$\mathcal{D}^{13}$

N91-12416

17. SUPERCONDUCTING SIX-AXIS ACCELEROMETER

Prof. H. J. Paik, University of Maryland

ABSTRACT

Highly sensitive superconducting accelerometers have been developed for application in gravitational wave detection and gravity gradiometry. A new superconducting accelerometer, capable of measuring both linear and angular accelerations, is under development at the University of Maryland. A single superconducting proof mass is magnetically levitated against gravity or any other drag force. Its relative positions and orientations with respect to the platform are monitored by six superconducting inductance bridges sharing a single amplifier, called SQUID (Superconducting Quantum Interference Device). Thus, the six degrees of freedom, the three linear acceleration components and the three angular acceleration components, of the platform are measured simultaneously. In order to improve the linearity and the dynamic range of the instrument, the demodulated outputs of the SQUID are fed back to appropriate levitation coils so that the proof mass remains at the null position for all six inductance bridges.

The expected intrinsic noise of the instrument is 4×10^{-12}m s^{-2} Hz$^{-½}$ for linear acceleration and 3×10^{-11} rad s^{-2} Hz$^{-½}$ for angular acceleration in 1-g environment. In 0-g, the linear acceleration sensitivity of the superconducting accelerometer could be improved by two orders of magnitude. We discuss the design and the operating principle of a laboratory prototype of the new instrument. Although such an advanced instrument is being developed primarily to satisfy the vibration and attitude measurement requirements for a space-borne superconducting gravity gradiometer, the superconducting six-axis accelerometer will have important applications in other terrestrial and space technologies.

INTRODUCTION

Applications in gravity survey and inertial navigation call for major improvements in the sensitivity of existing gravity gradiometers and accelerometers. A three-axis superconducting gravity gradiometer, which measures all three orthogonal in-line gravity gradient components, is being developed at the University of Maryland. Meanwhile, a prototype single-axis portion of a superconducting gravity gradiometer is being tested for its performance in a noisy terrestrial environment. Errors caused by common accelerations can seriously degrade the performance of the gradiometer because the ground has common accelerations which are several orders of magnitude larger than the extremely weak gravity gradient signals to be measured. An important error source of this kind comes from rotational motions which produce erroneous signals that are indistinguishable from gravity gradients. Although the errors along one of the three axes of a gradiometer caused by both torsional and tilting motions are minimized when that in-line axis is aligned with the vertical, such an orientation of the sensitive axis is not applicable to all the three orthogonal axes simultaneously. Availability of very sensitive accelerometers will provide knowledge of the exact motions of the gradiometer platform. Such precise information is useful to either develop a servo-controlled inertial platform or compensate for the errors caused by the motions of the platform. We are developing a "six-axis" superconducting accelerometer to measure all three linear and three angular accelerations of the platform. In this paper, we report the development status of the gradiometer including test results with the prototype gradiometer and also describe the principle and design of the accelerometer.

FEATURES OF THE GRADIOMETER

The design of the three-axis gravity gradiometer was given at another conference.[1] Here we describe the features of the instrument. The gradiometer consists of three pairs of coupled superconducting acceleration transducers mounted on the six faces of a precision cube.

Each acceleration transducer is a spring-mass type superconducting accelerometer[2] in which an applied acceleration signal produces a displacement of a proof mass suspended by a spring. The proof mass displacements for a pair of spring-masses in the common and differential modes of motion are detected by a coupled superonducting inductance-modulation circuit (Figure 1) and SQUID amplifiers. A passive coupling provided by the superconducting circuit with adjustable but persistent stored currents provide a quiet and stable means to accurately balance out the common linear accelerations for the measurement of the differential acceleration.

