MAGNETIC LEVITATION

To see gravity defied by the use of magnetic levitation in any form usually brings a sense of magic to the observer. Although mention of magnetic levitation these days probably brings to mind either a small permanent magnet floating above a superconductor or a high-speed magnetically levitated (maglev) train flying above a metal guideway, accounts of magnetic levitation go back to at least the 11th century (1). As we will see, magnetic levitation is robust, in that nature has provided many different ways to achieve it.

MAGNETIC LEVITATION METHODS

Magnetic Forces

The basic forces involved in magnetic levitation are derived from the basic laws of electricity and magnetism. The first basic force is the force between magnetic poles. Although isolated magnetic poles are not known to exist in nature, they constitute a convenient model and are discussed in most elementary science texts. For a pair of magnetic poles, opposite poles attract, like poles repel, and the force between point poles is proportional to the inverse square of the distance between them.

The second basic force involved in magnetic levitation is the force that occurs when a conductor moves in a magnetic field. This force is derived from Faraday's law and Lenz's law, which teach that a changing magnetic flux produces a voltage in a circuit in such a way that it opposes the change in flux. This law is responsible for jumping rings and eddy currents (2).

The response of a material to magnetic fields also produces a magnetic levitation force. A diamagnetic material, such as graphite, aluminum, or a superconductor, will be repulsed by a magnetic pole, whereas a paramagnetic material, such as oxygen or water, will be attracted to a magnetic pole. Ferromagnetic materials, such as iron, are strongly attracted to magnetic poles.

Earnshaw's Theorem

Earnshaw's theorem is an important theorem that affects the *static* levitation of magnetic systems. The theorem is developed from the property of curl- and divergence-free fields that precludes the existence of local, detached, scalar-potential maxima or minima. According to this classical theorem, it is impossible to attain stable equilibrium in a system in which only inverse-square-law electrostatic or magnetostatic forces are acting (3). Braunbek deduced that electric or magnetic suspension is not possible when all materials have $\epsilon_r > 1$ or $\mu_r > 1$, but that it is possible when materials with $\epsilon_r < 1$ or $\mu_r < 1$ are introduced (where ϵ_r is the relative electrical permittivity and μ_r is the relative magnetic permeability) (4). Earnshaw's theorem is grasped intuitively by most people when they release a permanent magnet next to the ferromagnetic door of their refrigerator. The magnet either moves to stick to the door, or it falls on the floor; it does not hover in space near the point where it was released. Braunbek (4), and later Boerdijk (5), experimentally demonstrated the stable levitation of small pieces of bismuth and graphite (these are slightly diamagnetic materials with $\mu_r < \approx 1$) in strong magnetic fields. Arkadiev (6) first reported the stable levitation of a strongly diamagnetic superconductor ($\mu_r \ll 1$). However, it was not until the discovery of superconductors with critical temperatures (i.e., temperatures at which a material enters the superconducting state) above that of liquid nitrogen that passively stable levitation became a common laboratory occurrence. We note that Earnshaw's theorem only applies to conditions of static stability and does not apply to dynamic systems.

Levitation of Permanent Magnets

Although magnetic levitation of one permanent magnet by another is not stable according to Earnshaw's theorem, this arrangement is still useful if stability is provided by other means. A simple rendition of such a levitation, originally proposed by Evershed (7), is shown in Fig. 1. Here the levitated object, that is, the rotor, consists of a permanent magnet below which hangs a rigid rod with a point on the bottom. Each permanent magnet is magnetized, as shown by the dark arrow in Fig. 1, with its north pole down. The permanent magnet of the rotor experiences an attractive force toward the stationary permanent magnet immediately above it. This system is statically stable in the radial direction but unstable in the vertical direction. The gap between the two magnets is adjusted in such a manner that the attractive force between

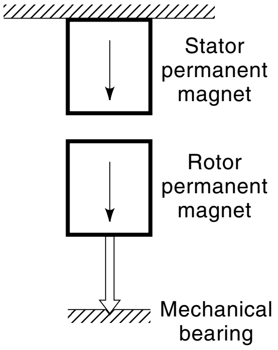


Figure 1. Evershed bearing design, in which most of the weight is provided by attraction between permanent magnets, and the remaining weight and vertical stability are provided by a small mechanical bearing.

the pair of magnets is just less than 100% of the rotor weight, so that the rotor would tend to fall. The remainder of the weight is provided by the small mechanical bearing at the bottom, which supplies sufficient stiffness for vertical stability and some additional radial stability.

