway conductors are the sheet-type guideway conductors and the discrete-coil-type guideway conductors. The sheet-type guideway conductors were used in many early maglev concepts. Currently, the Magneplane, one of the four U.S. maglev system designs, employs an arc-shaped sheet conductor for levitation and partial guidance. This report focuses on the discrete-coil-type guideways, but the model also can be applied to other coil-type guideways.

The horizontal single-loop coil guideway, shown in Figure 1.1, is the simplest coil-type guideway configuration and was used in many early EDS maglev concepts, including early versions of the Japanese MLU system. The single-loop coil-type guideway is frequently considered to be superior to the sheet-type guideway because of its relatively low magnetic drag force. The single-loop coil guideway, however, produces undesirable force pulsations that do not occur in the sheet-type guideway conductors; the amplitude of these force pulsations depends upon

FIGURE 1.1 Single-Loop Coil Guideway for Vertical Levitation

the coil pitch of the guideway. An alternative single-loop coil guideway concept is shown in Figure 1.2, where the horizontally arranged superconducting magnet array aboard the vehicle interacts with the vertically arranged single-loop coil array to produce a lateral guidance force. This configuration, originated in 1969,¹ follows the null-flux principle.

The double-row-loop coil guideway shown in Figure 1.3 consists of two arrays of horizontal-loop coils arranged in parallel, interacting with a vehicle-borne magnet array to produce levitation and guidance forces.² Two vehicle-borne magnet arrays aboard the vehicle interact with the two double-row loop coils to levitate and guide a maglev vehicle. In this case, the side-wall of the guideway can be omitted, and the cost of the guideway may be reduced. In addition, the double-row-loop coil guideway can be used to develop a simple electromagnetic guideway directional switch.

The null-flux coil suspension concept invented in 1969 has become very popular in the maglev community.¹ Japanese maglev researchers have further developed several versions of the null-flux coil suspension system, including the side-wall null-flux suspension system. The major advantage of the null-flux coil suspension system is that it can provide very high lift-to-drag ratios, typically several hundred, depending upon design and vertical offset. The horizontally arranged, figure-eight-shaped null-flux coil array (Figure 1.4) was employed in the Canadian maglev concept design for lateral guidance. The vertically arranged, figure-eight-shaped null-flux coil array has been used for side-wall vertical levitation systems, such as the Japanese MLU system (Figure 1.5) and, in the United States, Foster Miller's maglev concept. Recently, the Japanese maglev group has further improved the side-wall levitation system by cross-connecting the null-flux coil arrays mounted on the two side walls as shown in Figure 1.6. The cross-connected figure-eight-shaped null-flux coil suspension system can provide both null-flux levitation and guidance forces, with very high lift-to-drag and guidance-to-drag ratios.^{3,4}

Figure 1.7 shows a guideway configuration, developed by the Bechtel maglev team, called "flux-cancellation suspension." In this system, the octupole superconducting magnet arrays

FIGURE 1.2 Vertically Arranged Single-Loop Coil Guideway for Null-Flux Lateral Guidance

FIGURE 1.3 Double-Row-Loop Coil Guideway for Vertical Levitation and Lateral Guidance

FIGURE 1.4 Figure-Eight-Shaped Null-Flux Coil Guideway for Lateral Guidance

FIGURE 1.5 Figure-Eight-Shaped Null-Flux Coil Guideway for Vertical Levitation

FIGURE 1.6 Cross-Connected Figure-Eight-Shaped Null-Flux Coil Guideway for Vertical Levitation and Lateral Guidance

FIGURE 1.7 Flux-Cancellation Concept for Vertical Levitation

aboard the vehicle interact with the vertically arranged ladder guideway conductors to produce the levitation force. The system, in principle, is very similar to the null-flux concept because the net flux passing through the window of the ladder vanishes at the vertical equilibrium position. The approach used for analyzing the ladder guideway is similar to that used in other coil-type guideways previously discussed.

EDS propulsive systems consist of discrete propulsion coils interacting with vehicle superconducting magnets. The propulsive system interacts in a manner similar to the suspension systems. Thus, the model used for the computation of suspension forces can also be applied to the forces associated with propulsive systems.

Investigation of various types of coil-type guideway conductors, as well as propulsion windings, leads to the conclusion that coil-type guideway conductors have several unique features, depending on their configurations. First, various circuit models can be applied to the coil-type guideways. Second, all of the coil conductors used in maglev systems have a rectangular shape which can be treated as four finite-length conductors. The circuit parameters of the coil-type guideway can be obtained easily. Third, no ferromagnetic materials are used in EDS maglev systems, so a linear circuit model will be sufficient for the EDS coil guideway.

It should be noted that the circuit model used for maglev is motion-dependent, and the circuit parameters are functions of time and space as the vehicle moves forward. The dynamic circuit theory is very suited to coil-type maglev system analysis.

2 The Computer Simulation Model

2.1 Introduction

The COILGDWY computer program contains several independent computer codes for different coil-type guideways, including the figure-eight-shaped null-flux coil guideway and the loop coil guideway. These codes were developed on the basis of dynamic circuit theory, as discussed in previous papers.⁵ The unique feature of the theory is that it treats the maglev suspension system in terms of space- and time-dependent circuit parameters governed by a set of differential equations in matrix form, taking both end-effects and edge-effects of the system into consideration. Once the system of equations is solved for the current distribution, the forces acting between the vehicle's superconducting magnets and the guideway coils can be calculated in a straightforward manner. Therefore, the performance of the system can be investigated. The equations are usually solved for the currents in the time domain, so the method is well-suited for transient and dynamic analysis and for computer simulation of coil-type maglev systems. In this report, we apply dynamic circuit theory to the figure-eight-shaped null-flux coil guideway and demonstrate the utility and versatility of the approach and the utility of the COILGDWY computer codes. Validation of the COILGDWY computer codes may lead to a better understanding of the dynamic characteristics of the null-flux coil suspension concept.

