DESIGNING CONCRETE EDS MAGLEV GUIDEWAYS: POWER LOSSES IN METALLIC REINFORCEMENT

By David Beto[1] and Don Plotkin[2]

(Reviewed by the Urban Transportation Division)

ABSTRACT: Conventional reinforced concrete designs will have to be altered when designing a guideway for a maglev using an electrodynamically suspended (EDS) propulsion system. This type of propulsion system generates large magnetic fields that will develop magnetically induced, circulating eddy currents in any conventional steel reinforcement in close proximity to the magnets. These eddy currents, if large enough, may produce significant power losses that could adversely effect operation of the system. This paper presents a method and explanation for civil engineers to use for estimating the power losses due to the presence of metallic reinforcement. This procedure may be used to help guide future designs in the selection and placement of reinforcing material.

INTRODUCTION

A maglev that uses an electrodynamically suspended (EDS) system (using repelling magnetic forces) for propulsion and guidance will generate large magnetic fields within an area near the propulsion and guidance magnets. If metallic reinforcement is present in the guideway near these magnets, large eddy currents may be induced in the reinforcement as the maglev passes, resulting in unacceptably large power losses.

Civil engineers need to have a method for estimating potential power losses to guide the selection and placement of reinforcing material in a concrete EDS maglev guideway.

The method shown here is adapted from one used by the Bechtel Corporation (Bechtel Corp., San Francisco, Calif., unpublished internal report, 1992). After some manipulation and reorganization, these equations were put into a form that could be used to study beams from any type of EDS design. Full explanation of assumptions and typical examples can be found in Beto and Plotkin (U.S. Army Construction Engineering Research Laboratories, Champaign, Ill., unpublished draft technical report, 1996).

The method covers power loss only in the longitudinal reinforcement; losses in the lateral reinforcement are thought to be negligible. Neither are losses due to drag and other effects included. The method also assumes a circular cross sectional shape for the reinforcement.

THE METHOD

Reasonable estimates of propulsion system-related values needed to use this method should be available, even in the early stages of propulsion system design. Primarily, a magnetic field map showing magnetic field strengths at various distances from the propulsion and levitation magnets is needed. As magnetic field strengths may vary along the vehicle length, maps showing maximum and minimum fields may be needed. Examples are given in Figs. 1 and 2, which show a cross sectional view of the guideway beam, including proposed placement of longitudinal reinforcing. Contour lines indicate the magnetic field strength at given distances from the magnets. Values for common metallic material that might be used in guideway construction are given in Table 1. Equations for determining power loss are given in the proceeding, with an explanation of variables following.

The general procedure involves making a calculation of power loss for transverse and axial fields for each field strength level (contour line) shown on the magnetic field map and summing the results to obtain total power loss. As magnetic field strength may vary along the vehicle length, minimum and maximum values may be computed and properly weighted to determine a realistic average power loss. In addition to changes in magnetic field strength, separate calculations would also be required where reinforcement properties (material type or size) change.

Note that where the radius of the reinforcement (R) is much greater than the skin depth (δ), as would be true for conventional steel reinforcement, (3) and (5) apply, and the power loss from axial fields is one half the power loss from transverse fields. Note also that power loss varies with the square of the magnetic field strength level. To determine skin depth

$$\delta = (2\rho/\omega\mu)^{1/2} \qquad (1)$$

To determine power loss from transverse fields (along the length of the conductor)

$$\text{where } R << \delta,\ P_d = (\rho R^2/2\delta^4)(2\mu_o/\mu + \mu_o)^2|H_o|^2 \qquad (2)$$

$$\text{where } R >> \delta,\ P_d = (2\rho/R\delta)|H_o|^2 \qquad (3)$$

To determine power loss from axial fields (in the radial direction along the cross section, or radius, of the conductor)

$$\text{where } R << \delta,\ P_d = (\rho R^2/4\delta^4)|H_o|^2 \qquad (4)$$

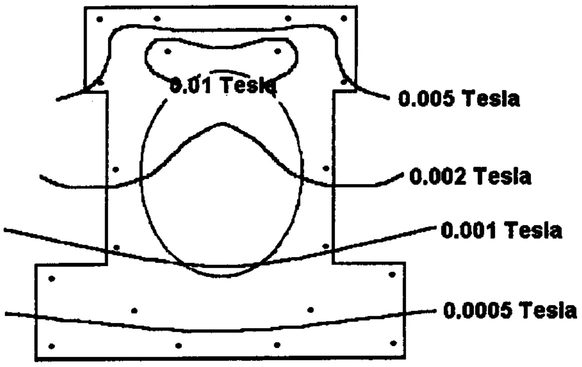

FIG. 1. Magnetic Field Distribution across Guideway Beam at Minimum Field Level

---

[1] Res. Asst., U.S. Army Constr. Engrg. Res. Lab., P.O. Box 9005, Champaign, IL 61826-9005.

