Experiments on a superconducting gyroscope with no moving parts

by R.M. Brady* and J.E. Zimmerman

Electromagnetic Technology division,
National Bureau of Standards,
Boulder,
Colorado 80303

*Permanent address: Trinity College,
Cambridge CB2 1TQ.
England

Abstract

This paper describes an experimental investigation on a new typ of superconducting gyroscope which has no moving parts. The theory of the effect by which the gyroscope works has been verified to an accurac of 5% , and a rotation rate of 1 radian per second could be distinguished. Several unexpected sources of noise were encountered, an these are described along with suggestions for overcoming them. It appears to be feasible to make improvements in the sensitivity achieved in this experiment of over four orders of magnitude

1 Introduction

Late last century Rowland (1) demonstrated that the charges on a capacitor generate magnetic fields when set into rotation. Here we describe experiments on a superconducting apparatus which measures this 'Rowland moment', and we discuss the possibility of building a sensitiv gyroscope using this effect. Preliminary work on the gyroscope has been reported previously (2,3,4).

The experiments have verified the theory of the effect to 5% , and a rotation rate of 1 radian per second could be detected. The most serious source of noise was the currents caused by mechanical deformations in the ambient magnetic field. Such deformations had a variety of causes, such as thermal contraction and inertial effects.

It appears to be feasible to improve the sensitivity by over four orders of magnitude by the use of a low magnetic field facility an with simple improvements to the design. The rotation rate of the earth might thus be detected. Improvements by six orders of magnitude over th performance obtained in our experiments would be required if the design were to be able to match the performance achieved with fibre-optic ring LASER gyroscopes (5).

In section 2 we describe the design of the gyroscope in detail, and in section 3 we give an analysis of the sources of noise which migh be expected to limit its sensitivity. Sections 4 and 5 describe the experiments, and in section 6 we discuss possible improvements to the design and describe preliminary experiments on other possible implementations of the apparatus.

There are other possible applications of the Rowland moment using superconductivity; in particular it might be possible to perform a calibrated measurement of the London moment using the effect See chapter 2.

Theory of the gyroscope

The essential features of the superconducting gyroscope are hown in figure 1. Two concentric cylinders of conducting material are harged up so that there is a high voltage between them, and the esulting Coulomb charges are shown symbolically in the figure. A slit xtends the length of the inner cylinder, and an ammeter is connected cross the slit so that it will detect any current flowing around the nner cylinder.

Consider what happens if the whole apparatus is set into otation in the plane of the diagram. If the Coulomb charges were to emain fixed in space so that they did not rotate with the apparatus, hen charge would be swept through the ammeter which would measure a eading directly. We shall assume however that the charges remain fixed n the surface of the metal, so that there is no direct reading. We hall see that the analysis does not rely upon this assumption.

Our analysis will be from the point of view of an observer in an nertial (nonrotating) frame. The fixed charges constitute currents as hey rotate with the apparatus so that there is a tendency for a agnetic field to be set up in the space between the cylinders. Lenz's aw can be applied to this situation. According to this law, if currents re able to flow in conductors so as to oppose the setting up of agnetic fields, then such currents will begin to flow spontaneously. In he case of our apparatus electric currents begin to flow around the two ylinders, opposing the currents due to the fixed Coulomb charges, so hat the field between the cylinders is cancelled. The effect is as if he 'fixed' charges were not pinned to the surface of the metal, but ere instead held fixed in space. The analysis therefore does not rely pon the assumption made above about the charges being fixed to the urface of the metal. These currents are detected by the ammeter and ive an indication of the rotation velocity of the apparatus.

the current which is indicative of rotation will decay quickly because of the resistance in the cylinders. The time constant for this decay will be governed by the usual L/R formula, and will depend upon the materials and the geometry used. Devices made using normal metals are unlikely to be useful for detecting frequencies of oscillation much below some megahertz; for practical purposes such devices would be useless.

However if superconductors and superconducting ammeters are used, there will be no resistance in the circuit and so the current will never decay. The reading on the ammeter will then be proportional to the rotation velocity of the device, provided that the initial conditions are set up appropriately. A superconducting apparatus might therefore be useful as a navigational gyroscope.

In the case of a superconducting apparatus, two points should be addressed. Firstly, the currents due to the fixed charges flow within the electrostatic penetration depth of the surface, whereas the electric currents flow within the superconducting magnetic penetration depth of the surface, so that cancellation of the magnetic field is not exact. In most cases this leads to a small correction, but we shall ignore this correction in our analysis. Secondly, a quantization condition in superconductors demands that a magnetic field (the London field (4,7)) threads the material of a rotating sample of superconductor. Provided that the same superconducting material is used for both cylinders, this London field turns out to be constant within the volume of the apparatus, so that it can be set up entirely by currents flowing in the outer surface. The reading on the ammeter is therefore unaffected by this effect. A fuller discussion of these two points is given in reference (4).

It is of interest to consider what happens if all of the space between the cylinders is filled with dielectric. The currents of rotation depend upon the charge densities which reside close to the must include both the Coulomb charges on the cylinders themselves, and also the charges associated with the ends of the aligned dipoles in the dielectric. The total charge is related by Gauss's theorem to the age gradient between the cylinders. Since this does not depend upon the dielectric constant, then the currents of rotation are unaltered if the space between the cylinders is filled with dielectric.

