EDGE EFFECTS ON FORCES AND MAGNETIC FIELDS PRODUCED BY A CONDUCTOR MOVING PAST A MAGNET

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***Abstract*-Experiments were performed to further understand the forces acting on magnets moving near the edge of a conducting strip and to produce a data set for the validation of analysis methods. Mapping the magnetic field gives information about the eddy currents induced in the conductor, which agrees with numerical calculations.**

INTRODUCTION

In a typical maglev design, rectangular superconducting magnets on the moving vehicles induce eddy currents in conducting guideways to achieve levitation by repulsion. The lift forces F_L, created by the opposing magnetic field of the eddy currents, and the drag forces F_D, created by eddy-current losses, are well understood for infinite conducting sheets [1]. Eddy currents in the conducting side walls of U-shaped guideways can produce the lateral forces necessary to guide the vehicle. This guidance force F_G is predictable for infinite conducting sheets. Guidance can also be accomplished by suspending the vehicle so that it overlaps the two flat parallel conductors in a split-guideway system [2-5].

If a magnet moves near the edge of a conductor, as shown in Fig. 1, a lateral repulsive force F_y tries to push it off the edge. In one of the earliest experimental and theoretical investigations of edge effects [6], F_L, F_D, and F_y were determined for a rectangular superconducting magnet held stationary over a rotating aluminum drum at different distances Y* of the magnet from the edge of the conductor. The drum was solid and simulated a very thick ($T \to \infty$) and fast-moving (140 m/s) guideway of width W. The lift force F_L was found to be reduced only slightly (20%) as the coil was moved at a constant height from the centered to the edge-aligned position ($Y^* = 0$), while F_y increased from 0 to 30% of F_L. Also, $(F_L+F_y)/F_D$ remained constant for all lateral positions, and edge effects were significant only when $Y^* < 2h$.

If the vehicle moves over the center of a guideway consisting of two parallel conducting strips, a stable guidance force can result from combining the lateral repulsive forces of the two individual strips [2-5]. Also, the same superconducting magnets can provide lift, guidance, and propulsion. In one such design [3,4], the magnets over-

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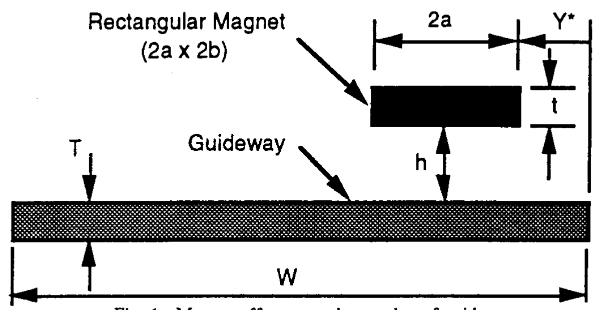

Fig. 1. Magnet offset toward one edge of guideway.

lapped each strip by less than 5% ($Y^* \leq -1.9a$ in Fig. 1). While the measured F_L were only 3% of the lift that would be obtained over the center of a wide conducting sheet, the guidance force was as large as the lift force. The lift-to-drag ratio F_L/F_D was small and depended in a sensitive way on the amount of overlap and magnet height. Also, no drag peak was observed.

In contrast, analysis of a closely-spaced linear array of magnets with alternating polarity over two parallel conducting strips showed drag peaks, and F_L/F_D became larger as the overlap of the magnets and the strips was minimized [5].

The purpose of our experiments is to further investigate edge effects and provide experimental results that can be used for validation of analysis methods. The experimental geometry investigated is similar to that of Borcherts and Davis [6], but $Y^* < 0$ are also tested to cover the range of parallel-strip guideway designs.

EXPERIMENTAL APPARATUS

We measured the steady-state forces acting on a rectangular FeBNd permanent magnet positioned above an aluminum (6061-T6) strip moving at surface velocities up to 36 m/s on the circumference of a 1.2-m-diameter flywheel. The test parameters were: 2a = 25.4 mm, 2b = 50.8 mm, T = t = 6.4 mm, W = 101.6 mm, h = 5 to 12.7 mm, and Y* = 38.1 to -38.1 mm. The out of roundness of the rim varied across its width, but was always less than ± 0.8 mm. The magnet was held stationary by a two-component force transducer, comprised of two single-component BLH C2G1 load cells. To measure all three force components, two different orientations of the force transducer were used for each magnet position and strip velocity. Agreement of the force component common to the two transducer orientations provided a measure of the experimental accuracy.

