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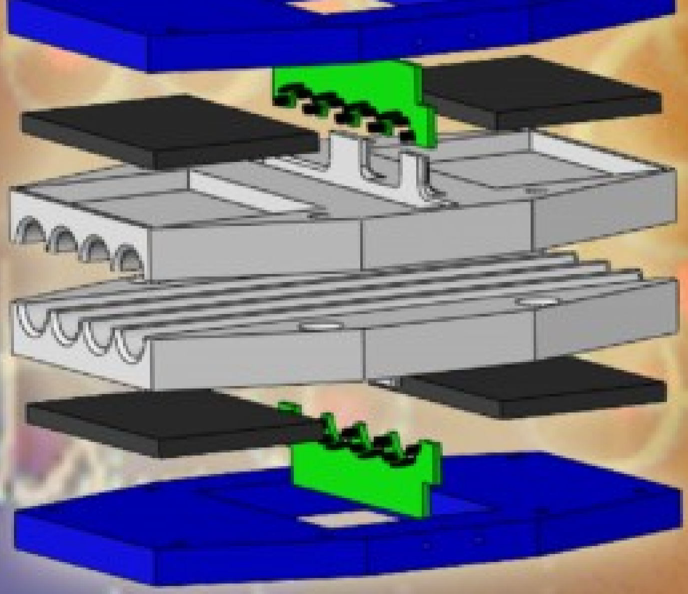

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Sensitivity Limits of a Magnetometer with an Air-core Pickup Coil

Kunihisa Tashiro, Shin-ichiro Inoue and Hiroyuki Wakiwaka
Department of Electrical and Electronic Engineering,
Shinshu University, Nagano wakasato 4-17-1, 380-8553, Japan
Tel.: +81-26-269-5216
E-mail: tashiro@shinshu-u.ac.jp

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Abstract: Sensitivity limits of magnetometers with air-core pickup coils are considered through three basic principles, Faraday's law, the definition of inductance and Ohm's law. This paper presents two simple equivalent circuit models for voltage detection and current detection, and describes their sensitivity with eight parameters. Both models require different methodology for optimal pickup coil design. The calculated results are in agreement with experimental results, and illustrate the advantages of magnetometers based on current detection model. *Copyright © 2010 IFSA.*

Keywords: Induction magnetometer, Air-core coil, Detection model, Equivalent circuit, Sensitivity limits.

1. Introduction

A magnetometer with a coil is capable to use two methods [1]. The first method is based on Faraday's law that the induced voltage across the coil is proportional to the derivative of the flux linkage. The second method is based on the definition of self-inductance [1-13]. Though most previous works mention magnetometers through Faraday's law, an approach from the definition of self-inductance is important when the target of the magnetic field is weak and of low-frequency. One reason is the necessity of an ideal analogue integrator which does not have 1/f noise, dc drift, and a limitation in gain [2]. A fluxgate magnetometer uses a change in the magnetic permeability of the core material at a few tens of kHz, in which a low-frequency flux linkage transfers to the modulated high frequency signal. This sensor is able to detect a DC magnetic field, but the modulation frequency limits the upper frequency. A change in magnetic permeability of the magnetic material also produces Barkhausen noise, and increases the white noise level of the magnetometer.

We have been developing induction magnetometers based on definition of inductance [9-13]. Our proposed design of the pickup coil is based on a Brooks coil [14]. This shape of the coil can achieve maximum inductance for a given length of winding wire, and the estimation error of the inductance is less than 3 % [12]. Induction magnetometers have the ability to detect weak magnetic fields from extremely low frequencies to those is in the audible range (0.01 Hz ~ 10 kHz). Although induction magnetometers were proposed in several papers [1-7], the technical details were usually not described.

