GRAVIMETER USING HIGH-TEMPERATURE SUPERCONDUCTOR BEARING*

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Gravimeter Using High-Temperature Superconducting Bearing

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Abstract—We have developed a sensitive gravimeter concept that uses an extremely low-friction bearing based on a permanent magnet (PM) levitated over a high-temperature superconductor (HTS). A mass is attached to the PM by means of a cantilevered beam, and the combination of PM and HTS forms a bearing platform that has low resistance to rotational motion but high resistance to horizontal, vertical, or tilting motion. The combination acts as a low-loss torsional pendulum that can be operated in any orientation. Gravity acts on the cantilevered beam and attached mass, accelerating them. Variations in gravity can be detected by time-of-flight acceleration, or by a control coil or electrode that would keep the mass stationary. Calculations suggest that the HTS gravimeter would be as sensitive as present-day superconducting gravimeters that need cooling to liquid helium temperatures, but the HTS gravimeter needs cooling only to liquid nitrogen temperatures.

I. INTRODUCTION

Development of bearings that employ the levitation of a permanent magnet (PM) over a high-temperature superconductor (HTS) has made significant progress in recent years. The levitation is passively stable with moderate stiffness in radial, vertical, and tilt directions and little resistance to rotational motion. Extensive advances have been made in understanding and reducing the rotational losses of HTS magnetic bearings [1]-[3]. Measured coefficient of friction for HTS bearings of $10^{-8}$ have been achieved, five orders of magnitude lower than the best mechanical
bearings. During this time, almost no work has been done on studying behavior of PM/HTS bearings during oscillations of less than one radian in amplitude. The present paper explores an application for this regime - its use as a sensitive gravimeter.

Gravimeters are presently in use commercially to detect geoids [4] and scientifically to study crustal motions and tides [5]. Present gravimeters, fieldable on trucks, planes, or ships, can measure differences in gravity to an accuracy of about 1 μGal (1 Gal = 0.01 m/s², i.e., 1 μGal is about 10⁻⁹ the acceleration of gravity at the Earth’s surface), which is sufficiently accurate to detect geoid signals which are often in the mGal range [4]. These gravimeters are typically of the LaCoste and Romberg type, which essentially consist of a mass suspended from a sensitive mechanical spring.

Laboratory gravimeters, employing low-temperature superconductors, exist that are sensitive to about 1 nGal [6]. The superconducting gravimeters use the Meissner effect to suspend superconducting niobium (or lead) spheres, as detector masses, in a magnetic field created by a persistent current in a superconducting coil [7], [8]. Levitation occurs because of flux exclusion at the surface of the sphere. At the liquid-helium temperatures used in such experiments, niobium is almost a type-I superconductor. Disadvantages are that Type-I superconductivity is lost at very low magnetic fields and thus only very small detector masses can be levitated, levitation of the spheres can become unstable at low chamber pressures [8], and trapped flux in the not-quite Type-I superconductors can confound the measurements [8]. A modification of the mechanical-spring-suspended mass design measures displacement of the levitated mass with sensitive SQUID sensors [9]. Because the gravimeter must measure a very small signal (e.g., the vertical oscillation) within a very large background (the force of gravity), it is extremely sensitive to any stray forces in the system. In all cases involving low-temperature
superconductors, the instrument is very temperature sensitive, and the temperature of the system must be controlled to within 5 μK [10].

A type of gravimeter that has been used for basic scientific studies, such as the measurement of the gravitation constant \(G = 6.67 \times 10^{-11} \text{ m}^3\text{kg}^{-1}\text{s}^{-2}\), and is approximately as sensitive as the superconducting gravimeter uses a pair of masses suspended by a fiber in a torsional pendulum [11]. Torsional fibers are useful in laboratory gravitational measurements because their restoring torque is proportional to the inverse fourth power of the fiber diameter, while supportable weight is proportional to the inverse square of the diameter. However, stability and breakage of these small fibers has been a continuing problem with torsion pendulums. Accelerations during assembly and handling create serious difficulty.

