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

National Maglev Initiative
Washington, DC 20590

This document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

July 1992
Final Report

DOT/FRA/NMI-92-08

11 - Advanced Systems
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.
ACKNOWLEDGEMENT

The author thanks Dr. T.C. Wang, a consultant of the Kaman Sciences Corporation, for his continued advice and inputs during the course of this work. The author also thanks Mr. R. Wlodyka of the Volpe National Transportation Systems Center (VNTSC) and Dr. J. Harding of the Federal Railroad Administration (FRA), and Dr. K.S.H. Lee of Kaman Sciences Corporation for their support and inputs, and thanks several reviewers from the Army Corps of Engineers and the National Maglev Initiative Office for their comments. Special thanks go to Mr. F. Wong and Ms. I. Wong of the Kaman Sciences Corporation for their support on the computer codes development.
## CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>2.0 MATHEMATICAL FORMULATION</td>
<td>3</td>
</tr>
<tr>
<td>3.0 SOME CONSIDERATIONS OF DESIGN ALTERNATIVES</td>
<td>14</td>
</tr>
<tr>
<td>3.1 A Linear Induction Motor Design for Both Propulsion and Levitation</td>
<td>14</td>
</tr>
<tr>
<td>3.2 An EMS Levitation Design Using Both Permanent Magnets and Electromagnets</td>
<td>24</td>
</tr>
<tr>
<td>4.0 SOME CONSIDERATIONS OF MAGNETIC FIELD SHIELDING SCHEMES</td>
<td>32</td>
</tr>
<tr>
<td>5.0 USER'S MANUAL</td>
<td>40</td>
</tr>
<tr>
<td>5.1 Computer Codes for Calculating Propulsion/Levitation Forces</td>
<td>40</td>
</tr>
<tr>
<td>5.2 Computer Codes for Quantifying Shielding Performances</td>
<td>69</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>89</td>
</tr>
<tr>
<td>APPENDIX A</td>
<td>90</td>
</tr>
</tbody>
</table>
FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Four layered model of a generic MAGLEV system.</td>
<td>4</td>
</tr>
<tr>
<td>2.</td>
<td>Propulsion forces ((f_y)) and attractive forces ((f_z)) as functions of the vehicle velocity ((v)) for various (\mu_{r2}) in a LIM design alternative, when the driving current sheet has (f = 400) Hz, (k\gamma_0 = 5\pi), (b = 2) m, and the reaction rail has (s = 10^6) S/m, and (h2 = h3 = 0.02) m.</td>
<td>15</td>
</tr>
<tr>
<td>(concluded).</td>
<td>Propulsion forces ((f_y)) and attractive forces ((f_z)) as functions of the vehicle velocity ((v)) for various (\mu_{r2}) in a LIM design alternative, when the driving current sheet has (f = 400) Hz, (k\gamma_0 = 5\pi), (b = 2) m, and the reaction rail has (s = 10^6) S/m, and (h2 = h3 = 0.02) m.</td>
<td>16</td>
</tr>
<tr>
<td>3.</td>
<td>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.</td>
<td>17</td>
</tr>
<tr>
<td>4.</td>
<td>Propulsion forces ((f_y)) and attractive forces ((f_z)) as functions of the relative permeability ((\mu_{r2})) of the reaction rail for 2 vehicle velocities in a LIM design alternative, when the driving current sheet has (f = 400) Hz, (k\gamma_0 = 5\pi), (b = 2) m, and the reaction rail has (\sigma = 10^6) S/m, and (h2 = h3 = 0.02) m.</td>
<td>19</td>
</tr>
<tr>
<td>5.</td>
<td>Propulsion forces ((f_y)) and attractive forces ((f_z)) as functions of conductivity ((\sigma)) of the reaction rail for 2 vehicle velocities in a LIM design alternative, when the driving current sheet has (f = 400) Hz, (k\gamma_0 = 5\pi), (b = 2) m, and the reaction rail has (\mu_{r2} = 500), and (h2 = h3 = 0.02) m.</td>
<td>20</td>
</tr>
<tr>
<td>6.</td>
<td>Propulsion forces ((f_y)) and attractive forces ((f_z)) 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, (k\gamma_0 = 5\pi), (b = 2) m, and the reaction rail has (s = 10^6) S/m (\mu_{r2} = 500), and (h2 = h3 = 0.02) m.</td>
<td>21</td>
</tr>
<tr>
<td>7.</td>
<td>Propulsion forces ((f_y)) and attractive forces ((f_z)) 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, (k\gamma_0 = 5\pi), (b = 2) m, and the reaction rail has (\sigma = 10^6) S/m, (\mu_{r2} = 500), and (h2 = h3 = 0.02) m.</td>
<td>22</td>
</tr>
<tr>
<td>8.</td>
<td>Propulsion forces ((f_y)) and attractive forces ((f_z)) 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 (k\gamma_0 = 5\pi), (b = 2) m, and the reaction rail has (\sigma = 10^6) S/m, (\mu_{r2} = 500), and (h2 = h3 = 0.02) m.</td>
<td>23</td>
</tr>
<tr>
<td>9.</td>
<td>A demonstration diagram for estimating the magnetization and equivalent current sheet of a combined permanent and electromagnet.</td>
<td>25</td>
</tr>
<tr>
<td>10.</td>
<td>Attractive forces ((f_z)) and drag forces ((-f_y)) as functions of the velocity ((v)) in an EMS levitation design alternative using magnets with 1 tesla/m0 uniform magnetization and two approximate pole lengths ((p\ell)), when (h2 = h3 = 0.02) m, (\mu_{r2} = 500), (\sigma = 10^6) S/m, and (b3 = 0.5) m.</td>
<td>27</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>11.</td>
<td>Attractive forces ($f_z$) and drag forces ($-f_y$) as functions of the relative permeability ($\mu_r$) of the reaction rail for 2 vehicle velocities in an EMS levitation design alternative using magnets with 1 tesla/$\mu_0$ uniform magnetization, when $h_2 = h_3 = 0.02$ m, $\sigma = 10^6$ S/m, and $b_3 = 0.5$ m.</td>
<td>28</td>
</tr>
<tr>
<td>12.</td>
<td>Attractive forces ($f_z$) and drag forces ($-f_y$) as functions of the conductivity ($\sigma$) of the reaction rail for 2 vehicle velocities in an EMS levitation design alternative using magnets with 1 tesla/$\mu_0$ uniform magnetization, when $h_2 = h_3 = 0.02$ m, $\mu_r = 500$ and $b_3 = 0.5$ m.</td>
<td>29</td>
</tr>
<tr>
<td>13.</td>
<td>Attractive forces ($f_z$) and drag forces ($-f_y$) as functions of the thickness ($h_2$) of the reaction rail for 2 vehicle velocities in an EMS levitation design alternative using magnets with 1 tesla/$\mu_0$ uniform magnetization, when $h_r = 500$, $\sigma = 10^6$ S/m, $b_3 = 0.5$ m and $h_3 = 0.02$ m.</td>
<td>30</td>
</tr>
<tr>
<td>14.</td>
<td>Attractive forces ($f_z$) and drag forces ($-f_y$) as functions of the gap width ($h_3$) between the magnet and the reaction rail for 2 vehicle velocities in an EMS levitation design alternative using magnets with 1 tesla/$\mu_0$ uniform magnetization, when $h_r = 500$, $\sigma = 10^6$ S/m, $b_3 = 0.5$ m and $h_2 = 0.02$ m.</td>
<td>31</td>
</tr>
<tr>
<td>15.</td>
<td>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 $h_{3,1} = 0.4$ m and $b_{3,1} = 1$ m.</td>
<td>33</td>
</tr>
<tr>
<td>16.</td>
<td>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 $h_{3,1} = 0.4$ m and $b_{3,1} = 1$ m.</td>
<td>34</td>
</tr>
<tr>
<td>17.</td>
<td>Stray magnetic fields as functions of the thickness and permeability of the passive shielding layer when the current source $I$ has $h_{3,1} = 0.4$ m and $b_{3,1} = 1$ m, and the active shielding current (-0.2I) has $h_{3,2} = 0.1$ m and $b_{3,2} = 0.5$ m.</td>
<td>35</td>
</tr>
<tr>
<td>18.</td>
<td>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.</td>
<td>36</td>
</tr>
<tr>
<td>19.</td>
<td>Stray magnetic fields as functions of the strength and location of the active shielding current, when the source current $I$ has $h_{3,1} = 0.4$ m and $b_{3,1} = 1$m, the active shielding current has $b_{3,2} = 0.25$ m, and the passive shielding layer has $\mu_r = 100$, $h_2 = 0.02$ m.</td>
<td>37</td>
</tr>
<tr>
<td>20.</td>
<td>Stray magnetic fields as functions of locations, when the source current $I$ has $h_{3,1} = 0.4$ m, $b_{3,1} = 1$ m, the active shielding current (-0.2I) has $h_{3,2} = 0.1$ m, $b_{3,2} = 0.25$ m, and the passive shielding layer has $h_2 = 0.02$ m.</td>
<td>38</td>
</tr>
<tr>
<td>21.</td>
<td>List of the main program &quot;maglev7.for.&quot;</td>
<td>42</td>
</tr>
<tr>
<td>21.</td>
<td>(Continued).</td>
<td>43</td>
</tr>
</tbody>
</table>
FIGURES (CONTINUED)

