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Introduction

1.1 Motivation

Superconducting QUantum Interference Devices (SQUIDs) are well known because they are the most sensitive sensors for measuring magnetic flux. In magnetometry, a SQUID with a field-to-flux transformer circuit (converter) construct is a magnetometer with high field sensitivity in the range of $\text{fT}/\sqrt{\text{Hz}}$ (one millionth of the earth's magnetic field). Therefore, the study of SQUID systems has never stopped.

Many books and reviews have elaborated on the SQUID principle and SQUID magnetometric systems as well as SQUID applications, e.g. "Superconductor Applications: SQUIDs and Machines" edited by B. B. Schwartz and S. Foner [1], "Physics and Applications of the Josephson Effect" edited by A. Barone and G. Paterno [2], and the NATO proceedings "SQUID Sensors: Fundamentals, Fabrication and Applications" edited by H. Weinstock [3]. In particular, "The SQUID Handbook," edited in 2004 by John Clarke and Alex I. Braginski comprehensively summarizes SQUID's theory and practice since SQUIDs have been discovered [4]. Hence, this book has become the new "bible" for researchers in the field. Furthermore, the review of "SQUID Magnetometers for Low-Frequency Applications" by Tapani Ryhänen et al. presented a novel formulation for SQUID operation and SQUID magnetometers for low-frequency applications, taking into account the coupling circuits and electronics [5].

Structurally, a direct current (dc) SQUID is a superconducting ring interrupted with two Josephson junctions. Predicatively, SQUIDs have very rich physical meanings, e.g. the Aharonov–Bohm effect, flux quantization, Meissner effect, Bardeen–Cooper–Schrieffer (BCS) theory, and the Josephson tunnel effect. However, starting from the view of electronic circuits, our first question is on what a dc SQUID is. In magnetometry, a dc SQUID should be regarded as a resistor-like element where its dynamic resistance is modulated by the flux Φ threading the SQUID's loop. In the readout technique, the dynamic resistance of the SQUID, $R_\text{d}(\Phi) = \partial V/\partial I$, i.e. the derivative of the voltage with respect to current, is the fundamental readout quantity, which is embodied in the current–voltage (I–V) characteristics of the SQUID. Here, the changing I–V characteristics are limited by two curves at the integer (upper limit) and half-integer (lower limit) of the flux quantum Φ_0, which reflect the quantity

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of magnetic flux in the SQUID loop. There is already abundant "know-how" to read out a resistor R. For example, one can measure a voltage V across R with a constant current flowing through R or measure a current I through R when a constant voltage V is connected to R in parallel. A dc SQUID can either be operated at constant current by measuring the voltage across it (called current bias mode) or at constant voltage by measuring the current through it (called voltage bias mode). In either bias mode, only the SQUID's $V(\Phi)$ or $I(\Phi)$ characteristics emerge. Similar to the change in I–V characteristics with the flux, $V(\Phi)$ and $I(\Phi)$ are also modulated by Φ. In brief, the essence of all three SQUID characteristics is recording the SQUID's dynamic resistance changes, $R_d(\Phi)$.

Generally, a SQUID system consists of the SQUID sensor and its readout electronics. The small SQUID signal leads to difficulty in reading out the SQUID's signal without additional noise contributions from the readout technique. Conventionally, one hopes to suppress such noise contribution below the intrinsic SQUID noise $\delta\Phi_s$. In other words, the measured system noise almost reaches $\delta\Phi_s$.

The main noise source in readout electronics is the preamplifier, which possesses two independent noise sources: the voltage noise V_n and the current noise I_n. Both of these noise sources are innate to the amplifier chip and cannot be changed. In order to compare these two noise contributions in a SQUID system, both types of electronic noise should be translated into a flux noise, $\delta\Phi_e$, in units of $\Phi_0/\sqrt{\text{Hz}}$ with SQUID's transfer coefficient of $\partial V/\partial\Phi$ or $\partial I/\partial\Phi$. In fact, the original SQUID parameters including the transfer coefficients are also innate to the particular SQUID and cannot be changed. However, the SQUID's apparent parameters at the input terminal of the preamplifier can be modified. Over the past half century, people have developed different readout schemes, where the electronic noise $\delta\Phi_e$ is suppressed by increasing the apparent transfer coefficients once a preamplifier is selected. Indeed, the modification of the apparent parameters is the main thread running through the book. Here, we will change the perspective to discuss the optimization of the SQUID system noise, i.e. how to match the SQUID parameters with the readout electronics.

