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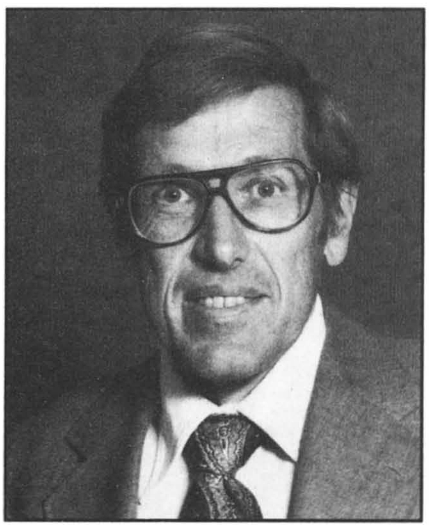

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Mention of magnetic levitation these days probably brings to mind either a small permanent magnet floating above a superconductor or a high-speed maglev train flying above a metal guideway. The principles of magnetic levitation, known for more than a century, have disappeared from most textbooks but are once again attracting considerable attention because of interesting applications made possible by superconductors and high-performance permanent magnets.

Classroom Demonstrations

Before we discuss these principles, we will describe three simple demonstrations of magnetic levitation that every physics student deserves to see in the classroom.

The "jumping ring" experiment (Fig. 1a)

A conducting ring, A, on an iron core will jump high in the air when the switch, S, is closed so that current flows in the coil, C, wrapped around the same iron core.[1] The changing magnetic flux in the iron core induces a large current in the conducting ring; according to Lenz's law, this induced current flows in a direction so as to oppose the change in flux, thus producing opposing magnetic poles between the coil and ring and thereby a repulsive force. Alternatively, an alternating current in the coil can be adjusted to maintain the ring at a fixed height.

It should be noted that the induced emf in the ring, which is proportional to $d\Phi/dt$, is 90° out of phase with the magnetic field, B. If the ring had only resistance, the induced current would likewise be 90° out of phase with B, and the average force on the ring would be zero. The inductive reactance of the ring, however, causes the current to lag the induced voltage, leading to a net force of repulsion on the ring.[2]

Magnet levitated over a superconductor (Fig. 1b)

The availability of materials (such as the "1, 2, 3" material, yttrium-barium copper oxide) that are superconducting at the boiling temperature of liquid nitrogen has made the levitation of a small magnet over a superconducting sample (or vice

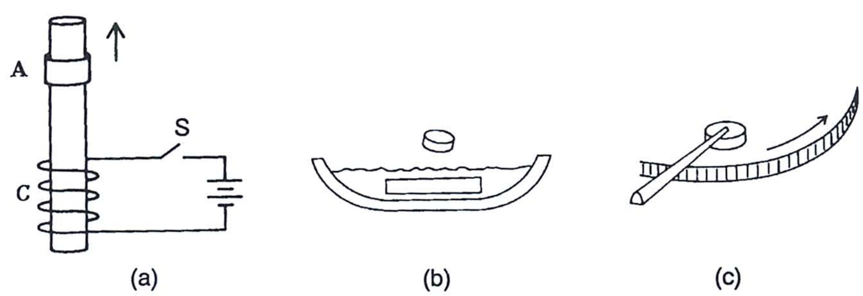


Fig. 1. Three demonstrations of magnetic levitation: (a) jumping ring experiment; (b) magnet levitated over a superconductor; (c) magnet levitated above a rapidly moving conductor.

versa) a familiar demonstration.[3] This demonstration, which depends upon the Meissner effect, will be discussed later in this paper.

Magnet levitated above a rapidly moving conductor (Fig. 1c)

A permanent magnet can be levitated above a rotating aluminum disk, as shown in Fig. 1c. Induced eddy currents cause the disk to act as a sort of "magnet mirror," the magnet being repelled by its induced magnetic image below the conductor. The faster the conducting disk rotates, the better the magnetic image it produces, approaching (as a limit) the behavior of a superconductor.

Another type of magnetic levitation involves suspending a ferromagnetic object in a magnetic field, as in a high-speed magnetic centrifuge,[4] or suspending a magnet below a ferromagnet, as in the electromagnetic suspension used in some maglev trains.[5] These types of magnetic levitation are more difficult to demonstrate in the classroom because the levitation force is unstable with changes in levitation height. The first type requires a magnetic field with a large gradient to establish an equilibrium position; in the second, the current in the electromagnet must be continuously adjusted to maintain a constant height.

Eddy Currents

Few textbooks discuss eddy currents satisfactorily. Two exceptions are books by Smythe[6] (1950) and Landau and Lifshitz[7] (1960), but these are not easily digested by undergraduate students. Maxwell[8] discusses eddy currents in his classic 1891 treatise, but an even better source is his paper of 1872, which begins with an intuitive discussion and later presents the mathematical description.[9] Saslow has discussed Maxwell's treatment of eddy currents and reformulated his mathematics in a more modern notation in two papers in the *American Journal of Physics.*[10]

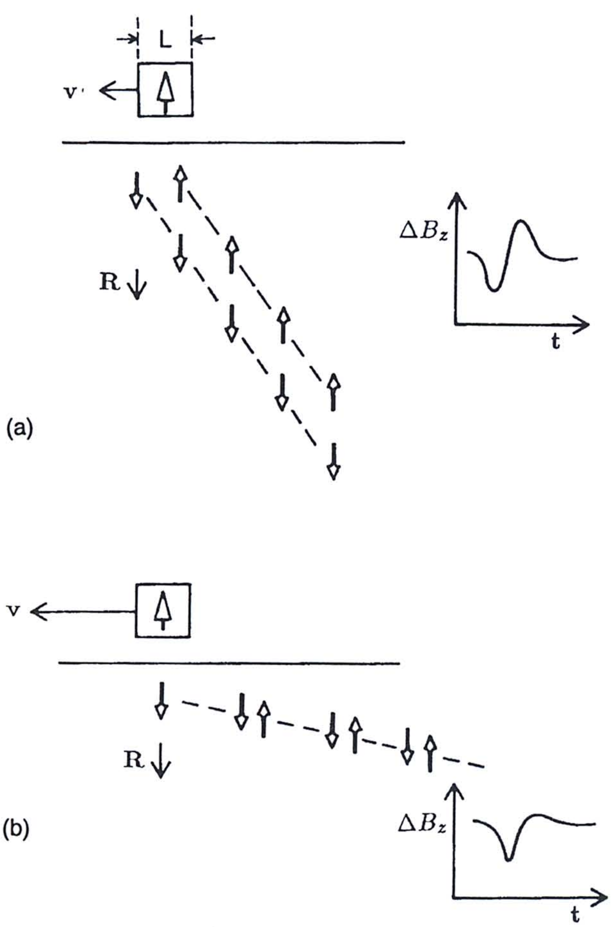
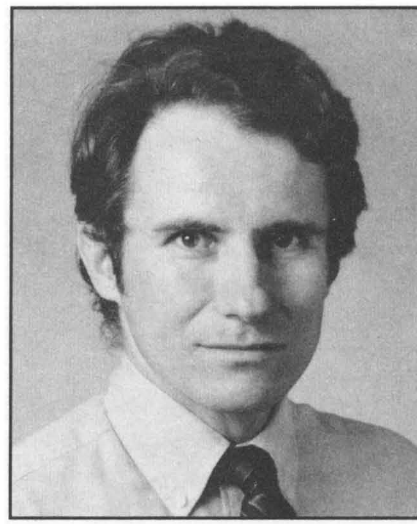