<table>
<thead>
<tr>
<th>Figure</th>
<th>(Continued).</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.</td>
<td>(Continued).</td>
<td>44</td>
</tr>
<tr>
<td>21.</td>
<td>(Continued).</td>
<td>45</td>
</tr>
<tr>
<td>21.</td>
<td>(Continued).</td>
<td>46</td>
</tr>
<tr>
<td>21.</td>
<td>(Continued).</td>
<td>47</td>
</tr>
<tr>
<td>21.</td>
<td>(Continued).</td>
<td>48</td>
</tr>
<tr>
<td>21.</td>
<td>(Continued).</td>
<td>49</td>
</tr>
<tr>
<td>21.</td>
<td>(Continued).</td>
<td>50</td>
</tr>
<tr>
<td>21.</td>
<td>(Concluded).</td>
<td>51</td>
</tr>
<tr>
<td>22.</td>
<td>List of the subroutine &quot;field7.for.&quot;</td>
<td>52</td>
</tr>
<tr>
<td>22.</td>
<td>(Concluded).</td>
<td>53</td>
</tr>
<tr>
<td>23.</td>
<td>List of the subroutine &quot;source7.for.&quot;</td>
<td>54</td>
</tr>
<tr>
<td>24.</td>
<td>List of the subroutine &quot;mlcom7.for.&quot;</td>
<td>55</td>
</tr>
<tr>
<td>25.</td>
<td>(a) An example run of &quot;maglev7.exe,&quot; for case1p = 1, i.e., for magnetic levitation.</td>
<td>56</td>
</tr>
<tr>
<td>25.</td>
<td>(b) Output of the example run.</td>
<td>57</td>
</tr>
<tr>
<td>25.</td>
<td>(c) Batch input file &quot;res5n&quot; for example run (a).</td>
<td>58</td>
</tr>
<tr>
<td>26.</td>
<td>(a) An example run of &quot;maglev7.exe,&quot; for case1p=2, i.e., for a LIM.</td>
<td>59</td>
</tr>
<tr>
<td>26.</td>
<td>(b) Output of the example run.</td>
<td>60</td>
</tr>
<tr>
<td>26.</td>
<td>(c) Batch input file &quot;res46&quot; for example run (a).</td>
<td>61</td>
</tr>
<tr>
<td>27.</td>
<td>(a) An example run of &quot;maglev7.exe,&quot; for case1p=3, i.e., for a LSM.</td>
<td>62</td>
</tr>
<tr>
<td>27.</td>
<td>(b) Output of the example run.</td>
<td>63</td>
</tr>
<tr>
<td>27.</td>
<td>(c) Batch input file &quot;res6&quot; for example run (a).</td>
<td>64</td>
</tr>
<tr>
<td>28.</td>
<td>List of the main program &quot;shield6.for.&quot;</td>
<td>70</td>
</tr>
<tr>
<td>28.</td>
<td>(Continued).</td>
<td>71</td>
</tr>
<tr>
<td>28.</td>
<td>(Continued).</td>
<td>72</td>
</tr>
<tr>
<td>28.</td>
<td>(Continued).</td>
<td>73</td>
</tr>
</tbody>
</table>
FIGURES (CONCLUDED)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>28.</td>
<td>74</td>
</tr>
<tr>
<td>28.</td>
<td>75</td>
</tr>
<tr>
<td>28.</td>
<td>76</td>
</tr>
<tr>
<td>28.</td>
<td>77</td>
</tr>
<tr>
<td>28.</td>
<td>78</td>
</tr>
<tr>
<td>28.</td>
<td>79</td>
</tr>
<tr>
<td>29.</td>
<td>80</td>
</tr>
<tr>
<td>29.</td>
<td>81</td>
</tr>
<tr>
<td>30.</td>
<td>82</td>
</tr>
<tr>
<td>31.</td>
<td>83</td>
</tr>
<tr>
<td>32.</td>
<td>84</td>
</tr>
<tr>
<td>33.</td>
<td>86</td>
</tr>
<tr>
<td>33.</td>
<td>87</td>
</tr>
<tr>
<td>33.</td>
<td>88</td>
</tr>
</tbody>
</table>

List of the subroutine "field6.for."
List of the subroutine "source6.for."
List of the subroutine "swap6.for."
List of the subroutine "shcom6.for."
(a) An example run of "shield6.exe."
(b) Output of the example run.
(c) Batch input file "res19" for example run (a).
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
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:

\[
\begin{align*}
\nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\
\nabla \times \mathbf{H} &= \mathbf{J} \\
\mathbf{J} &= \sigma \cdot (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \\
\mathbf{B} &= \mu \cdot \mathbf{H}
\end{align*}
\]

(1)

where \( \mathbf{E} \) and \( \mathbf{H} \) are the electric and magnetic field intensity vectors, respectively, \( \mathbf{B} \) is the magnetic induction vector, \( \mathbf{J} \) is the current-density vector, \( \mathbf{v} \) is the velocity of the medium, \( \mu \) and \( \sigma \) 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 $\mathbf{E}$ and $\mathbf{H}$) to obtain, for a non-singular $\mathbf{G}$ (i.e., $\mathbf{G} \neq 0$),

$$
\nabla \times [\mathbf{G}^{-1} \cdot (\nabla \times \mathbf{H})] = -\frac{\partial}{\partial t} (\mathbf{G} \cdot \mathbf{H}) - (\mathbf{V} \cdot \nabla)(\mathbf{G} \cdot \mathbf{H})
$$

$$
\nabla \times [\mathbf{G}^{-1} \cdot (\nabla \times \mathbf{E})] = -\frac{\partial}{\partial t} (\mathbf{G} \cdot \mathbf{E}) + \mathbf{G} \cdot (\mathbf{V} \times \nabla \times \mathbf{E})
$$

$$
J = \mathbf{G} \cdot (\mathbf{E} + \nabla \times (\mathbf{G} \cdot \mathbf{H}))
$$

$$
\mathbf{B} = \mathbf{G} \cdot \mathbf{H}
$$

and, for $\mathbf{G} = 0$,

$$
\nabla \times [\mathbf{G}^{-1} \cdot (\nabla \times \mathbf{E})] = 0
$$

$$
\nabla \times \mathbf{H} = J = 0
$$

$$
\nabla \cdot (\mathbf{G} \cdot \mathbf{H}) = 0
$$

$$
\mathbf{B} = \mathbf{G} \cdot \mathbf{H}
$$

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.

$$
A(t, x, y, z) = \frac{1}{(2\pi)^3} \int \int \int \tilde{A}(\omega, k_x, k_y, z) e^{i\omega t + ik_x x + ik_y y} d\omega dk_x dk_y
$$

$$
\tilde{A}(\omega, k_x, k_y, z) = \frac{1}{2\pi} \int \int \int \mathcal{A}(t, x, y, z) e^{-i\omega t - ik_x x - ik_y y} dt dx dy
$$

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 (\( \vec{B} \)) in layers 1, 3, and 4 as below:

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

\[
\begin{align*}
\vec{B}_{x1} &= I_x e^{k_x z} \\
\vec{B}_{y1} &= I_y e^{k_x z} \\
\vec{B}_{z1} &= I_z e^{k_x z}
\end{align*}
\]

with

\[
\begin{align*}
k_x^2 &= \frac{\mu_{1x} k_x^2 + \mu_{1y} k_y^2}{\mu_{1z}} \\
I_y &= \frac{\mu_{1y}}{\mu_{1z}} \left( \frac{k_y}{k_x} \right) I_x \\
I_z &= \frac{\mu_{1z}}{\mu_{1z}} \left( \frac{k_x}{i k_x} \right) I_x
\end{align*}
\]

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

\[
\begin{align*}
\vec{B}_{x3} &= \Pi_{x}^{(1)} e^{-k_z(z-h_2)} + \Pi_{x}^{(2)} e^{k_z(z-h_2)} \\
\vec{B}_{y3} &= \Pi_{y}^{(1)} e^{-k_z(z-h_2)} + \Pi_{y}^{(2)} e^{k_z(z-h_2)} \\
\vec{B}_{z3} &= \Pi_{z}^{(1)} e^{-k_z(z-h_2)} + \Pi_{z}^{(2)} e^{k_z(z-h_2)}
\end{align*}
\]

with

\[
\begin{align*}
k_z^2 &= k_x^2 + k_y^2 \\
\Pi_{y}^{(1)} &= \frac{k_y}{k_x} \Pi_{x}^{(1)} \\
\Pi_{z}^{(1)} &= \frac{k_z}{k_x} \Pi_{x}^{(1)} \\
\Pi_{y}^{(2)} &= \frac{k_y}{k_x} \Pi_{x}^{(2)} \\
\Pi_{z}^{(2)} &= \frac{k_z}{i k_x} \Pi_{x}^{(2)}
\end{align*}
\]
(c) layer 4 \((z \geq h_2 + h_3)\)

\[
\begin{align*}
\mathbf{B}_{x4} &= IV_x e^{-k_{x4}(z-h_2)} \\
\mathbf{B}_{y4} &= IV_y e^{-k_{x4}(z-h_2)} \\
\mathbf{B}_{z4} &= IV_z e^{-k_{x4}(z-h_2)}
\end{align*}
\]

with

\[
\begin{align*}
k_{x4}^2 &= \frac{\mu_{4x} k_x^2 + \mu_{4y} k_y^2}{\mu_{4z}} \\
IV_y &= \frac{\mu_{4y}}{\mu_{4x}} \frac{k_y}{k_x} IV_x \\
IV_z &= \frac{\mu_{4z}}{\mu_{4x}} \frac{ik_{x4}}{k_x} IV_x
\end{align*}
\]

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

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

\[
\begin{align*}
\mathbf{E}_{x2} &= (\Pi_{x}^{(1)} \cosh k_z^{(1)} z + \Pi_{y}^{(1)} \sinh k_z^{(1)} z) + (\Pi_{x}^{(2)} \cosh k_z^{(2)} z + \Pi_{y}^{(2)} \sinh k_z^{(2)} z) \\
\mathbf{E}_{y2} &= (\Pi_{y}^{(1)} \cosh k_z^{(1)} z + \Pi_{y}^{(1)} \sinh k_z^{(1)} z) + (\Pi_{y}^{(2)} \cosh k_z^{(2)} z + \Pi_{y}^{(2)} \sinh k_z^{(2)} z) \\
\mathbf{E}_{z2} &= (\Pi_{z}^{(1)} \sinh k_z^{(1)} z + \Pi_{z}^{(1)} \cosh k_z^{(1)} z) + (\Pi_{z}^{(2)} \sinh k_z^{(2)} z + \Pi_{z}^{(2)} \cosh k_z^{(2)} z)
\end{align*}
\]