According to the type of superconducting material used, SQUIDs can be divided into two groups: the low-temperature superconducting (LTS) SQUID, also called low-T_c SQUID, usually operated at 4.2 K (liquid helium temperature); and the high-temperature superconducting (HTS) SQUID, also called high-T_c SQUID, usually operated at 77 K (the liquid nitrogen temperature). The LTS material is typically niobium and HTS material is yttrium barium copper oxide ($YB_2Cu_3O_{7-x}$).

However, according to the working principles, the dc SQUID mentioned above is completely different from the radio frequency (rf) SQUID, which is a superconducting ring interrupted with only one junction. To read the signal from an rf SQUID, it is inductively coupled to an rf tank circuit, which connects to the readout electronics.

In this book, LTS (low-T_c) dc SQUID and HTS (high-T_c) rf SQUID systems, which are often used in magnetometry, will be highlighted. We will share our experiences and lessons, mostly from our own works, with readers, college students, and graduates in physics and engineering who have an interest in SQUID techniques, e.g. how to set up a simple SQUID system for themselves.

1.2 Contents of the Chapters

The book is organized into 12 chapters, where most of the content (from Chapters 2–11) is about the dc SQUIDs, and only the last chapter is related to rf SQUIDs. However, the dc SQUID bias reversal scheme [6], the $1/f$ noise study [7, 8], and the special readout scheme for the nano-SQUID [9, 10] are not included.

Chapter 1: This chapter is devoted to our motivation above and the subsequent chapter contents – why did we write this book, and what is it about?

Chapter 2: Because the Josephson junction (JJ) is the key element of SQUIDs, Josephson's equations should be first introduced. Then, JJs are analyzed with the resistively and capacitively shunted junction (RCSJ) model, thus introducing two important parameters: the Stewart–McCumber parameter β_c and the thermal rounding parameter Γ. To observe the features of JJs, one often uses the I–V characteristics, where the hysteresis behavior depends on the values of both β_c and Γ. Actually, the I–V characteristics describe the changing dynamic resistances R_d of the JJ, i.e. $R_d = \partial V/\partial I$. It was experimentally verified that the value of R_d depends not only on the junction shunt resistor R_J but also on the junction critical current I_c. Generally, JJs without hysteresis are suitable for SQUID operation. In fact, one habitually transforms the parameters β_c and Γ of the JJ into SQUID operation.

Chapter 3: For readout electronics, the dc SQUID is regarded as dynamic resistance $R_d(\Phi)$ modulated by the flux threading into the SQUID loop. The SQUID's I–V characteristics can be divided into three regions, and the SQUID is operated in the flux-modulated region (II). In fact, the behavior of $R_d(\Phi)$ is embodied in a SQUID's I–V characteristics. To measure a resistance R_d, one can impress a known current (current bias) into a SQUID and observe the voltage across the SQUID's dynamic resistance R_d. Alternatively, one can apply a constant voltage to the SQUID (voltage bias) and measure the current passing through R_d. Owing to the small $R_d \approx 10\,\Omega$ of the SQUID, an ideal current bias mode for SQUID operation can easily be realized. In contrast, an ideal voltage bias mode can hardly be achieved, as will be shown in the course of the chapter.

Chapter 4: Almost all SQUID readout electronics developed over the past half century have a common feature: they establish a so-called flux-locked loop (FLL) to realize linearization of the output voltage $V_{out}(\Phi)$ of the readout electronics; i.e. V_{out} is proportional to the flux change Φ. In this chapter, the principle and realization of the FLL are explained. It is a nulling method where a compensation flux always follows the measured flux, thus resulting in a total flux change of zero in the SQUID loop. In the FLL, the concept of the working point W comes up, and the "locked" and "unlocked" cases are discussed. In the FLL, a small flux change $\Delta\Phi$ near the working point W appears transiently, and a counter flux $-\Delta\Phi$ immediately compensates it so that the SQUID is continuously operated at a constant flux state. Therefore, the SQUID's $R_d(\Phi)$ near W can be expressed as $R_d(\Phi) = R_d + \Delta R_d$, where R_d is considered a fixed resistance and ΔR_d is a minor change with flux. According to the SQUID's bias modes, ΔR_d is translated into the readout quantity ΔV (or ΔI). For example, in practice, a current-biased SQUID can be regarded as a voltage source, $\Delta V = \Delta\Phi \times (\partial V/\partial\Phi)$, connecting to the fixed R_d in series (which seems to be the internal resistance of the voltage source), where $(\partial V/\partial\Phi)$ is the SQUID's flux-to-voltage transfer coefficient at the working point W. The description of the SQUID by means of a differential dynamic resistance is a new model concept.