Fig. 2. Maxwell's eddy current model applied to a magnet moving over a conducting plane: (a) low velocity; (b) high velocity. The vertical component of the induced images and the magnetic field due to the eddy currents are shown in each case.

Maxwell's intuitive treatment of eddy currents makes use of the principle of images, which he credits to Sir William Thomson. "In the case of the plane conducting sheet," Maxwell points out, "the imaginary system on the negative side of the sheet is not the simple image, positive or negative, of the real magnet or electro-magnet on the posi-



John Hull *is currently leader of the Superconductivity Applications Section in the Materials and Components Technology Division at Argonne National Laboratory (Argonne, IL 60439), where he has been a research scientist and engineer since 1980. He received his Ph.D. in physics from Iowa State University in 1979. His research interests include applications of superconductivity, levitation phenomena, and solar energy. He has received eight U.S. patents and authored over 50 scientific publications.*

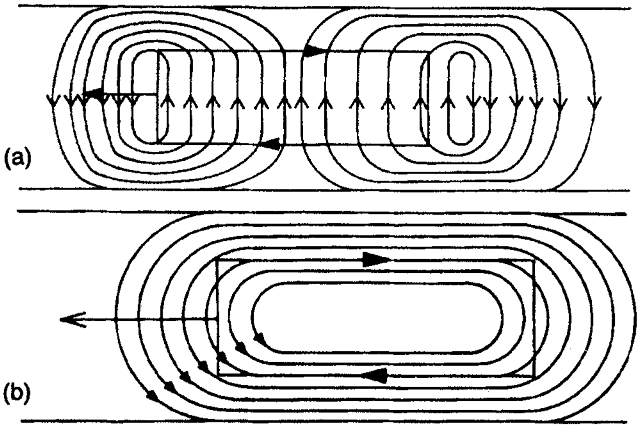


Fig. 3. Eddy currents induced by a rectangular current-carrying coil moving over a conducting plane: (a) low velocity; (b) high velocity (adapted from Ref. 12).

tive side, but consists of a moving train of images, the nature of which we now proceed to define."[8]

According to Maxwell's model, when a magnet passes a point on the conducting plane, it induces first a "positive" image, then a "negative" image. These images propagate downward at a velocity R, which is proportional to the specific resistivity (and to the reciprocal thickness if the sheet is thin compared with the skin depth). R is also the electrical resistance of a square portion of the conducting sheet; its value $R = \rho/2\pi h$ (ρ = resistivity, h = thickness) is independent of the size of the square. In electromagnetic units, R has the dimensions of velocity.

Two examples applying Maxwell's model are shown in Fig. 2. In the first example, the velocity, v, of the magnet is less than R. The positive image has moved down a distance $Rdt = RL/v$ when the negative image appears at the same location. Then, as the two images move away head-to-tail, the induced field falls toward zero. The vertical component of magnetic field ΔB_z due to the eddy currents has one direction near the leading edge of the moving magnet and the opposite direction at the trailing edge, which leads to the waveform shown at the right.

In the second example (Fig. 2b), the velocity is considerably greater than R. The positive image has moved only a small distance RL/v away when the negative image appears, and the two images nearly cancel each other thereafter. Now the magnetic field due to the eddy currents, ΔB_z, is predominantly in one direction, as shown in Fig. 2b.

To construct a mathematical description of the eddy currents due to a magnet moving over a conducting plane, it is generally easier to work with the magnetic vector potential $\vec{A}$.* Using Faraday's law, Ohm's law, and Ampère's law, Smythe[6] derives an equation for the vector potential inside the sheet [Eq. 11.09 (4) in Ref. 6]. Reitz[11] solves this equation for several types of moving magnets, including a monopole, a dipole, a long straight wire, two parallel wires, and a large rectangular coil. In each case he obtains a "wake of images," similar to those in Fig. 2, moving into the plate with a velocity $w = 2\rho/\mu_o h$, which is Maxwell's R expressed in rationalized MKS units.

A sketch of the eddy currents induced by a rectangular coil (or a permanent magnet magnetized normal to the plane) moving over a conducting sheet is shown in Fig. 3. At low velocities the eddy currents circulate in opposite directions