Because the nature of the coil is the fundamental basis of electromagnetism, the principles of induction magnetometers are easy to understand. However, the optimization of the design with numerous parameters is not easy. In order to simplify the design for the general shape of a pickup coil, we pay attention to the important relationships between flux linkage, current and voltage. In this paper, we find out four operation modes of a magnetometer which can be categorized with two detection models and two frequency ranges. The equivalent circuits for operation modes are based on Faraday's law, the definition of inductance, and Ohm's law. Because the sensitivity can be described with eight parameters for the modes, we can discuss the parameter dependencies. From those considerations, simplified descriptions of the sensitivity allow us to understand the merits of induction magnetometers. Some experimental results also show the validity of the models.

2. Air-core Coil

3.1 Model

We assume an air-core pickup of rectangular cross section. The self-inductance of the coil L [H] can be defined by the following equation [14, 15]:

$$L = P_0\, a n^2 \text{ [H]}, \tag{1}$$

where a [m] is the mean radius, n is the number of turns, and P_0 [H/m] is the coil coefficient defined by the coil shape. For examples, the value of P_0 for an ideal solenoid coil with finite length is determined by the product of the circular constant π, permeability of vacuum in H/m, length to diameter ratio of the coil, and the Nagaoka coefficient. If the ratio of a coil length, inner diameter, and outer diameter is constant, the value of P_0 becomes constant. The ratio of Brooks coil is 1:2:4. This shape of coil can achieve maximum inductance for a given length of winding wire, and the estimation error of the inductance is less than 3 % [12]. The value of P_0 for a Brooks coil can be described as follows:

$$P_0 = 1.6994 \times 10^{-6} \text{ H/m}. \tag{2}$$

The resistance of the coil can be expressed by following equation:

$$R = 2\pi\, a\, n\, \rho / s \text{ } [\Omega], \tag{3}$$

where ρ [Ωm] is the resistivity of the wire and s is the cross section of the wire. Assuming that a homogeneous magnetic flux B [T] is crossed with the mean cross section area S [m^2] and the number of turns n, Φ leads to the relationships:

$$S = \pi a^2 \text{ [m}^2\text{]}, \tag{4}$$

$$\Phi = nSB = \pi n a^2 B \text{ [Wb]}. \tag{5}$$

3.2. Faraday's Law

Fig. 1(a) shows a model based on Faraday's law. We assume that a homogeneous magnetic flux of f [Hz] is crossed with the coil. From (5) and Faraday's law, the induced voltage V [V] is expressed by the following equation:

$$V = (\mathrm{d}\Phi / \mathrm{d}t) = \mathrm{j}2\pi^2 f\, n\, a^2 B \text{ [V]}, \quad (6)$$

where j is an imaginary number. When we measure the voltage and integrate it with an ideal integrator, we can obtain the waveform of the magnetic flux density. The normalized voltage V / B can be expressed by the following equation:

$$V / B = \mathrm{j}2\pi^2 f\, n\, a^2 \text{ [V/T]}. \quad (7)$$

It is proportional to f, n, and a^2. It should be noted that the value does not depend on L if we don't consider current in the circuit.

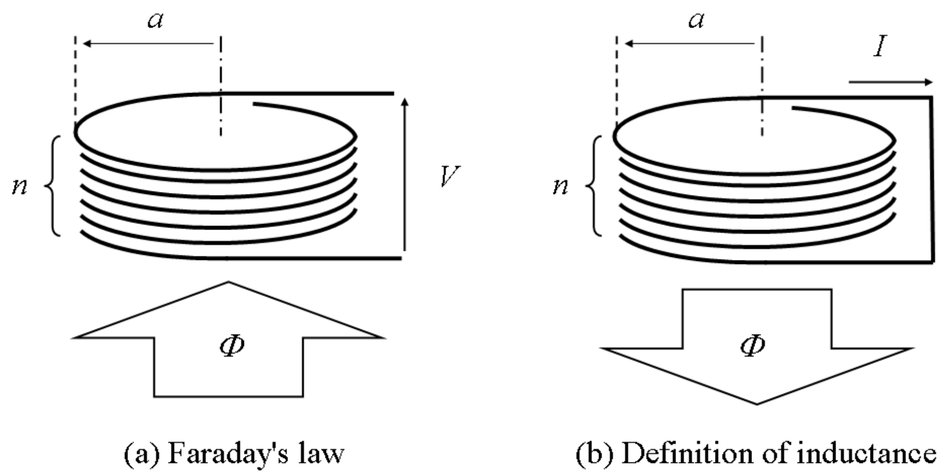


Fig. 1. Faraday's law and the definition of inductance.