and the magnetic induction \((\mathbf{B})\) as

\[
\begin{align*}
\text{i} \omega \mathbf{B}_{x2} &= \left\{ \left[ (ik_y \Pi_{x}^{(1)} - k_z^{(1)} \Pi_{y}^{(1)}) \sinh k_z^{(1)} z \right] + \left[ (ik_y \Pi_{x}^{(2)} - k_z^{(2)} \Pi_{y}^{(2)}) \cosh k_z^{(2)} z \right] \right. \\
&\quad + \left[ (ik_y \Pi_{y}^{(1)} - k_z^{(2)} \Pi_{y}^{(1)}) \sinh k_z^{(2)} z \right] + \left[ (ik_y \Pi_{y}^{(2)} - k_z^{(2)} \Pi_{y}^{(2)}) \cosh k_z^{(2)} z \right] \right\} \\
\text{i} \omega \mathbf{B}_{y2} &= \left\{ \left[ (k_z^{(1)} \Pi_{x}^{(1)} - ik_x \Pi_{x}^{(1)}) \sinh k_z^{(1)} z \right] + \left[ (k_z^{(1)} \Pi_{x}^{(2)} - ik_x \Pi_{x}^{(2)}) \cosh k_z^{(2)} z \right] \right. \\
&\quad + \left[ (k_z^{(2)} \Pi_{x}^{(1)} - ik_x \Pi_{x}^{(2)}) \sinh k_z^{(2)} z \right] + \left[ (k_z^{(2)} \Pi_{x}^{(2)} - ik_x \Pi_{x}^{(2)}) \cosh k_z^{(2)} z \right] \right\} \\
\text{i} \omega \mathbf{B}_{z2} &= \left\{ \left[ (ik_y \Pi_{y}^{(1)} - ik_x \Pi_{y}^{(1)}) \cosh k_z^{(1)} z \right] + \left[ (ik_y \Pi_{y}^{(2)} - ik_x \Pi_{y}^{(2)}) \sinh k_z^{(2)} z \right] \right. \\
&\quad + \left[ (ik_y \Pi_{y}^{(2)} - ik_x \Pi_{y}^{(2)}) \cosh k_z^{(2)} z \right] + \left[ (ik_y \Pi_{y}^{(2)} - ik_x \Pi_{y}^{(2)}) \sinh k_z^{(2)} z \right] \right\}
\end{align*}
\]
with $k_z^{(1)}$ and $k_z^{(2)}$ satisfying
\[
\mu_{2z} \sigma_z k_z^4 - \left( (\mu_{2z} \sigma_x + \mu_{2x} \sigma_z) k_x^2 + (\mu_{2z} \sigma_y + \mu_{2y} \sigma_z) k_y^2 - i(\omega - k_y v)\mu_{2z} \sigma_z (\sigma_x \mu_{2y} + \sigma_y \mu_{2x}) \right) k_z^2 \\
+ \left[ \mu_{2x} k_x^2 + \mu_{2y} k_y^2 - i(\omega - k_y v)\mu_{2x}\mu_{2y} \sigma_z \right] \sigma_x k_x^2 + \sigma_y k_y^2 - i(\omega - k_y v)\sigma_x \sigma_y \mu_{2z} = 0
\]
(10)

and $\Pi^{(1,2)}_{ye,o}$, $\Pi^{(1,2)}_{xe,o}$, $\Pi^{(1,2)}_{ze,o}$ related via
\[
\Pi^{(1,2)}_{ye,o} = R^{(1,2)} \Pi^{(1,2)}_{xe,o} \\
\Pi^{(1,2)}_{ze,o} = Q^{(1,2)} \Pi^{(1,2)}_{xe,o} \\
R^{(1,2)} = \frac{R_t^{(1,2)}}{R_b^{(1,2)}}
\]
(11)
\[
R_t^{(1,2)} = \left[ \mu_{2x} k_x^2 + \mu_{2y} k_y^2 - i(\omega - k_y v)\mu_{2x}\mu_{2y} \sigma_z \right] \\
\times \left[ \mu_{2y} k_y^2 - \mu_{2z} (k_z^{(1,2)})^2 - i(\omega - k_y v)\sigma_x \mu_{2y} \mu_{2z} \right] + \mu_{2x}\mu_{2z} k_x^2 (k_z^{(1,2)})^2
\]
\[
R_b^{(1,2)} = \mu_{2y} k_x \left\{ (k_y + i\sigma_x \nu) \mu_{2z} \left[ \mu_{2x} k_x^2 + \mu_{2y} k_y^2 - \mu_{2z} (k_z^{(1,2)})^2 - i(\omega - k_y v)\mu_{2x}\mu_{2y} \sigma_z \right] \\
- i\mu_{2z} (k_z^{(1,2)})^2 \nu (\mu_{2x} \sigma_z - \mu_{2z} \sigma_x) \right\}
\]
\[
Q^{(1,2)} = \frac{-k_z^{(1,2)}}{\mu_{2x} k_x^2 + \mu_{2y} k_y^2 - i(\omega - k_y v)\mu_{2x}\mu_{2y} \sigma_z}
\]
(11)

In the above equations, $\sigma_n$ ($n = x, y, \text{or } z$) is the conductivity of layer 2 in the $x,y,z$ direction, i.e.,
\[
\sigma = \hat{x}\hat{x}\sigma_x + \hat{y}\hat{y}\sigma_y + \hat{z}\hat{z}\sigma_z
\]
and $\mu_{mn}$ ($m = 1, 2, \text{or } 4$ and $n = x, y, \text{or } z$) is the permeability of layer $m$ in the $n$-direction, i.e.,
\[
\mu \mu_m = \hat{x}\hat{x}\mu_{mx} + \hat{y}\hat{y}\mu_{my} + \hat{z}\hat{z}\mu_{mz}, \quad m = 1, 2, \text{or } 4.
\]

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:
\[\tilde{B}_{z1} = \tilde{B}_{z2}, \quad \tilde{H}_{x1} = \tilde{H}_{x2} \text{(or, } \tilde{H}_{y1} = \tilde{H}_{y2}), \quad \text{at } z = 0\]

\[\tilde{B}_{z2} = \tilde{B}_{z3}, \quad \tilde{H}_{y2} - \tilde{H}_{y3} = \tilde{K}_{x2} \text{(or, } \tilde{H}_{x3} - \tilde{H}_{x2} = \tilde{K}_{y2}), \quad \text{at } z = h_2\]

\[\tilde{B}_{z3} = \tilde{B}_{z4}, \quad \tilde{H}_{y3} - \tilde{H}_{y4} = \tilde{K}_{x3} \text{(or, } \tilde{H}_{x4} - \tilde{H}_{x3} = \tilde{K}_{y3}), \quad \text{at } z = h_2 + h_3\]

\[\tilde{E}_{z2} - v\tilde{B}_{x2} = 0, \quad \text{at } z = 0, h_2\]

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

\[\Pi^{(2)}_x = e^{-k_z h_3} k_x \left[ \frac{\mu_{4z} k_{z4}}{\mu_o} \left( \frac{1}{V_1 + V_2} \frac{V_1 + V_2}{V_1 - V_2} e^{-2k_z h_3} \right) + k_z \left( \frac{1}{V_1 + V_2} \frac{V_1 + V_2}{V_1 - V_2} e^{-2k_z h_3} \right)^{-1} \right]

\times \left[ \mu_{4z} k_{z4} \tilde{K}_{x3} + \left( \mu_{4z} k_{z4} - \mu_o k_z \right) e^{-k_z h_3} \frac{V_1 \tilde{K}_{x3}}{V_1 - V_2} \right]

\[\Pi^{(1)}_x = -\frac{V_1 + V_2}{V_1 - V_2} \Pi^{(2)}_x - \frac{\mu_o k_x}{k_y} \frac{V_1 \tilde{K}_{x2}}{V_1 - V_2}

\Pi^{(1)}_{xe} = \frac{2 \Pi^{(2)}_x}{V_1 - V_2} + \frac{\mu_o k_x}{k_y} \frac{\tilde{K}_{x2}}{V_1 - V_2}

\Pi^{(1)}_{xo} = U \Pi^{(1)}_{xe}

\Pi^{(2)}_{xo} = S \Pi^{(1)}_{xo}

I_x = \frac{ik_x \mu_{1x}}{\omega k_{z1} \mu_{1z}} \left[ (k_x R^{(1)} - k_y) \Pi^{(1)}_{xe} + (k_x R^{(2)} - k_y) \Pi^{(2)}_{xe} \right]

IV_x = -\frac{\mu_{4x} k_x}{k_y} e^{k_x h_3} \left[ \tilde{K}_{x3} + \frac{V_1 \tilde{K}_{x2}}{V_1 - V_2} e^{-k_x h_3} \right.

\left. - \frac{k_y}{\mu_o k_x} e^{k_z h_3} \left( \frac{1}{V_1 + V_2} \frac{V_1 + V_2}{V_1 - V_2} e^{-2k_z h_3} \right) \Pi^{(2)}_x \right] \]
where

\[ V_1 = \frac{i k_x}{\omega k_z} \left[ (k_x R^{(1)} - k_y) \left( \cosh k_z \ h_2 + U \sinh k_z \ h_2 \right) \right. \]
\[ + \left( k_x R^{(1)} - k_y \right) \left( T \cosh k_z \ h_2 + SU \sinh k_z \ h_2 \right) \]
\[ V_2 = \frac{i \mu_0 k_x}{\omega \mu_0 2y k_z} \left[ (k_z^{(1)} - ik_x Q^{(1)}) \left( \sinh k_z \ h_2 + U \cosh k_z \ h_2 \right) \right. \]
\[ + \left( k_z^{(2)} - ik_x Q^{(2)} \right) \left( T \sinh k_z \ h_2 + SU \cosh k_z \ h_2 \right) \]
\[ T = T_t / T_b \]
\[ T_t = \sinh k_z^{(1)} \ h_2 \left[ (ik_y Q^{(1)} - k_z^{(1)} R^{(1)}) + S (ik_y Q^{(2)} - k_z^{(2)} R^{(2)}) \right] \]
\[ - \frac{\mu_0 k_x}{\mu_0 2y k_z} \left( k_x R^{(1)} - k_y \right) \left( \cosh k_z^{(1)} \ h_2 - \cosh k_z^{(2)} \ h_2 \right) \]
\[ T_b = S^{-1} \sinh k_z^{(2)} \ h_2 \left[ (ik_y Q^{(1)} - k_z^{(1)} R^{(1)}) + S (ik_y Q^{(2)} - k_z^{(2)} R^{(2)}) \right] \]
\[ + \frac{\mu_0 k_x}{\mu_0 2y k_z} \left( k_x R^{(2)} - k_y \right) \left( \cosh k_z^{(1)} \ h_2 - \cosh k_z^{(2)} \ h_2 \right) \]
\[ U = \left( \cosh k_z^{(1)} \ h_2 - \cosh k_z^{(2)} \ h_2 \right)^{-1} \left( S^{-1} T \sinh k_z^{(2)} \ h_2 - \sinh k_z^{(1)} \ h_2 \right) \]
\[ S = \left[ Q^{(2)} \left( 1 - \frac{k_y v}{\omega} \right) + \frac{k_z^{(2)} v}{i \omega} R^{(2)} \right]^{-1} \left[ Q^{(1)} \left( 1 - \frac{k_y v}{\omega} \right) + \frac{k_z^{(1)} v}{i \omega} R^{(1)} \right] \]

