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ANALYTICAL FORMULATION AND COMPUTER CODES FOR PARAMETRIC STUDIES OF A MAGLEV TRANSPORTATION SYSTEM

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16. Abstract

This report presents an analytical formulation and a description of its attendant computer codes for parametric studies of suspension and propulsion subsystems in a magnetically levitated vehicle (MAGLEV) transportation system. The analytical formulation involves the use of Fourier transforms and Maxwell's equations in solving a boundary-value problem (the formulation is given in Section 2, a reader who is not familiar with those topics may want to skip the section). The computer codes are versatile in that many design alternatives can be analyzed by simply changing some parameter values. Two specific design alternatives are studied using the computer codes. One is a combined propulsion and suspension subsystem using a linear induction motor (LIM). Another is a combined suspension subsystem using both permanent magnets and electromagnets. With minor modifications, the analysis and the computer codes can be utilized for design studies of magnetic field shielding. Some specific passive and active shielding examples are also given.

17. Key Words High Speed Ground Transportation, Magnetic Levitation (MAGLEV), Linear Induction Motor (LIM), Linear Synchronous Motor (LSM), Electromagnetic Suspension (EMS), Electrodynamic Suspension (EDS), Magnetic Field Shielding

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CONTENTS

FIGURES

FIGURES (CONTINUED)

FIGURES (CONTINUED)

FIGURES (CONCLUDED)

1.0 INTRODUCTION

There are many design alternatives for the propulsion and suspension subsystems of a magnetically levitated vehicle (MAGLEV). Over the last thirty years, many analyses and tests have been performed to study the performances of various design alternatives (References 1-7). References 1 and 2 give an overview of different MAGLEV designs and their advantages and disadvantages. The designs that have been reviewed in the references include the various U.S., Japanese, and German prototype systems. References 3-7 and the references quoted therein, and many others, present very diverse analytical and test results of the performance of subsystem design alternatives. The results cover the electromagnetic (EMS, or attractive) and the electrodynamic (EDS, or repulsive) suspension subsystems as well as linear induction motor (LIM) and linear synchronous motor (LSM) propulsion subsystems. Generally, a different analysis was used for each design alternative. This is undesirable for a design engineer because it makes his job more tedious. To simplify the design process a generic analysis has been performed and the formulas have been implemented into computer codes so that many design alternatives can be investigated by simply changing input parameter values. The following paragraphs describe some types of analyses capable of being performed by the computer codes developed on this program.

Linear induction motors (LIM) have been suggested as candidates for MAGLEV propulsion. Questions then arose as to whether they can provide enough propulsion and levitation forces simultaneously (References 2 and 7). The computer codes developed in this study can be used to help answer this question. This analysis is done by using the program described later in this report.

Recently, the concept of using permanent magnets as primary attractive suspension sources and electromagnets for stability control was re-initiated due to the advance in the permanent magnet technology (References 8 and 9). The computer codes developed and presented in this report in program described later can also be used to address the feasibility of this concept.

Effects of magnetic fields on humans have become a public concern. With the necessity of generating strong magnetic forces to accelerate and levitate the vehicles, large stray magnetic fields may be produced. These stray magnetic fields may erase stored data in onboard magnetic devices or cause other problems. Keeping the stray magnetic fields small in certain areas by shielding is indeed desirable. This is especially a problem when superconducting coils are used in a repulsive suspension subsystem. There are two shielding schemes available, passive and active, for such a purpose. The performances of the two shielding schemes can also be studied by the same generic analysis, with minor modifications on the computer codes mentioned in the last two paragraphs. The program presented later in this report can be used to analyze this problem.

In this report, Section 2.0 describes the scientific theory and mathematical formulations for the analysis. Sections 3.0 and 4.0 give example results of the design alternatives and shielding schemes. Section 5.0 is a user's manual on the use of the programs. The analysis makes use of the Fourier transforms and Maxwell's equations to solve a boundary-value problem. A reader who is not familiar with those topics may want to skip Section 2.

2.0 MATHEMATICAL FORMULATION

The four layered structure is shown in Figure 1. In this structure, layers 1 and 4 are taken to be non-conducting (either free space or infinitely thin laminated iron), layer 3 is free space, and layer 2 can be the reactive track having a constant uniaxial conductivity or free space. Layers 1, 2 and 4 are allowed to have uniaxial permeabilities. The uniaxial parameter values are used to approximate various material constructions, such as laminated irons, which may have different material properties in different directions. The magnetic-field sources, either current loops or magnet poles, are taken to be at the interface of layers 3 and 4, at the interface of layers 2 and 3, or at both interfaces. Layer 4 and the source at the interface of layers 3 and 4 can thus simulate the vehicle, while layers 1 and 2 and any possible source at the interface of layers 2 and 3 can simulate the guideway, or vice versa. The magnetic configurations described in Section 1.0 can be analyzed by doing a generic analysis on a four layer structure and assigning the appropriate characteristics to each layer. Since, in operation, there is a relative velocity between the vehicle and the guideway, the combined layers 1 and 2 are allowed to have a velocity (v) with respect to layer 4 which is taken to be stationary. Maxwell's equations in a moving medium together with Fourier transforms are used for the analysis.

Maxwell's equations involving moving magnetic material are complicated. However, with displacement currents and relativistic effects neglected, the Maxwell equations governing the electromagnetic behavior of the moving layers 1 and 2 are simplified to:

$$\begin{aligned} \nabla \times \underline{E} &= -\frac{\partial \underline{B}}{\partial t} \\ \nabla \times \underline{H} &= \underline{J} \\ \underline{J} &= \underset{\sim}{\sigma} \cdot (\underline{E} + \underline{v} \times \underline{B}) \\ \underline{B} &= \underset{\sim}{\mu} \cdot \underline{H} \end{aligned} \tag{1}$$

where $\underline{E}$ and $\underline{H}$ are the electric and magnetic field intensity vectors, respectively, $\underline{B}$ is the magnetic induction vector, $\underline{J}$ is the current-density vector, $\underline{v}$ is the velocity of the medium, $\underset{\sim}{\mu}$ and $\underset{\sim}{\sigma}$ are the permeability and conductivity tensors of the medium. The computer program described in this report allows the user to set conditions and/or parameters in the four layers and then solves the equations to provide levitation, thrust, and field strength. The remainder of this section provides details of the mathematical solution, and in subsections (i), (ii) and (iii), levitation, propulsion and shielding programs are discussed. Sample analyses are developed in Sections 3.0 & 4.0. The

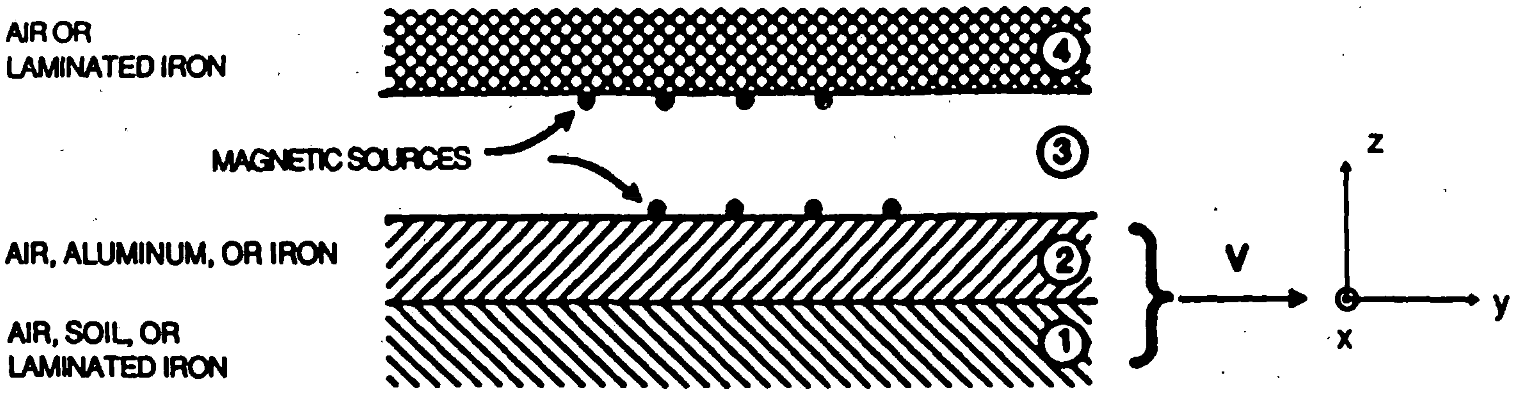


Figure 1. Four layered model of a generic MAGLEV system.

Note: The x axis is the lateral axis with the positive direction, +x, pointing out of the plane of the paper.

above coupled equations can be decoupled (between $\underline{E}$ and $\underline{H}$) to obtain, for a non-singular $\underset{\sim}{\sigma}$ (i.e., $\underset{\sim}{\sigma} \neq 0$),

$$\begin{aligned}
&\nabla \times [\underset{\sim}{\sigma}^{-1} \cdot (\nabla \times \underline{H})] = -\frac{\partial}{\partial t}(\underset{\sim}{\mu} \cdot \underline{H}) - (\underline{v} \cdot \nabla)(\underset{\sim}{\mu} \cdot \underline{H}) \\
&\nabla \times [\underset{\sim}{\mu}^{-1} \cdot (\nabla \times \underline{E})] = -\frac{\partial}{\partial t}(\underset{\sim}{\sigma} \cdot E) + \underset{\sim}{\sigma} \cdot (\underline{v} \times \nabla \times \underline{E}) \\
&\underline{J} = \underset{\sim}{\sigma} \cdot [\underline{E} + \underline{v} \times (\underset{\sim}{\mu} \cdot \underline{H}) \\
&\underline{B} = \underset{\sim}{\mu} \cdot \underline{H}
\end{aligned} \tag{2}$$

and, for $\underset{\sim}{\sigma} = 0$,

$$\begin{aligned}
&\nabla \times [\underset{\sim}{\mu}^{-1} \cdot (\nabla \times \underline{E})] = 0 \\
&\nabla \times \underline{H} = \underline{J} = 0 \\
&\nabla \cdot (\underset{\sim}{\mu} \cdot \underline{H}) = 0 \\
&\underline{B} = \underset{\sim}{\mu} \cdot \underline{H}
\end{aligned} \tag{3}$$

Equation 3 is applicable for layers 1, 2, and 4; Equation 2 for layer 2.

The following Fourier transform pair is then introduced to simplify partial differential equations (2) and (3) to ordinary differential equations.

$$\begin{aligned}
&\underline{A}(t, x, y, z) = \frac{1}{(2\pi)^2} \int \int_{-\infty}^{\infty} \int \tilde{\underline{A}}(\omega, k_x, k_y, z)\, e^{-i\omega t + ik_x x + ik_y y} d\omega\, dk_x\, dk_y \\
&\tilde{\underline{A}}(\omega, k_x, k_y, z) = \frac{1}{2\pi} \int \int_{-\infty}^{\infty} \int \underline{A}(t, x, y, z)\, e^{i\omega t - ik_x x - ik_y y} dt\, dx\, dy
\end{aligned} \tag{4}$$

With the use of Equation 4, a 3-dimensional problem can be solved. Limitations placed on such an approach are that it can not address detailed design features, such as, detailed magnet configurations, and that the edge effects due to a finite width of the reaction rail can not be analyzed.

By applying Equation 4 to Equation 3, one can express the non-trivial solutions for the magnetic induction ($\underline{\tilde{B}}$) in layers 1, 3, and 4 as below:

(a) layer 1 ($z \leq 0$)

$$
\begin{aligned}
\tilde{B}_{x1} &= I_x e^{k_{z1} z} \\
\tilde{B}_{y1} &= I_y e^{k_{z1} z} \\
\tilde{B}_{z1} &= I_z e^{k_{z1} z}
\end{aligned}
\qquad (5)
$$

with

$$
\begin{aligned}
k_{z1}^2 &= \frac{\mu_{1x}}{\mu_{1z}} k_x^2 + \frac{\mu_{1y}}{\mu_{1z}} k_y^2 \\
I_y &= \frac{\mu_{1y}}{\mu_{1x}} \frac{k_y}{k_x} I_x \\
I_z &= \frac{\mu_{1z}}{\mu_{1x}} \frac{k_{z1}}{i k_x} I_x
\end{aligned}
$$

(b) layer 3 ($h_2 \leq z \leq h_2 + h_3$)

$$
\begin{aligned}
\tilde{B}_{x3} &= \mathrm{III}_x^{(1)} e^{-k_z(z-h_2)} + \mathrm{III}_x^{(2)} e^{k_z(z-h_2)} \\
\tilde{B}_{y3} &= \mathrm{III}_y^{(1)} e^{-k_z(z-h_2)} + \mathrm{III}_y^{(2)} e^{k_z(z-h_2)} \\
\tilde{B}_{z3} &= \mathrm{III}_z^{(1)} e^{-k_z(z-h_2)} + \mathrm{III}_z^{(2)} e^{k_z(z-h_2)}
\end{aligned}
\qquad (6)
$$

with

$$
\begin{aligned}
k_z^2 &= k_x^2 + k_y^2 \\
\mathrm{III}_y^{(1)} &= \frac{k_y}{k_x} \mathrm{III}_x^{(1)} \\
\mathrm{III}_z^{(1)} &= i \frac{k_z}{k_x} \mathrm{III}_x^{(1)} \\
\mathrm{III}_y^{(2)} &= \frac{k_y}{k_x} \mathrm{III}_x^{(2)} \\
\mathrm{III}_z^{(2)} &= \frac{k_z}{i k_x} \mathrm{III}_x^{(2)}
\end{aligned}
$$

(c) layer 4 ($z \geq h_2+h_3$)

$$
\begin{aligned}
\tilde{B}_{x4} &= IV_x\, e^{-k_{z4}(z-h_2)} \\
\tilde{B}_{y4} &= IV_y\, e^{-k_{z4}(z-h_2)} \\
\tilde{B}_{z4} &= IV_z\, e^{-k_{z4}(z-h_2)}
\end{aligned}
\tag{7}
$$

with

$$
\begin{aligned}
k_{z4}^2 &= \frac{\mu_{4x}}{\mu_{4z}} k_x^2 + \frac{\mu_{4y}}{\mu_{4z}} k_y^2 \\
IV_y &= \frac{\mu_{4y}}{\mu_{4x}} \frac{k_y}{k_x} IV_x \\
IV_z &= \frac{\mu_{4z}}{\mu_{4x}} \frac{ik_{z4}}{k_x} IV_x
\end{aligned}
$$

Similarly, by applying Equation 4 to Equation 2, one can express the electric field intensity ($\underline{\tilde{E}}$) in layer 2 ($0 \leq z \leq h_2$) as

(d) layer 2 ($0 \leq z \leq h_2$)

$$
\begin{aligned}
\tilde{E}_{x2} &= (\Pi_{xe}^{(1)} \cosh k_z^{(1)} z + \Pi_{xo}^{(1)} \sinh k_z^{(1)} z) + (\Pi_{xe}^{(2)} \cosh k_z^{(2)} z + \Pi_{xo}^{(2)} \sinh k_z^{(2)} z) \\
\tilde{E}_{y2} &= (\Pi_{ye}^{(1)} \cosh k_z^{(1)} z + \Pi_{yo}^{(1)} \sinh k_z^{(1)} z) + (\Pi_{ye}^{(2)} \cosh k_z^{(2)} z + \Pi_{yo}^{(2)} \sinh k_z^{(2)} z) \\
\tilde{E}_{z2} &= (\Pi_{ze}^{(1)} \sinh k_z^{(1)} z + \Pi_{zo}^{(1)} \cosh k_z^{(1)} z) + (\Pi_{ze}^{(2)} \sinh k_z^{(2)} z + \Pi_{zo}^{(2)} \cosh k_z^{(2)} z)
\end{aligned}
\tag{8}
$$

and the magnetic induction ($\underline{\tilde{B}}$) as

$$
\begin{aligned}
i\omega\tilde{B}_{x2} = \Big\{ &\Big[(ik_y \Pi_{ze}^{(1)} - k_z^{(1)} \Pi_{ye}^{(1)}) \sinh k_z^{(1)} z\Big] + \Big[(ik_y \Pi_{zo}^{(1)} - k_z^{(1)} \Pi_{yo}^{(1)}) \cosh k_z^{(1)} z\Big] \\
&+ \Big[(ik_y\, \Pi_{ze}^{(2)} - k_z^{(2)}\, \Pi_{ye}^{(2)}) \sinh\, k_z^{(2)} z\Big] + \Big[(ik_y \Pi_{zo}^{(2)} - k_z^{(2)} \Pi_{yo}^{(2)}) \cosh k_z^{(2)} z\Big]\Big\} \\
i\omega\tilde{B}_{y2} = \Big\{ &\Big[(k_z^{(1)} \Pi_{xe}^{(1)} - ik_x \Pi_{ze}^{(1)}) \sinh k_z^{(1)} z\Big] + \Big[(k_z^{(1)} \Pi_{xo}^{(1)} - ik_x \Pi_{zo}^{(1)}) \cosh k_z^{(1)} z\Big] \\
&+ \Big[(k_z^{(2)}\, \Pi_{xe}^{(2)} - ik_x\, \Pi_{ze}^{(2)}) \sinh\, k_z^{(2)} z\Big] + \Big[(k_z^{(2)} \Pi_{xo}^{(2)} - ik_x \Pi_{zo}^{(2)}) \cosh k_z^{(2)} z\Big]\Big\} \\
i\omega\tilde{B}_{z2} = \Big\{ &\Big[(ik_x \Pi_{ye}^{(1)} - ik_y \Pi_{xe}^{(1)}) \cosh k_z^{(1)} z\Big] + \Big[(ik_x \Pi_{yo}^{(1)} - ik_y \Pi_{xo}^{(1)}) \sinh k_z^{(1)} z\Big] \\
&+ \Big[(ik_x\, \Pi_{ye}^{(2)} - ik_y\, \Pi_{xe}^{(2)}) \cosh\, k_z^{(2)} z\Big] + \Big[(ik_x \Pi_{yo}^{(2)} - ik_y \Pi_{xo}^{(2)}) \sinh k_z^{(2)} z\Big]\Big\}
\end{aligned}
\tag{9}
$$

with $k_z^{(1)}$ and $k_z^{(2)}$ satisfying

$$\begin{aligned}\mu_{2z}\sigma_z k_z^4 &- \Big[(\mu_{2z}\sigma_x + \mu_{2x}\sigma_z)k_x^2 + (\mu_{2z}\sigma_y + \mu_{2y}\sigma_z)k_y^2 - i(\omega - k_y v)\mu_{2z}\sigma_z(\sigma_x\mu_{2y} + \sigma_y\mu_{2x})\Big]k_z^2 \\ &+ \Big[\mu_{2x}k_x^2 + \mu_{2y}k_y^2 - i(\omega - k_y v)\mu_{2x}\mu_{2y}\sigma_z\Big]\Big[\sigma_x k_x^2 + \sigma_y k_y^2 - i(\omega - k_y v)\sigma_x\sigma_y\mu_{2z}\Big] = 0\end{aligned} \tag{10}$$

and $\Pi_{ye,o}^{(1,2)}$, $\Pi_{xe,o}^{(1,2)}$, $\Pi_{ze,o}^{(1,2)}$ related via

$$\begin{aligned}\Pi_{ye,o}^{(1,2)} &= R^{(1,2)}\,\Pi_{xe,o}^{(1,2)} \\ \Pi_{ze,o}^{(1,2)} &= Q^{(1,2)}\,\Pi_{xe,o}^{(1,2)} \\ R^{(1,2)} &= \frac{R_t^{(1,2)}}{R_b^{(1,2)}} \\ R_t^{(1,2)} &= \Big[\mu_{2x}k_x^2 + \mu_{2y}k_y^2 - i(\omega - k_y v)\mu_{2x}\mu_{2y}\sigma_z\Big] \\ &\quad \times\Big[\mu_{2y}k_y^2 - \mu_{2z}(k_z^{(1,2)})^2 - i(\omega - k_y v)\sigma_x\mu_{2y}\mu_{2z}\Big] + \mu_{2x}\mu_{2z}k_x^2(k_z^{(1,2)})^2 \\ R_b^{(1,2)} &= \mu_{2y}k_x\Big\{(k_y + i\sigma_x v\mu_{2z})\Big[\mu_{2x}k_x^2 + \mu_{2y}k_y^2 - \mu_{2z}(k_z^{(1,2)})^2 - i(\omega - k_y v)\mu_{2x}\mu_{2y}\sigma_z\Big] \\ &\quad - i\mu_{2z}(k_z^{(1,2)})^2 v(\mu_{2x}\sigma_z - \mu_{2z}\sigma_x)\Big\} \\ Q^{(1,2)} &= \frac{-k_z^{(1,2)}\Big[i\mu_{2x}k_x + (ik_y - v\mu_{2x}\sigma_z)\,\mu_{2y}\,R^{(1,2)}\Big]}{\mu_{2x}k_x^2 + \mu_{2y}k_y^2 - i(\omega - k_y v)\,\mu_{2x}\mu_{2y}\sigma_z}\end{aligned} \tag{11}$$

In the above equations, σ_n ($n = x, y$, or z) is the conductivity of layer 2 in the x,y,z direction, i.e.,

$$\underset{\sim}{\sigma} = \hat{x}\hat{x}\sigma_x + \hat{y}\hat{y}\sigma_y + \hat{z}\hat{z}\sigma_z \ ,$$

and μ_{mn} ($m = 1, 2$, or 4 and $n = x, y$, or z) is the permeability of layer m in the n-direction, i.e.,

$$\underset{\sim}{\mu}_m = \hat{x}\hat{x}\mu_{mx} + \hat{y}\hat{y}\mu_{my} + \hat{z}\hat{z}\mu_{mz}, \quad m = 1,\ 2, \text{ or } 4.$$

From Equations 5-11, it is observed that there are still eight unknown coefficients to be determined. They can be calculated by applying the following eight boundary conditions:

$$
\begin{aligned}
&\tilde{B}_{z1} = \tilde{B}_{z2}, \quad \tilde{H}_{x1} = \tilde{H}_{x2} (\text{or, } \tilde{H}_{y1} = \tilde{H}_{y2}), && \text{at } z = 0 \\
&\tilde{B}_{z2} = \tilde{B}_{z3}, \quad \tilde{H}_{y2} - \tilde{H}_{y3} = \tilde{K}_{x2} (\text{or, } \tilde{H}_{x3} - \tilde{H}_{x2} = \tilde{K}_{y2}), && \text{at } z = h_2 \\
&\tilde{B}_{z3} = \tilde{B}_{z4}, \quad \tilde{H}_{y3} - \tilde{H}_{y4} = \tilde{K}_{x3} (\text{or, } \tilde{H}_{x4} - \tilde{H}_{x3} = \tilde{K}_{y3}), && \text{at } z = h_2 + h_3
\end{aligned}
\tag{12}
$$

$$
\tilde{E}_{z2} - v\tilde{B}_{x2} = 0 , \qquad \text{at } z = 0,\ h_2
$$

The quantities $\tilde{K}_{mn}$ are the m-component (m=x, or y) of the surface current density at the interface of layers n and n+1.

After applying the boundary conditions, it is found that

$$
\begin{aligned}
\mathrm{III}_x^{(2)} &= e^{-k_z h_3} \frac{k_x}{k_y} \left[\frac{\mu_{4z}}{\mu_o} k_{z4} \left(1 - \frac{V_1 + V_2}{V_1 - V_2} e^{-2k_z h_3} \right) + k_z \left(1 + \frac{V_1 + V_2}{V_1 - V_2} e^{-2k_z h_3} \right) \right]^{-1} \\
&\quad \times \left[\mu_{4z} k_{z4} \tilde{K}_{x3} + (\mu_{4z} k_{z4} - \mu_o k_z)\, e^{-k_z h_3} \frac{V_1 \tilde{K}_{x2}}{V_1 - V_2} \right] \\
\mathrm{III}_x^{(1)} &= -\frac{V_1 + V_2}{V_1 - V_2} \mathrm{III}_x^{(2)} - \frac{\mu_o k_x}{k_y} \frac{V_1 \tilde{K}_{x2}}{V_1 - V_2} \\
\Pi_{xe}^{(1)} &= \frac{2\, \mathrm{III}_x^{(2)}}{V_1 - V_2} + \frac{\mu_o k_x}{k_y} \frac{\tilde{K}_{x2}}{V_1 - V_2} \\
\Pi_{xe}^{(2)} &= T\, \Pi_{xe}^{(1)} \\
\Pi_{xo}^{(1)} &= U\, \Pi_{xe}^{(1)} \\
\Pi_{xo}^{(2)} &= S\, \Pi_{xo}^{(1)} \\
\mathrm{I}_x &= \frac{i k_x \mu_{1x}}{\omega k_{z1} \mu_{1z}} \left[(k_x R^{(1)} - k_y)\, \Pi_{xe}^{(1)} + (k_x R^{(2)} - k_y)\, \Pi_{xe}^{(2)} \right] \\
\mathrm{IV}_x &= -\frac{\mu_{4x} k_x}{k_y} e^{k_{z4} h_3} \left[\tilde{K}_{x3} + \frac{V_1 \tilde{K}_{x2}}{V_1 - V_2} e^{-k_z h_3} \right. \\
&\quad \left. - \frac{k_y}{\mu_o k_x} e^{k_z h_3} \left(1 - \frac{V_1 + V_2}{V_1 - V_2} e^{-2k_z h_3} \right) \mathrm{III}_x^{(2)} \right]
\end{aligned}
\tag{13}
$$

where

$$V_1 = \frac{ik_x}{\omega k_z}\Big[(k_x R^{(1)} - k_y)\,(\cosh k_z^{(1)} h_2 + U \sinh k_z^{(1)} h_2)$$

$$+ (k_x R^{(1)} - k_y)\,(T \cosh k_z^{(2)} h_2 + SU \sinh k_z^{(2)} h_2)\Big]$$

$$V_2 = \frac{i\mu_o k_x}{\omega \mu_{2y} k_z}\Big[(k_z^{(1)} - ik_x Q^{(1)})\,(\sinh k_z^{(1)} h_2 + U \cosh k_z^{(1)} h_2)$$

$$+ (k_z^{(2)} - ik_x Q^{(2)})\,(T \sinh k_z^{(2)} h_2 + SU \cosh k_z^{(2)} h_2)\Big]$$

$$T = T_t / T_b$$

$$T_t = \sinh k_z^{(1)} h_2 \Big[(ik_y Q^{(1)} - k_z^{(1)} R^{(1)}) + S(ik_y Q^{(2)} - k_z^{(2)} R^{(2)})\Big]$$

$$- \frac{\mu_{2x} k_x}{\mu_{1z} k_{z1}}\,(k_x R^{(1)} - k_y)\,(\cosh k_z^{(1)} h_2 - \cosh k_z^{(2)} h_2)$$

$$T_b = S^{-1} \sinh k_z^{(2)} h_2 \Big[(ik_y Q^{(1)} - k_z^{(1)} R^{(1)}) + S(ik_y Q^{(2)} - k_z^{(2)} R^{(2)})\Big]$$

$$+ \frac{\mu_{2x} k_x}{\mu_{1z} k_{z1}}\,(k_x R^{(2)} - k_y)\,(\cosh k_z^{(1)} h_2 - \cosh k_z^{(2)} h_2) \tag{14}$$

$$U = \left(\cosh k_z^{(1)} h_2 - \cosh k_z^{(2)} h_2\right)^{-1} \left(S^{-1} T \sinh k_z^{(2)} h_2 - \sinh k_z^{(1)} h_2\right)$$

$$S = -\left[Q^{(2)}\left(1 - \frac{k_y v}{\omega}\right) + \frac{k_z^{(2)} v}{i\omega} R^{(2)}\right]^{-1} \left[Q^{(1)}\left(1 - \frac{k_y v}{\omega}\right) + \frac{k_z^{(1)} v}{i\omega} R^{(1)}\right]$$

With the above formulas given in Equations 4-14, the magnetic field at any arbitrary location can be calculated. The force ($\underline{F}$) that is exerted on layer 4 or the combination of layers 1 and 2 can be calculated from the surface integration of the stress tensor ($\underset{\sim}{T}$)

$$\underline{F} = \int_S \underset{\sim}{T} \cdot \hat{n}\, dS \tag{15}$$

where

$$\underset{\sim}{T} = \widetilde{\hat{i}\hat{j}}\, T_{ij}, \qquad i, j = x, y, z$$

$$T_{ij} = \mu_o (H_i H_j - \frac{1}{2}\delta_{ij} |\underline{H}|^2)$$

$$\delta_{ij} = \begin{cases} 1, & i = j \\ 0, & i \neq j \end{cases}$$

and $\hat{n}$ is the outward unit normal vector for the surface S enclosing the volume over which the force is to be calculated. The formulas are versatile and can be used to quantify the performance of various MAGLEV design alternatives and shielding approaches. In the next few paragraphs, some special applications will be discussed. These special applications will be implemented into specific computer codes to produce results to be discussed in Sections 3.0 and 4.0, and with code descriptions in Section 5.0.