Chapter 5: In the case of a direct readout scheme (DRS) where the SQUID directly connects to a preamplifier, the electronics noise $\delta\Phi_e$ is usually much larger than the SQUID intrinsic noise $\delta\Phi_s$. Two types of preamplifiers, commercial op-amps (e.g. AD797 from Analog Devices Inc. or LT1028 from Linear Technology Corp.) and parallel-connected bipolar pair transistors (PCBTs) (e.g. 3 × SSM2210 or 3 × SSM2220 from Analog Devices Inc.), are the most commonly used. Here, the noise characteristics, V_n and I_n, of these two types of preamplifiers are measured separately. Nevertheless, a DRS exhibits several advantages; e.g. the SQUID's original parameters can be directly determined, and the noise contributions from both sides, $\delta\Phi_e$ and $\delta\Phi_s$, can be separately analyzed. Especially, the SQUID's transfer coefficient $\partial V/\partial\Phi$ $(\partial I/\partial\Phi)$ at the working point W plays two important roles: (i) it bridges different kinds of noise sources, thus unifying all noise in units of $\Phi_0/\sqrt{\text{Hz}}$, as the SQUID is a flux sensor; and (ii) a large transfer coefficient is beneficial for reducing $\delta\Phi_e$. In fact, it was experimentally confirmed that the noise contribution of $\delta\Phi_e$ does not depend on the SQUID's bias modes. Furthermore, for strongly damped SQUIDs, $\delta\Phi_e$ in DRS dominates the system noise $\delta\Phi_{sys}$.

Chapter 6: In a SQUID magnetometric system, one strives for a high magnetic field sensitivity δB_{sys}, which involves two aspects: a field-to-flux transformer circuit (converter) and an ordinary SQUID system with an FLL. The former converts a magnetic field signal B into a flux Φ threading the SQUID loop, while the latter reads out the picked-up Φ. In Section 6.1, the requirements of the converter are discussed. In Section 6.2, we show that the SQUID system is characterized by three dimensionless parameters, β_c, Γ, and β_L. Note that the definitions of β_c and Γ for only a single JJ are given in Chapter 2. During SQUID operation, both parameters must be given a new connotation. Four SQUIDs with different β_c values were characterized. Here, a reasonable interpretation of the observed absence of hysteresis in the SQUID's I–V characteristics at high β_c is given. For SQUID operation, the dimensionless parameter β_L particularly describes the modulation depth of the SQUID. Importantly, $\beta_L \approx 1$ imposes a design condition on the product $L_s I_c$ – namely, all electrically readable values of SQUID parameters increase with increase in the SQUID's nominal β_c.

Chapter 7: The flux modulation scheme (FMS) was first introduced to the SQUID readout in 1968 and quickly became the standard readout technique for current-biased SQUIDs. To date, FMS electronics have been the most extensively used. The basic idea of the FMS is to perform an up-conversion of the SQUID's voltage swing at the input terminal of the preamplifier with a step-up transformer, thus reducing the noise contribution of $\delta\Phi_e$. In contrast to a DRS, where a dc circuit (amplifier and integrator) is employed, the FMS is an ac circuit, e.g. operating in the 100 kHz frequency range, because the transformer can pass only ac signals. However, a SQUID is often used to detect magnetic flux signals Φ with slow changes, even quasi-static signals. To resolve this challenge, a high-frequency modulation of the SQUID signal is employed in order to transform the low-frequency magnetic flux signal into the high-frequency regime. After up-conversion, demodulation is employed to convert the flux signal back to the low-frequency regime, thus realizing the transitions between ac and dc circuits.