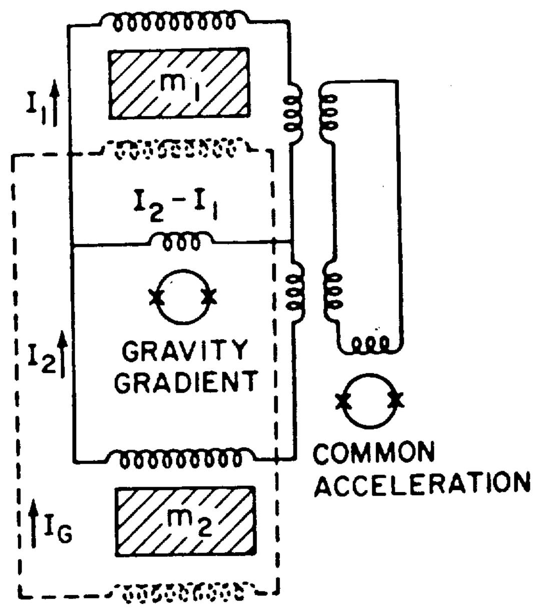


FIGURE 1. SCHEMATIC OF SUPERCONDUCTING CIRCUIT FOR EACH SINGLE-AXIS GRAVITY GRADIOMETER

The following considerations are important for each pair of coupled acceleration transducers:

1. In order to minimize the contamination of the signal by the SQUID amplifier noise, a very low proof mass resonance frequency in the differential mode is desirable in order to produce, for a given acceleration amplitude, a larger proof mass displacement before it is detected by the superconducting circuit.

2. The spring used in the suspension should have low loss in order to have lower thermal (Nyquist) noise from the spring.

3. A precise alignment of the sensitive axes together with a high degree of common mode rejection are needed in order to reject the relatively large common accelerations of the gradiometer platform.

As a compromise between alignment precision and sensitivity, a mechanical cantilever-spring suspension is used to confine the motion of the proof mass along a straight line. The mechanical suspension provides the convenience of employing mechanical precision to align the sensitive axes of a pair of in-line acceleration transducers along a common colinear direction and to align this common axis along a reference axis of the precision cube. The cantilever springs, which are relatively soft in the bending mode but stiff against stretching, provide the confinement for the motion of the proof mass to a one-dimensional motion. However, the mechanical suspension also raises the resonance frequency of the proof mass and hence sets an unnecessary limit on the sensitivity of the gradiometer to the order of 10^{-12} s^{-2} $Hz^{-1/2}$ for our present design. A passive superconducting negative spring, which lowers the resonance frequency without adding amplifier noise, is being developed[3] to extend the intrinsic sensitivity of the gradiometer.

Superconducting magnetic levitation of the proof mass against Earth's gravity also has an electromagnetic spring contribution. Yet, a pair of acceleration transducers can be combined in a "push-pull" configuration. By combining in series the levitation coils for a pair of proof masses, the electromagnetic spring constant of the coupled levitation coils becomes zero for the differential mode of motion but remains high for the common mode. The inductance modulations of the levitation coils in the differential mode add to zero for the series inductance so that no restoring force and hence no spring constant results.

The instrinsic instrument noise Γ_n of the gradiometer has a spectral density S_Γ given by[4]

$$S_\Gamma^2(f) = \frac{8\omega_0}{m\ell^2}\left[\frac{k_B T}{Q} + \frac{\omega_0}{2\beta\eta} E_n(f)\right], \text{ for } f < \omega_0/2\pi$$

