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Abstract

An experiment and a demonstration concerning transport by magnetic levitation (Maglev) are described. The lift, drag and radial forces on a magnet placed over a rotating conducting disc are measured versus the rotation frequency. The experiment relates to important topics of electromagnetism and could be a useful addition to the undergraduate physics laboratory. The clearly seen electrodynamic suspension is an attractive classroom demonstration.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Maglev (magnetic levitation) is a general term for any transportation system, in which vehicles are suspended and guided by electromagnetic forces [1, 2]. The magnetic field keeps the vehicle above the support structure called a guideway. The lack of friction allows the vehicles to travel at velocities of 500 km h^{-1}. There are two basic types of magnetic suspension:

- electromagnetic suspension due to attractive forces: electromagnets on the vehicle are drawn towards a steel rail, and their currents are automatically regulated to maintain a fixed gap between the rail and the vehicle;
- electrodynamic suspension due to repulsive forces: electromagnets on the vehicle induce in a conducting guideway eddy currents producing a repulsive force as the vehicle moves along the guideway.

The electrodynamic suspension based on Faraday and Lenz's laws has been known for a long time. Superconducting dc magnets on the vehicle are preferable due to their high magnetic fields and low losses, and the linear synchronous motor technology is applicable for electromagnetic forward motion. Nowadays, transportation by magnetic levitation has proven its feasibility and advantages.

Under laboratory conditions, electrodynamic suspension is possible with the usual permanent magnets. An experiment and a demonstration described below illustrate the concept of 'lift through motion', the basis of one of the techniques for wheelless transportation.

Many authors, including Landau and Lifshitz [3], considered eddy currents in conductors. Klauder [4] calculated the lift and drag forces on a long current-carrying wire moving over a conducting semi-infinite slab. Coffey *et al* [5] have found that at high velocities the levitation force can be calculated as if the guideway had infinite conductivity. At finite velocities, the resistivity of the guideway reduces the actual lift force and produces a drag force. Reitz [6] considered a magnetic dipole moving above a thin conducting plate. Davis and Reitz [7] calculated the eddy-current distribution in a perfectly conducting sheet or disc due to a magnetic monopole. Davis [8] presented a proof of the general relationship between the drag and lift forces. Saslow [9–11] considered several topics, including magnetic braking, induction motor, electromagnetic shielding and Maglev.

Many papers were devoted to the interaction of a conductor with a rotating magnetic field. Doyle and Gibson [12] described a simple classroom demonstration of retarding and repulsive forces on a permanent magnet put near a rotating conductor (Arago's effect). Wiederick *et al* [13] proposed an experiment on the magnetic braking of a thin aluminium disc freely rotating between the pole pieces of an electromagnet. Heald [14] presented an improved theory of this experiment. Marcuso *et al* [15, 16] computed the torque on a moving conductor by a localized magnetic field and confirmed the calculations by measurements of the deceleration of aluminium and copper discs rotating in the magnetic field. Aguirregabiria *et al* [17] studied the braking effect on a thin conducting disc rotating in a nonuniform magnetic field. Two papers of the present author were devoted to eddy currents [18] and magnetic braking [19].

2. Theoretical background

Electrodynamic suspension is caused by repulsive forces between electromagnets on the vehicle and eddy currents induced in a conducting guideway as the vehicle moves along it. The motion is a crucial requirement for obtaining a lift force. The currents in the guideway decay as the vehicle passes and electrical energy losses in the guideway therefore occur. The vehicle must compensate for these losses. This means that a drag unavoidably accompanies the lift. At high velocities, the electrodynamic drag decreases with increasing velocity, which is a very important feature of eddy-current transportation systems.

The complete theory of electrodynamic suspension is too complicated to be reproduced here. Therefore, only a general picture of the phenomenon will be given, as well as formulae important for the experiment presented.

A source of magnetic field, a monopole q, which 'instantaneously' appears at height z above a conducting plate, induces in the plate circular eddy currents, which maintain the instantaneous field in the plate (see, e.g., figure 1 in [10]). The monopole is the limit of a long thin bar magnet or a solenoid oriented perpendicular to the plate. The pole strength q has the dimensions of magnetic moment per unit length.

