EMITOR: Jurnal Teknik Elektro

Static Magnetic Field Meter Using Rotating Search Coil Method

Rustamaji *, Kania Sawitri, Adyarini
Program Studi Teknik Elektro – Institut Teknologi Nasional Bandung
Bandung, Indonesia
*rustamaji@itenas.ac.id

Abstract – *Static magnetic fields are always present in the environment around us and, in addition to their useful applications, they can also have negative impacts on humans. Consequently, it is essential to have a tool capable of measuring static magnetic fields. The purpose of this research is to develop a static magnetic field meter that can accurately measure weak magnetic fields. In this research, the design and realization of a static magnetic field meter using the rotating search coil method is implemented. The device includes key components such as a search coil, instrumentation and calibration amplifiers, and a display. Based on the results of measurements and tests that have been conducted, a static magnetic field meter with a coil area of* $A = 1.9625 \times 10^{-3}\, m^2$ *and a number of turns* $N = 14$ *at a specified angular frequency (*ω*) can detect and measure small static magnetic field densities (B) from various sources. Under stable conditions, in a laboratory without any additional magnetic sources, the meter can detect magnetic field densities in the range of* $B = 2.127$ *to* $2.375\, mT$*. When used with specific magnetic sources, the device can measure* $B = 7.422$ *to* $8.194\, mT$ *for a circular magnet,* $B = 11.03$ *to* $11.84\, mT$ *for a neodymium magnet, and* $B = 10.37$ *to* $11.78\, mT$ *for a smartphone. Overall, the device effectively detects and measures weak static magnetic fields with reliable measurement stability, demonstrated by the linear relationship between the supply voltage and the DC motor rotation, achieving a measurement sensitivity down to* $B = 2.127\, mT$*.*

Keywords – *Static Magnetic Fields; EMF; Search Coil; Instrumentation And Calibration Amplifier; Static Magnetic Field Detector.*

I. Introduction

ELECTRIC and magnetic fields are invisible lines of force generated by phenomena such as the Earth's magnetism, thunderstorms, and the use of electrical devices. A static magnetic field is a force field created by a magnet or a steady flow of electricity, such as in equipment that uses direct current (DC) [1]. The rapid development of technology in industry and medicine using static magnetic fields has resulted in increased exposure to these fields for humans and has led to a number of scientific studies on their possible health effects [2].

The effects of magnetic and electric fields on health are discussed in research, including the effects of exposure to strong magnetic static fields on patients during magnetic resonance imaging (MRI) [3], the impacts of magnetic field radiation on public health [4], a review of the bioeffects of static magnetic fields (SMF) [5], the effects of SMF on neural systems [6], and the impacts of electromagnetic radiation from mobile phones on the human brain [7].

Magnetic and electric fields can also affect electronic equipment, as discussed in research on the effects of static magnetic fields at cellular levels below 10 T [8]. Magnetic and electric fields can interfere with the function of pacemakers installed in the human body [9], influence measurements of static magnetic fields and very low frequency (VLF) in the environment around homes and workplaces [10], and impact the extensive use of cell phones by creating static magnetic fields near cell phone surfaces [11].

Given the importance of understanding the magnitude of magnetic fields—especially static magnetic fields around workplaces and residential areas—along with the potential negative effects of electric and magnetic fields on health [1–7] and electronic equipment [8–11], there is a need for continued research in this area. Additionally, limited work has been done on measuring weak static magnetic fields, and advancing technology to accurately measure these fields is essential. For these reasons, this research is undertaken.

In this study, static magnetic field measurement is performed using the "rotating search coil sensor" method because it has the advantage of being able to de-

The manuscript was received on September 18, 2024, revised on October 5, 2024, and published online on November 29, 2024. `Emitor` is a Journal of Electrical Engineering at Universitas Muhammadiyah Surakarta with ISSN (Print) 1411 – 8890 and ISSN (Online) 2541 – 4518, holding Sinta 3 accreditation. It is accessible at `https://journals2.ums.ac.id/index.php/emitor/index`.

tect magnetic fields $H < 1$ mT, with good accuracy [32] and good sensitivity for low magnetic field intensity investigations [16].

The purpose of this research is to produce a static magnetic field measuring device using the ”rotating search coil” method, which consists of: a rotating search coil sensor, instrumentation and calibration amplifiers, and display components. The circuit used in this measuring instrument is simple and uses readily available components. Furthermore, the results of this research can be used for the development of magnetic field measuring devices and can also be implemented in other scientific fields.