2.2. Definition of Inductance

Fig. 1(b) shows a model based on the definition of inductance. From (5) and the definition of inductance, the relationship between the current I [A] and flux linkage Φ is expressed by the following equation:

$$\Phi = LI \text{ [Wb]}, \quad (8)$$

$$I = (nSB)/L = (\pi n a^2 B) / L \text{ [Wb]}. \quad (9)$$

From (1), the normalized current I/B can be expressed by the following equation:

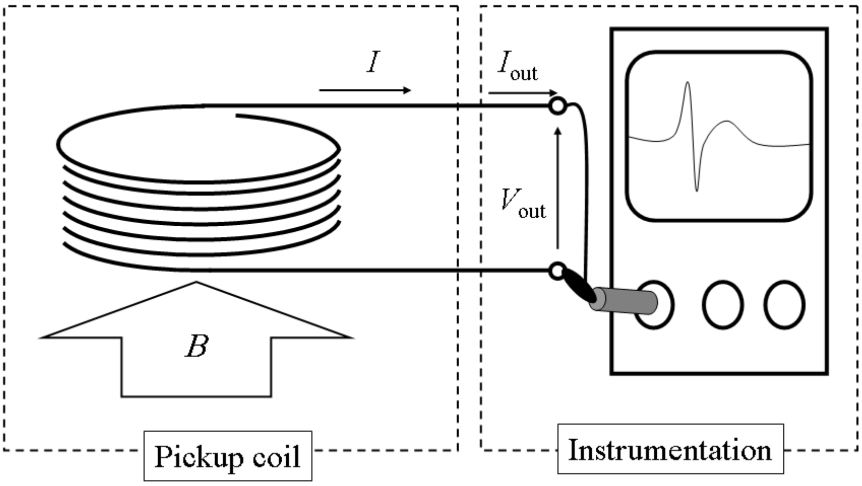
$$I / B = (\pi n a^2) / L = (\pi\, a) / (P_0\, n) \text{ [A/T]}. \quad (10)$$

Although the value is also proportional to n and a^2, it is inversely proportional to L. It should be noted that the value does not depend on f. In the analysis of a practical magnetometer, we have to take into account the resistance of the coil.

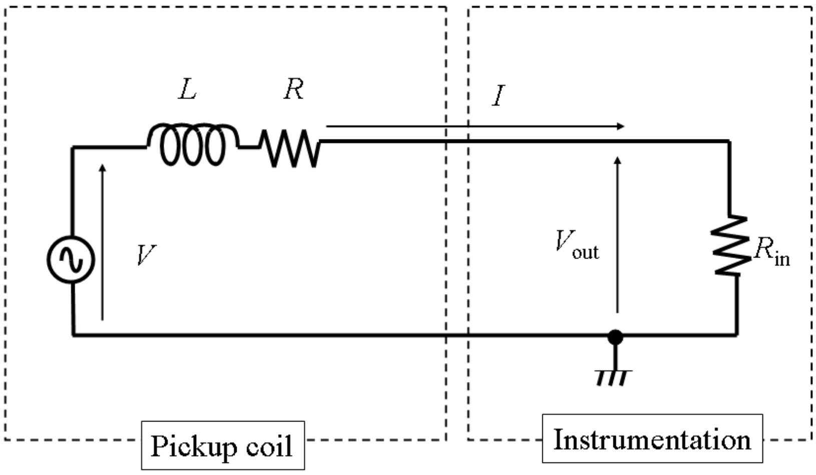
3. Voltage Detection Model

3.1. Model

Fig. 2 (a) shows the voltage detection model. A homogeneous magnetic flux is crossed with the coil. The induced voltage is measured using an instrumentation which has an input resistance of R_{in} [Ω]. Based on the Thevenin's theorem, the pickup coil can be replaced with parameters of *R*, *L*, and *V*. The values of those parameters are already known from (1), (3) and (7). Fig. 2(b) shows the equivalent circuits.



