An efficient calibration method for SQUID measurement system using three orthogonal Helmholtz coils*

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For a practical superconducting quantum interference device (SQUID) based measurement system, the Tesla/volt coefficient must be accurately calibrated. In this paper, we propose a highly efficient method of calibrating a SQUID magnetometer system using three orthogonal Helmholtz coils. The Tesla/volt coefficient is regarded as the magnitude of a vector pointing to the normal direction of the pickup coil. By applying magnetic fields through a three-dimensional Helmholtz coil, the Tesla/volt coefficient can be directly calculated from magnetometer responses to the three orthogonally applied magnetic fields. Calibration with alternating current (AC) field is normally used for better signal-to-noise ratio in noisy urban environments and the results are compared with the direct current (DC) calibration to avoid possible effects due to eddy current. In our experiment, a calibration relative error of about 6.89×10^{-4} is obtained, and the error is mainly caused by the non-orthogonality of three axes of the Helmholtz coils. The method does not need precise alignment of the magnetometer inside the Helmholtz coil. It can be used for the multichannel magnetometer system calibration effectively and accurately.

Keywords: SQUID, magnetometer, Tesla/volt coefficient calibration, three-dimensional Helmholtz coil

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1. Introduction

As an extremely sensitive magnetic sensor, superconducting quantum interference devices (SQUIDs) are widely used for the very weak magnetic field measurements, such as magnetocardiography (MCG), fetal MCG, magnetoencephalography (MEG), etc.[1,2] SQUID is usually driven in flux-locked loop (FLL) read-out electronics, so that the output voltage varies linearly with the magnetic field which is scaled by the Tesla/volt coefficient. As a magnetic sensor, the sensing field magnitude should be precisely known from the voltage output of the SQUID channel. Therefore, the Tesla/volt coefficient of the SQUID system is very important and must be accurately calibrated, especially for a multichannel system.

In order to calibrate a multichannel magnetometer system, two kinds of methods were previously studied. A most traditional method used the single Helmholtz coils. A uniform field was imposed right on the magnetometer and the corresponding voltage output was measured.[3–5] Although effective, the direction of the uniform field must be precisely along the normal direction of the SQUID pickup coil. The other method was based on the measurements of signals generated by many small calibration coils. The unknown sensor parameters, including the Tesla/volt coefficient, were numerically estimated by using complex algorithms.[6–10] Additionally, all of the calibration was performed under a certain AC frequency.

In this paper, we propose a simple and yet efficient calibration method for the SQUID magnetometer system by using three orthogonal Helmholtz coils. The Tesla/volt coefficient can be treated as the magnitude of a vector pointing to the normal direction of the magnetometer. Based on the orthogonal uniform field offered by the three-dimensional Helmholtz coil, the Tesla/volt coefficient can be directly calculated. In our experiment, calibration under different frequencies and the traditional single Helmholtz coils, is measured and compared.

2. Calibration method

2.1. Theory

The magnetometer relies on the integrated pickup coil that picks up the measuring field and couples it to the SQUID. The voltage response of the magnetometer is proportional to the flux passing through the pickup coil area, which can be expressed as:

$$V = \boldsymbol{B} \cdot \boldsymbol{S} k_{\phi}, \tag{1}$$

where $\boldsymbol{B}$, $\boldsymbol{S}$, and k_{ϕ} are the magnetic field, the pickup coil area, and the flux-to-voltage ratio, respectively. By introducing the normal direction of the magnetometer pickup coil, the

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Tesla/volt coefficient ($K_{\text{Tesla/volt}}$) can be treated as the magnitude of the following vector:

$$V = \boldsymbol{B} \cdot \boldsymbol{K}_{\text{Tesla/volt}}. \tag{2}$$

Figure 1 shows the calibration schematic for a SQUID magnetometer. The SQUID magnetometer can be arbitrarily placed in the orthogonal uniform magnetic field. By respectively applying the uniform field, the $\boldsymbol{K}_{\text{Tesla/volt}}$ is decomposed into three orthogonal components of K_x, K_y, and K_z.

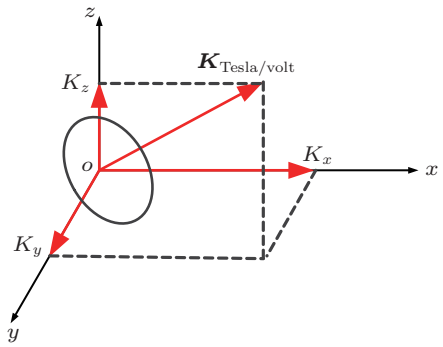


Fig. 1. (color online) Calibration schematic for a SQUID magnetometer.