If a SQUID is shunted by an element with impedance Z_s (e.g. the transformer), a change in the bias mode occurs. We introduce a dimensionless parameter $\chi = Z_s/R_d$ to quantitatively characterize the bias modes. In Section 7.1, we first introduce the so-called "mixed bias mode" concept. In Section 7.2, the FMS is discussed along with a conventional explanation. In Section 7.3, we revisit the FMS by analyzing the bias mode and the transfer characteristics of a step-up transformer.

Chapter 8: The DRS with flux feedback circuits in the "head stage" at the cryogenic temperature is highlighted in this chapter and in Chapter 9. The chapter starts with a comprehensive comparison of the different feedback schemes that have been employed in the recent decades. The techniques of additional positive feedback (APF), bias current feedback (BCF), and noise cancellation (NC) are categorized and discussed. Generally, there are two typical kinds of flux feedback circuits, the parallel feedback circuit (PFC) described in Chapter 8 and the series feedback circuit (SFC), which will follow in Chapter 9.

Indeed, we often use the differential chain rule of $R_d = (\partial V/\partial I) = (\partial V/\partial \Phi)/(\partial I/\partial \Phi)$ to analyze the flux feedback circuits. With the PFC, $(R_d)_{PFC}$ and $(\partial V/\partial \Phi)_{PFC}$ increase synchronously, while $(\partial I/\partial \Phi)_{PFC} = (\partial I/\partial \Phi)$ remains constant. However, using the SFC, $(R_d)_{SFC}$ decreases with the simultaneous increase in $(\partial I/\partial \Phi)_{SFC}$ because $(\partial V/\partial \Phi)_{SFC} = (\partial V/\partial \Phi)$. In fact, the large $(\partial V/\partial \Phi)_{PFC}$ has the benefit of suppressing the preamplifier's V_n. Separately, the large $(\partial I/\partial \Phi)_{SFC}$ reduces the noise contribution from the preamplifier's I_n. Although the behaviors of the apparent $V(\Phi)$ or $I(\Phi)$ in the two bias modes with the flux feedbacks (PFC and SFC) are very different, the effects of $\delta\Phi_e$ suppression are the same.

The PFC consists of a resistor R_p connected to a coil L_p in series that shunts to the SQUID, where L_p couples to the SQUID with a mutual inductance M_p. To simplify the analysis, we always take the flux feedback circuit in voltage bias mode, where two branches, the SQUID and PFC, are independent. Thus, the critical conditions of both flux feedbacks are easily obtained. In addition, we quantitatively analyze the PFC parameters and give their recommended regimes of operation. Indeed, it was experimentally proved that our analyses of both flux feedbacks agree well with the measured data.

Chapter 9: The SFC consists of a coil L_{se} connected to the SQUID in series, where L_{se} couples to the SQUID with a mutual inductance M_{se}. Because of SFC, the SQUID's apparent parameters $(R_d)_{SFC}$ at the input terminal of the preamplifier are reduced, thus reducing the preamplifier's current noise contribution, $\delta\Phi_{In}$.

A possible combination of the PFC and SFC is also discussed in Chapter 9. In practice, the two flux feedbacks via M_{se} and M_p are not independent, so adjusting M_{se} can also change M_p of the PFC, and vice versa. This leads to difficulties in reaching the designed mutual inductances. According to our experience, we do not recommend employing both flux feedbacks at the same time. For general SQUID applications, we suggest two practical concepts with flux feedback in a DRS: (i) an op-amp (preamplifier) with the PFC and (ii) a PCBT with the SFC.