(a) Model.



(b) Equivalent circuit.

Fig. 2. Induced voltage detection model.

From the Kirchhoff's voltage law (KVL), the current I can be expressed by the following equations:

$$V = L\,(\mathrm{d}I/\mathrm{d}t) + (R+R_{in})I \text{ [V]}, \tag{11}$$

$$I = (V/(R+R_{in}))\times(1/(1+\mathrm{j}(\omega L/(R+R_{in})))) \text{ [A]}. \tag{12}$$

Because the input resistance of the instrumentation is usually high as $R_{in} >> R$, we rewrite (12) and define a cutoff frequency f_v [Hz] by the following equations:

$$I = (V / R_{in})\times(1 / (1+j(\omega L / R_{in}))) \text{ [A]}, \quad (13)$$

$$f_v = R_{in} / (2\pi L) \text{ [Hz]}. \quad (14)$$

In this model, the input current to the instrumentation I_{out}[A] is I. From (1) , (13) and (14), I_{out} can be written as follows:

$$I_{out} = I = (V / R_{in}) \times (1/(1+j(f / f_v))) \text{ [A]}. \quad (15)$$

3.2. Low Frequency Region ($f << f_v$)

When the frequency f is much smaller than f_v, we can approximate (15) as follows:

$$I_{out} = V / R_{in} \text{ [A]}. \quad (16)$$

Based on Ohm's law, the input voltage of the instrumentation V_{out} is the product of I_{out} and R_{in}. From (6) and (16), the values of I_{out}/B and V_{out}/B can be expressed by the following equations:

$$I_{out} / B = j2\pi^2 f\, n\, a^2 / R_{in} \text{ [A/T]}, \quad (17)$$

$$V_{out} / B = j2\pi^2 f\, n\, a^2 \text{ [V/T]}. \quad (18)$$

In this paper, we call $|V_{out}/B|$ the sensitivity of magnetometer. This result shows that the sensitivity in the condition is defined by Faraday's law as same as (7). The value is proportional to f, n, and a^2, and does not depend on L.

3.3. High Frequency Region ($f >> f_v$)

When the frequency f is much larger than f_v, we can approximate (15) as follows:

$$I_{out} = -j\,(f_v / f) \times (V / R_{in}) \text{ [A]}. \quad (19)$$

From (1), (6), (14), (19) and Ohm's law, we can derive the following equations:

$$I_{out} / B = (\pi\, na^2) / L \text{ [A/T]}, \quad (20)$$

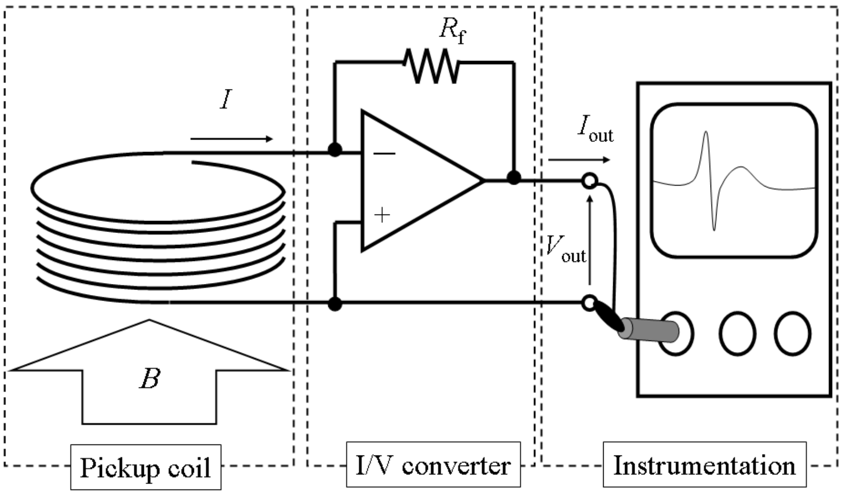
$$V_{out} / B = (\pi\, na^2 R_{in}) / L = (\pi\, a\, R_{in}) / (P_0\, n) \text{ [V/T]}. \quad (21)$$