To avoid such problems with fibers, levitation using a ferromagnetic rotor and active magnetic bearings for the determination of the acceleration of gravity has been attempted [7]. While considerable weight can be levitated with these bearings, the lack of constancy of the restoring torque proved to be a considerable problem in those experiments [7].

II. CONCEPT DESCRIPTION

The basic concept of the proposed gravimeter, shown in Fig. 1, is to levitate a PM over an HTS element, much as we do in our low-loss HTS bearings [1]. The bearing serves as a carrier for a platform supporting a cantilevered horizontal beam with a test mass at the end of the beam. This entire assembly is located in a vacuum chamber. The HTS components of the bearing are housed in a G-10 fiberglass-composite cryochamber, and any electrically conducting or magnetic components are far-removed from the vicinity of the permanent magnet and HTS elements. The combination of PM and HTS forms a bearing platform that has low resistance to rotational motion but has relatively high resistance to horizontal, vertical, or tilting
motion. In essence, the combination of PM and HTS acts as a low-loss torsional pendulum that can be operated in any orientation.

The HTS bearing will be field-cooled with the upper rotor assembly resting on a movable mechanical platform. After the platform is moved, the rotor portion of the HTS bearing will be free to oscillate about some equilibrium position. The test mass can be allowed to respond freely or, if needed, a mechanism will be developed to provide an opposing (restoring) force if damping is required for gravimeter applications. For example, it may be necessary to add some controlled damping to the system to obtain a small torsional amplitude from the initial levitated position. This could be accomplished easily by using eddy current dampers, in which an AC current is applied to small coils located adjacent to some conducting part of the rotor's cantilever beam.

To the first order, the PM is symmetrical about its rotational axis, so that gravity does not act to rotate it. Gravity acts on the cantilever beam and attached mass and accelerates them. A detector system measures the movement. The detector could be a set of capacitance sensors, a laser interferometer, a superconducting quantum interference device (SQUID), or other device that can measure a position on the mass or the cantilever. Variations in gravity can be detected by a time-of-flight acceleration or, alternatively, by a control coil or electrode that could be used to keep the mass stationary. For example, a small magnet added to the beam or mass can interact with a control coil. Gravitational force could also be measured by electrostatic means.

Many of the problems associated with Meissner levitation of spheres at 4 K are avoided if a PM is levitated over an HTS element at 77 K. Because of flux trapping, the levitated magnet is stable at all chamber pressures, and instead of interfering with a Type-I superconductivity, the flux trapping creates a low-loss, low-stiffness torsional spring. By decoupling the translational and tilt degrees of freedom from
the rotation of the levitated platform, we can suspend a large mass with low
torsional stiffness in a system that is mechanically very robust. Maintaining a
constant temperature should be easier at 77 K than at 4 K, because of heat capacities
that are higher by several orders of magnitude.

The use of HTSSs is a significant advantage over the levitation of a niobium (or
lead) sphere. The mass that can be levitated is severely limited by the low critical
field of these type-I low-temperature superconductors. Also, these type-I
superconductors are not stable against rotational movement. Because of flux
pinning, the HTSSs overcome these disadvantages. The ability to levitate large
masses is advantageous in that heavier gravimeter components (see Fig. 1) can be
levitated and long lever arms can be accommodated. This increases the sensitivity
of the gravimeter over a given angular motion of the device. Because of the larger
mass, the HTS bearing has a higher value for the dimensionless parameter $Q =
2\pi(\text{stored energy})/(\text{energy loss})$ by several orders of magnitude due to the very low
friction losses, there should be less thermal motion noise even though the HTS
bearing is at a higher temperature.

Calculations suggest that the HTS gravimeter would be as sensitive as present-
day superconducting gravimeters that need cooling to liquid-helium temperatures,
but the HTS gravimeter needs cooling only to liquid nitrogen temperatures.
Further, the stiffness of the HTS bearing should be equal or better than that of the
best available torsional fibers, and that the ratio of the stored energy to energy loss ($Q$
value) should be several orders of magnitude higher.

