Stable Levitation in Magnetic Bearings for Flywheel Energy Storage Systems

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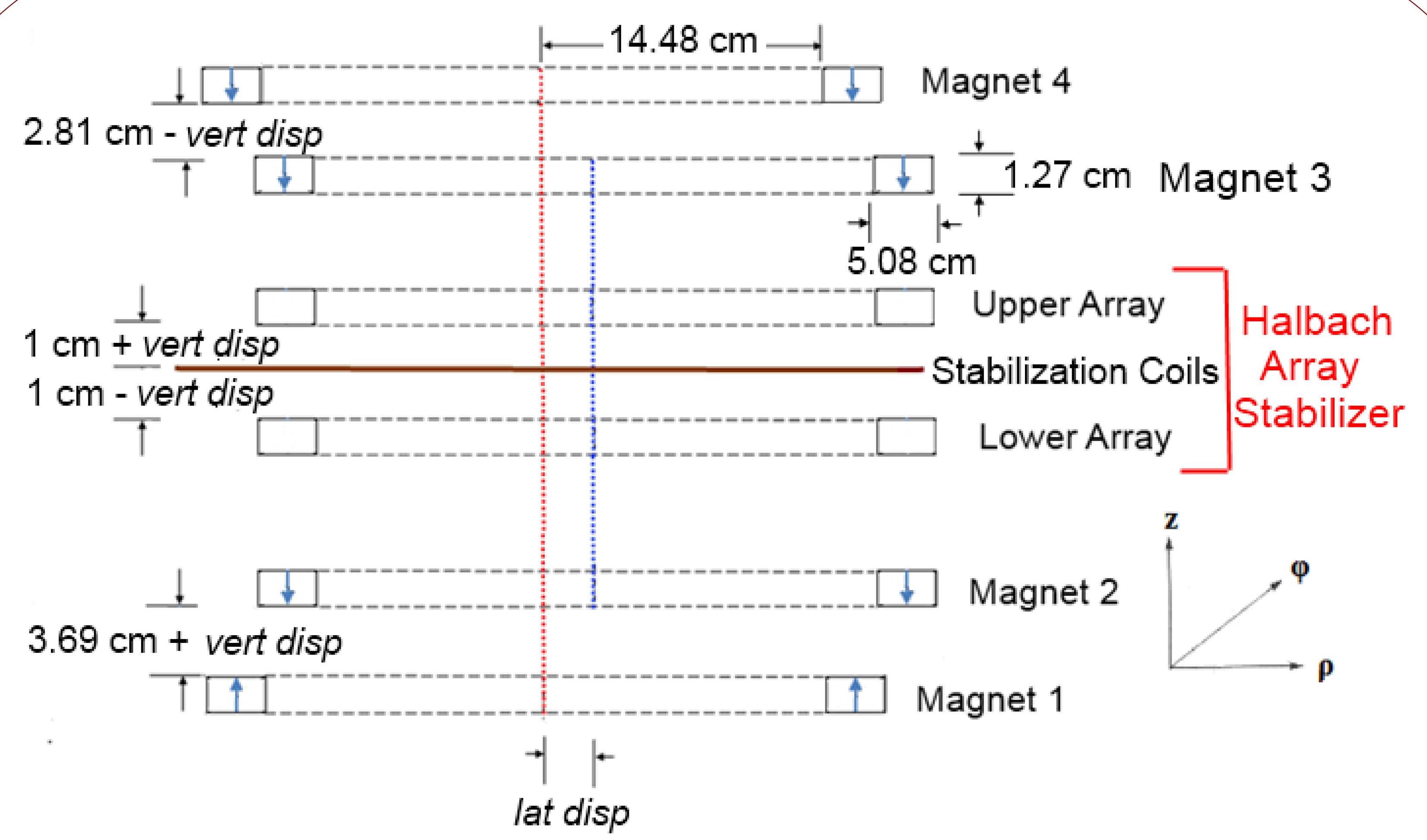
Motivation

- A flywheel energy storage system stores mechanical energy by accelerating a rotor, called the flywheel, to a very high speed.
- In order to decrease frictional energy losses, it is advantageous to use contactless magnetic bearings to levitate the rotor instead of conventional mechanical bearings.
- A significant challenge with magnetic bearings results from Earnshaw's Theorem, which states that it is impossible to stably levitate a rotor in all directions using only permanent magnets.
- However, by adding a Halbach array stabilizer, which induces currents in stabilization coils, to the levitation magnet system, this instability can be overcome.