In this paper, we call $|I_{out}/B|$ the transfer ratio of the magnetometer. This result shows that the transfer ratio in those conditions is defined by the definition of inductance the same as (10). The sensitivity of the magnetometer is proportional to a^2, n, $1/L$. It does not depend on f. From (21), it seems that the sensitivity becomes infinity if Rin is infinity. However, (21) is not approved for a finite frequency because f_v is also infinity, and the sensitivity can only be expressed by (18). In practice, the R_{in} is finite value. It should be noted that the inductance of the pickup coil should be considered when the target frequency is high.

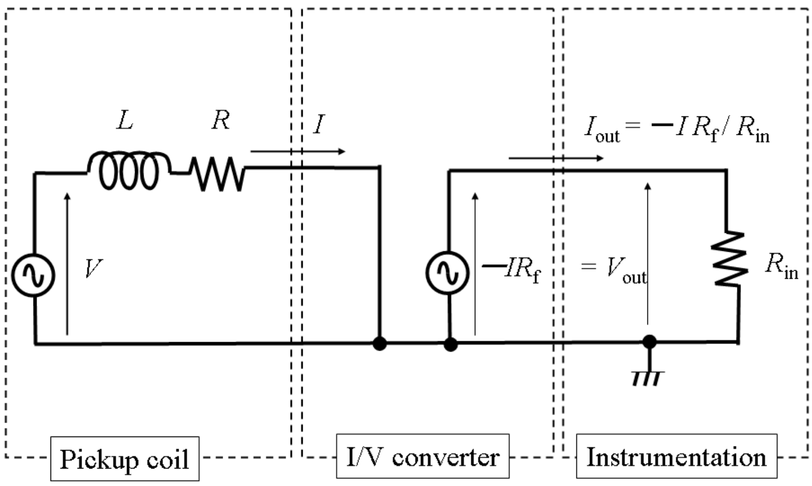
4. Current Detection Model

4.1. Model

Fig. 3(a) shows the current detection model with a current-to-voltage converter. Because the plus pin of the opamp is connected to the ground, the input resistance is zero and the pickup coil is in a virtual short. The output voltage of the current-to-voltage converter is the product of R_f and I. Fig. 3(b) shows the equivalent circuits.



(a) Model.



(b) Equivalent circuit.

Fig. 3. Induced current detection model.

Here, we define the cutoff frequency f_i as follows:

$$f_i = R / 2\pi L \text{ [Hz]}. \tag{22}$$

The pickup coil circuit is equivalent to Fig. 2 (b) with $R_{in} = 0$. From (1), (3), and (12), the current I can be expressed by the following equation:

$$I = (V / R) \times (1/(1+\mathrm{j}(f / f_i)))\ [\mathrm{A}]. \quad (23)$$

The input current to the instrumentation I_{out} [A] is the products of I and $-(R_f/R_{in})$. It can be written by the following equation:

$$I_{out} = -(R_f / R_{in}) \times (V / R) \times (1/(1+\mathrm{j}(f / f_i)))\ [\mathrm{A}]. \quad (24)$$

