Force and Torque Predictions in a Large-Gap Magnetic Suspension System

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INTRODUCTION: Wind tunnel Magnetic Suspension and Balance Systems (MSBS) are an example of “large-gap” suspensions, where a small ferromagnetic core is well separated from relatively large electromagnets producing the levitation fields[1]. The systems are open-loop unstable (require feedback control), so accurate prediction of forces and moments as a function of electromagnet currents is important.

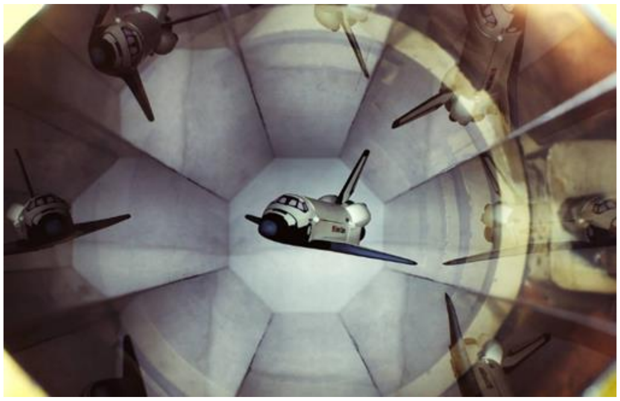


Figure 1. ODU/NASA “6-inch” MSBS

THEORETICAL BACKGROUND: The forces and moments on a permanent magnet can be derived from volume integrals, or by integrals of the Maxwell stress tensor over virtual or physical surfaces[2]. The latter technique must be applied with care as the integrand exhibits sharp peaks at physical corners but is more general.

$$\boldsymbol{F} = \mu_0 \iiint (\boldsymbol{M}.\nabla \boldsymbol{H})dV \;\; ; \;\; \boldsymbol{T} = \mu_0 \iiint (\boldsymbol{M} \times \boldsymbol{H})dV$$

$$d\boldsymbol{F}/_{dS} = -\frac{\mu_0}{2} \boldsymbol{H}^2 \hat{\boldsymbol{n}} + \mu_0 (\boldsymbol{H}.\hat{\boldsymbol{n}})\boldsymbol{H}$$

COMSOL’s formulation differs but is equivalent. The volume integrals can be evaluated from fields with the magnetic core removed. Virtual work methods cannot be used, since the system’s stored energy is very large, but the forces of interest are quite small[3].

COMPUTATIONAL METHODS: Calculations herein rely on the steady magnetic field interface (mf). The reference electromagnet geometry is depicted in Figures 2 & 3, with an example of fields and the distribution of Maxwell stress over a levitated core shown in Figure 4. The magnetization direction is vertical, and the applied fields produce a force in the x-direction, which is transverse to the cylinder axis. Improved accuracy appears possible by introduction of a control surface surrounding the core, a cube with sides 2 times the core diameter in this case.

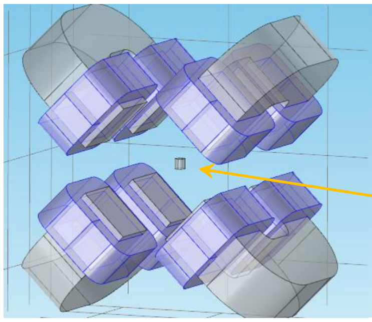


Figure 2. Electromagnet Assembly

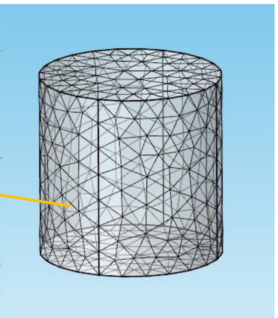


Figure 3. Magnet Surface Mesh

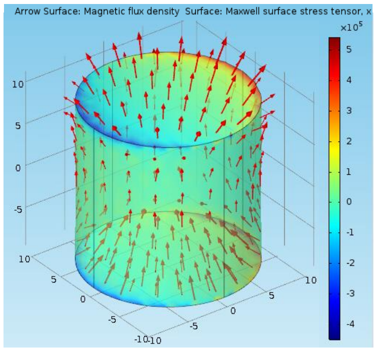
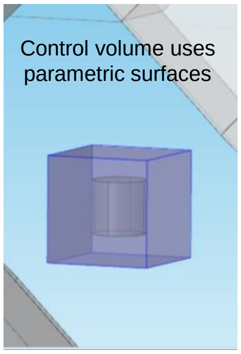


Figure 4. Field and Maxwell Stress Distribution over Magnetic Core



Control volume uses parametric surfaces

Figure 5. Control Volume (example - cube)

Case	Fx (N)
Analytic evaluation at centroid	24.870
Analytic evaluation, 2nd order integration	24.591
COMSOL fine grid (user-controlled, general physics)	24.213
Add boundary layer elements (4 layers)	25.118
Cubic control volume, L=2D	24.215

Table 1. Summary of Force Estimates

RESULTS: Scatter in results between different evaluations is of the order of ±2%, marginally inadequate for the current work. A more complete analysis will determine criteria for choice of grid refinement, control volume shape/size, etc.

CONCLUSIONS: Accurate force calculations for this type of configuration are challenging. Results are sensitive to grid refinement owing to the peaks of the Maxwell stress integrand at physical edges. Integration over surrounding control volumes may be superior. Best accuracy is a topic of further study.

REFERENCES:

1. Schoenenberger, M., et.al., Preliminary Aerodynamic Measurements from a Magnetic Suspension and Balance System in a Low-Speed Wind Tunnel, AIAA 2018-3323, June 2018
2. Ida, N., Bastos, J.P.A., Electromagnetics and Calculation of Fields, 2nd ed., Springer, 1997
3. COMSOL application gallery 20681, Electromagnetic Force Calculation Using Virtual Work and Maxwell Stress Tensor

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