With the above formulas given in Equations 4-14, the magnetic field at any arbitrary location can be calculated. The force (\( F \)) 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 (\( \tilde{T} \))

\[ F = \int_{S} \tilde{T} \cdot \tilde{n} \, dS \quad (15) \]

where

\[ \tilde{T} = \tilde{i j} \, T_{i j}, \quad i, j = x, y, z \]
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., \( K_2 = 0, \nu \neq 0 \)). On the other hand, for an EMS approach using forces between two magnetic field sources, both \( K_2 \) and \( K_3 \) will be non-zero, but \( \nu \) 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 (\( I_0 \)) and coil dimensions (\( a \times b \)) 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 \( K = \hat{n} \times M_m \). 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 \( I_0 \), dimensions \( a \times b \), and centered at the origin, \( K_x \), the \( x \)-component of the surface current, will be given by

\[
K_x = -\frac{2i}{\pi} \frac{I_0}{k_x} \sin \frac{k_x a}{2} \sin \frac{k_y b}{2} \cdot 2\pi \delta(\omega)
\]
(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 $K_3$ but a zero $K_2$. The LSM, on the other hand, will have both non-zero $K_3$ and $K_2$, but a non-conducting layer $L$. The travelling-wave source $K_3$ for both LIM and LSM will be alternating currents (AC), while the source $K_2$ for a LSM will be a DC.

For the computer code developed under this effort, the travelling wave source, with a phase velocity $\omega_0/k_\nu_0$, will be taken to occupy a rectangular area of $a \times b$, centered at $x = y = 0$. That is

$$\tilde{K}_{x3} = \frac{I_0}{b} \frac{e^{-i\omega_0 t + ik_\nu_0 y}}{b}, \quad \text{for} \quad -\frac{b}{2} \leq y \leq \frac{b}{2}, \quad -\frac{a}{2} \leq x \leq \frac{a}{2}$$

and

$$\tilde{K}_{x3} = \frac{I_0}{b} \frac{2}{\pi} \frac{1}{k_x} \frac{\sin k_x a}{2} \frac{1}{k_\nu_0 - k_y} \sin \left(\frac{k_\nu_0 y - k_y b}{2}\right) 2\pi \delta(\omega - \omega_0)$$

with

$$\sin(k_\nu_0 b/2) = 0$$

As for $K_2$ needed in a LSM, it is taken to be a rectangular loop of size $a_2 \times b_2$, centered at $(x_0, y_0)$ at $t = 0$, and moving at a velocity $v$ in the $y$-direction. $\tilde{K}_{x2}$, thus, takes the following form

$$\tilde{K}_{x2} = \frac{-2i}{\pi} \frac{I_0}{k_x} \sin \frac{k_x a_2}{2} \sin \frac{k_y b_2}{2} e^{-ik_x x_0 - ik_y y_0} 2\pi \delta(\omega - k_y v)$$

In Equations 16-18, $\delta(\omega - \omega_0)$ 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 $\tilde{K}_x$ 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 $\omega/k_{yo}$, 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 ($\mu_r$) 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 $5\pi$). 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 ($\approx \mu_0 f_0^2 / (2b)$) that can be analytically obtained for a case that $\mu_r$ and $h_2$ are larger and $h_3$ is
Figure 2. Propulsion forces ($f_y$) and attractive forces ($f_z$) as functions of the vehicle velocity ($v$) for various $\mu_2$ in a LIM design alternative, when the driving current sheet has $f = 400$ Hz, $k_y = 5\pi$, $b = 2$ m, and the reaction rail has $\sigma = 10^6$ S/m, and $h_2 = h_3 = 0.02$ m.
Figure 2. (concluded). Propulsion forces ($f_y$) and attractive forces ($f_z$) as functions of the vehicle velocity ($v$) for various $\mu r_2$ 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 $h_2 = h_3 = 0.02$ m.
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 ≥ 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_y = 5π and a reaction rail with 10^6 S/m conductivity, 500 μo permeability and 0.02 m thickness, the forces for a 0.02 m gap and vehicle velocity below 135 m/s, are:

\[
\begin{align*}
\text{propulsion forces (f_y)} &> 0.0068 \text{ newton/kN} \\
\text{levitation forces (f_z)} &> 0.064 \text{ newton/kN}
\end{align*}
\]

That is, if the source current (I_0) is 400 kN, then, the forces are

\[
\begin{align*}
\text{propulsion forces (f_y)} &> 1.1 \text{ kilo-newton} \\
\text{levitation forces (f_z)} &> 10 \text{ kilo-newton}
\end{align*}
\]
Figure 4. Propulsion forces ($f_y$) and attractive forces ($f_z$) as functions of the relative permeability ($\mu_2$) of the reaction rail for 2 vehicle velocities in a LIM design alternative, when the driving current sheet has $f = 400$ Hz, $k_0 = 5\pi$, $b = 2$ m, and the reaction rail has $\sigma = 10^6$ S/m, and $h_2 = h_3 = 0.02$ m.
Figure 5. Propulsion forces (\(f_y\)) and attractive forces (\(f_z\)) as functions of conductivity (\(\sigma\)) of the reaction rail for 2 vehicle velocities in a LIM design alternative, when the driving current sheet has \(f = 400\) Hz, \(k_y_0 = 5\pi\), \(b = 2\) m, and the reaction rail has \(\mu_2 = 500\), and \(h2 = h3 = 0.02\) m.
Figure 6. Propulsion forces ($f_y$) and attractive forces ($f_z$) as functions of the thickness ($h_2$) of the reaction rail for 2 vehicle velocities in a LIM design alternative, when the driving current sheet has $f = 400 \text{ Hz}$, $k_y = 5\pi$, $b = 2 \text{ m}$, and the reaction rail has $\sigma = 10^6 \text{ S/m}$, $\mu_2 = 500$, and $h_3 = 0.02 \text{ m}$. 
Figure 7. Propulsion forces ($f_y$) and attractive forces ($f_z$) as functions of the gap width ($h_3$) 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, $k y_0 = 5\pi$, $b = 2$ m, and the reaction rail has $\sigma = 10^6$ S/m, $\mu_2 = 500$, and $h_2 = 0.02$ m.
Figure 8. Propulsion forces ($f_y$) and attractive forces ($f_z$) 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 $k_y = 5\pi$, $b = 2m$, and the reaction rail has $\sigma = 10^6 \text{ S/m}$, $\mu_2 = 500$, and $h_2 = h_3 = 0.02 \text{ m}$. 
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 transverse (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.
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 ($bB^2/(2\mu_0)$) that can be analytically obtained for the case that $\mu r$ 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 $\mu_0$ 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 ($f_z$) and drag forces ($-f_y$) as functions of the velocity ($v$) in an EMS levitation design alternative using magnets with 1 tesla/$\mu_0$ uniform magnetization and two approximate pole lengths ($p\ell$), when $h_2 = h_3 = 0.02$ m, $\mu_2 = 500$, $\sigma = 10^6$ S/m, and $b_3 = 0.5$ m.
Figure 11. Attractive forces ($f_z$) and drag forces ($-f_y$) as functions of the relative permeability ($\mu_r$) of the reaction rail for 2 vehicle velocities in an EMS levitation design alternative using magnets with 1 tesla/$\mu_0$ uniform magnetization, when $h_2 = h_3 = 0.02$ m, $\sigma = 10^6$ S/m, and $b_3 = 0.5$ 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/μ₀ uniform magnetization, when h₂ = h₃ = 0.02 m, μ₂ = 500 and b₃ = 0.5 m.
Figure 13. Attractive forces ($f_z$) and drag forces ($-f_y$) as functions of the thickness ($h_2$) of the reaction rail for 2 vehicle velocities in an EMS levitation design alternative using magnets with 1 tesla/$\mu_0$ uniform magnetization, when $\mu_2 = 500$, $\sigma = 10^6$ S/m, $b_3 = 0.5$ m, and $h_3 = 0.02$ m.
Figure 14. Attractive forces ($f_z$) and drag forces ($-f_y$) as functions of the gap width ($h_3$) between the magnet and the reaction rail for 2 vehicle velocities in an EMS levitation design alternative using magnets with 1 tesla/$\mu_0$ uniform magnetization, when $\mu_r \approx 500$, $\sigma = 10^6$ S/m, $b_3 = 0.5$ m and $h_2 = 0.02$ 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 $h_{3.1} = 0.4$ m and $b_{3.1} = 1$ m.
Figure 17. Stray magnetic fields as functions of the thickness and permeability of the passive shielding layer when the current source 1 has $h_{3.1} = 0.4$ m and $b_{3.1} = 1$ m, and the active shielding current (-0.2I) has $h_{3.2} = 0.1$ m and $b_{3.2} = 0.5$ m.
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 $h_3 = 0.1\,\text{m}$ and $b_3 = 1\,\text{m}$, the active shielding current has $b_{3,2} = 0.25\,\text{m}$, and the passive shielding layer has $\mu_r = 100$, $h_2 = 0.02\,\text{m}$. 
Figure 20. Stray magnetic fields as functions of locations, when the source current I has $h_{3.1} = 0.4$ m, $b_{3.1} = 1$ m, the active shielding current (-0.2I) has $h_{3.2} = 0.1$ m, $b_{3.2} = 0.25$ m, and the passive shielding layer has $h_2 = 0.02$ m.
obtained from the complicated codes with analytical formulations for some special cases that formulations are possible. For example, when \( h_2 = 0, \text{curr}_2 = 0 \), the field at \((0, 0, -1.5m)\) is given as

\[
H / I = (b_{3-1}) \left\{ 2\pi \left[ \left( \frac{b_{3-1}}{2} \right)^2 + (h_{3-1} + 0.5)^2 \right] \right\}^{-1}
\]