3 Sensitivity of the gyroscope

It is possible to obtain an approximate expression for the size of the effect by neglecting the variation in radius of the two cylinders. We shall use the mean radius r in our approximate formulae. If the capacitance per unit length of circumference between the cylinders is C_o and a voltage V is applied between the cylinders, then there is a charge per unit length of circumference $Q_o = C_o V$. The current due to the fixed charges I_f when the apparatus is rotated at velocity ω is:

$$I_f = C_o V r \omega \qquad (3.1)$$

We shall take the case where the inductance L of the SQUID is equal to the inductance of the instrument, so that the induced current I flowing through the combined inductance of the instrument and the SQUID is given by $I = I_f / 2$.

It is important to evaluate the electrical energy $E = L I^2/2$ associated with the current induced by rotation. Writing the inductance L in terms of the inductance L_o per unit length of circumference between the two cylinders (note that the screening effect of one cylinder upon the inductance of the other must be taken into account), $L = 2 \pi r L_o$; and using the transmission-line equation for the velocity of light between the two cylinders $C_o L_o c^2 = 1$, one obtains with some algebraic manipulation:

$$2E = (1/2) (C \ V^2 / 2c^2) (r \omega)^2 \qquad (3.2)$$

$$= (1/2) (\epsilon_o \xi^2 / 2c^2) (r \omega)^2 \ U \qquad (3.3)$$

where in (3.3) we have expressed the energy stored in the capacitor

$C V^2 /2$ in terms of the electric field ξ between the cylinders and the volume of dielectric U between the cylinders.

These equations have a simple interpretation. The second factor in parentheses is the relativistic mass of the electrostatic energy stored in the capacitor, whilst the third factor is the velocity of motion of this mass. The expressions can therefore be interpreted as the kinetic energy of rotation of the electrostatic energy stored in the capacitor.

Formula (3.3) gives a reasonable approximation for the energy E, in all geometries of the rotation device which we have considered. For example, consider a device which is in the form of a spiral, with N turns wound round one another as shown in figure 2. If we make the approximation of neglecting the capacitance between the double layers of the spiral and the inductance of the spiral of double layers, then the capacitance is $C = 2 \pi r N C_0$ and the inductance is $L = 2 \pi r N L_0$. The energy $E = L I^2 /2$ associated with rotation is therefore given by the above equations (3.2) and (3.3). As before, it is necessary to assume some average value for r.

For the low frequencies under consideration, the best type of ammeter available is the Superconducting QUantum Interference Device, or SQUID (8,9,10,11). If a SQUID is inserted into a superconducting circuit which has inductance L, and if it is capable of detecting a current dI flowing through the circuit given a measuring time τ, then the figure-of-merit energy sensitivity of the SQUID is defined to be $dE/d\Omega = (1/2)\ L\ dI^2\ \tau$ [*] Provided that the noise in the SQUID is not dominated by flicker ('1/f') noise, then the minimum detectable energy decreases in proportion to the measurement time. A commercial SQUID is available which has an energy sensitivity of $dE/d\Omega = 5\ 10^{-29}$ Joules per Hertz, and SQUIDs with much better sensitivities have been reported (12,13). It has been suggested (14) that the sensitivity of a SQUID is ultimately limited by the uncertainty principle, so that one cannot do better than $dE/d\Omega = h/(4 \pi)$.

---

[*] The quantity $dE/d\Omega$ has the units of action and can also be called the action parameter of the SQUID.

We are now in a position to evaluate by how much the amplifier noise limits sensitivity to rotation velocity. Comparing the energy assocoated with rotation E with the SQUID energy sensitivity $dE/d\Omega$ with an averaging time τ, one obtains:

$$d\omega^2 = 4\, dE/d\Omega \quad c^2 / (\epsilon_0\, \xi^2\, r^2\, U\, \tau) \qquad (3.4)$$

If amplifier noise were the main limitation upon sensitivity, then a device with radius and height 10cm using a commercial SQUID with energy sensitivity $dE/d\Omega = 5\ 10^{-29}$ J/Hz, and using a dielectric with breakdown field $\xi = 10^8$ V/m, would therefore have a sensitivity to rotation of approximately

$$d\omega \cdot \tau^{1/2} = 5\ 10^{-6}\ (\text{ radian } / \text{ s })\ \text{Hz}^{-1/2} \qquad (3.5)$$

Note from (3.4) that if all the dimensions of the apparatus were increased by a factor n and the electric field between the cylinders were to be held constant, the minimum detectable rotation rate would be reduced by a factor of $n^{5/2}$. Similarly, the sensitivity to rotation velocity increases as the square root of the energy sensitivity of the SQUID. Sensitive designs of rotation device should be designed to have a large volume U of insulator. See for example the design shown in figure 2.

The second factor which might limit the sensitivity is leakage of current through the dielectric. If the instrument shown in figure 1 were left operating for one decay time t_d of the charge on the capacitor with the high voltage supply disconnected, then a total charge of approximately $Q = C\ V$ will have flowed through the system, and a proportion of this charge will have flowed through the ammeter. The exact proportion will depend upon the assymetry of the apparatus. On the other hand, a charge of approximately Q would flow through the ammeter if the apparatus were rotated through one full turn (the precise amount of charge will depend upon the relative inductances of the ammeter and of the rest of the circuit). One would therefore expect the sensitivity of the instrument to be limited to of order one rotation in one decay time, or a rotation rate of $2\pi / \tau$ radians per second (15).

The decay time t_d of a parallel plate capacitor made of a material with unity dielectric constant and with specific resistivity ρ, is given by $t_d = \epsilon_o \rho$. Polytetrafluoroethene, PTFE, has a specific resistivity greater than 10^{16} ohm metre (16), and so one would expect to be able to achieve a decay time greater than 10^5 seconds. This implies a limit to sensitivity of better than $6\ 10^{-4}$ radians per second.