The Main Idea



- The levitation magnet system is composed of Magnets 1-4. Magnets 1 and 4 are stationary while Magnets 2 and 3 are attached to the rotor.
- At the equilibrium position, the upper attracting magnets are positioned closer to each other than the lower repelling magnets in order to make the system stable to lateral displacements but unstable to vertical displacements.
- This vertical instability is addressed by adding a Halbach array stabilizer. The Halbach array stabilizer is composed of two stationary stabilization coils centered in the vertical direction between two rotating Halbach arrays.
- If the rotor is displaced from the equilibrium, the time-varying flux from the Halbach arrays induces a current in the coils. This current then interacts with the magnetic field of the arrays to provide a stabilizing force on the rotor in the vertical direction.

Procedure

- Magnetic fields from permanent magnets are calculated using superposition of fields due to patches of magnetization charge at the surfaces where the magnetization is discontinuous.

$$\vec{H} = \int_S \frac{\rho_{sm}}{4\pi\mu_0 R^2}\hat{a}_R ds$$

- Magnetic forces are computed using a superposition of forces on each patch of surface charge.

$$\vec{F}_{1on2} = \int_{S_2} \rho_{sm2}\vec{H}_1 ds$$

- The magnetic flux through the stabilization coils is computed by integrating the magnetic flux density from the Halbach arrays over the surface of the stabilization coils.

$$\lambda_{Arrays,\,Coil} = \int_{S_{Coil}} \vec{B}_{Arrays} \bullet d\vec{s}$$

- The induced currents in the coils are calculated by solving a system of two differential equations.

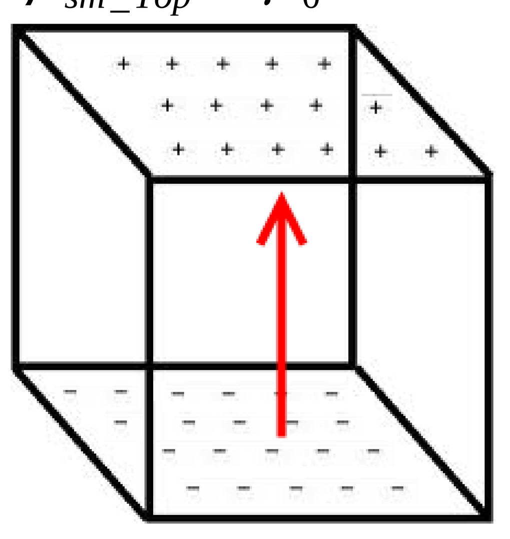
$$RI_1 + L\frac{dI_1}{dt} + M\frac{dI_2}{dt} = -\frac{d\lambda_{Arrays,Coil\,1}}{dt}$$

$$RI_2 + L\frac{dI_2}{dt} + M\frac{dI_1}{dt} = -\frac{d\lambda_{Arrays,Coil\,2}}{dt}$$

- The force on the rotor from the Halbach array stabilizer is computed using the Lorentz Force Law.

$$\vec{F}_{CoilOnArrays} = -\oint_{C_{Coil}} I_{Coil}\, d\vec{l} \times \vec{B}_{Arrays}$$