where m, $\omega_0/2\pi$, Q, ℓ, E_n and $\beta\eta$ are the mass, differential-mode resonance frequency, quality factor, baseline, SQUID amplifier noise and energy coupling factor, respectively. The design values in our present gradiometer are $m = 1.33$ kg, $Q > 10^5$, $\ell = 0.19$ m, $E_n = 3\times10^{-30}$ J Hz^{-1} (SHE dc SQUID at $f > 0.1$ Hz) and $\beta\eta = 0.5$. Without using a superconducting negative spring, $\omega_0/2\pi$ is about 7 Hz and $\Gamma_n(f) = 2\times10^{-12}$ s^{-2} Hz$^{-1/2}$. With the negative spring and a lower loss ($Q>10^6$), the instrument noise can be improved by another order of magnitude. Such a high sensitivity imposes stringent requirements on the acceleration noise of the platform. With an angular velocity noise of $\omega\theta_n$ at a signal frequency $\omega/2\pi$ and a linear acceleration noise of a_n, the gravity gradient errors induced by these common accelerations are, respectively, $(\omega\theta_n)^2$ and $a_n\varepsilon/\ell$, where ε is a geometrical alignment error. With our present design values of the gradiometer, the estimated requirements on the uncertainty of the common accelerations are $a_n < 10^{-9}$ m s^{-2} Hz$^{-1/2}$ and $\omega^2\theta_n < \omega\times10^{-6}$ rad s^{-1} Hz$^{-1/4}$. These requirements are easily met by using superconducting accelerometers. Both linear and angular acceleration readouts are available as secondary outputs in a tensor gravity gradiometer[5] which has both in-line and cross-line gradiometers. With the present three-axis in-line gradiometer, only the linear common acceleration outputs are available. A desired ancillary instrument is a dedicated superconducting accelerometer that measures all the acceleration components.

DESIGN OF THE ACCELEROMETER

The six degrees of freedom of a platform are three linear and three angular motions. The "six-axis" accelerometer under development utilizes the same principles of the gradiometer with two major differences:

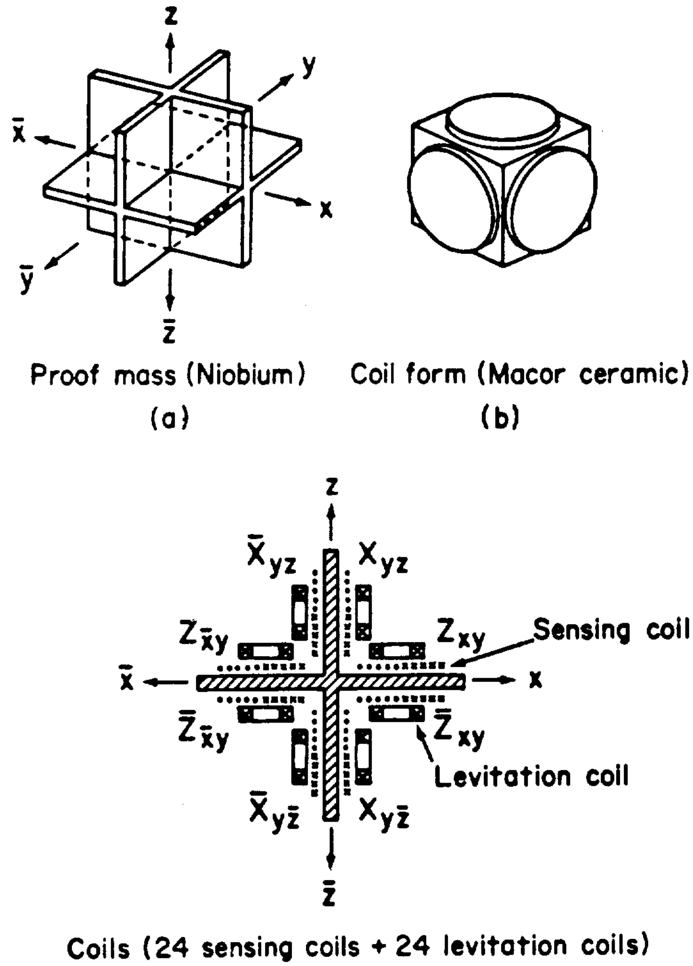
1. Because the accelerometer has no common mode balance requirement, only magnetic levitation (no mechanical spring) is used in the proof mass suspension. The proof mass resonance frequency can therefore be made low even in a simple design.

2. A single common proof mass has all the six degrees of freedom and can be conveniently shared by all the six component accelerometer circuits.