(i) Suspension as the primary application:

There are two suspension (or, levitation) approaches, namely, repulsive (or, EDS) and attractive (or, EMS). The EDS approach generally makes use of the repulsive force between a magnetic-field source (generally, superconducting current coils) and the eddy currents induced in a conductor (the reaction track) when the source is moving over it. The EMS approach relies on the force between magnets, either permanent magnets or electromagnets, or the force between a magnetic-field source and a ferromagnetic material with high permeability. For an EDS approach, or an EMS approach using high permeability material the source will exist only at the interface of layers 3 and 4 (i.e., $\underline{\tilde{K}}_2 = 0$, $v \neq 0$). On the other hand, for an EMS approach using forces between two magnetic field sources, both $\underline{\tilde{K}}_2$ and $\underline{\tilde{K}}_3$ will be non-zero, but v and the conductivity of layer 2 are in general zero.

In principle, the formulas derived can be used for any arbitrary current sources (which will produce the necessary magnetic fields). For the computer codes developed under this effort, rectangular current loops of a specific dimension will be implemented. Note that the current levels (I_o) and coil dimensions (a x b) are inputs to the programs. The current loops will also be superposed to simulate magnets, by imposing the approximation that inside the magnet the magnetization is uniform so that the magnet is equivalent to a current sheet with $\underline{K} = \hat{n} \times \underline{M}_m$. For suspension purpose, the current source will most possibly be a direct current (DC, i.e., $\omega = 2\pi f = 0$, f, source frequency). For a rectangular loop with current strength I_o, dimensions $a \times b$, and centered at the origin, $\tilde{K}_x$, the x-component of the surface current, will be given by

$$\tilde{K}_x = -\frac{2i}{\pi}\frac{I_o}{k_x}\sin\frac{k_x a}{2}\sin\frac{k_y b}{2} \cdot 2\pi\delta(\omega) \qquad (16)$$

(ii) Propulsion as the primary application:

Two propulsion approaches are considered, namely, the linear induction motor (LIM) and the linear synchronous motor (LSM). A linear induction motor makes use of the force between a "travelling" magnetic-field source and a conducting reactive track. A linear synchronous motor makes use of the force between a "travelling" magnetic-field source and another source moving at a synchronous speed (i.e., at a speed equal to the phase velocity of the travelling wave source field). The LIM thus has a non-zero $\underline{K}_3$ but a zero $\underline{K}_2$. The LSM, on the other hand, will have both non-zero $\underline{K}_3$ and $\underline{K}_2$, but a non-conducting layer 2. The travelling-wave source $\underline{K}_3$ for both LIM and LSM will be alternating currents (AC), while the source $\underline{K}_2$ for a LSM will be a DC.

For the computer code developed under this effort, the travelling wave source, with a phase velocity ω_o/k_{yo}, will be taken to occupy a rectangular area of $a \times b$, centered at $x = y = 0$. That is

$$\tilde{K}_{x3} = \frac{I_o}{b} e^{-i\omega_o t + ik_{yo} y} , \qquad \text{for} \qquad -\frac{b}{2} \leq y \leq \frac{b}{2}, \quad -\frac{a}{2} \leq x \leq \frac{a}{2} \tag{17}$$

and

$$\tilde{K}_{x3} = \frac{I_o}{b} \frac{2}{\pi} \frac{1}{k_x} \sin\frac{k_x a}{2} \frac{1}{k_{yo} - k_y} \sin\frac{(k_{yo} - k_y) b}{2} \, 2\pi\delta(\omega - \omega_o)$$

with

$$\sin(k_{yo} b/2) = 0$$

As for $\underline{K}_2$ needed in a LSM, it is taken to be a rectangular loop of size $a_2 \times b_2$, centered at (x_o, y_o) at $t = 0$, and moving at a velocity v in the y-direction. $\tilde{K}_{x2}$, thus, takes the following form

$$\tilde{K}_{x2} = \frac{-2i}{\pi} \frac{I_o}{k_x} \sin\frac{k_x a_2}{2} \sin\frac{k_y b_2}{2} e^{-ik_x x_o - ik_y y_o} \, 2\pi\delta(\omega - k_y v) \tag{18}$$

In Equations 16-18, $\delta(\omega - \omega_o)$ is the delta function.

(iii) Shielding as the primary application:

There are two shielding schemes, namely, passive and active. A passive approach makes use of material with high permeability to reduce the permeated magnetic fields. An active approach makes use of a secondary magnetic-field source of opposite polarity to reduce the magnetic field in the regions of interest. Sometimes, it may be advisable to use the combination of both approaches.

For example, one may use an active approach to reduce the magnetic field to a level which would allow the passive shielding material to have a higher permeability and thus better shielding performance.

In a MAGLEV system, the magnetic-field sources of most concern in producing stray magnetic field are the on board DC superconducting coils used for either EDS suspension or LSM propulsion. The passive shielding material and/or the active shielding source will also be on board and located between the superconducting coils and the passenger compartment. A zero velocity can thus be used in the formulas derived earlier. However, in order to consider a combined passive and active shielding approach, proper superpositions are needed to allow for two sources, the primary source plus one active shielding coil source. Both the primary source and the active shielding coil are rectangular loops of arbitrary sizes and locations. The $\bar{K}_x$ will thus take the form of Equation 16.

3.0 SOME CONSIDERATIONS OF DESIGN ALTERNATIVES

From Section 2.0, it is clear that the computer codes developed using the formulations derived therein can be used to analyze many design alternatives. In this section, two design alternatives will be analyzed to address their feasibilities, from the viewpoint of whether enough forces can be generated using reasonable capacities of sources. The two design alternatives are, a linear induction motor design for both propulsion and levitation, and an EMS levitation design using both permanent and electromagnets. The validation of the codes has been performed by running some very simple cases and comparing the results with those obtained from analysis. Such comparison for validation will be indicated along with some presentation of numerical results. It should also be emphasized that results obtained from the codes are to be treated as approximated values. This is because the modeling won't allow one to include detailed design considerations. If the model simulates the real design very closely, the approximation is expected to have errors of less than, say, ten percent.

3.1 A Linear induction Motor Design for Both Propulsion and Levitation

To analyze this design alternative, as described in Section 2.0, the source at the interface of layers 3 and 4 will be a current sheet travelling at a phase velocity of ω/k_{yo}, and layer 2 will be a conducting ferromagnetic material. The material needs to have a relatively high permeability to produce the necessary levitation force, and a conductivity high enough to produce the necessary propulsion force. The conductivity must be sufficiently small to avoid the induced eddy current from reducing the levitation force too much. That is to say, the purpose of this analysis is to investigate how the set of parameter values (on the conductivity, permeability, thickness of layer 2, gap width, and frequency (f) and phase velocity ($2\pi f/k_{yo}$) of the travelling-wave source) for this design produces propulsion and levitation forces over the velocity range of interest. For simplifying the investigation, the analysis in this example is performed by assuming no x-dependence, i.e., the coil width is large so that the transverse (x) variation is negligible, although the developed computer codes allow for x-dependent calculations, i.e., for finite width coils.

Figure 2 shows the propulsion and levitation forces as functions of the vehicle velocity (v) for various rail permeabilities (μ_{r2}) and a set of other source and track parameter values (see Figure 3 and Appendix A for definitions of the parameters). The source current sheet has a frequency (f) of 400 Hz and a phase velocity of 160 m/s (i.e., k_{yo}, the wavenumber, is 5π). As expected, the curves indicate zero propulsion and maximum levitation forces at a vehicle velocity equal to the phase velocity. At this velocity, the levitation force approaches that of an approximate result ($\approx \mu_o I_o^2 / (2b)$) that can be analytically obtained for a case that $\mu r2$ and h2 are larger and h3 is

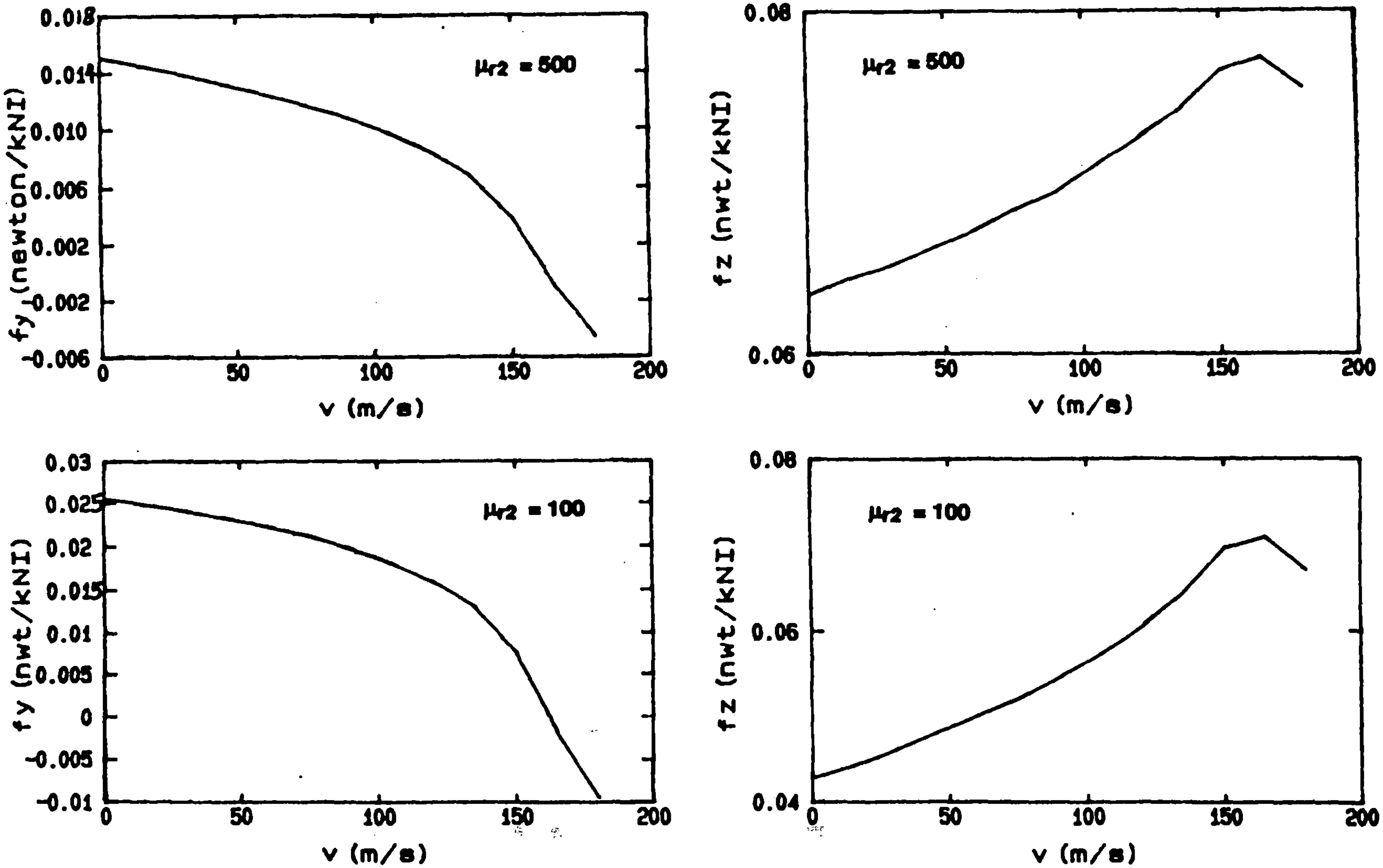


Figure 2. Propulsion forces (fy) and attractive forces (fz) as functions of the vehicle velocity (v) for various μ_{r2} in a LIM design alternative, when the driving current sheet has f = 400 Hz, $ky_0 = 5\pi$, b = 2 m, and the reaction rail has $\sigma = 10^6$ S/m, and h2 = h3 = 0.02 m.

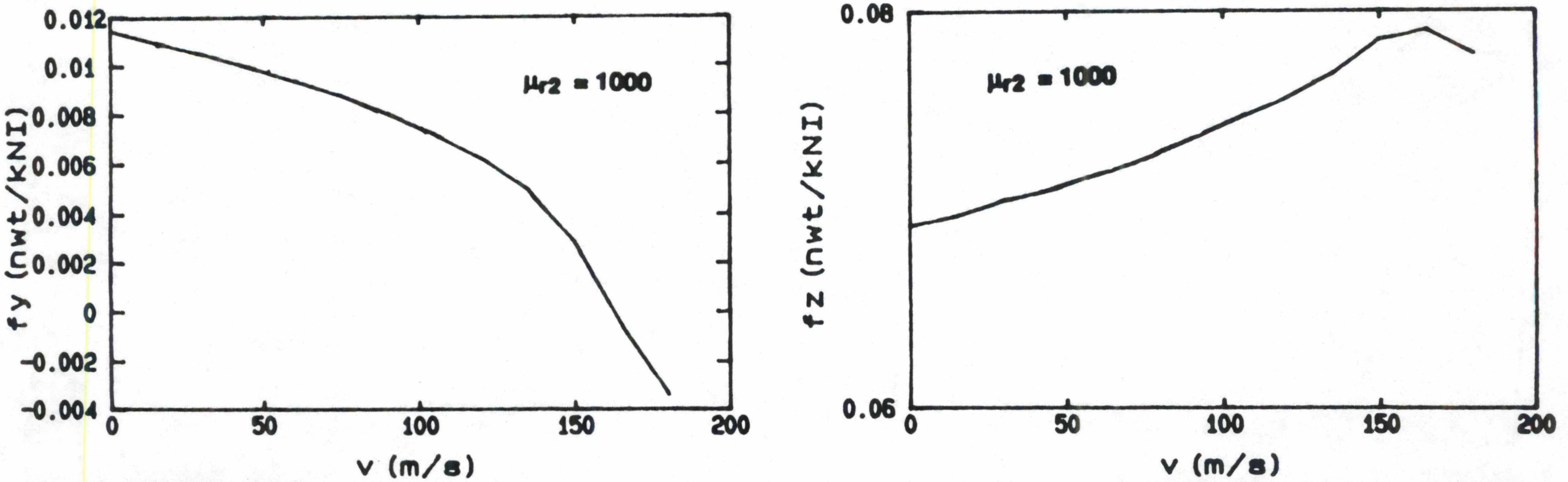
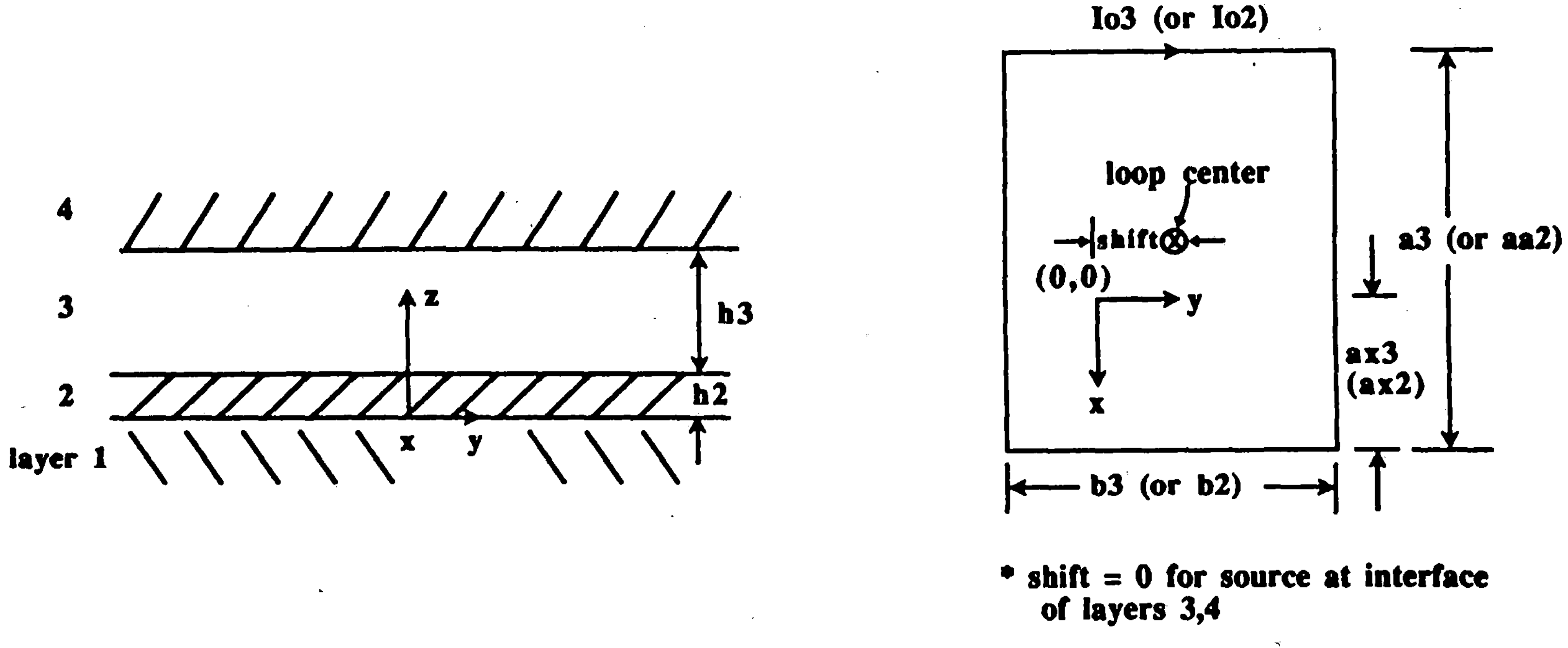


Figure 2. (concluded). Propulsion forces (fy) and attractive forces (fz) as functions of the vehicle velocity (v) for various μ_{r2} in a LIM design alternative, when the driving current sheet has f = 400 Hz, $ky_o = 5\pi$, b = 2 m, and the reaction rail has $\sigma = 10^6$ S/m, and h2 = h3 = 0.02 m.



* shift = 0 for source at interface of layers 3,4

side view

top view of source

Figure 3. A schematic diagram of a MAGLEV system with definitions of some parameter values used in the corresponding analyses and computer codes. Also, refer to Appendix A for additional explanation.

smaller. The levitation force generally increases with the permeability, while the propulsion force decreases. Such a dependence can be easily observed in Figure 4, which presents the forces as functions of the permeability of the reaction rail for two vehicle velocities. Figure 5 gives the forces as functions of the conductivity of the reaction rail for two vehicle velocities (0, and 135 m/s) and a set of values of other parameters (such as b = 2m, h2 = h3 = .02m, given in the figure). The propulsion force increases with conductivity, while the levitation force decreases.

Figure 6 gives the forces as functions of the thickness (h2) of the reaction rail for two vehicle velocities and a set of values of other parameters. The sharp changes in the curves at h2 = 0.01m are due to large step size (in h2). Each curve shows a constant value at h2 $\geq$ 0.01m. This is expected because the skin depth for the selected set of parameter values is very small compared to 0.01m. Increasing the thickness beyond 0.01m will not benefit the force performances. Figure 7 shows the dependence of the forces on the gap width (h3). The forces decrease quickly as the gap width increases. This demonstrates one reason why an attractive levitation approach needs to maintain a small gap width.

Figure 8 presents the dependence of the forces on the frequency (and, thus the phase velocity) of the travelling-wave source current. The phenomena that the propulsion force has a zero value and the levitation force has a maximum when the vehicle velocity is equal to the phase velocity of the source current are again observed.

The analysis presented in this report is not intended to be extensive, but just enough to give some understanding on the effects of various parameter values. To appreciate how strong the forces produced by such a combined design alternative are, one can use Figure 2 for a demonstration. For a travelling-wave source extended for 2 m (= b, in the longitudinal travelling direction) with f = 400 Hz and $k_{yo} = 5\pi$ and a reaction rail with 10^6 S/m conductivity, 500 μ_o permeability and 0.02 m thickness, the forces for a 0.02 m gap and vehicle velocity below 135 m/s, are:

propulsion forces (f_y) $\gtrsim$ 0.0068 newton/kNI

levitation forces (f_z) $\gtrsim$ 0.064 newton/kNI

That is, if the source current (I_o) is 400 kNI, then, the forces are

propulsion forces (f_y) $\gtrsim$ 1.1 kilo-newton

levitation forces (f_z) $\gtrsim$ is 10 kilo-newton

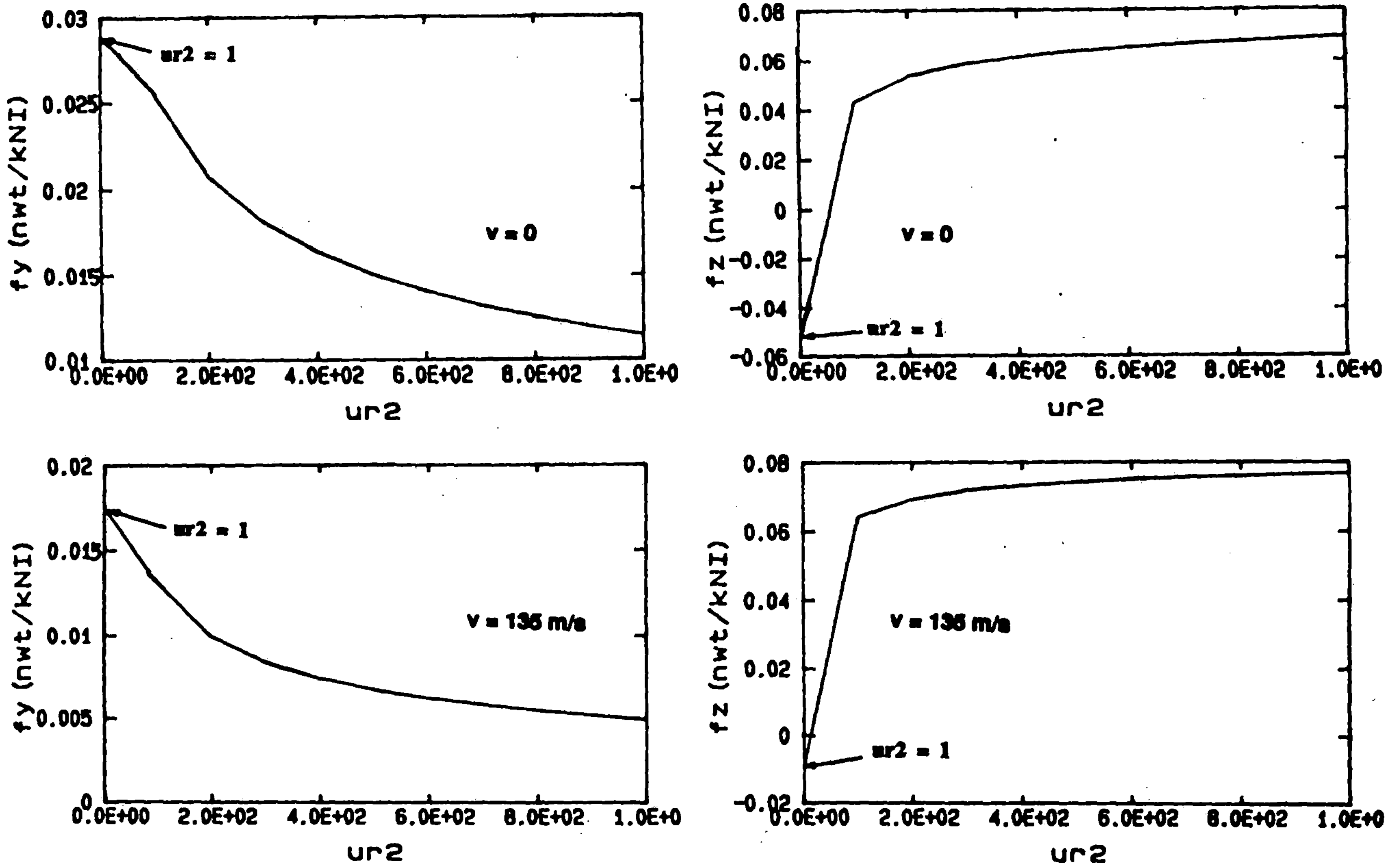


Figure 4. Propulsion forces (fy) and attractive forces (fz) as functions of the relative permeability (μ_{r2}) of the reaction rail for 2 vehicle velocities in a LIM design alternative, when the driving current sheet has f = 400 Hz, $ky_o = 5\pi$, b = 2 m, and the reaction rail has $\sigma = 10^6$ S/m, and h2 = h3 = 0.02 m.