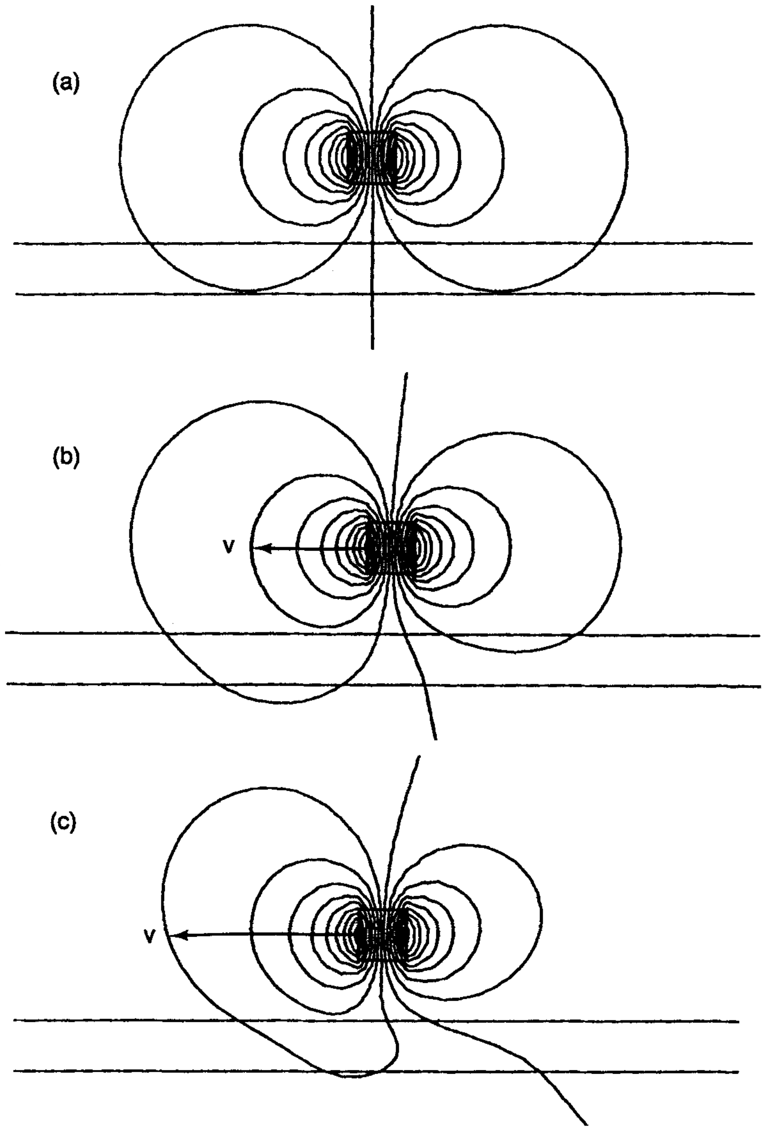


Fig. 4. Magnetic field calculated by a finite element method for a long magnet with a square cross section moving over a conducting plane. As the velocity of the magnet increases, less magnetic flux penetrates the conductor.[13] (a) v = 0; (b) v = 2 m/s; (c) v = 10 m/s.

*In electrostatics problems, it is often easier to calculate the scalar potential φ and then to use it for computing the electric field $\vec{E}$. Similarly, in magnetostatics it is often easier to calculate the magnetic vector potential $\vec{A}$ and to use it for computing the magnetic field $\vec{B}$.

at the leading edge and the trailing edge, whereas at high velocities they tend to follow the perimeter of the coil. This is consistent with Maxwell's magnetic image model in Fig. 2 and with Reitz's wake of images.

Figure 4 shows the magnetic field $\vec{B}$ under a long permanent magnet with a square cross section moving over a conducting plane. The magnetization is perpendicular to the plane. As the velocity increases, less magnetic flux penetrates the conductor, and the magnetic field due to the induced currents makes an increasingly important contribution to the total field.

Lift and Drag Forces on a Moving Magnet

The force on a magnet moving over a nonmagnetic conducting plane can be conveniently resolved into two components: a lift force perpendicular to the plane and a drag force opposite to the direction of motion. At low velocity, the drag force is proportional to velocity v and considerably greater than the lift force, which is proportional to v^2. As the velocity increases, however, the drag force reaches a maximum (referred to as the drag peak) and then decreases as $1/\sqrt{v}$. The lift force, on the other hand, which increases with v^2 at low velocity, overtakes the drag force as velocity increases and approaches an asymptotic value at high velocity, as shown in Fig. 5. The "lift-to-drag ratio," which is of considerable practical importance, is given by $F_L/F_D = v/w$.

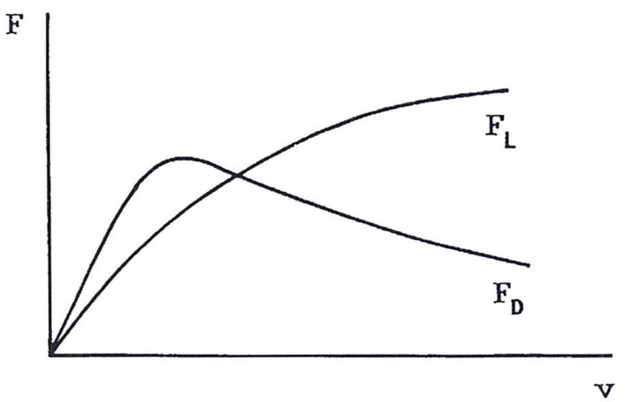


Fig. 5. Velocity dependence of lift force F_L and drag force F_D.

Qualitatively, these forces can be understood by considering magnet flux diffusion into the conductor. When a magnet moves over a conductor, the field tries to diffuse into the conductor. If the magnet is moving rapidly enough, the field will not penetrate very far into the conductor, and the flux compression between the magnet and the conductor causes a *lift* force. The flux that does penetrate the conductor is dragged along by the moving magnet, and the force required to drag this flux along is equal to the *drag* force.

At high speeds, less of the magnetic flux has time to penetrate the conductor. The lift force resulting from flux compression approaches an asymptotic limit, and the drag force approaches zero at high speed.

The lift force on a vertical dipole of moment m moving at velocity v at a height z_o above a conducting plane can be shown to be:[11]

$$F_L = \frac{3\mu_o m^2}{32\pi z_o^4}\left(1 - \frac{w}{\sqrt{v^2 + w^2}}\right) \qquad (1)$$

At high velocity, the lift force approaches the ideal lift from a single image: $3\mu_o m^2/32\pi z_o^4$; at low velocity, the factor in parentheses is approximately equal to $v^2/2w^2$, so the lift force increases as v^2.

The drag force, as already pointed out, is w/v times the lift force, so the drag force is proportional to v at low velocity. According to the thin-plate model that we have been discussing thus far, the drag force should fall off with $1/v$ as the lift force reaches its high-speed limit. However, at high velocity, penetration of the eddy currents and magnetic fields are limited to the skin depth, which is proportional to $v^{-1/2}$. As a first approximation, one might replace plate thickness by skin depth, in which case the drag force takes on a $v^{-1/2}$ dependence at high speed. The transition from thin-plate to skin-depth behavior should occur at about 30 m/s in a 1-cm-thick aluminum plate, for example.

Measuring Lift and Drag Forces

Several recent papers have described experiments for measuring the velocity-dependent drag force on a magnet over a moving conductor with fairly simple apparatus.[14–16] Byer et al.[17] describe a superconducting merry-go-round for measuring the lift force in the laboratory.

