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What type of levitation works best for levitating a broom from "Harry Potter"?

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Abstract
In this paper, the topic of levitation is discussed in the context of a broom's flight, and we ascertain which method would be most suitable for flight. Diamagnetism is the best effect to use as the internal field of the atoms and molecules within the diamagnetic material is lined up in opposition with an external field, this causes a repulsive force and if this repulsive force is strong enough then it leads to levitation. This investigation also advocates for active levitation as a method for controlling the magnetic force, and therefore the displacement of the broom.

Keywords: *Harry Potter; Magnetic levitation; Diamagnetism; Physics; Magic; Broomstick; Quidditch.*

Introduction
In "Harry Potter" [1], wizards play a game called Quidditch which uses flying brooms. Quidditch players use magic to control the brooms rather than conventional external control devices such as motors/engines. Levitation is a principle that requires the forces upon the levitating object to be balanced, which means the object requires an upward force to balance the weight exerted by the object on Earth [2]. An example of levitation in action is shown by the first functioning maglev train in 1984, where it was available for regular use by passengers [3]. Here's an example of what this principle looks like in action (figure 1):

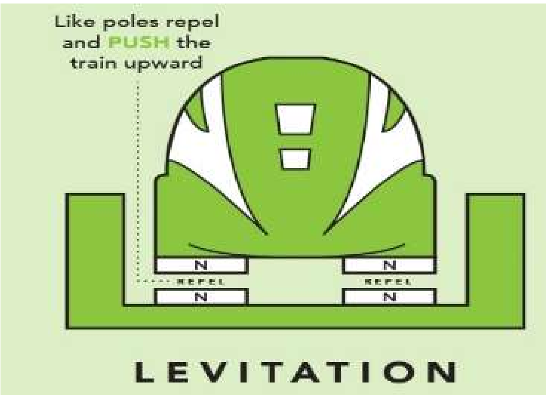

Figure 1 – Illustration of the principle of levitation where the poles are aligned, adapted from [3].

The original idea came about as an idea to impress an audience [4], and in the late 1960s James Powell and Gordon Danby used the principle of levitation to patent the first magnetically levitated train design [5]. We intend to use the principle of levitation to evaluate the feasibility of different methods of levitation to allow these brooms to fly. Magnetic levitation is used as magic isn't real and this would be the only way to allow flight without strapping an engine to the broom.

Key Concepts
Diamagnetism occurs when a magnetic field is applied to electrons, and they experience a Lorentz force which causes a current in the anticlockwise direction and a negative induced magnetic moment is produced [6]. The magnetic susceptibility is a value which shows the degree of magnetisation of a material when a magnetic field is applied [6]. Active levitation is a process where the displacement of the broom is actively manipulated to allow some control by the rider [7]. The magnetic flux density is the number of field lines passing through a unit area of material.

What is the most appropriate Diamagnetic material?
The applied magnetic field repels the diamagnetic material and if the repulsive force is strong enough then it leads to levitation. The ideal diamagnetic

material would be light enough so the gravitational force acting on the broom doesn't require a large magnetic force to counteract it, and the diamagnetic material should also have a low magnetic susceptibility. Pyrolytic graphite would be an ideal material for levitation, it has a magnetic susceptibility component, χ_z, of approximately -4.5×10^{-4} [8] (dimensionless quantity). This means the material shows strong directional diamagnetism which provides strong stability to freely levitating pyrolytic graphite [8].

There are several other advantages to using pyrolytic graphite [9]:

- Pyrolytic graphite levitation works at room temperatures with permanent magnets.
- Factors such as friction, stiffness changes, wear thermal expansion do not affect the overall measurement accuracy of the brooms flight.

Maintaining Stability of the Broom

For the broom to be stable in the magnetic field, a restoring force is usually required because it allows the broom to point back to its equilibrium position. A point charge in a field can be stable when at small displacements from the equilibrium if $U(x)$ (which is the potential as a function of displacement) is a local minimum at the equilibrium point [10]. Furthermore, diamagnetic materials can be stable in all directions but not unstable in all directions, so if stability is lost in 2 dimensions, then stability in one of the other dimensions is maintained [10]. For the broom to fly, we need stability in every direction so the magnetic fields can be manipulated without the broom losing control.

To control the overall stability, we can use strategically positioned permanent magnets to keep the levitation balanced. The permanent magnets, like the magnets on the surface of the railway track, can be strategically placed under the pitch and on the sides of the pitch to allow levitation. The problem with this is humans may not be able to withstand the force on themselves with the degree of magnetic flux density required to allow these brooms to levitate. Furthermore, the riders would need to remain on the pitch for the levitation to work.

Active levitation

The biggest problem other than stability is providing the magnetic force required to make the broom levitate. The factors that affect the magnetic force are magnetic field strength and the magnitude of the charge of charged particles [11]. The overall charge present is the sum of all the charge carriers present that are in the material. The way we can vary the force on these charged particles is through active levitation. Active levitation controls the object by varying the required magnetic force with the use of an electromagnet [12], this is illustrated with the following diagram (figure 2):

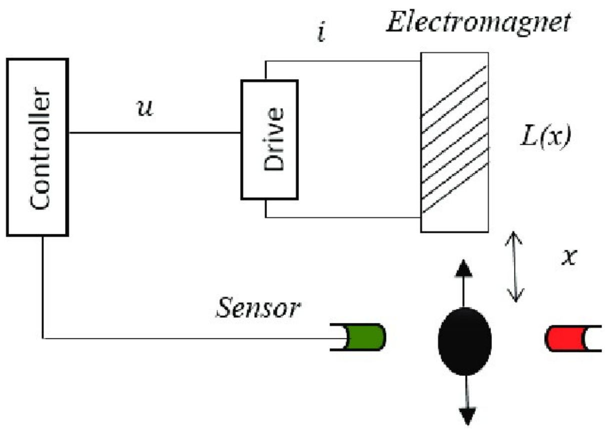

Figure 2 – Shows an electrical schematic of an active levitation system, adapted from [7].

The displacement of the broom needs to be measured to change the magnetic force accordingly [13]. The displacement of the broom can be measured using voltage and current. You can also measure the flux density at the air gap between the electromagnets and the diamagnetic coil [13]. The magnetic flux density tells you the strength and direction of the magnetic field around a magnet.

Conclusions

Pyrolytic graphite is the most ideal material to use for diamagnetic levitation, it is light and has a magnetic susceptibility that allows high magnetization. Furthermore, diamagnetic materials can be stable in all directions but cannot be unstable in all directions. Active levitation can be used to control the displacement of the broom in a 3-D spatial distribution, so diamagnetic materials could still be used for levitation provided the magnetic flux density could be changed accordingly.

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