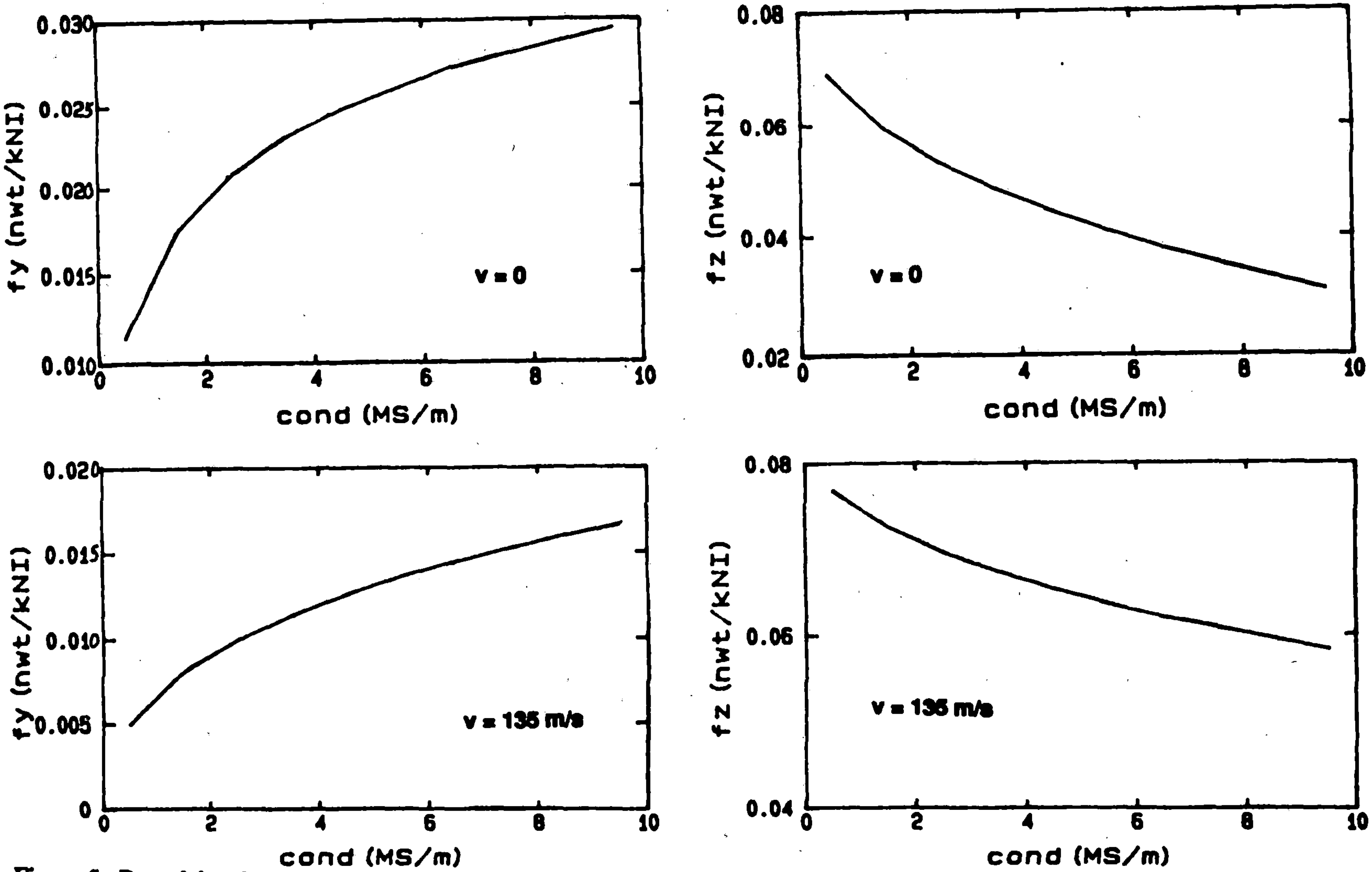


Figure 5. Propulsion forces (fy) and attractive forces (fz) as functions of conductivity (σ) of the reaction rail for 2 vehicle velocities in a LIM design alternative, when the driving current sheet has $f = 400$ Hz, $ky_0 = 5\pi$, $b = 2$ m, and the reaction rail has $\mu_{r2} = 500$, and $h2 = h3 = 0.02$ m.

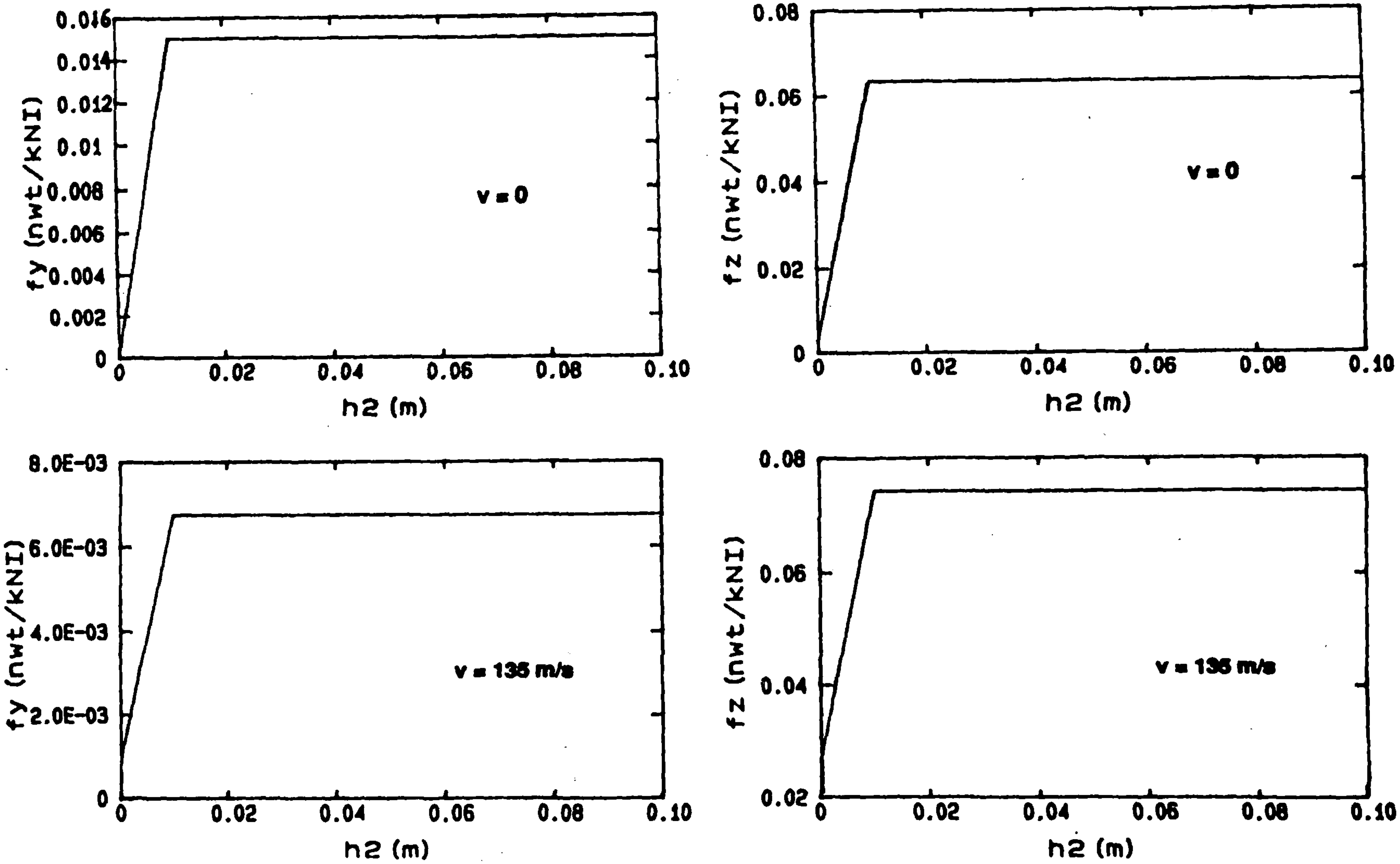


Figure 6. Propulsion forces (fy) and attractive forces (fz) as functions of the thickness (h2) of the reaction rail for 2 vehicle velocities in a LIM design alternative, when the driving current sheet has $f = 400$ Hz, $ky_o = 5\pi$, $b = 2$ m, and the reaction rail has $\sigma = 10^6$ S/m, $\mu_{r2} = 500$, and $h3 = 0.02$ m.

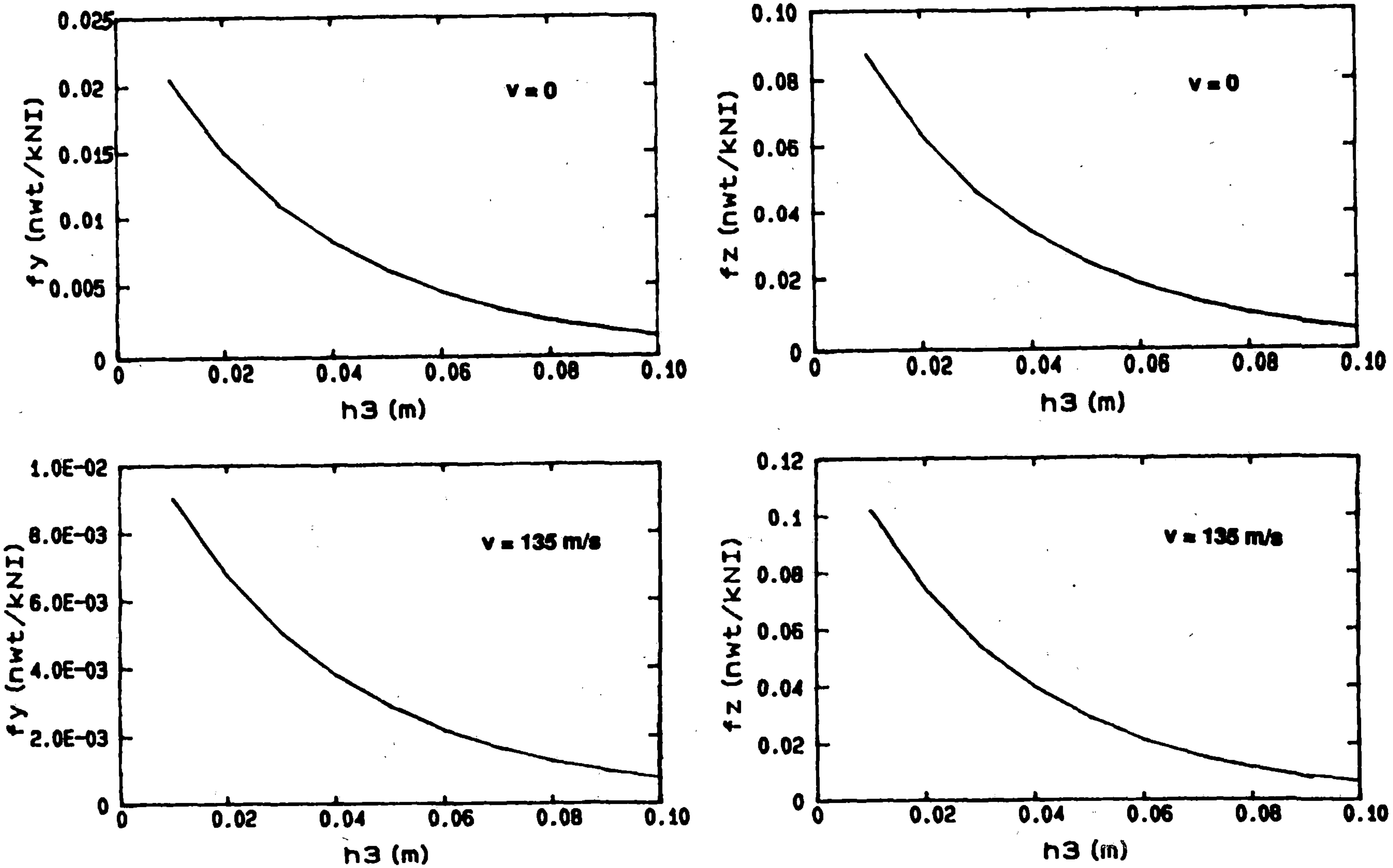


Figure 7. Propulsion forces (fy) and attractive forces (fz) as functions of the gap width (h3) between the current sheet source and the reaction rail for 2 vehicle velocities in a LIM design alternative, when the driving current sheet has $f = 400$ Hz, $ky_o = 5\pi$, $b = 2$ m, and the reaction rail has $\sigma = 10^6$ S/m, $\mu_{r2} = 500$, and $h2 = 0.02$ m.

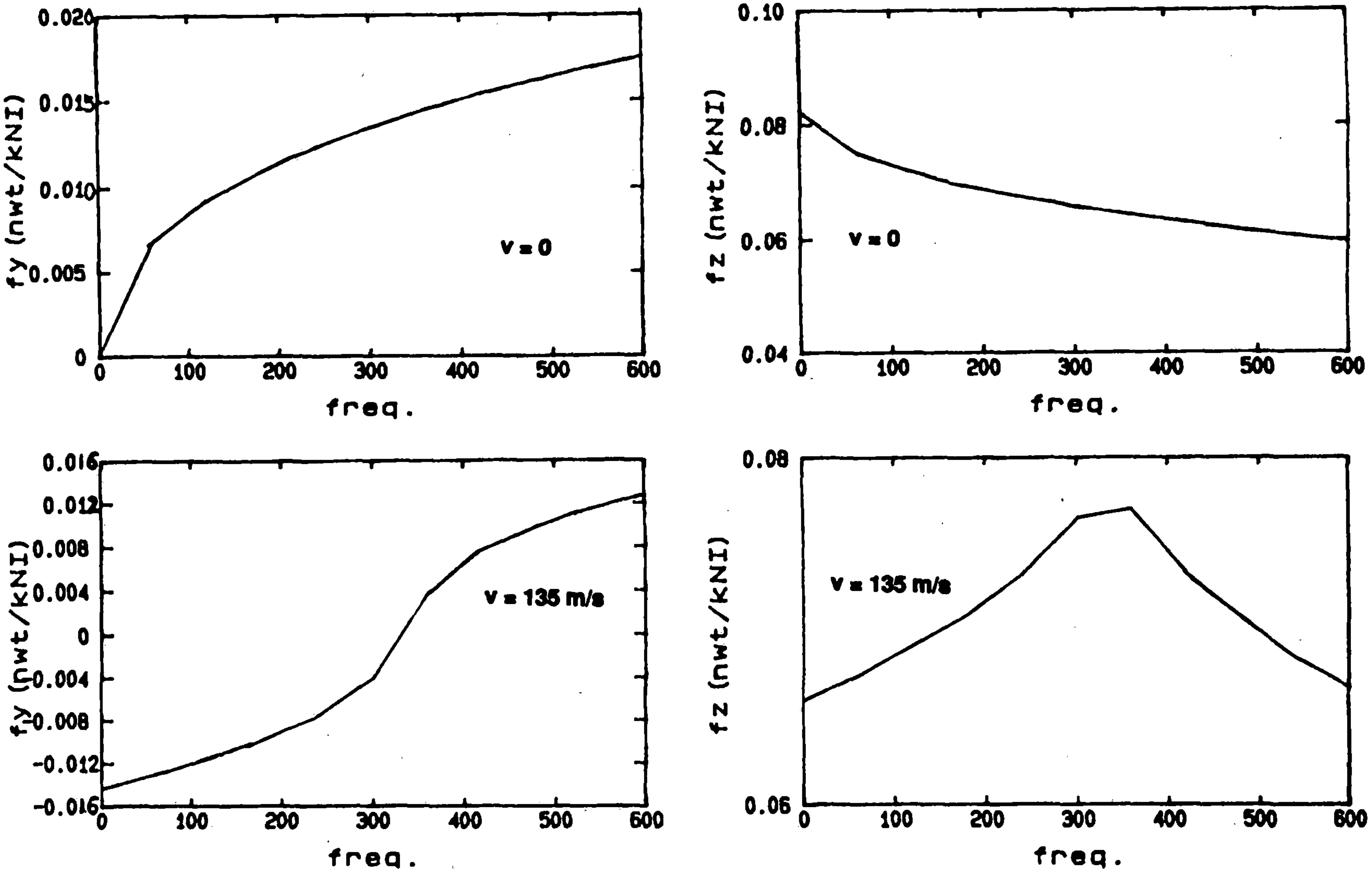


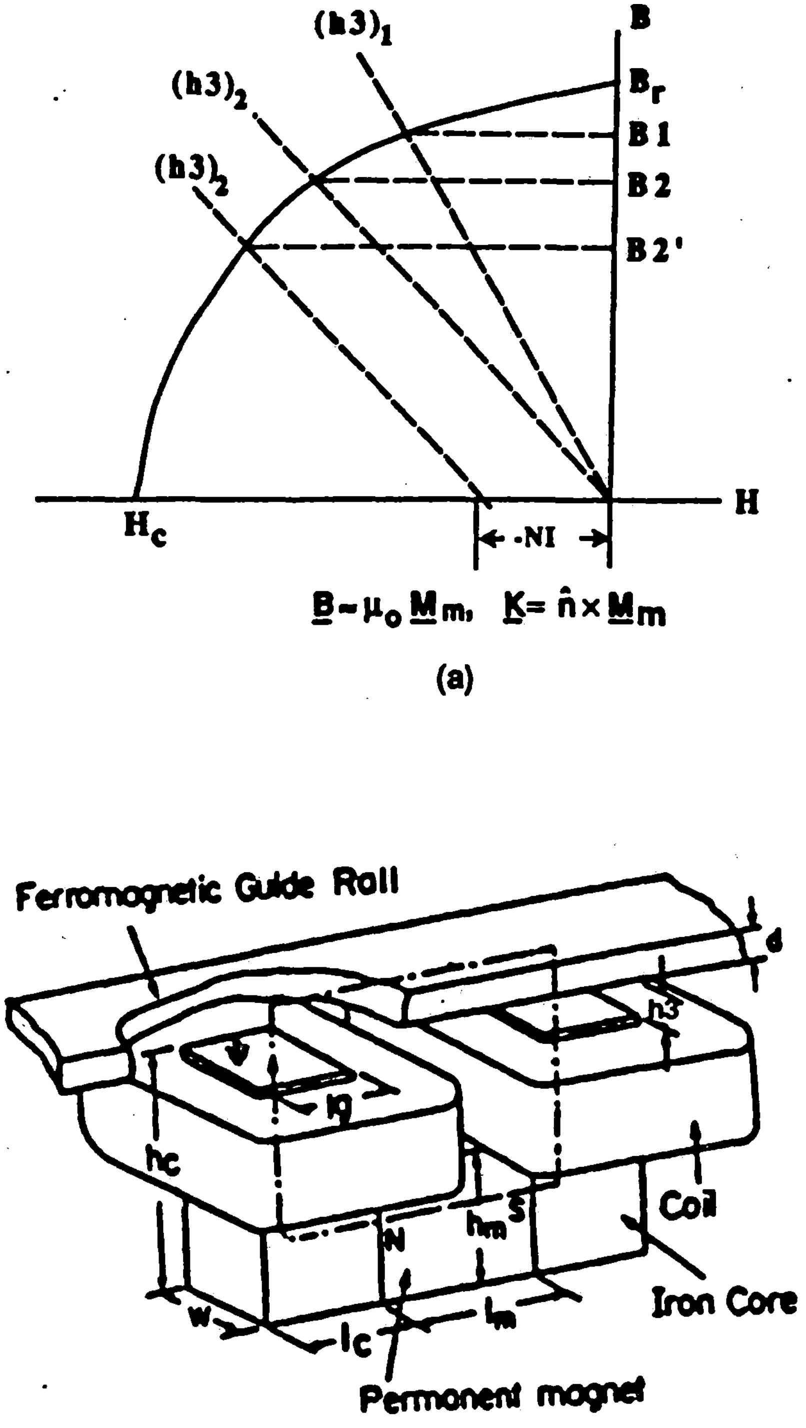
Figure 8. Propulsion forces (fy) and attractive forces (fz) as functions of the frequency (*f*) of the current sheet source for 2 vehicle velocities in a LIM design alternative, when the driving current sheet has kyo = 5π, b = 2m, and the reaction rail has $\sigma = 10^6$ S/m, $\mu_{r2} = 500$, and h2 = h3 = 0.02 m.

These forces can be increased by varying some of the parameter values or implementing and operating several units simultaneously. It should also be noted that the example calculations were performed by imposing the x-independent condition. That is, the results are given for per-unit-length of the transverse (x) direction. The calculations can also be performed for more realistic cases by allowing variation of coil size in the tranverse (x) direction using the developed codes.

3.2 An EMS Levitation Design Using Both Permanent Magnets and Electromagnets

To analyze this design alternative, as described in Section 2.0, the source will extend from the interface of layers 3 and 4 to some area inside layer 4, and layer 2 will be a ferromagnetic material. To minimize the reduction in the levitation force due to eddy current induced in layer 2, its conductivity should be kept as small as possible. The magnet source, in this formulation, is approximated as sheets of current loops. The magnitude of the current density on the current sheets is determined by the properties of the magnet material, the geometry of the magnet, the ampere-turns of the electromagnet, the gap width between the magnet and layer 2, and also the material properties of layer 2. To make the problem tractable, it is assumed that the reluctances inside the electromagnet and layer 2 are small (i.e., very high permeability). Under such an assumption, the equivalent surface current density of the current sheet for a combined permanent magnet and electromagnet design can be determined from the curve shown in Figure 9. Figure 9-a gives the magnetic induction vector (B) of a combined permanent magnet/electromagnet configuration such as that of Figure 9-b (taken from Fig. 1 of Ref. 8) as functions of the gap width (h3) and the ampere-turns of the electromagnet. Once a gap width and the ampere-turns are given, the magnetic induction vector read from such a curve can then be used to obtain the strength of the equivalent current loops. The forces can then be calculated from the superposition of those equivalent current loops. This superposition has also been implemented into the computer codes.

The purpose of this analysis is to find out certain requirements for permanent magnets to provide sufficient forces to levitate a vehicle. Such an attractive levitation scheme is unstable in the sense that without a feedback control a decrease (or increase) in the gap width (due to, e.g., the change in the vehicle weight) will tend to further decrease (or increase) the gap width. The introduction of electromagnets into this design serves to control the magnet's magnetization vector (and so, the magnitude of the equivalent current sheet) such that when the gap width changes the attractive force can change due to the change in magnetization. The design and detailed working principle of the feedback control is beyond the scope of this work and will not be discussed further here.



(a)

(b)

Figure 9. A demonstration diagram for estimating the magnetization and equivalent current sheet of a combined permanent and electromagnet.

Figure 10 shows the propulsion and levitation forces as functions of the vehicle velocity (v) for two pole lengths (pl) and a set of other source and track parameter values. The pole length is introduced to terminate the integration of the equivalent current sheet. From the figures (comparing the top to the bottom ones), it is observed that using a pole length of about ten times the magnet's longitudinal dimensions (b3) gives very good approximations. The figure also indicates that the attractive force (f_z) decreases with velocity and the drag force ($-f_y$) increases with velocity in the calculated velocity range (i.e., below 180 m/s). Figures 11 and 12 show the forces as functions of the permeability and conductivity of the reaction rail, respectively, for two vehicle velocities, when the vehicle is not moving ($v = 0$), the drag forces are expected to be zero and they are not presented. As for the levitation force (f_z), it does not change with conductivity when the vehicle is not moving (note, $f = 0$ is assumed), but increases with higher permeability. It is also observed that when the velocity is zero, the attractive force approaches that of an approximate result ($bB^2/(2\mu o)$) that can be analytically obtained for the case that $\mu r2$ and h2 are larger and h3 is smaller. At a vehicle velocity of 120 m/s, for the given set of parameter values, the levitation force decreases with conductivity but still increases with permeability. On the other hand, the drag force ($-f_y$) increases with conductivity but decreases with permeability.

Figure 13 shows the forces as functions of reaction rail thickness for two vehicle velocities. It indicates that increasing the thickness beyond 0.02 m does not improve the force performance very much. Of course, this number (of 0.02m) may change somewhat when other sets of parameter values are used. Figure 14 shows the dependences on the gap width (h3) between the magnet and the reaction rail. As expected, all the forces ($-f_y$ and f_z) decrease with increasing h3.

Similar to subsection 3.1, the results presented here are not extensive and are obtained by imposing the x-independent approximation. However, the results provide some data regarding the requirement on magnet strength. The figures show that with a reaction rail with 10^6 S/m conductivity (or lower), 500 μ_o permeability (or higher) and a 0.02 m thickness, a levitation force of more than 80 kilo-newton can be achieved with a magnet pole 0.5 m long, 1 m wide, 0.02m above the rail, with 1 tesla flux density. Such a flux density is easily obtainable using present magnet technologies.

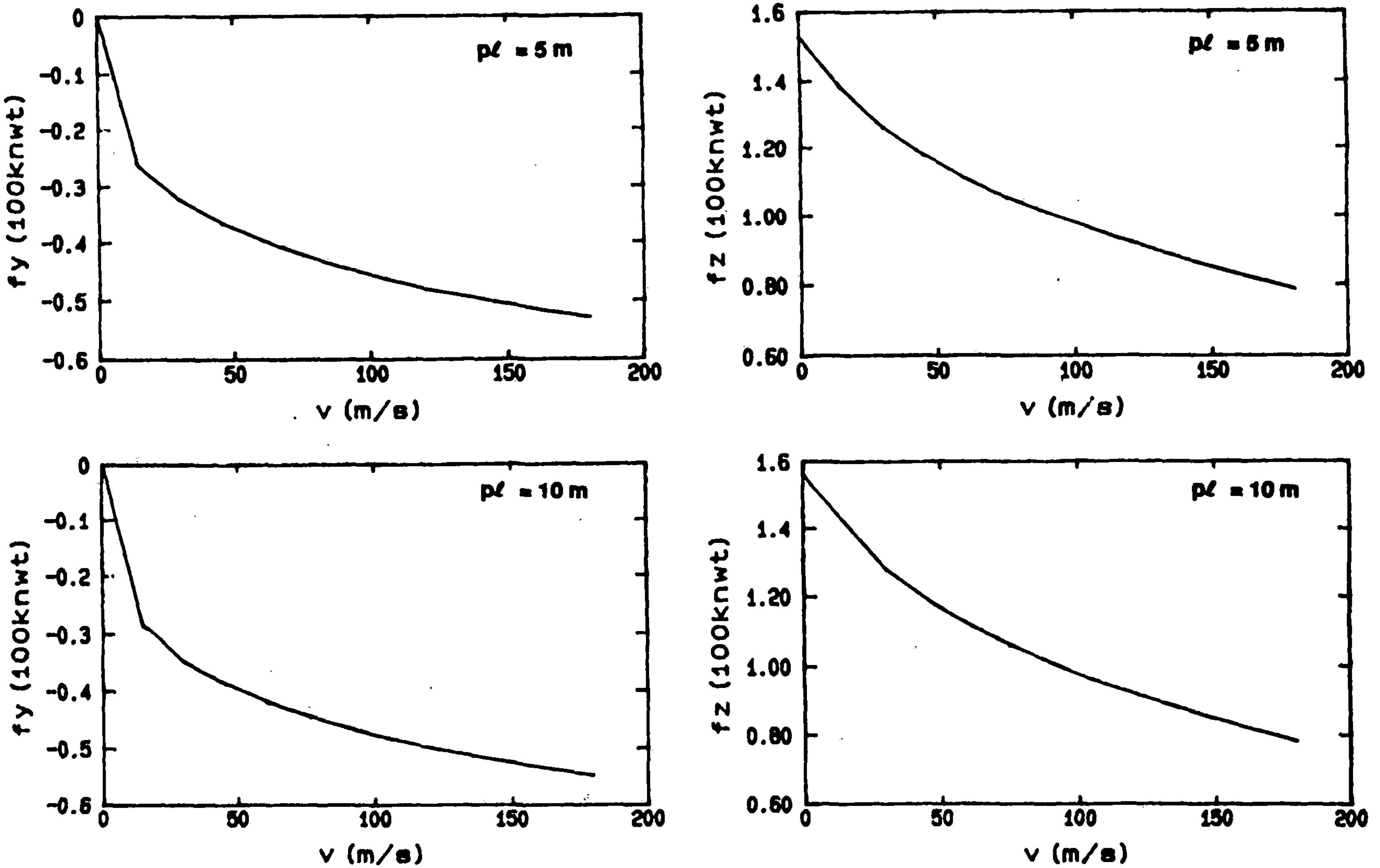


Figure 10. Attractive forces (fz) and drag forces (-fy) as functions of the velocity (v) in an EMS levitation design alternative using magnets with 1 tesla/μ_0 uniform magnetization and two approximate pole lengths (pℓ), when h2 = h3 = 0.02 m, μ_{r2} = 500, $\sigma = 10^6$ S/m, and b3 = 0.5 m.

