Fundamental electrophysics and engineering design of MAGLEV vehicles

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Gravity

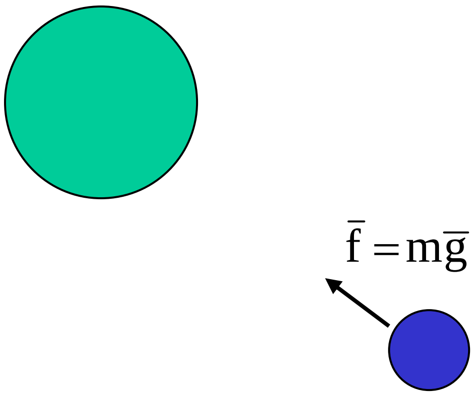
Mass

↓

Gravity field

↓

Force on another mass



Electricity

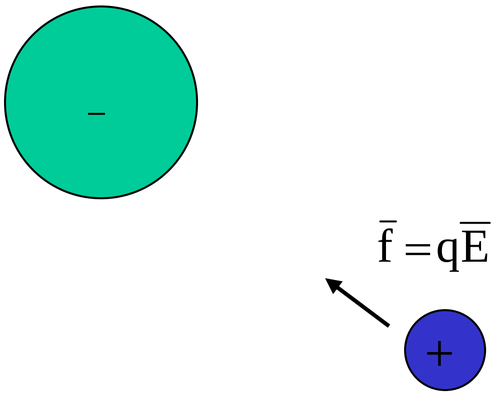
Charge

↓

Electric field

↓

Force on another charge



Magnetism

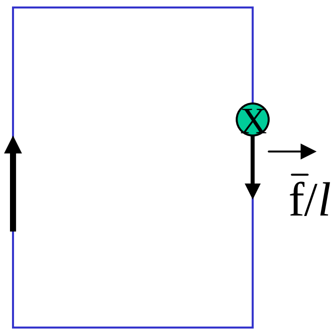
Current

↓

Magnetic field

↓

Force on another
Current segment



$$\bar{f}/l = \bar{i} \times \bar{B}$$

Magnetism (microscopic)

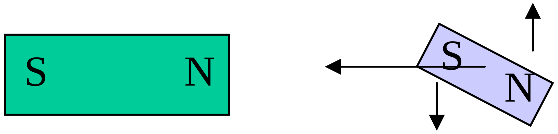
Microscopic current loops

↓

Magnetic field

↓

Force on other Microscopic current loops



Macroscopic description of assembly of microscopic forces:

Net force: opposite poles attract, same poles repel.

Torque: aligns to imposed field.

Sources –> Fields

Charge –> Electric field

$$\rho = div(\varepsilon_0 \overline{E})$$

Current –> Magnetic field

$$\overline{J} = curl(\frac{\overline{B}}{\mu_0})$$

Sources –> Fields

(the whole story, including time varying fields as sources of fields)

Maxwell's Equations

$$\rho = div(\varepsilon_0 \overline{E})$$

$$\overline{J} + \varepsilon_0 \frac{\partial \overline{E}}{\partial t} = curl(\frac{\overline{B}}{\mu_0})$$

$$0 = div(\overline{B})$$

$$-\frac{\partial \overline{B}}{\partial t} = curl(\overline{E})$$

Electromagnetic Waves

Even in a vacuum, where $\rho = 0$ and $\overline{J} = 0$:

$$0 = div(\varepsilon_0 \overline{E})$$

$$\varepsilon_0 \frac{\partial \overline{E}}{\partial t} = curl\left(\frac{\overline{B}}{\mu_0}\right)$$

$$0 = div(\overline{B})$$

$$-\frac{\partial \overline{B}}{\partial t} = curl(\overline{E})$$

Electromagnetic Waves

(continued)

$$\varepsilon_0 \frac{\partial \overline{E}}{\partial t} = curl(\frac{\overline{B}}{\mu_0})$$

$$-\frac{\partial \overline{B}}{\partial t} = curl(\overline{E})$$

$$\varepsilon_0 = 8.854 \text{ X} 10^{-12} \frac{\text{Farad}}{\text{m}} \qquad (\rho \rightarrow \overline{E})$$

$$\mu_0 = 1.257 \text{ X} 10^{-6} \frac{\text{Henry}}{\text{m}} \qquad (\overline{J} \rightarrow \overline{B})$$

$$\frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 3.00 \text{ X } 10^8 \text{m/s} = \text{c} = \text{speed of light in vacuum}$$

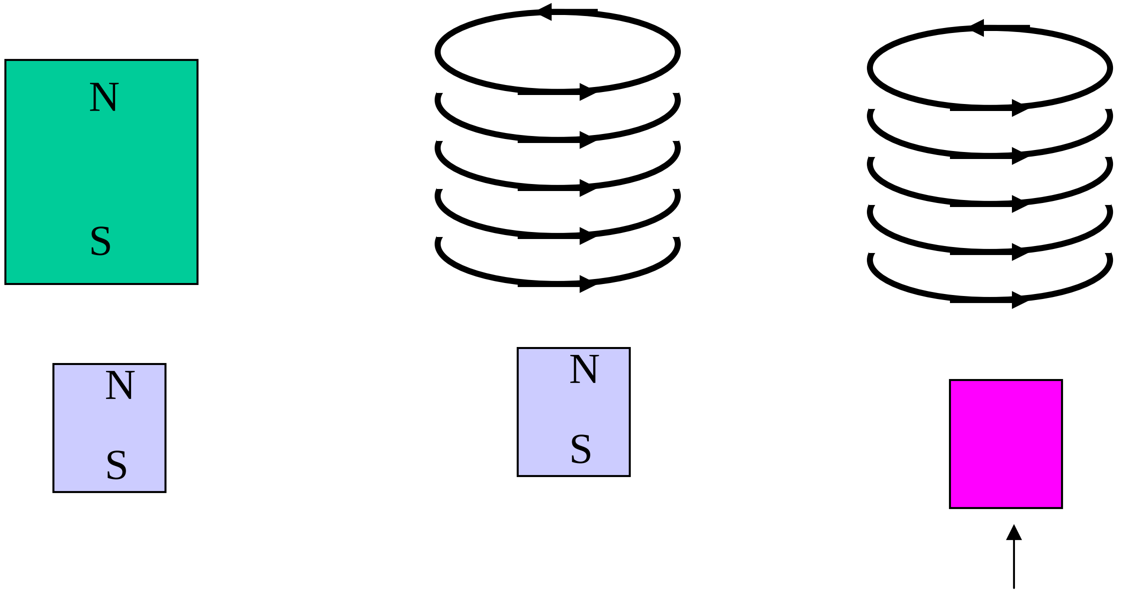
What does this have to do with MAGLEV?