The design of the accelerometer is shown in Figure 2. The proof mass, which is shown in Figure 2a with a Cartesian coordinate system coinciding with the sensitive axes of the accelerometer, has 24 superconducting planes. Motion of the proof mass at these planes produces inductance modulations of 24 corresponding sensing coils which are mounted on 8 identical coil forms. Figure 2b shows one of these coil forms. A cross-sectional view of the proof mass together with the sensing and levitation coils is shown in Figure 2c on a zx plane (y = 1/4 times the proof-mass side length) through the four quadrants yzx, $yz\bar{x}$, $y\bar{z}\bar{x}$ and $y\bar{z}x$. The notation on each coil specifies the location of the particular coil by giving a three letter label of the quadrant in which the coil lies and by indicating the sensitive axis of the coil in capital letter.

Both orthogonality and parallelism are required of the proof mass. An umbrella orientation (one trigonal axis being vertical) gives symmetry for the proof mass towards levitation. The accelerometer can be integrated into the center cube of the gradiometer. The coils are then aligned with reference to the cube.

The linear and angular components of motion of the proof mass can be sensed by taking various combinations of the sensing coils to form six bridge circuits, each containing four coils. The choice of the combination should also minimize the coupling of each circuit to all but one component of motion. A scheme of achieving this decoupling, provided a cubic symmetry is maintained and the displacements of the proof mass relative to the coils are kept small, is shown in Figure 3 for the bridge circuits of one component linear acceleration a_x and one component angular acceleration α_x, which are in the x direction. Figure 3 also shows the levitation coils with stored dc currents. Feedback is applied to the bridge circuit of these levitation coils in order to maintain the proof mass in the balanced positions of the bridges.



(c)

FIGURE 2. DESIGN OF A SIX-AXIS SUPERCONDUCTING ACCELEROMETER

Therefore, the feedback maintains the geometric symmetry of the system even in the presence of applied acceleration and minimizes the noise contribution from the driving oscillator of the bridge. Use of the ac bridge is intended to eliminate 1/f noise term due to the noise spectrum of the SQUID amplifier. A potentially economic and compact feature of sharing one SQUID amplifier among more than one bridge circuit is possible by connecting the bridge circuits, which use different ac modulation frequencies, to the same SQUID.

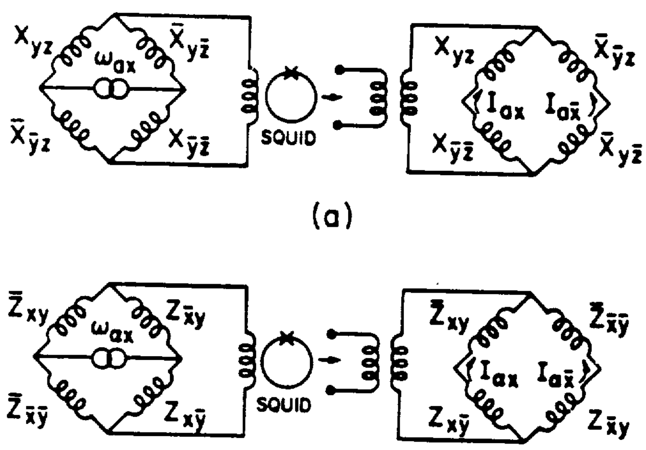
The intrinsic instrument noise of the accelerometer has terms similar to that of the gradiometer and can be shown to be[6]

$$S_{ai}(f) = \frac{4\omega_{a0}}{M}\left[\frac{k_B T}{Q} + \frac{\omega_0}{2\beta} E_n \; (\omega_{ai}/2\pi)\right]$$

for each linear acceleration component a_i, and

$$S_{\alpha i}(f) = \frac{4\omega_{\alpha 0}}{I}\left[\frac{k_B T}{Q} + \frac{\omega_0}{2\beta} E_n \; (\omega_{\alpha i}/2\pi)\right]$$