The Evershed design, either in the simple form shown in Fig. 1, or in some modification, is used in applications ranging from simple toys and watt-hour meters to high-speed centrifuges. This basic design may be combined with other magnetic levitation techniques and is often referred to as magnetic biasing.

Electromagnetic Levitation

Truly contact-free magnetic levitation can be attained by replacing the mechanical bearing in Fig. 1 with a small electromagnet and a feedback system, as shown in Fig. 2. As before, most of the levitation force is provided by the attractive force between the two permanent magnets. The coil in Fig. 2 is wired to magnetize the iron in the same sense that the permanent magnets are magnetized. Then, as in Fig. 1, when the coil is energized, the system is stable in the radial direction but unstable in the vertical direction. The feedback system consists of two sensors that detect the top and bottom edge of the levitated permanent magnet. For example, the sensors may be photocells that detect light from a light source to the left of the magnet. When light to the bottom sensor is obscured by the falling magnet, the current to the coil is turned on, and the attractive force increases. When light to the top sensor is obscured by the rising magnet, current to the coil is turned off, and the attractive force decreases. In such a manner, the magnet may be stably levitated.

This basic design forms the basis of most active magnetic-bearing concepts. As discussed in the applications section, the actual control algorithms and sensors may be more complicated then the simple system illustrated in Fig. 2.

Ac Levitation

The ability of electromagnetic forces to impart significant levitation forces through Faraday's law is well known from jumping-ring experiments (2) that are performed in many introductory physics classes. Consider the system shown in Fig. 3, in which a coil is stationed above a conducting plate. If the coil is energized with a pulse so that current flows as shown, by Faraday's law, eddy currents will be induced in the plate in such a way that magnetic flux is expelled from the plate. The effect of these eddy currents is that the coil will see its mirror image, as shown in Fig. 3, and the interaction between the coil and its image produces a repulsive levitation force. Because of the finite electrical conductivity of the plate, the eddy currents in the plate that arise from a current pulse in the coil will exponentially decay in time, as will the levitation force, after the pulse has ended. In the jumping ring experiment, the conducting plate consists of a ring that sits on top of the coil. When the coil is pulsed, the mutual repulsive force causes the ring to accelerate upward.

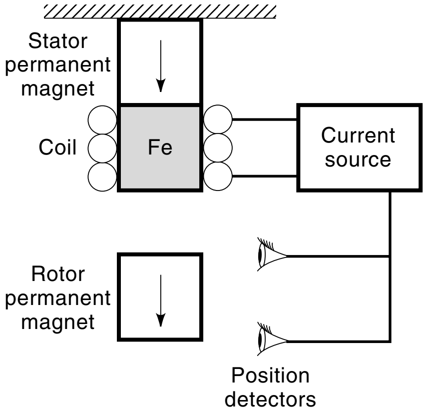


Figure 2. Attractive levitation of a permanent magnet with feedback control of an electromagnet.

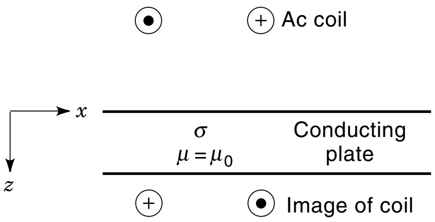


Figure 3. Repulsive levitation of an ac coil above a conducting sheet using method of images.