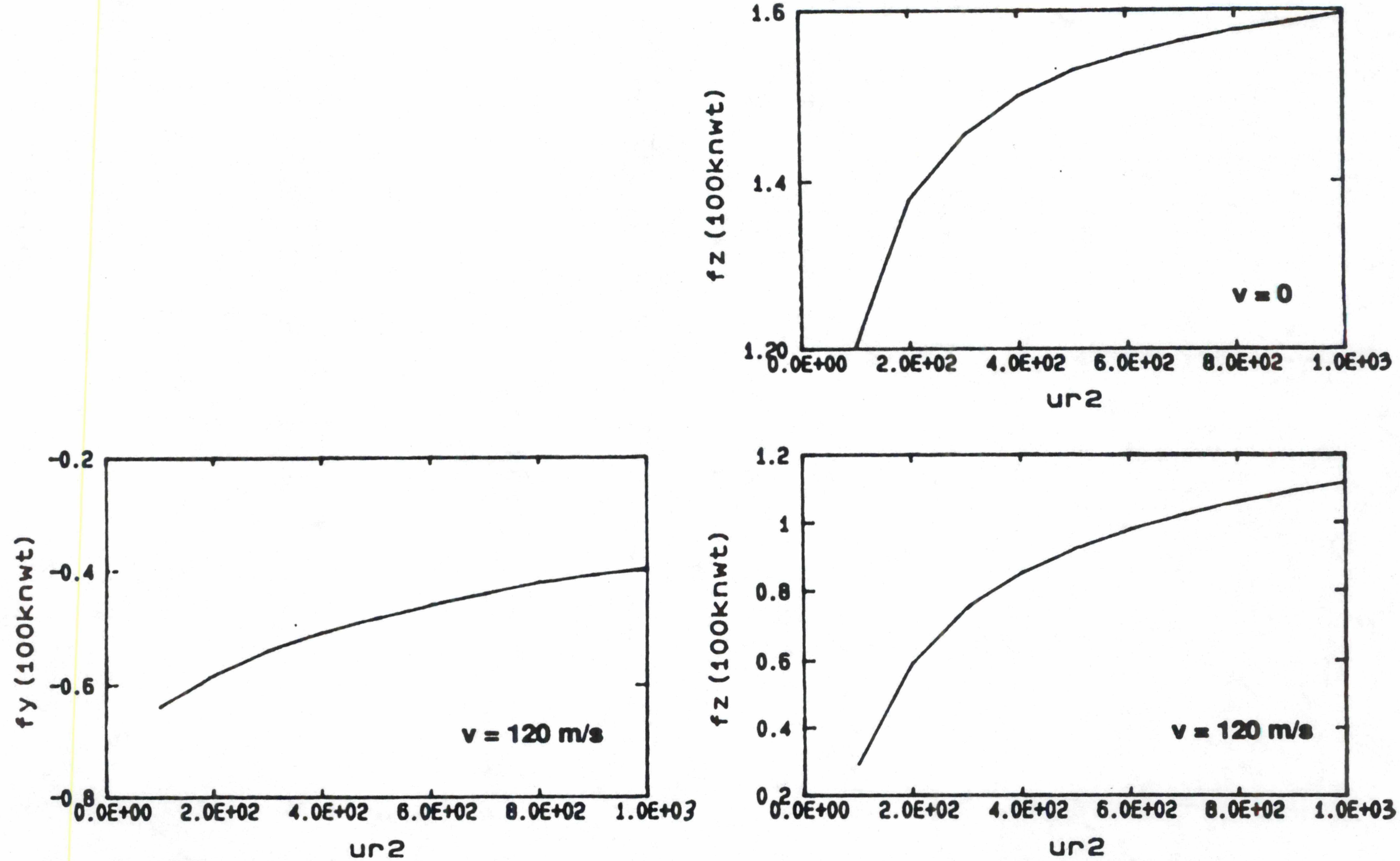


Figure 11. Attractive forces (fz) and drag forces (-fy) as functions of the relative permeability (μ_{r2}) of the reaction rail for 2 vehicle velocities in an EMS levitation design alternative using magnets with 1 tesla/μ_0 uniform magnetization, when h2 = h3 = 0.02 m, $\sigma = 10^6$ S/m, and b3 = 0.5 m.

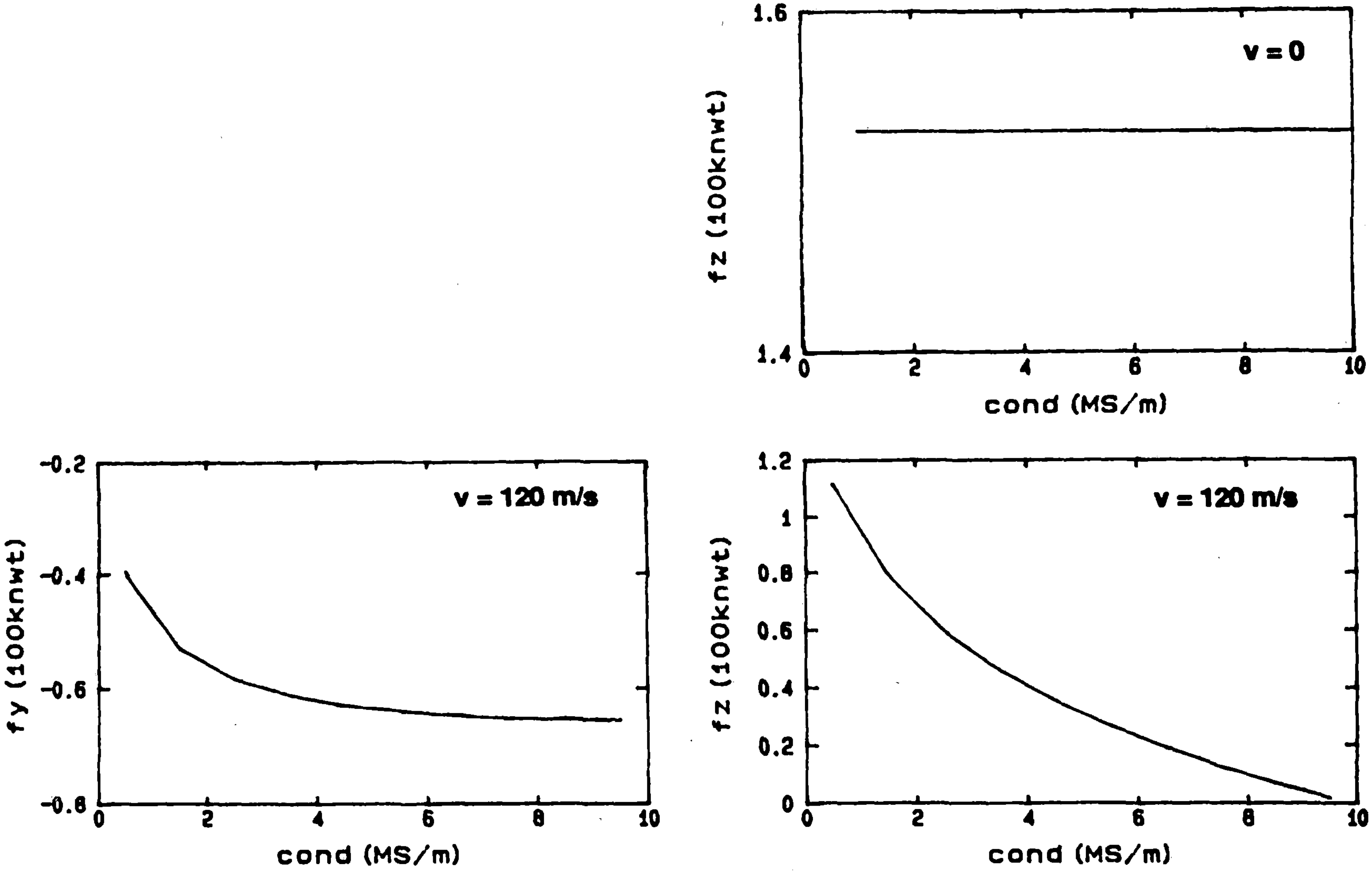


Figure 12. Attractive forces (fz) and drag forces (-fy) as functions of the conductivity (σ) of the reaction rail for 2 vehicle velocities in an EMS levitation design alternative using magnets with 1 tesla/μ_0 uniform magnetization, when h2 = h3 = 0.02 m, μ_{r2} = 500 and b3 = 0.5 m.

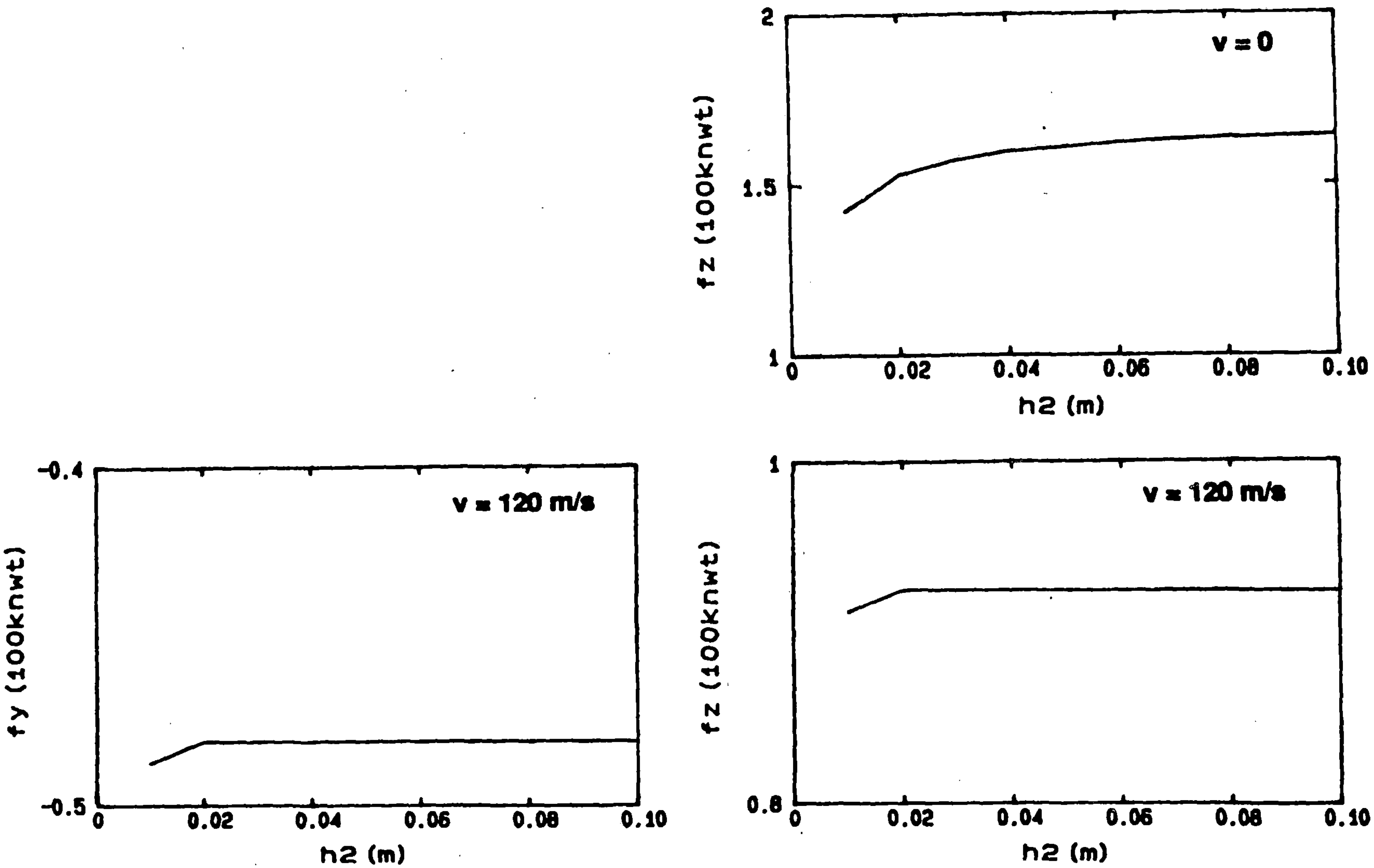


Figure 13. Attractive forces (fz) and drag forces (-fy) as functions of the thickness (h2) of the reaction rail for 2 vehicle velocities in an EMS levitation design alternative using magnets with 1 tesla/μ_0 uniform magnetization, when $\mu_{r2} = 500$, $\sigma = 10^6$ S/m, b3 = 0.5 m, and h3 = 0.02 m.

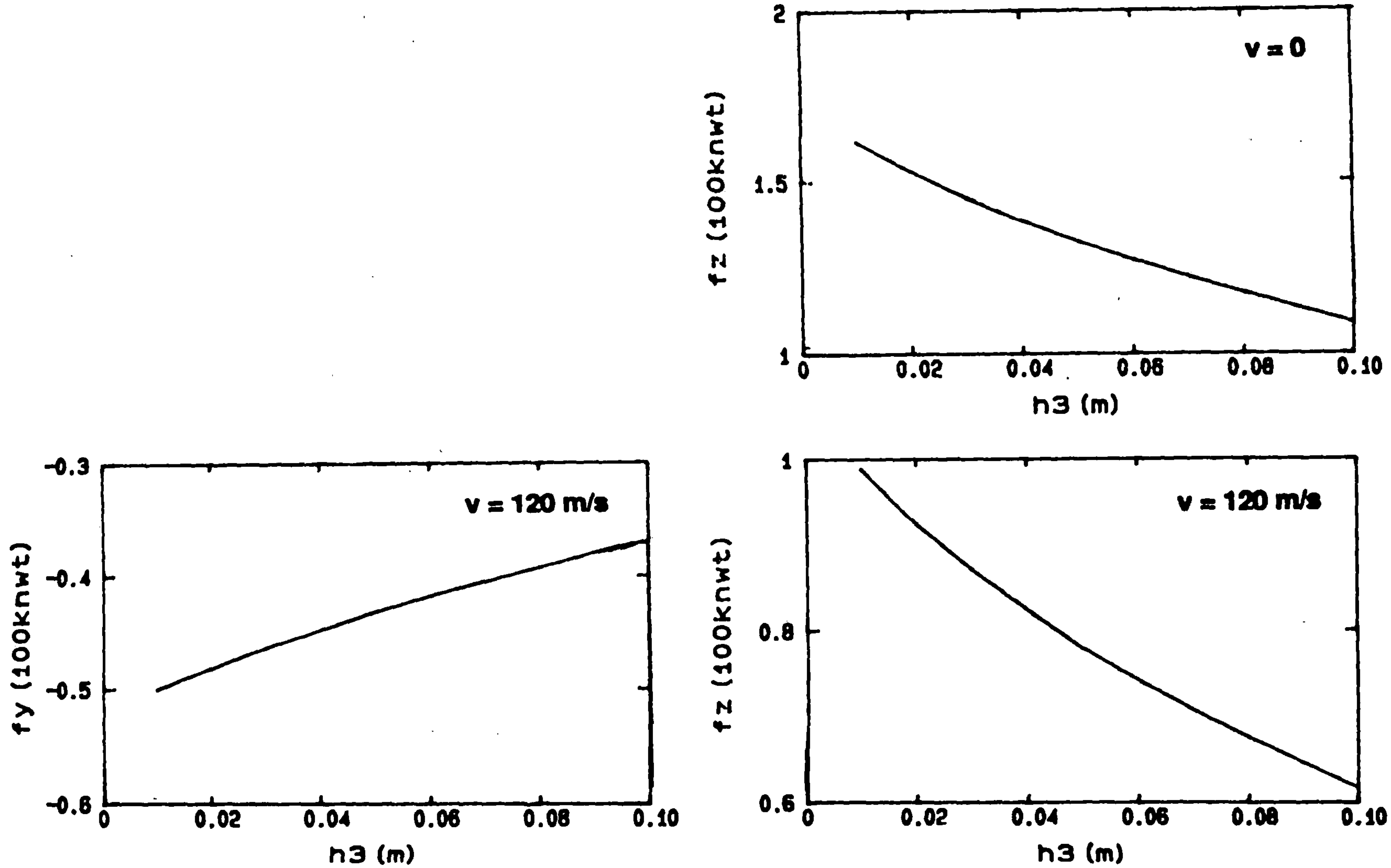


Figure 14. Attractive forces (fz) and drag forces (-fy) as functions of the gap width (h3) between the magnet and the reaction rail for 2 vehicle velocities in an EMS levitation design alternative using magnets with 1 tesla/μ_0 uniform magnetization, when $\mu_{r2} = 500$, $\sigma = 10^6$ S/m, b3 = 0.5 m and h2 = 0.02 m.

4.0 SOME CONSIDERATIONS OF MAGNETIC FIELD SHIELDING SCHEMES

There are two shielding schemes, namely, active and passive shielding. In some situations, it may be desirable to combine both schemes. To analyze a passive shielding problem, as described in Section 2.0, one places the source at the interface of layers 3 and 4, has layer 2 as the shielding material and calculates the fields in layer 1. To analyze an active shielding problem, one places the sources at both the interfaces of layers 2, 3 and layers 3, 4, takes layer 2 to be free space, and calculates the magnetic fields in either layer 1 or layer 4. To analyze a combined passive and active shielding problem, superposition of the model depicted in Figure 1 is needed. That is to say, one needs to use the model twice and sum the results. For the two times that the model is applied, the sources will have different heights from the interface of layers 2 and 3, and the field locations of interest will be inside layer 1, while layer 2 will be taken to have high permeability. Obviously, such a model will not be able to give a correct result when layer 2 has a nonlinear permeability. However, for shielding purposes, one definitely would select a layer 2 material so that under most operating field levels its permeability remains linear and has a high value. Even under a situation that the layer 2 material is driven into the nonlinear domain, such a linear model will also provide a means to estimate the upperbound of the penetrated stray magnetic fields. The active shielding loop should be placed between the magnetic field source and the passive shielding layer. This is because it can also serve the purpose of reducing the magnetic field intensities at the shielding layer so that the shielding material has a higher possibility of operating in the linear high permeability domain.

The purpose of this analysis is to demonstrate how the passive and/or active shielding schemes can reduce the magnetic fields to lower levels inside regions of concern. However, at this moment, since there is no clear-cut standard on the tolerable levels, the analysis will only study the magnetic-field reduction factors as functions of various parameters used to define the shielding schemes. For simplifying the analyses, the results presented will not be extensive and will be only for sources without the x-dependence, although the computer codes allow for the calculations of cases with x-dependent sources.

Figures 15-17 show how the stray magnetic fields are reduced when the thickness and the permeability of the passive shielding layer increase (see Figure 18 for the definitions of various parameters). Figure 19 shows how the strength and location of the active-shielding current affects the magnetic fields. Figure 20 indicates how the magnetic fields vary with location. A comparison of Figures 15, 16 and 17 also shows some effects due to the locations of the active-shielding currents. It is also noted that for code verification purpose, one can compare the numerical results

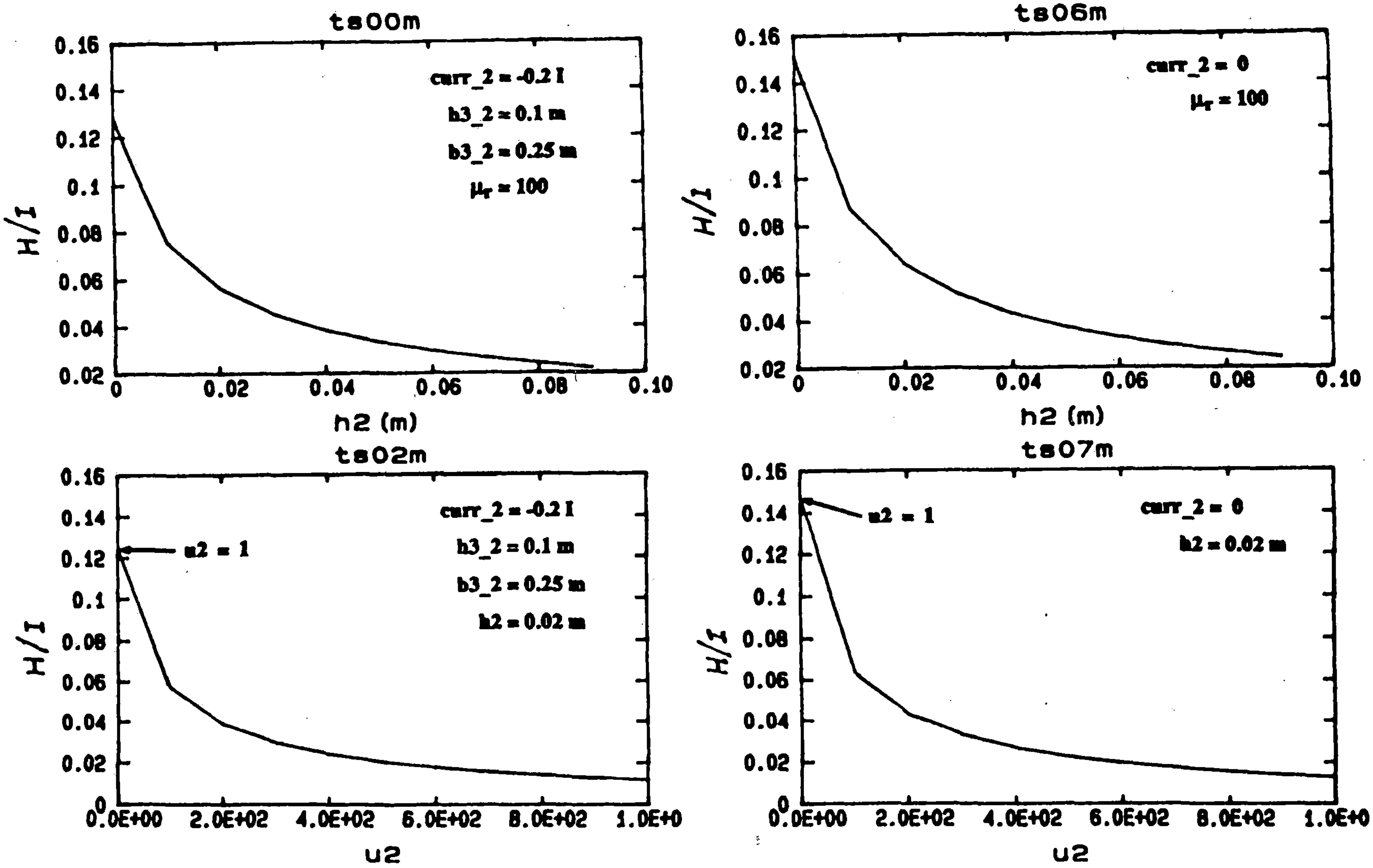


Figure 15. Stray magnetic field at (0,0, -0.5 m) as functions of the thickness and permeability of the passive shielding layer when the current source I has h3_1 = 0.4 m and b3_1 = 1 m.

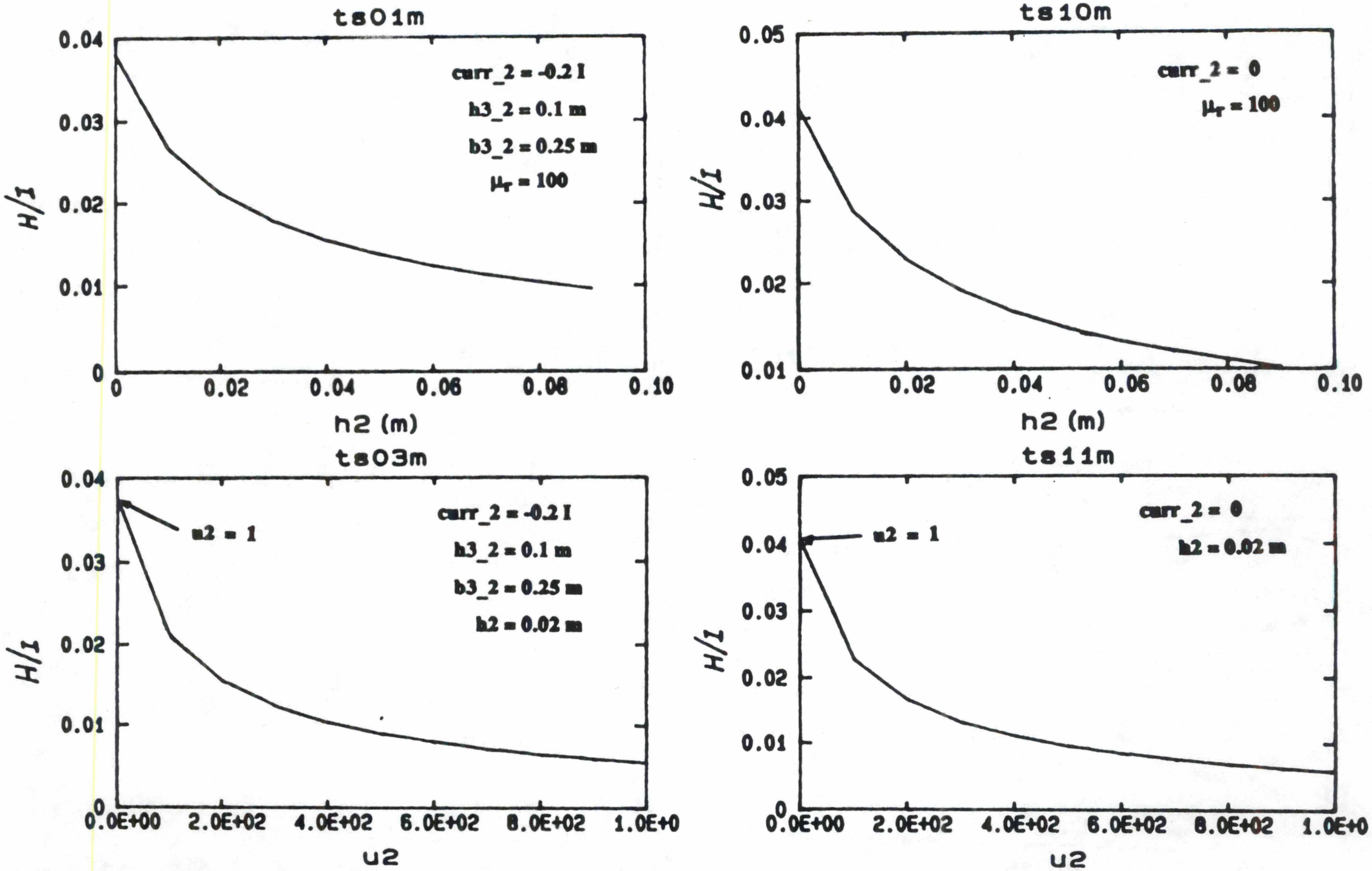


Figure 16. Stray magnetic field at (0,0, -1.5 m) as functions of the thickness and permeability of the passive shielding layer when the current source I has h3_1 = 0.4 m and b3_1 = 1 m.