Same fundamental physics describes:

- Light, lasers, X-rays, … (electromagnetic spectrum, why is the sky blue?)
- Wireless communications (radio, TV, cell phones, wireless computers, …)
- Integrated circuits (computer chips)
- Lightning
- Electrostatic precipitation
- Electrophotography & laser printers
- Microelectromechanical systems (MEMS)
- Magnetic memory (tapes, disks, MRAM, magnetic stripes, …)
- Rotating electrical machinery (generators & motors)
- Linear synchronous motor (LSM)
- Magnetic confinement for nuclear fusion
- MAGLEV

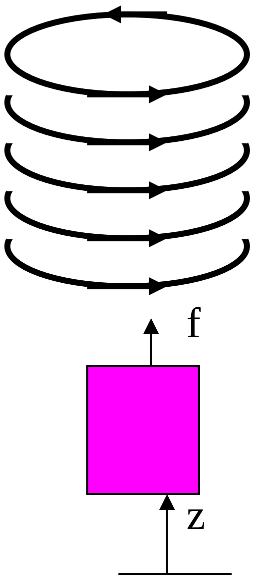
Attractive magnetic levitation:

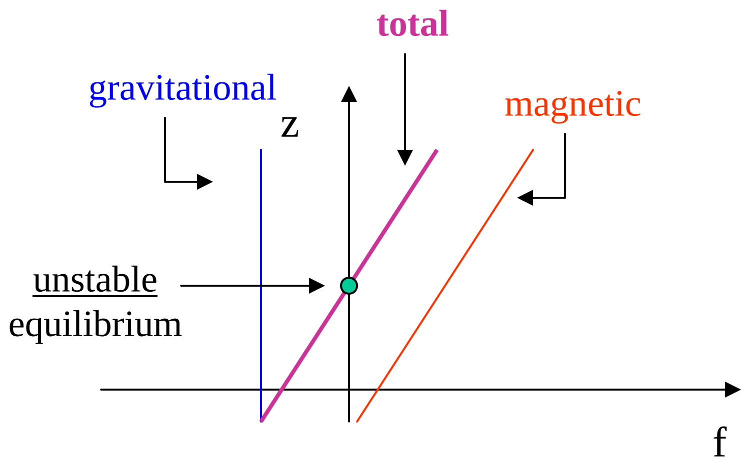
"Electromagnetic levitation"



ferromagnetic material,
e.g. steel:
induced magnetization

Attractive magnetic levitation:

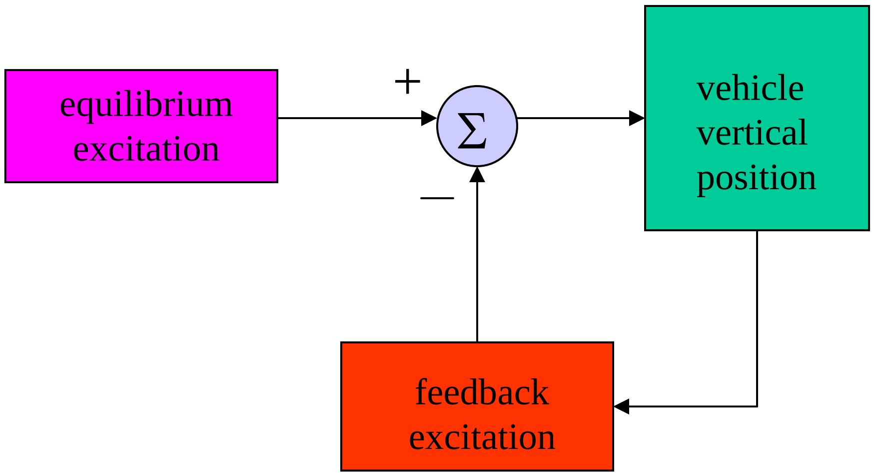




(inherently unstable)

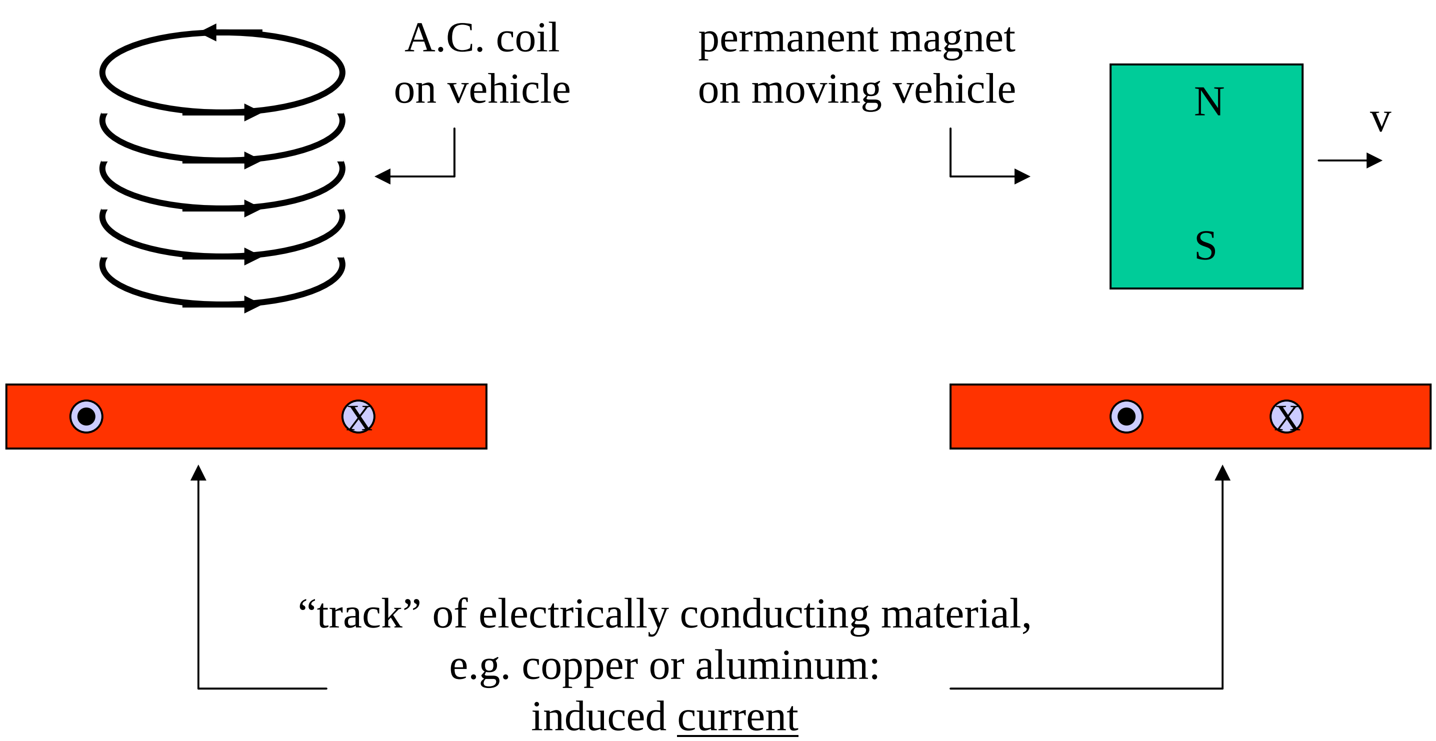
Attractive magnetic levitation:

requires feedback control system to stabilize



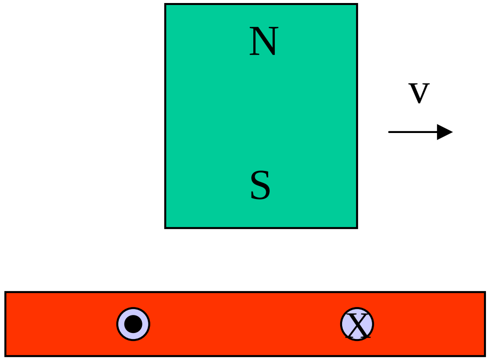
Repulsive magnetic levitation:

"Electrodynamic levitation"



Repulsive magnetic levitation:

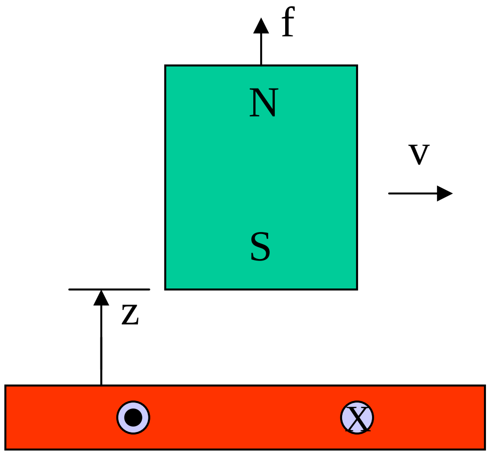
This interaction involves an induced electric field in the conducting material, caused by a time-varying imposed magnetic field.

