Superconducting Gravity Gradiometer for Moving-Base Applications

Our current focus in gravity gradiometers is on an instrument suitable for operation on an aircraft or ship. The design is based on superconducting accelerometer technology developed at the University of Maryland over the past two decades. One of the main perceived drawbacks of the Superconducting Gravity Gradiometer (SGG) has been the necessity for a liquid helium cryostat. To avoid this constraint, the SGG is being integrated with a closed-cycle refrigerator for operation at 3 K.

I. ANGULAR ACCELEROMETERS

Fig. 1 shows a drawing of a component angular accelerometer. The test mass rotates about a pivot at its center of mass. The pivot is designed to be highly compliant for rotation about the sensitive axis, but relatively stiff for motion in other degrees of freedom. At present, the accelerometers incorporate a flexure pivot; however, other geometries that can provide greater stiffness ratios are being considered. The design parameters are given in TABLE I. The superconducting angular accelerometer concept has been well tested. Three angular accelerometers of a similar design were integrated with the three-axis in-line SGG and their performance was carefully verified.

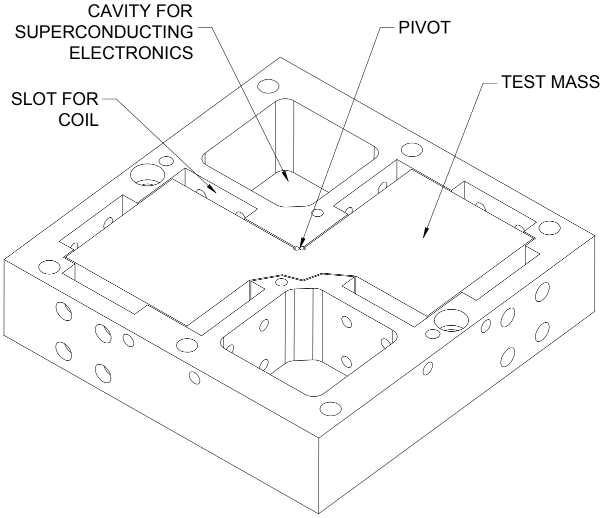

Fig. 1. A component angular accelerometer (10.2 × 10.2 × 2.5 cm)

II. GRADIOMETER

A gradiometer is formed from a pair of angular accelerometers mounted on opposite faces of a precision cube such that their pivot axes are aligned and their moment arms are perpendicular. Fig. 2 shows a schematic of the sensing circuit. It is similar to the basic accelerometer circuit except that coils from two accelerometers are connected in parallel with a single SQUID input coil. The difference between the excitation currents, I_1 and I_2, flows through the SQUID input coil. If the masses, springs, and coil spacings could be perfectly matched, then the two excitation currents would initially be set equal. As the two masses move, the instantaneous value of $I_1 - I_2$ is a measure of their *relative* displacement. That is, if both masses were to move in the same direction, I_1 and I_2 would change by the same amount, and no signal would be generated. In this way, the two acceleration signals are subtracted using persistent

TABLE I. Design parameters of the cross-component SGG.

Parameter	Symbol	Value
Mechanical		
Accelerometer mass	m	0.677 kg
Radius of gyration	R_g	3.25 cm
Major moment of inertia	J_{33}	7.1×10^{-4} kg m^2
$2J_{12}/J_{33}$	ξ	1.53
Radius to sensing coil	r_s	2.58 cm
Resonance frequency	$\omega_D/2\pi$	8.0 Hz
Quality factor	Q	1×10^4
Electrical		
SQUID resolution	E_{SQ}	$10^{-30}(1 + 0.1\ \mathrm{Hz}/f)\ \mathrm{J\ Hz}^{-1}$
SQUID dynamic range		$10^7\ \mathrm{Hz}^{1/2}$
Energy coupling	$\eta\beta$	0.2

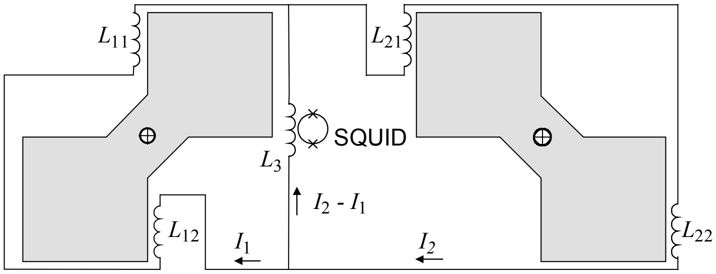

Fig. 2. Circuit schematic for the SGG

currents before amplification. In reality, it is not possible to perfectly match accelerometer components. Nevertheless, the ratio of I_1/I_2 can be adjusted to account for imbalances. During setup, each gradiometer is shaken sinusoidally about its axis, and the ratio of I_1/I_2 adjusted to minimize response. Each axis of the SGG has two such circuits. In the second, the direction of excitation current I_2 is reversed, so it senses only common-mode acceleration.