for each angular acceleration component α_i. Here, I is the moment of inertia of the proof mass whereas $\omega_{ai}/2\pi$ and $\omega_{\alpha i}/2\pi$ are the respective driving frequencies of the ac bridges. The design values, using a proof mass of 5 cm in each side, are $M = 0.1$ kg, $I = 3\times10^{-5}$ kg m^2, $\omega_a 0 = 2\pi \times 10$ s^{-1}, $\omega_\alpha 0 = 2\pi$ s^{-1}, $T = 4.2$ K, $Q = 10^5$, $\beta = 1/4$ and $E_n = 5 \times 10^{-29}$ J Hz^{-1} (SHE rf SQUID). The corresponding intrinsic noise levels are $\left|S_a(f)\right|^{1/2} = 4 \times 10^{-12}$ s^{-2} Hz$^{-1/2}$ and $\left|S_\alpha(f)\right|^{1/2} = 3 \times 10^{-11}$ rad s^{-2} Hz$^{-1/2}$. Sensitivity results are graphically shown in Figures 4 and 5.



Sensing coils ⟶ Feedback ⟶ Levitation coils

FIGURE 3. SCHEMATIC OF SENSING, LEVITATION AND FEEDBACK CIRCUIT FOR (a) A LINEAR ACCELERATION COMPONENT a_n, AND (b) AN ANGULAR ACCELERATION COMPONENT α_n