2.2 General Model

A maglev system can be represented by the dynamic circuit model, in which the system energy, power, and forces, as well as other quantities, are expressed in terms of their equivalent circuit parameters. Consider a maglev system in which m vehicle coils or conductors interact with n guideway coils or conductors to produce levitation, guidance, and propulsion forces. Assume $[i]$ and $[e]$ to be column $(m + n)$ matrices made up of the individual currents and voltages associated with the vehicle and guideway coils or conductors, respectively; $[L]$ to be a square $(m + n) \times (m + n)$ matrix, each element of which represents either the self-inductance of a vehicle or guideway coil or the mutual inductance between a vehicle coil and a guideway coil; and $[R]$ to be a diagonal $(m + n)$ elements matrix made up of the individual vehicle coil and guideway coil resistances. We can then write the system voltage equations in matrix form, on the basis of Kirchhoff's voltage law, as follows:

$$[e] = [R][i] + \frac{d}{dt} \{ [L][i] \}. \quad (2.1)$$

For a passive EDS guideway, the applied voltage term $[e]$ is zero. However, each guideway coil contains induced voltages in connection with the vehicle's motions. Letting v_x , v_y , and v_z be the

speeds of the vehicle in the x, y, and z directions, respectively, we can rewrite Equation 2.1 in terms of the induced voltages as

$$[L] \frac{d}{dt} [i] + [R] [i] = -v_x [G_x] [i] - v_y [G_y] [i] - v_z [G_z] [i] , \quad (2.2)$$

where $[G_x] = \partial[L]/\partial x$, $[G_y] = \partial[L]/\partial y$, and $[G_z] = \partial[L]/\partial z$ are the derivatives of the mutual inductance between the vehicle-borne superconducting coils and the guideway coils with respect to the three displacements. Three time-dependent force components, f_x , f_y , and f_z , are obtained:

$$f_x = \frac{1}{2} [i]^T [G_x] [i] , \quad (2.3)$$

$$f_y = \frac{1}{2} [i]^T [G_y] [i] , \quad (2.4)$$

and

$$f_z = \frac{1}{2} [i]^T [G_z] [i] , \quad (2.5)$$

where f_x is the force in the direction of vehicle motion, f_y is the force in the horizontal direction, and f_z is the force in the vertical direction. Note from Equation 2.2 that the currents induced in the guideway coils depend on the vehicle's dynamic motion. This implies that Equation 2.2 cannot be solved independently of the equations of motion of the vehicle. However, for the quasi-steady-state analysis focusing on the electromagnetic performance, the lateral and vertical speeds can be neglected and the longitudinal speed can be assumed to be constant. Since the mutual inductances and the derivatives of the mutual inductances in Equation 2.2 are functions of displacements that are, in turn, functions of time, the currents induced in the guideway coils can be solved by using an iterative process. For instance, by Euler's formula, multiplying the derivative of i by the time increment and adding the resulting value to the previous i will give a good approximation of the next i at time t :

$$[i(t)] = [i(t - \Delta t)] + \frac{d[i]}{dt} \Delta t , \quad (2.6)$$

where the time increment can be expressed in terms of the longitudinal displacement increment divided by speed (i.e. $\Delta t = \Delta x/v_x$). Equation 2.2 can also be solved by using other numerical approaches, including the Runge-Kutta method.

Time-averaged magnetic forces, F_x , F_y , and F_z , can be obtained by integrating Equations 2.3 through 2.5 over any desired time period:

$$F_x = \frac{1}{T} \int_0^T \frac{1}{2} [i]^T [G_x] [i] dt, \quad (2.7)$$

$$F_y = \frac{1}{T} \int_0^T \frac{1}{2} [i]^T [G_y] [i] dt, \quad (2.8)$$

and

$$F_z = \frac{1}{T} \int_0^T \frac{1}{2} [i]^T [G_z] [i] dt. \quad (2.9)$$

Assume that a figure-eight-shaped null-flux coil suspension system has m vehicle-borne superconducting coils interacting with n figure-eight-shaped null-flux coils. Since each figure-eight-shaped null-flux coil consists of two cross-connected loops, n figure-eight-shaped null-flux coils are expected to contain $2n$ loops. Name the upper row of the loops from 1 to n and the bottom row of the loop as $n + 1$ through $2n$. In other words, the upper loop of the i th figure-eight-shaped null-flux coil is named as the i th loop, and the bottom loop of that is named as the $n + i$ th loop. Applying Equations 2.3 through 2.5 to the figure-eight-shaped null-flux coil system gives

$$f_x = \sum_{i=1}^n \sum_{j=1}^m i_i I_j \left[\frac{\partial M_{i,j}}{\partial x} - \frac{\partial M_{n+i,j}}{\partial x} \right], \quad (2.10)$$

$$f_y = \sum_{i=1}^n \sum_{j=1}^m i_i I_j \left[\frac{\partial M_{i,j}}{\partial y} - \frac{\partial M_{n+i,j}}{\partial y} \right], \quad (2.11)$$

and

$$f_z = \sum_{i=1}^n \sum_{j=1}^m i_i I_j \left[\frac{\partial M_{i,j}}{\partial z} - \frac{\partial M_{n+i,j}}{\partial z} \right], \quad (2.12)$$