II. Research Methods

Magnetic field sensors can be divided into two categories, namely based on the magnetometer principles (vector and scalar) and gaussmeters. Judging from the magnetic field strength and the measurement range, the search coil is categorized as a vector magnetometer category as stated by M. Urbaniak [32]. According to Luca Bottura, search coils can be grouped into: (1) point coils, (2) line integral coils, (3) area coils, and (4) harmonic coils [33]; the rotating search coil method in this study belongs to the area coil group, where the search coil has good accuracy to detect static magnetic fields < 1 mT [32]. Search coil magnetometers are based on magnetic cores that provide external magnetic field reinforcement. Search coils are reliable, insensitive to radiation, and their good sensitivity is suitable for investigation of weak magnetic field strength [16]. The recommended limits for exposure to static magnetic fields in the workplace and the general public are summarized in Table 1. Due to the benefits of using

Table 1: Static magnetic field exposure limits

Exposure characteristics	Magnetic flux density
At the workplace (closed):	
Exposure to the head and body	2 T
Exposure to the limbs	8 T
In public (open):	
Exposure to any part of the body	400 mT

magnetic fields and the negative impacts of exposure to magnetic fields on humans and electronic equipment, research related to magnetic field measurements continues to be conducted, including:

1. Research aimed at improving magnetic field measurement facilities, such as construction of calibration facilities for search coil magnetometers [12] and the performance of magnetic search coils (MSC) in the form of three-axis search coil magnetometers with 200 mm long magnetic cores installed on the Arase satellite (ERG) for magnetic field observations of the radiation belt surrounding the Earth [13].
2. Research producing more sensitive and accurate magnetic field sensors with various methods, such as: cryogenic quadrupole search coil arrays in the form of 5-meter long quadrupoles for superconducting magnet measurements [14], magnetic sensors with two primary coils (excitation coils) and one secondary coil (pick-up coil) to measure very weak magnetic fields [15], search coil magnetometers for weak magnetic field measurements in space experiments [16], search coils as probes to measure 3D magnetic field fluctuations in the frequency bandwidth from 0.1 Hz to 4 kHz [17], micro-size search coil magnetometers for magnetic field distribution measurement [18], design of cryogenic search coil arrays for harmonic analysis of quadrupole magnets [19], development of advanced magnetic field sensors [20], search coil design for accelerator magnet measurements [21], magnetic sensors in the form of coils to measure magnetic fields by induction method [22], diamond-based quantum magnetometers with rotating diamonds to measure DC magnetic fields [23], and the design of search coil inductance for pulse induction metal detection [24].
3. Research on magnetic field sensor applications in various fields, such as: magnetic sensors and magnetometers in space and biomedical industries, advancements in smart grids, renewable energy sources, and electric vehicles [25]; high sensitivity solid-state magnetic field sensors, low power consumption, flexible substrates, and miniaturization for biosensor applications, ubiquitous sensor networks, wearables, smart devices, and others [26]; design of micro search coil magnetometers for energy monitoring in smart buildings [27]; and design of low frequency search coil magnetometers for ground-airborne frequency domain electromagnetic (GAFDEM) methods [28].
4. Reviews of magnetic field sensors, such as: reviews of induction coil sensors known as search coils, pickup coils, or magnetic loop sensors with air and ferromagnetic cores [29]; modeling and ways of improving induction magnetometers for AC and DC magnetic field measurement in space plasma physics [30]; and designs of resistive, capacitive, inductive, and magnetic (RCIM) sensors [31].

Search coils are used to detect magnetic fields. The sensitivity of the coil is linear with the magnetic field strength. The use of a search coil is based on Faraday’s induction law, where the magnitude of the electromotive force (EMF) on a coil with area A corresponds to the rate of change in time of the magnetic flux density B, as shown in Equation (1).

$$\text{EMF} = -\frac{\partial}{\partial t}\int_{\text{coil}} B\,ds = -\frac{\partial}{\partial t}(B\cdot A) \tag{1}$$

Changes in the magnetic flux density B in the coil can be caused by: (1) movement of the coil in a static magnetic field, (2) movement of the magnet around the fixed coil, and (3) time variations of the magnetic field around the fixed coil [33].

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$$\text{EMF} = -\frac{\partial}{\partial t}\int_{\text{coil}} B\,ds = -\frac{\partial}{\partial t}(B\cdot A) \tag{2}$$

Changes in the magnetic flux density B in the coil can be caused by: movement of the coil in a static magnetic field, movement of the magnet around the fixed coil, and time variations of the magnetic field around the fixed coil [33].

A search coil consists of one or more loops of conductor wire, exposed to a magnetic field B and generating an EMF or output voltage V_C according to Faraday's induction law. A coil with N closed turns stretched in area A with normal unit vector $\mathbf{n}$ and boundary ∂A, as shown in Figure 1.

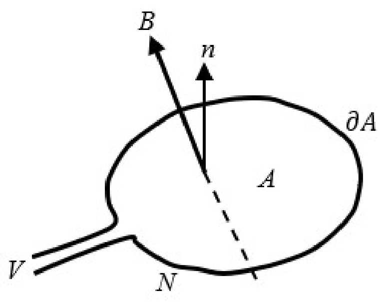

Figure 1: Schematic drawing of search coil

The output voltage V_C is given by the rate of change of total magnetic flux Φ, as in Equation (3):

$$\begin{aligned}\text{EMF} = V_C &= -\frac{d\Phi}{dt} = -\frac{d}{dt}\iint_A B\cdot\mathbf{n}\,dA \\ &= -\frac{d}{dt}\iint_A \frac{\partial B}{\partial t}\cdot\mathbf{n}\,dA - \oint_{\partial A}\mathbf{v}\times B\,dl\end{aligned} \tag{3}$$

As per Lenz's law, the $(-)$ sign means that the induced EMF generates a current that creates a field opposing the flux variation (right-hand rule). From Equation (3), the output voltage V_C can be generated in two ways: a time-varying magnetic field, usually measured with a fixed coil (known as a flux loop), or by moving and/or changing the shape of the coil with a local speed $\mathbf{v}$ (known as a harmonic coil or variable-geometry loop). If the coil geometry and position are known, the average field over the coil area can be estimated from either the instantaneous voltage or the time-integrated voltage, according to Equation (4).

$$\Phi - \Phi_0 = -\int_0^t V_C\,dt \tag{4}$$

Using integration, the measured volt-seconds are directly related to the magnetic flux variations between the initial and final configurations [21].