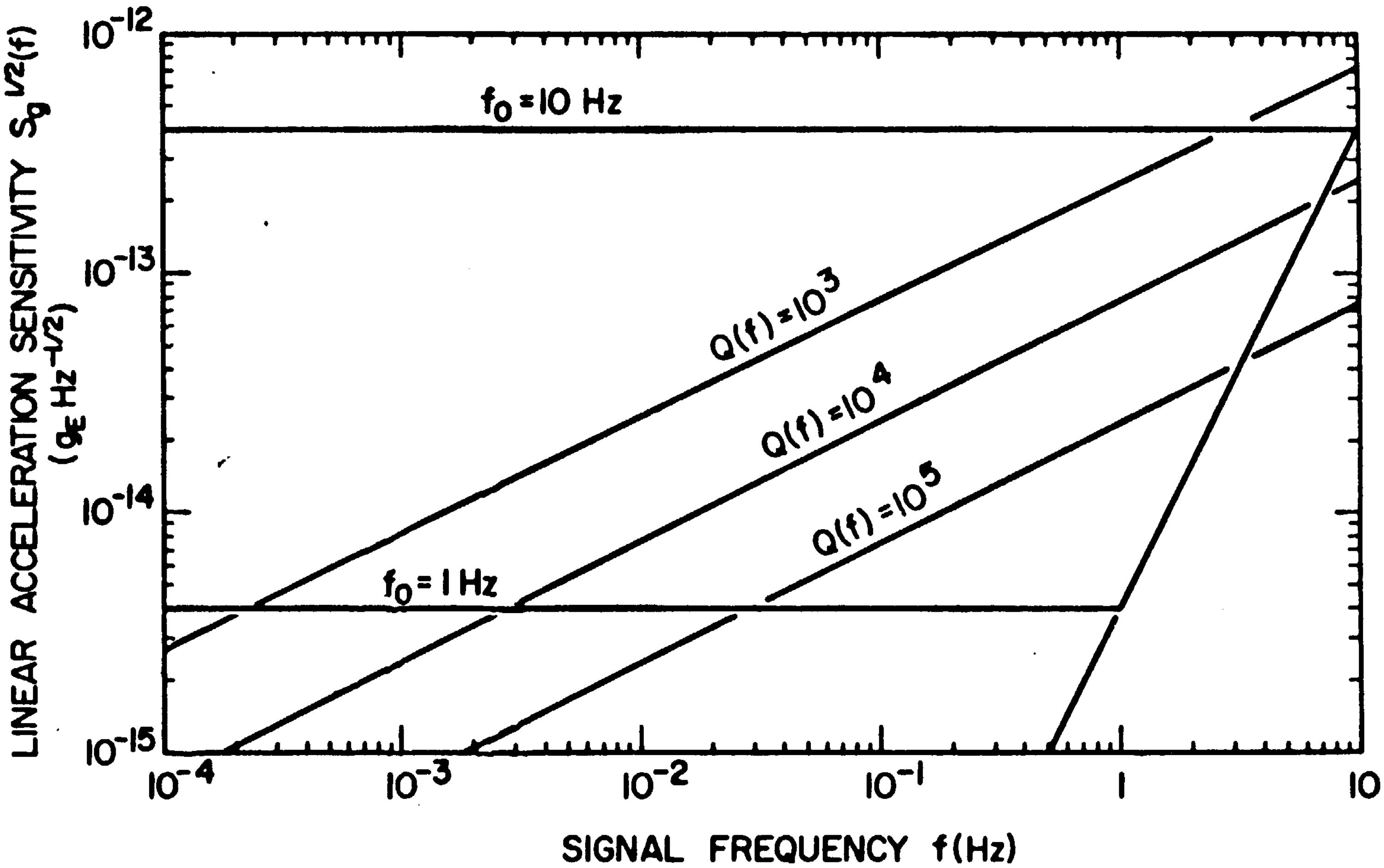


FIGURE 4. SIGNAL FREQUENCY f(Hz)