To provide a more continuous levitation force, it is necessary to provide another current pulse in the coil before the initial eddy currents have completely died away. This is most conveniently accomplished by supplying the coil with an alternating current. The general phenomenon can be quantitatively understood by considering an alternating magnetic field, $\boldsymbol{B} = B\boldsymbol{i}$ (where $\boldsymbol{i}$ is the unit vector in the x direction and $B = B_0 \exp(j\omega t)$ incident on the surface of a half space $z > 0$), with electrical conductivity σ and magnetic permeability μ, where j is the square root of -1, ω is the radial frequency, and t is time. One then must solve the magnetic diffusion equation

$$\partial^2 B/\partial z^2 = \mu\sigma\,\partial B/\partial t \tag{1}$$

The solution to Eq. (1) in the conducting half space is

$$B = B_0 \exp(-z/\delta)\exp[j(\omega t - z/\delta)] \tag{2}$$

where the skin depth δ is given by

$$\delta^2 = 2/\mu\sigma\omega$$

The current density $\boldsymbol{J}$ in the half space, given by Maxwell's equation $\boldsymbol{J} = \nabla \times \boldsymbol{H}$, is in the $-y$ direction; its magnitude is given by

$$J = (B_0/\mu\delta)(1 + j)\exp(-z/\delta)\exp[j(\omega t - z/\delta)] \tag{3}$$

Thus, we see that current density has the same exponential decay as the magnetic field but is phase-shifted by 45°. Here, the force per unit volume, given by $\boldsymbol{F} = \mathrm{Re}\{\boldsymbol{J}\} \times \mathrm{Re}\{\boldsymbol{B}\}$, is in the z direction and its magnitude is

$$F(z) = (B_0^2/\mu\delta)\exp(-2z/\delta)[1/2 - 2^{-1/2}\sin(2\omega t - 2z/\delta - \pi/4)] \tag{4}$$

The force consists of a time-independent part plus a sinusoidal part that is twice the applied frequency. The mean force on the plate is downward, as expected, with a corresponding force upward on an ac coil above the plate. The pressure P at the surface of the plate is given by

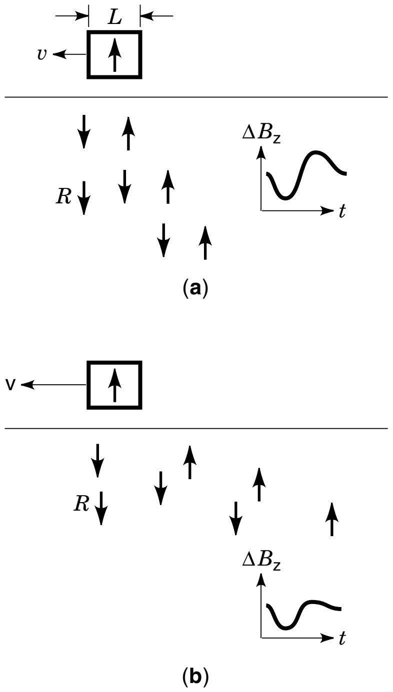
$$P = \int_0^\infty F(z)\,dz \tag{5}$$

$$P = (B_0^2/4\mu)[1 + \cos(2\omega t)] \tag{6}$$

The average levitation pressure is independent of frequency and proportional to the square of the applied magnetic field. To achieve a relatively constant levitation height, it is desirable that the period of the applied field $\tau = 2\pi/\omega$ be much smaller than the characteristic time of the mechanical motion. However, the frequency cannot be made arbitrarily high, because this type of levitation is associated with joule heating; the heating rate Q per unit volume is given by

$$Q = J^2/\sigma \tag{7}$$

From Eq. (3), we surmise that the maximum heating rate occurs at the surface and is proportional to the frequency, with the total heating rate proportional to the square root of the frequency.



(a)

(b)

Figure 4. 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.

Electrodynamic Levitation

In electrodynamic levitation, a moving magnet (permanent magnet, electromagnet, or superconducting magnet) interacts with a conducting sheet or a set of coils to produce a levitation force. A drag force, typically much higher than that associated with ferromagnetic suspensions, is associated with the eddy currents. However, above some speed, the drag force decreases as unity divided by the square root of the velocity. The system is passively stable, that is, no feedback is required. The disadvantage is that there is a minimum speed below which the levitation force is not sufficient, so some mechanical support is needed on startup.

The subject of eddy currents is a separate article in this encyclopedia; hence, here we limit the discussion to eddy currents caused by a moving magnet. The phenomenon can be understood by applying the principle of images, as shown in Fig. 4. In the case of a plane conducting sheet, the imaginary system on the negative side of the sheet is not the simple image, positive or negative, of the real magnet on the positive side, but consists of a moving train of images (2,8–11). According to this 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 when 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 that apply Maxwell's model are shown in Fig. 4. In the first example, the velocity v of the magnet is $< R$. 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. Because of the eddy currents, the vertical component of magnetic field ΔB_z is in 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 of the figure.