It might be possible to improve upon the above sensitivity by building a device with great symmetry (so that on average no decay current flows through the ammeter at all), or more simply by correcting for the mean leakage current which flows through the ammeter. In either case the sensitivity would be limited by random variations in leakage current. It is possible to estimate the order of magnitude of these variations by supposing that the passage of any one charge through the dielectric is uncorrelated with the passage of any other. The leakage current then obeys Poisson statistics, so that if the mean number of charges which leak through the dielectric in a given time is n, then the standard deviation in this number is $n^{1/2}$. The mean number of electronic charges leaking in a time τ through the dielectric of a rotation device is approximately $\tau Q/(e\, t_d)$, so that the minimum detectable rotation velocity is given by:

$$d\omega = (e\, t_d / Q \tau)^{1/2}\ 2\pi / t_d \qquad (3.6)$$

If a device holds a charge of 10^{-3} Coulombs, and has a decay time of 10^5 seconds, then the minimum detectable rotation rate would be of order:

$$d\omega . \tau^{1/2} = 3\ 10^{-10}\ (\text{radian} / \text{s})\ \text{Hz}^{-1/2} \qquad (3.7)$$

It should be emphasized that this derivation relies upon the assumption that the passage of charges through the dielectric is uncorrelated. This would be a bad approximation if, for example, a spark occurred; in a spark the passage of charge causes ionization which then facilitates the passage of more charge, leading to a strong correlation. We are not aware of any work upon the statistics of leakage current through insulators of this type.

The final source of noise to be discussed here results from insufficient screening of the ambient magnetic field. Any deformation of the superconducting gyroscope (on account of, for example, thermal contraction effects, gravitational deformations or electrostatic forces between the charged cylinders) will result in changes in the inductances of the coils and consequently to changes in the currents flowing around the coils if there is an ambient magnetic field. To reduce this effect, the field might be reduced using mu-metal shields or other methods to as low as 10^{-10} tesla (17), and in addition the whole apparatus might be placed inside a superconducting shield. Although superconducting shields do not exclude magnetic flux, they can be arranged to pin whatever fields are present.

To estimate the importance of the noise due to deformations in the ambient magnetic field, suppose that the separation of the plates t in the apparatus shown in figure 1 is reduced by dt. If there is an ambient magnetic field B_O, then the flux applied per unit length of circumference to the space between the cylinders is decreased by $d\phi = B_O\, dt$. On the other hand, if the electric field between the plates is ξ, then simple electromagnetism shows that the flux applied to the space between the cylinders per unit length of circumference upon rotation of the apparatus is $\phi = \omega\, t\, r\, \xi / c^2$. Equating these two gives a limitation to sensitivity of:

$$d\omega = c^2 B_O / (\xi r) (dt/t) \qquad (3.8)$$

It is relatively easy to obtain an extended region of space where the magnetic field is $2\ 10^{-7}$ tesla, and possible to obtain extended regions with fields of order 10^{-10} tesla (17). Using the value $\xi = 10^{8}$ V/m one obtains a limitation to sensitivity:

$$d\omega = 2\ 10^{3}\ (dt / t)\ \text{radian / s} \qquad (B_0 = 2\ 10^{-7}\ \text{T}) \qquad (3.9)$$

$$= 1\ (dt / t)\ \text{radian / s} \qquad (B_0 = 10^{-10}\text{T}) \qquad (3.10)$$

Young's modulus for PTFE increases from a room temperature value of $7\ 10^{8}$, to $7\ 10^{9}$ N m^{-2} at liquid helium temperature (18). To quantify but one deformation effect, an electric field of 10^{8} V/m would produce a stress of order one atmosphere pressure, leading to a strain of order $dt/t = 10^{-5}$ even at low temperature. Clearly, mechanical deformations are an important source of noise. This will be discussed further in the next sections, in the light of the experimental results.

Two further potential sources of noise have been suggested (24), but are not analysed in detail here. Firstly, weakly pinned flux lines in the shield around the apparatus might be driven around by temperature changes associated with the falling level of helium in the cryostat. Secondly, temperature fluctuations might give rise to inductance fluctuations via changes in the magnetic penetration depth. The analysis of these potential noise sources will depend critically on the detailed design of the apparatus, and such analysis is probably best left until the time when and if they become a practical problem.

4 Experimental apparatus

The experimental apparatus shown in figure 2 was built with the dimensions shown in the figure. A Swiss roll type of winding was chosen to provide a large capacitance between the conducting loops. As may be seen in the figure, the loops are completed and coupled to the SQUID by means of connections at one end of the Swiss roll.

The former around which the rotation device was wound was made of a brass cylinder with a brass flange soldered onto one end. This was electroplated with lead so that, when the lead became superconducting, external fields would be pinned and thermal noise currents in the brass would be screened. A flange of phenolic could be attached to the free end of the cylinder.

In the construction of the main windings of the rotation device, lead sheeting 0.15 mm thick was used as the superconductor, and the insulator was mylar polyester sheeting 0.125 mm thick. Four lengths of sheeting (mylar, lead, mylar, lead) were brought together and co-wound under tension around the former until there were 54 layers of four sheets each. A lathe was used to hold the unit whilst it was being wound and the lengths were individually kept in tension using a system of weights. When completed, the layers were kept in position by winding them tightly with string. This method of winding was not entirely satisfactory, for there were wrinkles in the completed windings. In a later experiment the windings were re-wound, smoothing out the layers by hand as they were wound on; this eliminated the wrinkles. In this experiment also a complete turn of earthed lead was wound around the outside of the Swiss roll in order to measure the effect that this would have upon sensitivity.

The materials of the device and of the former were chosen partly for their thermal contraction properties. The mylar and lead would contract by about 1% upon cooling to liquid helium temperature, whilst the brass of the former would contract considerably less (19). Therefore the windings would be under tension when cooled, thus increasing their mechanical stability.