[2] Civ. and Railway Engr., U.S. Army Constr. Engrg. Res. Lab., P.O. Box 9005, Champaign, IL.

Note. Discussion open until November 1, 1997. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on January 26, 1996. This paper is part of the *Journal of Transportation Engineering*, Vol. 123, No. 3, May/June, 1997. ©ASCE, ISSN 0733-947X/97/0003-0192–0194/$4.00 + $.50 per page. Paper No. 12522.

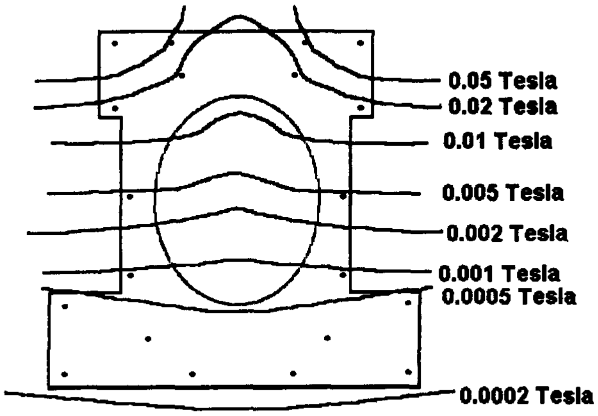

FIG. 2. Magnetic Field Distribution across Guideway Beam at Maximum Field Level

$$\text{where } R >> \delta,\ P_d = (\rho/R\delta)|H_o|^2 \qquad (5)$$

The physical properties of reinforcing steel are δ, ρ, R, and μ, where δ = the skin depth of a conductor. For any good conductor there is a skin effect wherein time-varying magnetic fields create induced currents that, in turn, create a reaction magnetic field that prevents current from penetrating very far into the conductors. The skin effect causes both the magnetic field density and the electric current density to attenuate exponentially with distance into the conductor. The distance required to attenuate by a factor $e = 2.718$ is called the skin depth. A small value of δ means fields do not penetrate very far into the metal.

ρ = the electrical resistivity of a conductor. It is the electrical resistance of a uniform rod of unit length and unit cross sectional area. R = the radius of the reinforcement, and μ = the permeability of a conductor, that is, the ease with which a field can establish magnetic induction in a particular material. The permeability of air is very low compared to that of most metals and thus is the reason we use metal wire to carry electric current.

The properties of magnetic fields are μ_o, P_d, $|H_o|$, and ω, where μ_o = the permeability of free space = $4\pi \times 10^{-7}$ Volt-s/Amp-m. P_d = power loss. In this case, it's the amount of power dissipated per unit volume of reinforcing material. $|H_o|$ = the strength of the magnetic field in amperes per meter, and ω = the frequency of the sinusoidal power input in rads/s.

EXAMPLE

The following example will demonstrate employment of the method and illustrate the effect of conventional steel reinforcement located near magnets in the guideway of an EDS maglev.

Initial design of an EDS maglev calls for a 30-m long vehicle with a maximum total propulsion, levitation, and guidance power output of 7 MW and a frequency of 60 Hz. The distribution of magnetic fields is sinusoidal along the length of the vehicle. The guideway beam, initial placement of reinforcement, and magnetic field maps at minimum and maximum points of the sinusoidal wave are given in Figs. 1 and 2. The radius of the reinforcement is 6 mm. Values for mild steel reinforcement are as shown in Table 1, and the following are obtained:

$$\omega = (2\pi \text{ rads})(60 \text{ Hz}) = 120\pi \text{ rads/s}$$

$$\delta = [(2)(0.118 \times 10^{-6})/(120\pi)(4\pi \times 10^{-7})(5{,}000)]^{1/2}$$

$$= 3.16 \times 10^{-4} \text{ m}$$

In Fig. 1, there are two reinforcing strands in the 0.01 Tesla area.