At the AAPT 1990 summer meeting, one of us (TR) exhibited a simple apparatus for demonstrating and measuring both lift and drag forces on a small permanent magnet over a rotating aluminum disk. To qualitatively demonstrate lift and drag forces, the magnet is attached to a flexible arm, A (a hacksaw blade serves nicely), that is pivoted so that the magnet moves freely in the vertical direction, as shown in Fig. 6. The 0.6-cm-thick aluminum disk is rotated at a maximum speed of 1725 rpm by a ¼-hp electric motor. When the motor is switched on and the disk accelerates, the magnet arm bends several centimeters due to a fairly strong drag force on the magnet. As the speed increases, the magnet begins to lift,

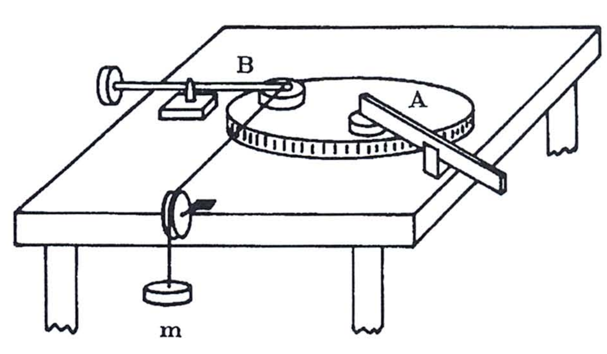


Fig. 6. Simple apparatus for demonstrating and measuring lift and drag forces on a small magnet over a rotating aluminum disk.

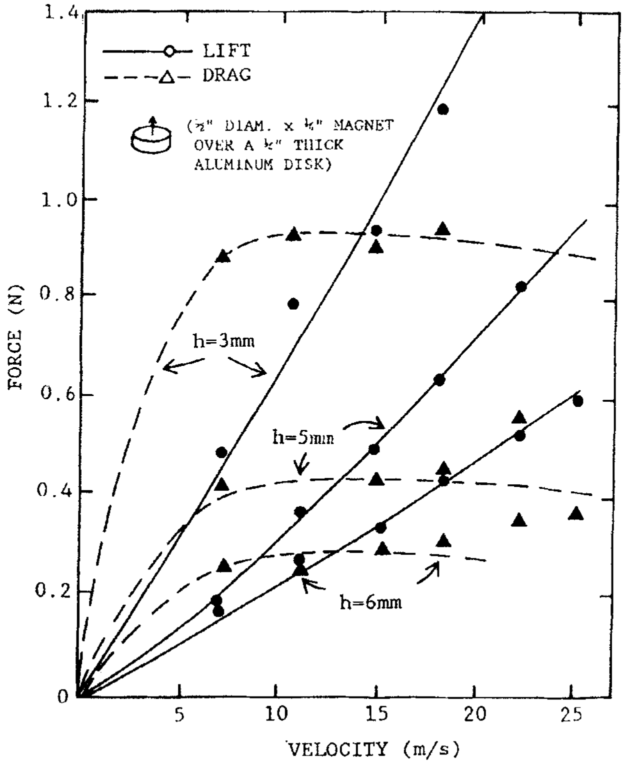


Fig. 7. Lift and drag forces on a 12.7-mm-diameter NdFeB magnet over a rotating aluminum disk having a thickness of 6.35 mm. The lift force increases with velocity, but the drag force decreases at velocities above the "drag peak."

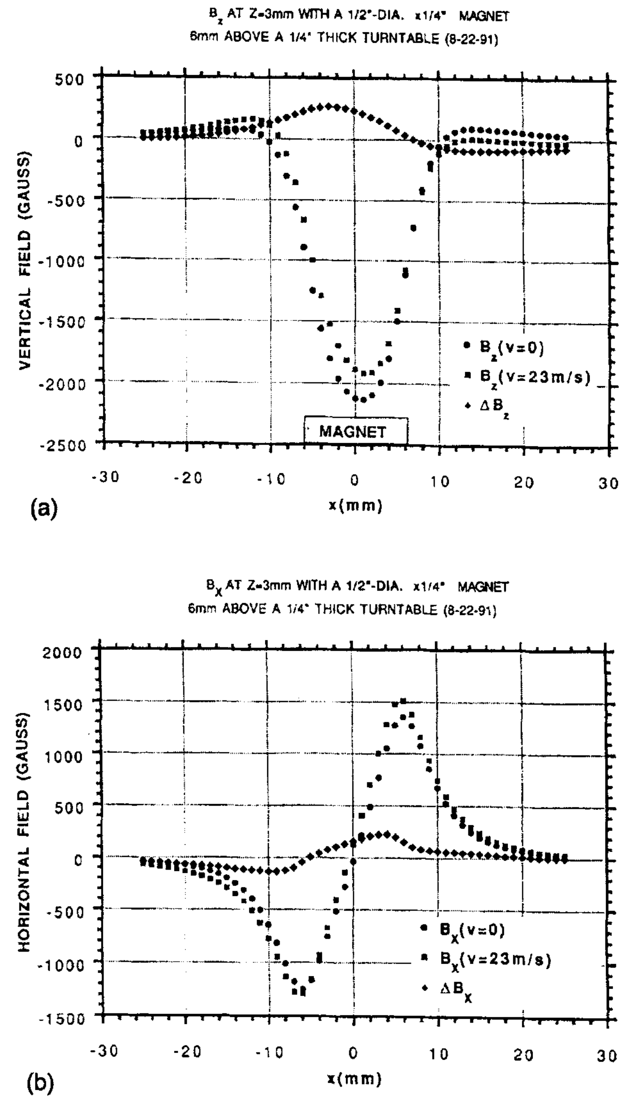


Fig. 8. Magnetic field 3 mm above the rotating disk shown in Fig. 6 with the magnet 6 mm above the disk; (a) vertical component, (b) horizontal component. Circles show fields at rest; squares show fields with the disk moving 23 m/s. The difference between these fields, shown as diamonds, represents the field due to induced eddy currents in the disk. The magnet moves in the negative *x* direction with respect to the disk.

which decreases the drag force (in addition to which, the drag force diminishes slowly above the drag peak).

A second magnet arm, B, for measuring lift and drag forces is a slightly modified phonograph pickup arm. To measure the drag force, a string runs from this arm over a pulley to a 20-g weight hanger. Mass is added to the magnet arm in 10-g increments, and the magnet height is measured with a small telescope with cross hairs (as used in wall galvanometers) attached to a micrometer slide. The velocity is varied by positioning the magnet at different radii over the rotating disk.

Lift and drag forces measured with this apparatus are shown as functions of velocity in Fig. 7. At the maximum velocity (25 m/s), we have passed the drag peak, but the lift force is nowhere close to its asymptotic limit.

To measure the magnetic fields due to induced eddy currents, we can position a Hall-effect probe under the magnet. The vertical and horizontal components of the magnetic field, measured in this way, are shown in Fig. 8. The circles show the magnetic field as a function of position with the disk at rest, and the squares show the field at a velocity of 23 m/s. The difference between these two fields is the field due to induced eddy currents, shown by the diamonds.

The vertical component of the magnetic field due to eddy currents is seen to reach its maximum value, in Fig. 8, at $x = -3$ mm, whereas the horizontal component reaches its maximum value at $x = 3.5$ mm. Thus the eddy current pattern is somewhere between the low-velocity and high-velocity configurations in Fig. 3. At lower speeds, maxima in the field components shift forward in the direction of magnet motion as the eddy-current pattern approaches the low-velocity configuration (illustrated in Fig. 3a).