where M_{ij} is the mutual inductance between the j th superconducting coil and the i th loop of the null-flux coil and I_j is the current in the j th superconducting coil. The time-averaged magnetic forces can be obtained by using Equations 2.7 through 2.9, in terms of numerical expressions, as

$$F_x = \frac{1}{k\Delta t} \sum_{l=1}^k \sum_{i=1}^n \sum_{j=1}^m i_i(t_l) I_j(t_l) \left[\frac{\partial M_{ij}(t_l)}{\partial x} - \frac{\partial M_{n+i,j}(t_l)}{\partial x} \right] \Delta t, \quad (2.13)$$

$$F_y = \frac{1}{k\Delta t} \sum_{l=1}^k \sum_{i=1}^n \sum_{j=1}^m i_i(t_l) I_j(t_l) \left[\frac{\partial M_{ij}(t_l)}{\partial y} - \frac{\partial M_{n+i,j}(t_l)}{\partial y} \right] \Delta t, \quad (2.14)$$

and

$$F_z = \frac{1}{k\Delta t} \sum_{l=1}^k \sum_{i=1}^n \sum_{j=1}^m i_i(t_l) I_j(t_l) \left[\frac{\partial M_{ij}(t_l)}{\partial z} - \frac{\partial M_{n+i,j}(t_l)}{\partial z} \right] \Delta t, \quad (2.15)$$

where the numerical integral is assumed to be conducted over a time period of $k\Delta t$ (i.e., k time increments, each of value Δt).

2.3 Determination of Circuit Parameters

2.3.1 Resistance and Inductance

The resistance of a rectangular loop coil having sides of $s_1 \times s_2$ (in meters), conductor cross-section per turn of $a \times b$ (in meters), and number of turns N can be expressed as

$$R = \frac{2(s_1 + s_2)N}{ab\sigma}, \quad (2.16)$$

where σ is the conductivity of the conductor. A figure-eight-shaped null-flux coil consists of two loop coils, so its resistance is twice the value given by Equation 2.16.

The inductance of a rectangular loop coil (in henrys) is given by

$$L = 10^{-6} N^2 \left\{ 0.9209 \left[(s_1 + s_1) \log_{10} \frac{2s_1 s_1}{a+b} - s_1 \log_{10} (s_1 + \sqrt{s_1^2 + s_2^2}) - s_2 \log_{10} (s_2 + \sqrt{s_1^2 + s_2^2}) \right] \right. \\ \left. + 0.4 \left[2\sqrt{s_1^2 + s_2^2} - \frac{s_1 + s_2}{2} + 0.447(a+b) \right] \right\}, \quad (2.17)$$

with all dimensions given in meters. Note that the resistance and inductance of the loop coils are constants, independent of the vehicle displacements.

2.3.2 Determination of Mutual Inductance

The most important parameters for the computer modeling are the mutual inductances between the guideway coils and the vehicle coils. These parameters are functions of the vehicle's displacements and need to be calculated at every time increment.

The fundamental relation for determining the mutual inductance between any two conductors defined by C_1 and C_2 is given by the Neumann formula

$$M = \frac{\mu_0}{4\pi} \int_{C_1} \int_{C_2} \frac{dx dx' + dy dy' + dz dz'}{[(x - x')^2 + (y - y')^2 + (z - z')^2]^{1/2}}, \quad (2.18)$$

where x , y , and z , and x' , y' , and z' are the integral variables for conductors C_1 and C_2 , respectively. Equation 2.18 can be generally applied to any geometry of the conductors. However, in some cases, it is difficult to obtain an analytical expression with Equation 2.18; therefore, numerical solution may become necessary. The simplest model for the determination of magnetic forces between the guideway coils and the vehicle coils is to treat the two coils as four finite-length conductors, as shown in Figure 2.1. The mutual inductance between the two

FIGURE 2.1 Interaction between Two Coils
Simplified as the Interaction between Four Effective
Conductors

filaments, as shown in Figure 2. 2, with length l and m , respectively, separated by a distance of d and with an overlapping length of δ , is⁶

$$M = \frac{\mu_0}{4\pi} \left[\alpha \sinh^{-1} \frac{\alpha}{d} - \beta \sinh^{-1} \frac{\beta}{d} - \gamma \beta \sinh^{-1} \frac{\gamma}{d} + \delta \beta \sinh^{-1} \frac{\delta}{d} - \sqrt{\alpha^2 + d^2} + \sqrt{\beta^2 + d^2} + \sqrt{\gamma^2 + d^2} + \sqrt{\delta^2 + d^2} \right], \quad (2.19)$$

where

$$\alpha = l + m - \delta,$$

$$\beta = l - \delta, \text{ and}$$

$$\gamma = m - \delta$$

Note that in the computer modeling, the variables l , m , d , and δ should be expressed in terms of x , y , and z , as shown in Figure 2.2, because d and δ are functions of displacements.

FIGURE 2.2 Determination of Mutual Inductance between Two Finite-Length Conductors

On the other hand, one can determine the mutual inductance between the two rectangular coils precisely, instead of using the two conductor formulas described by Equation 2.19. A general relation for the mutual inductance between the two rectangular coils, referring to Figure 2.3, is given by⁷

$$M = \frac{\mu_0}{4\pi} \sum_{i=1}^4 \sum_{j=1}^4 (-1)^{i+j} \ln \left[\Psi(x_j, y_j, 0; x'_i, y'_i, z_0) + \Psi(y_j, x_j, 0; y'_i, x'_i, z_0) \right] \quad (2.20)$$

where

$$\begin{aligned} \Psi(x, y, z, x', y', z') = & -(x - x') \ln \left[(x - x') + \sqrt{(x - x')^2 + (y - y')^2 + (z - z')^2} \right] \\ & + \sqrt{(x - x')^2 + (y - y')^2 + (z - z')^2}. \end{aligned}$$

Equation 2.20 is very effective and useful for most coil-type guideways, including the loop coil guideway and the figure-eight-shaped null-flux coil guideway.