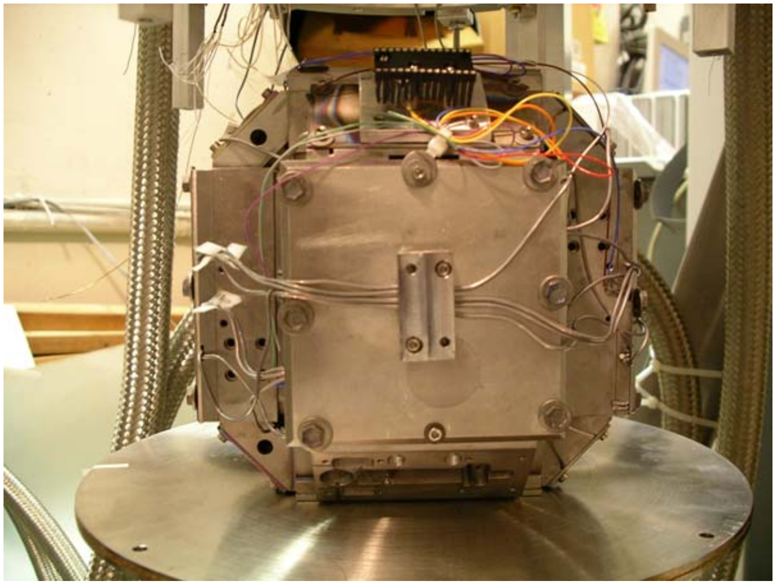

Fig. 3. The assembled SGG just before being integrated with the cryostat.

We have constructed an instrument comprised of a single gradiometer axis with two additional angular accelerometers to measure rotational motion in the orthogonal degrees of freedom. The assembled SGG is shown in Fig. 3.

III. LINEAR ACCELEROMETERS

The SGG also incorporates three linear accelerometers. These are necessary to correct for residual coupling to linear acceleration through imperfect mass balance. A perspective view of the linear accelerometer is shown in Fig. 4. Like the angular accelerometers, the proof mass and spring are cut from a single piece of niobium using a wire EDM. This should assure an axis alignment approaching 10^{-4} rad.

IV. CRYOSTAT

To eliminate the need for liquid helium, the new SGG is cooled by a closed-cycle refrigerator based on a dual-stage pulse-tube cold-head. The pulse-tube has no reciprocating piston in the cold head. An early study indicated this greatly reduced harmonics of pressure pulses.

Fig. 5 shows a drawing of the cryostat with the support structure and shakers. The total height of the cryostat and cold head is 95 cm. The outer diameter of the cryostat is 40 cm. The SGG is housed in its own vacuum can and supported with a vibration isolation stage. The dual vacuum arrangement permits the use of helium exchange gas to uniformly cool the SGG, while the isolation stage decouples the