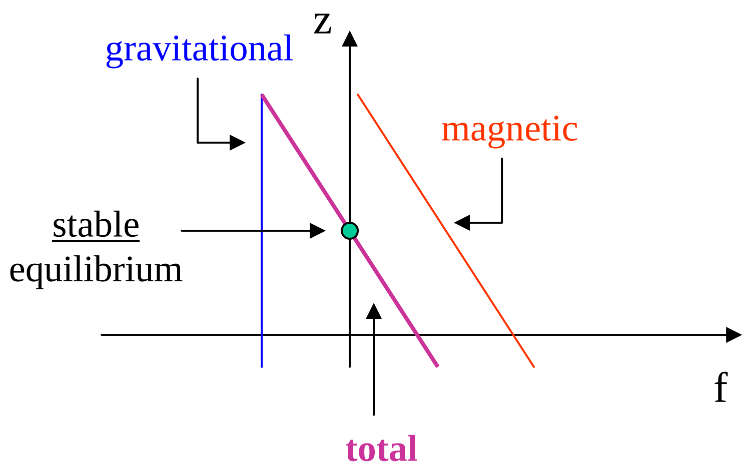


$$-\frac{\partial \overline{B}}{\partial t} = curl(\overline{E})$$

$$\overline{J} = \sigma \overline{E}$$

Repulsive magnetic levitation:

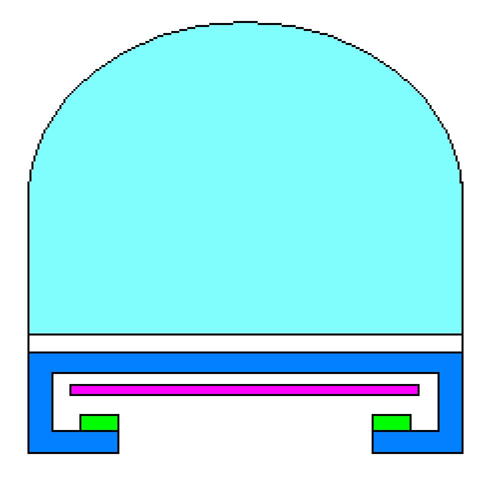




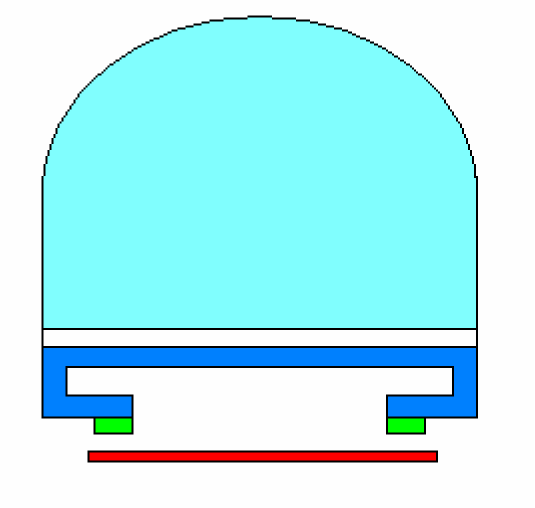
(inherently stable:
no feedback control system needed)

Either mechanism can be used to levitate a vehicle

- Attractive levitation



- Repulsive levitation



High speed (~ 450 km/hr) MAGLEV systems:

- German Transrapid:
  - Attractive (“electromagnetic”) levitation via conventional electromagnets
  - LSM propulsion

- Japanese MLX:
  - Repulsive (“electrodynamic”) levitation via superconducting magnets (on-board cryogenics)
  - LSM propulsion

Transrapid Test Vehicle TR-08

Germany, 1999

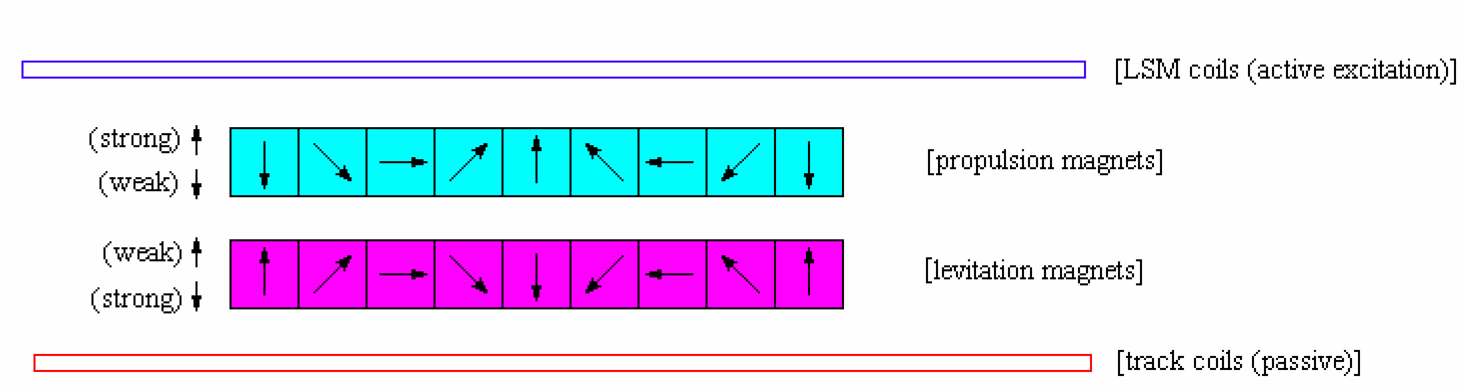
Null Flux Suspension Vehicle MLX01

Japan, 1997 (Yamanashi test facility)

