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FEASIBILITY STUDY OF STEADY STATE MAGNETIC FIELD MEASUREMENT

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A rotating magnetic probe testing system has been designed and constructed for the purpose of establishing a technique of the plasma current measurement on a steady state tokamak. An air turbine is employed to drive the rotating magnetic coil from the viewpoint of avoiding the use of an electric motor in the vicinity of the tokamak device. The signal induced on the rotating probe is transmitted to the amplifier through a transformer coupling. A long term testing on mechanical as well as electrical characteristics has been carried out to find key technical issues on this system. A continuous operation for more than one week has successfully been achieved.

Keywords : ITER, Diagnostics, Rotating Magnetic Probe, Steady State Tokamak, Steady State Magnetic Field Measurement, Feasibility Study

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This work is conducted as an ITER Technology R&D and this report corresponds to 1994 ITER Technology R&D Task Agreement on "Feasibility study of steady state magnetic field measurement" (T64).

This research was conducted under the commission to The National Institute for Fusion Science in 1994 FY.

[*1] National Institute for Fusion Science
[*2] Daido Institute of Technology
[*3] Japan Ultra-High Temperature Materials Institute

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定常磁場計測の可能性実証試験

日本原子力研究所那珂研究所ＩＴＥＲ開発室
川端　一男＊[1]・藤田　順次＊[1]・松浦　清剛＊[2]
坂田　政敬＊[2]・藤若　節也＊[3]・的場　　徹

（1995年７月６日受理）

定常トカマクにおけるプラズマ電流測定の手法確立のために，回転磁気プローブ試験システムが設計・製作された。トカマク装置の近くで電気モーターを使用することを避けるために，回転磁気コイルの駆動には空気タービンが採用されている。回転プローブに誘起された信号は変圧器結合で増幅器に伝達される。本システムの鍵となる技術的課題を見いだすために，電気特性及び機械特性の長期間試験を実施した。１週間以上の連続運転が成功裏に達成された。

本研究はＩＴＥＲ工学設計活動の一環として実施したもので，本報告は1994年ＩＴＥＲ工学Ｒ＆Ｄタスク協定（Ｔ64）に基づくものである。

本報告書は，核融合科学研究所に委託研究として平成６年度に実施した研究の成果をとりまとめたものである。

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1. INTRODUCTION

The magnetic probe is one of the important basic diagnostic techniques on a tokamak. With an increase in the duration of plasma sustainment, it is urged to develop a technique which can measure the steady state magnetic field, in order to obtain the magnitude and the position of the plasma current in a long pulsed tokamak fusion experimental reactor such as ITER.

For this purpose, a hybrid magnetic probe system has been proposed, which is based on a combination of a conventional magnetic probe for the measurement of fast varying magnetic field and a rotating magnetic probe for that of slowly varying field [1,2].

It is preferable to employ a non electric as well as magnetic power source to drive the rotating magnetic coil (rotor) in the vicinity of the tokamak device. It is also preferred not to use any mechanical contacts to pick up the electric signal induced in the rotor from the viewpoint of maintenance-free long life time of the system.

For the purpose of testing the principle of the hybrid magnetic probe system for long term operation, a testing magnetic probe system has been designed and constructed. The system has been operated continuously for more than one week, and technical problems which should be solved when applying to an actual tokamak device have been found.

In Section 2, several different types of the probe to pick up and transmit the magnetic field signal are compared from various aspects. A circuit to compensate the fluctuation of rotation speed is described in Section 3. A mechanical design of a transformer-coupled rotating coil and its testing are presented in Section 4. In Section 5, the long-time testing results are shown. It is concluded in Section 6.

2. COMPARISON OF PICK UP SYSTEMS FOR THE MAGNETIC FIELD DETECTION

The following three pick up systems for the magnetic field detection have been investigated; (a) rotating coil, (b) rotating conductor and (c) transformer-coupled rotating coil. The structure of each system is illustrated in Fig. 1 to show the operational principle.