In the second example [Fig. 4(b)], 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. 4(b).

Reitz (12) solved Maxwell's equation for several types of moving magnets with the geometry shown in Fig. 4. In each case, he obtained a "wake of images," similar to those shown in Fig. 4, moving into the plate with a velocity $w = 2\rho/\mu_0 h$, which is Maxwell's R expressed in rationalized mks units.

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 $v^{-1/2}$. On the other hand, the lift force, 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 $F_L/F_D = v/w$.

Qualitatively, these forces can be understood by considering the diffusion of magnetic flux into the conductor. When a magnet moves over a conductor, the flux tries to diffuse into

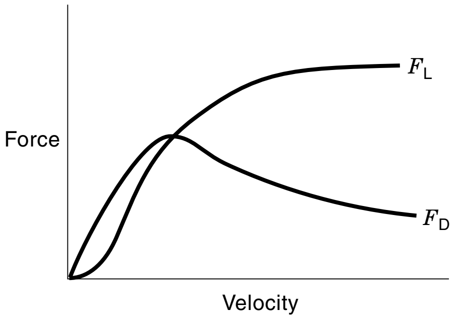


Figure 5. Velocity dependence of lift force F_L and drag force F_D.

the conductor. If the magnet is moving rapidly enough, the flux 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. At high speed, the lift force that is a result of flux compression approaches an asymptotic limit, and the drag force approaches zero.

The lift force on a vertical dipole of moment m moving at velocity v at a height z_0 above a conducting plane can be shown to be (12)

$$F_L = 3\mu_0 m^2/32\pi z_0^4[1 - w(v^2 + w^2)^{-1/2}] \tag{8}$$

At high velocity, the lift force approaches the ideal lift from a single image: $3\mu_0 m^2/32\pi z_0^4$; at low velocity, the factor in the brackets 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 is limited to the skin depth, which is proportional to $v^{-1/2}$. As a first approximation, one might replace plate thickness by skin depth 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.

One may improve on the basic system of a magnet moving over a conducting plate by using the null-flux-geometry system (13) shown in Fig. 6. When the moving magnet or coil is in the symmetry plane, no net flux threads the track loop so that lift and drag forces approach zero. Lift forces increase linearly and drag forces as the square of the (small) displacement Δh from the symmetry plane. The velocity dependence of null-flux systems is the same as that of the eddy current systems.

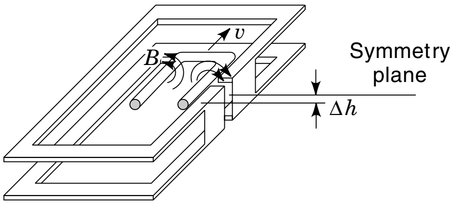


Figure 6. Null-flux geometry, showing full stationary null-flux coil and one half of levitated coil moving with velocity v and displacement from the symmetry plane by Δh.

Levitation by Tuned Resonators

Several magnetic bearing concepts involve passive techniques. These concepts have the advantage of simplicity and the lack of a control system. One system achieves a stable stiffness characteristic by using an *LC*-circuit excited slightly off resonance (14). The *LC*-circuit is formed with the inductance of the electromagnetic bearing coil and a capacitor. The mechanical displacement of the rotor changes the inductance of the electromagnet. The *LC* circuit is operated near resonance and tuned in such a way that it approaches resonance as the rotor moves away from the electromagnet. This increases the current from the ac voltage source and thus pulls the rotor back to its nominal position. The low forces and stiffnesses of this system, coupled with the necessity for continuous ac energization of the coils, are disadvantages. The system is also subject to a low-frequency, negative-damping instability, and auxiliary damping is usually required for stability.