Induction coil sensors (also called search coil sensors, pickup coil sensors, or magnetic antennas) are a type of magnetic sensor. According to Faraday's induction law, when magnetic flux Φ (T m^2) passes through a coil with N turns and area A (m^2), an EMF or voltage V (V) is generated at the coil ends, as shown in Equation (5).

$$\begin{aligned}V &= -N\cdot\frac{d\Phi}{dt} = -N\cdot A\cdot\frac{dB}{dt} \\ &= -\mu_0\cdot N\cdot A\cdot\frac{dH}{dt}\end{aligned} \tag{5}$$

From Equation (5), the output signal voltage V (V) of the coil sensor depends on the rate of change of the magnetic flux density dB/dt. The result obtained is proportional to the magnetic flux density B (T). A large sensitivity of the coil can be achieved by using a large number of turns N and a large active area A (m^2) [29].

The limitation of the induction coil sensor, which is only sensitive to varying magnetic fields, can be addressed by moving the coil, known as a moving coil sensor, as shown in Figure 2 [29].

Figure 2: DC magnetic sensor with rotating coil

A rotating coil with a stable rotation speed ω (radians/second) allows for accurate DC magnetic field measurement. The main requirement of Faraday's law, namely the variation in flux B (T), is fulfilled because the sensor area A (m^2) changes as a sinusoidal function $A\cos\omega t$, and the magnitude of the induced voltage is $V = -B \cdot N \cdot A\sin\omega t$ volts [29].

The methodology in this research involves design, realization, and measurement and testing, to develop a "static magnetic field meter using the rotating search coil method" capable of detecting static magnetic fields, as described in [29].

The circuit of the static magnetic field meter using the rotating search coil method in this research consists of a sensor in the form of a rotating search coil, an instrumentation amplifier, a calibration amplifier, and a display. The block diagram of the static magnetic field meter using the rotating search coil method is shown in Figure 3.

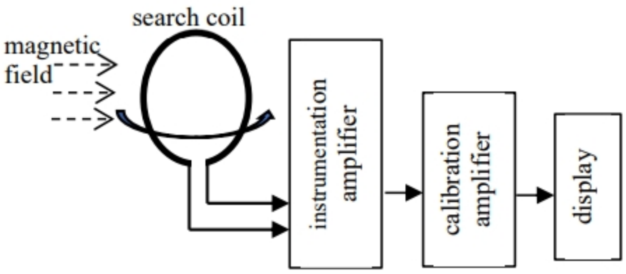

Figure 3: Block diagram of static magnetic field meter using rotating search coil method

From Figure 3, the static magnetic field meter using the rotating search coil method consists of a rotating search coil as a sensor to detect a static magnetic field, an instrumentation amplifier to amplify the EMF output of the search coil (which is initially very weak), a calibration amplifier to further amplify and condition the signal from the instrumentation amplifier so it can be displayed, and a display that shows the results of the static magnetic field measurements as EMF in volts (V).

The static magnetic field meter uses the rotating search coil method with the following specifications: a search coil as a static magnetic field sensor rotated by a DC motor; the search coil is circular with N turns of enameled copper wire, a radius r, and surface area A; instrumentation and calibration amplifiers using op-amps; an LCD display that shows the measured magnetic field as EMF in volts (V); and a rotating search coil capable of detecting static magnetic fields (H $<$ 1 mT) and displaying the results as EMF in volts (V).

i. Rotating Search Coil

The search coil is a circle with a radius of $r = 0.025\,\text{m}$, formed from $N = 14$ turns of enameled copper wire, as shown in Figure 4.

The search coil attached to the rotating motor shaft

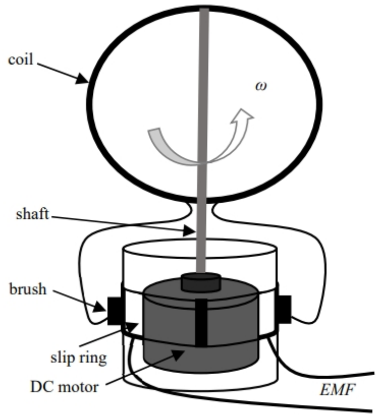

Figure 4: Schematic diagram of the rotating search coil

will capture the magnetic field, generating an EMF or coil output voltage through the rotating brush, which is then forwarded to the slip ring. From the slip ring, the EMF flows to the instrumentation and calibration amplifier to be amplified and adjusted so that the level can be displayed on the display.