Chapter 10: In many applications, the objective of a SQUID system is not to achieve utmost sensitivity but to rather have a SQUID system with simplicity, user-friendliness, robustness, with a high resistance against disturbances, good stability, and acceptable system noise $\delta\Phi_{\text{sys}}$. In this way, we should abandon the traditional ideas to pursue a low readout electronics noise $\delta\Phi_{\text{e}}$ that is lower than the intrinsic SQUID noise $\delta\Phi_{\text{s}}$. In contrast, tolerating a relatively large $\delta\Phi_{\text{s}}$ of a weakly damped SQUID with a large β_{c} to achieve a suitable $\delta\Phi_{\text{sys}}$ is a practical approach. Indeed, our novel paradigm for SQUID readout is to strive for equally high SQUID and electronics noise, $\delta\Phi_{\text{s}} \approx \delta\Phi_{\text{e}}$, as a basis to set up a simple and reliable SQUID system. The drawback of always striving for lowest SQUID system noise is the vulnerability of the system to fitting the exact amount of feedback in PFC or SFC schemes, thus leading to complexity and instability of the SQUID readout circuitry. Our concept of a weakly damped SQUID system does not yield the very best system noise $\delta\Phi_{\text{sys}}$ but rather a $\delta\Phi_{\text{sys}}$, which is suitable for applications. Most importantly, this concept tolerates deviations of the SQUID parameters in a large range, as we have shown by performing a statistical analysis of 101 SQUID magnetometers. Thereby, we proved the applicability of weakly damped SQUIDs with DRS to be employed in a multichannel SQUID system. For this purpose, "single-chip readout electronics" (SCREs) consisting of only one op-amp was developed. The equivalent circuit of the SCRE is used as the cover of this book. We characterized this system and demonstrated its applicability to magnetocardiography (MCG) and the transient electromagnetic (TEM) method in geophysical measurements.

Chapter 11: Two special dc SQUID readout schemes, the two-stage scheme and the double relaxation oscillation (D-ROS) scheme, are introduced. Both of them are suitable for observation of the SQUID's intrinsic noise $\delta\Phi_{\text{s}}$, i.e. $\delta\Phi_{\text{e}} < \delta\Phi_{\text{s}}$. In fact, the $\delta\Phi_{\text{s}}$ values in the two readout schemes are quite different. The two-stage readout scheme possesses a very small $\delta\Phi_{\text{e}}$, which can be lower than the $\delta\Phi_{\text{s}}$ of a SQUID with $\beta_{\text{c}} < 1$. In contrast, the un-shunted SQUID in the D-ROS scheme presents a large $\delta\Phi_{\text{s}}$ and a large $\partial V/\partial\Phi$, thus leading to $\delta\Phi_{\text{s}} < \delta\Phi_{\text{e}}$ in the system.

Actually, the two-stage readout scheme consists of a voltage-biased sensing SQUID and a sensitive SQUID-ammeter (the reading SQUID). The real trick of the two-stage scheme is the "flux amplifier," where the reading SQUID measures only the "amplified flux." In the closed voltage biased circuit of the sensing SQUID, a ring current $\Delta I = \Delta\Phi \times (\partial I/\partial\Phi)_{\text{Sensing}}$ is modulated by the measured flux $\Delta\Phi$. Here, ΔI flows through a coil L_{a} which is inductively coupled to the reading SQUID via the mutual inductance M_{a}, thus generating a further flux in the reading SQUID. Thus, the flux of $\Delta I \times M_{\text{a}}$ for the reading SQUID is amplified by a factor, $G_{\text{F}} = [(\partial I/\partial\Phi)_{\text{Sensing}} \times M_{\text{a}}]$, where $G_{\text{F}} > 1$. Therefore, the system noise of the reading SQUID can be regarded as the readout noise $\delta\Phi_{\text{e}}$ for the sensing SQUID. In other words, the two-stage scheme realizes a readout electronics noise $\delta\Phi_{\text{e}}$ below the product of $G_{\text{F}} \times (\delta\Phi_{\text{s}})_{\text{Sensing}}$. In brief, for intrinsic SQUID noise studies, the $\delta\Phi_{\text{s}}$ of most SQUIDs is calibrated with the two-stage readout scheme.