By the orthogonal synthesis, the $K_{\text{Tesla/volt}}$ can be expressed by

$$K_{\text{Tesla/volt}} = \sqrt{K_x^2 + K_y^2 + K_z^2},$$

$$K_x = \frac{V_x}{B_x}; \quad K_y = \frac{V_y}{B_y}; \quad K_z = \frac{V_z}{B_z} \tag{3}$$

where B_x, B_y, and B_z are the magnitudes of the applied three orthogonal uniform fields; V_x, V_y, and V_z are the corresponding voltage responses of the magnetometer under the applied field B_x, B_y, and B_z respectively. By recording the applied magnetic fields and voltage responses, the Tesla/volt coefficient can be directly calculated.

2.2. Numerical simulation

In this method, the calibration accuracy is directly influenced by two key parameters of the field uniformity and orthogonality of the three-dimensional Helmholtz coil. In order to evaluate the influences, digital simulation on these two parameters is first performed.

2.2.1. Field uniformity calculation

The field uniformity of one pair of Helmholtz coils is defined by the uniformity error $\Delta\varepsilon(x,y,z)$, which is expressed as

$$\Delta\varepsilon\,(x,y,z) = \left| \frac{B_{\text{Axi}}\,(x,y,z) - B_{\text{Axi}}\,(0,0,0)}{B_{\text{Axi}}\,(0,0,0)} \right|, \tag{4}$$

where $B_{\text{Axi}}\,(0,0,0)$ is the magnetic field at the center of the Helmholtz coil and $B_{\text{Axi}}\,(x,y,z)$ is an analytical expression of the axial magnetic field for the Helmholtz coil in all space, which is given by[11,12]

$$\begin{aligned}
&B_{\text{Axi}}(x,y,z) \\
&= \frac{\mu_0 N I_0}{4\pi} \sum_{i=0}^{1}\sum_{j=0}^{1} \left\{ \frac{a/2+(-1)^i\cdot x}{[a/2+(-1)^i\cdot x]^2+[d/2+(-1)^{i+j}\cdot z]^2} \left[\frac{a/2+(-1)^j\cdot y}{\sqrt{[a/2+(-1)^i\cdot x]^2+[a/2+(-1)^j\cdot y]^2+[d/2+(-1)^{i+j}\cdot z]^2}} \right.\right. \\
&\left. + \frac{a/2-(-1)^j\cdot y}{\sqrt{[a/2+(-1)^i\cdot x]^2+[a/2-(-1)^j\cdot y]^2+[d/2+(-1)^{i+j}\cdot z]^2}} \right] + \frac{a/2+(-1)^j\cdot y}{[a/2+(-1)^j\cdot y]^2+[d/2+(-1)^{i+j}\cdot z]^2} \\
&\times \left[\frac{a/2+(-1)^i\cdot x}{\sqrt{[a/2+(-1)^i\cdot x]^2+[a/2+(-1)^j\cdot y]^2+[d/2+(-1)^{i+j}\cdot z]^2}} \right. \\
&\left.\left. + \frac{a/2-(-1)^i\cdot x}{\sqrt{[a/2-(-1)^i\cdot x]^2+[a/2+(-1)^j\cdot y]^2+[d/2+(-1)^{i+j}\cdot z]^2}} \right] \right\}
\end{aligned} \tag{5}$$

with N being the coil turns, I_0 the current value, a the coil side length, and d the coil distance. In our simulation, a volume of 10 cm×10 cm×10 cm in the central area is chosen to estimate the field uniformity. Table 1 gives the $\Delta\varepsilon(x,y,z)$ under different coil side lengths. For a higher calibration accuracy, the side length of the Helmholtz coil should be larger than 1.5 m.

Table 1. Values of uniformity error $\Delta\varepsilon$ of Helmholtz coil under different coil sizes.