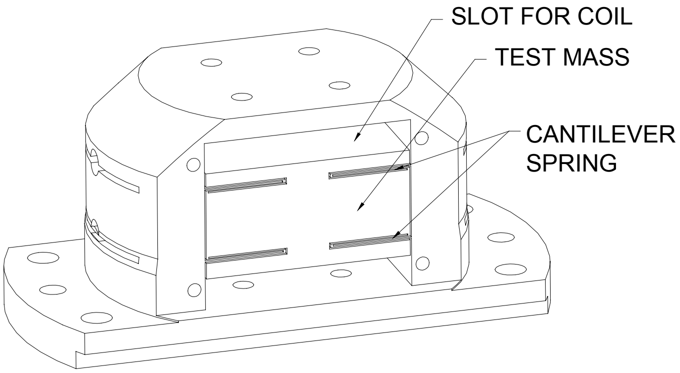

Fig. 4. Linear accelerometer

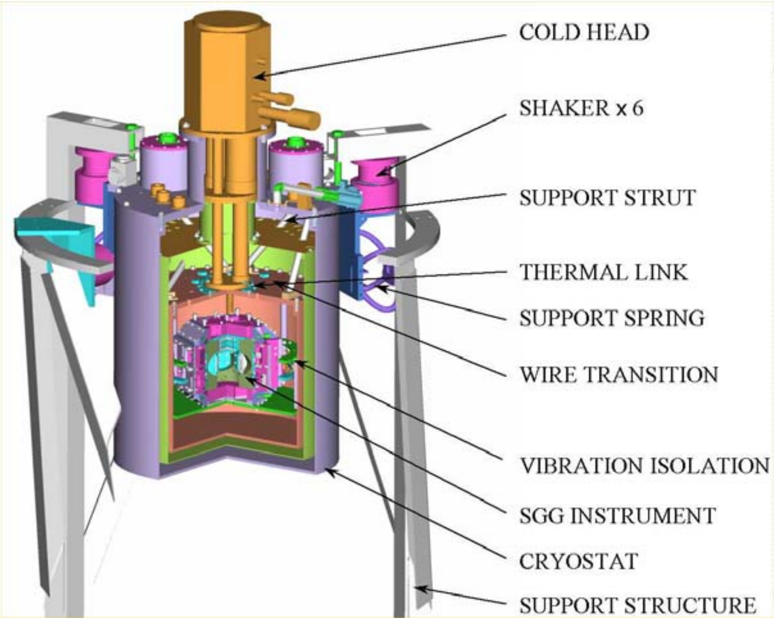

Fig. 5. A cut away view of the SGG, cryostat, and support structure.

SGG from high-frequency cold-head and compressor vibrations.

Fig. 6. The partially assembled cryostat showing the fiberglass strut structure supporting the SGG vacuum can.

The support structure is integrated with six shakers that permit motion to be applied in any degree of freedom. The shaking is required for the initial balance and the determination of error coefficients.

Fig. 6 shows a the six legged fiberglass strut structure that supports the SGG vacuum can. The rigid design eliminates modes near SGG resonances. Fig. 7 shows the cryostat housing the SGG on the support structure with shakers.

V. ESTIMATED PERFORMANCE

Testing has begun on the SGG. TABLE II shows expected performance characteristics. To determine the requirements an aircraft motion environment places on a gravity gradiometer, we measured the acceleration environment on a Carson Services Twin Otter survey plane during straight and level flight.

Based on these motion measurements and the characteristics in TABLE II, we can esti-

TABLE II. Estimated performance characteristics

Term	Magnitude
Intrinsic Instrument noise	$0.03\,(1 + 0.1\,\mathrm{Hz}/f)^{-1/2}$ $\mathrm{E\,Hz^{-1/2}}$
Temperature fluctuations	$0.1\ \mathrm{E\,Hz^{-1/2}}$
Angular acceleration rejection	
1st order	3×10^{7}
2nd order	$10^{6}\ \mathrm{E\,(rad\,s^{-2})^{-2}}$
Linear acceleration rejection	
1st order	$30\ \mathrm{E\,(m\,s^{-2})^{-1}}$
2nd order	$12\ \mathrm{E\,(m\,s^{-2})^{-2}}$
Axis alignment	10^{-4} rad
Bias stability	$0.1\ \mathrm{E\,hr^{-1}}$
Dynamic range	10^{6} (1 Hz bandwidth)
Frequency response	$10^{-7} - 3$ Hz

Fig. 7. The assembled cryostat on the support structure.

mate the requirements for a gravity survey system. The data indicate the necessity of a gyro-stabilized platform to reduce angular motion to a tolerable level. A gradiometer sensitivity of < 1 E $\mathrm{Hz}^{-1/2}$ (1 E ≡ 10^{-9} s^{-2}) over a bandwidth of 1 Hz is sufficient to detect most geophysical features. To achieve this sensitivity, the platform should provide approximately 40-dB attenuation in all three axes below 5 Hz and a roll-off of 40 dB per decade from 5 Hz to 50 Hz. We are investigating various platform options to meet these criteria. These including hexapods and gimbaled systems. Our estimates of the major error sources, with the SGG mounted on such a platform, are given in Table II.

Table III. Major error sources for a moving base SGG.

Error source	Magnitude (E rms 0.001 – 1 Hz)
Thermal noise	0.03
Linear acceleration	0.12
Angular acceleration	0.006
Angular velocity (centrifugal acceleration)	0.09
Nonlinear response to angular acceleration	0.12
Nonlinear response to linear acceleration	0.20
Temperature fluctuations	0.10
Total	0.30

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