In the case of a superconductor, the surface currents completely cancel the magnetic field inside the plate (Meissner's effect). The field outside the plate is obtainable by superimposing the source field and the field due to the image of the source (that is, monopole $-q$ at $-z$). On the $z = 0$ plane, this leads to a zero normal component and a doubled transverse component of the resulting magnetic field. Above the plate, the field exerts a repulsive force on the monopole proportional to the normal component of the field. Due to the axial symmetry of the eddy currents, other components of the force are zero. The surface currents in the superconducting plate do not decay, and the repulsive force continues infinitely. The levitation of a permanent magnet over a superconductor is a subject of a well-known demonstration.

In the case of a normal metal, eddy currents decay in time, which depends on the conductivity of the plate. To maintain the currents, changes in the external magnetic field must continue, for instance, by moving the monopole parallel to the plate. It is important that the external magnetic field penetrates a normal metal. Due to high conductivity of the metal, the penetration can be slow relative to the changes in the external field. The movement of the monopole breaks the symmetry of the eddy currents: their distribution in front of the monopole and behind it becomes different. This causes a horizontal component of the magnetic field and a horizontal force on the monopole. According to Lenz's law, this force is directed opposite to the movement of the monopole. The phenomenon is well known as magnetic braking. Both lift and drag forces depend on the conductivity and thickness of the plate and on the velocity of the monopole. At very high velocities, the lift force produced by eddy currents in a normal metal approaches that produced by persistent currents in a superconductor.

Reitz [6] considered a magnetic dipole (a magnet or a current-carrying coil) moving with velocity v at fixed height h above a plate of conductivity σ and thickness d. The plate was assumed thin compared to the skin depth for the dominant frequencies in the exciting field; therefore, the current density in the plate does not depend on the z coordinate. The electromagnetic disturbance of a moving dipole has a broad frequency spectrum, but the dominant frequency is of the order of $\omega = v/h$. The penetration of the magnetic field into the plate is characterized by the parameter $w = 2/\mu_0\sigma d$, which has the dimensions of a velocity. The lift force on a monopole was found to be

$$F_{\mathrm{L}} = (\mu_0 q^2/16\pi h^2)[1 - w/(v^2 + w^2)^{1/2}], \tag{1}$$

where μ_0 is the permeability of free space. A magnetic dipole of moment m oriented vertically was considered constructed of two monopoles. For the dipole, the lift force is

$$F_{\mathrm{L}} = (3\mu_0 m^2/32\pi h^4)[1 - w/(v^2 + w^2)^{1/2}]. \tag{2}$$

In both cases, the lift-to-drag ratio equals

$$F_{\mathrm{L}}/F_{\mathrm{D}} = (v/w). \tag{3}$$

At high velocities, the lift force asymptotically approaches a constant, while the drag force is inversely proportional to the velocity. This means that the propulsive power to overcome the electrodynamic drag becomes independent of the velocity. For a thick conducting plate, the drag force at high velocities becomes proportional to $v^{-1/2}$.

Saslow [11] presented a theoretical analysis of two examples considered by Maxwell, a monopole moving above a thin conducting sheet and a monopole above a rotating thin conducting disc. In the case of a rotating disc, a radial component of the force on the monopole (towards the centre of the disc) appears, which is also justified by Lenz's law—the eddy currents push the monopole into the region where the linear velocity of the disc and hence the eddy currents decrease. The three components of the force on the monopole are given by the formulae:

$$F_{\mathrm{L}} = A\omega^2 r^2, \tag{4}$$

$$F_{\mathrm{D}} = A\omega r w, \tag{5}$$

$$F_{\mathrm{R}} = 2Ah\omega^2 r, \tag{6}$$

where $A = \mu_0 q^2/32\pi h^2 w^2$, ω is the angular rotation frequency and r is the distance between the monopole and the axis of the disc. The formulae are valid in the low-velocity limit, where $\omega r \ll w$. The radius of the disc is assumed to be much larger than the distance r.

Saslow [11] argued that Maxwell's results 'make him the grandfather, if not the father, of eddy-current Maglev transportation systems'.