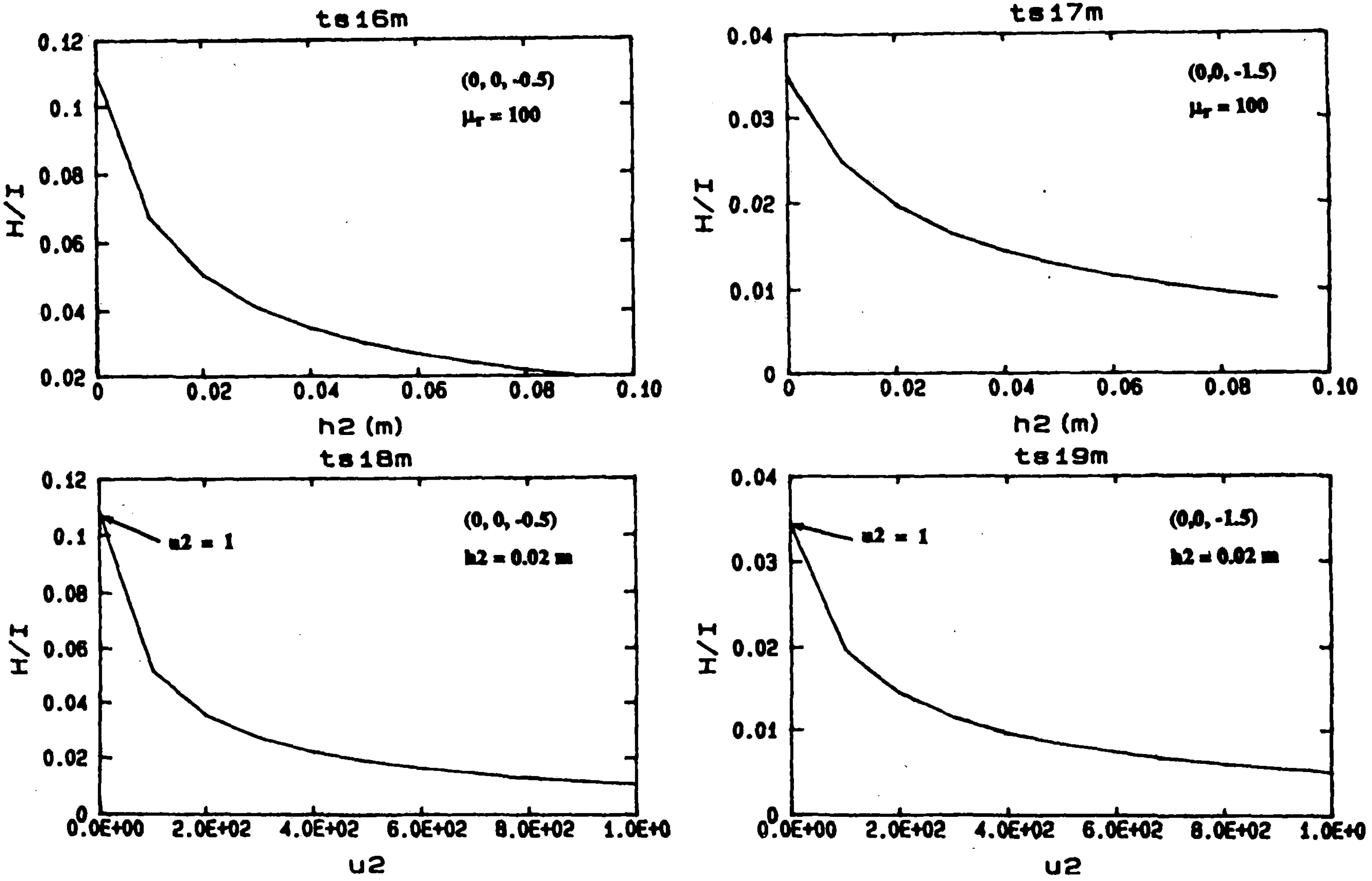
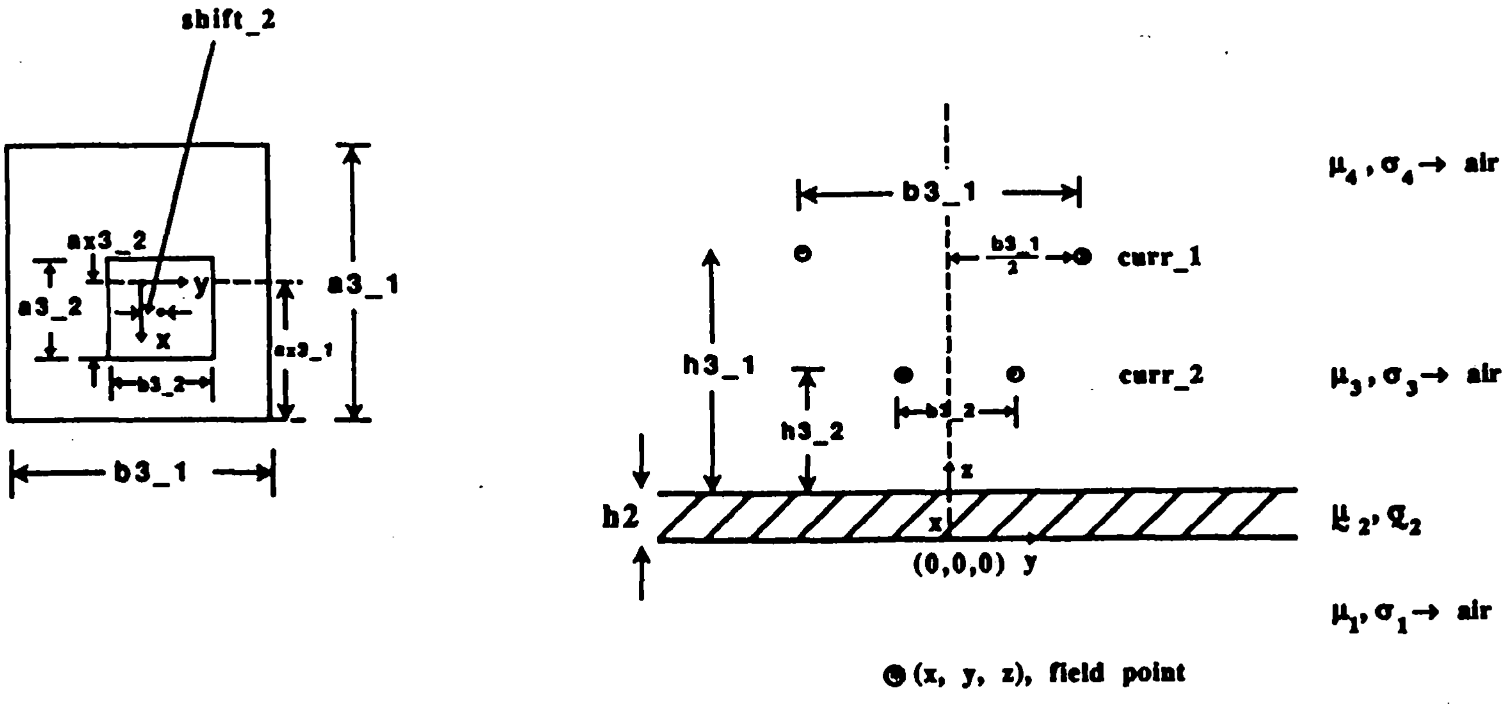


Figure 17. Stray magnetic fields as functions of the thickness and permeability of the passive shielding layer when the current source I has h3_1 = 0.4 m and b3_1 = 1 m, and the active shielding current (-0.2I) has h3_2 = 0.1 m and b3_2 = 0.5 m.



top view of current loops

side view

Figure 18. A schematic diagram of passive and active magnetic field shielding schemes with definitions of some parameter values used in the corresponding analyses and computer codes. Also refer to Appendix A for additional explanation.

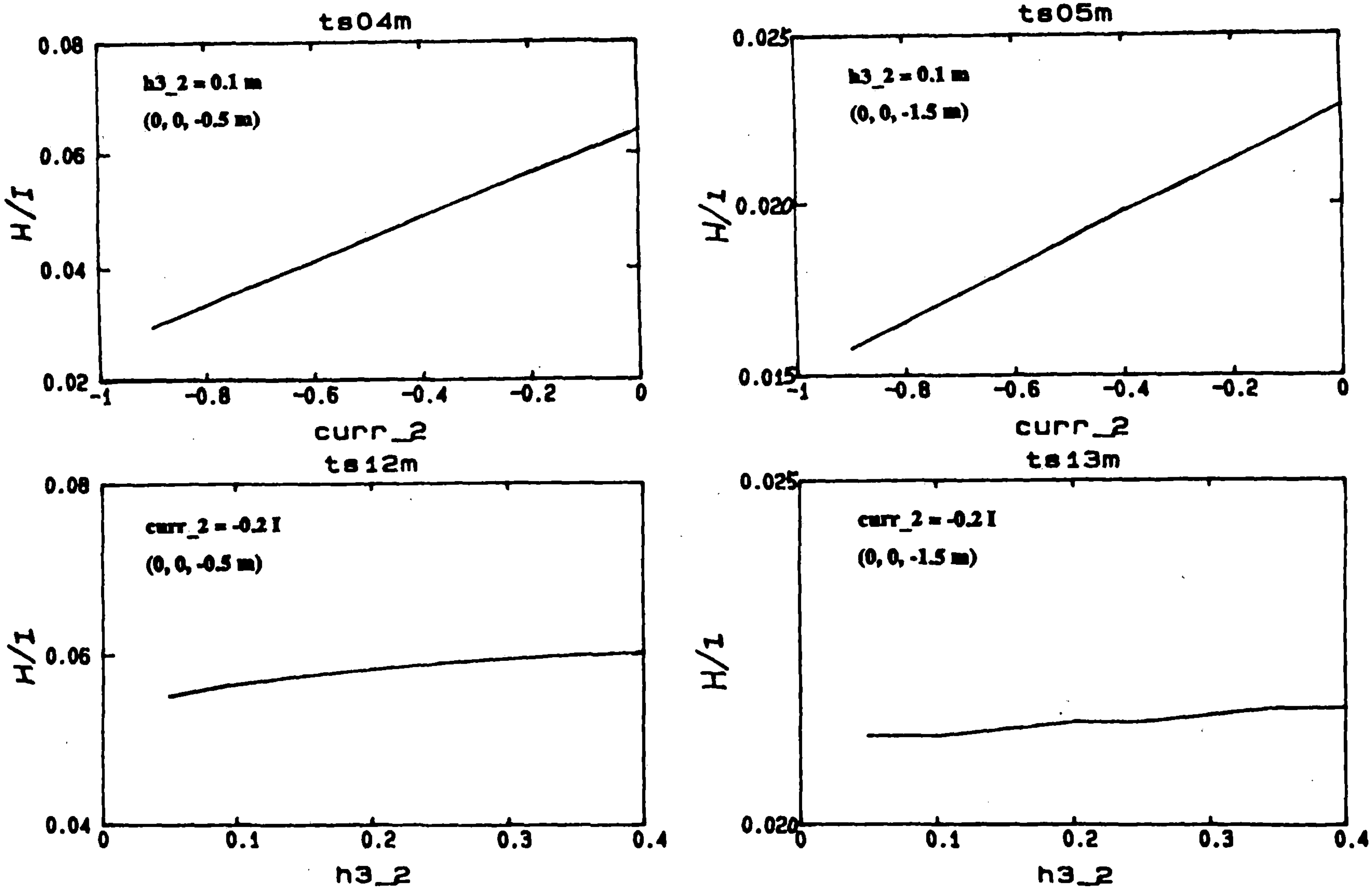


Figure 19. Stray magnetic fields as functions of the strength and location of the active shielding current, when the source current I has h3_1 = 0.4 m and b3_1 = 1m, the active shielding current has b3_2 = 0.25 m, and the passive shielding layer has μ_r = 100, h2 = 0.02 m.

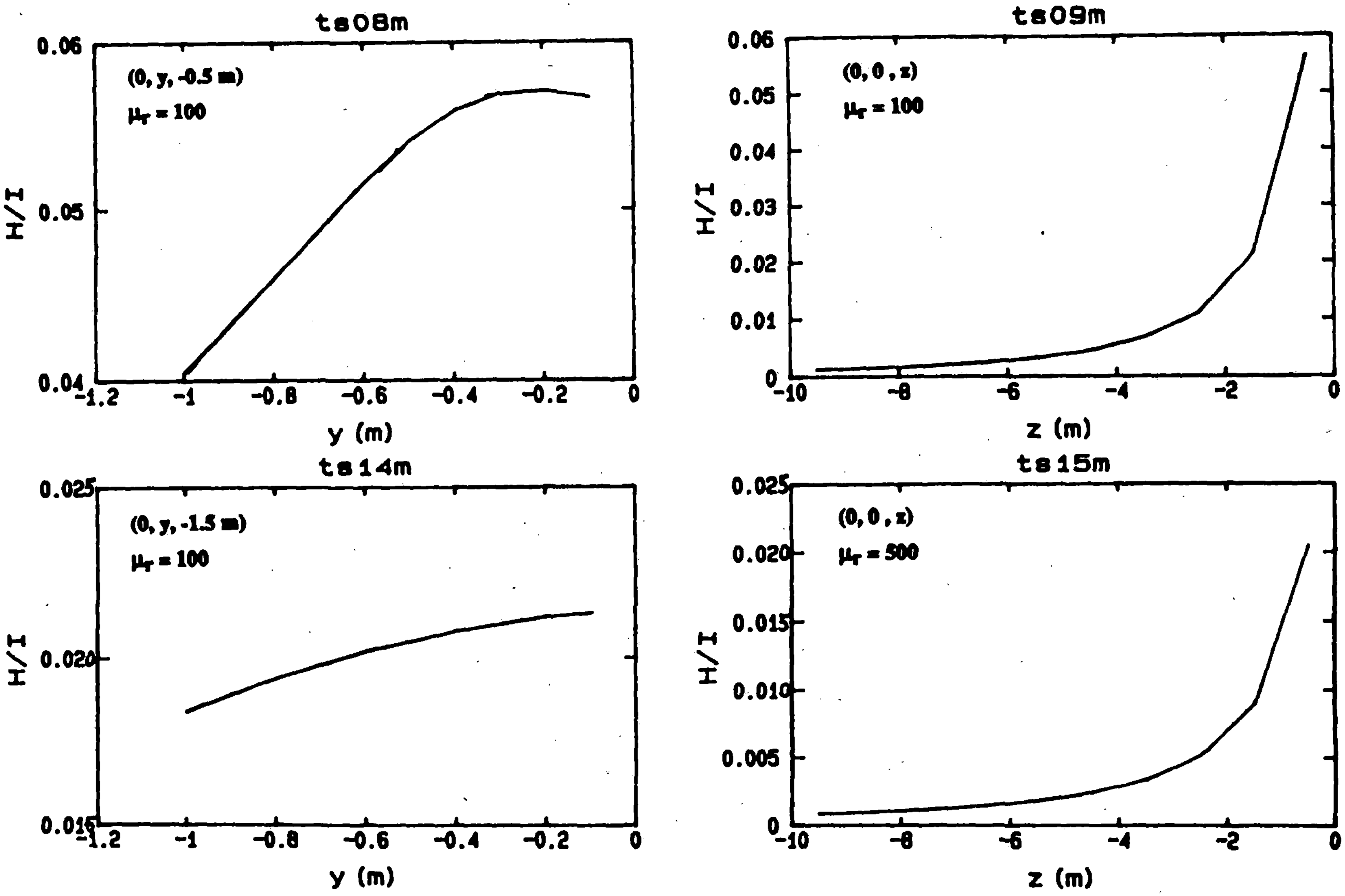


Figure 20. Stray magnetic fields as functions of locations, when the source current I has h3_1 = 0.4 m, b3_1 = 1 m, the active shieldilng current (-0.2I) has h3_2 = 0.1 m, b3_2 = 0.25 m, and the passive shielding layer has h2 = 0.02 m.

obtained from the complicated codes with analytical formulations for some special cases that formulations are possible. For example, when $h2 = 0$, $curr\_2 = 0$, the field at (0, 0, -1.5m) is given as

$$H / I \approx (b3\_1)\left\{2\pi\left[\left(\frac{b3\_1}{2}\right)^2 + (h3\_1 + 0.5)^2\right]\right\}^{-1}$$

which agrees with the numerical results shown in the figures. More systematic runs are required to determine the suitable parameters of the passive shielding layer and/or active shielding currents, once the standards on the tolerable stray magnetic fields are established.

The results in Figures 15-17 and 19-20 are given in a normalized unit. Once the strength of the current source is known, the stray magnetic fields can be easily obtained. For example, take "ts00m" of Figure 15. The curve is obtained for an active shielding current of -0.2I, with $b3_2 = 0.25$m, $h3_2 = 0.1$m, $shift\_2 = 0$, and a passive shielding layer with $\mu_r = 100$, when the current source I has $b3\_1 = 1$ m and $h3\_1 = 0.4$ m, and the field point is at $y = 0$, $z = -0.5$ m. From the curve, if $I = 10^5$ Amp-turns, then the stray magnetic field is

$B = \mu_o H \sim 0.128 \times 10^5 \times 4\pi \times 10^{-7} \times 10^4 \sim 160$ gauss, when $h2 = 0$ (i.e., no passive shielding),

and is equal to

$B = \mu_o H \sim 0.0383 \times 10^5 \times 4\pi \times 10^{-7} \times 10^4 \sim 48$ gauss, when $h2 = 4$ cm.

That is, a reduction factor of about 3 is achieved by a 4 cm thick layer with 100 μ_o permeability. The reduction factor will be larger if the permeability is higher than 100 μ_o. If the permeability is 200 μ_o, then, from "ts02m" of Figure 15, a thickness of only 2 cm can achieve the same (reduction by a factor of 3) shielding effectiveness.

5.0 USER'S MANUAL

Although the mathematical formulation to derive formulas for calculating the propulsion/levitation forces in MAGLEV subsystems and for quantifying shielding performances are very similar, two different sets of computer codes were developed for easier use. These two sets will be described separately. All the source and executable codes can be put into a floppy disk (Table 1). The codes are written in Standard FORTRAN-77, which runs on an IBM PC or its compatibles with 640 kilobytes of RAM. The MS-DOS 4.0 operating system is used with the Microsoft FORTRAN Optimizing Compiler, Version 5.0. MKS units are used for implementation of the codes.

5.1 COMPUTER CODES FOR CALCULATING PROPULSION/LEVITATION FORCES

The source codes for calculating the forces are given as "*7. for" in Table 1 while the executable program is "maglev7.exe." A listing of the source codes is given as Figure 21 for the main program (maglev7.for), and as Figures 22 - 24 for the subroutines. A brief description of the source codes is given below:

field7.for: for calculating the fields in the transformed domain $(\omega, \underline{k})$ at locations of interest by implementing most of the equations in Section 2.0 before Eq. 14

source7.for: for implementing the source equations of Eqs. 16-18

mlcom7.for: for setting up all the common variables

maglev7.for: the main program for calculating the forces by carrying out the necessary integrals

The user must begin the program by selecting the drive containing the software, e.g., C:, in the example shown in Figures 25-27. At the prompt the user must enter the executable program name, for motor analysis the name is "maglev7" and, later in subsection 5.2, for shielding analysis "shield6". The programs are interactive menu-driven and will prompt the user for input parameters. The first input requested is the output file prefix. This should be entered as a 1 to 8 character name. The computer will store data generated by the program in files with that prefix and suffixes that indicate the quantity calculated. For example, if the program is to calculate force and the user assign the prefix "t5n", and then force in the x direction would be stored in file "t5n.fx", force in the y direction would be stored in file "t5n.fy", and force in the z direction would be stored

Table 1. List of the source and executable codes in the floppy disk.

```
C:\>dir a:

 Volume in drive A has no label
 Volume Serial Number is 176A-1800
 Directory of  A:\

SHIELD6  EXE     74752 05-27-92   3:13p
MAGLEV7  EXE     72688 06-04-92  11:17a
SOURCE6  FOR       542 12-20-91   2:54p
SHCOM6   FOR       812 01-29-92   2:31a
FIELD6   FOR      4386 02-26-92  10:57a
SWAP6    FOR       477 12-20-91   2:56p
SHIELD6  FOR     17556 05-27-92   3:08p
MAGLEV7  FOR     18181 06-04-92  11:16a
SOURCE7  FOR      1239 03-25-92   8:39a
MLCOM7   FOR       675 03-25-92   8:39a
FIELD7   FOR      4140 03-25-92   8:39a
RES19              112 07-21-92  12:30p
RES6               122 07-21-92  12:30p
RES46              103 07-21-92  12:30p
RES5N               90 06-04-92  11:54a
       15 File(s)     157696 bytes free
```

```
      program maglev
c     for fourier transform in both x and y directions
      include 'mlcom7.for'

      integer*2      casem,nh,nh3,n,k,loopvar,nc,kc,dn,dk
      character*1    iso1,iso4,iso2u,iso2s
      character*14   name
      real*8       ur1,ur4,ur2,axyz,freq
      real*8       Fx,Fy,Fz,ky,dky,error,fctr
      real*8       lvmin,lvmax,dlv,lv,pl,fctnh
      real*8       ur1x,ur1y,ur1z,ur2x,ur2y,ur2z,ur4x,ur4y,ur4z
      complex*16   Hx1,Hx2,Hy1,Hy2,Hz1,Hz2,termx,termy,termz
      complex*16   Fxintg,Fyintg,Fzintg,Fxsum,Fysum,Fzsum

c     call clr_scr
      kyo3=0.
      b3=0.
      a3=0.
      b2=0.
      aa2=0.
      write(6,1020)
      read(5,'(a)')name
c     write(6,1030)
c     read(5,*) error
c     write(6,1040)
c     read(5,*) dkx,dky
      error=1.0e-6

      write(6,1011)
      read(5,'(a)') iso1
      if (iso1.eq.'y') then
         write(6,1101)
         read(5,*) ur1
         u1x=ur1*uo*1.000001
         u1y=ur1*uo
         u1z=ur1*uo*0.999999
      else
         write(6,1100)
         read(5,*) ur1x,ur1y,ur1z
         u1x=ur1x*uo*1.000001
         u1y=ur1y*uo
         u1z=ur1z*uo*0.999999
      endif
      write(6,1012)
      read(5,'(a)') iso4
      if (iso4.eq.'y') then
         write(6,1161)
         read(5,*) ur4
         u4x=ur4*uo*0.999999
         u4y=ur4*uo*1.000001
         u4z=ur4*uo
      else
         write(6,1160)
         read(5,*) ur4x,ur4y,ur4z
         u4x=ur4x*uo*0.999999
         u4y=ur4y*uo*1.000001
         u4z=ur4z*uo
      endif
      write(6,1013)
      read(5,'(a)') iso2s
```

Figure 21. List of the main program "maglev7.for."

```
      write(6,1014)
      read(5,'(a)') iso2u

      write(6,1170)
      read(5,*) caselp
      write(6,1180)
      read(5,*) case
c source always exists at z=h2+h3
c     write(6,1200)
c     read(5,'(a)') case3
      case3='y'
      write(6,1205)
      read(5,*) IO3

c     if (case3.eq.'y') then
         write(6,1210)
         read(5,*) casem
         pl=0.
c       if (casem.eq.2) then
c           write(6,1215)
c           read(5,*) pl
c        endif
         if (caselp.eq.3) then
  30        write(6,2020)
            read(5,*) loopvar
            if (loopvar.le.0 .or. loopvar.gt.6) then
               write(6,2005)
               goto 30
            endif
c readjust loopvar number to match other caselp cases
            if (loopvar.eq.1) then
               loopvar=loopvar+1
            else
               loopvar=loopvar+3
            endif
         else if (caselp.eq.2) then
  10        write(6,2000)
            read(5,*) loopvar
            if (loopvar.le.0 .or. loopvar.gt.7) then
               write(6,2005)
               goto 10
            endif
         else
  20        write(6,2010)
            read(5,*) loopvar
            if (loopvar.le.0 .or. loopvar.gt.6) then
               write(6,2005)
               goto 20
            endif
         endif
c     endif
      write(6,2050)
      read(5,*) lvmin,lvmax,dlv

      if (loopvar.eq.1) then
         write(6,1061)
         read(5,*) freq
         if (iso2s.eq.'y') then
            write(6,1081)
            read(5,*) sxyz
```

Figure 21. (Continued).

```
   else
      write(6,1080)
      read(5,*) sx,sy,sz
   endif
   if (iso2u.eq.'y') then
      write(6,1121)
      read(5,*) ur2
   else
      write(6,1120)
      read(5,*) ur2x,ur2y,ur2z
   endif
   write(6,2200)
   read(5,*) h3,v
else if (loopvar.eq.2) then
   write(6,1062)
   read(5,*) h2
   if (iso2s.eq.'y') then
      write(6,1081)
      read(5,*) sxyz
   else
      write(6,1080)
      read(5,*) sx,sy,sz
   endif
   if (iso2u.eq.'y') then
      write(6,1121)
      read(5,*) ur2
   else
      write(6,1120)
      read(5,*) ur2x,ur2y,ur2z
   endif
   write(6,2200)
   read(5,*) h3,v
else if (loopvar.eq.3) then
   write(6,1060)
   read(5,*) h2,freq
   if (iso2u.eq.'y') then
      write(6,1121)
      read(5,*) ur2
   else
     write(6,1120)
     read(5,*) ur2x,ur2y,ur2z
   endif
   write(6,2200)
   read(5,*) h3,v
else if (loopvar.eq.4) then
   write(6,1060)
   read(5,*) h2,freq
   if (iso2s.eq.'y') then
      write(6,1081)
      read(5,*) sxyz
   else
      write(6,1080)
      read(5,*) sx,sy,sz
   endif
   write(6,2200)
   read(5,*) h3,v
else if (loopvar.eq.5) then
   write(6,1060)
   read(5,*) h2,freq
   if (iso2s.eq.'y') then
```

Figure 21. (Continued).

```
      write(6,1081)
      read(5,*) sxyz
   else
      write(6,1080)
      read(5,*) sx,sy,sz
   endif
   if (iso2u.eq.'y') then
      write(6,1121)
      read(5,*) ur2
   else
      write(6,1120)
      read(5,*) ur2x,ur2y,ur2z
   endif
   write(6,2201)
   read(5,*) v
else if (loopvar.eq.6) then
   write(6,1060)
   read(5,*) h2,freq
   if (iso2s.eq.'y') then
      write(6,1081)
      read(5,*) sxyz
   else
      write(6,1080)
      read(5,*) sx,sy,sz
   endif
   if (iso2u.eq.'y') then
      write(6,1121)
      read(5,*) ur2
   else
      write(6,1120)
      read(5,*) ur2x,ur2y,ur2z
   endif
   write(6,2202)
   read(5,*) h3
else if (loopvar.eq.7) then
   write(6,1060)
   read(5,*) h2,freq
   if (iso2s.eq.'y') then
      write(6,1081)
      read(5,*) sxyz
   else
      write(6,1080)
      read(5,*) sx,sy,sz
   endif
   if (iso2u.eq.'y') then
      write(6,1121)
      read(5,*) ur2
   else
      write(6,1120)
      read(5,*) ur2x,ur2y,ur2z
   endif
   write(6,2200)
   read(5,*) h3,v
else if (loopvar.eq.8 .or. loopvar.eq.9) then
   write(6,1060)
   read(5,*) h2,freq
   if (iso2s.eq.'y') then
      write(6,1081)
      read(5,*) sxyz
   else
```