Miscellaneous Levitation Methods

The Levitron® is a toy, manufactured by Fascinations in Seattle, Washington, that consists of a spinning permanent magnet in the form of a top. The spinning magnet is repelled by a magnet of opposite polarity in a stationary base beneath the top. The levitation height is such that the top is statically stable in the vertical direction and unstable in the radial direction. As designed, the top is also statically unstable to rotation of the magnetic moment. The concept of the Levitron is similar to that of other passive magnetic bearing concepts, in that its stability is dynamical (1,15,16). It is distinguished from other passive magnetic bearing concepts in that its stability is the result of the tendency of its precession axis to align with the local field direction: that is, when the top moves radially away from equilibrium, the magnetic moment of the top will rotate so as to point in the direction of the magnetic field from the stationary magnet. This rotation of the moment adds a term to the potential energy of the system that is not present if the magnetic moment is decoupled from the radial excursion. There is a rotational frequency range for the dynamic stability. The top must be spinning fast enough so the gyroscopic action prevents it from flipping over. However, if the top is spinning too fast, the gyroscopic action will maintain the direction of the moment vertical, and it cannot reorient fast enough to point in the direction of the magnetic field. If the top is able to precess several times around the field line during the time scale of a radial excursion, the system is said to be adiabatically stable. The same concept is used to trap cold neutrons and produce Bose–Einstein condensation (16). Under presently investigated conditions, the frequency range in which the top is stable is rather small, and the stability is rather fragile. It is not clear whether this concept would be useful in practical magnetic bearings.

Somewhat related to the Levitron levitation technique is the levitation of weakly diamagnetic materials in high magnetic fields. For example, a 16 T steady magnetic field has been used to levitate a living frog (17). The magnetic field induces a magnetic moment m in the diamagnetic material that is in the opposite direction to the applied field B, where the magnitude of the moment is given by

$$m = |\chi| VB/\mu_0$$

where χ is the susceptibility of the material (water, which constitutes the majority of the mass of most living creatures, is weakly diamagnetic with $\chi = -1.3 \times 10^{-5}$), V is the material volume, and μ_0 is the permeabilty of free space. The magnetic moment of the diamagnetic material interacts with the gradient of the applied magnetic field to produce a levitation force. The vertical component of this force against gravity is given by

$$F_z = m\, dB/dz$$

For the levitation to be stable, the levitated object must be placed where the energy is a minimum. This is only possible with diamagnetic objects. Further, the levitation is stable because, like the Levitron, the magnetic moment of the diamagnetic object rotates with the applied magnetic field.

Another magnetic levitation technique that is dynamically stable is analogous to the strong-focussing technique used in particle accelerators (18). In this system the static stability of the magnetic system alternates as the levitated part rotates. During one portion of the rotation, the system is radially stable and vertically unstable. During the next portion of the rotation, the system is vertically stable and radially unstable. For some frequency ranges, such a system can be dynamically stable.

Magnitude of Levitation Pressure

The levitation pressure of a magnetic system is considerably smaller than that of most mechanical systems. Here, we consider two systems: two magnetized objects, such as a pair of permanent magnets or a permanent magnet and a ferromagnet; and a coil traveling at some velocity v over a conducting sheet.

The maximum magnetic pressure P between two magnetized objects of magnetization M_1 and M_2 occurs at zero gap between the two objects and is given by

$$P = M_1 M_2 / 2\mu_0$$

where $\mu_0 = 4\pi \times 10^{-7}$. As convenient reference, for $\mu_0 M_1 = \mu_0 M_2 = 1.0$ T, the pressure is 400 kPa. In a sintered NdFeB permanent magnet, M is typically between 1 and 1.5 T; ferromagnetic materials may achieve magnetizations up to about 2.5 T.

For a set of dc coils of alternating polarity of spatial period L moving at a height h over a conducting sheet, the maximum levitation pressure is given by the pressure of the image force and is

$$P_\text{I} = (1/2\pi\mu_0) B_0^2 \exp(-4\pi h/L)$$

where B_0 is the rms (spatially averaged) value of the magnetic induction in the plane of the magnets. With a NbTi superconducting coil, B_0 can easily be 5 T.