With a radius of $r = 0.025\,\text{m}$, the search coil has an area $A = \pi r^2 = 1.9625 \times 10^{-3}\,\text{m}^2$. The search coil is rotated by a DC motor (voltage rating 24 V) with a speed in units of rate per minute (rpm). When expressed in terms of angular frequency ω, this becomes Equation (6):

$$\omega = \text{rpm} \times \frac{2\pi}{60}\ \text{rad/s} \tag{6}$$

A search coil with area A (m^2) and a number of N turns, rotating harmoniously with an angular frequency ω (rad/s), sweeps the magnetic flux density B (T) of a static magnetic field source. Thus, it behaves as if a varying magnetic field is formed, equal to $B(t) = B\cos\omega t$. Therefore, the EMF or voltage V (volt) at the ends of the coil is given by Equations (7) and (8) [31]:

$$\text{EMF} = V = -N \cdot \frac{d\Phi(t)}{dt} = -N \cdot A \cdot \frac{dB(t)}{dt} \tag{7}$$

Since $B(t) = B\cos\omega t$, then:

$$\text{EMF} = V = -N \cdot A \cdot \frac{d(B\cos\omega t)}{dt} = N \cdot A \cdot \omega \cdot B\sin\omega t \tag{8}$$

By considering the direction of the magnetic field vector B (forming a 90° angle) to the face of the search coil or $\sin\omega t = 1$, Equation (9) is obtained:

$$\text{EMF} = V = N \cdot A \cdot \omega \cdot B \quad \text{(volt)} \tag{9}$$

When Equation (9) is rearranged, the magnetic flux density B (in weber/m^2) of the measurement result is obtained as Equation (10).

$$B = \frac{\text{EMF} = V}{N \cdot A \cdot \omega} \quad \text{weber/m}^2 \text{ or tesla} \tag{10}$$

If $A = 1.9625 \times 10^{-3}\,\text{m}^2$ and $N = 14$ turns, Equation (11) is obtained:

$$B = \frac{\text{EMF} = V}{27.475 \cdot \omega} \times 10^3 \quad \text{weber/m}^2 \text{ or tesla} \tag{11}$$

ii. Instrumentation and Calibration Amplifier

The instrumentation and calibration amplifier circuit is built from an operational amplifier (Op-amp) in the form of an IC type LM741 [34], as shown in Figure 5.

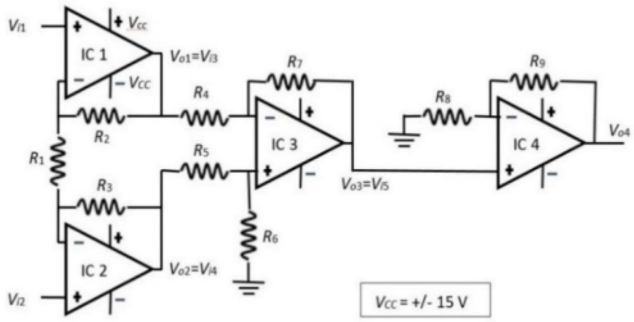

Figure 5: Instrumentation and calibration amplifier circuits

The instrumentation amplifier consists of a buffer amplifier (IC 1 and IC 2) and a differential amplifier (IC 3). The buffer amplifier, composed of two op-amp ICs (LM741), input resistor R_1, and feedback resistor ($R_2 = R_3$), has an output voltage equal to the input voltage, also called unity gain, as in Equation (12):

$$V_{o1} = V_{i1} \quad \text{and} \quad V_{o2} = V_{i2} \tag{12}$$

where $V_{i1} = V_{i2} =$ EMF or output voltage V_{coil} from the ends of the coil. To obtain a buffer amplifier gain of 1, resistors $R_1 = 10\,\text{k}\Omega$ and $R_2 = R_3 = 10\,\text{k}\Omega$ are installed.

The differential amplifier, consisting of an op-amp IC (LM741), input resistors ($R_4 = R_5$), and feedback resistors ($R_6 = R_7$), has the output voltage equation V_{o3} as shown in Equations (13) and (14):

$$V_{o3} = (V_{i2} - V_{i1})\left(1 + \frac{2R_2}{R_1}\right)\frac{R_7}{R_4} \tag{13}$$

or

$$V_{o3} = (V_{i2} - V_{i1})\left(1 + \frac{2R_3}{R_1}\right)\frac{R_6}{R_5} \tag{14}$$

where $(V_{i2} - V_{i1}) = \text{EMF} = V_{\text{coil}}$. Thus, the gain of the instrumentation amplifier (IAG) is as given in Equation (15):

$$\text{IAG} = \frac{V_{o3}}{V_{\text{coil}}} = \left(1 + \frac{2R_3}{R_1}\right)\frac{R_6}{R_5} \tag{15}$$

To achieve an instrumentation amplifier gain of 30, resistors are set as follows: $R_1 = R_2 = R_3 = 10\,\text{k}\Omega$, $R_4 = R_5 = 10\,\text{k}\Omega$, and $R_6 = R_7 = 100\,\text{k}\Omega$.

The calibration amplifier, composed of an op-amp IC (LM741), input resistor R_8, and feedback resistor R_9, has the output voltage equation V_{o4} as in Equation (16):

$$V_{o4} = V_{i5}\left(1 + \frac{R_9}{R_8}\right) \tag{16}$$

Thus, the gain of the calibration amplifier is given by Equation (17):

$$\text{Calibration amplifier gain} = \frac{V_{o4}}{V_{i5}} = \left(1 + \frac{R_9}{R_8}\right) \tag{17}$$

To achieve a calibration amplifier gain of 11, resistors $R_8 = 10\,\text{k}\Omega$ and $R_9 = 100\,\text{k}\Omega$ are used. The total gain of the instrumentation and calibration amplifier is calculated as the product: (instrumentation amplifier gain) $\times$ (calibration amplifier gain) $= 30 \times 11 = 330$.