4.2. Low Frequency Region ($f << f_i$)

When the frequency f is much smaller than f_i, we can approximate (24) as follows:

$$I_{out} = -(R_f / R_{in}) \times (V / R)\ [\mathrm{A}]. \quad (25)$$

From (3), (6), (25) and Ohm's law, the transfer ratio and sensitivity of the magnetometer can be written by the following equations:

$$I_{out} / B = -(R_f / R_{in}) \times \mathrm{j}2\pi^2 f\, n\, a^2 / R\ [\mathrm{A/T}], \quad (26)$$

$$V_{out} / B = -(R_f / R) \times \mathrm{j}2\pi^2 f\, n\, a^2 = -\mathrm{j}\, \pi\, a\, s\, f\, R_f / \rho\ [\mathrm{V/T}]. \quad (27)$$

Compared with the voltage detection model under the same frequency condition, the sensitivity is gained (R_f / R) times. In contrast, the value does not depend on n.

4.3. High Frequency Region ($f >> f_i$)

When the frequency f is much smaller than f_i, we can approximate (24) as follows:

$$I_{out} = \mathrm{j}\ (f_i / f) \times (R_f / R_{in}) \times (V / R)\ [\mathrm{A}]. \quad (28)$$

From (1), (6), (22), (28) and Ohm's law, the transfer ratio and sensitivity of the magnetometer can be written by the following equations:

$$I_{out} / B = -(R_f / R_{in}) \times (\pi\, n a^2) / L\ [\mathrm{A/T}], \quad (29)$$

$$V_{out} / B = -(R_f\, \pi\, n a^2) / L = -\pi\, a\, R_f\ / (P_0\, n)\ [\mathrm{V/T}]. \quad (30)$$

Compared with the voltage detection model under the same frequency condition, the sensitivity is R_f times, and the sensitivity does not depend on R_{in}.

5. Discussion

5.1. Dependence of Parameters

We have defined the four operational conditions of a magnetometer with an air-core pickup coil. The conditions were categorized by two detection models (voltage, current) and two cutoff frequencies (f_v, f_i). The sensitivities of the magnetometer (V_{out}/B) were described with five parameters (a, n P_0, ρ, s) for the coil design and three parameters (f, R_{in}, R_f) for the electronics. Table 1 shows their relationship.

The mean radius, a, should be large to increase the sensitivities. It should be noted that the sensitivities of all conditions are proportional to a^2 if L does not depend on a. However, L is proportional to a as in (1). In the voltage detection model in the low frequency region ($f \ll f_v$), the sensitivity is proportional to a^2 as in (18). Because the sensitivity does not depend on L, the same relationship is Faraday's law as in (7). In other conditions, the sensitivity is proportional to a as in (21), (27), and (30).

The number of turns, n, should be considered when a current exists in the pickup coil. Based on Faraday's law, the voltage transfer ratio of the pickup coil (V/B) is proportional to n^2 as in (7). In contrast, based on the definition of inductance, the current transfer ratio of the pickup coil is inversely proportional to n as in (10). Understanding this contradiction is the key point for the design of a high-sensitivity magnetometer. For a voltage detection model, an increase of n makes the sensitivity large as in (18). From (14), we should estimate f_v because the R_{in} is a finite value in practical cases. If the target frequency is higher than f_v, we have to consider the design because the sensitivity is inversely proportional to n.

Let's consider the sensitivity of current detection model in the low frequency region ($f \ll f_i$). According to (27), the resistivity and cross section of the wire, ρ and s, only appear as in (27). In contrast, the sensitivity does not depend on n.

Table 1. Summary of parameters.

Property		Eq. number	parameter							
			a [m]	n	P_0 [H/m]	ρ [Ω m]	s [m^2]	f [Hz]	R_{in} [Ω]	R_f [Ω]
Coil property	L [H]	(1)	a	n^2	P_0					
	R [Ω]	(3)	a	n		ρ	$1/s$			
Faraday's law	$\|V/B\|$ [V/T]	(7)	a^2	n				f		
Definition of inductance	$\|I/B\|$ [A/T]	(10)	a	$1/n$	$1/P_0$					
Induced voltage detection model	f_v [Hz]	(14)	$1/a$	$1/n^2$	$1/P_0$				R_{in}	
($f \ll f_v$)	$\|V_{out}/B\|$ [V/T]	(18)	a^2	n				f		
($f \gg f_v$)	$\|V_{out}/B\|$ [V/T]	(21)	a	$1/n$	$1/P_0$				R_{in}	
Induced current detection model	f_i [Hz]	(22)		$1/n$	$1/P_0$	ρ	$1/s$			
($f \ll f_i$)	$\|V_{out}/B\|$ [V/T]	(27)	a			$1/\rho$	s	f		R_f
($f \gg f_i$)	$\|V_{out}/B\|$ [V/T]	(30)	a	$1/n$	$1/P_0$					R_f