The lift and drag forces measured with this simple apparatus compare nicely with those made using larger permanent magnets and superconducting coils with conducting strips on large rotating wheels. At Argonne, for example, we use a 1.2-m-diameter wheel, and the magnets are mounted on strain gauges to allow precise measurement of lift and drag forces at speeds up to 38 m/s. Other similar test wheels have been operated at up to 130 m/s.[18]

Aside from shedding new light on a basic problem that has interested physicists for a century or more, an understanding of forces on moving magnets is vitally important to the design

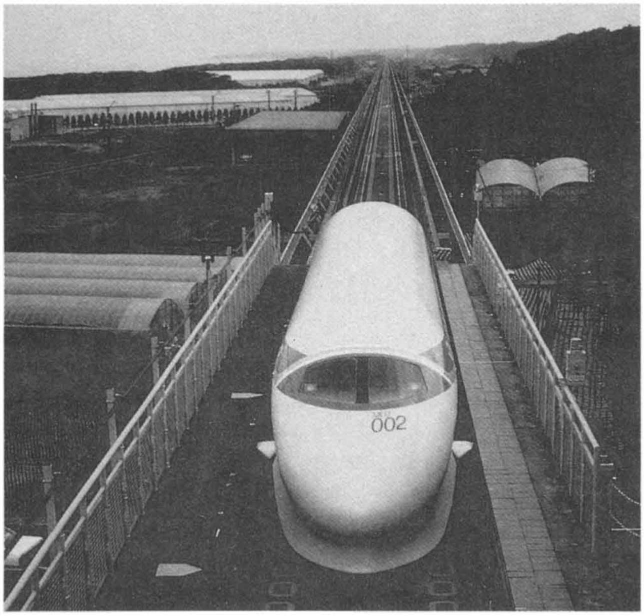


Fig. 9. MLU-002 maglev vehicle in Japan (photo courtesy of the Japan Railways Group).

of magnetically levitated vehicles for high-speed ground transportation.

Maglev Vehicles

A brief history

As early as 1907 Robert Goddard, better known as the father of modern rocketry, but then a student at Worcester Polytechnic Institute, published a story in which many of the key features of a maglev transportation system were described.[19] In 1912, a French engineer named Emile Bachelet proposed a magnetically levitated vehicle for delivering mail.[20] His vehicle was levitated by copper-wound electromagnets moving over a pair of aluminum strips. Because of the large power consumption, however, Bachelet's proposal was not taken very seriously, and the idea lay more or less dormant for half a century.

In 1963 J.R. Powell, a physicist at Brookhaven National Laboratory, suggested using superconducting magnets to levitate a train over a superconducting guideway.[21] Powell and G.R. Danby proposed a system using a less expensive conducting guideway at room temperature in 1967.[22] Later, they conceived the novel idea of a "null-flux" suspension system that would minimize the drag force and thus require much less propulsion power.[23]

During the late 1960s, groups at the Stanford Research Institute and at Atomic International studied the feasibility of a Mach-10 rocket sled employing magnetic levitation. This principle was later applied to high-speed trains by Coffey et al.[24] and by Guderjahn.[25] In 1972, the group at Stanford Research Institute constructed and demonstrated a vehicle levitated with superconducting magnets over a continuous aluminum guideway 160 m long.

At about the same time, a team from MIT, Raytheon, and United Engineers designed the *magneplane* system, in which lightweight cylindrical vehicles, propelled by a synchronously traveling magnetic field, travel in a curved aluminum trough. One advantage of the curved trough is that the vehicle is free to assume the correct bank angle when negotiating curves, the guideway itself being banked only at approximately the desired angle.[26] The magneplane concept was tested with a 1⁄25-scale model system using both permanent magnets and superconducting coils for levitation above a 116-m-long synchronized guideway.[27]

Research groups at the Ford Motor Company Scientific Laboratories[28,29] and at the University of Toronto and Queen's and McGill Universities in Canada[30,31] carefully studied magnetic levitation and electromagnetic propulsion; although they did not construct test vehicles, these groups contributed immensely to our understanding of the basic physics and engineering principles involved.

Maglev systems became objects of considerable study in several other countries, most notably Japan, Germany, and the United Kingdom. Research in Germany, which began in the early 1970s, was initially directed both toward electromagnetic systems using attractive levitation forces and electrodynamic systems using repulsive forces, but in recent years only electromagnetic systems have been seriously considered.[32,33] In Japan, research and development efforts on electromagnetic (attractive) and electrodynamic (repulsive) systems have been proceeded in parallel programs spearheaded by Japan Air Lines and Japan Rail, respectively.[34-36] The most successful project in the UK was the Wolfson levitation project at the University of Warwick, which began about 1973.[37,38]

In the United States, however, virtually all support for maglev research ended about 1975, and very little work was

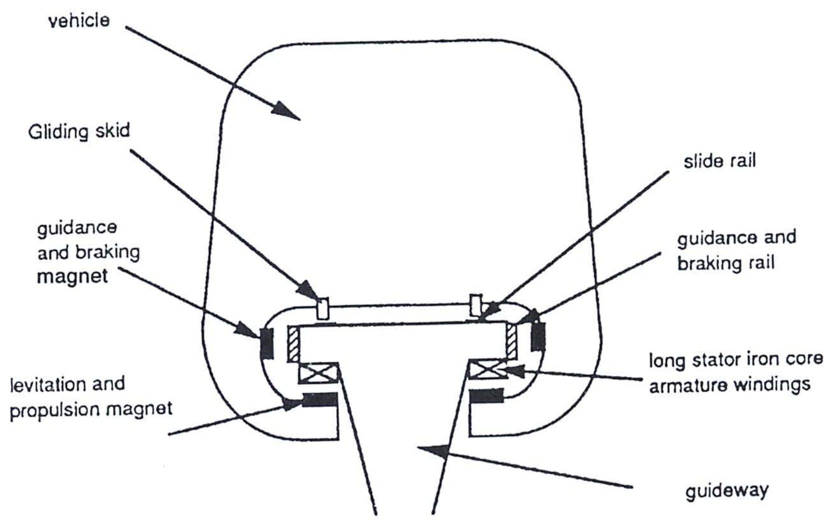


Fig. 10. Schematic diagram of Transrapid maglev system (Germany).