Magnetic fields for the centered, edge-aligned, and 25%-overlap positions of the magnet (Y^* = 38.1, 0, and -28.6 mm, respectively) were measured by moving a single-component F. W. Bell (HTG-1-0608) gaussmeter probe parallel to the centerlines and longitudinal edges of the magnet. The sensing area of the Hall-effect element was less than 2 mm in diameter. All three field components (in the lift, drag, and lateral directions) were measured for a magnet height of 12.7 mm and a probe height of 5.9 mm. The magnetic fields due to the eddy currents induced in the moving guideway were determined by subtracting the magnetic fields with the flywheel at rest from the fields with the flywheel moving.

Ability to exactly position the magnet and gaussmeter probe, with respect to the guideway and to each other, dominated our experimental error, estimated at ± 5%.

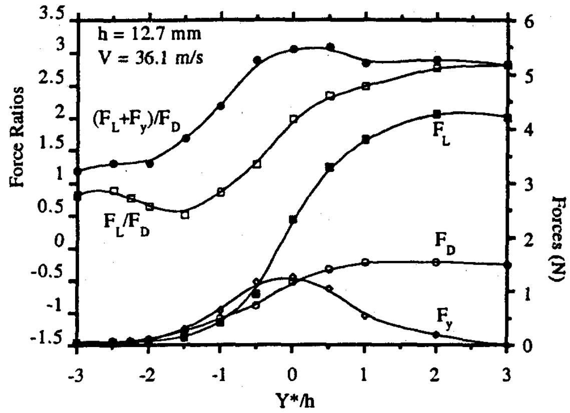

Fig. 2. Effects of proximity of guideway edge on magnetic forces and their ratios

DISCUSSION OF RESULTS

Force measurements were made for the centered magnet position (Y^* = 38.1 mm) and compared to closed-form solutions for a single current-carrying coil at different coil currents [1]. A 25.4- x 50.8-mm rectangular coil with a current of 6000 A, located at the center height of the magnet, gave excellent quantitative fits to the measured forces at all magnet heights and velocities.

The measured lift and drag forces were found to decrease by one to two orders of magnitude as Y^*/h was decreased and the magnet was moved off the edge of the guideway. Figure 2 shows typical results at V = 36.1 m/s and h = 12.7 mm. The maximum lateral force occurred when the edges of the magnet and guideway were nearly flush. In contrast to the experimental results for a thick guideway at high speeds and the theory for a thin guideway in the high-speed limit [6], the lift force in Fig. 2 is reduced by factors of two to three due to the presence of the edge. This suggests that eddy-current skin depth and surface area of the edge are both important.

The force ratios (F_L/F_D) and [$(F_L+F_y)/F_D$] decreased significantly as the magnet was moved off the edge of the guideway. The F_L/F_D ratio recovered slightly when the magnet was almost completely off the guideway ($Y^* < -2h$). The $(F_L+F_y)/F_D$ ratio was nearly constant when the magnet and guideway completely overlapped ($Y^* \geq 0$), as previously shown [6], and in the region of F_L/F_D recovery, as previously suspected [4]. The recovery region was identified [4] as optimal for the design of dual-strip guideways using gap-spanning magnets only, although the data suggest that positions with more magnet and guideway overlap can produce larger guidance forces and lift-to-drag ratios.

Magnetic field measurements for Y^* = 0, shown in Fig. 3, suggest that the eddy currents are concentrated near the edge of the guideway. Eddy-current directional patterns in the guideway were extrapolated from the magnetic field data and added to Fig. 3. Clearly, some eddy currents must flow on the conductor's edge, especially at higher velocities.

As the velocity increases from 4.5 to 36.1 m/s, the shift toward the rear of the eddy currents (the transition to the high-speed limit) was inhibited near the guideway's edge, as previously observed [7] for all eddy currents at a very small overlap of the magnet and guideway (Y^* = -1.9a). The eddy currents away from the edge of the rim showed more of a shift. Smaller shifts were observed for Y^* = -28.1 mm, and again the eddy currents closer to the edge were inhibited more. Finally, no distinct drag force peak was observed when the magnet overlapped the edge of the guideway.

The above results are corroborated using the finite-element code ELECTRA[1], where we modeled the magnet as a rectangular coil with the same outside dimensions. The calculated forces agreed with the measured forces to ±10%. Eddy currents in a plane just below the upper surface of the guideway are shown in Fig. 4. When the outside edge of the coil is at the edge of the guideway (Y^* = 0), the center of each eddy-current vortex is somewhat closer to the inside corners of the coil and the eddy current density at the guideway's edge is much larger than when the coil is near the center of the guideway (Y^* = 25.4 mm). The inhibition of the shift toward the rear of the vortex center with increased velocity is attributed to the more rapid lateral diffusion of this higher-density edge current into the coil's immediate wake. Similar behavior is seen for $Y^* < 0$ and could account for the absence of a drag peak as the velocity increases.