Precautions had to be taken to prevent electrical breakdown when the device was cooled using liquid helium. Although in tests using a Van de Graaff generator at room temperature in air the insulation was able to withstand in excess of 20 kilovolts (a field of over 10^8 V/m), breakdown around the edges of the insulation was found to be a major problem when in a helium atmosphere. In simple experiments in a helium atmosphere using the mylar and lead sheeting, it was found that breakdown would occur at about 1kV almost independently of the path length around the edge of the insulation. About the same breakdown voltage was observed in gaseous helium at room temperature as in liquid helium. The cause of breakdown is the high electric field near the edges of the lead sheet. In this region, helium ions are formed which then migrate around the edges of the insulation, driven by the electric field. Although helium has a high ionization potential, its atoms have no vibration or rotation states through which an ion can dissipate the energy it gains from the electric field. This results in highly mobile ions and a lower breakdown field than for air. (20,21). This problem is compounded by the high dielectric constant of mylar (2.8 at 100 Hz (18)), which causes there to be a higher field in the helium region than there would otherwise be.

A partial solution to the breakdown problem involved spreading clean vacuum grease around the edges of the lead sheeting so that it became squashed between the mylar layers. If care was taken in spreading the grease, 4 kilovolts could be applied with a leakage current of less than 10 nA in both gaseous and liquid helium. Although vacuum grease becomes brittle when is immersed in liquid nitrogen, it does not crack unless hit sharply. We assume the grease did not crack in our low temperature experiments.

Thus, in order to alleviate the problem of breakdown, vacuum grease was spread around the edges of the lead sheet which was to be charged up to high potential. When the apparatus was tested in gaseous helium at room temperature, the leakage current at 3.5 kV was less than 10 nA, corresponding to a decay time for the charge on the capacitor (0.58 microfarad) of $2\ 10^5$ seconds, or approximately 2 days. Because of the possibility of damaging the SQUID and its electronics if breakdown did occur, the apparatus was not operated above 1 kilovolt potential whilst in liquid helium. At this voltage the leakage current in the liquid helium was less than 1 nA. This safety precaution severely limited the sensitivity of the instrument.

Connections made of strips of the lead 3 mm wide, were brought out through holes in the phenolic flange at one end of the Swiss roll in order to enable the loops to be completed and coupled to the SQUID. The lead strips were separated from one another using the mylar insulation with a minimum width of 13 mm, and vacuum grease was spread around the edges of the lead strip which was to be connected to high voltage. The strips were run as close together as possible to minimize stray inductance, and the strip which was to be at earth potential was wound twice around the fractional-turn SQUID (9). Where necessary, connections between the strips were made using ordinary solder and a cool soldering iron so that the lead did not melt. This particular SQUID was used because the point contact could be readjusted immediately if an electromagnetic pulse from high voltage breakdown of the capacitor altered the critical current (which actually happened once or twice).

To be able to calibrate the instrument, a long solenoid of known dimensions was inserted between the connecting strips. A flux could be applied to the windings by passing a current through the solenoid, and the resulting change in SQUID output could be measured to provide the calibration.

The whole apparatus was placed inside a brass can electroplated with lead, and the joins in the can were made using Wood's metal as a solder and dilute hydrochloric acid as a flux. The rod for adjusting the point contact of the SQUID and also the electrical connections were brought out through re-entrant lead-plated brass tubes which were designed to screen external magnetic fields, and resistors of 1 Mohm were included in all low-frequency lines in order to prevent radio-frequency interference from entering the can. Further magnetic screening was provided by a second can of the lead sheeting (not shown in the figure) soldered at its joins with multicore solder and a cool iron, and tied tightly in place on the outside of the lead plated brass can. The earth connection was brought out from the rotation device through a 1 Mohm resistor to the earthed can. Connections were made so that liquid helium could be forced to circulate around the inside of the can during the transfer of helium, as shown in the figure, and consequently only 13 litres of liquid were needed to cool down and immerse the whole apparatus (which weighed 7.6 kg) from the temperature of liquid nitrogen.

The whole apparatus was mounted inside two pyrex glass dewars. an outer one to contain liquid nitrogen, and an inner one for liquid helium. The dewars could be raised off the floor using a winch and nylon rope, and they could be rotated about a vertical axis by twisting the rope. In this way the dewar could be rotated without causing excessive mechanical vibration. (In preliminary experiments it was found that rotating the apparatus inside the dewar led to vibration and noise in the output.) The dewars themselves were placed inside a can of mu-metal to which coils were added in order to null out stray magnetic fields in the vertical direction. The external magnetic field could be measured using a flux-gate magnetometer. Over the dimensions of the experiment, it was possible to obtain a remnant field less than 100 nT in the vertical direction, and less than 1500 nT in the horizontal direction.

The calculation of the electrical properties of the apparatus is outlined in appendix 1 . The calculation uses only geometric measurements and the values of fundamental constants for input, and it makes the approximation of neglecting end effects. The properties calculated include the inductance L presented to the SQUID by the windings; the inductance L_{SQ} presented to the windings by the SQUID (taking into account the transformer ratio of 24:1 from two turns around the SQUID and the 12 holes of the SQUID); and the stray inductance in the leads to the SQUID. In addition a calibration constant C_{cal} is calculated. This is the ratio of flux applied to the windings through the calibration coil, to the flux measured in the SQUID as a result, i.e. $C_{cal} = \phi_{\text{calibration coil}} / \phi_{\text{SQUID}}$. It depends upon the coupling of the coil to the SQUID, and can be measured accurately in the experimental apparatus as a check on the calculation. The calculations relating to one particular run (the seventh run) are as follows:

Inductance of windings	L	11 nH
Stray inductance in connections	L_{st}	40 nH
Transformed SQUID inductance	L_{SQ}	21 nH
Calibration constant	C_{cal}	82.2
SQUID output upon rotation	ϕ_{out}	0.042 ϕ_o /(kV rad/sec)

Note that the inductance of the windings L is small because of the screening effect of one loop upon the other. In this run the stray inductance in the connections was larger than had been anticipated because the lead strips had slipped relative to one another during construction. Both the quantities C_{cal} and ϕ_{out} could be measured accurately in the experimental apparatus, using the size of the flux quantum as a calibration for the SQUID flux.