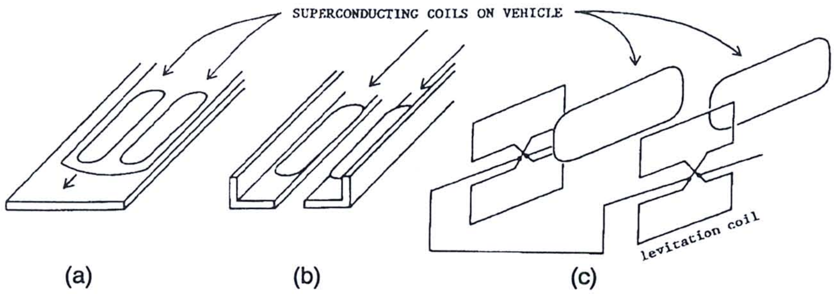


Fig. 11. Three different arrangements for electrodynamic levitation systems: (a) superconducting coils over a flat conducting guideway; (b) superconducting coils with a split L-shape guideway; (c) superconducting coils with short-circuit figure-8 coils connected in a "null-flux" arrangement. Arrangement (c) is similar to that used in the proposed Japanese maglev system.

done from that time until very recently. Research and development continued in Japan and Germany (see Fig. 9 and cover photo), and full-scale vehicles have been tested in both countries. Plans are being made to construct a system based on the German electromagnetic (Transrapid) technology in Orlando, Florida, which will probably be the first public maglev system in the United States.

Electromagnetic (attractive force) suspension (levitation)

Electromagnetic systems (EMS) depend upon the attractive forces between electromagnets and a ferromagnetic (steel) guideway, as shown in Fig. 10. Because the force of attraction increases with decreasing distance, such systems are inherently unstable and the magnet currents must be carefully controlled to maintain the desired suspension height. Furthermore, the magnet-to-guideway spacing needs to be small (only a few centimeters at most). On the other hand, it is possible to maintain magnetic suspension even when the vehicle is standing still, which is not true for electrodynamic (repulsive force) systems. In the system in Fig. 10, a separate set of electromagnets provides horizontal guidance force, but the levitation magnets, acted on by a moving magnetic field from the guideway, provide the propulsion force. The German Transrapid TR-07 vehicle is designed to carry 200 passengers at a maximum speed of 500 km/hr. The levitation height is 8 mm, and power consumption is estimated to be 43 MW at 400 km/hr.

Electrodynamic (repulsive force) levitation

Electrodynamic systems (EDS) depend upon repulsive forces between moving magnets and the eddy currents they induce in a conducting (aluminum) guideway or in conducting loops, as shown in Fig. 11. The repulsive levitation force is inherently stable with distance, and comparatively large levitation heights (20 to 30 cm) are attainable by using superconducting magnets. Three different configurations are shown in Fig. 11: a flat horizontal conductor, a split L-shape conductor, and an array of short-circuit coils on the sidewalls. Each has its own advantages and disadvantages. The proposed Japanese high-speed maglev system uses interconnected figure-8 ("null-flux") coils on the sidewalls, as shown in Fig. 11c. The null-flux arrangement tends to reduce the magnetic drag force and thus the propulsion power needed.

Levitation with Permanent Magnets and Superconductors

According to Earnshaw's classical theorem (1842), it is not possible to have stable equilibrium in a system with only inverse-square-law electrostatic or magnetostatic forces.[39] Braunbeck (1939) deduced that electric or magnetic suspension is not possible when all materials have $\varepsilon_r \geq 1$ or $\mu_r \geq 1$, but that it is possible when materials with $\varepsilon_r < 1$ or $\mu_r < 1$ are introduced (where ε_r and μ_r are the relative electrical permittivity and magnetic permeability, respectively).[40]

Although diamagnetic ($\mu_r < 1$) specimens such as bismuth and graphite can be levitated in strong magnetic fields,[40,41]

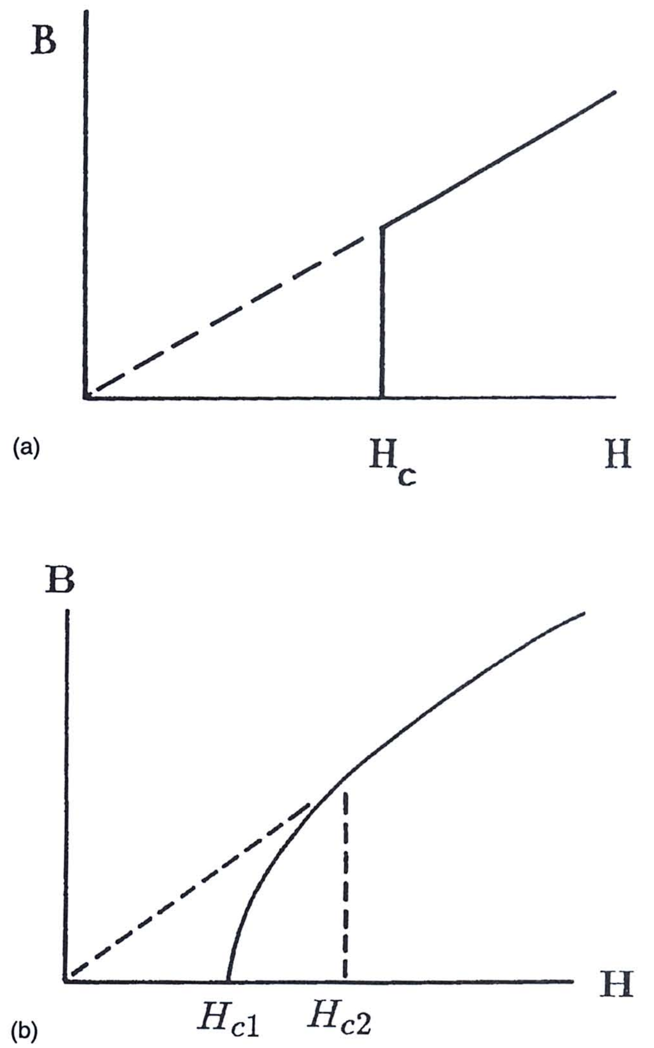


Fig. 12. *BH* curves for two types of superconductors: (a) Type I superconductor with one critical field H_c; (b) Type II superconductor with two critical fields H_{c1} and H_{c2}.

the forces are too weak to be of practical interest (except, perhaps, in microgravity environments). With superconducting materials, on the other hand, which in some circumstances can be characterized as "ideal diamagnets" with $\mu_r = 0$, the levitation force can be quite strong. This was first demonstrated in 1945 by Arkadiev, who levitated a magnet over a concave lead plate immersed in liquid helium.[42]

Perfect diamagnetism, which requires that the magnetic field $B = 0$ within the superconductor, is one of two basic properties observed in superconductors, the other being zero electrical resistivity. Expulsion of magnetic flux by a superconductor, discovered by Meissner and Ochsenfeld in 1933, has become known as the Meissner effect.[43] It has formed the basis of many classroom demonstration experiments such as those described in a recent paper in this journal.[44] (Properly speaking, the term Meissner effect describes only the field-cooled behavior, i.e., the expulsion of the existing magnetic flux from the superconductor as it is cooled below its transition temperature. In many current discussions, however, the term has been corrupted somewhat to include all diamagnetic behavior of superconductors.)