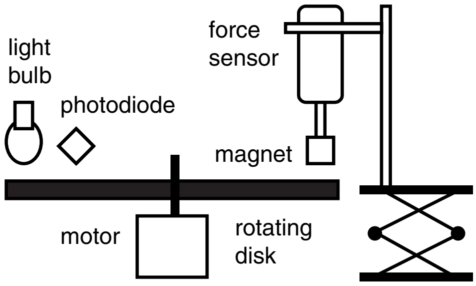

Figure 1. Diagram of the experimental setup arranged for measurements of the lift force.

3. Experimental details

The experiment consists of measurements of forces on a magnet placed over a rotating aluminium disc, and of demonstration of electrodynamic suspension. The experiment follows that recommended by PASCO scientific [20]; however, the levitation is not achieved in the PASCO experiment. In our case, the levitation became possible due to increasing the rotation velocity of the disc and probably due to using a more suitable permanent magnet. The three components of the force on the magnet are determined with the PASCO's data-acquisition system versus the rotation velocity and for different gaps between the magnet and the disc. With a proper rotation frequency, the lift force becomes sufficient to prevail over the weight of the magnet.

The experimental setup is simple and easy to build (figure 1). An aluminium disc, 20 cm in diameter and 1 cm in thickness, is brought to rotation by an induction motor (115 V, 0.65 A). We use a cylindrical NdFeB permanent magnet, 18 mm in diameter and 18 mm in height, magnetized along the axis of the cylinder up to about 1.3 T. The *ScienceWorkshop* data-acquisition system with the *DataStudio* software from PASCO scientific controls the experiments. The three components of the electrodynamic force on the magnet are measured in turn with the PASCO's *Force sensor* (CI-6537), which can be positioned vertically or horizontally. The magnet is attached to the sensor; the magnetic dipole is aligned vertically in both cases.

In the induction motor used, the rotation frequency of the magnetic field is 25 Hz. The rotation frequency of the rotor is somewhat less, depending on the load of the motor (see, e.g., [21]). The frequency is measured with a photodiode looking at the disc illuminated from above by a light bulb. A piece of paper with black spots painted on it is laid on the disc and electrical pulses from the photodiode provide data on the rotation frequency. These pulses are amplified and then fed to the digital input of the *ScienceWorkshop 750 Interface* intended for the *Rotary motion sensor*. With a 1 Hz *Sample rate*, this input is capable of measuring the frequency of incoming pulses. This method was already described [22]. In order to increase the number of experimental points, the *Sample rate* in the present measurements is set to 5 Hz. With the data-acquisition system, many experimental data are obtainable in a short time. A photo shows the experimental setup arranged for measurements of the radial component of the electrodynamic force (figure 2).

4. Forces on the magnet and magnetic suspension

The aluminium disc is brought to rotation and attains its steady velocity in several seconds, then the motor is switched off. The force on the magnet and the rotation frequency are

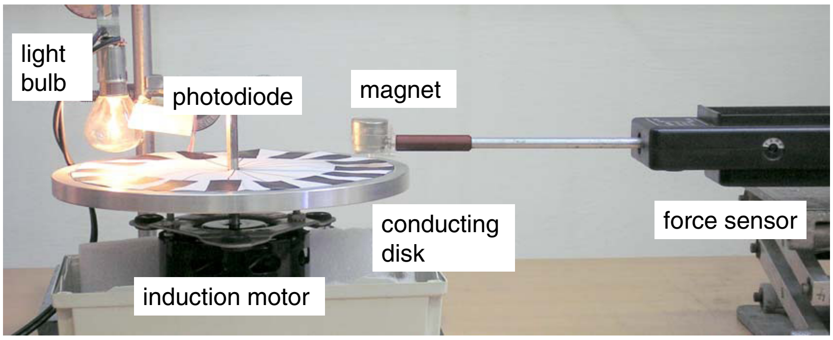

Figure 2. The experimental setup arranged for measurements of the radial force.