APPLICATIONS

Levitation Melting

We have seen earlier that an ac coil may levitate over a conducting plate by means of eddy currents induced in the plate. If an ac coil is wound in approximately the shape shown in Fig. 7, it may support a conducting liquid. In the case shown in Fig. 7, the coil supports the sloping sides of the levitated liquid, but there is a "magnetic hole" at the bottom of the coil. The levitated liquid is prevented from leaving the magnetic trap through this hole by its own surface tension. The size of the melt is then determined by the surface tension, and levitation melters are usually only capable of supporting masses substantially less than 1 kg. Such levitators are often used to conduct reactions in which contamination of the sample with material from the crucible walls cannot be tolerated. In such a case, the original charge is often solid and the induction heating from the eddy currents melts the charge. Such devices are also used when a highly homogeneous final product is desired, because eddy currents cause significant stirring of a molten metal. The levitation melter is also used to accurately determine the surface tension of liquids, equilibria between liquid metals and gases, and thermal diffusion.

Efforts to increase the mass of molten material to be levitated have involved the use of a water-cooled copper jacket with thin vertical slots surrounded by a conventional solenoidal coil. Such a device, usually referred to as a cold crucible (19), can levitate kilogram quantities of molten metal. The shape of the metal that is levitated in cold crucibles is mostly spherical. Attempts to levitate low-aspect-ratio sheets of molten metal must accommodate the tendency of the free surface to undergo a Rayleigh–Taylor instability (20).

Electromagnetic Casting

The basic principles of electromagnetic levitation can be applied to create vertical walls of molten metal. These principles have been applied for many years in the moldless casting of aluminum ingots, in which the top of the ingot is surrounded by an electromagnetic fence and the molten metal is cooled from below. The ingot is moved downward and new molten metal is added to the top at the same rate as the metal solidifies. The advantage to this system is that the outer skin of the ingot is free of contamination and mold marks. Recently,

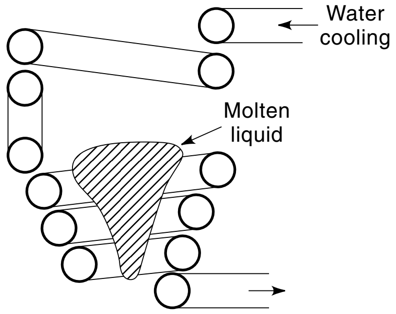


Figure 7. Typical construction of water-cooled coil system for levitation of molten metals. The upper coil is in series opposition to the lower coil. The molten metal assumes approximately the shape and position shown.

similar principles have been applied to create electromagnetic edge dams for twin-roll casting of steel.

Maglev Transport

Maglev transport involves the levitation of vehicles by one of the magnetic levitation principles discussed earlier. There is then no mechanical contact between the vehicle to be transported and the guideway that directs its travel. This application has been considered primarily for high-speed transport of people via trains, where damage to the tracks by a high-speed wheel-on-steel-rail system can be significant. However, maglev transport as an application is also being applied in clean-room environments where electronic dimensions are becoming increasingly smaller and contamination caused by rubbing or rolling contact cannot be tolerated.

The history of maglev transport has been detailed in ref. 2 and several of the reading list entries. 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. In 1912, a French engineer Emile Bachelet proposed a magnetically levitated vehicle for delivering mail. 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. Powell and G. R. Danby proposed in 1967 a system that used a less expensive conducting guideway at room temperature. 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 (13).

During the late 1960s, groups at the Stanford Research Institute and at Atomic International studied the feasibility of a Mach-10 rocket sled that employed magnetic levitation. The maglev principle was later applied to high-speed trains by Coffey et al. and Guderjahn. In 1972 the group at Stanford Research Institute constructed and demonstrated a vehicle that was levitated with superconducting magnets over a continuous 160-m-long aluminum guideway. The vehicle, weighing several hundred kilograms, demonstrated both passive and active electromagnetic damping of the vehicle's motion (21).

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, but the guideway itself is banked at only approximately the desired angle. The magneplane concept was tested with a 1/25-scale model system that used both permanent magnets and superconducting coils for levitation above a 116-m-long synchronized guideway.

Research groups at the Ford Motor Company Scientific Laboratories (12,22), the University of Toronto, and McGill University (23,24) 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. The initial research effort in the United States ended about 1975. Interest revived again around 1989, when four major conceptual designs were funded for several years by the federal government (25), after which government funding again disappeared.

Maglev systems have been studied in several other countries, most notably Japan, Germany, and the United Kingdom. The only maglev train ever in commercial service was a 600-m-long route in Birmingham, England that connected the airport to a conventional rail line. This service operated from 1984 to 1995. Its service was terminated mainly because of lack of parts in a one-of-a-kind technology.

Research in Germany and Japan has continued to the present, and full-scale vehicles have been tested in both countries. The two main maglev technologies that are being pursued at this time may be broadly classified as electromagnetic systems (EMSs), in which active feedback and electromagnets are used, and electrodynamic systems (EDSs), in which repulsive forces are generated by eddy currents that are induced in the guideway by the passage of a superconducting magnet.

EMSs depend on the attractive forces between electromagnets and a ferromagnetic (steel) guideway, as shown in Fig. 8. This system is under intensive investigation in Germany. The magnet-to-guideway spacing must be small (only a few centimeters at most), and this requires that the straightness tolerances of the guideway must be relatively small. On the other hand, it is possible to maintain magnetic suspension even when the vehicles are standing still, which is not true for EDSs. In the system shown in Fig. 8, a separate set of electromagnets provides horizontal guidance force, and 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/h. The levitation height is 8 mm, and power consumption is estimated to be 43 MW at 400 km/h. A full-scale prototype of the Transrapid has run for many years on a 30 km test track in Emsland, Germany. Plans call for the Transrapid to enter commercial service in 2005 on a 292 km route that connects Hamburg to Berlin.

EDSs depend on repulsive forces between moving magnets and the eddy currents they induce in a conducting aluminum guideway or in conducting loops, as shown in Fig. 6. This system is being intensively investigated in Japan. The repulsive levitation force is inherently stable with distance, and com-

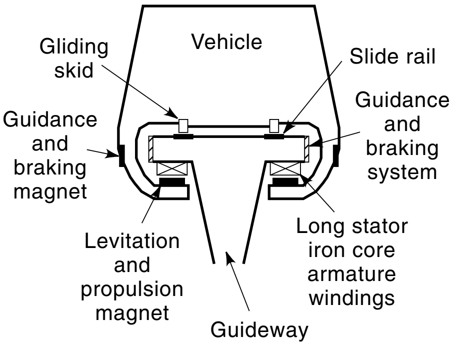


Figure 8. Schematic diagram of Transrapid maglev system (Germany).

paratively large levitation heights (20 cm to 30 cm) are attainable by using superconducting magnets. Various guideway configurations, such as a flat horizontal conductor, a split L-shape conductor, and an array of short-circuit coils on the sidewalls, have been investigated. Each has its advantages and disadvantages. The proposed Japanese high-speed maglev system involves the use of interconnected figure-8 ("null-flux") coils on the sidewalls. The null-flux arrangement tends to reduce the magnetic drag force and thus the propulsion power needed. A prototype of this system has been operated for many years on a 7-km-long test track in Miyazaki, Japan. The Japanese currently plan to construct a commercial version that will operate between Tokyo and Osaka, with the first part of this route, a 42-km-long test track, in the Yamanashi prefecture. A three-car test train achieved the design speed of 550 km/h on this test track in December 1997.

Magnetic Bearings

In active magnetic bearings (AMB), the attractive force between an energized magnet and a ferromagnetic body acts to achieve levitation. Typically, the magnet is an electromagnet, and the rotor is a ferromagnet. Such a system is inherently unstable, so, depending on the position of the rotor, active feedback is used to modulate the field of the electromagnet.

For decades, AMBs have been used in industrial applications; recently they have been used in oilfree turbomolecular vacuum pumps, compressors for gas pipelines, machine spindles for cutting operations, x-ray tube rotating anodes, pumps for cryogenics, turbo expanders in air separation plants, momentum wheels for satellite applications, flywheel prototypes, and sensitive pressure gauges. The three principal advantages of an AMB are: (1) absence of lubrication oil (required in most mechanical bearings); (2) the ability to attain higher speeds without the heating caused by mechanical friction; and (3) the ability to change in real time the stiffness and damping of the bearing to meet operating requirements.

In the basic setup of an AMB, position signals from gap sensors are used by a controller/power amplifier to set the appropriate currents and voltages of the electromagnets in such a way that stable levitation is achieved. In the example of an iron rotor below a ferromagnet, if the rotor starts to fall so that the gap becomes too large, the current in the magnet is increased to increase the attractive force. Similarly, if the gap becomes too small, the current is decreased. Control becomes effective when the bearing is activated and does not require any motion to levitate.