FIGURE 2.3 Determination of Mutual Inductance between Two Rectangular Coils

2.4 Introduction to the Computer Code

Several computer codes have been developed, on the basis of the dynamic circuit model, for the computation of magnetic forces for several different coil-type guideways. Each code may differ slightly from others. However, the main programs of these codes are very similar; Figure 2.4 illustrates a flow chart of the main programs. The program basically consists of several parts: input data process, circuit parameter computations, solution of the system equations, time-dependent and time-averaged force computations, and the output data process. The input data include the dimensions of guideway coils and superconducting coils, material specifications, vehicle speed, superconducting coil currents, and other program parameters. The circuit parameters, stored in matrix form, include the resistances and inductances of the guideway coils, the mutual inductances between the vehicle coils and the guideway coils, and the derivatives of the mutual inductances. Of these parameters, the resistances and inductances are constant and are calculated at the beginning of the program. However, the mutual inductances and their derivatives are functions of displacements and are calculated at every time increment. The currents induced in the guideway coils are then obtained by solving Equation 2.1, and the time-dependent magnetic forces and the time-averaged magnetic forces are determined from using Equations 2.10 through 2.12 and Equations 2.13 through 2.15, respectively. The output data contain the simulation results stored in several files that can be used as input by some graphical programs.

2.5 Numerical Example

To demonstrate the capabilities of the dynamic circuit model and to help the reader understand the performance of a maglev system using the null-flux suspension concept, an EDS

FIGURE 2.4 Block Diagram of the Main Program

maglev system, developed in Japan, using side-wall null-flux suspension, is used as a numerical example. Figure 2.5 shows a cross-sectional view of the system on which the computer simulations were based; Table 1 gives the corresponding dimensions. The force-velocity characteristic curve is shown in Figure 2.6, where one can see that the lift force on a 700-kA-T SCM is 15 kN at 250 km/h and 16 kN at 500 km/h, with a vertical displacement of 3 cm. The drag force approaches a maximum value of 0.25 kN at about 20 km/h, and it is only about 0.064 kN at 500 km/h, resulting in a lift-to-drag ratio of over 250. Figure 2.7 shows the lift and lift-to-drag ratio as functions of vertical displacement. A maximum lift force of 41.5 kN appears at a vertical displacement of 11.5 cm; this gives a safety factor, defined as the maximum lift over full-load lift (3 cm), of 2.5 to 3.5. It can be concluded from this computation that a vehicle having twelve SCMs is able to lift 180 kN at a vertical displacement of 3 cm for vehicle speeds higher than 250 km/h, as shown in Figures 2.6 and 2.7. At lower speeds, the vertical displacement is expected to increase in order to achieve the same amount of lift force. As shown in Figure 2.7, at a 3 cm vertical displacement, for example, the lift-to-drag ratio is 280, corresponding to 1 kN of drag force with 280 kN of lift force. The program can also calculate the time-dependent magnetic force pulsation resulting from the discrete coil guideway, as shown in Figure 2.8. This information is useful for the design of superconducting magnets and other mechanical components.

FIGURE 2.5 Side-Wall Suspension System (cross section)

TABLE 2.1 Data Used for Computer Simulation

Parameter	Value
Vehicle	
Total weight (tonnes)	17
Maximum velocity (km/h)	500
Height (m)	3.7
Width (m)	3
Number of SCMs	12
Superconducting magnet (SCM)	
Length (x-direction) (m)	1.7
Height (z-direction) (m)	0.5
Gap between magnets (m)	0.4
Current (NI) (kA-T)	700
Ground null-flux coil	
Length (x-direction) (m)	0.55
Height (z-direction) (m)	0.31
Distance between upper and lower loops (m)	0.12
Distance between null-flux coils (m)	0.15
Number of turns	36
Al conductor (cross section) (cm ²)	1

FIGURE 2.6 Null-Flux Lift and Drag Force as Functions of Vehicle Velocity (air gap = 20 cm, vertical displacement = 3 cm, SCM current = 700 kA-T)

FIGURE 2.7 Null-Flux Lift and Lift-to-Drag Ratio per SCM as Functions of Vertical Displacement

FIGURE 2.8 Null-Flux Lift as a Function of Time

3 Experimental Verification

3.1 Experimental Apparatus

To verify the computer code based on the dynamic circuit theory, an experimental device was developed for the measurement of magnetic force of the figure-eight-shaped null-flux coils, as shown in Figure 3.1. A schematic diagram of the experimental null-flux apparatus is shown in Figure 3.2. The apparatus consists of a PVC drum, with an inside diameter of 0.24 m; figure-eight-shaped coils; magnet and force transducer; and a network/spectrum analyzer. The figure-eight-shaped null-flux coils were mounted on the inside surface of a PVC drum (Figures 3.3 and 3.4). The drum was then statically balanced to insure safety. The rotational speed of the drum could be varied from 0 to 1800 rpm with a maximum linear speed of 22.6 m/s. Speed is calculated at the center of the coil. A NdFeB permanent magnet (25.4 mm square by 3.175 mm thick) was attached to a 9251A tri-axial piezoelectric force transducer and both were mounted on a support bar suspended over the moving coils. The design of the bar minimized resonance effects and cross-talk interference with the transducer. The support bar was cantilevered from a separate, massive concrete block to minimize coupling between the support bar and the drum. The coil drum is mounted on a milling machine table for three-dimensional positioning of the drum and coils.