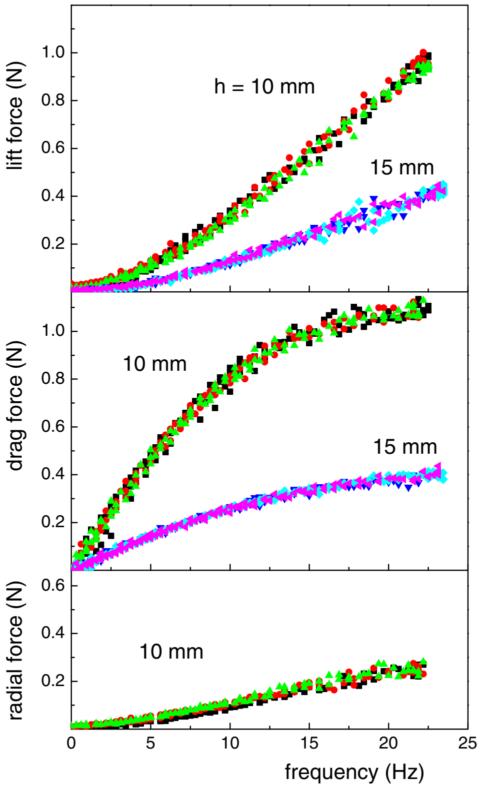

Figure 3. Lift, drag and radial forces versus rotation frequency.

measured during a run including periods of acceleration and deceleration of the disc. During each run, *DataStudio* plots a graph of the force versus the rotation frequency. Experimental data from three runs for a given gap are collected in one graph. In the measurements, the gaps h between the magnet and the disc are 10 and 15 mm. The radial force is several times lower than the lift or drag force; therefore, it is measured only for a 10 mm gap. With our motor, measurements at smaller gaps are impossible since the magnetic braking strongly decreases the rotation frequency.

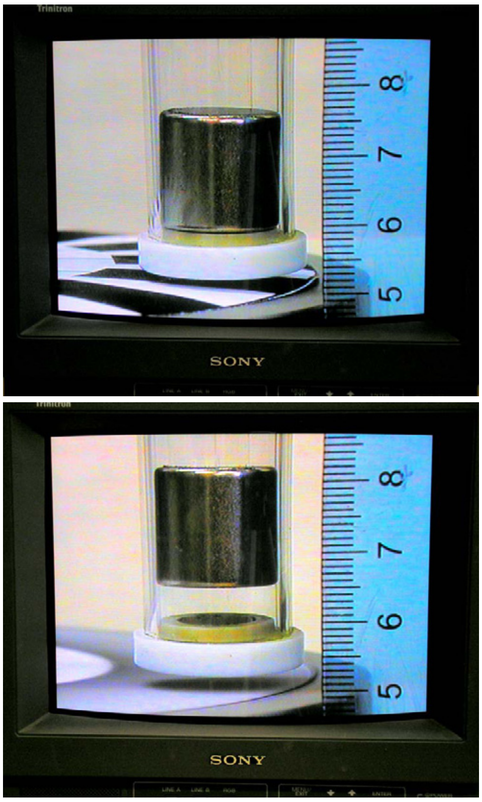

Figure 4. Demonstration of electrodynamic suspension with a video camera.

The conditions of the experiment do not coincide with those accepted for the theoretical analysis, namely: (i) the dipole approximation is not applicable; (ii) the thickness of the rotating disc is comparable with the skin depth; (iii) the distance between the magnet and the axis of the disc is close to the disc radius; (iv) neither the low-velocity limit, $v \ll w$, nor the high-velocity limit, $v \gg w$, is fulfilled. Nevertheless, the results obtained (figure 3) are in qualitative agreement with calculations (see figure 5 in [11]). The lift-to-drag ratio increases with the rotation frequency, but remains somewhat less than one even at the highest frequencies. At the edge of the disc, the highest linear velocity is about 15 m s^{-1}, that is, 50 km h^{-1}, which is an order of magnitude lower than that for magnetically levitated transport. For the latter, the lift-to-drag ratio is much more favourable.

The weight of our magnet, about 0.34 N, is less than the maximum lift force obtained at 10 and 15 mm gaps, so that electrodynamic suspension of the magnet is quite possible. To demonstrate the suspension, the magnet is placed into a glass tube positioned vertically over the disc. After switching on the motor, the magnet gradually moves upwards, according to the increase in the rotation frequency, and reaches an equilibrium position, where the lift force just balances its weight. After switching off the motor, the magnet gradually returns to its lower position. The crucial role of the motion of the disc is thus clearly seen. The magnet is not free because its position is constrained by the containing tube. This limitation is necessary to oppose the drag force, an unavoidable attribute of electrodynamic suspension. The suspension is demonstrated with a video camera and a monitor (figure 4).