5 Experimental Results

In this section we first discuss the best quantitative measurements of the rotation effect, which were obtained in the last run (the seventh), before moving on to a discussion of the noise problems which were encountered in this and previous runs.

Figure 3 shows the chart recorder traces of the SQUID output used to calibrate the instrument. In the upper trace, the battery powered calibration coil was used to apply a calculated 17.4 flux quanta to the coils. The change in output on the trace in response to this flux was 2.25 V. The lower trace shows the change in SQUID output upon allowing one flux quantum to enter the SQUID (acheived by breaking the feedback loop around the SQUID for a short time), namely 10.5 V. Combining these two results, one concludes that it is necessary to apply 81.2 flux quanta to the calibration coil in order to obtain one flux quantum in the SQUID. This calibration is in agreement with the geometric calculations for C_{cal} (see above and appendix 1) to within 2% .

In the upper trace of figure 4, the leads to the calibration coil were disconnected and there was no voltage applied to the rotation device, so that no change in output was expected as a result of rotation. The apparatus was suspended off the floor and rotated, so twisting up the rope. There was indeed little change in output during this rotation, as may be seen from the trace. (We shall discuss later the various noise sources which evidence themselves here.)

Immediately after taking the upper trace, the capacitance of the device was charged to 1 kilovolt (to an accuracy of 2%) and the high voltage connection was removed to ensure a stable voltage. The output upon rotation is shown in the lower trace. Inspection of the traces shows that there is an effect which depends upon the voltage and upon the direction and velocity of rotation. In order to quantify the effect, the area under five of the curves was measured. Counting rotation in both directions in a positive sense, these five curves represented a total rotation of 40 turns, and the total area under them was 10.9 ϕ_0 s . This yields a sensitivity of 0.0434 ϕ_0/(rad/s). Each curve could be measured to an accuracy of 10% (the major source of error being shifts in the baseline), so that averaging over 5 curves, the accuracy was 10% / $\sqrt{5}$, or approximately 5% . The measured response is in agreement with the calculation (see above and appendix 1) to better than 4% . We conclude that the rotation effect has been measured and found in agreement with theory to an accuracy of 5% . It may be seen in the figure that the noise had magnitude of about 0.4 V , corresponding to a rotation rate of approximately 1 radian/second.

We now move on to a discussion of the various sources of noise which were encountered. Radio-frequency interference (which affects the operation of the SQUID) was one noise source which could be overcome relatively easily, by inserting resistors in all leads out of the can, and by screening the cryostat using aluminium foil. Moving a powerful magnet near the cryostat gave no deflection measureable above the ambient noise, so that changes in the external magnetic field were not a problem. The most serious noise sources were all associated with the ambient magnetic field which was present at the time of cooling the apparatus to superconducting temperature, and which became pinned in the apparatus. These noise sources diminished approximately in proportion to the ambient field present during cooling, and we discuss these next.

Figure 5 shows a trace taken during an early experiment (the fifth), in which there were wrinkles in the windings of the rotation device. (After this experiment, the layers were re-wound to eliminate wrinkles, as described in section 4 .) With no voltage applied, rotating the device gave a deflection which did not depend upon the direction of rotation. We attribute this effect to centrifugal forces causing the windings to expand radially and so to change their interaction with the ambient magnetic field. Since the centrifugal force increases as the square of the rotation velocity, then the SQUID deflection would be expected to be proportional to $(n/t)^2$ if the rotation velocity can be kept constant, where n is the number of turns and t is the time taken. The area A under a curve would therefore be given by $A = k\,n^2 / t$, where k is a constant. The values of k calculated for the four curves shown in the figure were respectively 0.20 , 0.19 , 0.16 and 0.14 . The torque in the suspending cord made it difficult to maintain a constant rotation velocity for the longer times involved in the latter two curves, and it is to this difficulty that we attribute the lower values of k associated with these curves. These measurements are consistent with the centrifugal explanation.

We now estimate the order of magnitude of the expansion associated with the centrifugal effect. If the component of magnetic field in a vertical direction pinned during cooling is B_{vert} , and the area between the windings is A_w , then the flux appearing in the SQUID is $B_{vert} A_w / C_{cal}$. Supposing that the centrifugal effect causes a fractional expansion f of the winding, then the resulting change in the SQUID output is given by $f\,B_{vert} A_w / C_{cal}$. For this experiment the vertical component of magnetic field B_{vert} was nulled to better than 100 nT during cooling, and the calibration constant C_{cal} was calculated to be 50. The area between the windings A_w was 0.002 m^3. Using the above formula with data extracted from figure 5 , we deduce that the fractional expansion f was of order 0.003% .

After this experiment the layers were re-wound more tightly, and the centrifugal effect was no longer discernible above the other sources of noise. (The last experiment was cooled intentionally in a vertical magnetic field of 1000 nT, 10 times larger than this experiment, and a small centrifugal effect may be discerned in figure 4a . It also appears that cycling the apparatus between room temperature and liquid helium caused the layers to become less tightly packed in this last experiment.)