The key elements of the D-ROS readout scheme are a hysteretic SQUID and a shunted circuit, the latter of which consists of a coil L_{ro} and a resistor R_{ro} in series. Here, the L_{ro} is not coupled to the SQUID. When a constant current I_{b} above the SQUID's I_{c} flows through the parallel circuit, the D-ROS becomes active to oscillate. In fact, the initial motivation of the D-ROS readout scheme was to achieve a high flux-to-voltage transfer coefficient $\partial V/\partial\Phi$, e.g. in the $10\,\mathrm{mV}/\Phi_0$ region, thus simplifying the readout electronics and improving the slew rate. As an important consequence, the $\delta\Phi_s$ and the value of $\partial V/\partial\Phi$ in D-ROS scheme are high due to the un-shunted SQUID parameter $\beta_c \to \infty$. However, the system noise $\delta\Phi_{sys}$ of D-ROS is still acceptable for recording signals of, e.g. human biomagnetism; moreover, the large $\delta\Phi_s$ ($\approx\delta\Phi_{sys}$) improves the system robustness. Therefore, some commercial multichannel SQUID systems for MCG and magnetoencephalography (MEG) are equipped with the D-ROS scheme.

Chapter 12: An rf SQUID is inductively coupled to a tank circuit that connects to the readout electronics. According to the parameter β_e of rf SQUIDs, there are two working modes: the dissipative mode and the dispersive mode. In the dissipative mode, the rf SQUID acts as a damping resistance for the tank circuit; i.e. the quality factor of the tank circuit, Q, is changed with changing flux $\Delta\Phi$. In the dispersive mode, the rf SQUID is regarded as an additional inductance L_{SQ} inserted into the tank circuit, where the value of L_{SQ} is modulated with varying $\Delta\Phi$. However, for both working modes, the readout electronics is the same. The system noise $\delta\Phi_{sys}$ of the rf SQUID consists of three independent parts: the intrinsic SQUID noise $\delta\Phi_s$, the readout electronics noise $\delta\Phi_e$, and the thermal noise of the tank circuit, $\delta\Phi_T$, thus resulting in $\delta\Phi_{sys}^2 = \delta\Phi_s^2 + \delta\Phi_e^2 + \delta\Phi_T^2$. Conventionally, the pumping (resonance) frequency f_0 of the tank circuit is limited to approximately 30 MHz due to the distributed inductance and capacitance of the connection wires between the tank circuit at, e.g. 4.2 K, and the readout electronics at room temperature (RT). Taking an (capacitor-) inductor-tap on the tank circuit, the f_0 can rise up to the gigahertz range; thus the impedance across the tank circuit becomes very high. However, the impedance at the tap point remains low. Therefore, a standard 50 Ω transmission line is employed to connect the tap point of the tank circuit with the readout electronics at RT, where a bipolar transistor acts as a low-noise preamplifier. We define a dimensionless ratio κ to describe the position of the tap, where $\kappa = Z_{\mathrm{rf,input}}/Z_{\mathrm{rf,T}}$, in which the impedance $Z_{\mathrm{rf,input}}$ at the tap point should approximately be 50 Ω and the high impedance $Z_{\mathrm{rf,T}} = 2\pi f_0 L_T Q$ appears across the $L_T C_T$ tank circuit.

Two main achievements have been attained in HTS rf SQUID research: (i) Instead of the conventional $L_T C_T$ tank circuit, superconducting planar resonators or substrate resonators were developed for rf SQUID operation. This new kind of resonator possesses a high resonance frequency f_0 and a large quality factor Q_0, thus leading to a large $Z_{\mathrm{rf,T}}$ across the tank circuit. To match the 50 Ω impedance, the ratio of $\kappa \ll 1$ can reduce the effective temperature of the tank circuit, thus decreasing its thermal noise, $\delta\Phi_T$. (ii) With such resonators, some high harmonic components of the $V_{\mathrm{rf}}(\Phi)$ characteristics can be observed, thus changing the shapes of $V_{\mathrm{rf}}(\Phi)$, where its slopes become steeper. Consequently, a large transfer coefficient ($\partial V_{\mathrm{rf}}/\partial\Phi$) appears at the working point W, so the readout noise $\delta\Phi_e$ is suppressed. Ultimately, some HTS rf SQUIDs in resonator version demonstrated that their $\delta\Phi_{sys}$ was close to the SQUID's thermal noise limit. Furthermore, using a planar HTS field-to-flux transfer coil system with a pick-up area of $10 \times 10\,\mathrm{mm}^2$ in a three-layer structure, the HTS rf SQUID magnetometer consisting of a thin-film rf SQUID and this transfer coil system in flip-chip configuration reached a field sensitivity of approximately 10 fT/$\sqrt{\text{Hz}}$ at 77 K.

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