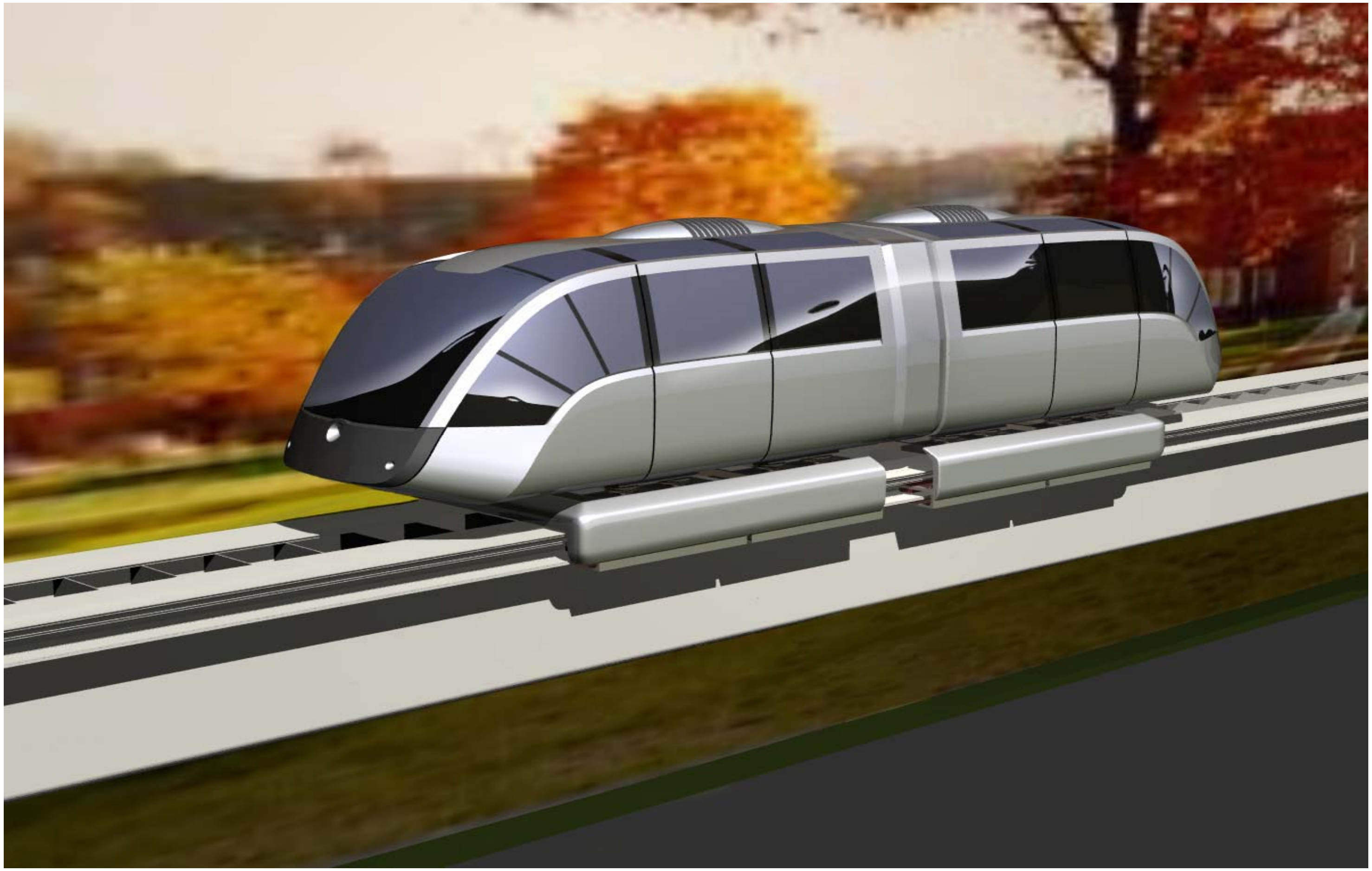
Low speed urban MAGLEV concept:

- Permanent (NdFeB) magnet arrays on vehicle:
  - Repulsive ("electrodynamic") levitation via induced currents in track coils
  - LSM propulsion