As the drum rotates clockwise, there is an induced voltage in the coils due to the relative motion of the magnet-coil system. This voltage creates current flow (except at equilibrium position), which results in a secondary magnetic field in opposition to the change in flux due to relative motion. Interactions between the piezoelectric crystals within the transducer create a charge, which is sent from the transducer to an Endevco 2730 charge amplifier. The charge amplifier converts the charge to voltage, and relays this V_{out} to a Hewlett-Packard (HP) Vectra Network/Spectrum Analyzer. Through a math conversion subroutine within the HP unit, this voltage history can be transformed into a force-time history.

3.2 Dynamic Characteristics of Single-Turn Figure-Eight-Shaped Null-Flux Coils

The first experiment was conducted with five different configurations of figure-eight-shaped null-flux coils mounted sequentially around the inner surface of the drum. Figure 3.5 shows the positions of the five coils inside the PVC drum. All figure-eight-shaped null-flux coils are made with two single-turn No. 12-copper-magnet-wire loops. Figure 3.6 shows the five single-turn figure-eight-shaped null-flux coil configurations.

- Configuration A: a figure-eight-shaped null-flux coil with two 25.4-mm-square loops.

FIGURE 3.1 Photograph of the Experimental Null-Flux Apparatus

FIGURE 3.2 Schematic of the Experimental Null-Flux Apparatus

FIGURE 3.3 Experimental Null-Flux Apparatus (front view)

FIGURE 3.4 Magnet Orientation (top view)

FIGURE 3.5 Null-Flux Coil Configuration Positions in Drum (cross section)

FIGURE 3.6 Single-Turn Figure-Eight-Shaped Null-Flux Coil Configurations (top view)

- Configuration B: eight figure-eight-shaped coils with loop dimensions of 25.4×6.35 mm.
- Configuration C: four figure-eight-shaped coils with loop dimensions of 25.4×12.7 mm.
- Configuration D: two figure-eight-shaped coils, each coil has two 25.4-mm-square loops.
- Configuration E: four figure-eight-shaped coils, each coil with 25.4-mm-square loops.

Three dimensional magnetic forces were measured and calculated for different air gaps (distance between the bottom surface of the magnet and the center plane of the coils) in the z axis direction, and the horizontal displacement (y) between the magnet and the figure-eight-shaped coils. Figure 3.7 shows the measured lift, guidance, and drag forces acting on the permanent magnet at a speed of 22.6 m/s, as a function of time (horizontal offset $y = 10.2$ mm and air gap $z = 4$ mm). The horizontal displacement y coordinate is zero when the magnet is centered over the figure-eight-shaped null-flux coils. This is defined as the null-flux equilibrium.

Note that each time-history (as shown in Figure 3.6) shows magnetic forces for five different coil configurations (A, B, C, D, and E). The top signal represents the null-flux *lift force* (y) (parallel to the length of the coil), the middle signal gives the *drag force* (x) (opposing the motion), and the bottom signal shows the *guidance signal* (z) (perpendicular to the coil).

The drag force due to a single null-flux coil (configuration A) consists of two impulses that occur when the magnet approaches and departs from the center of the coil. The superposition of similar pairs of impulses for configurations B through E result in waveforms B to E in Figure 3.7. The impulse overlap is caused by the fact there is no space between the parallel-arranged null-flux coils for coil configurations B through E. The lift (y directed) and guidance forces (z directed) alternate their sign from positive to negative, or from negative to positive, as the magnet crosses the null-flux coils. This phenomenon is caused by the transition time between the magnet and the null-flux coils being no longer than the time constant of the null-flux coils.⁵

A computer simulation of calculated magnetic forces as a function of time for null-flux coil configuration A, using one of the COILGDWY codes, is shown in Figure 3.8. A comparison of the measured forces (Figure 3.7) and the computer calculated forecast (Figure 3.8) shows that a quantitative agreement was achieved between the calculated and measured results. By using the same COILGDWY computer code, one can also predict the characteristics of the null-flux coil configurations at a speed of 100 m/s, as shown in Figure 3.9, where the lift force has larger negative impulses and the guidance force has larger positive impulses. That is, the time-averaged lift and guidance forces increase as the velocity increases. Figure 3.10 shows the time-averaged

FIGURE 3.7 Measured Magnetic Forces as a Function of Time for Null-Flux Coil Configurations A through E (velocity = 22.6 m/s, horizontal displacement $y = 10.2$ mm, air gap $z = 4$ mm)

magnetic forces corresponding to the null-flux coil configuration A, where the lift force is less than the drag force (lift-to-drag ratio is less than one) for speeds lower than about 55 m/s, and greater than the drag force (lift-to-drag ratio greater than one) for speeds higher than about 55 m/s. This, of course, is not acceptable to a normal maglev system where the null-flux lift is usually much larger than the drag force.

Figures 3.11 and 3.12 show the time-averaged magnetic force dependence on horizontal displacement (y) for speeds of 22.6 m/s and 100 m/s, respectively. Note that at high speed (100 m/s), the null-flux lift force characteristics improve. It can be concluded from these results that the characteristic ratio (defined as the time constant of the null-flux divided by the time required by the magnet to transverse across one null-flux coil distance) of the null-flux coil used in this experiment is too small. To improve the lift-to-drag ratio, it is necessary to either increase the speed or increase the time constant of the null-flux coils.