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 \( b_{3-2} = 0.25m, h_{3-2} = 0.1m, \text{shift}_2 = 0 \), and a passive shielding layer with \( \mu_r = 100 \), when the current source \( I \) has \( b_{3-1} = 1m \) and \( h_{3-1} = 0.4m \), and the field point is at \( y = 0, z = -0.5m \). From the curve, if \( I = 10^5 \) Amp-turns, then the stray magnetic field is

\[
B = \mu_0 H = 0.128 \times 10^5 \times 4\pi \times 10^{-7} \times 10^4 = 160 \text{ gauss}, \text{ when } h_2 = 0 (\text{i.e., no passive shielding}),
\]

and is equal to

\[
B = \mu_0 H = 0.0383 \times 10^5 \times 4\pi \times 10^{-7} \times 10^4 = 48 \text{ gauss}, \text{ when } h_2 = 4 \text{ cm}.
\]

That is, a reduction factor of about 3 is achieved by a 4 cm thick layer with 100 \( \mu_0 \) permeability. The reduction factor will be larger if the permeability is higher than 100 \( \mu_0 \). If the permeability is 200 \( \mu_0 \), 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 (ω, 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:\

<table>
<thead>
<tr>
<th>File</th>
<th>Type</th>
<th>Size</th>
<th>Date</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHIELD6</td>
<td>EXE</td>
<td>74752</td>
<td>05-27-92</td>
<td>3:13p</td>
</tr>
<tr>
<td>MAGLEV7</td>
<td>EXE</td>
<td>72688</td>
<td>06-04-92</td>
<td>11:17a</td>
</tr>
<tr>
<td>SOURCE6</td>
<td>FOR</td>
<td>542</td>
<td>12-20-91</td>
<td>2:54p</td>
</tr>
<tr>
<td>SHCON6</td>
<td>FOR</td>
<td>812</td>
<td>01-29-92</td>
<td>2:31a</td>
</tr>
<tr>
<td>FIELD6</td>
<td>FOR</td>
<td>4386</td>
<td>02-26-92</td>
<td>10:57a</td>
</tr>
<tr>
<td>SWAP6</td>
<td>FOR</td>
<td>477</td>
<td>12-20-91</td>
<td>2:56p</td>
</tr>
<tr>
<td>SHIELD6</td>
<td>FOR</td>
<td>17556</td>
<td>05-27-92</td>
<td>3:08p</td>
</tr>
<tr>
<td>MAGLEV7</td>
<td>FOR</td>
<td>18181</td>
<td>06-04-92</td>
<td>11:16a</td>
</tr>
<tr>
<td>SOURCE7</td>
<td>FOR</td>
<td>1239</td>
<td>03-25-92</td>
<td>8:39a</td>
</tr>
<tr>
<td>NLCON7</td>
<td>FOR</td>
<td>675</td>
<td>03-25-92</td>
<td>8:39a</td>
</tr>
<tr>
<td>FIELD7</td>
<td>FOR</td>
<td>4140</td>
<td>03-25-92</td>
<td>8:39a</td>
</tr>
<tr>
<td>RES19</td>
<td></td>
<td>112</td>
<td>07-21-92</td>
<td>12:30p</td>
</tr>
<tr>
<td>RES6</td>
<td></td>
<td>122</td>
<td>07-21-92</td>
<td>12:30p</td>
</tr>
<tr>
<td>RES46</td>
<td></td>
<td>103</td>
<td>07-21-92</td>
<td>12:30p</td>
</tr>
<tr>
<td>RES5N</td>
<td></td>
<td>90</td>
<td>06-04-92</td>
<td>11:54a</td>
</tr>
</tbody>
</table>

15 File(s) 157696 bytes free
program maglev
  c for fourier transform in both x and y directions
  include 'micon7.for'
  integer*2 cases,nb,n3,n,k,loopvar,nc,kc,dn,dk
  character*1 iso1,iso4,iso2u,iso2s
  character*14 name
  real*8 url,ur4,ur2,axy,freq
  real*8 Fx,Fy,Fs,ky,dky,error,fctr
  real*8 lvmn,lvmx,d1v,lv,p1,flcnh
  real*8 urlx,urly,urls,ur2x,ur2y,ur2s,ur4x,ur4y,ur4s
  complex*16 Hx1,Hx2,Hy1,Hy2,Hs1,Hs2,termx,termy,termz
  complex*16 Psintg,Pyintg,Pzintg,Fxsum,Fysum,Fzsum

  c call clr_scr
  kyo3=0.
  b3=0.
  a3=0.
  b2=0.
  a2=0.
  write(6,1020)
  read(5,'(a)') name
  write(6,1030)
  c read(5,* ) error
  write(6,1040)
  c read(5,* ) dx,dy
  error=1.0e-6

  write(6,1011)
  read(5,'(a)') iso1
  if (iso1.eq.'y') then
    write(6,1101)
    read(5,* ) url
    urlx=urlx*uo=1.000001
    urly=urly*uo
    url=url=url*uo=0.999999
  else
    write(6,1100)
    read(5,* ) ur4x,ur4y,ur4s
    ur4x=ur4x*uo=0.999999
    ur4y=ur4y*uo=1.000001
    ur4=ur4*uo
  endif
  write(6,1012)
  read(5,'(a)') iso4
  if (iso4.eq.'y') then
    write(6,1161)
    read(5,* ) ur4
    ur4x=ur4x*uo=0.999999
    ur4y=ur4y*uo=1.000001
    ur4=ur4*uo
  else
    write(6,1160)
    read(5,* ) ur4x,ur4y,ur4z
    ur4x=ur4x*uo=0.999999
    ur4y=ur4y*uo=1.000001
    ur4=ur4*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 $z=h_2+h_3$
c write(6,1200)
c read(5,'(a)') case3
case3='y'
write(6,1205)
read(5,* ) 103

c if (case3.eq.'y') then
write(6,1210)
read(5,* ) caseem
pi=0.
c if (caseem.eq.2) then
write(6,1215)
c read(5,* ) pi
c endif
if (caselp.eq.3) then
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
write(6,2000)
read(5,* ) loopvar
if (loopvar.le.0 .or. loopvar.gt.7) then
write(6,2005)
goto 10
endif
else
write(6,1010)
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,* ) lvmmin,lvmmax,dlv

if (loopvar.eq.1) then
write(6,1061)
read(5,* ) freq
if (iso2z.eq.'y') then
write(6,1081)
read(5,* ) sxyz

Figure 21. (Continued).
else
    write(6,1080)
    read(5,*) sz,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 (iso2z.eq.'y') then
write(6,1081)
read(5,*) axyz
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 (iso2z.eq.'y') then
write(6,1081)
read(5,*) axyz
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 (iso2z.eq.'y') then

Figure 21. (Continued).
write(6,1081)
read(5,*), ssyz
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 (iso2u.eq.'y') then
write(6,1081)
read(5,*), ssyz
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 (iso2u.eq.'y') then
write(6,1081)
read(5,*), ssyz
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 (iso2u.eq.'y') then
write(6,1081)
read(5,*), ssyz
else
write(6,1060)
read(5,*), h2, freq
if (iso2u.eq.'y') then
write(6,1081)
read(5,*), ssyz
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=sxys
sy=sxys*0.999999
sz=sxys*1.000001
endif
endif
if (loopvar.ne.4) then
if (iso2u.eq.'y') then
u2x=ur2*x0
u2y=ur2*y0*0.999999
u2z=ur2*z0*1.000001
else
u2x=ur2*x0
u2y=ur2*y0*0.999999
u2z=ur2*z0*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 (casep.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='Fz', status='unknown')
open(unit=12, file='Fx', status='unknown')
open(unit=13, file='Fs', 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*u0
    u2y=ur2y*u0
    u2z=ur2z*u0
  else if (loopvar.eq.5) then
    h3=lv
  else if (loopvar.eq.6) then
    v=lv
  else if (loopvar.eq.7) then
    kyo=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
    w=1.e-6
  endif
  if (h2.eq.0.) then
    h2=1.e-6
  endif
  if (sx.eq.0.) then
    sx=1.000001e-6
enddo 140

Figure 21. (Continued).
endif
if (sy.eq.0.) then
  sy=0.999999e-6
endif
if (as.eq.0.) then
  as=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 (cases.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.
Fssum=0.
c
check for convergence in n
50 if (((cda(b(Fyintg).gt.error) .eq. cda(b(Fysum)) .and.
  2 cda(b(Fyintg).gt.error) .eq. cda(b(Fssum)) .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 nc=nc,nc,dn
  kcy=1
  Fxintg=0.
  Fyintg=0.
  Fssintg=0.
c
check for convergence in ky
60 if (((cda(b(Fyintg).gt.error) .eq. cda(b(Fyintg)) .and.
  2 (cda(b(Fyintg).gt.error) .eq. cda(b(Fyintg)) .or.
  2 (kc.eq.-1) .or.
  2 ((casep.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.
terms=0.
do 240 kc,kc,dk
   if (k.ne.0) then
      ky=k*dky
   else
      ky=1.e-6
   endif
   if (casep.eq.3) then
      ky=y/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=Hx+fctnh/u0+Hx1
      Hy1=Hy+fctnh/u0+Hy1
      Hz1=Hz+fctnh/u0+Hz1
   continue
   Bx2=dconjg(Bx1)
   By2=dconjg(By1)
   Bz2=dconjg(Bz1)
   termx=termx+Hx1*Bz2
   termy=termy+Hy1*Bz2
   terms=terms+Hx1*Bz2-Hx1*B2-By1*By2
   continue
   Fxintg=Fxintg+termx
   Fyintg=Fyintg+termy
   Fzintg=Fzintg+terms
   if (casep.eq.3) then
      termx=0.
      termy=0.
      terms=0.
   endif
   goto 50
   endif
   Fzsum=Fzsum+Fxintg
   Fysum=Fysum+Fyintg
   Fxsum=Fxsum+Fzintg
   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 (casep.eq.1) then
    fctr=2.
  else if (casep.eq.2) then
    fctr=2.*(pl/uo)**2.
  endif
else if (casep.eq.2) then
  fctr=1./b3
else if (casep.eq.3) then
  fctr=1./b3
endif

Fx=.5*dreal(uo*Fxsum*dky*dx)*fctr
Fy=.5*dreal(uo*Fysum*dky*dx)*fctr
Fs=.25*dreal(uo*Fysum*dky*dx)*fctr

open output files
open(unit=11,file=name,status='unknown')
write(11,1400) lv,Fx
write(12,1400) lv,Fy
write(13,1400) lv,Fs
write(14,1420) kc,nc

continue

close(11)
close(12)
close(13)
c

suff(1)='Fx'
do 25 il=1,3
cfname=name//suff(11)
ufname(il)=il+10
copen(unit=ufname(il),file=fname,status='unknown')
cwrite(ufname(il),4000) pts
c25 continue

c format statements :

1000 format(
  1 15x,'********************************************','
  2/15x,'**
  3/15x,'** PROGRAM : HAGLEV **
  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 dx,dy : ',$)
1050 format(/5x,'Enter rail thickness--h1 in m,freq : ',$)
1060 format(/5x,'Enter freq : ',$)
1062 format(/5x,'Enter rail thickness--h2 in m : ',$)
c1063 format(/5x,'Enter l=loop h1, 2=loop v, j=loop : ',$)
c1066 format(/5x,'Enter h3min, h3max, dh3 : ',$)
1069 format(/5x,'Enter gap--h3 in m : ',$)
c1072 format(/5x,'Enter vmin, vmax, dv : ',$)

Figure 21. (Continued).
Figure 21. (Concluded).
fields at layer 3 at $n=h_2+h_3$, and prepares for other layers

```
subroutine field(n,ky)
include 'alcom7.for'

integer*2 n
real*8 kx,ky,kx1,kx3,kx4
complex*16 X,b,c,kx2(2),ks(2),R(2),Q(2)
complex*16 S,T,U,V1,V2
complex*16 temp,IIIx(2),IIIy(2),IIIz(2)
complex*16 IIIl(2)
complex*16 IX,IX,IXs,IXy,IXz
complex*16 IIx2(2),IIx3(2),IIx4(2),IIy1(2),IIz1(2)
complex*16 csinh,ccosh,p

c sinh(p)=.5*(cexp(p)-cexp(-p))
ccosh(p)=.5*(cexp(p)+cexp(-p))
i=dcmplx(0.,1.)
call source(n,ky)

if (n.eq.0) then
  kx=1.e-6
else
  kx=n*dx
endif
x=dcmplx(kx*kx*u2y+ky*ky/u2x, -(w-ky*v)*as)
b=dcmplx(-as/as+u2y/u2z)*kx-(asy/as+u2y/u2z)*ky*ky,
2 (-w-ky*v) *(as*u2y+asy*u2z))
c=(u2x*u2y*x/(u2y*as)) *dcmplx(as*kx*ky*ky*ky,
2 -(w-ky*v)*sx*sy*u2x)
ks2(1)=.5*(-b+cdqrt(b*b-4.*c))
ks2(2)=.5*(-b-cdqrt(b*b-4.*c))
ks1=cdqrt(kx*kx*ky)
ks1=cdqrt((ux/ux1)*kx*(uy/uy1)*ky*ky)
kx=cdqrt((ux/ux)*kx*(uy/uy)*ky*ky)
R(1)= u2x*u2y*X*(u2y*ky*ky-u2z*ks2(1)-i*(w-ky*v)*as+u2y*u2z)+
2 u2x*u2z*kx*kx2(1)
R(1)=R(1)/ u2y*((kx*ky+ix*ky*ky*v=ux2*u2y*X-u2z*ks2(1))-1)
2 u2x*ks2(1)+i*ky*X*(ux2*ux2-ux2=ux2))
R(2)= u2x*u2y*X*(u2y*ky*ky-u2z*ks2(2)-i*(w-ky*v)*as+u2y*u2z)+
2 u2x*u2z*kx*kx2(2)
R(2)=R(2)/ u2y*((kx*ky+ix*ky*ky+ux2*u2y*X-u2z*ks2(2))-1)
2 u2x*ks2(2)+i*ky*X*(ux2*ux2-ux2=ux2))
Q(1)=ks1*i*u2z*ks1*(i*ky*v-ux2*as)=u2y*R(1)/
2 (u2x*u2y*Y)
Q(2)=ks1*i*u2z*ks1*(i*ky*v-ux2*as)=u2y*R(2)/
2 (u2x*u2y*Y)
S=(Q(1)*(1.-ky*v/w)+ks1)*v*W(1)/(1.)
2 (Q(2)*(1.-ky*v/w)+ks2)*v*W(2)/(1.)
T= csinh(ks1)*h2*+
2 (i*ky*Q(1)-ks1*R(1)+S*(i*ky*Q(2)-ks2)*R(2))-
2 (u2x*ks1/kx1)/ (ux2*ks1)
2 (ccosh(ks1)*h2-ccosh(ks2)*h2))
T=T/(1.8*csinh(ks2)*h2)*
2 (i*ky*Q(1)-ks1*R(1)+S*(i*ky*Q(2)-ks2)*R(2))+
2 (u2x*ks1/kx1)/ (ux2*ks1)
2 (ccosh(ks1)*h2-ccosh(ks2)*h2))
```

Figure 22. List of the subroutine "field7.for."
Figure 22. (Concluded).
subroutine source(n,ky)
include 'mlcom.7.for'

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

K3=0.
K2=0.
kx=n*dx
lp2=0.
if (case2.eq.'y') then
  lp2=IO2*(-2.*i/dsqrt(2.*pi))*dsin(ky*b2/2.)
endif

if (case1p.eq.1) then
  lp3=IO3*(-2.*i/dsqrt(2.*pi))*dsin(ky*b3/2.)
else
  lp3=IO3*(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)*
      dsin(kx*a3/2.)*cexp(-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)*
      dsin(kx*aa2/2.)*cexp(-i*kx*(ax2-aa2/2.))
    endif
  endif
endif

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

return
end

Figure 23. List of the subroutine "source7.for."
common variables share by maglev and field

implicit none

integer*2 case, caselp
character*1 case2, case3
real*8 h2, h3, h3p, uo, pi, W0, sx, sy, sz, w, v, dklx
real*8 ulx, 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, W0, sx, sy, sz, w, v, dklx
common /b/ ulx, 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."
Enter output file name prefix: t5n
Is layer 1 isotropic? (y,n) : y
Enter layer1 iso.rel.permea.--url : 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 : l.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.
\[ C:\> \text{type t5n.fx} \]
\[
\begin{array}{rrr}
\text{100E-03} & -1.79E-09 \\
\text{150E+02} & 0.639E-07 \\
\text{300E+02} & 0.436E-06 \\
\text{450E+02} & -0.343E-07 \\
\text{600E+02} & 0.126E-06 \\
\text{750E+02} & -1.25E-06 \\
\text{900E+02} & 0.870E-06 \\
\text{105E+03} & -0.378E-06 \\
\text{120E+03} & 0.111E-05 \\
\text{135E+03} & -0.619E-07 \\
\text{150E+03} & 0.700E-07 \\
\text{165E+03} & -0.406E-06 \\
\text{180E+03} & 0.708E-07 \\
\end{array}
\]

\[ C:\> \text{type t5n.fy} \]
\[
\begin{array}{rrr}
\text{100E-03} & 0.298E+00 \\
\text{150E+02} & -0.263E+05 \\
\text{300E+02} & 0.322E+05 \\
\text{450E+02} & -0.363E+05 \\
\text{600E+02} & 0.395E+05 \\
\text{750E+02} & -0.422E+05 \\
\text{900E+02} & 0.445E+05 \\
\text{105E+03} & -0.464E+05 \\
\text{120E+03} & 0.480E+05 \\
\text{135E+03} & -0.494E+05 \\
\text{150E+03} & 0.507E+05 \\
\text{165E+03} & -0.518E+05 \\
\text{180E+03} & 0.528E+05 \\
\end{array}
\]

\[ C:\> \text{type t5n.fz} \]
\[
\begin{array}{rrr}
\text{100E-03} & 0.153E+06 \\
\text{150E+02} & 0.138E+06 \\
\text{300E+02} & 0.126E+06 \\
\text{450E+02} & 0.118E+06 \\
\text{600E+02} & 0.112E+06 \\
\text{750E+02} & 0.106E+06 \\
\text{900E+02} & 0.101E+06 \\
\text{105E+03} & 0.964E+05 \\
\text{120E+03} & 0.924E+05 \\
\text{135E+03} & 0.886E+05 \\
\text{150E+03} & 0.852E+05 \\
\text{165E+03} & 0.820E+05 \\
\text{180E+03} & 0.790E+05 \\
\end{array}
\]

Figure 25. (b) Output of the example run.
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.--url : 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--103 : 1.

Is it a magnet? l=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 l/m,note w/kyo3=phase velocity: 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.
<table>
<thead>
<tr>
<th></th>
<th>C:&gt;type t46.fx</th>
<th></th>
<th>C:&gt;type t46.fy</th>
<th></th>
<th>C:&gt;type t46.fz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>.500E+06</td>
<td>.567E-15</td>
<td>.500E+06</td>
<td>.495E-08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>.150E+07</td>
<td>.766E-15</td>
<td>.150E+07</td>
<td>.806E-08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>.250E+07</td>
<td>.885E-15</td>
<td>.250E+07</td>
<td>.998E-08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>.450E+07</td>
<td>1.04E-14</td>
<td>.450E+07</td>
<td>.126E-07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>.650E+07</td>
<td>1.16E-14</td>
<td>.650E+07</td>
<td>.145E-07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>.750E+07</td>
<td>1.20E-14</td>
<td>.750E+07</td>
<td>.153E-07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>.850E+07</td>
<td>1.25E-14</td>
<td>.850E+07</td>
<td>.159E-07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>.950E+07</td>
<td>1.28E-14</td>
<td>.950E+07</td>
<td>.166E-07</td>
</tr>
</tbody>
</table>

Figure 26. (b) Output of the example run.
Figure 26. (c) Batch input file "res46" for example run (a).
Figure 27. (a) An example run of "maglev7.exe," for case lp=3, i.e., for a LSM.
<table>
<thead>
<tr>
<th>x</th>
<th>y</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td></td>
</tr>
<tr>
<td>0.628E+02</td>
<td>-0.570E-17</td>
<td></td>
</tr>
<tr>
<td>0.126E+03</td>
<td>-0.198E-16</td>
<td></td>
</tr>
<tr>
<td>0.188E+03</td>
<td>-0.498E-16</td>
<td></td>
</tr>
<tr>
<td>0.251E+03</td>
<td>-0.272E-16</td>
<td></td>
</tr>
<tr>
<td>0.314E+03</td>
<td>-0.266E-16</td>
<td></td>
</tr>
<tr>
<td>0.377E+03</td>
<td>-0.221E-15</td>
<td></td>
</tr>
<tr>
<td>0.440E+03</td>
<td>-0.167E-16</td>
<td></td>
</tr>
<tr>
<td>0.503E+03</td>
<td>-0.105E-16</td>
<td></td>
</tr>
<tr>
<td>0.565E+03</td>
<td>-0.111E-16</td>
<td></td>
</tr>
<tr>
<td>0.628E+03</td>
<td>-0.215E-17</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>x</th>
<th>y</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00E+00</td>
<td>-0.303E-16</td>
<td></td>
</tr>
<tr>
<td>0.628E+02</td>
<td>-0.101E-08</td>
<td></td>
</tr>
<tr>
<td>0.126E+03</td>
<td>-0.222E-08</td>
<td></td>
</tr>
<tr>
<td>0.188E+03</td>
<td>-0.682E-08</td>
<td></td>
</tr>
<tr>
<td>0.251E+03</td>
<td>-0.430E-08</td>
<td></td>
</tr>
<tr>
<td>0.314E+03</td>
<td>-0.467E-08</td>
<td></td>
</tr>
<tr>
<td>0.377E+03</td>
<td>-0.443E-07</td>
<td></td>
</tr>
<tr>
<td>0.440E+03</td>
<td>-0.366E-08</td>
<td></td>
</tr>
<tr>
<td>0.503E+03</td>
<td>-0.258E-08</td>
<td></td>
</tr>
<tr>
<td>0.565E+03</td>
<td>-0.298E-08</td>
<td></td>
</tr>
<tr>
<td>0.628E+03</td>
<td>-0.633E-09</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>x</th>
<th>y</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00E+00</td>
<td>-0.109E-06</td>
<td></td>
</tr>
<tr>
<td>0.628E+02</td>
<td>-0.194E-07</td>
<td></td>
</tr>
<tr>
<td>0.126E+03</td>
<td>-0.210E-07</td>
<td></td>
</tr>
<tr>
<td>0.188E+03</td>
<td>-0.211E-10</td>
<td></td>
</tr>
<tr>
<td>0.251E+03</td>
<td>-0.205E-07</td>
<td></td>
</tr>
<tr>
<td>0.314E+03</td>
<td>-0.184E-07</td>
<td></td>
</tr>
<tr>
<td>0.377E+03</td>
<td>-0.121E-08</td>
<td></td>
</tr>
<tr>
<td>0.440E+03</td>
<td>-0.110E-07</td>
<td></td>
</tr>
<tr>
<td>0.503E+03</td>
<td>-0.717E-08</td>
<td></td>
</tr>
<tr>
<td>0.565E+03</td>
<td>-0.122E-10</td>
<td></td>
</tr>
<tr>
<td>0.628E+03</td>
<td>-0.154E-08</td>
<td></td>
</tr>
</tbody>
</table>

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

\[ \text{maglev7 < res5n} \]

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:

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

\[ s_j = \text{conductivity of the j-th component (again, uniaxial conductivity has been assumed for layer 2) in layer 2, j = x, y, z} \]

\[ H_{j1} = \text{j-th component of the magnetic field intensity at the interface of layers 3 and 4, j = x, y, z} \]

\[ F_j = \text{j-th component of the force exerted on layer 4, j = x, y, z} \]

\[ k_{yo}, f, v = \text{wave number, frequency of the source current, and velocity of the vehicle} \]
\[ (\text{Note, } k_{yo}b^3/2 \text{ has to be multiples of } \pi) \]
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 "dks," "dky," and "error," respectively. From many test runs, it is estimated that values of "error" < \(10^{-6}\), and "\(a \cdot dks\)" (or "\(b \cdot dky\)"") < 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 ($k_2, f, ..., v$) 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/$\mu_0$ 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 anisotropic 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 anisotropic 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, $\mu = \mu_0$, $\sigma = 0$
layer 2: reaction rail, $\mu = \mu_0$, or high $\mu$ (e.g., 100 $\mu_0$)

$$\sigma = 10^5 - 10^7 \text{ S/m}$$
layer 3: air, $\mu = \mu_0$, $\sigma = 0$,
layer 4: laminated iron, $\sigma = 0$, high $\mu$, or air, $\mu = \mu_0$, $\sigma = 0$.

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 $v_{ph} = (\omega/ky_0)$ occupying a rectangular area $b_3 \times a_3$ ($b_3$ in the travelling direction, $a_3$ 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 $\sin(ky_0b/2)$ is 0 (note, $b = b_3$).

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 $\mu = \mu_0$, $\sigma = 0$. 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 (o, 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 'shome6.for'

integer n, k, nc, dk, dn, dk, loopvar
character*1 iso1, iso4, iso3u, iso3a
character*14 name
real*8 hx, hy, dky, ky, twoip, error, Plintg, P4intg, Plsum, P4sum
real*8 Fnl, Fne, lmin, lmax, dlv, lv, kycond, kxcond, B1mag, B4mag
real*8 urx, ury, urlx, ur2x, ur2y, ur4x, ur4y, u4x
real*8 url, ur, ur2, ur4, yxys, freq
complex*16 Hx1, Hx4, Hy1, Hy4, Hs1, Hs4, termx, termy, temp4x, temp4y
complex*16 Hx1, Hx4, Hy1, Hy4, Hs1, Hs4, termx, temp4x, temp4y
complex*16 Hx1, Hx4, Hy1, Hy4, Hs1, Hs4, termx, temp4x, temp4y
complex*16 Hx1, Hx4, Hy1, Hy4, Hs1, Hs4, termx, temp4x, temp4y

    call clr_scr
b1_1=0.
b1_2=0.
a1_1=0.
a1_2=0.
write(6,1020)
read(5, '(a)') name
write(6, 1030)
read(5,*) curr_l
write(6, 1035)
c read(5,*) error
c write(6, 1040)
c read(5,*) dx, dky
c error=1.0e-6
c write(6, 1070)
read(5,*) freq, y
write(6, 1075)
read(5, '(a)') iso1
if (iso1.eq.'y') then
write(6,1105)
read(5,*) url
ulx=url*uo*1.000001
uly=url*uo
url=url*uo*0.999999
else
write(6,1100)
read(5,*) urlx, urly, urls
ulx=urlx*uo*1.000001
uly=urly*uo
url=urls*uo*0.999999
endif
write(6, 1077)
read(5, '(a)') iso4
if (iso4.eq.'y') then
write(6,1165)
read(5,*) ur4
ux=urx*uo*0.999999
uy=ury*uo*1.000001
ux=ux*uo
else
write(6,1160)
read(5,*) ur4x, ur4y, ur4s
ux=ur4x*uo*0.999999
uy=ury*uo*1.000001
ux=ux*uo

eendit
write(6,1077)
read(5, '(a)') iso4
if (iso4.eq.'y') then
write(6,1165)
read(5,*) ur4
ux=urx*uo*0.999999
uy=ury*uo*1.000001
ux=ux*uo
else
write(6,1160)
read(5,*) ur4x, ur4y, ur4s
ux=ur4x*uo*0.999999
uy=ury*uo*1.000001
ux=ux*uo

Figure 28. List of the main program "shield6.for."
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
read(5,*) curr_2
if (curr_2.eq.0) then
  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).
Figure 28. (Continued).
read(3,*) b3_1, a3_1, ax3_1
if (curr_2.ne.0.) then
  write(6,1243)
  read(3,*) 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 (v.eq.0.0) then
    v=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

c
shift_1=0.
k=1
if (s.lt.0.) then
  hi = s
  Hxi=0.
  Hyi=0.
  Hzi=0.
else
  hi = s
  Hxi=0.
  Hyi=0.
  Hzi=0.
endif
check for convergence in ky
50 if (s.lt.0.) then
  kycond = Pintg-(error*Plsum)
else
  kycond = P4intg-(error*P4sum)
endif
if ((kycond.gt.0.) .or.
  (kc.eq.-1).or.
  (((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 (s.lt.0.) then
      Hxlintg=0.
      Hylintg=0.
      Hzlintg=0.
    else
      Hxlintg=0.
      Hylintg=0.
      Hzlintg=0.
    endif
    if (k.ne.0) then
      ky=k*dky
    else
      ky=1.e-6
    endif
check for convergence in kx
60 if (s.lt.0.) then
  kxcond = Pn1-(error*Plintg)
else
  kxcond = Pn4-(error*P4intg)
endif

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
tempix=0.
tempiy=0.
tempiz=0.
else
tempix=0.
tempiy=0.
tempiz=0.
endif
do 200 n=-nc,nc,dn
if (n.ne.0) then
  kx=n*dx
else
  kx=1.e-6
endif
call swap(1)
call field(n,ky)
if (z.lt.0.) then
  Hx1=Bx1/uo
  Hy1=By1/uo
  Hz1=Bz1/uo
else
  Hx4=Bx4/uo
  Hy4=By4/uo
  Hz4=Bz4/uo
endif
if (curr_2.ne.0) then
call swap(2)
call field(n,ky)
if (z.lt.0.) then
  Hx1=Hx1+Bx1/uo
  Hy1=Hy1+By1/uo
  Hz1=Hz1+Bz1/uo
else
  Hx4=Hx4+Bx4/uo
  Hy4=Hy4+By4/uo
  Hz4=Hz4+Bz4/uo
endif
endif
term=cexp(i*kx*x)
if (z.lt.0.) then
tempix=tempix+Hx1*term
tempiy=tempiy+Hy1*term
tempiz=tempiz+Hz1*term
else
  tempix=tempix+Hx4*term
  tempiy=tempiy+Hy4*term
endif

Figure 28. (Continued).
Figure 28. (Continued).
Figure 28. (Continued).
Figure 28. (Concluded).
fields at layer 1 at n=h1 & layer 4 at n=h4

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

integer*4 n
real*4  kx,ky,kx1,kx2,kx3,kx4,term1,term2
complex*16 x,b,c,kx2(2),kx(2),R(2),Q(2)
complex*16 B,T,0,VI,V2
complex*16 temp,IIIx(2),IIIy(2),IIIz(2)
complex*16 IIIx(2)
complex*16 Igx,igy,IGx,IGy,IGz
complex*16 IIx(2),IIyo(2),IIso(2),IIx1(2),IIyl(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=1.e-6
else
kx=n*dx
endif