(a) Rotating coil

This system is the simplest and ideal in principle. For the application to ITER, however, it is necessary to develop a good electric contact with a long life time. The output V_s is expressed as below when the magnetic field intensity B is present. It changes with the rotational angular frequency ω, and is proportional to ω.

$$V_s = B\,N\,S\,\omega\,\sin\omega t, \qquad (1)$$

where N is the number of turns and S is the area of the coil.

(b) Rotating conductor

Although the mechanical structure of the rotor is the simplest, the analysis of electric characteristics is complicated. The output is expressed as below, because the mutual inductance M between the rotor and stator changes with time approxi-mately as $M \propto M_0 \sin\omega t$, where M_0 is the maximum value of M. It changes with a frequency

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2ω, and is proportional to ω^2. The sensitivity of this method is low because the mutual inductance M is small.

$$V_s \propto B\,M_0\,\omega^2 \sin 2\omega\, t. \qquad (2)$$

(c) Transformer-coupled rotating coil.

This method has an advantage that no mechanical contact is necessary to transmit the signal induced in the rotor, even though the electric characteristic is similar to (a). The output is expressed as below. It changes with the frequency of ω, and is proportional to ω^2. Here, M is mutual inductance of the transformer.

$$V_s \propto B\,S\,M\,\omega^2 \sin \omega\, t. \qquad (3)$$

A comparison of above three methods is summarized in Table 1.

3. COMPENSATION CIRCUIT FOR THE FLUCTUATION OF ROTATION SPEED

In order to attain the accuracy of magnetic field measurement, it is necessary either to keep the rotation speed constant, or employ a compensation circuit which has a proper frequency response, because the sensitivity is proportional to either ω or ω^2.

Assuming that the transformer coupled rotating coil method will be employed, the following compensation circuits are investigated, instead of designing complicated feedback control system to keep the rotation speed constant. The circuit should have a frequency response of inverse proportional to the square of frequency, because the output voltage is proportional to ω^2.

(a) Two-stage *RC* circuit

This is the simplest circuit which has a characteristic of inverse proportional to ω^2. The circuit diagram and its frequency characteristics are shown in Fig. 2 (a) and (b), respectively. The operation frequency of this circuit with a frequency response required should be sufficiently higher than the cross-over frequency $1/\tau$. In this frequency range, however, the gain of the circuit is two orders of magnitude smaller than that in the flat characteristic range. Noises of low frequency component give a significant effect on the operation of this circuit. From these reasons, no good results were obtained with this compensation circuit.

(b) *LC* circuit

The circuit diagram is shown in Fig. 3. The output signal from this circuit is expressed as below, so that the required frequency response is obtainable in the frequency range of $\omega^2 LC \gg 1$, $\omega^2 LC \gg \omega L/R$.

$$\frac{V_{out}}{V_{in}} = \frac{1}{\{(1 - \omega^2 LC) + j\omega L/R\}} \qquad (4)$$

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Figure 5 is the numerically calculated results based on the equivalent circuit shown in Fig.4. In this case, the maximum gain at around 70 Hz is only 2 to 3 times that at around 130 Hz.

Effectiveness of this compensation circuit is verified experimentally. Output voltages with and without the compensation circuit are shown in Fig. 6 (a) and (b), respectively. Here the output voltage of 1 V corresponds approximately to 7 Gauss.

4. MECHANICAL DESIGN OF THE PICK UP SYSTEM

The detection head of the rotating magnetic probe consists of one-turn coil for pick up and 1.5-turn primary coil of a coupling transformer as is shown in Fig.7. The rotor is driven by a high speed air turbine operated at an air pressure of 6 atms. An air bearing operated at a pressure of 3 atms is employed for long term operation with high revolution speed as high as 10,000 rpm. The actual rotation speed was 130 r/s at an air pressure of 6 atms. The air consumption on the air turbine was 2.6 lit/min, and that on the air bearing was 6.3 lit/min at an air pressure of 3 atms.

It is necessary to keep the air pressure constant as possible, because the rotation speed is sensitive to the air pressure supplied. A high precision electronically controlled regulator is used to control the air pressure to drive the rotor.

A detail of the mechanical structure is shown in Fig. 8.