If a magnet is brought close to a superconductor, the configuration of magnetic field lines is essentially the same as would appear if an "image magnet" were located the same distance below the surface of the superconductor. The magnet floats over the superconductor at a height at which the repulsive force between the real and image magnet is equal to the weight of the magnet. In Arkadiev's experiment, using a lead superconductor, the levitation height was determined solely by the size and strength of the magnet and the size of the superconducting sample. Furthermore, a concave surface was required to give the magnet lateral stability.

Demonstrating levitation of a magnet over a superconductor these days is usually done with oxides that are superconducting at the boiling temperature of liquid nitrogen, 77 K. Due to a phenomenon called "flux pinning" in these materials, a concave surface is not needed for lateral stability as was the case in the metallic lead samples used by Arkadiev. A magnet floating over a Type II (high-temperature) superconductor, such as yttrium-barium-copper oxide, can be pushed to the edge of the superconductor without loss of lateral stability. Furthermore, the magnet will float at different heights over such superconductors.[45-47]

Lead and other Type I superconductors retain $B = 0$ up until a certain critical H-field, H_c, is reached, at which point they lose their superconductivity and $B = \mu_0 H$, as shown in Fig. 12a. Type II superconductors, on the other hand, have two critical values of H-field, H_{c1} and H_{c2}. Below H_{c1}, the entire specimen is superconducting, but between H_{c1} and H_{c2}, parts of the sample are superconducting and parts are not, leading to the situation shown in Fig. 12b. Magnetic field lines penetrate the "normal" or nonsuperconducting regions, and furthermore they become pinned in place in these regions, which accounts for the lateral stability of a magnet floating above a sample of Type II materials even if it has a flat surface.

Due to flux pinning, the levitation force on a magnet over a Type II superconductor is different when the magnet approaches the sample than when it is moving away, as shown in Fig. 13. When the magnet is brought nearer, the lower critical field H_{c1} is reached, and more and more flux penetrates the superconductor. When the magnet is moved away, the repulsive force between the magnet and its image decreases. In addition, the pinned flux lines cause an attractive force that reduces the net repulsive force. This results in a force-vs-distance curve with hysteresis, as shown in Fig. 13.

In Fig. 13, the repulsive force equals the weight of the magnet, mg, at points A and B or at any point on the line connecting them. Point B represents the levitation height for a magnet lowered onto the superconductor. If the magnet is pushed down onto the superconductor and then released at point C, it will move to the stable point A. Likewise, if the magnet rests on the superconductor when it is cooled, it will rise to point A.

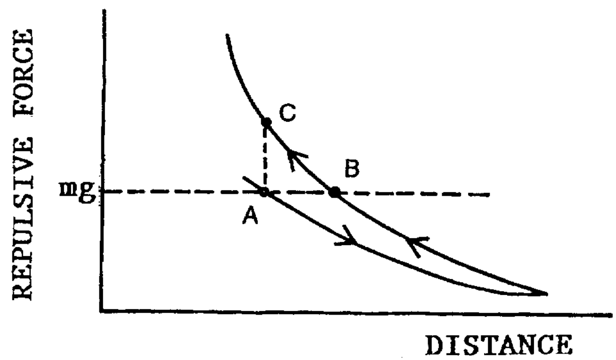


Fig. 13. Force on a magnet levitated over a Type II superconductor. The upper curve represents the force when the magnet approaches and the lower curve the force for the magnet moving away. A magnet whose weight is *mg* can levitate stably at point A, point B, or any point on the dashed line between them.

In principle, knowledge of the magnetization behavior of the superconductor as the applied field varies should allow one to predict levitation behavior. Because the magnetization is not uniform throughout the superconducting sample, however, many magnetization measurements and a large computational effort would be required.[48] In practice, it is more profitable to measure the levitation force as a function of distance, as shown in Fig. 14.

Levitation forces between permanent magnets and high-temperature ceramic superconductors are markedly hysteretic, in some cases even resulting in an attractive force, as shown in Fig. 14. The minor hysteresis loops in Fig. 14 were obtained by briefly reversing the ascent/descent motion of the magnet. The dynamic levitation stiffness, given by the slopes of the minor hysteresis loops, is a useful parameter in the design of magnetic bearings. The effective magnetic stiffness is notably affected by the amplitude of motion of the magnet[49] and by the size and geometry of both the magnet and the superconducting sample.[50]

When a cylindrical magnet is levitated over a high-temperature superconductor such that the magnet's axis of sym-

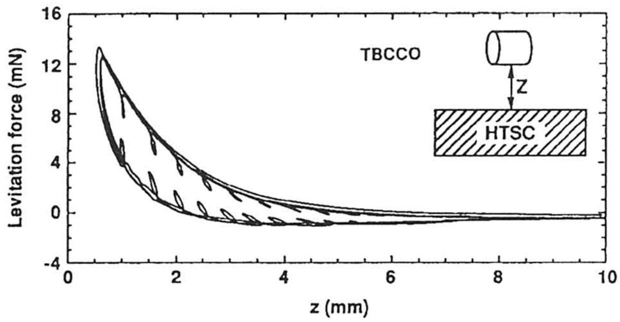


Fig. 14. Levitation force vs magnet height for a NdFeB permanent magnet over a TBCCO ($Tl_2Ba_2Ca_2Cu_3O_x$) superconductor, showing one major and several minor hysteresis loops (from Ref. 48).

metry is horizontal, under some conditions the magnet will rotate spontaneously and continue to do so indefinitely. A magnet at rest will first begin to oscillate, with the rotational amplitude increasing with time. Finally, the amplitude in one direction becomes large enough that a complete rotation occurs, and the magnet continues rotating in that direction, eventually attaining a maximum rotational frequency of about 1 Hz. These phenomena have been observed by a number of researchers and quantitatively explained by Ma et al.[51] While convective instabilities of the boundary layer of air surrounding the magnet seem to enhance the motion, the phenomenon also occurs with NdFeB (neodymium-iron-boron) magnets in vacuum. In this case the physical cause resides in the temperature dependence of the magnetization, which increases from its value at 300 K as the temperature decreases, peaks at about 160 K, and then decreases again and is nearly constant for temperatures below 100 K. With a temperature gradient across the magnet, the magnetization is larger at the bottom of the magnet. The center of levitation force lies below the center of gravity, a configuration that is mechanically unstable and starts the oscillation.