FIGURE 3.8 Computer-Calculated Magnetic Forces Acting on Various Figure-Eight-Shaped Null-Flux Coils, Using the Same Parameters as in Figure 3.7

3.3 Dynamic Force Characteristics

As observed from both the computer simulations and the experimental results discussed in the previous section, the time-dependent magnetic force waveforms involve both positive and negative impulses as the magnet passes over the stationary guideway coils. The time-averaged magnetic forces are determined by the areas enclosed by the positive and negative impulses. The objective of a null-flux coil suspension system design is to obtain a greater time-averaged lift force, or to increase the difference between the two impulses. Thus, it is essential to understand the mechanism of the dynamic force waveforms. Figures 3.13 through 3.15 show different models that can explain the characteristics of the dynamic forces. Figure 3.13 (a) shows a permanent magnet (with the north pole facing down and the south pole facing up) approaching a stationary guideway coil, which senses a downward increasing flux. According to the Lenz's law, an induced current flowing in the coil produces a flux apposing the increasing flux caused by the moving magnet. At this point, the system is analogous to two permanent magnets with the north poles facing each other. The repulsive force, F , between the two can be resolved into two components: the drag force component, F_x , which is opposite to the motion direction, and the lift force component, F_z , which is repulsive force between the magnet and the coil. Their time-dependent waveforms are shown in solid lines in Figure 3.13 (b) and 3.13 (c), respectively.

FIGURE 3.9 Computer-Calculated Magnetic Forces as a Function of Time for Null-Flux Coil Configurations A through E at a Speed of 100 m/s

Figure 3.14 shows a permanent magnet moving away from a stationary guideway coil. In this case, the total flux linking the coil decreases as the magnet moves away from the coil. Again, according to the Lenz's law, a current induced in the coil prevents the total flux from decreasing if the time constant of the coil is shorter than the traverse time of the magnet. Note in Figure 3.14 (a) that the current induced in the coil changes its direction, as compared to Figure 3.13 (a). At this point, the system is analogous to two magnets with the north pole facing to the south pole. An attractive force, F , between the magnet and the coil is developed. This force can be resolved into two components: the vertically attractive force, F_z , and the longitudinal force, F_x . The corresponding time-dependent force waveforms are shown in solid lines in Figure 3.14 (b) and (c), respectively. Note that the second impulse is generally smaller than the first one because of the time constant of the stationary guideway coil. Thus, the time-averaged lift force is positive and the time-averaged drag is always negative.

However, the second impulses of the lift and drag forces become positive as the time constant of the coil *increases*, or the speed of the magnet *increases*, as shown in Figure 3.15. At a higher speed, or at longer time constant, the traverse time of the magnet passing over the stationary guideway coil is much shorter than the time constant of the stationary guideway coil. The current induced in the stationary guideway coil does not have time to change its direction during the time the magnet passes over the coil. Thus, the lift or the guidance forces have only one positive impulse. The drag force still involves two impulses, but the second, associated with a conservative energy component, is positive, as shown in Figures 3.15b and 3.15d.

FIGURE 3.10 Time-Averaged Magnetic Forces of Null-Flux Coil Configuration A as a Function of Speed (horizontal displacement $y = 5$ mm, air gap $z = 4$ mm)

FIGURE 3.11 Time-Averaged Magnetic Forces of Coil Configuration A as a Function of Horizontal Displacement at a Speed of 22.6 m/s

FIGURE 3.12 Time-Averaged Magnetic Forces of Coil Configuration A as a Function of Horizontal Displacement at a Speed of 100 m/s

3.4 Dynamic Characteristics of Thick Single-Turn Figure-Eight-Shaped Null-Flux Coil

For further investigation of the null-flux coil characteristics, a single-turn figure-eight-shaped null-flux coil with relatively large conductor cross-section was designed (Figure 3.16). This thick null-flux coil was 50.8-mm high and 25.4-mm wide with a conductor cross-section of 6.4×3.2 mm. Thus, the time constant of the new coil was about 6 times higher than that of the old coils made with No. 12 copper magnet wire.

Results of the computer simulations conducted with the thick single-turn null-flux coil are shown in Figures 3.17 through 3.21. Lift, guidance, and drag forces as a function of time at speeds of 22.6 m/s and 100 m/s are shown in Figures 3.17 and 3.18, respectively, where the guidance force (z directed) is several times larger than the lift force (y directed) because the lateral displacement (y) is large, 11 mm. Note that the first impulse of the lift and guidance force waveforms are substantial. However, the second impulse of both waveforms are much reduced because of the increase of the time constant of the null-flux coils. This leads to a reasonable value of the time-averaged magnetic forces as shown in Figure 3.19, where the lift-to-drag ratio can be calculated to be 13 at a speed of 120 m/s for a lateral displacement $y = 5$ mm.

Figures 3.20 and 3.21 show the dependence of the time-averaged magnetic forces and the lift-to-drag ratio on the lateral displacement (y) at speeds 22.6 m/s and 100 m/s, respectively. As

(a) A Permanent Magnet approaching a Stationary Guideway Coil

(b) Lift Force Waveform

(c) Longitudinal Force Waveform

FIGURE 3.13 Force Characteristics of a Permanent Magnet Approaching a Stationary Guideway Coil

(a) Permanent Magnet Departure from the Stationary Guideway Coil

(b) Lift Force Waveform

(c) Longitudinal Force Waveform

FIGURE 3.14 Force Characteristics of a Permanent Magnet Departing from a Stationary Guideway Coil

(a) Permanent Magnet Approaching a Stationary Guideway Coil at High Speed or High Time Constant

(b) Permanent Magnet Departure from a Stationary Guideway Coil at High Speed or High Time Constant

(c) Lift Force Waveform

(d) Longitudinal Force Waveform

FIGURE 3.15 Force Characteristics of a Permanent Magnet Passing over a Stationary Guideway Coil at High Speed or High Time Constant