5. LONG TIME TEST

The testing device has been operated for 170 hours without any serious trouble, under the condition of the rotation speed being 7,800 rpm, and a uniform magnetic field intensity of 25 Gauss generated in a Helmholtz coil with a coil current of 1. The full recorded chart of the output signal from the magnetic probe system and the room temperature is shown in Fig. 9. Because no rotation frequency compensation circuit is employed in this stage, the output signal shows a drift of one-day cycle, probably due to the change of rotation speed with the room temperature. This variation is small enough to be cancelled with a rotation frequency compensation circuit.

There found no serious problems, such as abnormal change of rotation speed, heating, noise and others.

6. CONCLUSION

In this fiscal year 1994, a research activity was concentrated on developing mechanical structure of the rotating magnetic field pick up system. A transformer-coupled rotating coil energized with an air turbine was employed. The variation of output signal dependent on the fluctuation of the revolution speed is shown to be compensated with a circuit which has a frequency response of the gain being inversely proportional to the square of rotation frequency.

The rotating coil system constructed was tested for over seven days, that is 170 hours, without any serious problems.

A typical sensitivity of 0.1 V/Gauss with a resolution of 0.05 Gauss is obtained on this system.

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Table 1 Comparison of three pick up systems for rotating magnetic probe.

	Rotating coil	Rotating conductor	Transformer-coupled rotating coil
Mechanical structure	problems on electric contact	simple	a little complicated
Life time	short	long	medium
Electric characteristics	simple in analysis	complicated in analysis	not simple in analysis
Detection frequency	f	$2f$	f
Detection sensitivity	high	low	medium
Temperature dependence	no	yes	yes
Frequency dependence of sensitivity	f	f^2	f^2
Frequency response of compensation circuit	$1/f$	$1/f^2$	$1/f^2$
Direction of the magnetic field detected (rotation axis : Z)	perpendicular to Z (X, Y)	perpendicular to both Z and stator coil axis Y (X)	perpendicular to Z (X, Y)
Effect of fluctuating magnetic field	low	magnetic field component linked to stator coil (Y)	magnetic field component linked to the secondary coil of the coupling transformer (Z)