Magnetic Bearings

Magnetic levitation forces can be used to suspend high-speed rotating devices without mechanical friction. Three different types of magnetic bearings are possible:

1. Coil-magnet systems using direct current
2. Electrodynamic or induced eddy-current devices
3. Passive Meissner-effect bearings using Type II superconductors

Coil-magnet systems have been successfully used for several years to suspend ultra-high-speed rotors.[4] The simplest type of magnetic bearing, however, which can be stable without a feedback mechanism, is the third type using Type II superconductors. Speeds in excess of 100,000 rpm have been achieved with passive bearings of this type.[52]

A simple magnetic bearing consists of a permanent magnet rotor suspended between two superconductors, as shown in Fig. 15. Magnetic repulsion forces cause the rotor to be suspended in midair, when it is able to spin freely; the only friction is caused by aerodynamic and magnetic drag. If the rotor tries to drift off center, a restoring force due to flux pinning restores it. This is known as the *magnetic stiffness* of the bearing and is an important design parameter.

To increase the magnetic stiffness in a practical bearing, a superconducting cylinder that acts as a radial bearing might be added. This increases the magnetic drag on the rotor, however. Superconducting bearings need to be controlled in five directions: up, down, side-to-side, pitch, and yaw. Efforts to increase magnetic stiffness, through clever design and improved materials, are underway at several laboratories. Although a low-stiffness bearing is more forgiving of an out-of-balance rotor, most applications require a larger stiffness than is presently available.

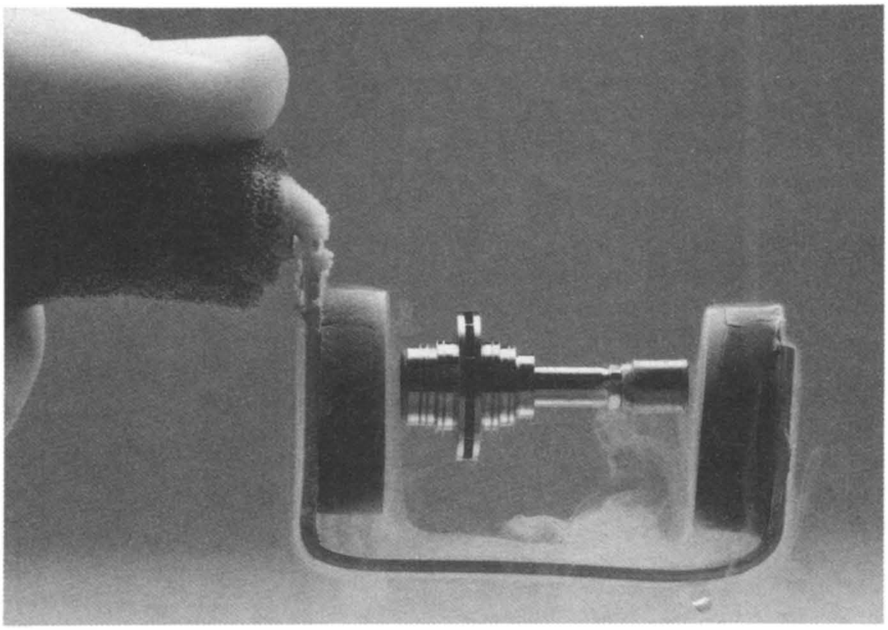


Fig. 15. A simple magnet bearing consisting of a permanent magnet rotor suspended between two superconductors (courtesy of Allied Signal).

Lift force is not generally considered to be a problem. Actually, magnetic pressure is a better parameter for characterizing bearings, because it does not depend upon the area of the magnet of the superconductor. Pressures of 10^5 N/m^2 have been obtained with a permanent magnet and a superconductor, which is probably large enough for magnetic bearings.

Figure 16 is a schematic of a simple motor constructed by Argonne summer student Christopher Gabrys (University of Vermont) using magnetic bearings. The ends of the rotor have cylindrical NdFeB magnets that can either be supported by repulsive levitation over two high-temperature superconductors or by attractive levitation underneath the same superconductors. (To achieve attractive levitation, flux from the bear-

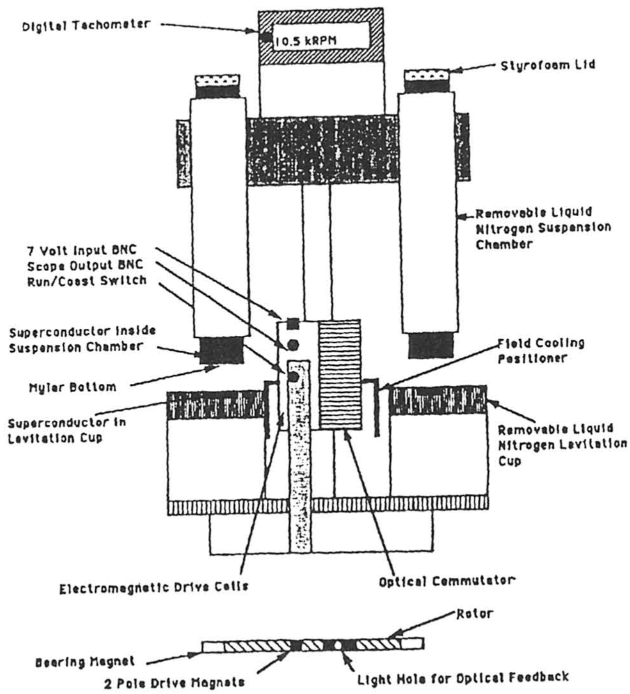


Fig. 16. High-temperature superconductivity journal bearing motor.

ing magnets is allowed to penetrate the superconductors prior to cooling. Field-cooling allows an attractive force.) The rotor can be driven above 10,000 rpm by three magnetic coils controlled by an optical commutator.[53]

Because a continuous current path is not required in bearings, high-temperature superconducting materials can be embedded in a metal or epoxy matrix to avoid the brittleness of ceramic materials.[54] Another way to improve bearing performance could be the use of superconducting solenoids, or trapped-flux superconducting "permanent" magnets.[55,56]

Conclusion

Magnetic levitation is a timely and interesting subject that illustrates a number of physical principles and has a variety of practical applications. Although the basic principles are easily understood, some rather subtle aspects will provide a challenge to researchers for years to come. Several eye-catching, thought-provoking demonstration experiments can be done with simple and inexpensive equipment. A discussion of these experiments should be included in every introductory physics course!

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