The HTS gravimeter could be used to determine the status of petroleum fields
and other geological structures. It may be miniaturizable to fit into oil-well
boreholes, with some loss in accuracy. Refrigerators for cooling to liquid-nitrogen
temperatures are commercially available and relatively robust. It should be noted
that a 1 nGal sensitivity is sufficient to detect a 200 gm mass at a distance of 1 meter -
therefore, the gravimeter could be used to detect landmines in the field. Another potential application is to detect masses of moving trucks at a distance. Finally, the gravimeter could be used to determine the value of the gravitational constant to improved accuracy.

III. SMALL ROTATIONS IN HTS BEARINGS

Since we propose to use HTS bearing technology as the basis of levitation for the torsional pendulum, we may estimate the torsional stiffness of the HTS system from coefficient of friction (COF = rotor drag/lift force) measurements in spindown experiments of bearings. It is relatively easy to achieve COFs of $10^{-7}$ in these systems, and COFs of $10^{-8}$ have been achieved by shimming the levitated magnet with ferromagnetic shims [2] and also by the using an Evershed bearing design [3]. By combining the two techniques, it should be possible to obtain COFs of $10^{-9}$.

As an example, we can assume a COF of $10^{-7}$ due to hysteresis loss in the HTS and that the levitated weight is 10 N, typical of that used in our laboratory experiments. The drag force is then 1 μN, occurring at a radius of 40 mm, and the torque is then 40 nNm. If we assume that this average drag torque is due to a potential well that operates over a 180° rotation, this corresponds to a torsional stiffness $\approx 10$ nNm/rad, equivalent to the torsional stiffness of the best fibers typically used in gravity measurements [7]. As mentioned above, it should be possible to obtain an improvement (i.e., reduced losses) in the HTS bearing of at least two orders of magnitude.

The above analysis assumes that torsional stiffness occurs by hysteresis loss of flux lines moving from one pinning center to the next as the permanent magnet rotates above the HTS. For small-amplitude oscillations, the stiffness is known to be higher [12], but this effect is minimal for the improved melt-textured YBCO samples that are used in present HTS bearing systems [13].
Hysteresis loss in an HTS bearing system has not been measured for small oscillations about an equilibrium; however, it can be estimated from our spindown experiments. Continuing our previous example, a drag force of 1 μN corresponds to a hysteretic loss = 250 nJ per revolution. The loss is known to be proportional to the cube of the magnetic field variation. In order to make some estimate of the energy ratio Q, we assume that the field variation is linear with displacement. We will argue later that this is a conservative assumption. The energy loss is then given by

\[ \Delta E = \alpha x^3 \]  

so that \( \alpha = 2.5 \times 10^{-7} / (0.25)^3 = 16 \mu \text{Jm}^{-3} \). Defining Q in the usual way as \( 2\pi \) times the stored energy divided by the energy loss, we have

\[ Q = 2\pi E / \Delta E = 2\pi (1/2 \ k x^2) / (\alpha x^3) = \pi k / (\alpha x) \]  

Using our estimated values for \( \alpha \) and the stiffness \( k \), and assuming \( x = 1 \mu \text{m} \) for the test mass displacement, we estimate

\[ Q \approx 2 \times 10^6. \]

This estimate for Q is several orders of magnitude higher than that usually obtained for torsional fiber systems.

We are assuming here that the stiffness is independent of the amplitude of the motion, which appears to hold for good melt-textured HTS for small amplitudes [12], [13]. The estimate of the losses made here is somewhat uncertain, in that it is suggested [2] that for very small losses, such as what we propose to accomplish, that surface phenomena may be important in determining the losses and that the loss is proportional to the square of the displacement rather than the cube. On the other hand, if the displacements are small, as opposed to the rotating bearing study of Ref. 2, the flux lines may move elastically in their pinning centers, and then the losses are expected to be even smaller. In this case, it may be possible to design the system so that stiffness decouples from the loss. Clearly, experimental studies are required to resolve this.
IV. DESIGN EXAMPLE CALCULATION

To determine the general feasibility of the HTS gravimeter, we present here a calculational example of an initial unoptimized design. We assume that the test mass is a sphere with mass 200 g and that the proof mass is a sphere with mass 10 kg. Assuming a density of 8 g/cm³, the radius of the test mass is 1.81 cm and the radius of the proof mass is 6.68 cm. This suggests that the minimal distance separating the centers of the spheres will be 10 cm. The force of gravity between an adjacent mass pair is

\[ F_{12} = -\frac{Gm_1m_2}{R^2} \]  

(3)

giving \( F_{12} = 1.33 \) nN. The equivalent acceleration of gravity is 6.67 nm/s² or a little less than 1 μGal. The proof mass may be placed at a larger distance to achieve smaller accelerations.