For $Y^* < 0$, examination of current density shows a tendency for the current to run along the guideway edge. This suggests that F_y could be increased by thickening the guideway along the edge.

CONCLUSIONS

An FeBNd permanent magnet can be successfully used to study magnetic fields and forces near the edge of a conductor,

[1]Vector Fields, Ltd., 24 Bankside, Kidlington, Oxford OX51JE,England

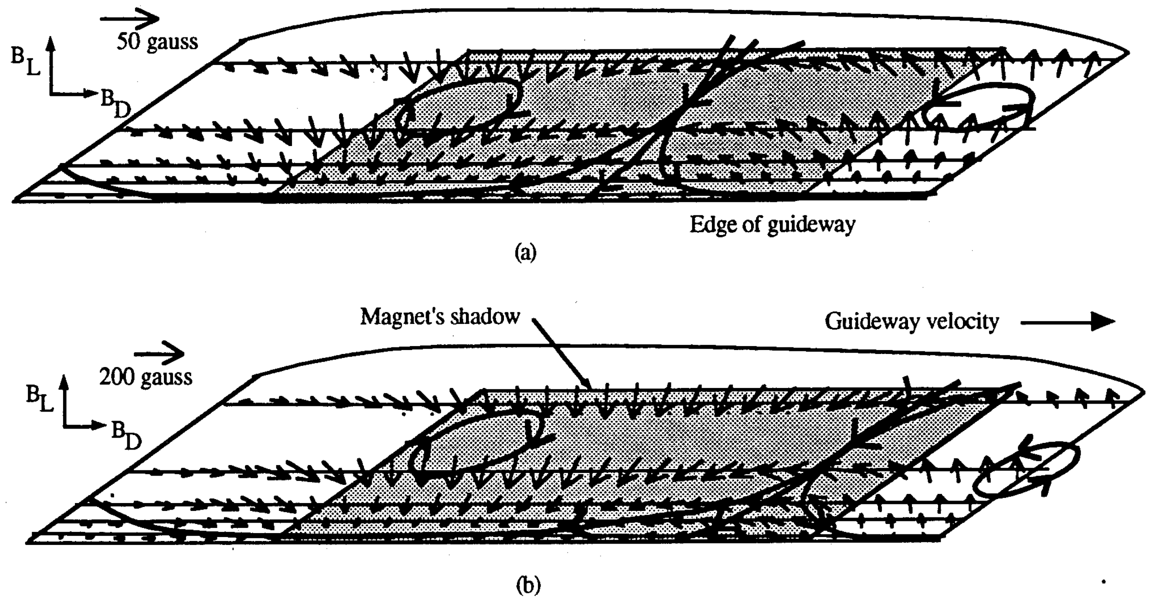

Fig. 3. Magnetic field in lift and drag directions at 5.9 mm above guideway for Y* = 0: (a) V = 4.5 m/s, and (b) V = 36.1 m/s.

in order to validate analytical methods for analyzing forces in a parallel-conductor maglev design.

Agreement between our experimental results and those obtained by finite-element calculations using the ELECTRA computer code were acceptable. The force ratio $(F_L+F_y)/F_D$ cannot be assumed constant for $Y^* \leq 0$, as was found for $Y^* \geq 0$ [6]. The sensitivity of the forces to the surface area of the edge of the conductor remains to be determined, especially at high velocities. For increasing velocities, the shifts toward the rear of the two opposing guideway eddy-current loops were inhibited over all or part of the current field, depending on the amount of magnet-guideway overlap.

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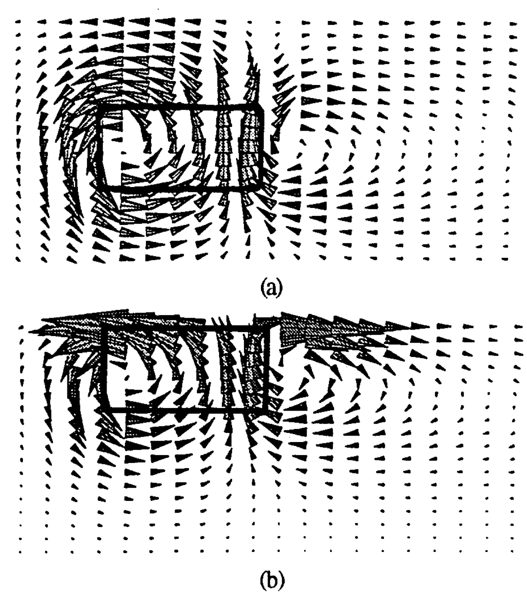

Fig. 4 Eddy-current distribution just below top surface of guideway for V = 40 m/s: (a) Y* = 25.4 mm and (b) Y* = 0. Coil is moving left.