FIGURE 3.16 Thick Single-Turn Figure-Eight-Shaped Null-Flux Coil

FIGURE 3.17 Magnetic Force Waveforms at a Speed of 22.6 m/s and a Lateral Displacement of 11 mm

FIGURE 3.18 Magnetic Force Waveforms at a Speed of 100 m/s and a Lateral Displacement of 11 mm

FIGURE 3.19 Dependence of Time-Averaged Magnetic Force on Speed at a Lateral Displacement of 5 mm

FIGURE 3.20 Time-Averaged Magnetic Forces as a Function of Lateral Displacement at a Speed of 22.6 m/s

FIGURE 3.21 Time-Averaged Magnetic Forces as a Function of Lateral Displacement at a Speed of 100 m/s

expected, for figure-eight-shaped null-flux coil suspension systems, the lift-to-drag ratio approaches infinity at the lateral displacement null-flux equilibrium position, $y = 0$. The lift force increases for a small lateral displacement approaches a maximum value at a lateral displacement of about 8 mm and then decreases for lateral displacement larger than 8 mm. The guidance and drag forces, however, continue to increase as the lateral displacement increases and reaches a maximum value at a lateral displacement of about 13 mm, where the equivalent SCM is centered with one of the loops of the figure-eight-shaped null-flux coil.

Various experiments were conducted with the thick figure-eight-shaped null-flux coil. Testing indicated that the thick coil increased the measurement range, as expected, by a factor of four. The lift force characteristics displayed the expected dependence upon lateral displacement (y). As shown in Figures 3.20 and 3.21, the lift force maximized at $y = \pm 8$ mm away from the null-flux region, and went to zero at $y = \pm 13$ mm. The latter position is indicative of when the magnet passes directly over one of the loops. This position also represents where the drag and guidance forces maximize.

However, as the magnet is approached by the center of the coil, the time histories failed to display the expected null-flux characteristics ($F_x = F_y = F_z = 0$). While the lift force tended to minimize near the center of the coil, the drag and guidances forces maintained relatively large impulses. This is because of the skin effect resulting from the eddy current loss in the relatively larger cross-section of the conductor. This suggests that the parallelly-connected multi-turn coil is necessary to reduce the skin effect.

3.5 Multi-Turn Figure-Eight-Shaped Null-Flux Coil Experiment

In an effort to reduce the skin-effect that occurs in the thick single-turn null-flux coil, several multi-turn figure-eight-shaped null-flux coils were designed and tested. Various wire gauges were tested in an attempt to utilize the full cross-sectional area allowed by the physical constraints of the system. The most efficient coil was a nine-turn, 16 AWG copper coil with a single crossover within the plane of the coil. This coil was tested for various displacements.

The nine-turn series coil displayed the natural null-flux characteristics, absent in the thick-coil trials, thus reinforcing the eddy current explanation. The force signals were well behaved over the entire lateral y -displacement. Each force impulse component displayed the expected dependency on lateral displacement seen in the first two experiments (single-turn thin and single-turn thick). The lift force maximized around $y = \pm 8$ mm and went to zero around $y = \pm 13$ mm, while drag and guidance maximized at around $y = \pm 13$ mm position. The one concern about this coil was that it only increased the measurement range by a factor of slightly over two.

Once the experimental data was gathered for the various coils, it was necessary to determine the flux density of the permanent magnet. Since the COILGDWY code models a SCM moving past null-flux coils, it is necessary to model the permanent magnet as a superconducting

coil with a certain number of ampere turns (A-T), or superconducting current I_s . The force on the magnet is directly proportional to the current I_s , so this term must be known with some accuracy.

The magnetic flux of the magnet was measured using a standard Hall probe and Labview data acquisition application. The field was measured along the vertical and horizontal sides, as well as through the center of the magnet. The data was then compared to computationally produced data for a SCM of the same dimensions and various amounts of current. The results are shown in Figures 3.22 and 3.23. Figure 3.22 shows the simulated flux density curve using a current value of 1930 A-T. Figure 3.23 shows the experimental flux density using the Hall probe data. The slight magnetic anomaly on the right peak of the experimental data curve, Figure 3.23, is most likely due to demagnetization from the longstanding relative motion of the coils.

The comparisons between computational and experimental data for two multi-turn coils is shown in Figures 3.24 through 3.29. Figures 3.24, 3.25, and 3.26 shows corresponding lift, guidance, and drag comparisons for the nine-turn series coil. Overall, the results for this coil were excellent, with only around a 5% difference between the computer-based results and the experimental results.

FIGURE 3.22 Calculated Flux Density Produced by a Superconducting Coil as a Function of Lateral Distance (SCM coil with 1930 A-T, simulating a permanent magnet 25.4 mm square by 3.2 mm thick)

FIGURE 3.23 Flux Density Measured on Permanent Magnet using Standard Hall Probe (magnet is 25.4 mm square by 3.2 mm thick)

Figures 3.27, 3.28, and 3.29 show the sample data comparisons for two five-turn parallel coils. Although the theoretical data maintains the same shape as the experimental data, there is a difference in magnitude between 20–25%, with the experimental being the larger of the two. Possible explanations for this discrepancy include the sensitivity of the system to slight changes in coil orientation, lack of coil symmetry due to method of creation, and difficulty in establishing the coil origin ($y = 0$).