Halbach permanent magnet arrays



(Envisioned) Pittsburgh Urban Maglev vehicle

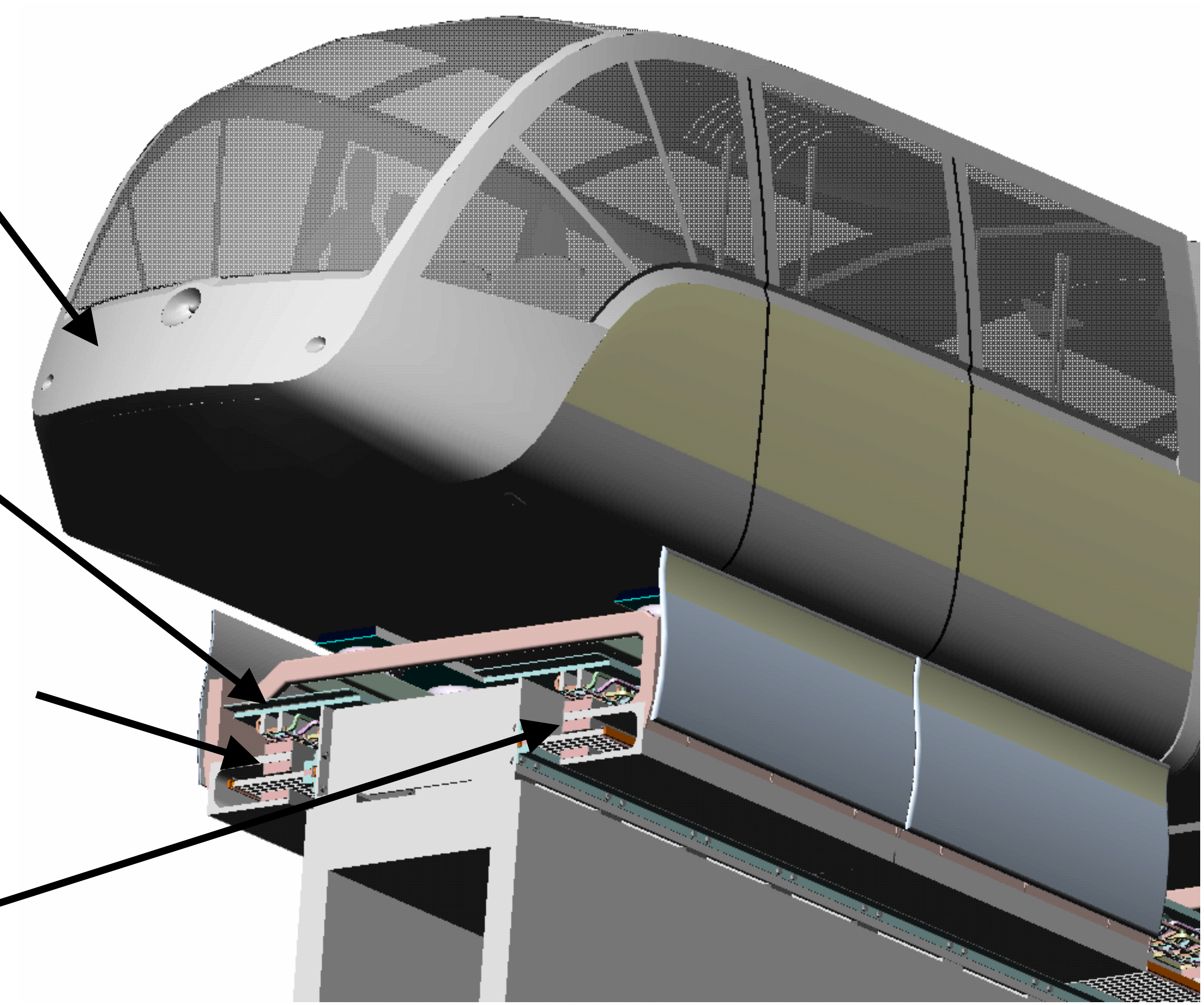


Vehicle on Guideway

Linear Synchronous Motor

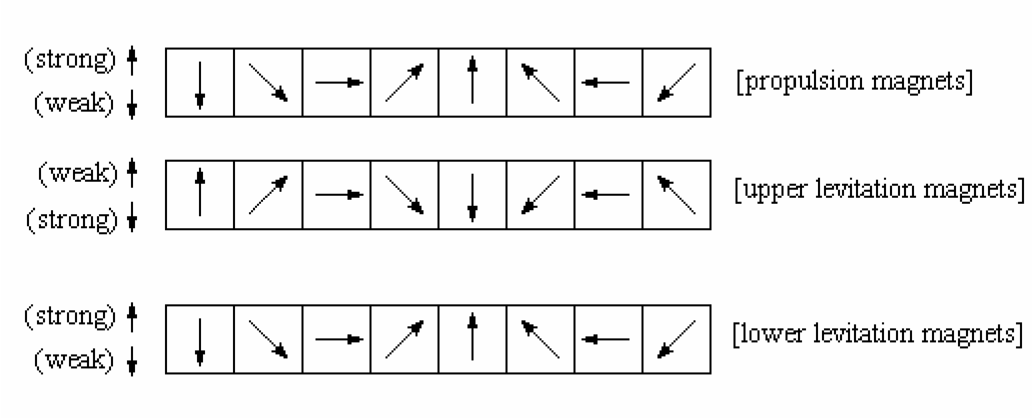
Suspension Track

Double Sided Magnet Array



Magnetic fields from known sources:

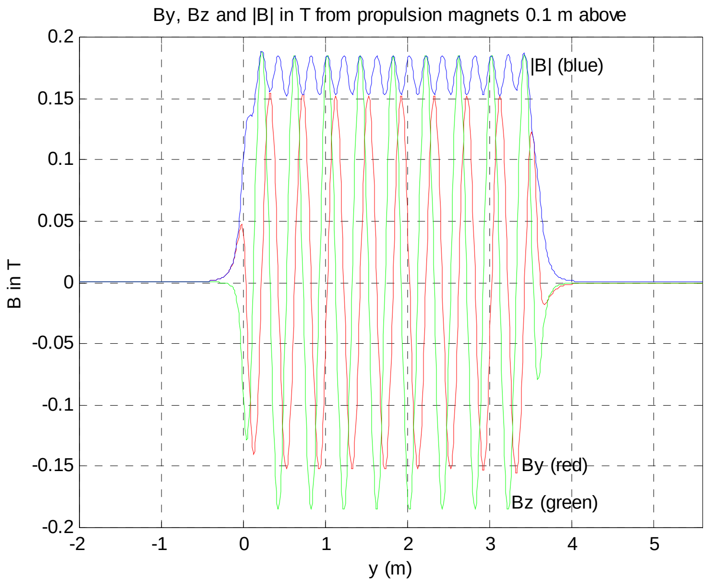
computing passenger compartment field levels



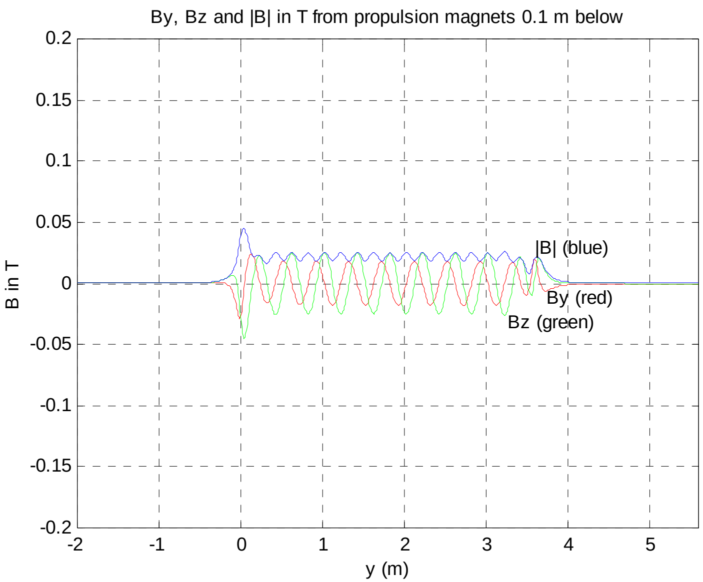
Halbach array fields: basic structure via magnetization charge description:

- **propulsion magnet near fields (0.1 m above & below):**

components & magnitude above



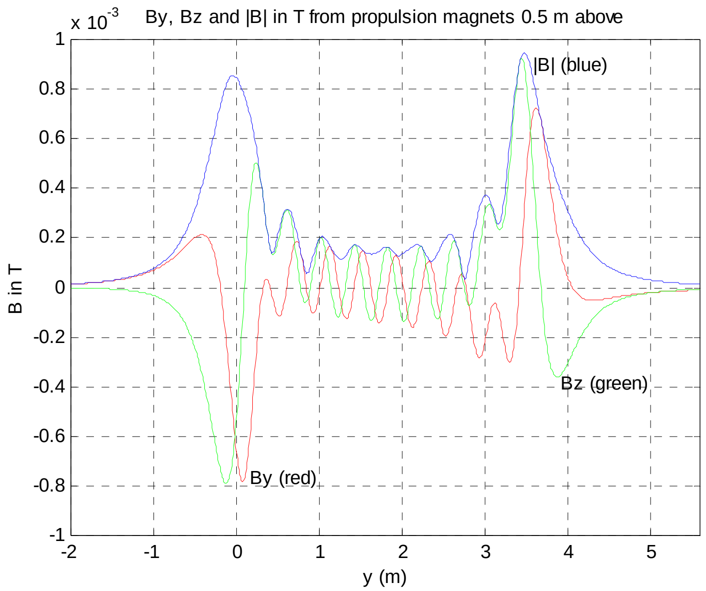
components & magnitude below



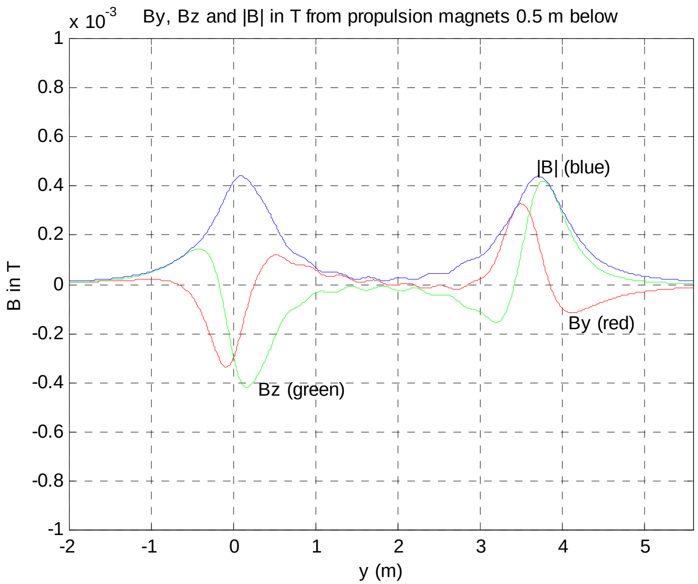
Halbach array fields: basic structure via magnetization charge description:

- **propulsion magnet far fields (0.5 m above & below):**

components & magnitude above



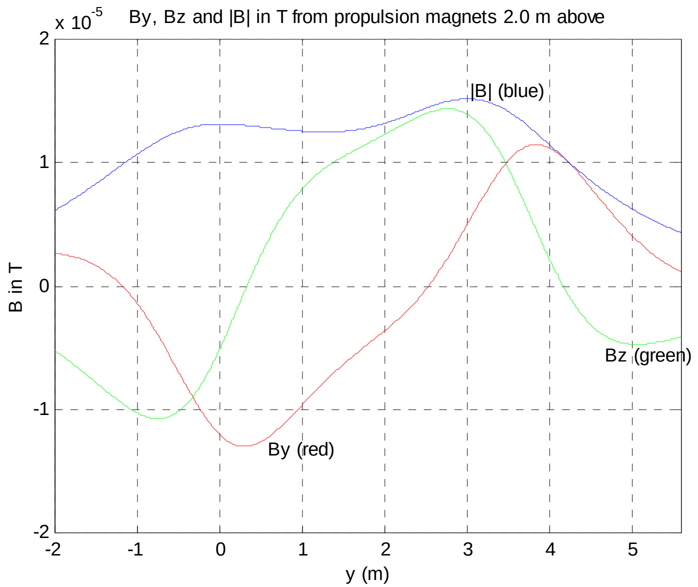
components & magnitude below



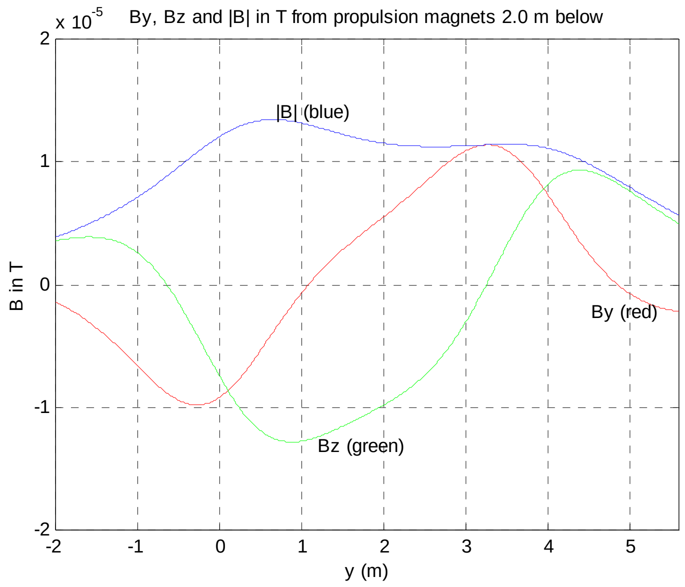
Halbach array fields: basic structure via magnetization charge description:

- **propulsion magnet very far fields (2.0 m above & below):**

components & magnitude above

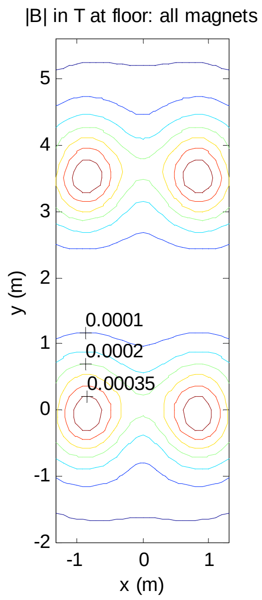


components & magnitude below

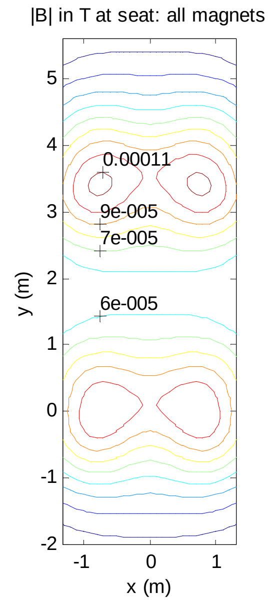


Fields in passenger compartment magnetization charge description:

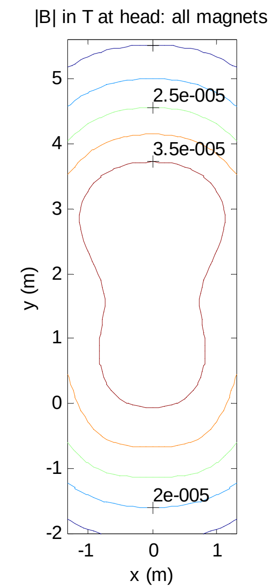
floor level contour plot



seat level contour plot

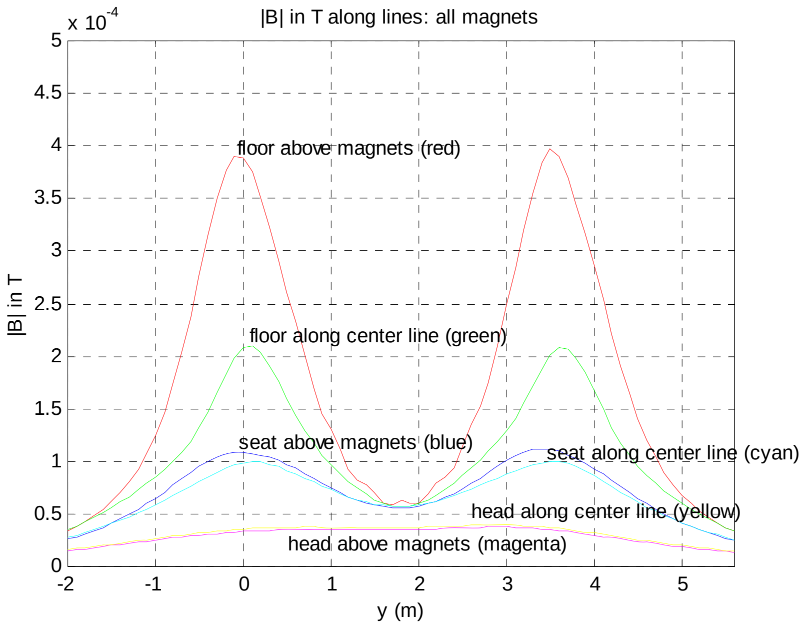


head level contour plot

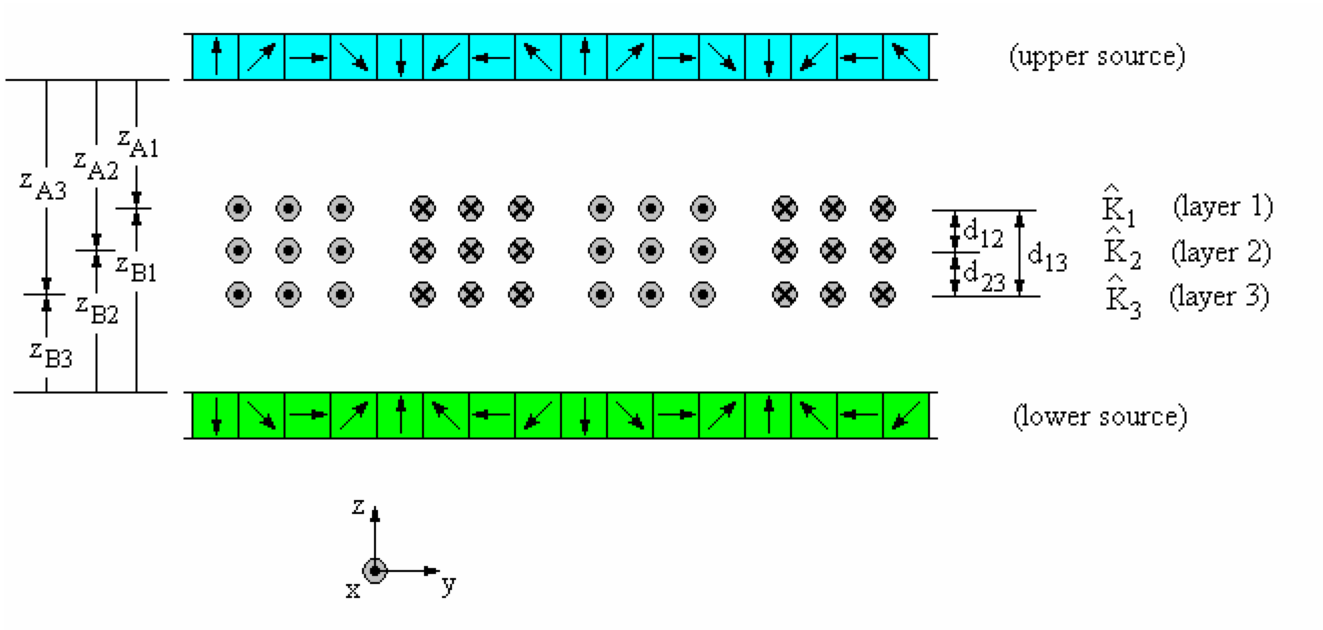


Fields in passenger compartment magnetization charge description:

line plots at floor, seat and head levels



Electromechanics: computing lift & drag versus velocity



Faraday's Law for rectangular contours in lamination planes: $\oint_C \overline{E} \bullet \overline{dl} = -\frac{d}{dt}\int_S \mu_0 \overline{H} \bullet \overline{n}\, da$

$$2\ell \hat{E}_x = -j\omega\left[\hat{\Lambda}_A + \hat{\Lambda}_B + p\left(\hat{\Lambda}_{self} + \sum \hat{\Lambda}_b + \sum \hat{\Lambda}_a\right)\right]$$

Electric field related to surface currents in lamination planes: $E_x = \frac{K_x}{\sigma\Delta}$

Time constant for induced currents: $\tau_m = \frac{\mu_0 \sigma \Delta \lambda}{4\pi}$

Driving frequency based upon vehicle velocity: $\omega = 2\pi \frac{v}{\lambda}$

All induced currents in laminations take the forms:

$$\overline{K} = \bar{i}_x \,\mathrm{Re}\left\{ \hat{K} \exp\left[j \frac{2\pi}{\lambda}(vt - y) \right] \right\}$$

Resultant fields (above and below) any one lamination are:

$$\hat{\overline{H}}_a(y,z) = \frac{\hat{K}}{2}\left[-\bar{i}_y + (j)\bar{i}_z \right] e^{-jky} e^{-kz}$$

$$\hat{\overline{H}}_b(y,z) = \frac{\hat{K}}{2}\left[+\bar{i}_y + (j)\bar{i}_z \right] e^{-jky} e^{+kz}$$

Simultaneous equations governing induced currents in laminations:

$$\begin{bmatrix} \left(1+\frac{1}{j\omega p\tau_m}\right) & e^{-kd_{12}} & e^{-kd_{13}} & \bullet\bullet\bullet \\ e^{-kd_{12}} & \left(1+\frac{1}{j\omega p\tau_m}\right) & e^{-kd_{23}} & \bullet\bullet\bullet \\ e^{-kd_{13}} & e^{-kd_{23}} & \left(1+\frac{1}{j\omega p\tau_m}\right) & \bullet\bullet\bullet \\ \bullet\bullet\bullet & \bullet\bullet\bullet & \bullet\bullet\bullet & \bullet\bullet\bullet \end{bmatrix} \begin{bmatrix} \hat{K}_1 \\ \hat{K}_2 \\ \hat{K}_3 \\ \bullet\bullet\bullet \end{bmatrix}$$

$$= \frac{j2}{p\ell} \begin{bmatrix} \int_{-\ell/2}^{\ell/2} \hat{H}_z^A(x, z_{A1})dx + \int_{-\ell/2}^{\ell/2} \hat{H}_z^B(x, z_{B1})dx \\ \int_{-\ell/2}^{\ell/2} \hat{H}_z^A(x, z_{A2})dx + \int_{-\ell/2}^{\ell/2} \hat{H}_z^B(x, z_{B2})dx \\ \int_{-\ell/2}^{\ell/2} \hat{H}_z^A(x, z_{A3})dx + \int_{-\ell/2}^{\ell/2} \hat{H}_z^B(x, z_{B3})dx \\ \bullet\bullet\bullet \end{bmatrix} \equiv \frac{j2}{p\ell} \begin{bmatrix} \hat{I}_z^1 \\ \hat{I}_z^2 \\ \hat{I}_z^3 \\ \bullet\bullet\bullet \end{bmatrix}$$

Time-averaged lift and drag forces (per wavelength) on vehicle:

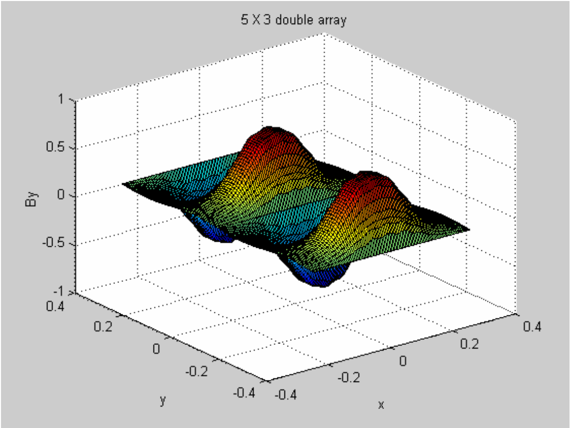
$$L_\lambda = -\frac{\mu_0 \lambda p}{2} \sum_i \operatorname{Re}\left\{ \int_{-\ell/2}^{\ell/2} \hat{K}_i^* \left[\hat{H}_y^A(x, z_{Ai}) + \hat{H}_y^B(x, z_{Bi}) \right] dx \right\} \equiv -\frac{\mu_0 \lambda p}{2} \sum_i \operatorname{Re}\left\{ \hat{K}_i^* \hat{I}_y^i \right\}$$

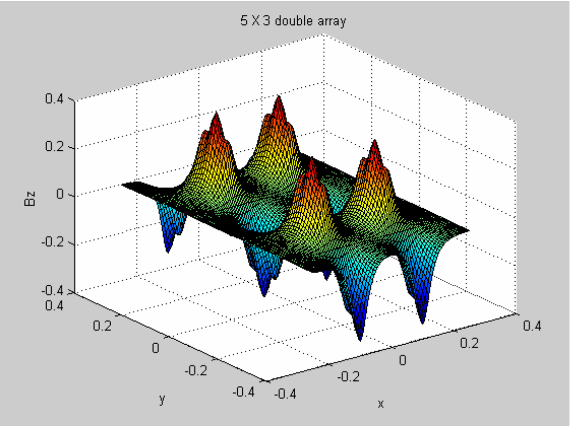
$$D_\lambda = -\frac{\mu_0 \lambda p}{2} \sum_i \operatorname{Re}\left\{ \int_{-\ell/2}^{\ell/2} \hat{K}_i^* \left[\hat{H}_z^A(x, z_{Ai}) + \hat{H}_z^B(x, z_{Bi}) \right] dx \right\} \equiv -\frac{\mu_0 \lambda p}{2} \sum_i \operatorname{Re}\left\{ \hat{K}_i^* \hat{I}_z^i \right\}$$

Horizontal (y) and vertical (z) field components are based upon 3-D magnetization charge description.