X=dcmplx(kx*kx/kx/u2y*ky*ky/u2x, -(w-ky*v)*ss)
b=dcmplx(-(sx/ss+u2z/u2x)*kx-(sy/ss+u2y/u2z)*ky*ky,
  2*(w-ky*v)*(sx*u2y+sy*u2x))
c=(u2x*u2y*x/(u2z*ss))*dcmplx((kx*ky*ky)*ss,
  2
  -(w-ky*v)*sy*u2z)
kx2(1)+.5*(-b+cdxqrt(b*b-4.*c))
kx2(2)+.5*(-b-cdxqrt(b*b-4.*c))
kx(1)+cdxqrt(kx2(1))
kx(2)=cdxqrt(kx2(2))
kx=cdxqrt(kx*ky+kx)
kx1=cdxqrt((u1x/u1a)*kx+kx+(u1y/u1a)*hy*ky)
kx2=cdxqrt((u4x/u4a)*kx+kx+(u4y/u4a)*hy*ky)

R(1)=( u2x*u2y*x*(u3y*ky*ky-u3s*ks2(1))-
  i*(w-ky*v)*sz*su2y*su2z)
  2
R(1)=R(1)/( u2x*u2y*x*(u3y*ky+i*kx*sz*su2y*su2z)*)
  2
R(2)=( u2x*u2y*x*(u3y*ky*ky-u3s*ks2(2))-
  i*(w-ky*v)*sz*su2y*su2z)
  2
R(2)=R(2)/( u2x*u2y*x*(u3y*ky+i*kx*sz*su2y*su2z)*)
  2
Q(1)=kx1*(i*u2x*kx+(i*ky-v*u2x*ax)*u2y*R(1)) /
  2
  (u2x*u2y*x)
Q(2)=kx2*(i*u2x*kx+(i*ky-v*u2x*ax)*u2y*R(2)) /
  2
  (u2x*u2y*x)

S=(Q(1)*(1.-ky*v+w)+ks1)*v*R(1)/(ks1) /
  2
(Q(2)*(1.-ky*v+w)+ks2)*v*R(2)/(ks2) /
  2
T< csinh(kx1)*h2>
  2
  (i*ky*Q(1)-kx1*R1)+S*(i*ky*Q(2)-kx2*R2))-
  2
  (u2x*ks1/(u1*ks1))**(kx*R1-kx1)*
  2
  (ccosh(kx1)*h2)-ccosh(kx2)*h2))
T=T*/ (1./S)*csinh(kx2)*h2>
  2
  (i*ky*Q(1)-kx2*R1)+S*(i*ky*Q(2)-kx2*R2))*
  2
  (u2x*ks1/(u1*ks1))**(kx*R1-kx2)*
  2
  (ccosh(kx1)*h2)-ccosh(kx2)*h2))

Figure 29. List of the subroutine "field6.for."
\[
U = \frac{(T/S)\text{csinh}(ks(2)^2h2) - \text{csinh}(ks(1)^2h2)}{(ccosh(ks(1)^2h2) - \text{ccosh}(ks(2)^2h2))} \\
V1 = (i*ks/(w*ks3)) \ast (kx*R(1)-ky) \ast (ccosh(ks(1)^2h2) + U \ast \text{csinh}(ks(1)^2h2)) + \\
V2 = (i*ks/(w*u2y*ky)) \ast (kx*R(2)-ky) \ast (T*ccosh(ks(2)^2h2) + S* \text{csinh}(ks(2)^2h2)) \\
\text{temp} = (V1 + V2)/(V1 - V2) \ast \text{dexp}(-2.*ks3*h3) \\
IIIx(2) = (u4z*ks4*K3 + (V1*K2/(V1 - V2)) \ast \text{dexp}(-ks3*h3) \ast \\
\text{temp} = (dexp(ks3*h3) \ast (u4z/u0) \ast (ky*ks4/kx) \ast (1. - \text{temp}) + \\
\text{temp} = (ky*ks3/kx) \ast (1. + \text{temp})) \\
IIIx(1) = (2. \ast IIIx(2) + u0*ks*K2/ky)/(V1 - V2) \\
IIIx(1) = u0*ks*K2/(2. * ky) - (V1 + V2) \ast IIIx(1)/2. \\
IIIx(1) = S*IIIx(1) \\
IIIx(2) = T*IIIx(1) \\
IIIx0(1) = U*IIIx(1) \\
IIIx0(2) = S*IIIx0(1) \\
IIIx0(2) = Q(2) \ast IIIx0(2) \\
IIIx0(1) = Q(1) \ast IIIx0(1) \\
IIIx(2) = Q(2) \ast IIIx(1) \\
III(1) = Q(1) \ast IIIx(1) \\
IIIy(2) = R(2) \ast IIIx(2) \\
IIIy(1) = R(1) \ast IIIx(1) \\
IIIy(2) = R(2) \ast IIIx(2) \\
IIIy(1) = R(1) \ast IIIx(1) \\
IIIy(1) = (ky/kx) \ast IIIx(1) \\
IIIy(2) = (ky/kx) \ast IIIx(2) \\
IIIz(1) = (i*ks3/kx) \ast IIIx(1) \\
IIIz(2) = (-i*ks3/kx) \ast IIIx(2)
if (e.lt.0.) then
  Ix=(i*ux*ux/(w*kz1*ux))
  2  (((ux*R(1)-ky)*IIx1(1)+(ux*R(2)-ky)*IIx1(2))
  Iy=(ux*R(0)/ux)*Ix
  iz=-i*ux*ux/ux)*Ix

  term1=exp(kz1*hl)
  Bx1=Ix*term1
  By1=Iy*term1
  Bz1=Iz*term1
else
  IVx=(-ux*ux/ky)*exp(kz1*hl)
  2  (K3+K2*exp(kz1*hl)*V1/(V1-V2)-
  2  (1./uc)*(ky/kz)*exp(kz1*hl)*(1-temp)*IIx1(2))
  IVy=(ux*ky/(ux*ux))*IVx
  IVz=(i*ux*ux/ux)*IVx

  term4=exp(-kz1*(h1-h2))
  Bx4=IVx*term4
  By4=IVy*term4
  Bz4=IVz*term4
endif
return
end

Figure 29. (Concluded).
subroutine source(n, ky)
    include 'ahcoaS .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)

end subroutine source

Figure 30. List of the subroutine "source6.for."
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."
shcom6.for

common variables share by shield, field, source, swap

implicit none

integer*2    case
double precision     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 /e/    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 ν 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/I₀, 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.
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 : 1.06

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


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

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>CODED SYMBOL</th>
<th>DEFINITION</th>
<th>UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mu_{ij}, i = 1,2,4, j = x,y,z)</td>
<td>(uij)</td>
<td>permeability of the (j)-th component in the (i)-th layer</td>
<td>henry/m</td>
</tr>
<tr>
<td>(\mu_{rij}, i = 1,2,4, j = x,y,z)</td>
<td>(urij)</td>
<td>relative permeability of the (j)-th component in the (i)-th layer</td>
<td>unitless</td>
</tr>
<tr>
<td>(\mu_o(=\mu_{ij}/\mu_{rij}))</td>
<td>(uo)</td>
<td>free space permeability</td>
<td>henry/m</td>
</tr>
<tr>
<td>(\sigma_j (j=x,y,z))</td>
<td>(sj)</td>
<td>conductivity of the (j)-th component in the 2nd layer</td>
<td>S/m</td>
</tr>
<tr>
<td>(F_j, j=x,y,z)</td>
<td>(Fj)</td>
<td>force in the (j)-th direction</td>
<td>newton</td>
</tr>
<tr>
<td>(k_{yo})</td>
<td>(k_yo3)</td>
<td>wavenumber of the traveling wave source (at the interface of layers 3 &amp; 4)</td>
<td>1/m</td>
</tr>
<tr>
<td>(\omega (=2\pi f))</td>
<td>(w)</td>
<td>radian frequency of the source</td>
<td>radian</td>
</tr>
<tr>
<td>(v)</td>
<td>(v)</td>
<td>velocity of the vehicle</td>
<td>m/s</td>
</tr>
<tr>
<td>(h_2)</td>
<td>(h2)</td>
<td>thickness of layer 2</td>
<td>m</td>
</tr>
<tr>
<td>(h_3)</td>
<td>(h3)</td>
<td>gap width</td>
<td>m</td>
</tr>
<tr>
<td>(b(3) [b_2]^{**})</td>
<td>(b_3, b_2)</td>
<td>longitudinal (in the traveling (y-) direction) dimensions of the sources at interfaces of layers 3,4 [layers 2,3]</td>
<td>m</td>
</tr>
<tr>
<td>(a(3) [a_2])</td>
<td>(a_3, a_2)</td>
<td>transverse (x-) dimensions of the sources at interfaces of layers 3,4 [layers 2,3]</td>
<td>m</td>
</tr>
</tbody>
</table>

*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*

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

*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*

<table>
<thead>
<tr>
<th>VARIABLE (&amp; CODED SYMBOL)</th>
<th>DEFINITION</th>
<th>UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>b₃₁ [b₃₂]**</td>
<td>longitudinal (y-) dimensions of the primary source [the shielding loop]</td>
<td>m</td>
</tr>
<tr>
<td>a₃₁ [a₃₂]</td>
<td>transverse (x-) dimensions of the primary source [the shielding loop]</td>
<td>m</td>
</tr>
<tr>
<td>shift₂</td>
<td>longitudinal (y-) coordinate of the center of the shielding loop (center of the primary source is the origin)</td>
<td>m</td>
</tr>
<tr>
<td>ax₃₂</td>
<td>transverse (x-) coordinate of the edge of the shielding loop 1</td>
<td>m</td>
</tr>
<tr>
<td>(ax₃₁=0.5 · a₃₁)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>curr₂</td>
<td>amperse-turn of the shielding loop</td>
<td>amp-turn</td>
</tr>
<tr>
<td>(curr₁=1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>h₃₁ [h₃₂]</td>
<td>heights of the primary source [the shielding loop] from the shielding layer</td>
<td>m</td>
</tr>
</tbody>
</table>

*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 [ ].