Helmholtz coil side length/m	$\Delta\varepsilon$ (0.05 m, 0.05 m, 0.05 m)
$a = 0.5$	5.11×10^{-3}
$a = 1.0$	3.21×10^{-4}
$a = 1.5$	6.35×10^{-5}
$a = 2.0$	2.01×10^{-5}
$a = 2.5$	8.23×10^{-6}

2.2.2. Field orthogonality calculation

For the field orthogonality of three-dimensional Helmholtz coil, a parameter of the orthogonality error $\Delta\varepsilon(\alpha,\beta,\gamma)$ is used. Figure 2 shows the relationship between orthogonal field $\boldsymbol{B}$ and non-orthogonal field $\boldsymbol{B}'$. The $\theta(\alpha,\beta,\gamma)$ is defined as the non-orthogonal angle of the three-dimensional Helmholtz coil. The field $\boldsymbol{B}$ can be calculated by the field $\boldsymbol{B}'$ according to Eq. (6).[13]

$$\boldsymbol{B}' = A \times \boldsymbol{B} = \begin{bmatrix} \sin\gamma & \cos\alpha\cos\gamma & \sin\alpha\cos\gamma \\ 0 & \cos\beta & -\sin\beta \\ 0 & 0 & 1 \end{bmatrix} \times \boldsymbol{B}. \tag{6}$$

The $\Delta\varepsilon(\alpha,\beta,\gamma)$ corresponding to $\theta(\alpha,\beta,\gamma)$ is defined as follows:

$$\Delta\varepsilon(,\beta,\gamma)=\left|\frac{|\boldsymbol{B}'|-|\boldsymbol{B}|}{|\boldsymbol{B}|}\right|, \tag{7}$$

which can directly reflect the effect of the non-orthogonal field on the calibration accuracy. Table 2 gives the values of orthogonality error $\Delta\varepsilon(\alpha,\beta,\gamma)$ under several different values of $\theta(\alpha,\beta,\gamma)$. It shows that the orthogonality error rises fast with the non-orthogonal angle.

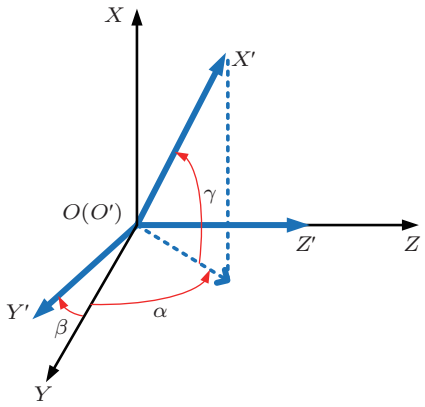


Fig. 2. (color online) Relationship between orthogonal field $\boldsymbol{B}$ and non-orthogonal field $\boldsymbol{B}'$. α is the angle between $O'X'$ and XOY; β is the angle between $O'Y'$ and OY; γ is the angle between $O'X'$ and YOZ.

Table 2. Calculated values of orthogonality error $\Delta\varepsilon(x,y,z)$.

$\theta(\alpha,\beta,\gamma)$	$\Delta\varepsilon(x,y,z)$
0.1° (0.1°, 0.1°, 89.9°)	1.49×10^{-4}
0.25° (0.25°, 0.25°, 89.75°)	3.68×10^{-4}
0.5° (0.5°, 0.5°, 89.5°)	7.18×10^{-4}
0.75° (0.75°, 0.75°, 89.25°)	1.10×10^{-3}
1° (1°, 1°, 89°)	1.40×10^{-3}

2.3. Experiment setup

Figure 3 shows the calibration experiment setup. Consider the independence of sensor orientation in our method, then three vector magnetometers will be selected to be calibrated. The magnetometers are fixed on a ceramic cube holder with a coverage volume of about 2 cm×2 cm×2 cm, which is placed in the center of the three-dimensional Helmholtz coil. In our experiment, the coil side lengths of the three pairs of Helmholtz coil are selected to be 1.9 m, 2.0 m, and 2.1 m respectively. The uniformity error is calculated to be less than 2.5×10^{-5}. The non-orthogonal angle of the three-dimensional Helmholtz coil is within 0.5° with which the orthogonality error is calculated to be less than 7.2×10^{-4}.

Based on the experiment setup, the calibration under different applied frequencies from DC to several tens Hz are performed and compared with each other. Moreover, the independence of sensor orientation is also evaluated by rotating the cryostat along the XY-plane.

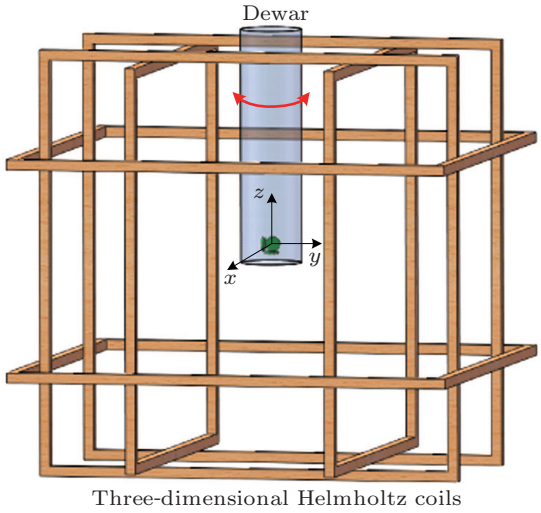


Fig. 3. (color online) The calibration setup.