Figure 21. (Continued).

```
      write(6,1080)
      read(5,*) sx,sy,sz
   endif
   if (iso2u.eq.'y') then
      write(6,1121)
      read(5,*) ur2
   else
      write(6,1120)
      read(5,*) ur2x,ur2y,ur2z
   endif
   write(6,2200)
   read(5,*) h3,v
endif

if (loopvar.ne.3) then
   if (iso2s.eq.'y') then
      sx=sxyz
      sy=sxyz*0.999999
      sz=sxyz*1.000001
   endif
endif

if (loopvar.ne.4) then
   if (iso2u.eq.'y') then
      u2x=ur2*uo
      u2y=ur2*uo*0.999999
      u2z=ur2*uo*1.000001
   else
      u2x=ur2x*uo
      u2y=ur2y*uo*0.999999
      u2z=ur2z*uo*1.000001
   endif
endif

if (case3.eq.'y') then
   if (case.eq.1) then
      write(6,1220)
      read(5,*) b3
   else if (case.gt.1) then
      write(6,1240)
      read(5,*) b3,a3,ax3
   endif
   if (loopvar.ne.7) then
      if (caselp.ge.2) then
         write(6,1250)
         read(5,*) kyo3
      endif
   endif
endif

write(6,1260)
read(5,'(a)') case2
if (case2.eq.'y') then
   write(6,1265)
   read(5,*) I02
   if (loopvar.ne.8) then
      write(6,1280)
      read(5,*) shift
   endif
   if (case.eq.1) then
```

Figure 21. (Continued).

```
      if (loopvar.ne.9) then
         write(6,1300)
         read(5,*) b2
      endif
   else if (case.gt.1) then
      if (loopvar.ne.9) then
         write(6,1320)
         read(5,*) b2,aa2,ax2
      else
         write(6,1321)
         read(5,*) aa2,ax2
      endif
   endif
endif

write(6,2300)
open(unit=11,file=name//'.Fx',status='unknown')
open(unit=12,file=name//'.Fy',status='unknown')
open(unit=13,file=name//'.Fz',status='unknown')

do 140 lv=lvmin,lvmax,dlv
   if (loopvar.eq.1) then
      h2=lv
   else if (loopvar.eq.2) then
      freq=lv
   else if (loopvar.eq.3) then
      sx=lv*1.000001
      sy=lv*1.000002
      sz=lv*0.999999
   else if (loopvar.eq.4) then
      ur2x=lv
      ur2y=lv*0.999999
      ur2z=lv*1.000001
      u2x=ur2x*uo
      u2y=ur2y*uo
      u2z=ur2z*uo
   else if (loopvar.eq.5) then
      h3=lv
   else if (loopvar.eq.6) then
      v=lv
   else if (loopvar.eq.7) then
      kyo3=lv
   else if (loopvar.eq.8) then
      shift=lv
   else if (loopvar.eq.9) then
      b2=lv
   endif

   w=2.0*pi*freq
    if (w.eq.0.) then
      w=1.e-6
    endif
    if (v.eq.0.) then
      v=1.e-6
    endif
    if (h2.eq.0.) then
      h2=1.e-6
    endif
    if (sx.eq.0.) then
      sx=1.000001e-6
```

Figure 21. (Continued).

```
         endif
         if (ay.eq.0.) then
           ay=0.999999e-6
         endif
         if (az.eq.0.) then
           az=1.e-6
         endif

         dky=0.05/b3
         if ((case2.eq.'y') .and. (b2.gt.b3)) then
           dky=0.05/b2
         endif
         dkx=0.05
         if (case.eq.2) then
           dkx=0.05/a3
           if ((case2.eq.'y') .and. (aa2.gt.a3)) then
             dkx=0.05/aa2
           endif
         endif

         if (casem.eq.2) then
           pl=10.0*b3
           if ((case.eq.2) .and. (b3.gt.a3)) then
             pl=10.0*a3
           endif
         endif

        nc=-1
        Fxsum=0.
        Fysum=0.
        Fzsum=0.
c       check for convergence in n
  50    if (((cdabs(Fyintg).gt.error*cdabs(Fysum)) .and.
     2     (cdabs(Fzintg).gt.error*cdabs(Fzsum))) .or.
     2     (nc.eq.-1) .or.
     2     ((case.ne.1).and.(abs(nc*dkx*a3).lt.70.) .and.
     2     (abs(nc*dkx*aa2).lt.70.))) then
           nc=nc+1
           if (nc.eq.0) then
              dn=1
           else
              dn=2*nc
           endif
           do 180 n=-nc,nc,dn
              kc=-1
              Fxintg=0.
              Fyintg=0.
              Fzintg=0.
c             check for convergence in ky
  60          if (((cdabs(termy).gt.error*cdabs(Fyintg)) .and.
     2           (cdabs(termz).gt.error*cdabs(Fzintg))) .or.
     2           (kc.eq.-1) .or.
     2        ((caselp.ne.3).and.((abs(kc*dky-kyo3)*b3).lt.70.) .and.
     2           (abs(kc*dky*b2).lt.70.))) then
                 kc=kc+1
                 if (kc.eq.0) then
                    dk=1
                 else
                    dk=2*kc
                 endif
```

Figure 21. (Continued).

```
               termx=0.
               termy=0.
               termz=0.
               do 240 k=-kc,kc,dk
                  if (k.ne.0) then
                     ky=k*dky
                  else
                     ky=1e-6
                  endif
                  if (caselp.eq.3) then
                     ky=w/v
                     dky=1.
                  endif
                  Hx1=0.
                  Hy1=0.
                  Hz1=0.
                  nh3=int(pl/h3)+1
                  if(nh3.eq.1) then
                    fctnh=1.
                   else
                    fctnh=h3/pl
                  endif
                  do 300 nh=1, nh3
                    h3p=h3+(nh-1)*h3
                    call field(n,ky)
                    if(nh3.gt.1 .and. nh.eq.nh3) then
                      fctnh=1.-h3*(nh-1)/pl
                    endif
                    Hx1=Bx*fctnh/uo+Hx1
                    Hy1=By*fctnh/uo+Hy1
                    Hz1=Bz*fctnh/uo+Hz1
300               continue

                    Hx2=dconjg(Hx1)
                    Hy2=dconjg(Hy1)
                    Hz2=dconjg(Hz1)

                  termx=termx+Hx1*Hz2
                  termy=termy+Hy1*Hz2
                  termz=termz+Hz1*Hz2-Hx1*Hx2-Hy1*Hy2
240            continue
               Fxintg=Fxintg+termx
               Fyintg=Fyintg+termy
               Fzintg=Fzintg+termz
               if (caselp.eq.3) then
                  termx=0.
                  termy=0.
                  termz=0.
               endif
               goto 60
            endif
            Fxsum=Fxsum+Fxintg
            Fysum=Fysum+Fyintg
            Fzsum=Fzsum+Fzintg
180      continue
         if (case.eq.1) then
            dkx=1./(2.*pi)
            Fxintg=0.
            Fyintg=0.
            Fzintg=0.
```

Figure 21. (Continued).

```
            endif
            goto 50
         endif
         if (caselp.eq.1) then
            if (casem.eq.1) then
               fctr=2.
            else if (casem.eq.2) then
               fctr=2.*((pl/uo)**2.)
            endif
         else if (caselp.eq.2) then
            fctr=1./(b3**2.)
         else if (caselp.eq.3) then
            fctr=1./b3
         endif
         Fx=.5*dreal(uo*Fxsum*dky*dkx)*fctr
         Fy=.5*dreal(uo*Fysum*dky*dkx)*fctr
         Fz=.25*dreal(uo*Fzsum*dky*dkx)*fctr

c        open output files
c        open(unit=11,file=name,status='unknown')
         write(11,1400) lv,Fx
         write(12,1400) lv,Fy
         write(13,1400) lv,Fz
c        write(6,1420) kc,nc
  140 continue
      close(11)
      close(12)
      close(13)

c     suff(1)='_Fx'
c     do 25 i1=1,3
c        fname=name//suff(i1)
c        ufname(i1)=i1+10
c        open(unit=ufname(i1),file=fname,status='unknown')
c        write(ufname(i1),4000) pts
c25   continue

c Format statements :

 1000 format(
     1 15x,'********************************************',
     2/15x,'*                                          *',
     3/15x,'*            PROGRAM : MAGLEV              *',
     4/15x,'*                                          *',
     5/15x,'********************************************')
 1010 format(/5x,'This program calculates Fx,Fy,Fz')
 1011 format(/5x,'Is layer 1 isotropic? (y,n) : ',$)
 1012 format(/5x,'Is layer 4 isotropic? (y,n) : ',$)
 1013 format(/5x,'Is layer 2 conductivity isotropic? (y,n) : ',$)
 1014 format(/5x,'Is layer 2 permeability isotropic? (y,n) : ',$)
 1020 format(/5x,'Enter output file name prefix: ',$)
 1030 format(/5x,'Enter error tolerance (0-1): ',$)
 1040 format(/5x,'Enter dkx,dky : ',$)
 1060 format(/5x,'Enter rail thickness--h2 in m,freq : ',$)
 1061 format(/5x,'Enter freq : ',$)
 1062 format(/5x,'Enter rail thickness--h2 in m: ',$)
c 1063 format(/5x,'Enter 1=loop h3, 2=loop v, 3=no loop : ',$)
c 1066 format(/5x,'Enter h3min, h3max, dh3 : ',$)
 1069 format(/5x,'Enter gap--h3 in m: ',$)
c 1072 format(/5x,'Enter vmin, vmax, dv : ',$)
```

Figure 21. (Continued).

```
 1075 format(/5x,'Enter velocity--v in m/s: ',$)
 1080 format(/5x,'Enter aniso. conductivity--sx,sy,sz in S/m: ',$)
 1081 format(/5x,'Enter iso. conductivity--sxyz in S/m : ',$)
 1100 format(/5x,'Enter layer1 aniso.rel.permea.--ur1x,ur1y,ur1z : ',$)
 1101 format(/5x,'Enter layer1 iso.rel.permea.--ur1 : ',$)
 1120 format(/5x,'Enter layer2 aniso.rel.permea.--ur2x,ur2y,ur2z : ',$)
 1121 format(/5x,'Enter layer2 is0.rel.permea.--ur2 : ',$)
 1160 format(/5x,'Enter layer4 aniso.rel.permea.--ur4x,ur4y,ur4z : ',$)
 1161 format(/5x,'Enter layer4 iso.rel.permea.--ur4 : ',$)
 1170 format(/5x,'Enter which case, 1=levitation, 2=LIM, 3=LSM : ',$)
 1180 format(/5x,'Enter which case, 1=no x dependence,2-D, '
     2            '2=with x dependence,3-D: ',$)
 1200 format(/5x,'Does source exist at z=h2+h3 (y,n) : ',$)
 1205 format(/5x,'Enter amp-turns for loop,tesla for magnet,at z=h2+h3-
     2I03 :',$)
 1210 format(/5x,'Is it a magnet? 1=loop, 2=magnet : ',$)
c 1215 format(/5x,'Enter pole length,pl : ',$)
 1220 format(/5x,'Enter source length--b3 in m: ',$)
 1240 format(/5x,'Enter loop leng.,width,edge loc--b3,a3,ax3 in m: ',$)
 1250 format(/5x,'Enter kyo3 in 1/m,note w/ky03=phase velocilty: ',$)
 1260 format(/5x,'Does source exist at z=h2 (y,n),no for LIM : ',$)
 1265 format(/5x,'Enter amp-turns at z=h2--I02 : ',$)
 1280 format(/5x,'Enter long.shiftofsour. at z=h2 to z=h2+h3 in m: ',$)
 1300 format(/5x,'Enter source length at z=h2--b2 in m: ',$)
 1320 format(/5x,'Enter loop leng.,width,edge loc--b2,a2,ax2 in m: ',$)
 1321 format(/5x,'Enter loop width,edge loc--a2,ax2 in m: ',$)
 1400 format(2(e12.3))
 1420 format(/5x,'kc=',i6,'nc=',i6)
 2000 format(/5x,'Enter parameter to loop:',
     2        /5x,'  1. rail thickness h2',
     2        /5x,'  2. source freq',
     2        /5x,'  3. rail conductivity sx',
     2        /5x,'  4. rail rel.permeability--ur2',
     2        /5x,'  5. gap--h3',
     2        /5x,'  6. velocity--v',
     2        /5x,'  7. wave number det. source phase velocity--kyo3',
     2        /5x,'Select (1,..,7): ',$)
 2005 format(/5x,'Input error: loop parameter is OUT of range!',
     2' Please try again.')
 2010 format(/5x,'Enter parameter to loop:',
     2        /5x,'  1. rail thickness--h2',
     2        /5x,'  2. source freq.',
     2        /5x,'  3. rail conductivity--sx',
     2        /5x,'  4. rail rel. permeability--ur2',
     2        /5x,'  5. gap--h3',
     2        /5x,'  6. velocity--v',
     2        /5x,'Select (1,..,6): ',$)
 2020 format(/5x,'Enter parameter to loop:',
     2        /5x,'  1. source freq.',
     2        /5x,'  2. gap--h3',
     2        /5x,'  3. velocity--v',
     2        /5x,'  4. wave number det. source phase velocity--kyo3',
     2        /5x,'  5. rel longitudinal loop loc.of 2 sources--shift',
     2        /5x,'  6. loop length of source at z=h2--b2',
     2        /5x,'Select (1,..,6): ',$)
 2050 format(/5x,'Enter min, max and stepsize for above selected',
     2' parameter: ',$)
 2200 format(/5x,'Enter gap--h3 in m,velocity--v in m/s: ',$)
 2201 format(/5x,'Enter velocity--v in m/s: ',$)
 2202 format(/5x,'Enter gap--h3 in m: ',$)
 2300 format(//5x,'Please wait, calculating ....',/)
      end
```

Figure 21. (Concluded).

```
c     fields at layer 3 at z=h2+h3, and prepares for other layers

      subroutine field(n,ky)
      include 'mlcom7.for'

      integer*2   n
      real*8      kx,ky,kz1,kz3,kz4
      complex*16  X,b,c,kz2(2),kz(2),R(2),Q(2)
      complex*16  S,T,U,V1,V2
      complex*16  temp,IIIx(2),IIIy(2),IIIz(2)
      complex*16  IIxl(2)
c     complex*16  Ix,Iy,Iz,IVx,IVy,IVz
c     complex*16  IIxo(2),IIyo(2),IIzo(2),IIxl(2),IIyl(2),IIzl(2)
      complex*16  csinh,ccosh,p

      csinh(p)=.5*(cdexp(p)-cdexp(-p))
      ccosh(p)=.5*(cdexp(p)+cdexp(-p))
      i=dcmplx(0.,1.)
      call source(n,ky)

      if (n.eq.0) then
        kx=1e-6
      else
        kx=n*dkx
      endif
      X=dcmplx(kx*kx/u2y+ky*ky/u2x, -(w-ky*v)*sz)
      b=dcmplx(-(sx/sz+u2x/u2z)*kx*kx-(sy/sz+u2y/u2z)*ky*ky,
     2         (w-ky*v)*(sx*u2y+sy*u2x))
      c=(u2x*u2y*X/(u2z*sz))*dcmplx(sx*kx*kx+sy*ky*ky,
     2                                -(w-ky*v)*sx*sy*u2z)
      kz2(1)=.5*(-b+cdsqrt(b*b-4.*c))
      kz2(2)=.5*(-b-cdsqrt(b*b-4.*c))
      kz(1)=cdsqrt(kz2(1))
      kz(2)=cdsqrt(kz2(2))
      kz3=dsqrt(kx*kx+ky*ky)
      kz1=dsqrt((u1x/u1z)*kx*kx+(u1y/u1z)*ky*ky)
      kz4=dsqrt((u4x/u4z)*kx*kx+(u4y/u4z)*ky*ky)

      R(1)=( u2x*u2y*X*(u2y*ky*ky-u2z*kz2(1)-i*(w-ky*v)*sx*u2y*u2z)+
     2       u2x*u2z*kx*kx*kz2(1) )
      R(1)=R(1)/( u2y*((kx*ky+i*kx*sx*v*u2z)*(u2x*u2y*X-u2z*kz2(1))-
     2            u2z*kz2(1)*i*kx*v*(u2x*sz-sx*u2z)) )
      R(2)=( u2x*u2y*X*(u2y*ky*ky-u2z*kz2(2)-i*(w-ky*v)*sx*u2y*u2z)+
     2       u2x*u2z*kx*kx*kz2(2) )
      R(2)=R(2)/( u2y*((kx*ky+i*kx*sx*v*u2z)*(u2x*u2y*X-u2z*kz2(2))-
     2            u2z*kz2(2)*i*kx*v*(u2x*sz-sx*u2z)) )
      Q(1)=-kz(1)*(i*u2x*kx+(i*ky-v*u2x*sz)*u2y*R(1)) /
     2       (u2x*u2y*X)
      Q(2)=-kz(2)*(i*u2x*kx+(i*ky-v*u2x*sz)*u2y*R(2)) /
     2       (u2x*u2y*X)
      S=-(Q(1)*(1.-ky*v/w)+kz(1)*v*R(1)/(i*w)) /
     2   (Q(2)*(1.-ky*v/w)+kz(2)*v*R(2)/(i*w))
      T=( csinh(kz(1)*h2)*
     2    (i*ky*Q(1)-kz(1)*R(1)+S*(i*ky*Q(2)-kz(2)*R(2)))-
     2    (u2x*kx/(u1z*kz1))*(kx*R(1)-ky)*
     2    (ccosh(kz(1)*h2)-ccosh(kz(2)*h2)) )
      T=T/( (1./S)*csinh(kz(2)*h2)*
     2    (i*ky*Q(1)-kz(1)*R(1)+S*(i*ky*Q(2)-kz(2)*R(2)))+
     2    (u2x*kx/(u1z*kz1))*(kx*R(2)-ky)*
     2    (ccosh(kz(1)*h2)-ccosh(kz(2)*h2)) )
```

Figure 22. List of the subroutine "field7.for."

```
      U=( (T/S)*csinh(kz(2)*h2)-csinh(kz(1)*h2) ) /
     2 ( ccosh(kz(1)*h2)-ccosh(kz(2)*h2) )
      V1=(i*kx/(w*kz3)) * (
     2   (kx*R(1)-ky)*(ccosh(kz(1)*h2)+U*csinh(kz(1)*h2))+
     2   (kx*R(2)-ky)*(T*ccosh(kz(2)*h2)+S*U*csinh(kz(2)*h2)) )
      V2=(i*uo*kx/(w*u2y*ky)) * (
     2   (kz(1)-i*kx*Q(1))*(csinh(kz(1)*h2)+U*ccosh(kz(1)*h2))+
     2   (kz(2)-i*kx*Q(2))*(T*csinh(kz(2)*h2)+S*U*ccosh(kz(2)*h2)) )

      temp=((V1+V2)/(V1-V2))*dexp(-2.*kz3*h3p)
      IIIx(2)=(u4z*kz4*K3+(V1*K2/(V1-V2))*dexp(-kz3*h3p)*
     2        (u4z*kz4-uo*kz3))
     2        /(dexp(kz3*h3p)*((u4z/uo)*(ky*kz4/kx)*(1.-temp)+
     2                    (ky*kz3/kx)*(1.+temp)))
      IIx1(1)=(2.*IIIx(2)+uo*kx*K2/ky)/(V1-V2)
      IIIx(1)=-uo*kx*K2/(2.*ky)-(V1+V2)*IIx1(1)/2.

      IIx1(2)=T*IIx1(1)
c     IIxo(1)=U*IIx1(1)
c     IIxo(2)=S*IIxo(1)

c     IIzo(2)=Q(2)*IIxo(2)
c     IIzo(1)=Q(1)*IIxo(1)
c     IIz1(2)=Q(2)*IIx1(2)
c     IIz1(1)=Q(1)*IIx1(1)
c     IIyo(2)=R(2)*IIxo(2)
c     IIyo(1)=R(1)*IIxo(1)
c     IIy1(2)=R(2)*IIx1(2)
c     IIy1(1)=R(1)*IIx1(1)

      IIIy(1)=(ky/kx)*IIIx(1)
      IIIy(2)=(ky/kx)*IIIx(2)
      IIIz(1)=(i*kz3/kx)*IIIx(1)
      IIIz(2)=(-i*kz3/kx)*IIIx(2)

      Bx=IIIx(1)*dexp(-kz3*h3)+IIIx(2)*dexp(kz3*h3)
      By=IIIy(1)*dexp(-kz3*h3)+IIIy(2)*dexp(kz3*h3)
      Bz=IIIz(1)*dexp(-kz3*h3)+IIIz(2)*dexp(kz3*h3)

c     Ix=(i*kx*u1x/(w*kz1*u1z))*
c    2   ((kx*R(1)-ky)*IIx1(1)+(kx*R(2)-ky)*IIx1(2))
c     Iy=(u1y*ky/(u1x*kx))*Ix
c     Iz=(-i*u1z*kz1/(u1x*kx))*Ix

c     temp=((V1+V2)/(V1-V2))*dexp(-2.*kz3*h3)
c     IVx=(-u4x*kx/ky)*dexp(kz4*h3)*
c    2    (K3+K2*exp(-kz3*h3)*V1/(V1-V2)-
c    2     (1./uo)*(ky/kx)*dexp(kz3*h3)*(1.-temp)*IIIx(2))
c     IVy=(u4y*ky/(u4x*kx))*IVx
c     IVz=(i*u4z*kz4/(u4x*kx))*IVx

      return
      end
```

Figure 22. (Concluded).

```
c     sources K2 & K3 at layers z=h2 & h2+h3

      subroutine source(n,ky)
      include 'mlcom7.for'

      integer*2   n
      real*8      kx,ky
      complex*16  lp3,lp2

      K3=0.
      K2=0.
      kx=n*dkx
      lp2=0.
      if (case2.eq.'y') then
        lp2=I02*(-2.*i/dsqrt(2.*pi))*dsin(ky*b2/2.)
      endif

      if (caselp.eq.1) then
        lp3=I03*(-2.*i/dsqrt(2.*pi))*dsin(ky*b3/2.)
      else
        lp3=I03*(2./dsqrt(2.*pi))*dsin((kyo3-ky)*b3/2.)/(kyo3-ky)
      endif

      if (case.eq.1) then
          if (case3.eq.'y') then
            K3=lp3*dsqrt(2.*pi)
          endif
          if (case2.eq.'y') then
            K2=lp2*dsqrt(2.*pi)
          endif
      endif

      if (case.eq.2) then
        if (case3.eq.'y') then
          if (n.eq.0) then
            K3=lp3*a3/dsqrt(2.*pi)
          else
            K3=(lp3/kx)*dsqrt(2./pi)*
     2       dsin(kx*a3/2.)*cdexp(-i*kx*(ax3-a3/2.))
          endif
        endif
        if (case2.eq.'y') then
          if (n.eq.0) then
            K2=lp2*aa2/dsqrt(2.*pi)
          else
            K2=(lp2/kx)*dsqrt(2./pi)*
     2       dsin(kx*aa2/2.)*cdexp(-i*kx*(ax2-aa2/2.))
          endif
        endif
      endif


      if (case2.eq.'y') then
        K2=K2*cdexp(-i*ky*shift)
      endif

      return
      end
```

Figure 23. List of the subroutine "source7.for."

```
c       mlcom7.for
c       common variables share by maglev and field

   *    implicit none

        integer*2    case,caselp
        character*1  case2,case3
        real*8       h2,h3,h3p,uo,pi,Wo,sx,sy,sz,w,v,dkx
        real*8       u1x,u1y,u1z,u2x,u2y,u2z,u3x,u3y,u3z,u4x,u4y,u4z
        real*8       aa2,a3,ax2,ax3,b2,b3,shift,kyo3,I03,I02
        complex*16   Bx,By,Bz,K2,K3,i

        parameter (pi=3.141592654, uo=1.2566371e-6)

        common /a/   h2,h3,h3p,Wo,sx,sy,sz,w,v,dkx
        common /b/   u1x,u1y,u1z,u2x,u2y,u2z,u3x,u3y,u3z,u4x,u4y,u4z
        common /c/   Bx,By,Bz,K2,K3,i
        common /d/   aa2,a3,ax2,ax3,b2,b3,shift,kyo3,I03,I02
        common /e/   case,case2,case3,caselp
```

Figure 24. List of the subroutine "mlcom7.for."

```
C:\>maglev7

    Enter output file name prefix: t5n

    Is layer 1 isotropic? (y,n) : y

    Enter layer1 iso.rel.permea.--ur1 : 1.

    Is layer 4 isotropic? (y,n) : y

    Enter layer4 iso.rel.permea.--ur4 : 1.

    Is layer 2 conductivity isotropic? (y,n) : y

    Is layer 2 permeability isotropic? (y,n) : y

    Enter which case, 1=levitation, 2=LIM, 3=LSM : 1

    Enter which case, 1=no x dependence,2-D, 2=with x dependence,3-D: 1

    Enter amp-turns for loop,tesla for magnet,at z=h2+h3--I03 :1.

    Is it a magnet? 1=loop, 2=magnet : 2

    Enter parameter to loop:
      1. rail thickness--h2
      2. source freq.
      3. rail conductivity--sx
      4. rail rel. permeability--ur2
      5. gap--h3
      6. velocity--v
    Select (1,..,6): 6

    Enter min, max and stepsize for above selected parameter: 0. 180.1 15.

    Enter rail thickness--h2 in m,freq : 0.02 0.

    Enter iso. conductivity--sxyz in S/m : 1.e6

    Enter layer2 isO.rel.permea.--ur2 : 500.

    Enter gap--h3 in m: 0.02

    Enter source length--b3 in m: 0.5

    Does source exist at z=h2 (y,n),no for LIM : n


    Please wait, calculating ....
```

Figure 25. (a) An example run of "maglev7.exe," for case1p = 1, i.e., for magnetic levitation.

```
C:\>type t5n.fx
         .100E-03   -.179E-09
         .150E+02    .639E-07
         .300E+02    .436E-06
         .450E+02   -.343E-07
         .600E+02    .126E-06
         .750E+02   -.125E-06
         .900E+02    .870E-06
         .105E+03    .378E-06
         .120E+03    .111E-05
         .135E+03   -.619E-07
         .150E+03   -.700E-07
         .165E+03   -.406E-06
         .180E+03    .708E-07

C:\>type t5n.fy
         .100E-03   -.298E+00
         .150E+02   -.263E+05
         .300E+02   -.322E+05
         .450E+02   -.363E+05
         .600E+02   -.395E+05
         .750E+02   -.422E+05
         .900E+02   -.445E+05
         .105E+03   -.464E+05
         .120E+03   -.480E+05
         .135E+03   -.494E+05
         .150E+03   -.507E+05
         .165E+03   -.518E+05
         .180E+03   -.528E+05

C:\>type t5n.fz
         .100E-03    .153E+06
         .150E+02    .138E+06
         .300E+02    .126E+06
         .450E+02    .118E+06
         .600E+02    .112E+06
         .750E+02    .106E+06
         .900E+02    .101E+06
         .105E+03    .964E+05
         .120E+03    .924E+05
         .135E+03    .886E+05
         .150E+03    .852E+05
         .165E+03    .820E+05
         .180E+03    .790E+05
```

Figure 25. (b) Output of the example run.

```
t5n
y
1.
y
1.
y
y
1
1
1.
2
6
0. 180.1 15.
0.02 0.
1.e6
500.
0.02
0.5
n
```