$$\rho_{sm\_Top} = \mu_0 M$$

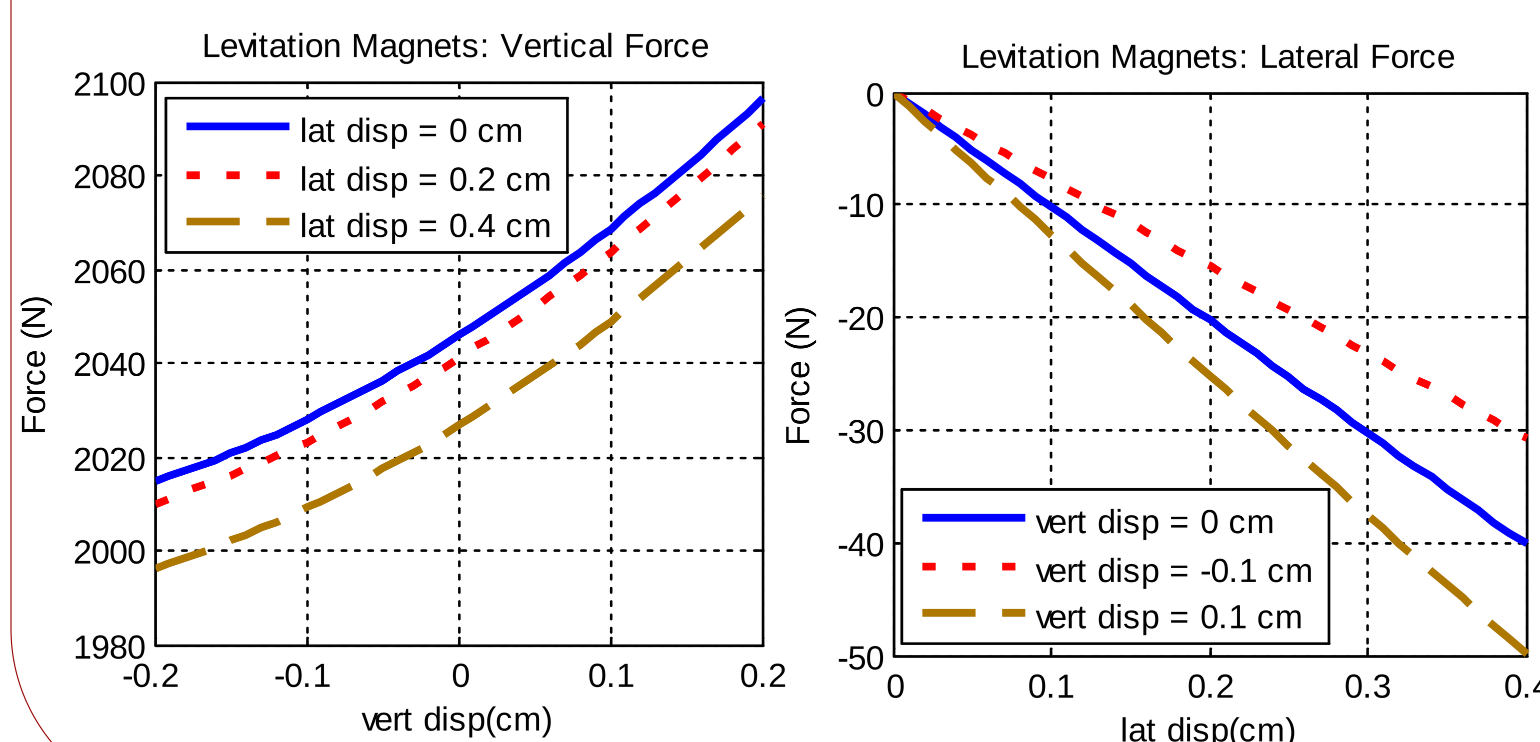


$$\rho_{sm\_Bottom} = -\mu_0 M$$

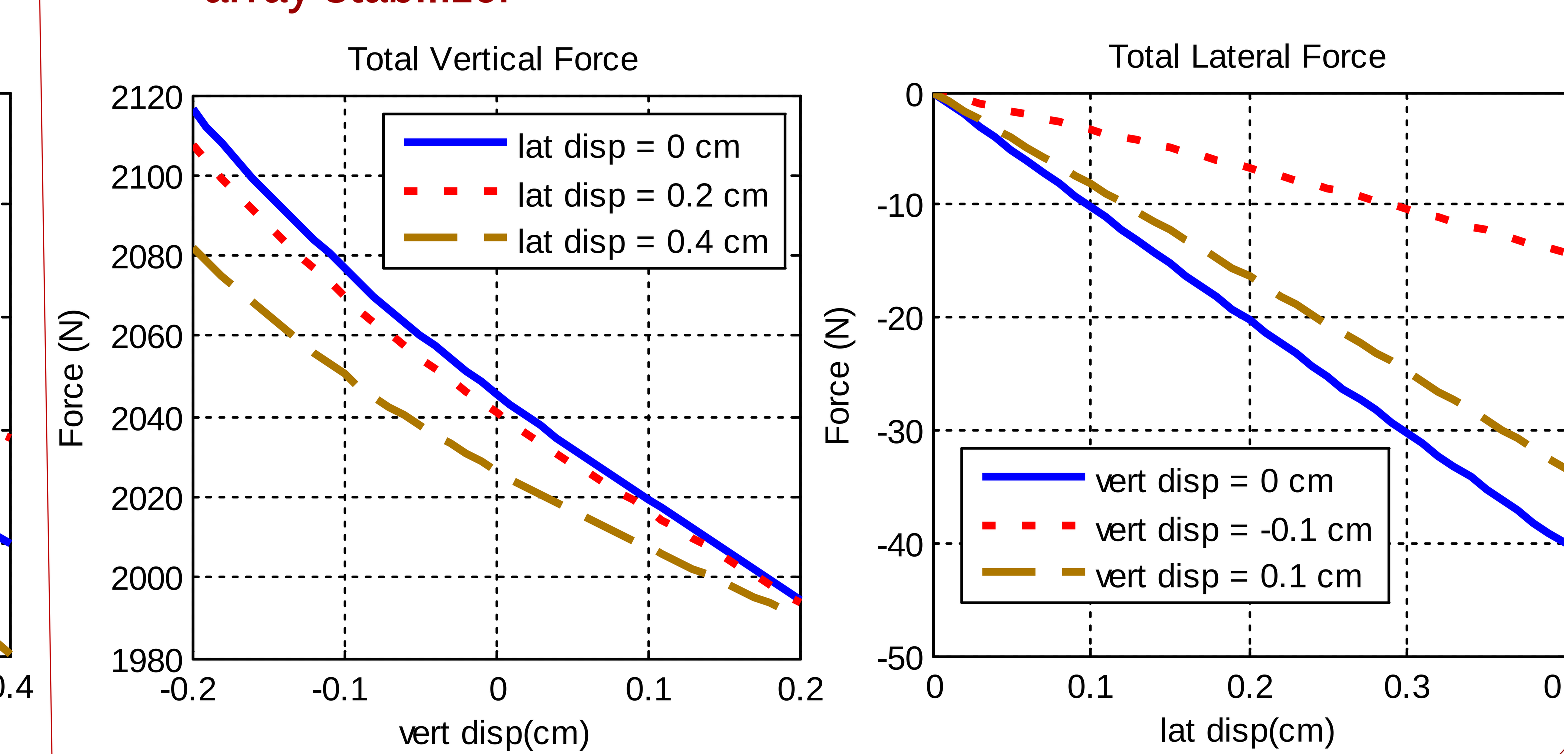
- Ex. A cube that is magnetized in the positive vertical direction can be modeled as a patch of positive magnetic charge on the top surface and a patch of negative magnetic charge on the bottom surface.

Simulation results

- Force plots for the levitation magnets only



- Force plots for the total magnetic bearing system, including both the levitation magnets and the Halbach array stabilizer



Conclusions & Future Work

Conclusions

- The levitation magnet system by itself is unstable to vertical rotor displacements, as the slope of the vertical force curve is positive.
- The total magnetic bearing system, including the levitation magnets and the Halbach array stabilizer, is stable to both lateral and vertical rotor displacements.

Future Work

- Analyze the tilt stability of the rotor
- Compute the drag torque on the rotor, which adds to the frictional losses of the system
- Consider advantages and disadvantages of alternative magnetic bearing designs

Acknowledgment

This work is supported by Lawrence Livermore National Laboratory.

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