If the test sphere is located at a radius of 30 cm from the center of the rotor, the torque on the system is 400 pNm. Ignoring the moment of inertia contributions from the permanent magnet and the cantilever beam, the moment about the rotor pivot is 18 mNm². The angular acceleration is \( 2.2 \times 10^{-8} \) rad/s².

Assuming that we put our reflective tape for the position measurement by a laser interferometer at a radius of 25 cm, and that we can measure no better than 100 nm, we can measure an angle \( \Delta \theta \) of 400 nrad. If the distance traversed is 0.1 mm, giving a sensitivity of 1 ngal to the measurement, then the time required with this acceleration is about 190 s.

While many refinements must be made to the estimates made here, it seems clear that the use of HTS bearings has the potential to measure the acceleration of
gravity to an accuracy equivalent to gravimeters using low-temperature superconductors.

V. NOISE SOURCES

System noise is also an important criteria in determining the sensitivity of an instrument. The principal noise sources for the gravimeter are ground vibration, electromagnetic effects, and convection.

Seismic activity, storms, waves, solar heating, and man-made disturbances all contribute to ground vibrations. However, even rather simple passive isolation, particularly "multibase" isolation, has been proven to be very effective in reducing ground noise.

Electromagnetic effects are of two kinds, the first arising from external disturbances both natural and man-made. Externally generated noise is reduced by shielding. The second source is internal and includes magnetic impurities in the material of construction and the electrostatic charge build-up on the test mass/oscillator. Charging is important when the system is operated at low air pressure. Care must be taken to reduce impurities and discharge any static charges.

Special care must be taken to reduce temperature fluctuation, daily changes in the ambient condition, and air draft. Because the rotating part of the system will be in a vacuum environment, these effects are expected to be minimal.

Thermal noise is an intrinsic part of any system. Let the detector consisting of the test mass/masses be modeled as a generalized linear oscillator represented by the following equation of motion:

\[ I \frac{d^2\theta}{dt^2} + \beta \frac{d\theta}{dt} + \kappa \theta = f(t), \]
where $\theta$ is the angular displacement, $t$ is time, $I$ is the moment of inertia, $\beta$ is the damping coefficient, $\kappa$ is the torsional stiffness, and $f(t)$ is the random ambient torques acting on the oscillator. Define the RMS noise velocity to be $U_{\text{RMS}}$, so the square of $U_{\text{RMS}}$ is given by

$$[U_{\text{RMS}}]^2 = \langle (d\theta/dt)^2 \rangle = k_B T/I \quad (5)$$

where $k_B$ is Boltzmann's constant, and $T$ is temperature. If an RC filter is connected to the output of the position detector, then the RMS uncertainty in the angular position is [6]

$$<\theta>^2 = (\beta \ k_B \ T/ \kappa^2) \ RC \quad (6)$$

when $RC >> (\kappa/I)^{1/2}$, where $R$ is resistance, and $C$ is capacitance. In our example, $\beta = 3 \times 10^{-9}$ Nms, and $k = 10^{-8}$ Nm/rad, and assuming $RC = 1$, we find

$$<\theta> = 180 \ \text{nrad}$$

which is less than our assumed detectable value of 400 nrad.

VI. CONCLUSIONS

We have presented a gravimeter concept, based on the levitation of a PM over an HTS. Calculations suggest that the sensitivity of this apparatus should be at least 1 nGal, which is the best sensitivity of existing instruments.
REFERENCES


**FIGURE CAPTIONS**

Fig. 1. Schematic of HTS gravimeter concept.
Fig. 1