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Design and manufacture of a high-resolution 1D superconducting gravimeter

Frank Schmaljohann[1], Daniel Hagedorn[1], Frank Löffler[1]

[1]*Physikalisch-Technische Bundesanstalt, Bundesallee 100, D-38116 Braunschweig*

Frank.schmaljohann@ptb.de

Abstract

Superconducting gravimeters are state-of-the-art for measuring the local gravitational field with highest precision. However, for significant proof of the so-called Slichter modes - a reflection of seismic waves at the Earth's inner core boundary - the resolution is too low.
The fully new gravimeter design also uses superconducting coils for the levitation of a test mass, but there are two fundamental differences: First, the detection of the variation in position of the test mass is done by SQUIDs (Superconducting QUantum Interference Device) which allows an improvement in terms of resolution by a factor of up to 100. Second, the design of the test mass was changed, having a coned opening on both sides. This leads to less weight and a smaller current needed for levitation and the change in position can actually be detected by the SQUID sensors. To avoid wobbling of the test mass after levitation, size deviations were kept down to a minimum within the range of one micrometre in a specifically developed turning process. In comparison to a solid niobium test mass, Mg, Ti and Al alloys were coated with niobium by magnetron sputtering and tested. Furthermore, manufacturing of the levitation coils on tapered surfaces was developed, as well as coils on the inner surface of rings.

Superconducting gravimeter, SQUID sensors, instrumentation design

1. Introduction

For the measurement of the local gravitational field with highest precision, superconducting gravimeters are state-of-the-art. Commercially available instruments use a niobium sphere as test mass which is levitated by superconducting coils with persistent electric currents. Spacial displacement caused by minor variations of the gravitational field is detected by measuring the capacitance between the sphere and surrounding electrodes. The resolution of these gravimeters is about 0.1 - 1 nm/s² in magnitude over a year's duration [1]. Nevertheless, for significant proof of the predicted Slichter modes, a possible reflection of seismic waves at the Earth's inner core boundary, the resolution and long-term stability is still too low [2,3].

In this paper a newly designed gravimetric sensor is proposed which also uses superconducting coils for levitation, but in a very different and novel setup. In addition, the detection of the test masses' special displacement is conducted by SQUIDs (Superconducting QUantum Interference Device) which technically allows an improvement in terms of resolution by a factor of up to 100.

2. Gravimeter design

The entire sensor is installed in a vacuum tube which fits into a commercially available liquid helium cryostat. Adapted heat shielding and wiring allow a sensor temperature of down to 5 K when immersed. Helium gas at several 100 Pa serves as heat transfer agent while allowing the test mass to float freely with minimal friction.

The novel sensor design was determined by two requirements. Firstly the sensor should be utilisable in both a vertical and horizontal setup to allow directional measurement. Secondly the sensor's mass should be minimised to increase its sensitivity. As a superconducting setup for the levitation is needed to ensure a persistent electric current and, therefore, a permanent magnetic field, the test mass and wire coils are made of superconducting material.

The new test mass has a coned opening on both sides with a diameter of 21 mm and a total length of about 27 mm. Sectional Nb or NbTi wire coils embedded in two adapted cone heads (top and bottom) provide the combined persistent levitation field, see figure 4. One additional loop in the lower cone allows minor correction to the test mass's position within the magnetic field. Within this setup the test mass's movement is restricted to an axial displacement, only (disregarding a possible rotation or wobbling which, over the duration of the measurement, is checked by friction caused by the He gas).

Both faces of the test mass are surrounded by pick-up coils which are connected to the SQUID (see figure 1).

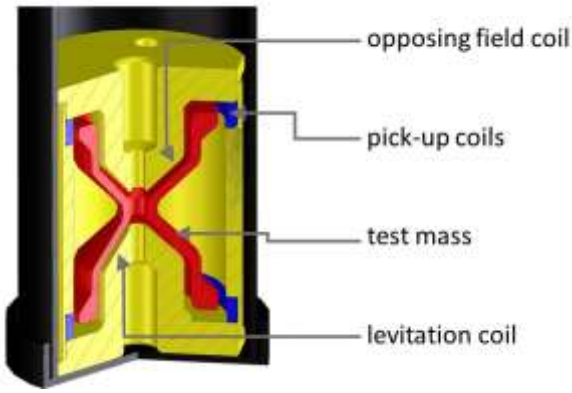

Figure 1. Sensor setup with test mass and coil areas

Above the sensor setup, additional measuring equipment like a temperature sensor and a terminal board is situated. In addition, a fiber-optic displacement sensor can detect the movement of the test mass in the range from micrometre to millimetre, before the SQUID sensors are put to use. It is even possible to identify a possible rotation of the test mass.

3. Manufacturing of the test mass

To reduce wobbling or rotation of the test mass after levitation in the first place, size deviations were kept down to a minimum within the range of one micrometre in a specifically developed turning process [4]. Instead of a solid niobium test mass, Ti, Mg and Al alloys were coated with niobium by magnetron sputtering for superconducting properties and tested afterwards.

In figure 2, a test mass made of Ti6Al4V is shown after the turning process and subsequent coating with niobium. Considering the complex shape of the test mass, deviations of form and dimensions are below 2 µm overall (measured with CMM Leitz Reference 600). The application of the Nb coating is a challenging task as the thickness of the Nb layer has to exceed 2 λ_L (about 200 nm) over the entire surface to guarantee a persistent superconductive current.

Figure 2. Ti6Al4V test mass after turning, fully coated with niobium

An overview of the possible achievements in weight saving by the use of suitable alloys in comparison to a standard niobium sphere is given in table 1.

Table 1 weight comparison of the different metals and shapes

		Calculated mass
Sphere Ø25.4 mm	Niobium	70.1 g
Novel test mass	Niobium	17.5 g
	Ti6Al4V	9.0 g
	MgAl8Zn1	3.7 g

4. Manufacturing of the coils

The pick-up coils were wound onto a carrier with an adapted micro-manufacturing presented earlier [5]. The superconducting wires were located precisely in parallel by a 2-axes system and fixed in this position using a low-temperature qualified adhesive. Afterwards the coil was detracted from the carrier and glued into the support seen in figure 3. By this means, the coil is in close proximity to the test mass.

The levitation coils are manufactured by hand, winding the superconducting wire onto a custom-made carrier which acts as a negative mould. Up to six windings were successfully set on top of each other. Next, the complete levitation coils are separated from the mould to fix them onto the actual part, shown in figure 4. The oval groover with a tool path width of only 0.3 mm on the tapered surface were manufactured by a 5-axis milling machine.

Figure 3. Pick-up coil for the SQUID sensor

Figure 4. Levitation coils inserted into milled paths of a tapered surface

5. Conclusions

A fully new one dimensional superconducting gravimeter design with a novel approach for the shape of the test mass was shown. The manufacturing of the test mass in the micrometre range was successful with different alloys. Also, a full-faced niobium coating by magnetron sputtering was proven. Manufacturing steps for coils with superconducting wire of different sizes and shapes were introduced.

First tests revealed that improvements to the full-faced niobium coating in terms of a uniform film thickness are needed. For an analysis of the actual enhancement of test masses with lower weight, the manufacture of a solid niobium test mass is projected.

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