FIGURE 3.24a Computer-Calculated Lift Force Impulse as a Function of Time for Nine-Turn Series Coil (25.4-mm $\times$ 66.7-mm $\times$ 4.3-mm null-flux coil incident upon a 25.4-mm by 25.4-mm square, 3.2-mm-thick SCM coil at $y = -10.2$ mm, $z = 5.65$ mm, and speed = 22.6 m/s)

FIGURE 3.24b Experimental Lift Force Impulse as a Function of Time for Nine-Turn Series Coil (25.4-mm $\times$ 66.7-mm $\times$ 4.3-mm null-flux coil incident upon a 25.4-mm square, 3.2-mm-thick NdFeB permanent magnet at $y = -10.2$ mm, $z = 5.65$ mm, and speed = 22.6 m/s)

FIGURE 3.25a Computer-Calculated Guidance Force Impulse as a Function of Time for Nine-Turn Series Coil (25.4-mm $\times$ 66.7-mm $\times$ 4.3-mm null-flux coil incident upon a 25.4-mm square, 3.2-mm-thick SCM coil at $y = -10.2$ mm, $z = 5.65$ mm, and speed = 22.6 m/s)

FIGURE 3.25b Experimental Guidance Force Impulse as a Function of Time for Nine-Turn Series Coil (25.4-mm $\times$ 66.7-mm $\times$ 4.3-mm null-flux coil incident upon a 25.4-mm square, 3.2-mm-thick NdFeB permanent magnet at $y = -10.2$ mm, $z = 5.65$ mm, and speed = 22.6 m/s)

FIGURE 3.26a Computer-Calculated Drag Force Impulse as a Function of Time for Nine-Turn Series Coil (25.4-mm $\times$ 66.7-mm $\times$ 4.3-mm null-flux coil incident upon a 25.4-mm square, 3.2-mm-thick SCM coil at $y = -10.2$ mm, $z = 5.65$ mm, and speed 22.6 = m/s)

FIGURE 3.26b Experimental Drag Force Impulse as a Function of Time for Nine-Turn Series Coil (25.4-mm $\times$ 66.7-mm $\times$ 4.3-mm null-flux coil incident upon a 25.4-mm square 3.2-mm-thick NdFeB Permanent magnet at $y = -10.2$ mm, $z = 5.65$ mm, and speed = 22.6 m/s)

FIGURE 3.27a Computer-Calculated Lift Force Impulse as a Function of Time for Two Five-Turn Parallel Coils (26.4-mm $\times$ 62.0-mm $\times$ 5.8-mm null-flux coil incident upon a 25.4-mm square, 3.2-mm-thick permanent magnet at $y = -10.2$ mm, $z = 6.67$ mm, and speed = 22.6 m/s)

FIGURE 3.27b Experimental Lift Force Impulse as a Function of Time for Two Five-Turn Parallel Coils (26.4-mm $\times$ 62.0-mm $\times$ 5.8-mm null-flux coil incident upon a 25.4-mm square, 3.2-mm-thick NdFeB permanent magnet at $y = -10.2$ mm, $z = 6.67$ mm, and speed = 22.6 m/s)

FIGURE 3.28a Computer-Calculated Guidance Force Impulse as a Function of Time for Two Five-Turn Parallel Coils (26.4-mm $\times$ 62.0-mm $\times$ 5.8-mm null flux coil incident upon a 25.4-mm square, 3.2-mm-thick permanent magnet at $y = -10.3$ -mm, $z = 6.67$ -mm, and speed = 22.6 m/s)

FIGURE 3.28b Experimental Guidance Force Impulse as a Function of Time for Two Five-Turn Parallel Coils (26.4-mm $\times$ 62.0 mm $\times$ 5.8-mm null-flux coil incident upon a 25.4-mm square, 3.2-mm-thick, NdFeB permanent magnet at $y = 10.3$ mm, $z = 6.67$ mm, and speed = 22.6 m/s)

FIGURE 3.29a Computer-Calculated Drag Force Impulse as a Function of Time for Two Five-Turn Parallel Coils (null-flux coil: length = 26.4-mm, height = 62.0 mm, and thickness = 5.8 mm; permanent magnet: length = 25.4 mm, height = 25.4, and thickness = 3.2 mm; magnet coordinates: $y = -10.3$ mm, $z = 6.67$ mm, and speed = 22.6 m/s)

FIGURE 3.29b Experimental Drag Force Impulse as a Function of Time for Two Five-Turn Parallel Coils (null-flux coil: length = 26.4 mm, height = 62.0 mm, and thickness = 5.8 mm; permanent magnet: length = 25.4 mm, height = 25.4, and thickness = 3.2 mm; NdFeB permanent magnet at $y = -10.3$ mm, $z = 6.67$ mm, and speed = 22.6 m/s)

4 Conclusions

The figure-eight-shaped null-flux coil suspension is an important maglev concept developed in Japan during the past decade. The concept has many advantages over other suspension systems. In particular, it provides very high lift-to-drag or lift-to-guidance ratios with a relatively simple configuration.

A computer code named "COILGDWY" was developed at ANL to simulate the performance of the figure-eight-shaped null-flux coil suspension system. The code can be used to simulate a superconducting coil (or vehicle coil) moving above a figure-eight-shaped null-flux coil guideway. Three-dimensional magnetic forces acting on the vehicle coils as functions of time or displacement can be determined. Design parameters for a maglev system can be obtained from the simulations.

A laboratory model consisting of a rotating PVC drum mounted with several groups of figure-eight-shaped null-flux coils interacting with a permanent magnet was constructed for the verification of the computer code. Transient magnetic forces were measured and compared with the results obtained from the computer model. Good agreement between the experimental results and the computer simulation was obtained. Although the verification was made at a small scale, the computer code is expected to be valid for large-scale simulations because of the linearity of the EDS maglev system.

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