An advantage of the AMB is that it can adapt to operating conditions and communicate with its environment. Within certain limits, the AMB can be set to operate with arbitrary stiffness and damping, and the gap between the rotor and electromagnet can be changed. A rigid rotor can be made to rotate about its principal axis without transmitting vibrations to the foundation. By changing the stiffness and damping, the rotor is capable of easily crossing the critical speeds of the bearings. In addition, bending vibrations of an elastic rotor can be significantly reduced by an appropriately designed active control loop.

Analog controllers were used in early AMBs; however, the tendency now is toward digital controllers. The design of early AMB systems was usually based on proportional-integral-differential (PID) control algorithms. Generally, the feedback law is chosen to be linear and is developed on the basis of the system linearized about the static equilibrium position. Recent investigations have shown that there is performance merit in the use of certain nonlinear feedback laws. Typically, switching amplifiers are used to power the coils. These amplifiers are basically transistor switches that connect the coils to a dc voltage. The transistors are either on or off and produce a square wave voltage on the coil, with the result that a sawtooth current is produced in the inductive load. By controlling the on and off times, most current wave forms can be produced in the coils. The disadvantage of the switching amplifiers is the oscillation in the current, which causes remagnetization loss in the magnetic bearing. However, the shorter the switching period, the weaker these oscillations.

Typically, a high-frequency carrier signal is used in the position sensor, which provides a linear signal versus the rotor location. Optical sensors, inductive displacement sensors, capacitance sensors, Hall effect sensors, and eddy current sensors are commonly used. The sensors must be contact free and capable of measuring a rotating surface. The surface quality of the rotor and the homogeneity of the material at the sensor will influence the measurements. A bad surface will produce noise disturbances, and geometry errors may cause disturbances in the rotational frequency or in multiples thereof. Training of the sensors while in place may alleviate some of these noise problems. In this technique, the rotor is rotated at some fixed speed, the surface is measured over many revolutions, and the average of the measurements for a given set of angles is stored in a computer memory so the sensor remembers the surface. The set of data serves as a background, which is subtracted from the measurement during regular operation.

A new type of AMB, currently under development, does not involve the use of sensors. Instead of the usual current amplifier, a voltage amplifier is used. The current in the amplifier is measured and a control algorithm can be developed so that the rotor can be stabilized from this measurement.

One of the fundamental limitations of an AMB is that the bearing force slew rate is limited because the magnet coils are inductive and the power supply to the driving amplifier has a maximum voltage. The slew rate limitation causes the bearing force to change more slowly than the control signal demands and thus introduces a phase lag. Another way to state this is that the inductance of the coils and the maximum voltage provide an upper limit to the stiffness of the system.

In principle, the current requirements of the coils of an AMB can be made arbitrarily small if the sensors have a high enough resolution and the sensor and power electronics are fast enough to respond. That is, less force is needed (and therefore less current) to return a rotor from a 1 μm deviation from equilibrium than it does to return it from a 1 mm excursion. As sensors become faster and achieve greater resolution, and as power electronics become faster, one may expect that the losses in AMBs will decrease. At some point, the homogeneity of the rotor and the magnet system will then provide the determining limit of these losses.

For a complete rotor, five degrees of freedom must be controlled. If magnetic biasing is used, the system can often be designed so just one degree of freedom need be controlled. Because an AMB typically provides stable stiffness in only one direction, it may be appropriate to design the magnetic bias with a rather large stiffness that provides stability in all directions but one. Then, only one AMB controller is required to stabilize against movement in the unstable direction.

In any of the bearing systems discussed in this section, considerable advantage in terms of reduced losses can be achieved by using a magnetic bias to take up most of the bearing load. (For example, see discussion of Fig. 1.) The rotational losses of a permanent magnet pair generally consist of eddy currents induced in one of the magnets by the azimuthal field inhomogeneity of the other. These losses are typically smaller than those associated with the bearing that makes up the stabilizing part of the system. Low-loss magnetic biasing can also be accomplished with a combination of permanent magnet and ferromagnet.

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JOHN R. HULL
Argonne National Laboratory