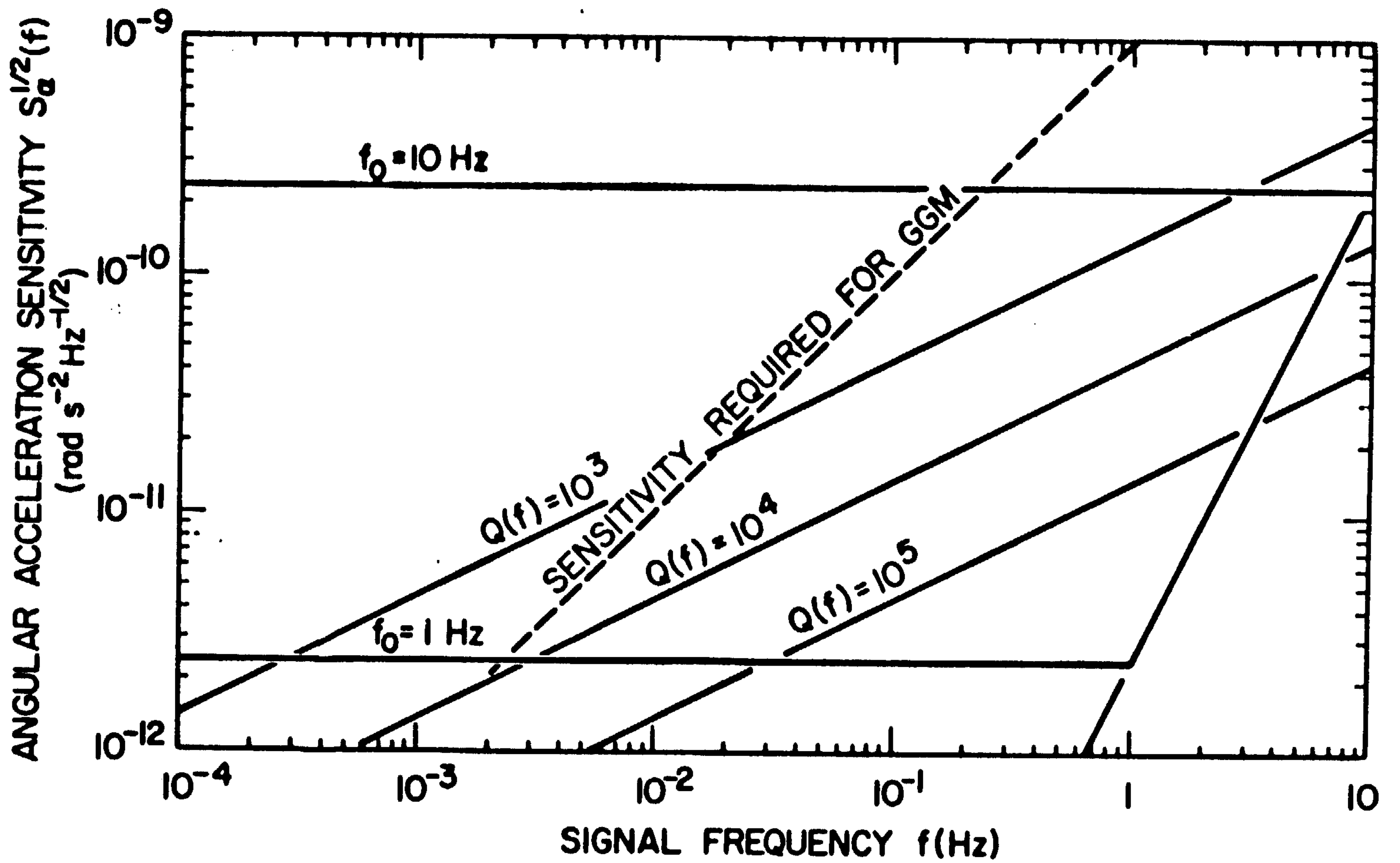


FIGURE 5. SIGNAL FREQUENCY f(Hz)

TEST RESULTS OF PROTOTYPE GRADIOMETER

A single axis prototype gradiometer, which is smaller in size and has a similar superconducting circuit to the one shown in Figure 1, is being tested in a noisy environment. The values of the parameters are $m = 0.4$ kg, $\ell = 15$ cm, $\omega_0 = 25$ Hz, $E_n = 5.9 \times 10^{-29}$ J Hz$^{-1/2}$ and $\beta\eta = 0.1$. The measured Q of the gradiometer is over 30,000 making the thermal noise term of the gradiometer negligible compared with the SQUID amplifier noise term which is 7×10^{-11} s^{-2} Hz$^{-1/2}$. The linear acceleration noise of the gradiometer platform is measured by the gradiometer itself to be approximately 1.5×10^{-7} m s^{-2} Hz$^{-1/2}$ at below 1 Hz but the angular acceleration noise of the gradiometer platform at such low frequencies requires too high a sensitivity for room temperature instrumentation.

The gradiometer is mounted along one axis of a cube which has one trigonal axis vertical. The gradiometer platform is suspended from outside the dewar by a long vibration isolation filter which has a vertical resonance frequency of about 1.1 Hz and a pendulum frequency of 0.3 Hz.[4] High frequency vertical vibrations of the ground are attenuated by the passive filter. Horizontal vibrations at all frequencies are isolated by the pendulum but has a residual coupling to several degrees of motion of the platform due to the imperfect nature of the pendulum, which has to compromise between heat leak and rigidity, to several modes of motion. The heat leak through this filter and through radiation is small, but another source of temperature fluctuations at the gradiometer platform is a residual heat exchange with the Helium bath by conduction through the lead wires and through the residual gas of the vacuum. The thermal isolation of the gradiometer platform, together with a large heat capacity of the gradiometer system, behaves like a low-pass filter. A shaker is used to produce a vertical acceleration during the common mode balance procedure, and both this shaker and the dewar are shielded by μ-metal against electromagnetic interference.

The observed noise spectrum is shown in Figure 6. The upper trace of the figure shows the backgound common acceleration measured by the gradiometer when the gradiometer is charged with supercurrents in an accelerometer mode.[4] The instrument noise of the gradiometer, which has been determined indirectly from measurements of Q and amplifier noise, is indicated by a dotted line which is at a level of almost 10^5 below that of the acceleration noise. This instrument noise is what we expect

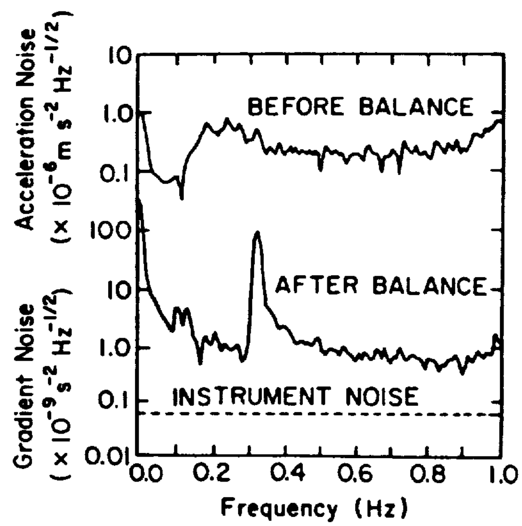


FIGURE 6. Noise measured by the gravity gradiometer before and after common mode balance when tested in terrestial environment. The vertical scale is the same continuous measure of common/ differential acceleration output of the gradiometer, although the lower region of the scale is expressed in terms of gravity gradient.