A second cause of noise was mechanical deformation. Swinging of the dewar led to noise output through gravitational deformation, and angular accelerations at the beginning and end of rotations caused noise which can be seen clearly in the traces of figures 4 and 5 . Some deformations were hysteretic, leading to a change in the baseline as may be seen in these figures. These effects were of the same order of magnitude as the centrifugal effect described above, so similar dimensional changes (0.003% or so) were involved here; but figure 4 shows that, unlike the centrifugal effect, this source of noise could not be eliminated by winding the layers more tightly.

The third type of noise manifested itself as a continuous drift in the SQUID output, and it is illustrated in figure 6a . Typically the rate was of order one flux quantum in the SQUID every 15 minutes or so, and it continued for several days. As far as could be determined, the drift did not depend upon mechanical agitation, nor did it depend upon the voltage applied to the capacitance of the device. The drift decayed over time, and figure 7 shows how the rate varied with time for one experiment (the fourth). It appears here that there are two 1/e decay times: 11 hours which dominates the bahaviour for about a day, and 54 hours which can be seen after this. Figure 6b shows the drift seen in run 6 , for which the layers of the rotation device had been re-wound tightly: in this experiment small jumps in the output could be seen but the jumps were not systematically in the same direction. Table 1 shows a comparison of the drift rates seen in the various runs.

There are two possible explanations for the drift observed. According to one explanation, flux trapped in the superconducting parts of the apparatus is jumping from pinning sites to sites of lower energy, so changing the flux applied to the windings and causing drift in the output. The process is thermally activated, so that it decays exponentially with time. The 1/e decay time increases as the more easily dislodged flux lines are removed and the decay becomes dominated by the more tightly bound flux lines. The decay rate according to this explanation will be proportional to the ambient magnetic field upon cooling, and the decay itself will occur by jumps rather than as a continuous process.

Although all of these features are observed, this explanation does not account for the disappearance of systematic drift in run 6 , nor its reappearance in run 7 ; neither can it account for the unusually short decay time seen in run 3A . A further problem with this explanation concerns the magnitude of the effect. To take a particular example, a drift rate was measured in run 5 of 0.6 ϕ_o /hr, which corresponds to a change in the flux applied to the 0.002 m^2 between the windings of 30 ϕ_o /hr (taking into account the calibration constant); in other words this would correspond to a flux movement of 15000 ϕ_o m^{-2} hr^{-1}. In order to check the order of magnitude of the flux motion effect, a simple experiment was performed in which a commercial SQUID had a magnetic field sensing loop 3 mm diameter of niobium wire attached to its input, and this was placed inside a can of the lead sheeting and it was cooled slowly to 4K in an ambient magnetic field of approximately 200 nT. Systematic drift was not seen. The measured flux drift was less than 15 ϕ_o m^{-2} hr^{-1} , a factor of 1000 smaller than was observed in the rotation experiment. Since there was only a single layer of lead to pin the flux in this simple experiment, whereas there were 56 such layers in the rotation device, one would have expected the flux motion to be far larger in the simple experiment, contrary to what was observed.

A clue to the true explanation of the drift is provided by the observation that the drift displays a strong dependence upon mechanical properties and upon the thermal history of the experiment. All of the runs except for run 3A were precooled for a period of approximately 18 hours with liquid nitrogen, prior to transfer of liquid helium; run 3A followed on directly from the previous run so that the apparatus had not been allowed to warm up above 77K before the helium transfer. In all of the experiments, the 1/e decay times are given to a reasonable approximation simply by the time since the last major temperature change. It appears that the effect is related to thermal contraction. This conclusion is supported by the data from the later runs, in which the windings had been re-packed more tightly, and in which the magnitude of the effect was consequently reduced.

As was discussed earlier, the windings were designed to contract by about 1% upon cooling from room temperature, whilst the former around which they were wound would contract considerably less. The intention of this was to stress the windings and so to increase their mechanical stability. It appears that, on the contrary, the stress may have been a major cause of mechanical instability and hence of noise: we believe that in our experiments the stress relaxed over a period of hours, producing the observed noise. Sites which relax quickly will have dominated the drift at short times, whilst the drift at longer times will be dominated by sites which relax more slowly. The total movement can be estimated from the SQUID output (see the above analysis relating to the centrifugal effect): in experiments 3A , 4 and 5 it was of order 1% , the same order of magnitude as the contraction of the windings themselves. Some plastic deformation of the windings certainly occurred during the low temperature runs, since the windings were never as tight when returned to room temperature. It is of interest to note that the relaxation of stress occurred in jumps rather than smoothly. If this is the correct explanation for the noise, we believe this long term relaxation at low temperature to be a new effect which has not been observed before.

To summarize this section, we have verified the theory of the rotation effect quantitatively to an accuracy of 5% . Several noise sources were encountered, the most serious of which are related to mechanical stability and to the ambient magnetic field which is pinned in the apparatus at the time of cooling to superconducting temperature. A rotation rate of about 1 radian/second could be distinguished above the noise.

6 Further developments

There were several problems with the design of the apparatus described above. Thermal contraction and the heavy weight of the unit both made it prone to mechanical deformation, producing a serious noise problem through interaction with the ambient magnetic field, whilst problems of breakdown around the edges of the mylar gave a severe limitation to the voltage which could be applied. In this section we suggest possible ways round these problems, and describe preliminary experiments performed with these in mind.

There are several ways to modify the apparatus in order to improve the sensitivity, whilst keeping the basic design unchanged. The problem of mechanical distortion could be attacked by reducing the weight: the lead could be replaced by some other superconductor which is not torn so easily and so which can be rolled out thinner (niobium is available commercially in 0.001 inch thick sheets). Alternatively the superconductor could be vacuum-deposited directly onto the insulator, much in the way that aluminium is deposited on strips of insulator in the construction of commercial capacitors. The problem of thermal contraction might be attacked by the use of a suitable plastic former rather than a brass one. Since all the major sources of noise were associated with the ambient magnetic field, they might be alleviated by the use of a low magnetic field facility (17) to reduce the ambient field during cool down. Finally, the problem of electrical breakdown might be attacked by heating up the ends of the capacitor so that the mylar melts and seals up the ends. In a preliminary experiment several layers of mylar were brought together and the ends were heated using a small flame. Figure 8 is a micrograph of a cross section of the result: the sealing appears to be satisfactory. A controlled temperature hot air gun might be useful in obtaining uniform heating and to prevent any burning of the mylar.

Using the estimates given in sections 3 and 4, sealing the ends of the capacitor would improve the breakdown voltage by more than an order of magnitude, whilst the use of a low magnetic field facility would achieve ambient magnetic fields three orders of magnitude smaller than were used in our experiments. If no further sources of noise are encountered, these modifications would therefore improve sensitivity to rotation velocity by over four orders of magnitude.

A second method of overcoming these noise problems involves a change in the basic design of the apparatus. See figure 9 . In this design, the problem of breakdown around the edges is overcome simply by removing the edges: the windings which are to be at high voltage are enclosed within a flexible tube of PTFE. The tube is immersed in mercury kept at earth potential, which acts as the counterelectrode of the rotation device and which solidifies at low temperature, so keeping the windings mechanically rigid. Because mercury becomes superconducting at 4.05 K , the apparatus must be kept below this temperature. Alternatively the mercury might be amalgamated with a good superconductor to increase its transition trmperature.

Some preliminary experiments were performed with this design in mind. A simple rotation device was built and tested which used PTFE tubing and very high voltages, but which did not use the mercury.

In high voltage tests, a commercial Van de Graaff generator was found to be unsatisfactory because of the difficulty of controlling the voltage and the possibility of damage through excessive voltage. A simple, home-made generator was therefore used: the design (22) used a cola can for the top charge collector (the sharp edges were taped up with electrical tape, and corona discharge around them served to limit the voltage to about 50 kV) and the belt was of polyvinylchloride electrical insulating tape stuck to itself. The belt was driven round by motor over two crowned pulleys of bakolite and of nylon supported using a tube of lucite, and charge was transferred with brushes of aluminium foil. The whole apparatus took a day to build. Since the charge took some seconds to build up, adequate control over the voltage could be obtained by switching the motor on and off or by discharging the coke can; an electrostatic voltmeter was used to measure the voltage. See figure 10.

Standard 0.3 mm walled PTFE tubing was able to withstand the full voltage available from the generator, although if the tubing was stretched or otherwise abused it would break down, particularly if it had been cooled to low temperature at some stage in its history. In the experiments we used niobium wire 0.3 mm diameter inside two PTFE tubes, with an outer diameter of 1.7 mm . A three-way connection between the two ends of the coil and the high voltage input was needed in the new rotation device, so in preliminary experiments several different materials were tried for potting an end of the tubing. No glues were found which withstood the voltage adequately at room temperature. Vacuum grease was able to withstand 12 kV through a path length of about 2cm , whilst in a similar geometry both a commercial plastic glue (which is applied by melting using a special tool) and a clear (23) plastic material intended for repairing downhill skis, which can be melted using a hot-air gun, were able to withstand the full voltage. In our experiments the ski repair plastic was used because it was better able to withstand the thermal shock of cooling. A satisfactory three-way connection was made by spot welding the ends of the niobium wires which had been threaded inside the PTFE tubes, roughening the very ends of the tubes using emery paper to increase adhesion, and potting the result in inside a former of PTFE with ski repair plastic heated with a hot air gun.

A simple rotation device was made using this technology. The niobium wire inside its tubing was wrapped in a single layer of 9 turns around a multihole SQUID of diameter 2.5 cm and height 2 cm, and it was joined to itself and to the high voltage lead using a three-way connection described above. The whole device was bound tightly with string and enclosed in a lead shield. It was anticipated that the device would have high mechanical stability because there was only one layer of insulation around the rigid SQUID, and it was calculated that the sensitivity would be 2 10^{-3} radians per second with 30 kV applied if it were limited by SQUID noise.

This design was successful in reducing the mechanical deformation which had been noticed in the previous experiment. No drift was seen, and it was necessary to handle the apparatus very roughly before any mechanical deformation was evidenced. On the other hand, a new and severe type of noise was noticed which was associated with the high voltage applied to the apparatus. When the niobium wire was charged up inside the double PTFE tube connecting the apparatus to the Van de Graaff generator, the field in the vicinity of the tube attracted charges to the surface. It was possible to wipe these charges onto the tube by waving a hand near it, and crackling would be heard as the charges were transferred. (The insulation did not break down since the charges could later be wiped off the surface with a crackling noise if the wire inside the tube was discharged.) The transfer of charge in this way was associated with a large and hysteretic change typically of order one flux quantum in the SQUID output. Rotating the apparatus whilst charged up produced a similar output, which we attribute to charges being wiped onto the surface within the apparatus through some mechanism which is perhaps connected with motion of the liquid helium.

The SQUID output was not associated with the large charging currents which flowed instantaneously, since a similar output was obtained if a long resistor chain of ten 5 Mohm resistors was used to reduce the charging currents. The electric field in the PTFE was approximately 10^5 V/m , and as was mentioned in section 3 , a field of this order is associated with a stress of order one atmosphere pressure and consequently would produce a strain of order 10^{-5} in solid PTFE at low temperature. We attribute the SQUID readings to dimensional distortions caused by changes in the electric field as charges were wiped onto the apparatus. The motion due to wiping of charge was calculated from the SQUID readings to be of order 100 nm (1 part in 10^5). Since the change in voltage due to wiping of charge was typically less than 5% , then taking into account looseness in the windings this is in reasonable agreement with the expected motion.

Distortion due to the electric field could therefore be an important source of noise in sensitive instruments. The distortion would vary as the square of the electric field, whereas the signal would rise linearly with this field, so that there may be an optimal voltage for lowest noise. It may be important to pot the whole device including the high voltage leads to prevent the wiping of charge onto the surface and hence to keep the voltage constant. In the case of a mercury potted device, the symmetry of field around the wire inside the tube might reduce the amount of mechanical deformation and so reduce the importance of this source of noise. The experience of these preliminary experiments does however lead one to be pessimistic about the sensitivity attainable with this tubular type of design.

References

(1) A.D. Moore 'Henry A. Rowland'
Scientific American, February 1982. p. 150

(2) R.M. Brady Fellowship dissertation, Trinity College,
Cambridge. August, 1980

(3) R.M. Brady 'A superconducting gyroscope with no moving parts'
IEEE Transactions on magnetics (1980 Applied
Superconductivity Conference), Jan. 1981, p.981

(4) R.M. Brady 'Correction to the formula for the London moment
of a rotating superconductor'
To be published in J. Low Temp. Phys. 49, 1/2

(5) R.A. Bergh, H.C. Lefevre, H.J. Shaw; and J.L. Davis, S. Ezekiel
Optics Letters, 6, p. 502 and p. 505 (1981)

(6) See chapter 2

(7) A good discussion of the London moment is found in
J. Williams 'Superconductivity and its applications'
Pion Ltd. London, 1970. p. 46

(8) D.B. Sullivan
'Superconducting Quantum Interference Devices:
an Operational Guide for rf-Biased Systems'
NBS Technical note 629
US Department of Commerce publication, Nov. 1972

(9) J.E. Zimmerman

'Sensitivity Enhancement of Superconducting Quantum Interference Devices through the use of Fractional-Turn Loops'

J. Applied Physics, 42, 11, p.47, (1971)

(10) M. Tinkham 'Introduction to Superconductivity'

McGraw-Hill, 1975. Chapter 6.

(11) J.E. Zimmerman and A.H. Silver

'Quantum Effects in type II superconductors'

Phys. Lett. 10, 1, p.47 (1971)

(12) A. Long, T.D. Clark, R.J. Prance and M.G. Richards

'High Performance UHF SQUID magnetometer'

Rev. Sci. Instrum. 50, 11, p.1376, (1979)

(13) M. Cromar and P. Carelli

'Low-noise tunnel junction dc SQUIDs'

Appl. Phys. Lett. 38, 9, p.723, 1981.

(14) J. Kurkijarvi

'Collective Quantum Tunnelling, Ultimate Sensitivity of the AC SQUID, and All That'

J. Low Temp. Physics, 45, 1/2, p.37, 1981

(15) A.B. Pippard

has suggested the simple analysis given above.

(16) Chemical Rubber Company

Handbook of tables for applied engineering science. page 118.

(17) D.U. Gubser, S.A. Wolf and J.E. Cox
'Shielding of longitudinal magnetic fields with thin, closely spaced, concentric cylinders of high poermeability material'
Rev. Sci. Instrum. 50, 6, p.751 (June 1979)

(18) Schramm, Clark and Reed
'A Compilation and evaluation of mechanical, thermal and electrical properties of selected polymers'
U.S. National Bureau of Standards
monograph no. 132

(19) D.H.J. Goodall
Cryogenic data wallchart; A.P.T. Division, Culham Laboratory, England. March 1970

(20) J. Gerhold 'Dielectric breakdown of helium at low temperatures'
Cryogenics, October 1972. p. 370

(21) K.M. Mathes
'Dielectric properties of cryogenic liquids'
IEEE Trans. on Electrical Insulation,
El-2, no. 1, April 1967. p. 24

(22) C.L. Stong 'Homemade Van de Graaff generator'
Scientific American book of projects for the amateur scientist;
Simon and Schuster, New York, 1960

(23) Standard clear downhill ski repair plastic is easily available in ski-ing areas. It appears to contain polythene.

(24) J. Gallop Private communication

Acknowledgements

We thank R.C. Ball, D. Bartlett, M.W. Cromar, B.D. Josephson, R.L. Kautz, B. Muhlfelder, A.B. Pippard and J.R. Waldram for helpful discussions. The simple explanation given in section 2 for the operation of the gyroscope emerged during discussions with A.B. Pippard. This work was supported in turn by the Science Research Council; Trinity College, Cambridge; and the U.S. Office of Naval Research.

Table 1 - Comparison of drift between runs

Run	drift rate 3 hrs after cooling to 4K	1/e decay time	later 1/e decay time
3	not measured	10 hrs	not measured
3A%	6 Φ_0/hr	2 hrs	4 hrs (seen at 3 hrs.)
4	11 Φ_0/hr	11 hrs	54 hrs (seen at 22 hrs.)
5*	0.6 Φ_0/hr	10 hrs	not measured
6*	systematic drift not seen (capacitance re-wound for this run)		
7	1.6 Φ_0/hr	28 hrs	not measured

* for these runs the ambient magnetic field during cooling was less than 100 nT in a vertical direction.

% this run followed directly on from run 3 ; the apparatus was not warmed up above 77K between these runs.