Figure 25. (c) Batch input file "res5n" for example run (a).

```
C:\>maglev7
  Enter output file name prefix: t46

  Is layer 1 isotropic? (y,n) : y

  Enter layer1 iso.rel.permea.--ur1 : 1.

  Is layer 4 isotropic? (y,n) : y

  Enter layer4 iso.rel.permea.--ur4 : 1.

  Is layer 2 conductivity isotropic? (y,n) : y

  Is layer 2 permeability isotropic? (y,n) : y

  Enter which case, 1=levitation, 2=LIM, 3=LSM : 2

  Enter which case, 1=no x dependence,2-D, 2=with x dependence,3-D: 1

  Enter amp-turns for loop,tesla for magnet,at z=h2+h3--I03 :1.

  Is it a magnet? 1=loop, 2=magnet : 1

  Enter parameter to loop:
    1. rail thickness h2
    2. source freq
    3. rail conductivity sx
    4. rail rel.permeability--ur2
    5. gap--h3
    6. velocity--v
    7. wave number det. source phase velocity--kyo3
  Select (1,..,7): 3

  Enter min, max and stepsize for above selected parameter: 5.e5 1.e7 1.e6

  Enter rail thickness--h2 in m,freq : .02 400.

  Enter layer2 isO.rel.permea.--ur2 : 500.

  Enter gap--h3 in m,velocity--v in m/s: .02 135.

  Enter source length--b3 in m: 2.

  Enter kyo3 in 1/m,note w/ky03=phase velocilty: 15.70796327

  Does source exist at z=h2 (y,n),no for LIM : n


  Please wait, calculating ....
```

Figure 26. (a) An example run of "maglev7.exe," for case1p=2, i.e., for a LIM.

```
C:\>type t46.fx
     .500E+06      .567E-15
     .150E+07      .766E-15
     .250E+07      .885E-15
     .350E+07      .973E-15
     .450E+07      .104E-14
     .550E+07      .111E-14
     .650E+07      .116E-14
     .750E+07      .120E-14
     .850E+07      .125E-14
     .950E+07      .128E-14

C:\>type t46.fy
     .500E+06      .495E-08
     .150E+07      .806E-08
     .250E+07      .998E-08
     .350E+07      .114E-07
     .450E+07      .126E-07
     .550E+07      .136E-07
     .650E+07      .145E-07
     .750E+07      .153E-07
     .850E+07      .159E-07
     .950E+07      .166E-07

C:\>type t46.fz
     .500E+06      .768E-07
     .150E+07      .724E-07
     .250E+07      .695E-07
     .350E+07      .672E-07
     .450E+07      .653E-07
     .550E+07      .636E-07
     .650E+07      .621E-07
     .750E+07      .607E-07
     .850E+07      .594E-07
     .950E+07      .582E-07
```

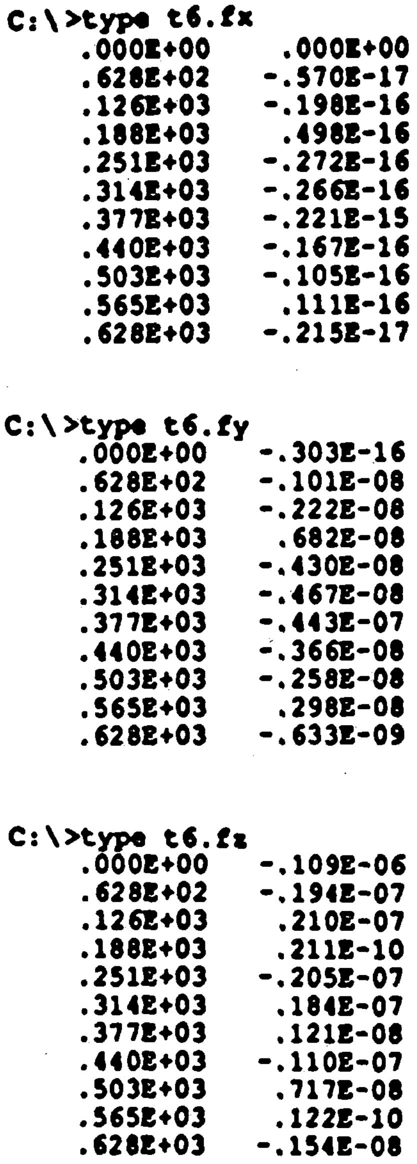
Figure 26. (b) Output of the example run.

```
t46
y
1.
y
1.
y
y
2
1
1.
1
3
5.e5 1.e7 1.e6
.02 400.
500.
.02 135.
2.
15.70796327
n
```

Figure 26. (c) Batch input file "res46" for example run (a).

```
C:\>maglev7

    Enter output file name prefix: t6

    Is layer 1 isotropic? (y,n) : y

    Enter layer1 iso.rel.permea.--ur1 : 1.

    Is layer 4 isotropic? (y,n) : y

    Enter layer4 iso.rel.permea.--ur4 : 1.

    Is layer 2 conductivity isotropic? (y,n) : y

    Is layer 2 permeability isotropic? (y,n) : y

    Enter which case, 1=levitation, 2=LIM, 3=LSM : 3

    Enter which case, 1=no x dependence,2-D, 2=with x dependence,3-D: 2

    Enter amp-turns for loop,tesla for magnet,at z=h2+h3--I03 :1.

    Is it a magnet? 1=loop, 2=magnet : 1

    Enter parameter to loop:
      1. source freq.
      2. gap--h3
      3. velocity--v
      4. wave number det. source phase velocity--kyo3
      5. rel longitudinal loop loc.of 2 sources--shift
      6. loop length of source at z=h2--b2
    Select (1,..,6): 1

    Enter min, max and stepsize for above selected parameter: 0. 100. 10.

    Enter rail thickness--h2 in m: .02

    Enter iso. conductivity--sxyz in S/m : 0.

    Enter layer2 is0.rel.permea.--ur2 : 1.

    Enter gap--h3 in m,velocity--v in m/s: .1 120.

    Enter loop leng.,width,edge loc--b3,a3,ax3 in m: 10. .5 .25

    Enter kyo3 in 1/m,note w/ky03=phase velocilty: 3.141592654

    Does source exist at z=h2 (y,n),no for LIM : y

    Enter amp-turns at z=h2--I02 : 1.

    Enter long.shiftofsour. at z=h2 to z=h2+h3 in m: 2.

    Enter loop leng.,width,edge loc--b2,a2,ax2 in m: 1. .5 .25

    Please wait, calculating ....
```

Figure 27. (a) An example run of "maglev7.exe," for case1p=3, i.e., for a LSM.



```
C:\>type t6.fx
         .000E+00     .000E+00
         .628E+02    -.570E-17
         .126E+03    -.198E-16
         .188E+03     .498E-16
         .251E+03    -.272E-16
         .314E+03    -.266E-16
         .377E+03    -.221E-15
         .440E+03    -.167E-16
         .503E+03    -.105E-16
         .565E+03     .111E-16
         .628E+03    -.215E-17

C:\>type t6.fy
         .000E+00    -.303E-16
         .628E+02    -.101E-08
         .126E+03    -.222E-08
         .188E+03     .682E-08
         .251E+03    -.430E-08
         .314E+03    -.467E-08
         .377E+03    -.443E-07
         .440E+03    -.366E-08
         .503E+03    -.258E-08
         .565E+03     .298E-08
         .628E+03    -.633E-09

C:\>type t6.fz
         .000E+00    -.109E-06
         .628E+02    -.194E-07
         .126E+03     .210E-07
         .188E+03     .211E-10
         .251E+03    -.205E-07
         .314E+03     .184E-07
         .377E+03     .121E-08
         .440E+03    -.110E-07
         .503E+03     .717E-08
         .565E+03     .122E-10
         .628E+03    -.154E-08
```

Figure 27. (b) Output of the example run.

```
t6
y
1.
y
1.
y
y
3
2
1.
1
1
0. 100. 10.
.02
0.
1.
.1 120.
10. .5 .25
3.141592654
y
1.
2.
1. .5 .25
```

Figure 27. (c) Batch input file "res6" for example run (a).

in file "t5n.fz". The program will then ask for user inputs to define the specific problem to be solved. Specific user inputs requested will vary as functions of previous inputs. For instance, if the response to the question "Is layer 1 isotropic?" is "yes", the program will ask for "iso.rel.permea.(isotropic relative permeability)". If the answer is "no", then the program will ask the relative permeabilities in the x, y, and z directions. The examples which follow present examples for inputs to LSM propulsion, levitation, LIM propulsion and, later in subsection 5.2 for shielding problems where responses to menu driven requests are shown. Output data files containing solutions to the problems are printed following the pages with program inputs (i.e., as part "b" of each figure).

Rather than follow the program menus as shown, the user has the option of preparing batch input files in the format shown on part "c" of each figure. The example input files are also given in the disk as listed in Table 1 as "res*" files. The input file must follow the format shown and be stored as a user defined file name using whatever editor the user prefers. The batch run can then be run by simply typing, if the input file is "res5n",

```
maglev7 < res5n
```

The geometrical variables used in the codes are described in Figure 3 and Appendix A. Some variables for material properties, source parameters, field and force values, are also given below:

urij = relative permeability of j-th component (notice that uniaxial permeability $\underset{\sim}{u} = \hat{x}\hat{x}\, u_{xx} + \hat{y}\hat{y}\, u_{yy} + \hat{z}\hat{z}\, u_{zz}$ has been assumed) in the ith layer, i = 1, 2, 4, j=x, y, z

sj = conductivity of the j-th component (again, uniaxial conductivity has been assumed for layer 2) in layer 2, j = x, y, z

Hj1 = j-th component of the magnetic field intensity at the interface of layers 3 and 4, j = x, y, z

Fj = j-th component of the force exerted on layer 4, j = x, y, z

k_{yo}, f, v = wave number, frequency of the source current, and velocity of the vehicle (Note, $k_{yo} \cdot b3/2$ has to be multiples of π)

The variable names introduced in Section 2.0 are mostly preserved in the subroutine "field7.for." For performing the integrations, some variables need to be introduced to define the increments and to check for the convergence. They are given as "dkx," "dky," and "error," respectively. From many test runs, it is estimated that values of "error" $\leq 10^{-6}$, and "a • dkx" (or "b • dky") ≤ 0.1 will give reasonably accurate results. In the above conditions, "a" represents "a3" and "aa2", and "b" represents "b3" and "b2." These criteria for the determination of integration parameters have also been implemented into the codes and are transparent to the users.

These computer codes are intended to be very versatile for running various option cases. They can be used to address purely levitation design alternatives, and to address LIM and LSM propulsion approaches, by inputing different values for parameter "caselp". They allow the sources to be current loops or magnets (but only at the interface of layers 3 and 4), to be at the interface of layers 3 and 4, and/or at the interface of layers 2 and 3, and to be x-independent or not. For this reason, several variables are introduced to identify the options, which are listed below, and also explained in Appendix A.

case: = 1, for x-independent (i.e., 2-dimensional problem, when the lateral dimension is large); = 2, for x-dependent

caselp: = 1, for levitation only; = 2, for LIM; = 3, for LSM

case2: ="y", when source present at interface of layers 2, 3; ="n", when not present

case3: ="y", when source present at interface of layers 3, 4; = "n", when not present

casem: =1, for current loop source; =2, for magnet source.

In the case of magnet source, the pole length for the equivalent current sheets introduced to approximate the magnet source is needed. The common rule is to use a pole length about ten times the pole-face length (b3) or width (a3) whichever is smaller. Again, this rule has been implemented in the program and is transparent to the user. It should also be noted that the computer codes in their present form require that LSM layer 2 be nonconducting with free space permeability.

The formulation presented in Section 2.0 allows for the materials in layers 1, 2, 4 to be anisotropic. The computer codes are prepared for such anisotropic materials. No attempt has been made to rederive the formulas for the isotropic case for implementation into the computer codes. However, the results of an isotropic case can be obtained by introducing slightly anisotropic properties to the material, e.g., less than 0.1% difference. Such an approximate approach has been implemented into the codes for handling the isotropic cases. The formulations are not prepared to handle some variables with zero values. To prevent overflows from occurring, a small value (such as 10^{-6}) is introduced to approximate a zero value for such variables. This leads to negligible errors in the results and is transparent to the user.

To run the computer codes which one variable is allowed to step through many values while all other variables remain fixed, a looping structure is introduced. Depending on the options determined by the variable "caselp", different sets of "looping" variables are selected. For example, when caselp = 1 is selected to address a levitation problem, there are six looping variables (k2, f, ..., v) for a user to choose. If v is chosen (i.e., 6 is chosen as input, as shown in Fig. 25b), then the program will ask the minimum, maximum and step size of v, and the specific values of other variables.

With the above description, three sample runs, corresponding to "caselp" = 1, 2, and 3, respectively, for levitation, LIM, and LSM are demonstrated as Figures 25a, 26a, and 27a. The corresponding output files are given as Figures 25b, 26b, and 27b. The output files give the forces in the x(transverse), y (propulsion) and z (levitation) directions. The first column of each file is the looping parameter, for Figure 25b, it is the velocity (m/s), for Figure 26b, it is the conductivity (S/m), and for Figure 27b, it is the frequency. The force unit is Newton. The source strength of Figure 25b is 1 tesla/μ_0 magnetization, and those of Figures 26b and 27b have I_0 = 1 amp. Since an x-independent condition is used for the example runs, zero forces in the x-direction (f_x) are expected. The nonzero small values for f_x in the output files are due to unavoidable truncation errors. Sometimes, it is more convenient to perform batch runs. The batch files for the above example runs are given in Figures 25c, 26c and 27c. To enable the users to be more familiar with running the codes, more descriptions are now given to two of the above example runs.

(a) LIM(i.e., Figure 26)

For a LIM, layer 1 will be free space. This is because if the source is on the vehicle, then layer 1 very possibly is the soil. If the source is not on the vehicle, then layer 1 will be the air (behind the reaction conductor on the vehicle). Layer 2 will be the reaction rail with conductivity. If the LIM is also intended to provide some attractive levitation force, the reaction rail can be taken to have high permeability. If the reaction rail is constructed in such a way that the current flow has some preferable directions, an anisotripic conductivity can be used (Note, anisotropic permeability can also be used, if some exotic laminations provide performance advantages). Layer 3 is the gap area, which is air. Layer 4, for a LIM, very possibly is laminated back iron (can be air too), i.e., has high permeability (Again, the codes allow for anisotripic permeability). Of course, the laminated back iron won't cover layer 4 completely, but the effect of the layer beyond the back iron is expected to be very small. That is, either introducing an additional layer 5 taken to be air, or assuming that layer to be the same as the laminated iron will give a similar result. To summarize, for a LIM

layer 1: air, or, soil, $\mu = \mu_o$, $\sigma = 0$
layer 2: reaction rail, $\mu = \mu_o$, or high μ (e.g., 100 μ_o)
$\sigma = 10^5 - 10^7$ S/m
layer 3: air, $\mu = \mu_o$, $\sigma = 0$,
layer 4: laminated iron, $\sigma = 0$, high μ, or air, $\mu = \mu_o$, $\sigma = 0$.

Next, consider the source. The codes at their present form, for a LIM would only allow a travelling current sheet located at the interface of layers 3 and 4 with frequency $f(=\omega/2\pi)$ and phase velocity $v_{ph} = (\omega/ky_o)$ occupying a rectangular area b3 x a3 (b3 in the travelling direction, a3 in the transverse direction). However, if a different source is preferred, simple modification on subroutine "source 7.for" can be made to incorporate the new source to the codes. The travelling current sheet is a good approximation for a 3-phase stator winding and is given as Eq. 17 in the report. with a constraint that $\sin(ky_ob/2)$ is 0 (note, b = b3).

With the above description, the sample run of Figure 26 becomes self-explanatory. However, if some of the questions are answered differently from listed, different sets of questions may be given afterward. For example, if the 7-th question (Is layer 2 permeability isotropic? (y,n)) is answered "n", then the 15-th question (enter ur2:) will ask for values of 3 variables (ur2x, ur2y, ur2z), instead of just 1 (ur2). Another example, if the 9-th question (enter which case, 1 = no x-dependence, 2 = with x-dependence:) is answered "2", then, the 17-th question (Enter parameter b3:) will ask for values of 3 variables (b3, a3, ax3), instead of just 1 (b3).

(b) LSM (i.e., Figure 27)

Similar to a LIM, layer 1 for a LSM will also be a free space with $\mu = \mu_o$, $\sigma = 0$. This is also true for layer 3. As for layers 2 and 4, they may be somewhat different. This is because, a LSM makes use of the forces between two magnetic field sources, does not make use of induced-current effect. For this reason, layer 2 is also a free space. As for layer 4, it is most possible also free space.

Regarding the sources, for the codes at their present form, a LSM will have a source at the interface of layers 3 and 4 similar to that of a LIM. At the interface of layers 2 and 3, the codes will allow for a DC current loop (of size b2xa2) shifted in any arbitrary way with respect to the source at the interface of layers 3 and 4. Again, it is emphasized that since the foundation is given, simple modification on subroutine "source 7.for" can be made to incorporate other desired source configurations.

With the above description, the sample run of Figure 27 becomes self-explanatory. The primary differences between a LSM run and a LIM run are:

- The 8-th question, LSM is answered with a "3", LIM with a "2"
- LSM has zero conductivity in layer 2, while LIM has nonzero conductivity
- LSM has source at the interface of layers 2 and 3, while LIM does not. This is why "n" is answered for a LIM run for the last question, while "y" in a LSM run for the last 4-th question. The last 3 questions for a LSM run (after a "y" answer before them) are to quantify the sources at the interface of layers 2 and 3.

5.2 COMPUTER CODES FOR QUANTIFYING SHIELDING PERFORMANCES

The source codes for calculating the stray magnetic fields for various shielding schemes are given as "*6.for" in Table 1, while the executable is "shield6.exe" A listing of the source codes is given as Figure 28 for the main program (shield6.for), and as Figures 29-32 for the subroutines. A brief description of the source codes is given below:

field6.for:	for calculating the fields in the transformed domain (ω, $\underline{k}$) at locations of interest by implementing most of the equations in Section 2.0 before Eq. 14
source6.for:	for implementing the source equation of Eq. 16
shcom6.for:	for setting up all the common variables
swap6.for:	for swapping source variables of the primary source and the active shielding source so that same field calculation subroutine can be used
shield6.for:	the main program to calculate the magnetic field intensities at locations of interest, either in layer 1 or layer 4 by performing necessary integrations

The geometrical variables used in the codes are described in Figure 18 and in Appendix A. Most of the variables for looping and option selections, material properties, source parameters, field and integral calculations are similar to those used in the MAGLEV force codes as given in

```
      program shield
      include 'shcom6.for'

      integer*2       n,k,nc,kc,dn,dk,loopvar
      character*1     iso1,iso4,iso2u,iso2s
      character*14    name
      real*8          kx,ky,dky,x,y,twopi,error,P1intg,P4intg,P1sum,P4sum
      real*8          Pn1,Pn4,lvmin,lvmax,dlv,lv,kycond,kxcond,H1mag,H4mag
      real*8          ur1x,ur1y,ur1z,ur2x,ur2y,ur2z,ur4x,ur4y,ur4z
      real*8          ur1,ur4,ur2,axyz,freq
      complex*16 Hx1,Hx4,Hy1,Hy4,Hz1,Hz4,termn,termk,temp1x,temp1y
      complex*16 Hxn1,Hxn4,Hyn1,Hyn4,Hzn1,Hzn4,temp1z,temp4x,temp4y
      complex*16 Hx1intg,Hy1intg,Hz1intg,Hx1sum,Hy1sum,Hz1sum,temp4z
      complex*16 Hx4intg,Hy4intg,Hz4intg,Hx4sum,Hy4sum,Hz4sum

c     call clr_scr
      b3_1=0.
      b3_2=0.
      a3_1=0.
      a3_2=0.
      write(6,1020)
      read(5,'(a)') name
      write(6,1030)
      read(5,*) curr_1
c     write(6,1035)
c     read(5,*) error
c     write(6,1040)
c     read(5,*) dkx,dky
      error=1.0e-6
      write(6,1070)
      read(5,*) freq,v
      write(6,1075)
      read(5,'(a)') iso1
      if (iso1.eq.'y') then
         write(6,1105)
         read(5,*) ur1
         u1x=ur1*uo*1.000001
         u1y=ur1*uo
         u1z=ur1*uo*0.999999
      else
         write(6,1100)
         read(5,*) ur1x,ur1y,ur1z
         u1x=ur1x*uo*1.000001
         u1y=ur1y*uo
         u1z=ur1z*uo*0.999999
      endif
      write(6,1077)
      read(5,'(a)') iso4
      if (iso4.eq.'y') then
         write(6,1165)
         read(5,*) ur4
         u4x=ur4*uo*0.999999
         u4y=ur4*uo*1.000001
         u4z=ur4*uo
      else
         write(6,1160)
         read(5,*) ur4x,ur4y,ur4z
         u4x=ur4x*uo*0.999999
         u4y=ur4y*uo*1.000001
         u4z=ur4z*uo
```

Figure 28. List of the main program "shield6.for."

```
      endif
      write(6,1086)
      read(5,'(a)') iso2s
      if (iso2s.eq.'y') then
         write(6,1085)
         read(5,*) sxyz
         sx=sxyz*1.000001
         sy=sxyz*0.999999
         sz=sxyz
      else
         write(6,1080)
         read(5,*) sx,sy,sz
      endif
      write(6,1087)
      read(5,'(a)') iso2u
      write(6,1180)
      read(5,*) case

10    write(6,2000)
      read(5,*) loopvar
      if (loopvar.le.0 .or. loopvar.gt.8) then
         write(6,2010)
         goto 10
      endif
      write(6,2050)
      read(5,*) lvmin,lvmax,dlv

      if (loopvar.eq.1) then
         write(6,1053)
         read(5,*) y,z
         write(6,1060)
         read(5,*) h2,h3_1
         write(6,1031)
         read(5,*) curr_2
         if (iso2u.eq.'y') then
            write(6,1125)
            read(5,*) ur2
         else
            write(6,1120)
            read(5,*) ur2x,ur2y,ur2z
         endif
      else if (loopvar.eq.2) then
         write(6,1054)
         read(5,*) x,z
         write(6,1060)
         read(5,*) h2,h3_1
         write(6,1031)
         read(5,*) curr_2
         if (iso2u.eq.'y') then
            write(6,1125)
            read(5,*) ur2
         else
            write(6,1120)
            read(5,*) ur2x,ur2y,ur2z
         endif
      else if (loopvar.eq.3) then
         write(6,1052)
         read(5,*) x,y
         write(6,1060)
         read(5,*) h2,h3_1
```

Figure 28. (Continued).

```
         write(6,1031)
         read(5,*) curr_2
         if (iso2u.eq.'y') then
            write(6,1125)
            read(5,*) ur2
         else
            write(6,1120)
            read(5,*) ur2x,ur2y,ur2z
         endif
      else if (loopvar.eq.4) then
         write(6,1051)
         read(5,*) x,y,z
         write(6,1061)
         read(5,*) h3_1
         write(6,1031)
         read(5,*) curr_2
         if (iso2u.eq.'y') then
            write(6,1125)
            read(5,*) ur2
         else
            write(6,1120)
            read(5,*) ur2x,ur2y,ur2z
         endif
      else if (loopvar.eq.5) then
         write(6,1051)
         read(5,*) x,y,z
         write(6,1062)
         read(5,*) h2
         write(6,1031)
         read(5,*) curr_2
         if (iso2u.eq.'y') then
            write(6,1125)
            read(5,*) ur2
         else
            write(6,1120)
            read(5,*) ur2x,ur2y,ur2z
         endif
      else if (loopvar.eq.6) then
         write(6,1051)
         read(5,*) x,y,z
         write(6,1060)
         read(5,*) h2,h3_1
 505     write(6,1032)
         read(5,*) curr_2
         if (curr_2.eq.0.) then
            write(6,2100)
            goto 505
         endif
         if (iso2u.eq.'y') then
            write(6,1125)
            read(5,*) ur2
         else
            write(6,1120)
            read(5,*) ur2x,ur2y,ur2z
         endif
      else if (loopvar.eq.7) then
         write(6,1051)
         read(5,*) x,y,z
         write(6,1060)
         read(5,*) h2,h3_1
```

Figure 28. (Continued).

```
   write(6,1031)
   read(5,*) curr_2
else if (loopvar.eq.8) then
   write(6,1051)
   read(5,*) x,y,z
   write(6,1060)
   read(5,*) h2,h3_1
   if (iso2u.eq.'y') then
      write(6,1125)
      read(5,*) ur2
   else
      write(6,1120)
      read(5,*) ur2x,ur2y,ur2z
   endif
   write(6,1065)
   read(5,*) h3_2,shift_2
   if (case.eq.1) then
      write(6,1220)
      read(5,*) b3_1
      write(6,1225)
      read(5,*) b3_2
   else if (case.gt.1) then
      write(6,1240)
      read(5,*) b3_1,a3_1,ax3_1
      write(6,1245)
      read(5,*) b3_2,a3_2,ax3_2
   endif
endif

if (loopvar.ne.7) then
   if (iso2u.eq.'y') then
      u2x=ur2*uo
      u2y=ur2*uo*0.999999
      u2z=ur2*uo*1.000001
   else
      u2x=ur2x*uo
      u2y=ur2y*uo*0.999999
      u2z=ur2z*uo*1.000001
   endif
endif

if (loopvar.ne.8) then
   if (curr_2.ne.0.) then
      if (loopvar.ne.6) then
         write(6,1065)
         read(5,*) h3_2,shift_2
      else
         write(6,1066)
         read(5,*) shift_2
      endif
   endif
   if (case.eq.1) then
      write(6,1220)
      read(5,*) b3_1
      if (curr_2.ne.0.) then
         write(6,1225)
         read(5,*) b3_2
      endif
   else if (case.gt.1) then
      write(6,1240)
```

Figure 28. (Continued).

```
      read(5,*) b3_1,a3_1,ax3_1
      if (curr_2.ne.0.) then
         write(6,1245)
         read(5,*) b3_2,a3_2,ax3_2
      endif
   endif
endif

write(6,2200)
open(unit=11,file=name//'.Hx',status='unknown')
open(unit=12,file=name//'.Hy',status='unknown')
open(unit=13,file=name//'.Hz',status='unknown')
open(unit=14,file=name//'.Hm',status='unknown')

do 99 lv=lvmin,lvmax,dlv
   if (loopvar.eq.1) then
      x = lv
   else if (loopvar.eq.2) then
      y = lv
   else if (loopvar.eq.3) then
      z = lv
   else if (loopvar.eq.4) then
      h2 = lv
   else if (loopvar.eq.5) then
      h3_1 = lv
   else if (loopvar.eq.6) then
      h3_2 = lv
   else if (loopvar.eq.7) then
      ur2x = lv
      ur2y = lv
      ur2z = lv
      u2x=ur2x*uo
      u2y=ur2y*uo*0.999999
      u2z=ur2z*uo*1.000001
   else if (loopvar.eq.8) then
      curr_2 = lv
   endif

   w=2.0*pi*freq
   if (w.eq.0.0) then
     w=1.0e-6
   endif
   if (v.eq.0.0) then
     v=1.0e-6
   endif
   if (h2.eq.0.0) then
     h2=1.0e-6
   endif
   if (sx.eq.0.0) then
     sx=1.0e-6
   endif
   if (sy.eq.0.0) then
     sy=1.000001e-6
   endif
   if (sz.eq.0.0) then
     sz=0.999999e-6
   endif

   dky=0.05/b3_1
   if ((curr_2.ne.0.0) .and. (b3_2.gt.b3_1)) then
```