from the output of the gradiometer if it were tested in a quiet environment or if we can suppress the environment-induced noise. During the balance, (by adjusting the stored supercurrents) the measured (differential) acceleration output of the gradiometer lowers by an amount proportional to the degree of common mode balance achieved. This proportionality is well maintained until the level shown in the lower solid curve is reached. At this point, the gradiometer noise level no longer decreases with the improvement of common mode balance. The noise floor is then 10 times higher than the indirectly measured intrinsic noise but is an improvement of about 10 dB over what we reported previously.[7] Besides noise peaks due to the modes of the vibration isolation used, excess noise is also evident near dc and a drift of about 10^{-8} s^{-2} per hour has been measured on a chart recorder. The cause of the excess $1/f^n$ noise is that temperature changes modulate the penetration depth and hence the inductances of the superconducting circuit.[8] The drift was about 10 times higher[7] when the He exchange gas pressure was higher and was thus giving a shorter thermal time constant.

CONCLUSIONS

Superconducting techniques can provide orders of magnitude of improvement for the instrinsic instrument noise of both gravity gradiometer and accelerometer. In the terrestial environment, however, the demonstration of the intrinsic noise of these gravity instruments also necessitates a careful suppression or compensation of environment-induced noise. Our prototype gravity gradiometer presently has its sensitivity limited by environment-induced noise to a noise floor of 7×10^{-10} s^{-2} $Hz^{-1/2}$. Availability of very sensitive accelerometers to monitor the motion of the gradiometer platform is an important error-reduction step towards demonstrating the intrinsic noise of a very sensitive gradiometer when used as a gravity survey system. A similar contribution is obtained from the gradiometer with respect to the accelerometer as an inertial navigation system. We are making parallel efforts in developing both of these superconducting gravity instruments.

REFERENCES

1. H. A. Chan, M. V. Moody, H. J. Paik and J. W. Parke, "Development of Three-Axis Superconducting Gravity Gradiometer," Proc. of 17th Int. Conf. on Low Temp. Phys., edited by U. Eckern et al, Elsevier Science Publishers B. V., 1984, pp. 927-928.

2. H. J. Paik, "Superconducting Turnable-diaphragm Transducer for Sensitive Acceleration Measurements," J. Appl. Phys., Vol. 47, pp. 1168-1178, 1976.

3. J. W. Parke, H. J. Paik, H. A. Chan and M. V. Moody, "Sensitivity Enhancement of Inertial Instruments by Means of a Superconducting Negative Spring," Proc. of 10th Int. Cryogenic Engineering Conf., Otaniemi, Finland, 1984.

4. H. A. Chan, "Null Test of Gravitational Inverse Square Law with a Superconducting Gravity Gradiometer," PhD thesis, University of Maryland, College Park, Maryland 1982.

5. H. J. Paik, "Superconducting Tensor Gravity Gradiometer for Satellite Geodesy and Inertial Navigation," J. Astronaut. Sci., Vol. 29, pp. 1-18, 1981.

6. H. J. Paik, private communication.

7. M. V. Moody, H. A. Chan and H. J. Paik, "Preliminary Tests of a Newly Developed Superconducting Gravity Gradiometer," IEEE Trans. Mag., Vol. MAG-19, pp. 461-463, 1983.

8. M. V. Moody, H. A. Chan, H. J. Paik and C. Stephens, "A Superconducting Penetration Depth Thermometer," Proc. of 17th Int. Conf. on Low Temp. Phys., edited by U. Eckern et al, Elsevier Science Publishers B. V., 1984, pp. 407-408.