Our magnet levitates at about $h_0 = 17$ mm above the rotating disc. With a normal metal, the lift force should be smaller than that with a superconductor. For a superconductor, this force is given by equation (2), with $v \gg w$:

$$F_L = (3\mu_0 m^2/32\pi h^4). \tag{7}$$

From this equation, the equilibrium height of a magnet levitated over a superconductor is

$$h_0 = (3 \times 10^{-7} m^2/8P)^{1/4}, \tag{8}$$

where P is the weight of the magnet.

The magnetic moment m of our magnet was determined by measurements of the magnetic field of the dipole [23]. It equals nearly 4.5 A m^2. With this value, the above equation gives $h_0 \cong 39$ mm.

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References

[1] Danby G T and Powell J R 1998 Transport by magnetic levitation *Encyclopedia of Applied Physics* vol 22 (New York: Wiley-VCH) pp 233–61
[2] Kolm H H and Thornton R D 1973 Electromagnetic flight *Sci. Am.* **229** (2) 17–25
[3] Landau L D and Lifshitz E M 1960 *Electrodynamics of Continuous Media* (Oxford: Pergamon)
[4] Klauder L T 1969 A magnetic field diffusion problem *Am. J. Phys* **37** 323–5
[5] Coffey H T, Chilton F and Barbee T W 1969 Suspension and guidance of vehicles by superconducting magnets *J. Appl. Phys.* **40** 2161
[6] Reitz J R 1970 Forces on moving magnets due to eddy currents *J. Appl. Phys.* **41** 2067–71
[7] Davis L C and Reitz J R 1971 Eddy currents in finite conducting sheets *J. Appl. Phys.* **42** 4119–27
[8] Davis L C 1972 Drag force on a magnet moving near a thin conductor *J. Appl. Phys.* **43** 4256–7
[9] Saslow W M 1987 Electromechanical implications of Faraday's law: a problem collection *Am. J. Phys.* **55** 986–93
[10] Saslow W M 1991 How a superconductor supports a magnet, how magnetically 'soft' iron attracts a magnet, and eddy currents for the uninitiated *Am. J. Phys.* **59** 16–25
[11] Saslow W M 1992 Maxwell's theory of eddy currents in thin conducting sheets, and applications to electromagnetic shielding and MAGLEV *Am. J. Phys.* **60** 693–711
[12] Doyle W T and Gibson R 1979 Demonstration of eddy current forces *Am. J. Phys.* **47** 470–1
[13] Wiederick H D, Gauthier N, Campbell D A and Rochon P 1987 Magnetic braking: simple theory and experiment *Am. J. Phys.* **55** 500–3
[14] Heald M A 1988 Magnetic braking: improved theory *Am. J. Phys.* **56** 521–2
[15] Marcuso M, Gass R, Jones D and Rowlett C 1991 Magnetic drag in the quasi-static limit: a computational method *Am. J. Phys.* **59** 1118–23
[16] Marcuso M, Gass R, Jones D and Rowlett C 1991 Magnetic drag in the quasi-static limit: experimental data and analysis *Am. J. Phys.* **59** 1123–9
[17] Aguirregabiria J M, Hernández A and Rivas M 1997 Magnetic braking revisited *Am. J. Phys.* **65** 851–6
[18] Kraftmakher Y 2000 Eddy currents: contactless measurement of electrical resistivity *Am. J. Phys.* **68** 375–9
[19] Kraftmakher Y 2005 Demonstration of Lenz's law with an induction motor *Phys. Educ.* **40** 281–4
[20] PASCO scientific, 10101 Foothills Blvd, Roseville, CA 95747–7100, www.pasco.com
[21] Kraftmakher Y 2001 Two experiments with rotating magnetic field *Eur. J. Phys.* **22** 477–82
[22] Kraftmakher Y 2007 *Experiments and Demonstrations in Physics. Bar-Ilan Physics Laboratory* (Singapore: World Scientific)
[23] Kraftmakher Y 2007 Magnetic field of a dipole and the dipole–dipole interaction *Eur. J. Phys.* **28** 409–14