Figure 28. (Continued).

```
           dky=0.05/b3_2
         endif
         dkx=0.05
         if (case.eq.2) then
           dkx=0.05/a3_1
           if ((curr_2.ne.0.0) .and. (a3_2.gt.a3_1)) then
             dkx=0.05/a3_2
           endif
         endif

         shift_1=0.
         kc=-1
         if (z.lt.0.) then
            h1 = z
            Hx1sum=0.
            Hy1sum=0.
            Hz1sum=0.
         else
            h4 = z
            Hx4sum=0.
            Hy4sum=0.
            Hz4sum=0.
         endif
c        check for convergence in ky
  50     if (z.lt.0.) then
            kycond = P1intg-(error*P1sum)
         else
            kycond = P4intg-(error*P4sum)
         endif
         if ((kycond.gt.0.) .or.
     2      (kc.eq.-1).or.
     2      (((kc*dky*b3_2).lt.70.).and.((kc*dky*b3_1).lt.70.))) then
            kc=kc+1
            if (kc.eq.0) then
               dk=1
            else
               dk=2*kc
            endif

            do 180 k=-kc,kc,dk
               nc=-1
               if (z.lt.0.) then
                  Hx1intg=0.
                  Hy1intg=0.
                  Hz1intg=0.
               else
                  Hx4intg=0.
                  Hy4intg=0.
                  Hz4intg=0.
               endif
               if (k.ne.0) then
                  ky=k*dky
               else
                  ky=1.e-6
               endif
c              check for convergence in kx
  60           if (z.lt.0.) then
                  kxcond = Pn1-(error*P1intg)
               else
                  kxcond = Pn4-(error*P4intg)
```

Figure 28. (Continued).

```
          endif
          if ((kxcond.gt.0.) .or.
2            (nc.eq.-1) .or.
2            ((case.ne.1).and.
2      (((nc*dkx*a3_2).lt.70.).and.((nc*dkx*a3_1).lt.70.)))) then
             nc=nc+1
             if (nc.eq.0) then
                dn=1
             else
                dn=2*nc
             endif
             if (z.lt.0.) then
                temp1x=0.
                temp1y=0.
                temp1z=0.
             else
                temp4x=0.
                temp4y=0.
                temp4z=0.
             endif
             do 200 n=-nc,nc,dn
                if (n.ne.0) then
                   kx=n*dkx
                else
                   kx=1.e-6
                endif
                call swap(1)
                call field(n,ky)
                if (z.lt.0.) then
                   Hxn1=Bx1/uo
                   Hyn1=By1/uo
                   Hzn1=Bz1/uo
                else
                   Hxn4=Bx4/uo
                   Hyn4=By4/uo
                   Hzn4=Bz4/uo
                endif

                if (curr_2.ne.0.) then
                   call swap(2)
                   call field(n,ky)
                   if (z.lt.0.) then
                      Hxn1=Hxn1+Bx1/uo
                      Hyn1=Hyn1+By1/uo
                      Hzn1=Hzn1+Bz1/uo
                   else
                      Hxn4=Hxn4+Bx4/uo
                      Hyn4=Hyn4+By4/uo
                      Hzn4=Hzn4+Bz4/uo
                   endif
                endif

                termn=cdexp(i*kx*x)
                if (z.lt.0.) then
                   temp1x=temp1x+Hxn1*termn
                   temp1y=temp1y+Hyn1*termn
                   temp1z=temp1z+Hzn1*termn
                else
                   temp4x=temp4x+Hxn4*termn
                   temp4y=temp4y+Hyn4*termn
```

Figure 28. (Continued).

```
                     temp4z=temp4z+Hzn4*termn
                  endif
200            continue
               if (z.lt.0.) then
                  Hx1intg=Hx1intg+temp1x
                  Hy1intg=Hy1intg+temp1y
                  Hz1intg=Hz1intg+temp1z
                  Pn1=dsqrt(cdabs(temp1x**2+temp1y**2+temp1z**2))
                  P1intg=dsqrt(cdabs(Hx1intg**2+Hy1intg**2+
     2                           Hz1intg**2))
               else
                  Hx4intg=Hx4intg+temp4x
                  Hy4intg=Hy4intg+temp4y
                  Hz4intg=Hz4intg+temp4z
                  Pn4=dsqrt(cdabs(temp4x**2+temp4y**2+temp4z**2))
                  P4intg=dsqrt(cdabs(Hx4intg**2+Hy4intg**2+
     2                           Hz4intg**2))
               endif
               if (case.eq.1) then
                  dkx=1.
                  if (z.lt.0.) then
                     Pn1=0.
                  else
                     Pn4=0.
                  endif
               endif
               goto 60
            endif
            termk=cdexp(i*ky*y)
            if (z.lt.0.) then
               Hx1sum=Hx1sum+Hx1intg*termk
               Hy1sum=Hy1sum+Hy1intg*termk
               Hz1sum=Hz1sum+Hz1intg*termk
            else
               Hx4sum=Hx4sum+Hx4intg*termk
               Hy4sum=Hy4sum+Hy4intg*termk
               Hz4sum=Hz4sum+Hz4intg*termk
            endif
180      continue
         if (z.lt.0.) then
            P1sum=dsqrt(cdabs(Hx1sum**2+Hy1sum**2+Hz1sum**2))
         else
            P4sum=dsqrt(cdabs(Hx4sum**2+Hy4sum**2+Hz4sum**2))
         endif
         goto 50
      endif
      twopi=2.*pi
      if (z.lt.0.) then
         Hx1=Hx1sum*dky*dkx/twopi
         Hy1=Hy1sum*dky*dkx/twopi
         Hz1=Hz1sum*dky*dkx/twopi
         H1mag=dsqrt(cdabs(Hx1**2+Hy1**2+Hz1**2))
         write(11,1400) lv,Hx1
         write(12,1400) lv,Hy1
         write(13,1400) lv,Hz1
         write(14,1410) lv,H1mag
      else
         Hx4=Hx4sum*dky*dkx/twopi
         Hy4=Hy4sum*dky*dkx/twopi
         Hz4=Hz4sum*dky*dkx/twopi
```

Figure 28. (Continued).

```
          H4mag=dsqrt(cdabs(Hx4**2+Hy4**2+Hz4**2))
          write(11,1400) lv,Hx4
          write(12,1400) lv,Hy4
          write(13,1400) lv,Hz4
          write(14,1410) lv,H4mag
        endif

 99   continue
      close(11)
      close(12)
      close(13)
      close(14)
c     write(6,1530) kc,nc

c Format statements :

 1000 format(
     1 15x,'*********************************************',
     2/15x,'*                                           *',
     3/15x,'*             PROGRAM : SHIELD              *',
     4/15x,'*                                           *',
     5/15x,'*********************************************')
 1010 format(/5x,'This program calculates Hx,Hy,Hz')
 1020 format(/5x,'Enter output file name: ',$)
 1030 format(/5x,'Enter source curr_1 ,not=0,in amp-turns: ',$)
 1031 format(/5x,'Enter shield curr_2, in amp-turns: ',$)
 1032 format(/5x,'Enter shield curr_2 ,not=0,in amp-turns: ',$)
c 1035 format(/5x,'Enter error tolerance (0-1) : ',$)
c 1040 format(/5x,'Enter dkx,dky : ',$)
 1051 format(/5x,'Enter field loc. x,y,z in m: ',$)
 1052 format(/5x,'Enter field loc. x,y in m: ',$)
 1053 format(/5x,'Enter field loc. y,z in m: ',$)
 1054 format(/5x,'Enter field loc. x,z in m: ',$)
c 1055 format(/5x,'Enter h1,h4 : ',$)
 1060 format(/5x,'Enter shld thick--h2;height of curr_1--h3_1 in m: ',$)
 1061 format(/5x,'Enter height of curr_1--h3_1 in m: ',$)
 1062 format(/5x,'Enter shield thickness--h2 in m: ',$)
 1065 format(/5x,'Enter height&y-coord.of curr_2--h3_2,shift,in m : ',$)
 1066 format(/5x,'Enter y-coord. of curr_2--shift in m: ',$)
 1070 format(/5x,'Enter freq&velocity--freq in hertz,v in m/s: ',$)
 1075 format(/5x,'Is layer 1 isotropic? (y,n) : ',$)
 1077 format(/5x,'Is layer 4 isotropic? (y,n) : ',$)
 1080 format(/5x,'Enter aniso.conductivity--sx,sy,sz in S/m: ',$)
 1085 format(/5x,'Enter iso.conductivity--sxyz in S/m : ',$)
 1086 format(/5x,'Is layer 2 conductivity isotropic? (y,n) : ',$)
 1087 format(/5x,'Is layer 2 permeability isotropic? (y,n) : ',$)
 1100 format(/5x,'Enter layer1 aniso.rel.permea.--ur1x,ur1y,ur1z : ',$)
 1105 format(/5x,'Enter layer1 iso.rel.permea.--ur1 : ',$)
 1120 format(/5x,'Enter layer2 aniso.rel.permea.--ur2x,ur2y,ur2z : ',$)
 1125 format(/5x,'Enter layer2 iso.rel.permea.--ur2 : ',$)
 1160 format(/5x,'Enter layer4 aniso.rel.permea.--ur4x,ur4y,ur4z : ',$)
 1165 format(/5x,'Enter layer4 iso.rel.permea.--ur4 : ',$)
 1180 format(/5x,'Enter which case, 1=no x dependence(2-D), '
     2           '2=with x dependence(3-D): ',$)
 1220 format(/5x,'Enter source loop length--b3_1 in m: ',$)
 1225 format(/5x,'Enter shield loop length--b3_2 in m : ',$)
 1240 format(/5x,'Enter sour.loop lngth,wdth,edge loc--b3,a3,ax3 in m:',$)
 1245 format(/5x,'Enter shld.loop lngth,wdth,edge loc--b3,a3,ax3 in m:',$)
 1400 format(e12.3,2(e12.3))
 1410 format(2(e12.3))
```

Figure 28. (Continued).

```
c 1530 format(/5x,'kc=',i6,'  nc=',i6)
 1460 format(i5,f10.3,3(e12.3))
 2000 format(/5x,'Enter parameter to loop:'
     2        /5x,'  1. field loc x-coord.x,'
     2        /5x,'  2. field loc y-coord.y,'
     2        /5x,'  3. field loc z-coord.z,'
     2        /5x,'  4. shield thickness,h2,'
     2        /5x,'  5. source loop height,h3_1,'
     2        /5x,'  6. shield loop height,h3_2,'
     2        /5x,'  7. shield relative permeability,ur2,'
     2        /5x,'  8. shield current,curr_2,'
     2        /5x,'Select(1,..,8): ',$)
 2010 format(/5x,'Input error: loop parameter is OUT of range!',
     2' Please try again.')
 2050 format(/5x,'Enter min, max and stepsize for above selected',
     2' parameter: ',$)
 2100 format(/5x,'Input Error: curr_2 CANNOT be zero!',
     2' Please try again.')
 2200 format(//5x,'Please wait, calculating ....',/)
      end
```

Figure 28. (Concluded).

```
c     fields at layer 1 at z=h1 & layer 4 at z=h4

      subroutine field(n,ky)
      include 'shcom6.for'

      integer*2   n
      real*8      kx,ky,kz1,kz3,kz4,term1,term4
      complex*16  X,b,c,kz2(2),kz(2),R(2),Q(2)
      complex*16  S,T,U,V1,V2
      complex*16  temp,IIIx(2),IIIy(2),IIIz(2)
      complex*16  IIx1(2)
      complex*16  Ix,Iy,Iz,IVx,IVy,IVz
c     complex*16  IIxo(2),IIyo(2),IIzo(2),IIx1(2),IIy1(2),IIz1(2)
      complex*16  csinh,ccosh,p

      csinh(p)=.5*(cdexp(p)-cdexp(-p))
      ccosh(p)=.5*(cdexp(p)+cdexp(-p))
      i=dcmplx(0.,1.)
      call source(n,ky)

      if (n.eq.0) then
        kx=1e-6
      else
        kx=n*dkx
      endif
      X=dcmplx(kx*kx/u2y+ky*ky/u2x, -(w-ky*v)*sz)
      b=dcmplx(-(sx/sz+u2x/u2z)*kx*kx-(sy/sz+u2y/u2z)*ky*ky,
     2         (w-ky*v)*(sx*u2y+sy*u2x))
      c=(u2x*u2y*X/(u2z*sz))*dcmplx(sx*kx*kx+sy*ky*ky,
     2                              -(w-ky*v)*sx*sy*u2z)
      kz2(1)=.5*(-b+cdsqrt(b*b-4.*c))
      kz2(2)=.5*(-b-cdsqrt(b*b-4.*c))
      kz(1)=cdsqrt(kz2(1))
      kz(2)=cdsqrt(kz2(2))
      kz3=dsqrt(kx*kx+ky*ky)
      kz1=dsqrt((u1x/u1z)*kx*kx+(u1y/u1z)*ky*ky)
      kz4=dsqrt((u4x/u4z)*kx*kx+(u4y/u4z)*ky*ky)

      R(1)=( u2x*u2y*X*(u2y*ky*ky-u2z*kz2(1)-i*(w-ky*v)*sx*u2y*u2z)+
     2       u2x*u2z*kx*kx*kz2(1) )
      R(1)=R(1)/( u2y*((kx*ky+i*kx*sx*v*u2z)*(u2x*u2y*X-u2z*kz2(1))-
     2            u2z*kz2(1)*i*kx*v*(u2x*sz-sx*u2z)) )
      R(2)=( u2x*u2y*X*(u2y*ky*ky-u2z*kz2(2)-i*(w-ky*v)*sx*u2y*u2z)+
     2       u2x*u2z*kx*kx*kz2(2) )
      R(2)=R(2)/( u2y*((kx*ky+i*kx*sx*v*u2z)*(u2x*u2y*X-u2z*kz2(2))-
     2            u2z*kz2(2)*i*kx*v*(u2x*sz-sx*u2z)) )
      Q(1)=-kz(1)*(i*u2x*kx+(i*ky-v*u2x*sz)*u2y*R(1)) /
     2       (u2x*u2y*X)
      Q(2)=-kz(2)*(i*u2x*kx+(i*ky-v*u2x*sz)*u2y*R(2)) /
     2       (u2x*u2y*X)
      S=-(Q(1)*(1.-ky*v/w)+kz(1)*v*R(1)/(i*w)) /
     2    (Q(2)*(1.-ky*v/w)+kz(2)*v*R(2)/(i*w))
      T=( csinh(kz(1)*h2)*
     2     (i*ky*Q(1)-kz(1)*R(1)+S*(i*ky*Q(2)-kz(2)*R(2)))-
     2     (u2x*kx/(u1z*kz1))*(kx*R(1)-ky)*
     2     (ccosh(kz(1)*h2)-ccosh(kz(2)*h2)) )
      T=T/( (1./S)*csinh(kz(2)*h2)*
     2     (i*ky*Q(1)-kz(1)*R(1)+S*(i*ky*Q(2)-kz(2)*R(2)))+
     2     (u2x*kx/(u1z*kz1))*(kx*R(2)-ky)*
     2     (ccosh(kz(1)*h2)-ccosh(kz(2)*h2)) )
```

Figure 29. List of the subroutine "field6.for."

```
      U=( (T/S)*csinh(kz(2)*h2)-csinh(kz(1)*h2) ) /
     2  ( ccosh(kz(1)*h2)-ccosh(kz(2)*h2) )
      V1=(i*kx/(w*kz3)) * (
     2    (kx*R(1)-ky)*(ccosh(kz(1)*h2)+U*csinh(kz(1)*h2))+
     2    (kx*R(2)-ky)*(T*ccosh(kz(2)*h2)+S*U*csinh(kz(2)*h2)) )
      V2=(i*uo*kx/(w*u2y*ky)) * (
     2    (kz(1)-i*kx*Q(1))*(csinh(kz(1)*h2)+U*ccosh(kz(1)*h2))+
     2    (kz(2)-i*kx*Q(2))*(T*csinh(kz(2)*h2)+S*U*ccosh(kz(2)*h2)) )

      temp=((V1+V2)/(V1-V2))*dexp(-2.*kz3*h3)
      IIIx(2)=(u4z*kz4*K3+(V1*K2/(V1-V2))*dexp(-kz3*h3)*
     2          (u4z*kz4-uo*kz3))
     2          /(dexp(kz3*h3)*((u4z/uo)*(ky*kz4/kx)*(1.-temp)+
     2                         (ky*kz3/kx)*(1.+temp)))
      IIxl(1)=(2.*IIIx(2)+uo*kx*K2/ky)/(V1-V2)
      IIIx(1)=-uo*kx*K2/(2.*ky)-(V1+V2)*IIxl(1)/2.

      IIxl(2)=T*IIxl(1)
c     IIxo(1)=U*IIxl(1)
c     IIxo(2)=S*IIxo(1)

c     IIzo(2)=Q(2)*IIxo(2)
c     IIzo(1)=Q(1)*IIxo(1)
c     IIzl(2)=Q(2)*IIxl(2)
c     IIzl(1)=Q(1)*IIxl(1)
c     IIyo(2)=R(2)*IIxo(2)
c     IIyo(1)=R(1)*IIxo(1)
c     IIyl(2)=R(2)*IIxl(2)
c     IIyl(1)=R(1)*IIxl(1)

c     IIIy(1)=(ky/kx)*IIIx(1)
c     IIIy(2)=(ky/kx)*IIIx(2)
c     IIIz(1)=(i*kz3/kx)*IIIx(1)
c     IIIz(2)=(-i*kz3/kx)*IIIx(2)
```

```
c     Bx=IIIx(1)*dexp(-kz3*h3)+IIIx(2)*dexp(kz3*h3)
c     By=IIIy(1)*dexp(-kz3*h3)+IIIy(2)*dexp(kz3*h3)
c     Bz=IIIz(1)*dexp(-kz3*h3)+IIIz(2)*dexp(kz3*h3)

      if (z.lt.0.) then
         Ix=(i*kx*u1x/(w*kz1*u1z))*
     2        ((kx*R(1)-ky)*IIx1(1)+(kx*R(2)-ky)*IIx1(2))
         Iy=(u1y*ky/(u1x*kx))*Ix
         Iz=(-i*u1z*kz1/(u1x*kx))*Ix

         term1=dexp(kz1*h1)
         Bx1=Ix*term1
         By1=Iy*term1
         Bz1=Iz*term1
      else
         IVx=(-u4x*kx/ky)*dexp(kz4*h3)*
     2        (K3+K2*dexp(-kz3*h3)*V1/(V1-V2)-
     2        (1./uo)*(ky/kx)*dexp(kz3*h3)*(1.-temp)*IIIx(2))
         IVy=(u4y*ky/(u4x*kx))*IVx
         IVz=(i*u4z*kz4/(u4x*kx))*IVx

         term4=dexp(-kz4*(h4-h2))
         Bx4=IVx*term4
         By4=IVy*term4
         Bz4=IVz*term4
      endif
      return
      end
```

Figure 29. (Concluded).

```
c     sources  K3 at layer 3 z=h2+h3

      subroutine source(n,ky)
      include 'shcom6.for'

      integer*2   n
      real*8      kx,ky

      K3=0.

      if (case.eq.1) then
            K3=(-2.*i)*dsin(ky*b3/2.)
      endif

      if (case.eq.2) then
          if (n.eq.0) then
            kx=1.e-6
            K3=(-i/pi)*dsin(ky*b3/2.)*a3
          else
            kx=n*dkx
            K3=(-2.*i/(kx*pi))*dsin(ky*b3/2.)*
     2       dsin(kx*a3/2.)*cdexp(-i*kx*(ax3-a3/2.))
          endif
      endif


      K3=K3*curr*cdexp(-i*ky*shift)

      return
      end
```

Figure 30. List of the subroutine "source6.for."

```
c       swapping parameters for shielding calculating

        subroutine swap(loop)
        include 'shcom6.for'

        integer*2   loop

        if (loop.eq.1) then
          h3=h3_1
          a3=a3_1
          ax3=ax3_1
          b3=b3_1
          shift=shift_1
          curr=curr_1
        endif

        if (loop.eq.2) then
          h3=h3_2
          a3=a3_2
          ax3=ax3_2
          b3=b3_2
          shift=shift_2
          curr=curr_2
        endif

        return
        end
```

Figure 31. List of the subroutine "swap6.for."

```
c     shcom6.for
c     common variables share by shield, field, source, swap

      implicit none

      integer*2   case
      real*8      dkx,h1,h4,h2,h3,h3_1,h3_2,uo,pi,sx,sy,sz,w,v,z
      real*8      u1x,u1y,u1z,u2x,u2y,u2z,u3x,u3y,u3z,u4x,u4y,u4z
      real*8      a3,ax3,b3,shift,curr,curr_1,curr_2
      real*8      a3_1,ax3_1,b3_1,a3_2,ax3_2,b3_2,shift_1,shift_2
      complex*16  Bx4,By4,Bz4,Bx1,By1,Bz1,K2,K3,i

      parameter (pi=3.141592654, uo=1.2566371e-6)

      common /a/  dkx,h1,h4,h2,h3,h3_1,h3_2,sx,sy,sz,w,v,z
      common /b/  u1x,u1y,u1z,u2x,u2y,u2z,u3x,u3y,u3z,u4x,u4y,u4z
      common /c/  Bx4,By4,Bz4,Bx1,By1,Bz1,K2,K3,i
      common /d/  a3,ax3,b3,shift,curr,curr_1,curr_2
      common /d/  a3_1,ax3_1,b3_1,a3_2,ax3_2,b3_2,shift_1,shift_2
      common /e/  case
```

Figure 32. List of the subroutine "shcom6.for."

subsection 5.1. The main difference is that an additional current loop (curr_2) for active shielding is introduced between the primary source (curr_1) and the "possible" passive shielding layer 2. It should also be noted that for most shielding application ω (or f) and v are set to 0, because most possibly the shielding installation will be on board the vehicle and the primary source will be the superconducting coils for repulsive levitation.

With the above description, a sample run is demonstrated as Figure 33a. The corresponding results are given as Figure 33b. The output file gives the magnitude of the normalized magnetic field intensity (H/I_o, dimension m^{-1}) in the second column as a function of the looping parameter (μr2, for this example) in the first column. The suffix "hm" of the output file name is to indicate magnitude of the H field. The program will also output the field components in x, y, and z directions, For those field components, the file suffixes will be "hx," "hy," and "hz," respectively. The corresponding batch input file is given as Figure 33c.

```
C:\>shield6

     Enter output file name: ts19

     Enter source curr_1 ,not=0,in amp-turns: 1.

     Enter freq&velocity--freq in hertz,v in m/s: 0. 0.

     Is layer 1 isotropic? (y,n) : y

     Enter layer1 iso.rel.permea.--ur1 : 1.

     Is layer 4 isotropic? (y,n) : y

     Enter layer4 iso.rel.permea.--ur4 : 1.

     Is layer 2 conductivity isotropic? (y,n) : y

     Enter iso.conductivity--sxyz in S/m : 1.e6

     Is layer 2 permeability isotropic? (y,n) : y

     Enter which case, 1=no x dependence(2-D), 2=with x dependence(3-D): 1

     Enter parameter to loop:
       1. field loc x-coord.x,
       2. field loc y-coord.y,
       3. field loc z-coord.z,
       4. shield thickness,h2,
       5. source loop height,h3_1,
       6. shield loop height,h3_2,
       7. shield relative permeability,ur2,
       8. shield current,curr_2,
     Select(1,..,8): 7

     Enter min, max and stepsize for above selected parameter: 1. 1001. 100.

     Enter field loc. x,y,z in m: 0. 0. -1.5

     Enter shld thick--h2;height of curr_1--h3_1 in m: .02 .4

     Enter shield curr_2, in amp-turns: -.2

     Enter height&y-coord.of curr_2--h3_2,shift,in m : .1 0.

     Enter source loop length--b3_1 in m: 1.

     Enter shield loop length--b3_2 in m : .5


     Please wait, calculating ....
```

Figure 33. (a) An example run of "shield6.exe."

```
C:\>type ts19.hm

    .100E+01    .345E-01
    .101E+03    .197E-01
    .201E+03    .144E-01
    .301E+03    .115E-01
    .401E+03    .964E-02
    .501E+03    .832E-02
    .601E+03    .734E-02
    .701E+03    .657E-02
    .801E+03    .596E-02
    .901E+03    .545E-02
    .100E+04    .503E-02
```

Figure 33. (b) Output of the example run.

```
ts19
1.
0. 0.
y
1.
y
1.
y
1.e6
y
1
7
1.   1001.   100.
0.   0.   -1.5
.02   .4
-.2
.1  0.
1.
.5
```

Figure 33. (c) Batch input file "res19" for example run (a).

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APPENDIX A. More Descriptions for Variables and Symbols Used in the Main Text*

VARIABLE	CODED SYMBOL	DEFINITION	UNIT
μ_{ij}, $i = 1,2,4$, $j = x,y,z$	uij	permeability of the j-th component in the i-th layer	henry/m
μ_{rij}, $i = 1,2,4$, $j = x,y,z$	urij	relative permeability of the j-th component in the i-th layer	unitless
$\mu_o(=\mu_{ij}/\mu_{rij})$	uo	free space permeability	henry/m
σ_j $(j=x,y,z)$	sj	conductivity of the j-th component in the 2nd layer	S/m
F_j, $j=x,y,z$	Fj	force in the j-th direction	newton
k_{yo}	kyo3	wavenumber of the traveling wave source (at the interface of layers 3 & 4)	1/m
ω $(=2\pi f)$	w	radian frequency of the source	radian
v	v	velocity of the vehicle	m/s
h_2	h2	thickness of layer 2	m
h_3	h3	gap width	m
$b_{(3)}$ $[b_2]$**	b3, b2	longitudinal (in the traveling (y-) direction) dimensions of the sources at interfaces of layers 3,4 [layers 2,3]	m
$a_{(3)}$ $[a_2]$	a3, aa2	transverse (x-) dimensions of the sources at interfaces of layers 3,4 [layers 2,3]	m

*SI units are used through the codes, also refer to Figure 3 and pages 8, 40 in the main text.
**corresponding definition is also indicated inside [ ].

APPENDIX A - CONT'D*

VARIABLE & CODED SYMBOL	DEFINITION	UNIT
shift	longitudinal (y-) coordinate of the center of the source at interface of layers 2,3	m
ax3 [ax2]**	transverse (x-) coordinates of the edges of the sources at interfaces of layers 3,4 [layers 2,3]	m
case	=1, for x-independent =2, with x-dependence	unitless
caselp	=1, for levitation application =2, for LIM application =3, for LSM application	unitless
case2 [case3]	="y", when source exists at interfaces of layers 2,3 [layers 3,4] ="n", when no source at interface of layers 2,3 [layers 3,4]	character
casem	=1, for current loop source =2, for magnet source	unitless

*SI units are used throughout the codes, also refer to Figures 3 and pages 8, 40 in the report
**corresponding definition is also indicated inside [ ].

APPENDIX A--CONCLUDED*

VARIABLE (& CODED SYMBOL)	DEFINITION	UNIT
b3_1 [b3_2]**	logitudinal (y_) dimensions of the primary source [the shielding loop]	m
a3_1 [a3_2]	transverse (x-) dimensions of the primary source [the shielding loop]	m
shift_2	longitudinal (y-) coordinate of the center of the shielding loop (center of the primary source is the origin)	m
ax3_2 (ax3_1=0.5 • a3_1)	transverse (x-) coordinate of the edge of the shielding loop 1	m
curr_2 (curr_1=1)	amperse-turn of the shielding loop (1 amp-turn is assumed for the primary source)	amp-turn
h3_1 [h3_2]	heights of the primary source [the shielding loop] from the shielding layer	m

*SI units are used throughout the codes, also refer to Figures 3 and pages 8, 40 in the report
**corresponding definition is also indicated inside [ ].

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