3. Calibration results and discussions

Calibration with AC field is normally used for better signal-to-noise ratio in noisy urban environments. In order to avoid possible effects due to eddy current, the AC calibration results are compared with DC calibration results. The calibration results under different frequencies from DC to 30 Hz are shown in Table 3. The calibration relative error is defined as dividing the maximum value minus the minimum value by the average value. During the DC calibration, although field fluctuation at low frequency is inevitable under an unshielded environment, the coefficient can be obtained by linear fitting of the voltage response with the field under different DC currents. The coefficient $K_{\mathrm{Tesla/volt}}$ of this magnetometer is measured to be 0.2266 V/μT with a relative error of 3.098×10^{-4}. Moreover, the calibration results are shown to be independent of frequency.

Table 3. Several calibration results under different frequencies from DC to 30 Hz.

Frequency/Hz	$K_{\mathrm{Tesla/volt}}$/(V/μT)
DC	0.22663
1	0.22664
5	0.22662
10	0.22664
20	0.22666
30	0.22669

In order to illustrate the particularity with respect to the traditional method, comparison measurements are carried out. Figure 4 shows the comparison results between the traditional method and our method. The magnetometers are rotated along the XY plane 10 times. The rotation angle between magnetometer 1 and the X axis is controlled within ±5° which is the same as the case between magnetometer 2 and the Y axis. Magnetometer 3 is always along the Z axis. Figure 4(a) shows the calibration results of the three

magnetometers using the traditional method. The calibration relative errors of magnetometer 1 and 2 are 1.26×10^{-2} and 1.30×10^{-2} respectively. However, the calibration relative error is 1.45×10^{-4} for magnetometer 3, which is right along the field direction. It is obvious that the calibration relative error of the traditional method is greatly dependent on the relative angle between the magnetometer and the field direction. Figure 4(b) shows the corresponding calibration results of our method. On the contrary, the calibration results are not influenced by the changing of magnetometer angle. The maximum calibration relative error of the three magnetometers is 6.89×10^{-4}. Based on previous digital simulation, the error was mainly caused by the non-orthogonal direction of the three-dimensional Helmholtz coil. In the calibration of the multichannel system, the SQUID magnetometers are placed in the uniform field area of the three-dimensional Helmholtz coil and three orthogonal uniform fields are applied respectively. There is no need to consider the different placements and orientations of SQUID magnetometer in Dewar, the Tesla/volt coefficient of each channel can be simultaneously calibrated.

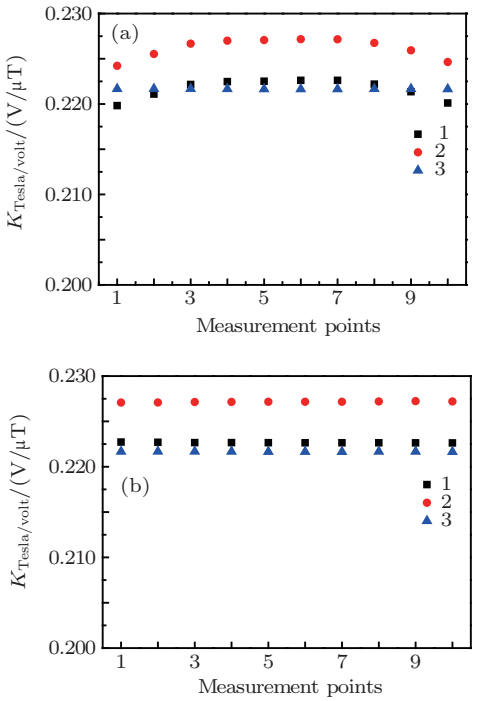


Fig. 4. (color online) Comparison of measurement result between the traditional method (a) and our method (b): 1, 2, and 3 are three magnetometers; measurement points correspond to different rotation angles.

4. Conclusions

We propose an efficient calibration method for the SQUID measurement systems using three orthogonal Helmholtz Coils. A calibration relative error of about 6.89×10^{-4} is achieved, which is mainly due to the non-orthogonal applied field. The results are shown to be independent of the applied frequency and sensor orientation. Without requiring the precise alignment of the magnetometer and complex algorithm, this method will be very convenient and effective for multichannel SQUID magnetometer system calibration.

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