5.2. Experimental Verification

In order to confirm the behaviour of the parameter n of interest, we compared three kinds of our developed induction magnetometer. Fig. 4 shows the comparison of the measured frequency response. Plot data represents experimental results, and lines represent calculated results from (27). All of the pickup coils were Brooks coil, wound by a copper wire of 0.5 mm diameter. The same current-to-converter with R_f = 1 MΩ was used for the electronics. However, the parameters of a and n are different. The coil of a = 45 mm has been developed based on an optimum design method [9]. The number of turns was defined by an optimum wire diameter of 0.5 mm. The coils of a = 75 have been developed through the consideration of the space factor of the pickup coil [11]. It had been already reported that the estimated values of f_i and (V_{out}/B) in the high frequency regions were in good agreement with the measured values [12]. However, the values of (V_{out}/B) in the low frequency regions were not discussed with theoretical approaches. The measured values in the low frequency regions were in good agreement with the calculated results from (27).

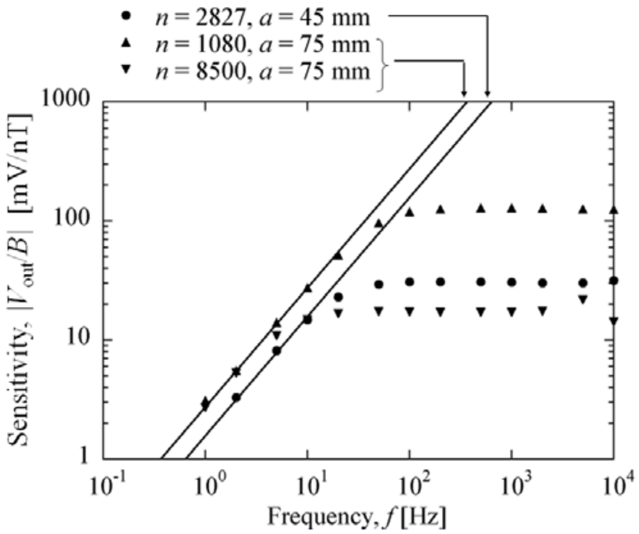


Fig. 4. Sensitivity as a function of frequency, as parameters of *n* and *a*. Plot data represents experimental results, and lines represent calculated results from Eq. (27).

For a clear understanding of the sensitivity limits, we compared the frequency responses of the two detection models. Fig. 5 shows the frequency response of experimental results and calculated results for the coil of a = 45 mm. Plot data represents experimental results of the current detection model, and lines represent calculated results. We can see that the measured values were greater than the calculated values over 10 kHz. It had been already reported that the phenomena was due to the capacitance of the wire between the pickup coil and electronics [10]. Excluding the resonance phenomena, the validity of our proposed equations was successfully confirmed. Although, the sensitivity of the voltage detection model is proportional to n, the required n is larger than 4,000,000 to obtain the similar sensitivity of our induction magnetometer in the low frequency region. It should be also noted that for an increase of n making the sensitivity large for the voltage detection model, the value of R become large. Because the Johnson noise is proportional to $R^{1/2}$, the noise floor level of the magnetometer becomes worse.