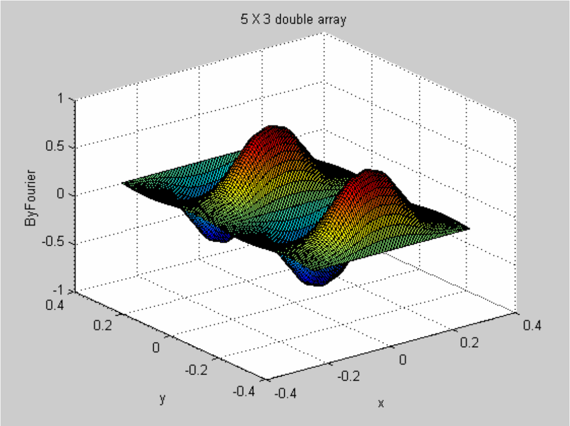
Complex amplitudes are based upon first Fourier components of y dependences at each value of x.

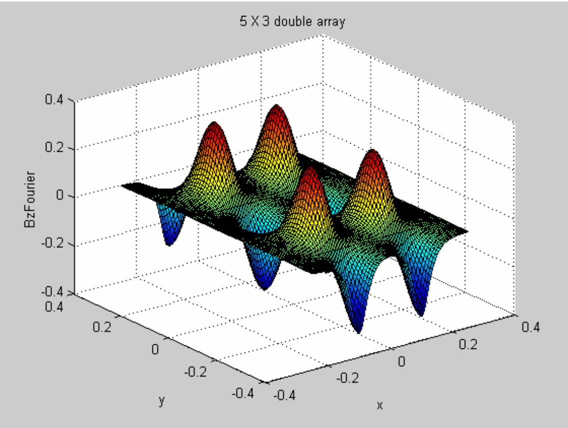
Double (5 above X 3 below) array
Full 3-D magnetization charge fields:





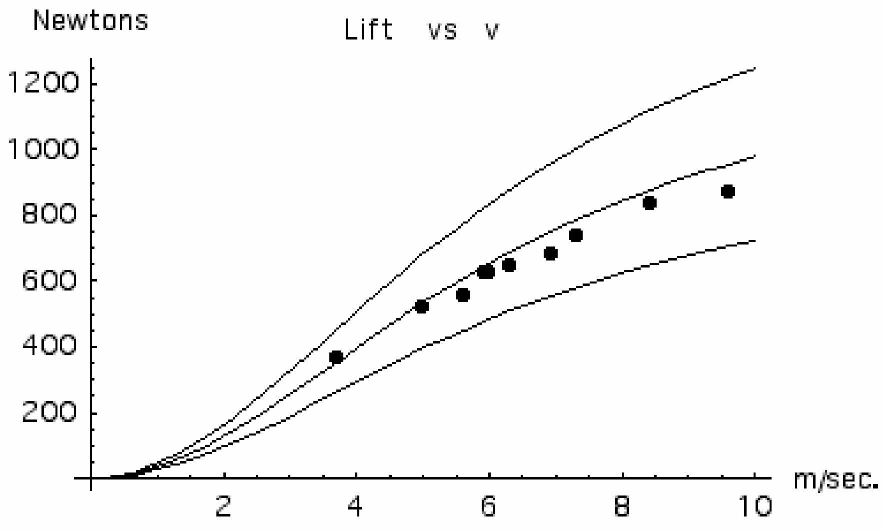
Double (5 above X 3 below) array
First Fourier component approximations:





Comparison with Dick Post's model for LLNL test rig

Post:



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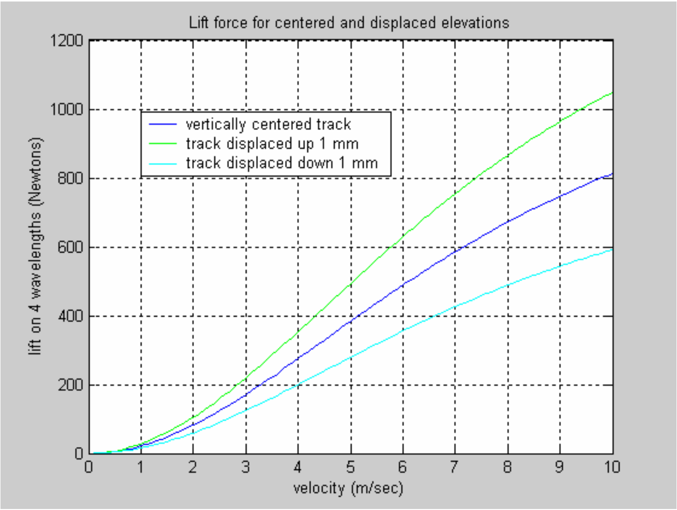

Comparison with Dick Post's model for LLNL test rig

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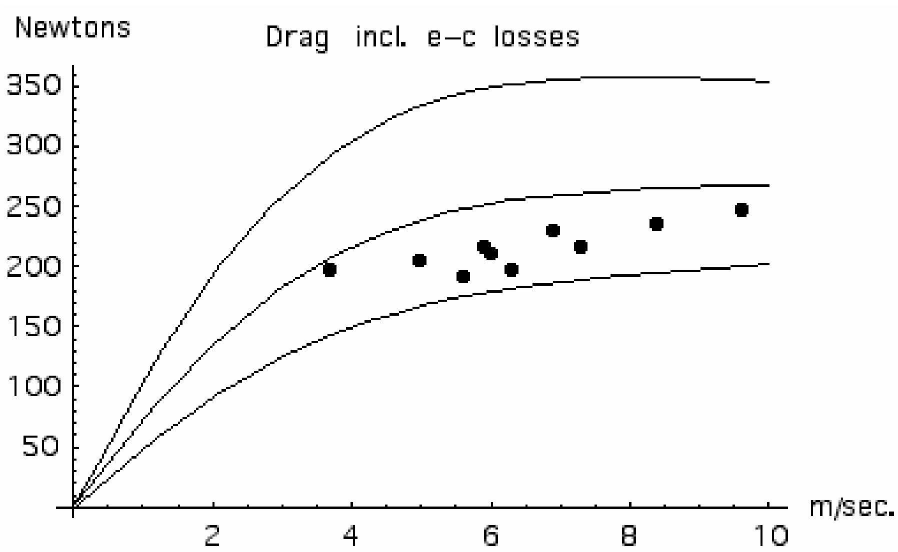

Hoburg: