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Design and manufacture of components for the development of superconducting gravity gradiometer

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Abstract

The gravity gradiometer is widely used not only for resource exploration, gravity DB-based navigation, but also for measurement of Newtonian constant. Among the gravity gradiometers, SQUID (Superconducting Quantum Interference Device)-based detection system is known to be the most sensitive technology. The superconducting gravity gradiometer consists of two proof masses with flat leaf springs sensitive to gravity change, a SQUID detection system to measure magnetic flux change due to the proof mass displacement, and a cryogenic system to accommodate those two components. In this paper, an optimized superconducting gravity gradiometer is designed and the characteristics of each component manufactured are described. In order to reduce noise and improve sensitivity, two mass-spring systems with low resonant frequency of around 11.5 Hz and high Q-factor around 8000 under low vacuum were fabricated. In addition, a pair of flat spiral coils for levitation and sensing were fabricated to levitate the proof mass to null position and to induce a sensitive magnetic flux change corresponding to its displacement. The SQUID detection system connected to the sensing coil through a flux transformer was built and the spectrum noise at 1 Hz was about 5.6 $\mu\Phi_0/\sqrt{Hz}$. A magnetically shielded cryostat cooled down by liquid helium was sealed with μ-metal sheet to reduce the electromagnetic wave interference and its long-term temperature stability under ±5 mK could be obtained without any control. The persistent current induced in the flat spiral coil was maintained for over 12 days without additional liquid helium. In the future works, after assembling the components into one system, the displacement of the proof mass corresponding to gravity changes could be presented.

Superconducting, Gravity, Gravity Gradiometer, SQUID

1. Introduction

A SGG (Superconducting Gravity Gradiometer) is a pair of identical proof masses coupled to SQUID (Superconducting Quantum Interference Device), which is a very sensitive device used to detect a quantized magnetic flux change in the superconducting loop accroding to the proof mass displacement due to gravity change. Two proof masses with constant distance are characterized by very high spatial resolution because they measure differential gravity rather than gravity. In addition, the gravitational gradient by the differential measurement can distinguish gravitational acceleration from platform acceleration, so that the effects of vibration are eliminated. Figure 1 shows a schematic diagram of a SGG. Each proof mass has a levitation and sensing coil to which a permanent current is applied. When the same permanent current is applied to the sensing coil, the current induced in the coil, L_I, changes with the displacement difference of the proof mass due to the difference in gravity, and the quantized flux is detected in the SQUID through the transformer. [1-4]

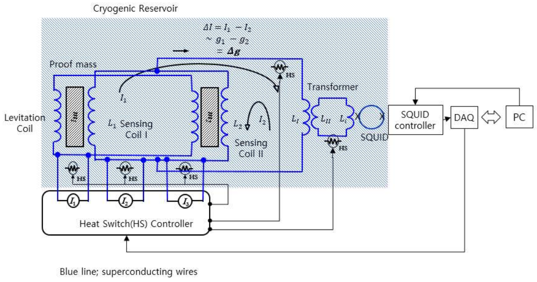


Figure 1. Schematic diagram of superconducting gravimeter

The SGG design theory was well known in the previous study[1]. The main design variables based on the analysis are as shown in Table 1 for a sensitivity of 1 E ($10^{-9}/s^2$).

Table 1 SGG design variables based on the KRISS model

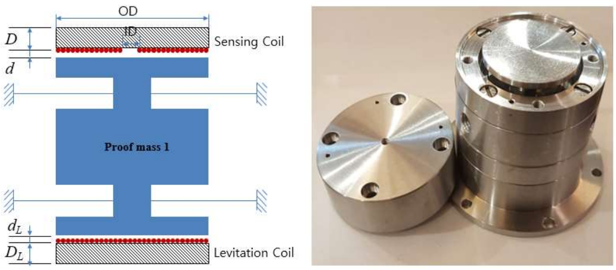
Design variables		Value
mass		$m_1 = m_2 = 90$ g
Flat spiral coil diameter		OD = 30 mm, ID = 6 mm
Flat spiral coil area		$A = 6.79\times10^{-4}$ m^2
Nb wire diameter		$\phi_d = 0.15$ mm
Levitation Coil	Back plate distance	$D_L = 13$ mm
	Mass distance	$d_L = 0.45$ mm
Sensing Coil	Back plate distance	$D = 13$ mm
	Mass distance	$d = 0.15$ mm
Output impedance		$L_I = 5.52$ μH
Transformer impedance		$L_{II} = 8.05$ μH
SQUID input impedance (fixed)		$L_i = 1.8$ μH

*Symbols are shown in Figure 1 and 2

Based on the above design, the proof mass with flat spiral coils, and the SQUID detection system with heat switches, and a cryogenic system to accommodate those two components were manufactured for the SGG development. This paper describes each component's manufacturing results and its performances.

2. Mass-spring-coil System

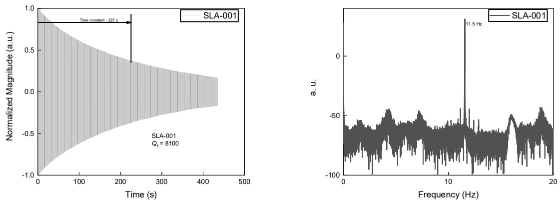
The mass-spring-coil system as shown in Figure 2 can be used as one gravimeter component. It is well known that the lower the resonance frequency, the smaller the noise of the SGG. In addition, the high Q-factor is important to improve the sensitivity / repeatability of gravimeter.



(a) Layout (b) Nb assembly

Figure 2. Mass-spring-coil system

A long time constant of decaying free-vibration and a low resonance frequency are necessary for high sensitivity. At low vacuum conditions of 10^{-1} Torr, a long time constant of 225 s and a low resonance frequency of 11.5 Hz were obtained, resulting in a high Q-factor of more than 8100.



(a) Free vibration in vacuum (b) Resonant frequency

Figure 4. Mechanical characteristics of mass-spring system

3. SQUID detection system

The magnetic noise of a magnetically shielded SQUID system is very important when measuring quantized flux changes due to gravity changes. The magnetic flux output noise of the SQUID coupled to the sensing coil of the gravity gradiometer is shown in the Figure 5. The flux noise using the feedback current ($2.4 \times 10^{-4} \mu A/\sqrt{Hz}$) and sensitivity ($43.03\ \mu A/\Phi_0$) of the SQUID can be obtained with $5.6\ \mu\Phi_0/\sqrt{Hz}$, which is good enough for the system performance.

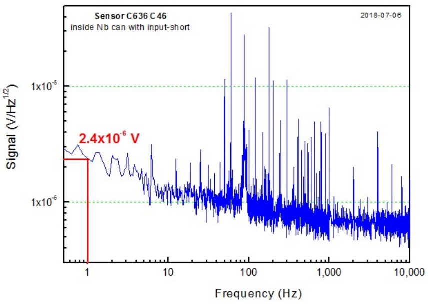


Figure 5. SQUID output noise

4. Magnetically shielded liquid helium cryostat

A magnetically shielded liquid helium cryostat with μ-metal sheet that accommodates a pair of mass-spring-coil system and a SQUID detection system was designed and manufactured as shown in Figure 6.

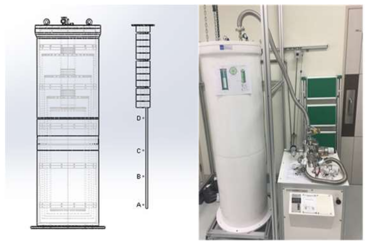
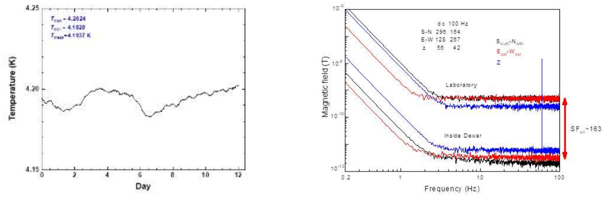


Figure 6. Magnetically shielded liquid helium cryostat



(a) Temperature stability (b) Magnetic shielding

Figure 7. Liquid helium cryostat performance

The long-term temperature stability under ±5 mK at approximately 4.2 K could be obtained over 12 days without any control as shown in Figure 7(a). The temperature change depends on the boiling point change depending on the atmospheric pressure. Magnetic shielding factors for earth field was estimated to be about 200 in transverse, and 56 in vertical as shown in Figure 7(b).

The persistent current induced in the flat spiral coil by heat switch controller as shown in Figure 8 was maintained for over 12 days without additional liquid helium. It can be concluded that the current is not lost because the current charge and discharge shapes and area are the same.

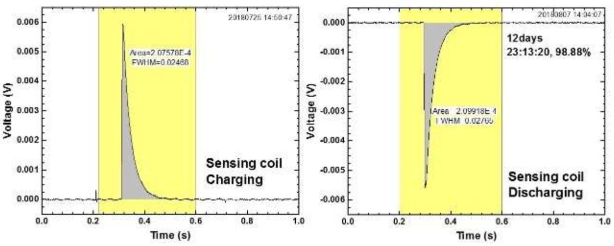


Figure 8. Persistant current charging and discharging results

5. Conclusions

The components for the development of superconducting gravity gradiometer have been successfully developed for the performance of SGG with 1 E senstitivity. The mass-spring system with flat spiral coils has a high Q-factor even at low vacuum. The SQUID sensing noise is sufficient to measure small quantized magnetic flux change according to the gravity change. A magnetically-shielded cryostat is very stable even when operated for a long period without additional liquid helium charging. In the near future, the components will be assembled and operated for sensitive differential gravity measurements.

References

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