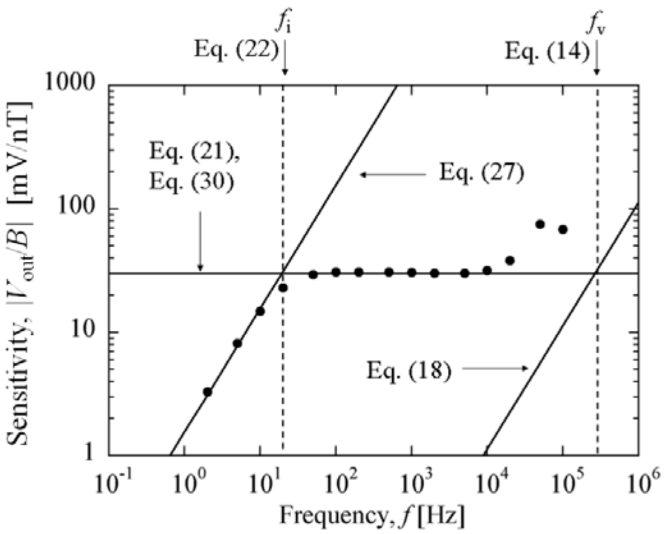


Fig. 5. Comparison of frequency response of two models. Plot data represents experimental results of the current detection model, and lines represent calculated results. (a = 45 mm, n = 2827, R =70 Ω, L = 0.611 H).

5.3. Sensitivity Limit

The sensitivity of both detection models is limited in the high frequency region. If we assumed that $R_f = R_{in}$, the sensitivities can be described by the same equation as in (21) and (30). In order to simplify the equations of the sensitivity, we introduced two symbols:

$$F = 2\pi^2 f\, n\, a^2 \text{ [V/T]}, \tag{31}$$

$$G = (R_f\, \pi\, na^2) / L = (R_{in}\, \pi\, na^2) / L \text{ [V/T]}. \tag{32}$$

Fig. 6 illustrates the frequency response of the sensitivity for the two detection models. Table 2 shows a summary of the sensitivity at four operational conditions. From the results, four important tips were found.

1) In the low frequency region, the sensitivity of the current detection model is (R_f /R) times than that of the voltage detection model.
2) The limit value of the sensitivity G is inversely proportional to L.
3) In the current detection model, a suitable value of n exists. In the low frequency region, the sensitivity does not depend on n.
4) Although an increase of n makes the sensitivity large in the voltage detection model, the value of R becomes large. Because the Johnson noise is proportional to $R^{1/2}$, the noise floor level of the magnetometer becomes worse.

Table 2. Summary of the sensitivity limits.

Frequency	Detection model	
	Voltage	Current
Low	F	$(R_f /R)\times F$
High	G	G

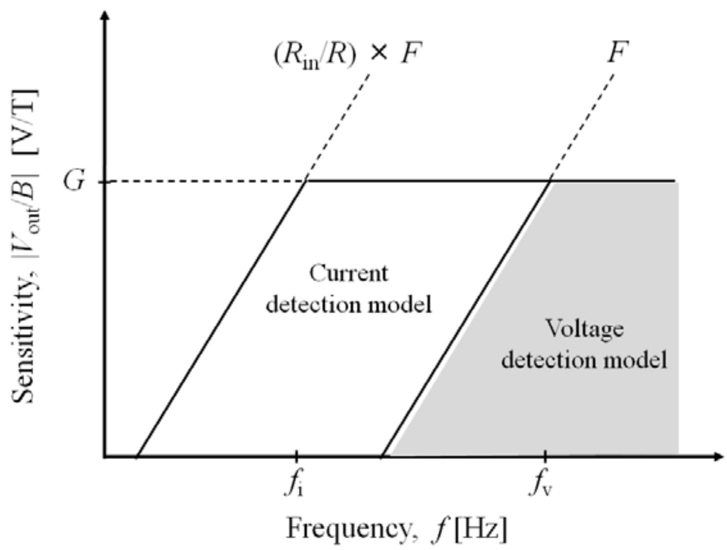


Fig. 6. Theoretical frequency response of the sensitivity for the two detection model.

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc.

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- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
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