TABLE 1. Electrical Properties of Common Metals at 20°C

Material (1)	μ/μ_o (2)	ρ (μohm-m) (3)	δ at 60 Hz (mm) (4)
Copper	1	0.01724	8.5
Aluminum	1	0.0283	10.9
Steel: mild	5,000	0.118	0.316
Steel: stainless	1	0.910	62.0

TABLE 2. Summary of Power Losses from Example

Magnetic field strength level (Tesla) (1)	Minimum Field Level		Maximum Field Level	
	Number of reinforcing strands (2)	Power loss (kW/m) (3)	Number of reinforcing strands (4)	Power loss (kW/m) (5)
0.0500	—	—	4	134.00
0.0200	—	—	4	21.44
0.0100	2	2.68	—	—
0.0050	6	2.01	2	0.67
0.0020	2	0.11	—	—
0.0010	2	0.03	2	0.03
0.0005	6	0.02	4	0.01
0.0002	—	—	4	0.00

Note: Total power loss for column (3) = 4.85; total power loss for column (5) = 156.15.

$$n = \text{number of reinforcing strands} = 2$$

$$\mu_o H_o = 0.01 \text{ T (or 0.01 Tesla)}$$

$$H_o = 0.01 \text{ T}/4\pi \times 10^{-7} \text{ Volt-s/Amp-m} = 7{,}957.75 \text{ A/m}$$

As R (6 mm) is much larger than δ (0.316 mm), (3) and (5) are used. Power loss from transverse fields is as follows:

$$P_t = [2\rho/R\delta]|H_o|^2 = [(2)(0.118 \times 10^{-6})/(.006)$$

$$\cdot(3.156 \times 10^{-4})]|7{,}957.75|^2 = 7.89 \text{ MW/m}^3$$

Power loss from axial fields is as follows:

$$P_a = 1/2 \times \text{transverse power loss} = 3.95 \text{ MW/m}^3$$

Total loss at 0.01 Tesla level is

P_{t1} = loss per volume of reinforcement (transverse

+ axial field losses) = 7.89 MW/m^3 + 3.95 MW/m^3

= 11.84 MW/m^3

Area of reinforcement = $n\pi R^2 = 2\pi(.006)^2 = 2.26 \times 10^{-4}$ m^2

P_{t1} = loss per meter of guideway length = 11.84 MW/m^3 × 2.26

× 10^{-4} m^2 = 2.68 kW/m

The power losses for remaining field strength levels at the minimum field level and maximum field level are given in Table 2. The final step is to figure the total average power loss over the length of the maglev. At minimum field, P = 4.85 kW/m × 30 m = 145.5 kW = 0.1455 MW and at maximum field P = 156.15 kW/m × 30 m = 4,684 kW = 4.684 MW. For a sinusoidal distribution, the average power is calculated as follows:

$$P_{avg} = P_{min} + [2P_{max}/\pi] \qquad (6a)$$

$$P_{avg} = 0.1455 \text{ MW} + [2(4.68 \text{ MW})/\pi] \qquad (6b)$$

$$P_{avg} = 3.12 \text{ MW} \qquad (6c)$$

As the maximum power for the vehicle was given as 7 MW, this would represent a 45% power loss due to the steel reinforcement, far above an acceptable level.

SUMMARY AND RECOMMENDATIONS

The method presented here is for estimating primary power losses in a concrete EDS maglev guideway due to magnetically induced currents in metallic reinforcing. This method can be used by guideway designers to help in the selection and placement of reinforcing to minimize power losses. Where alterations in placement or reinforcement type still result in excessive power loss, the method can be used to help guide changes in guideway geometry to reduce power loss to acceptable levels.

Through experimenting with the method and assessing the results with respect to various propulsion system and beam designs, the writers offer the following basic guidelines for using the method and for keeping power losses within acceptable levels:

1. Do not estimate a field distribution; doing so may result in large errors. Obtain a field map from the propulsion system designers.
2. As a general rule, try to limit conventional steel reinforcement to areas with a magnetic field strength less than 0.001 Tesla.
3. Find the total power loss in the reinforcement by determining the power loss for each magnetic field strength level along the vehicle length, and each reinforcement size and type, and adding the results. This should give a rough idea of whether the placement of the reinforcement is acceptable.
4. If the power loss is excessive, use the equations to make adjustments to the design to bring the power loss within acceptable limits.

ACKNOWLEDGMENTS

This work was performed as part of the National Maglev Initiative, a government-industry consortium in which the U.S. Army Corps of Engineers participated. The Corps performed guideway design, construction, and cost analyses under the direction of the Huntsville Division. The work performed by the U.S. Army Construction Engineering Research Laboratories was directed by Ilker Adiguzel and Simon Kim.