Falling Slowly:
Understanding Magnetic Braking

BAMS project - Physics II / Electromagnetism

Abstract.

A magnet can fall slowly through a copper tube without touching its walls. In this project you will explain why and build a model that predicts its motion. Starting with one conducting ring, you will connect induction, currents, magnetic forces and energy transfer, then extend the model to a tube and study the effects of its material and shape.



One ring provides the building block for a tube; magnetic braking opposes the fall.

Prerequisites / Difficulty.

- Basic mechanics, derivatives and integrals of one variable. Simple differential equations can be learned during the project.
- Some Python is useful for the simulations, which form a central part of the project, and can be learned within the group.

Introductory, with possible extensions. Physics II is recommended but not necessary. Your first reading will introduce current, resistance, magnetic flux and induction.

What we will do.

1. Understand induction in one ring. Study Faraday's law, Lenz's law and Joule heating. Consider a magnet moving along a conducting ring's axis. How does the current change as it passes through? What changes if it moves faster or its poles are reversed? A useful starting model for the flux is

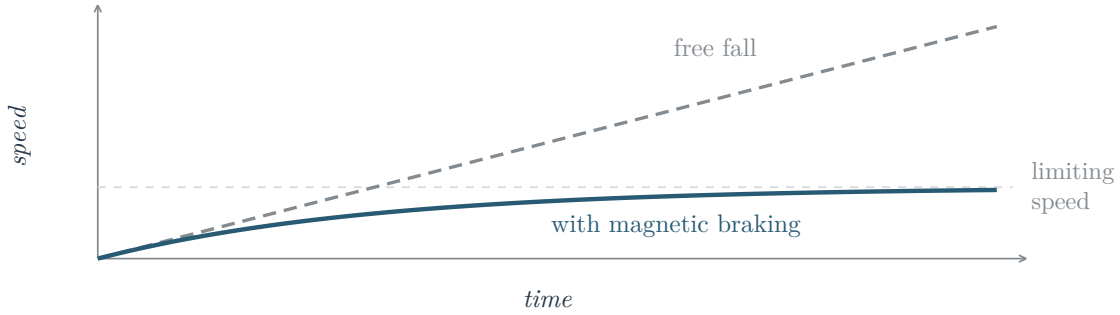
$$\Phi(z) = \Phi_0 \left(1 + \frac{z^2}{a^2}\right)^{-3/2},$$

where z is the magnet's signed distance from the ring plane, a is the ring radius and Φ_0 sets the flux scale. Begin with slow axial motion and negligible self-inductance.

2. Connect current, force and energy. Find the force on the magnet and explain where its lost mechanical energy goes. How does braking depend on speed, resistance and magnet strength? Use an energy balance to check your description.

3. Build a model of the tube. Treat a thin-walled tube as a collection of conducting rings. Relate their resistance to the material and geometry, then combine their effects. How do tube radius, wall thickness and conductivity affect braking? Compare a finite tube with the interior of a very long one, stating which quantities you keep fixed.

4. Simulate the falling motion. Build a numerical model using the magnetic force. Plot position and speed, and calculate the transit time. Does the magnet reach an approximately constant speed before leaving the tube? Compare your finite-tube model with a simpler model using linear drag. Use realistic parameters from the references, vary a physical parameter and explain how the motion changes. When is the simpler description accurate?



Qualitative speed curves for release from rest. The braking curve represents a long-tube model with linear drag.

Further directions.

The same model can be extended through the following questions:

- **Measuring conductivity.** Can a fall time reveal the tube's conductivity? What must you know about the magnet, and can different parameter choices give the same motion?
- **Two magnets.** Hold two magnets at a fixed separation with a non-magnetic support. Do they always fall more slowly than one? Study the effects of separation and orientation, accounting for both the field and the total mass.
- **Inductive effects.** Include self-inductance and stored magnetic energy. When is the instantaneous-current approximation reasonable? Can the ring briefly return energy to the magnet? Examine what changes at very low resistance.

Expected outcome.

Collect your model, calculations and simulations in an illustrated report and shared notebook. Connect the current pulse, magnetic force and falling motion. State the assumptions, explain the main parameter dependences through clear plots and compare predictions with the references or available measurements.

Starting materials.

Foundations. OpenStax, *University Physics*, vol. 2, sections 13.1, 13.2 and 13.5 on induction; sections 14.1, 14.3 and 14.4 for the extension to inductance and stored energy. Open textbook.

Main reference. G. Donoso, C. L. Ladera and P. Martín (2009), *Magnet fall inside a conductive pipe: motion and the role of the pipe wall thickness*, Eur. J. Phys. 30, 855-869. Use its model and figures to compare theory and experiment. Full text.

Extensions. Donoso et al. (2011), *Damped fall of magnets inside a conducting pipe*, for the two-magnet system. Article.

Conductivity. J. Íñiguez et al. (2004), *Study of the conductivity of a metallic tube by analysing the damped fall of a magnet*. Article.

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