The complete circuit of the static magnetic field meter using the rotating search coil method is shown in Figure 6, while the circuit layout with the device mounted on a printed circuit board (PCB) is shown in Figure 7.

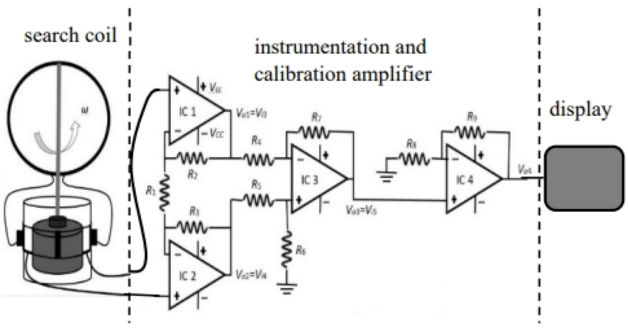

Figure 6: Complete circuit of static magnetic field meter using rotating search coil method

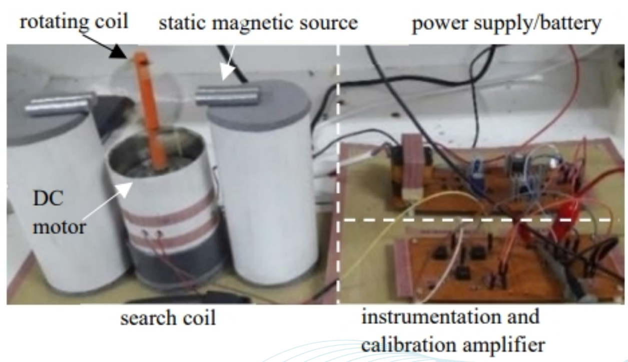

Figure 7: Circuit layout with the device mounted on a PCB

From Figure 7, the circuit layout of the static magnetic field measuring circuit using the rotating search coil method consists of a search coil, instrumentation and calibration amplifier, and display.

III. Research Results and Discussion

From the design of a static magnetic field meter using the rotating search coil method, measurements of each component and tests to detect a static magnetic field were carried out. The tests were conducted under controlled conditions in a laboratory room, ensuring that no other magnetic sources were present except for the measured magnetic source. Noise and interference from other signals were ignored, and the distance between the coil and the magnetic source was maintained at approximately 5 cm. The block diagram of the static magnetic field meter test setup is shown in Figure 8.

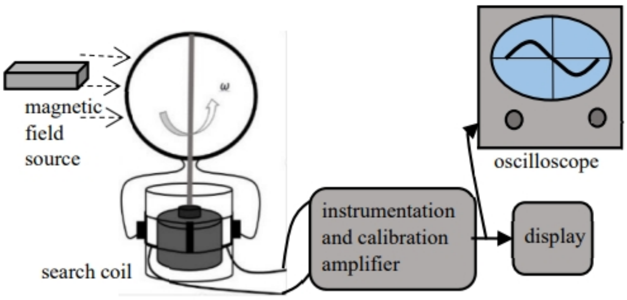

Figure 8: Block diagram of static magnetic field meter test using rotating search coil method

From Figure 8, the rotating search coil of the static magnetic field meter detects the static magnetic field from the magnetic source.

i. Search Coil

Testing the rotation of the search coil was conducted by applying a supply voltage of 1.5 to 12 Vdc to the DC motor. The search coil has an area $A = 1.9625 \times 10^{-3}\,\text{m}^2$ and a number of turns $N = 14$. The rotational speed (rpm) for different DC motor voltages, measured using a Lutron DT-2236 tachometer, and its conversion to angular frequency ω (rad/s), are shown in Table 2 and Figure 9.

From Table 2, it can be observed that as the power supply voltage applied to the DC motor increases, the rotational speed (rpm) or angular frequency ω (rad/s) of the coil also increases. Figure 9 shows a linear trend between the supply voltage and the angular frequency ω of the DC motor.

ii. Instrumentation and Calibration Amplifier

The input and output signals of the instrumentation and calibration test results are shown in Figures 10 and 11.

From testing, the instrumentation amplifier achieved a voltage gain of approximately ±30, and the calibration amplifier achieved a gain of ±11, resulting in a total voltage gain of ±330 as planned.

Table 2: Rotating speed and angular frequency of search coil vs DC motor voltage

DC motor voltage (V)	Rotating speed (rpm)	Angular frequency ω (rad/s)
1.5	228.6	23.946
2	233.9	24.496
2.5	247.9	25.968
3	248.7	26.054
3.5	276.7	28.976
4	279.3	29.249
4.5	280.5	29.381
5	300.6	31.482
5.5	310.5	32.518
6	321.5	33.677
6.5	336.4	35.235
7	339.5	35.562
7.5	346.7	36.311
8	356.1	37.295
8.5	366.4	38.375
9	372.8	39.041
9.5	380.2	39.824
10	383.4	40.152
10.5	394.6	41.328
11	403.1	42.217
11.5	411.6	43.109
12	423.6	44.367

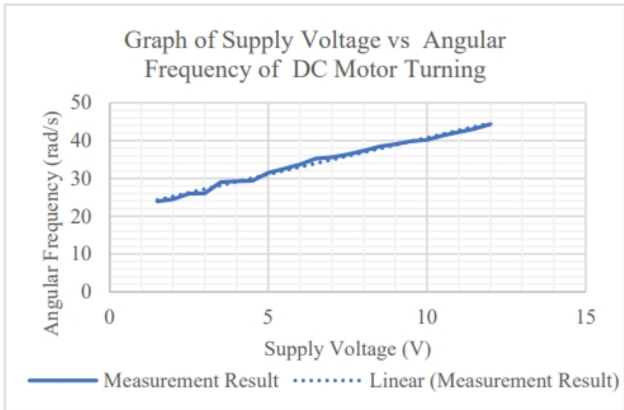

Figure 9: Graph of supply voltage vs angular frequency of DC motor turning

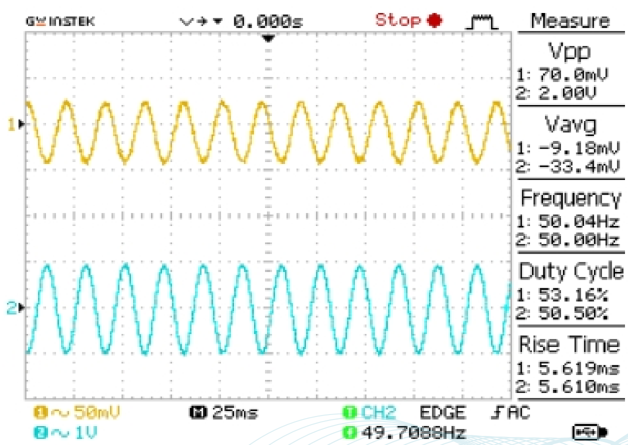

Figure 10: 70 mVpp input signal with a frequency of 50.04 Hz (top), and 2.0 Vpp output signal with a frequency of 50.00 Hz (bottom) from the instrumentation amplifier

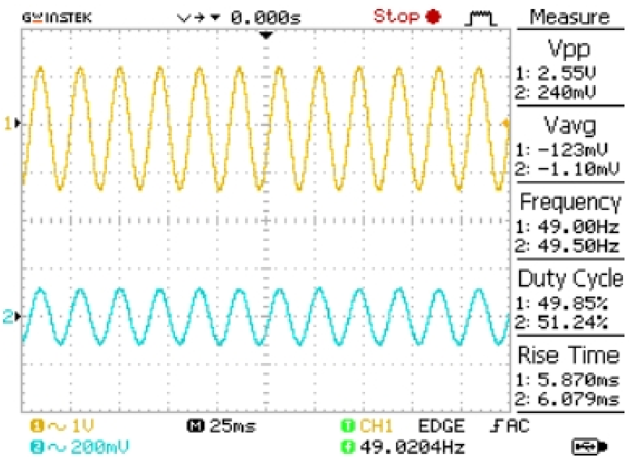

Figure 11: 240 mVpp with a frequency of 49.50 Hz (bottom), and output signal 2.55 Vpp with a frequency of 49.00 Hz (top) from the calibration amplifier

iii. Testing a Static Magnetic Field Meter

The rotating search coil functions to detect or capture magnetic field flux from a static magnetic field source. The static magnetic field density B is measured, and the results are read at the ends of the coil in the form of EMF (V). After being amplified, it is displayed on the display in the form of EMF (V). Testing of the static magnetic field meter using the rotating search coil method was carried out several times with different magnetic field sources.

Tests of the static magnetic field meter, with a specific search coil rotation speed, were conducted to measure static magnetic fields outdoors and in the laboratory. The results are shown in Table 3.

From Table 3, it can be seen that the magnetic field meter with a motor supply voltage from 1.5 to 12 V showed the following results: (a) outdoor testing without any electronic equipment in the area did not detect (did not measure) the presence of a magnetic field, and (b) testing in the laboratory detected a magnetic field between 2.127 to 2.375 mT. At a motor supply voltage of 12 V (angular frequency $\omega = 44.367$ rad/s), the device detected a magnetic field of 2.264 mT, which is well below the safe threshold of 400 mT.

Testing of the static magnetic field meter with a certain rotation speed of the search coil was conducted to measure the magnetic field from various sources, including a circular magnet, a neodymium magnet, and a smartphone. The output signal (EMF) of the static magnetic field meter, recorded with a GW Instek GOS-1102A-V oscilloscope when the motor voltage was set to 12 V, is shown in Figure 12 for a circular magnet and a neodymium magnet.

From Table 4, it can be seen that the magnetic field meter with a motor supply voltage from 1.5 to

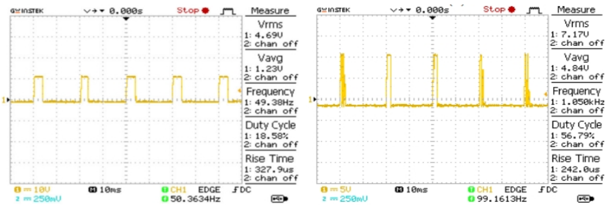

Figure 12: Output signal (EMF) of a static magnetic field meter from a static magnetic field source of (a) circular and (b) neodymium

12 V detected the following for various magnetic field sources: (a) circular magnets with a measured static magnetic field density B between 7.422 to 9.234 mT, with a stable B value between 7.422 to 8.194 mT at a motor supply voltage of 5 to 12 V. At a motor supply voltage of 12 V (angular frequency $\omega = 44.367$ rad/s), the EMF was measured at 9.155 mV or $B = 7.51$ mT; (b) neodymium magnets, with a measured static magnetic field density B between 10.65 to 11.84 mT, and a stable B value from 11.03 up to 11.84 mT at a motor supply voltage of 4 to 12 V. At a motor supply voltage of 12 V (angular frequency $\omega = 44.367$ rad/s), the EMF was 13.78 mV or $B = 11.30$ mT; and (c) smartphone X, with a measured static magnetic field density B between 7.77 to 11.78 mT, with a stable B value between 10.37 to 11.78 mT at a motor supply voltage of 12 V (angular frequency $\omega = 44.367$ rad/s) and an EMF of 12.641 mV or $B = 10.37$ mT.

From all these tests, the amount of static magnetic field density B that is read in the form of EMF is influenced by the stability of the DC motor rotation and the tightness of the contact between the brush and the slip ring that transmits the EMF from the coil end to the amplifier circuit. The value of B from several measured magnetic field sources was detected to be far below the safe threshold of 400 mT [2, 11].

The results of the design, realization, measurement, and testing indicate that the static magnetic field meter performs effectively, successfully detecting and measuring weak static magnetic field densities B. The device also demonstrates strong measurement stability, as evidenced by the linear relationship observed between supply voltage and DC motor rotation. With a coil area of $A = 1.9625 \times 10^{-3}$ m^2 and $N = 14$, the search coil is capable of detecting static magnetic field densities as low as 2.127 mT, highlighting its impressive sensitivity. This sensitivity aligns with findings in previous studies, where rotating search coils have been shown to detect weak static magnetic fields [16, 32].

Furthermore, Table 5 provides a comparison of this research's outcomes with those of prior studies, underscoring that the approach used here yields superior results for measuring weak static magnetic fields.

Table 3: Static magnetic fields outdoors and inside the laboratory

Voltage of DC motor (V)	Rotational speed (rpm)	Angular frequency ω (rad/s)	Outdoor	Inside the Lab	
				max EMF (mV)	B (mT)
1.5	228.6	23.946	Not detected	1.541	2.342
2	233.9	24.496		1.598	2.375
2.5	247.9	25.968		1.684	2.374
3	248.7	26.054		1.641	2.292
3.5	276.7	28.976		1.88	2.361
4	279.3	29.249		1.842	2.292
4.5	280.5	29.381		1.898	2.352
5	300.6	31.482		1.931	2.233
5.5	310.5	32.518		1.999	2.237
6	321.5	33.677		2.06	2.226
6.5	336.4	35.235		2.06	2.127
7	339.5	35.562		2.127	2.176
7.5	346.7	36.311		2.327	2.333
8	356.1	37.295		2.393	2.335
8.5	366.4	38.375		2.43	2.305
9	372.8	39.041		2.479	2.311
9.5	380.2	39.824		2.531	2.313
10	383.4	40.152		2.594	2.347
10.5	394.6	41.328		2.688	2.368
11	403.1	42.217		2.750	2.371
11.5	411.6	43.109		2.774	2.342
12	423.6	44.367		2.76	2.264

Table 4: Static magnetic fields from different magnet sources

V	ω	Circular magnet			Neodymium magnet			Smartphone X		
		Display	Coil		Display	Coil		Display	Coil	
		Max EMF	Max EMF	B	Max EMF	Max EMF	B	Max EMF	Max EMF	B
1.5	23.946	1.694	5.133	7.802	2.536	7.68	11.67	16.987	5.148	7.82
2	24.496	1.72	5.212	7.744	2.548	7.72	11.47	17.254	5.228	7.77
2.5	25.968	1.973	5.979	8.338	2.628	7.96	11.16	19.845	6.014	8.43
3	26.054	2.055	6.227	8.699	2.667	8.08	11.29	20.065	6.080	8.49
3.5	28.976	2.082	6.309	7.925	2.804	8.48	10.65	20.441	6.194	7.78
4	29.249	2.449	7.421	9.234	3.082	9.34	11.62	23.723	7.189	9.06
4.5	29.381	2.35	7.121	8.821	3.14	9.52	11.79	24.225	7.341	9.10
5	31.482	2.217	6.718	7.767	3.330	10.09	11.67	25.513	7.731	8.94
5.5	32.518	2.416	7.321	8.194	3.482	10.55	11.80	25.607	7.760	8.69
6	33.677	2.449	7.421	8.02	3.501	10.61	11.47	26.910	8.155	8.81
6.5	35.235	2.371	7.185	7.422	3.744	11.43	11.81	27.051	8.197	8.47
7	35.562	2.504	7.588	7.766	3.631	11.00	11.26	28.621	8.673	8.88
7.5	36.311	2.517	7.627	7.645	3.663	11.01	11.04	36.628	11.094	11.12
8	37.295	2.740	8.303	8.103	3.850	11.67	11.39	38.120	11.552	11.27
8.5	38.375	2.721	8.245	7.82	4.009	12.15	11.52	40.082	12.422	11.78
9	39.041	2.832	8.582	8.001	3.903	11.83	11.03	38.010	11.518	10.74
9.5	39.824	2.900	8.788	8.032	4.163	12.62	11.53	39.925	12.098	11.06
10	40.152	2.950	8.94	7.873	4.311	13.06	11.84	40.993	12.422	11.26
10.5	41.328	3.003	9.1	8.014	4.159	12.60	11.10	41.527	12.584	11.08
11	42.217	3.040	9.212	7.942	4.082	13.61	11.73	40.977	12.417	10.71
11.5	43.109	3.036	9.2	7.767	4.137	13.79	11.64	41.354	12.532	10.58
12	44.367	3.021	9.155	7.51	4.134	13.78	11.30	41.715	12.641	10.37

Table 5: Comparison between the research results and other studies that have been conducted

This Research	Methods	Measured Magnetic Object/Source
Static magnetic field meter using rotating search coil method	Method: rotating search coil with a coil area $A = 1.9625 \times 10^{-3}\,\mathrm{m}^2$ and the number of turns $N = 14$	Measured magnetic object/source: static magnetic field
	Magnetic search coil (MSC) is a three-axis search coil magnetometer with 200-mm-long magnetic core [13]	Magnetic fields of frequency of several kHz in the radiation belts surrounding the Earth
	Cryogenic quadrupole search coil array of 5-meter long quadrupoles [14]	Superconducting magnet
	Magnetic sensor with two primary coils (excitation coil) and one secondary coil (pick-up coil) [15]	Dynamic magnetic field (varying field) is very weak
	Search coils magnetometer [16]	Weak magnetic field in space experiments
	Search coil does not rotate [17]	Magnetic field fluctuations over a frequency bandwidth from 0.1 Hz to 4 kHz
	Micro-size search coil magnetometer [18]	Magnetic field distribution
	Cryogenic search coil array of three triplets of coils [19]	Quadrupole magnets
	Magnetic sensor (thin-film devices) based on bulk functional magnetic materials [20]	Magnetic field sensor
	Search Coil [21]	Accelerator magnets
	Magnetic sensor in the form of a coil to measure the magnetic field by induction method [22]	Dynamic magnetic field (varying field)
	Diamond-based quantum magnetometers [23]	Converted AC magnetic field
	Search coil inductance [24]	Pulse induction metal detection
	Solid state magnetic field sensors: hall effect, giant magnetoresistance, tunnel magnetoresistance, anisotropic magnetoresistance, and giant magnetoimpedance [26]	Magnetic field for biosensor application, ubiquitous sensor network, wearable, smart devices, etc.
	Micro search coil magnetometer in the form of planar spiral inductor [27]	Energy monitoring in smart buildings
	Search coil magnetometer with air core [28]	Vertical component of magnetic field signals in ground–airborne frequency domain electromagnetic (GAFDEM)
	Induction coil sensor with air and ferromagnetic core [29]	Dynamic magnetic field (varying field)
	Induction magnetometers [30]	AC and DC magnetic fields in space plasma physics

The advancements made in this study can be applied to the development of magnetic field measuring devices, potentially benefiting a range of related scientific fields and advancing capabilities in precise magnetic field detection. This research stands out due to the utilization of a rotating search coil method to measure static magnetic fields, an approach rarely employed compared to other studies that primarily focus on dynamic magnetic fields or specific applications. The comparison in the table highlights that this research contributes significantly by addressing a gap in magnetic field studies using a simple yet effective technique. This method is particularly relevant for specific applications requiring high accuracy in small-scale static magnetic field measurements. Furthermore, the parameters employed in this study, such as the coil area ($A = 1.9625 \times 10^{-3}, \mathrm{m}^2$) and the number of turns ($N = 14$), provide a unique configuration that differentiates this research from others. Overall, this study offers a novel solution that can be expanded for technical applications demanding precision in static magnetic field measurement.

IV. Conclusions

This research has successfully developed a static magnetic field meter using the rotating search coil method. With a coil area of $A = 1.9625 \times 10^{-3}\,\mathrm{m}^2$ and a number of turns $N = 14$, the device can detect and measure static magnetic field density B from various magnetic field sources at relatively weak levels. Under stable conditions, the meter detects $B = 2.127$ to $2.375\,\mathrm{mT}$ in the laboratory without any magnetic source. With specific magnetic sources, the device can detect $B = 7.422$ to $8.194\,\mathrm{mT}$ for circular magnets, $B = 11.03$ to $11.84\,\mathrm{mT}$ for neodymium magnets, and $B = 10.37$ to $11.78\,\mathrm{mT}$ for a smartphone. The measurement stability is satisfactory, as evidenced by the linear relationship between supply voltage and DC motor rotation speed. The device has a measurement sensitivity of $B = 2.127\,\mathrm{mT}$. Further research is recommended to improve the stability of motor rotation, enhance measurement sensitivity, and provide better display capabilities for magnetic field B.

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