SUPERCONDUCTING LEVITATION

The levitation of a permanent magnet over a superconductor is one of the basic tests of superconductivity, and it is a sight that has inspired the investigation of applications not possible with any other technology (1–5). In this article, I briefly review the fundamental physics of superconductor levitation, discuss basic levitational phenomena and the features of superconductor levitation pertinent to bearings, and mention some possible applications of superconductor levitation, with emphasis on high-efficiency flywheel energy storage.

STABLE LEVITATION

In its simplest form, a superconducting levitational system comprises a permanent magnet levitated in a stable position over a superconductor. This stability is in stark contrast to most magnetic systems, which are statically unstable. Earnshaw showed that there is no stable, static 3-D arrangement of a collection of poles (electric, magnetic, or gravitational) whose magnitudes do not change and which interact via a $1/r^2$ force law (6). Braunbek extended the result to show that no stable static configuration exists when paramagnetic or ferromagnetic material is included in the arrangement (7). These results collectively are often referred to as Earnshaw's theorem. 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 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.

Diamagnetic materials, such as superconductors, are not governed by Earnshaw's theorem, and they enable the possibility of creating stable levitation systems. One of the fundamental properties of superconductors is their tendency to exclude magnetic flux from their interiors. This exclusion of magnetic flux (the Meissner effect), makes them behave like strong diamagnets. Accordingly, a superconductor with a permanent magnet positioned close above it, as shown in Fig. 1(a), develops a shielding current, which excludes flux so that the actual magnet "sees" its mirror image.

More specifically, if the magnetization of a permanent magnet is in the vertical direction, with its north pole down, the image is also vertically magnetized, but with its north pole up, exerting a repulsive force on the real magnet. The closer the magnet moves to the superconductor, the stronger the repulsive force. The farther away the magnet moves, the weaker the force. In fact, if the magnet flips over so that the opposite (south) pole faces the superconductor, the screening currents in the superconductor will reverse so as to reverse the magnetization of the image in the superconductor, maintaining the repulsive interaction. This setup yields levitation stable in the vertical direction. Horizontal stability is obtained if the superconductor is given a concave shape, so that vertical superconducting walls are formed around the magnet, as first demonstrated by Arkadiev using lead, a Type-I superconductor, in which magnetic flux is totally excluded from the interior (8).

From a technological viewpoint, the most useful superconductors are usually Type-II superconductors, in which, above a first critical field, H_{c1}, it is energetically favorable for magnetic flux to enter the interior of the superconductor in discrete localized regions that become normal (i.e., not superconducting) with each region of flux surrounded by a small vortex of superconducting shielding current. In Type-II superconductors, the stability of the levitational phenomena resulting from the diamagnetic response is greatly enhanced by the additional phenomena resulting from flux pinning, shown in Fig. 1(b). A flux pinning center is a nonsuperconducting region, such as an inclusion, crack, or other crystalline defect. Because the superconducting region surrounding the nonsuperconducting center is strongly inclined to exclude magnetic flux, a magnetic flux line through the center often becomes trapped there. When a sufficient number of flux lines is trapped in the superconductor, the permanent magnet re-

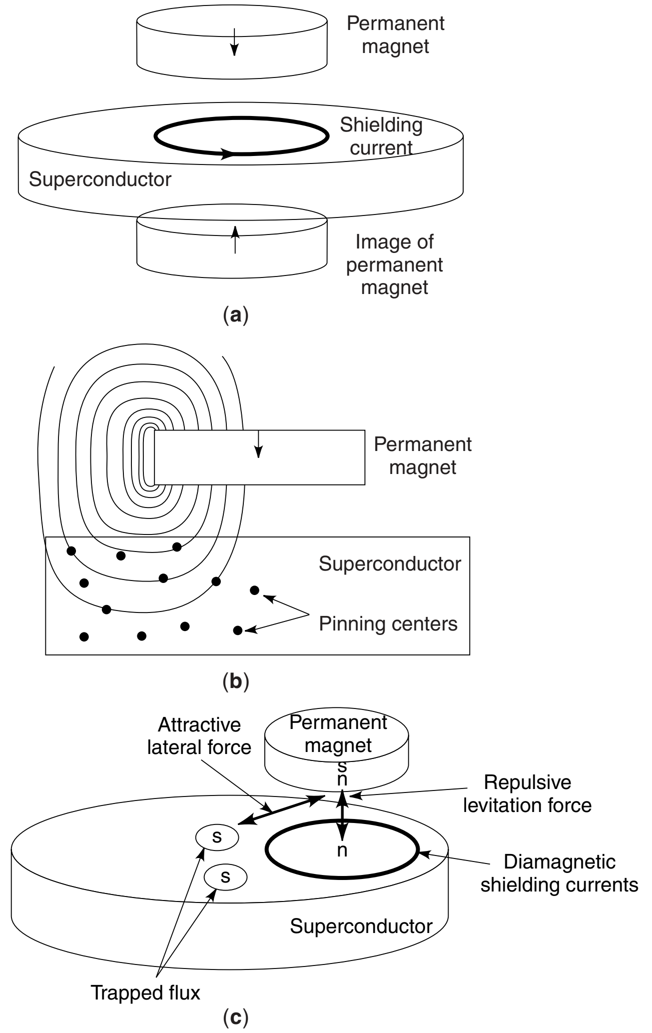

Figure 1. Schematic diagrams of levitation basics: (a) diamagnetic response; (b) flux pinning; (c) flux trapping.

mains levitated in position, even over a flat surface. The flux lines between the permanent magnet and the superconductor act in an imperfect analogy to mechanical springs with attachments on the permanent magnet and in the superconductor. If the magnet moves a small distance laterally, so that the flux lines remain in their pinning centers, the flux lines bend and produce a laterally restoring shear force, according to the Maxwell electromagnetic stress tensor. If the magnet moves vertically or horizontally, the "springs" pull the magnet back to its equilibrium position. If the flux pinning is sufficiently strong, the magnet is stably suspended below the superconductor (9) or even along its side (10).

If the magnet moves far enough laterally that the flux lines move from their original pinning centers to new ones, then an additional stabilizing force, involving trapped flux, begins to act. Trapped flux consists in regions of induced magnetization in the superconductor of the same pole orientation as the levitated magnet and results from movement of flux lines from their pinning centers that decreases the local flux. As shown in Fig. 1(c), this results in an attractive interaction that reduces the levitation force but provides a lateral restoring force.

SUPERCONDUCTOR LEVITATORS

Interest in the potential of superconductor levitation in various applications greatly increased with the discovery of superconductors whose critical temperatures (i.e., temperatures at which they transit from the normal state to the superconducting state) exceeded the boiling point of nitrogen. Although one could create a superconducting wire magnet for levitation, most of the present efforts involve the use of bulk superconductors or thin-film superconductors. Unlike superconducting wire applications, in which the supercurrent must pass from grain to grain along quite a distance, the supercurrent for levitation applications needs to circulate only within individual grains.

The present material of choice for superconducting levitation is Y-Ba-Cu-O (YBCO) because it exhibits a high magnetic irreversibility field at liquid nitrogen temperatures and has the ability to grow large grains. In addition to the two temperature-dependent phase-transition fields, H_{c1} and H_{c2}, all superconductors have a magnetic irreversibility field, H_{irr}, that lies between H_{c1} and H_{c2}. H_{irr} is the field at which the magnetization M as a function of applied field H is no longer double-valued (11). For the low-temperature superconductors NbTi and Nb_3Sn, H_{irr} is extremely close to H_{c2}, and there is no important distinction between them. At higher temperatures, thermal activation is much greater, which leads to easier flux motion near H_{c2} for HTSs. H_{irr} marks a phase transition between the region where magnetic flux is solidly pinned in the superconductor and the region where flux may move. Sometimes the curve is said to denote the boundary between the region where flux is frozen and the region where flux is melted. Of all the known HTSs, YBCO has a relatively low critical temperature of 92 K, but it has the highest irreversibility curve at 77 K and lower temperatures. For stable levitation, it is important that the flux be frozen in the superconductor. Otherwise, the permanent magnet would slowly lose levitation height.

The magnetization of the superconductor is proportional to the product of the critical current density and the grain diameter. Large grain diameters are important to achieve sufficiently large magnetizations for useful levitation forces. In bulk materials, the grains grow to diameters of several centimeters when made by a melt-texturing process (12). In the present state of the art, the upper limit of the grain diameter produced by this process is about 10 cm. The ability to produce good-quality YBCO thin films is also limited to about this size.

LEVITATIONAL PHENOMENOLOGY

If the permanent magnet is pulled hard enough to the side or vertically, it is possible to move one or more of the trapped flux lines into new pinning centers and so change the equilibrium position. Such a change results in a hysteretic effect in the levitational force and an associated energy loss if it occurs in a cyclic pattern. To explore the hysteretic effect, it is convenient to divide the behavior into two processes. The first is called field-cooled. It occurs when the superconductor is cooled below its critical temperature while there is a substantial magnetic field present, that is, the permanent magnet is close to the superconductor. Field cooling produces less repulsive levitation force but can be used to make an attractive-force bearing. The second is called zero-field-cooled. It occurs when the superconductor is cooled below its critical temperature in the absence of a magnetic field, that is, when the permanent magnet is far from the superconductor. Zero-field cooling results in the largest repulsive force but may be practically inconvenient, because it requires the cooling of the superconductor prior to the assembly of the bearing.

The hysteretic nature of the levitational phenomenon for movements in the vertical direction is illustrated in Fig. 2. In this example, a cylindrical, vertically magnetized permanent magnet was kept with its bottom surface at a height of 10.0 mm above the top surface of a cylindrical YBCO superconductor while the YBCO was cooled, essentially a zero-field-cooled condition. Then the magnet was slowly brought down to a position 1 mm above the superconductor, and the force was measured at various points along this first descent. Then the magnet was moved away from the superconductor, back to its original zero-field-cooled position. Then it followed a second descent during which a minor reversal of 0.4 mm was made at a distance of 2.0 mm. A second ascent was identical with the first, and a third descent was identical with the second, etc. As seen in Fig. 2, the force during the first descent is always larger than the force during the second. Upon reversal from 1 mm during the first ascent, the force drops very quickly and even becomes negative, indicating an attractive force. A combination of the first ascent and second descent forms a major hysteretic loop, and the area under the curve is equivalent to the hysteretic energy loss. The width of the minor loop is much smaller than that of the major loop. Thus, the superconductor acts as a nonlinear damper, and the damping coefficient increases with amplitude. From Fig. 2, it is also clear that the slope of the minor loop, which represents the magnetomechanical stiffness of the system, is considerably higher than that determined from the major loop.

A feature of the first descent is that over several millimeters above the superconductor surface, the force is exponential with distance, as shown in Fig. 3. In practice, it is difficult to measure the force immediately above the superconductor, partly because surfaces are not flat, but mainly because the surface is usually covered with liquid nitrogen. The exponential behavior shown in Fig. 3 allows extrapolating the force to

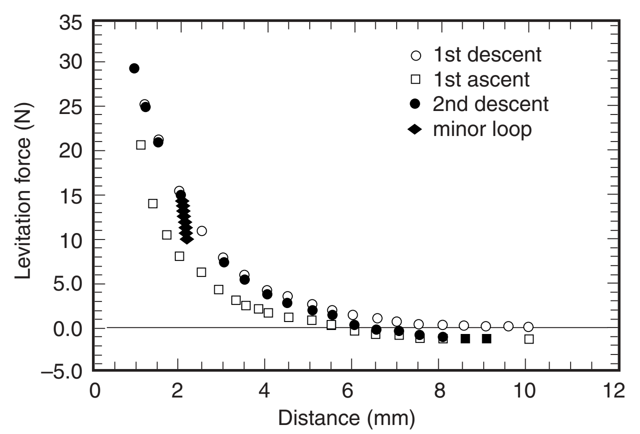

Figure 2. Levitation force versus distance between the permanent magnet and superconductor.

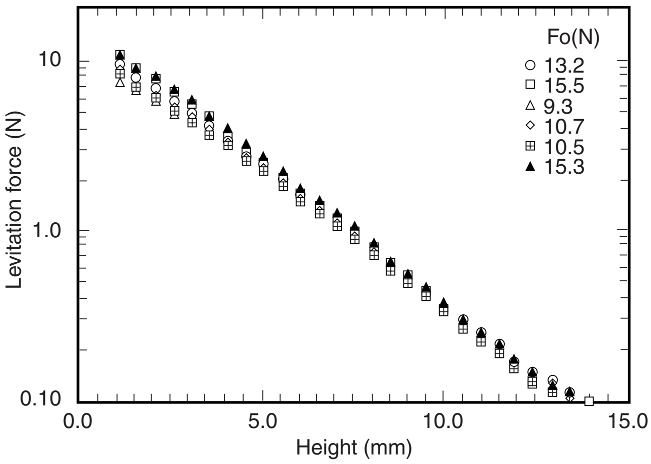

Figure 3. Levitation force versus distance on first descent between reference magnet and several superconductors, showing the levitation force extrapolated to zero height.

the surface, and various superconductors can be compared this way by using a permanent magnet of known strength.

In the examples shown in Figs. 2 and 3, the superconductor was cooled while the permanent magnet was far from its surface, that is, zero-field-cooled. In the field-cooled case, the levitational force is approximately zero after the superconductor is cooled below its critical temperature. However, the magnetomechanical stiffness is approximately the same as for the zero-field-cooled case at the same separating distance. The stiffness is dependent on the amplitude of vibration (13,14). For small amplitudes, the stiffness is constant, but, after some critical amplitude that depends on height, the stiffness begins to decrease as the amplitude increases. The higher the current density of the superconductor, the higher the critical value for the onset of stiffness decrease.

The levitational force that the superconductor provides is proportional to its average magnetization, which is proportional to the product of its grain diameter times its critical current density. The critical current density in typical melt-textured YBCO samples at 77 K is about 40 kA per cm^2, which, together with a diameter of several cm, allows the levitational pressures between the YBCO and an NdFeB permanent magnet to be as high as about 280 kPa (~40 psi). Such pressures have been measured in the author's laboratory with the very best YBCO samples. However, this pressure occurs at zero separation distance. In a practical system with a finite separation, the pressure will be at least a factor of 2 to 3 times lower.

Thin-film YBCO often has critical current densities that exceed 1 MA per cm^2. Because the thickness of these films is only about 1 micron, they do not provide much levitational force. However, the stiffness of such films is often of the same order as that produced by bulk materials of greater thickness (15).

THEORETICAL MODELS

Various theoretical models account for different aspects of superconductor behavior when a permanent magnet approaches. In many cases in which hysteretic behavior is not important, the superconductor is a pure diamagnet and the magnet is a set of magnetic dipoles (16). A "frozen" mirror image may be used in conjunction with the diamagnetic mirror image to describe the elastic properties and energy loss in a field-cooled system (17). The Bean model, which assumes that the current circulating in the superconductor is either at its critical value or zero, is often used in efforts to address the hysteretic behavior (18).

SUPERCONDUCTING BEARINGS

If the azimuthal homogeneity of the magnetic field of the permanent magnet is high, for example, if the magnet is a cylinder with uniform magnetization throughout, the levitated magnet rotates freely above the superconductor. As long as the distribution of magnetic flux in the superconductor does not change, rotation encounters no resistance. If the magnet is spinning, the hysteretic loss in the superconductor decreases the rotational rate.

In an electromechanical system, such as a magnetic bearing, the parameters of interest are the levitational force, stiffness, damping, and rotational loss. The 280 kPa levitational pressure is lower than that achievable in a conventional electromagnetic bearing (~1 MPa) and significantly lower than that typically achieved in mechanical roller bearings (≥10 MPa). The amount of mass levitated directly depends on the number and size of permanent magnets and superconductors available. In the present early period of technological development for superconducting bearings, several laboratories have stably levitated masses greater than 100 kg.

In practical superconductor bearings, the low levitational pressure available in the interaction between the permanent magnet and the superconductor is often augmented by various hybrid schemes in which interactions between pairs of permanent magnets provide the bulk of the levitational force. These interactions are unstable, as Earnshaw's theorem predicts, but the inclusion of a properly designed superconducting component in the bearing is sufficient to stabilize the complete bearing. Augmentation takes the form of an Evershed-type design, in which a pair of permanent magnets is in attractive levitation, employs permanent magnets in repulsive levitation, or uses active magnetic bearings (5).

The hysteretic nature of a superconducting bearing also makes damping of translational motion amplitude-dependent. For low-amplitude vibrations, damping is small, but quickly increases as the vibrational amplitude increases. This hysteretic nature of the HTS bearing thus contributes to the robustness of the system. The hysteretic nature also results in a larger uncertainty of the equilibrium position of the rotor than is typical in most rotating machinery. This uncertainty requires larger running gaps between moving and stationary parts.

The ease with which a permanent magnet spins, when levitated over a superconductor, and the absence of contact between the surfaces, produce the illusion that the rotation is frictionless. In reality, small magnetic losses gradually slow the rotation. The losses are primarily the result of azimuthal inhomogeneities in the magnetization of the permanent magnet, which produce hysteretic loss in the superconductor. Typically, in permanent magnets with the best homogeneities, at a fixed radius above the rotating surface, the amplitude of the ac component of the magnetic field is of the order of 1% of the average field at that radius. Although small, this inhomogeneity is sufficient to cause a detectable decay in rotational rate when the magnet spins in vacuum.

A figure of note for the rotational decay of a bearing is the coefficient of friction (COF), defined as the rotational drag force divided by the levitational force (weight of the levitated rotor). The COF for a mechanical roller bearing is of the order of 10^{-3}. The COF for an active magnetic bearing is about 10^{-4} when parasitic losses for the feedback circuits and power for the electromagnets are factored in. Measured COFs for simple superconductor bearings are as low as 10^{-7}. The parasitic losses of a superconducting bearing are the power required to keep the superconductor cold. For refrigerators that operate at about 30% of Carnot efficiency (the theoretical maximum) about 14 W of electricity are required to remove 1 W of heat at liquid nitrogen temperatures. Thus, the equivalent COF for an HTS bearing is about 2×10^{-6}, about two orders of magnitude lower than the best alternative bearing.

Two magnetomechanical resonances occur in a magnetically suspended rotor with a polar moment of inertia greater than the transverse moment (i.e., a disk geometry): one is vertical and one is radial. In practice, the vertical resonance has a minimal effect on the COF in most superconducting bearing systems. The radial resonance occurs when the rotational frequency is close to that of the natural radial frequency of the rotor's vibration. If the rotor has a transverse moment of inertia greater than its polar moment, then there is an additional resonance, having the form of a conical vibration, that is, with the top of the rotor moving to one side while the bottom of the rotor moves to the opposite side. Because superconducting bearings have low stiffness, the resonances occur at low frequencies on the order of several hertz. This, together with the large clearances possible with superconducting bearings, leads to a robust bearing system.

Figure 4 shows the COF as a function of rotational frequency for a cylindrical permanent magnet levitated 10 mm above a single YBCO cylinder and spinning in a vacuum chamber. One may divide the behavior into three regions: below the resonance, the radial resonance, and above the resonance. Below the resonance ($f < 3$ Hz), the losses are caused

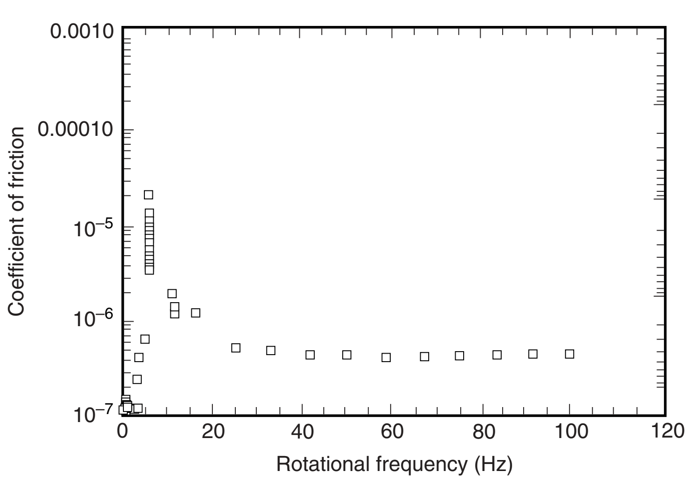

Figure 4. Coefficient of friction versus rotational frequency for a 25.4 mm dia., 9.6 mm high cylindrical permanent magnet levitated 10 mm above a YBCO cylinder.

by the inhomogeneity of the permanent magnet's field. The resonance region (3–20 Hz), shown in Fig. 4, is relatively broad. In some systems, especially those with well-balanced rotors, the resonance is very narrow. Above the resonance (>20 Hz), the losses are affected by an additional factor, which is caused by the rotation of the magnet about its center of mass rather than its center of geometry or center of magnetism. As shown in Fig. 4, above and below the resonance, the losses are mostly velocity-independent. However, detailed studies of losses in superconducting bearings show that small velocity-dependent effects are present which are intrinsic to the superconductors (19–21).

Because of size limitations encountered when high-performance bulk superconductors are produced, a large bearing system needs an array of superconductors. In the case of a single magnet levitated over an array of superconductors, an additional loss arises from magnetization of the individual superconductors upon levitation. The magnetization of the array leads to an ac magnetic field seen by the rotating permanent magnet and eddy current losses that depend on the electrical conductivity of the permanent magnet.

Some alternative bearing concepts that involve superconductors exhibit even lower COFs. The Evershed-type hybrid has a COF of just over 10^{-8} (22). The velocity-dependent losses associated with superconducting arrays are also greatly reduced with this bearing design. A mixed-μ (where μ is the magnetic permeability) bearing (23) has a COF of just over 10^{-9}. In this bearing, a soft ferromagnetic cylinder ($\mu > 1$) is levitated in attractive levitation between two permanent magnets and stabilized by a superconductor ($\mu < 1$) placed between the rotor and each of the permanent magnets.

APPLICATIONS

The availability of superconducting bearings that are so nearly friction-free naturally leads to their consideration for flywheel energy storage. Flywheels with conventional bearings typically experience high-speed idling (i.e., no power input or output) losses of the order of about 1% per hour. With superconducting bearings, it is believed that losses as little as 0.1% per hour are achievable. When coupled with efficient motors/generators and power electronics (capable of losses as low as 4% on input and output), the potential exists for constructing flywheels with diurnal storage efficiencies of 90%. Probably only one other technology is capable of achieving such high diurnal storage efficiencies: large superconducting magnetic energy storage, which employs superconducting coils hundreds of meters in diameter.

Electric utilities have a great need for inexpensive energy storage, such as flywheels, because their inexpensive baseload capacity is typically underutilized at night and they must use expensive generating sources to meet their peak loads during the day. A distributed network of diurnal-storage devices could also make use of underutilized capacity in transmission lines at night and add robustness to the electric grid. These factors are expected to become more important in the coming deregulation of the electric utility industry. Efficient energy storage would also be beneficial to renewable energy technologies, such as photovoltaics and wind turbines.

With modern graphite fiber/epoxy materials, the inertial section of a flywheel rotates with rim speeds well in excess of

1000 m/s and achieves energy densities greater than those of advanced batteries. The kinetic energy in a (large) Frisbee-sized flywheel with this rim speed is about 1 kWh, and a person-sized flywheel could store 20–40 kWh. Although design concepts for flywheels that employ superconducting bearings with up to 10 MWh have been proposed, the most advanced experimental versions at present are in the 100 Wh to 1 kWh class.

Because superconducting levitation is versatile over a wide range of stiffness and damping, it has been suggested for numerous applications. Superconducting bearings, like magnetic bearings, do not require a lubricant, which could be a major advantage in harsh chemical or thermal environments. Superconducting bearings are particularly interesting for cryogenic turbopumps. The low friction of the superconducting bearing allows its use in high-precision gyroscopes and gravimeters. The hysteretic nature of superconducting levitation has suggested its use in docking vehicles in space. As one vehicle approaches another it would experience a decelerating repulsive force. After the relative velocities have disappeared at a small separation distance, the vehicles would experience an attractive force if their distances tend to separate. The stable levitational force suggests application in magnetically levitated conveyor systems in clean-room environments where high purity requirements mandate no mechanical contact. Trapped-field HTSs have been suggested for constructing vehicle magnets to be used in electrodynamic levitation of high-speed trains (see MAGNETIC LEVITATION).

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JOHN R. HULL
Argonne National Laboratory

SUPERCONDUCTING MAGNETS. See MAGNETIC REFRIGERATION; MAGNETS FOR MAGNETIC RESONANCE ANALYSIS AND IMAGING.