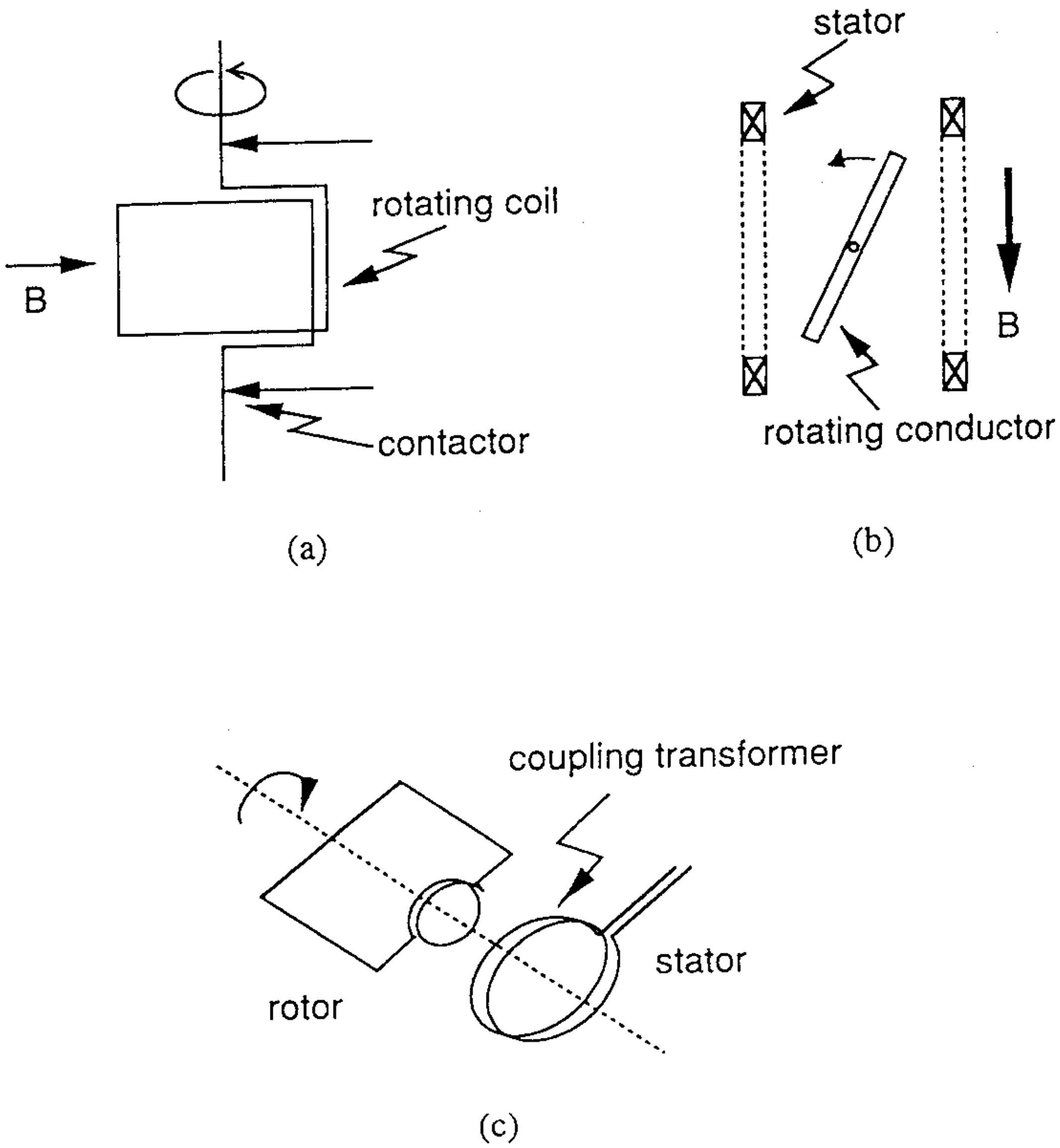
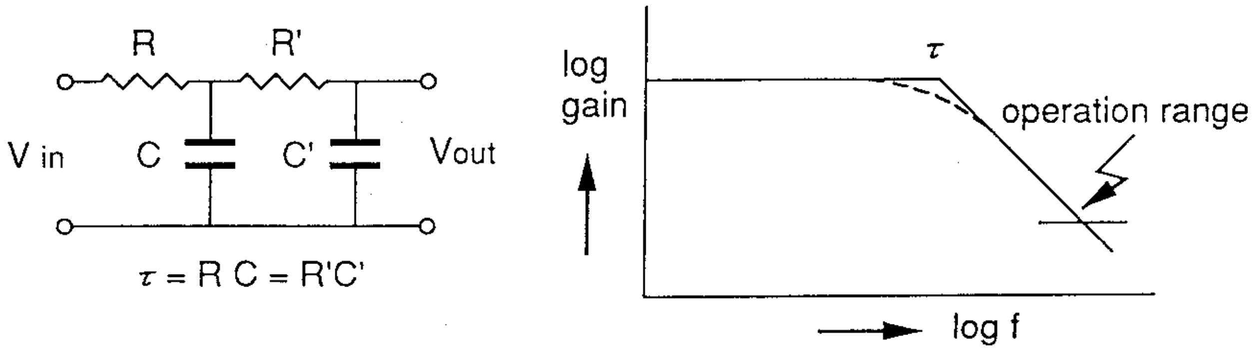


Fig. 1 Schematic diagrams of pick up systems for magnetic field detection. (a) rotating coil, (b) rotating conductor and (c) transformer–coupled rotating coil.



(a)

(b)

Fig. 2 Circuit diagram (a) and the frequency response (b) of a compensation circuit with 2-stage RC ladders.

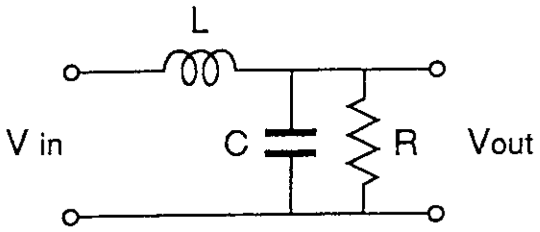


Fig. 3 Circuit diagram of a compensation circuit with L and C.

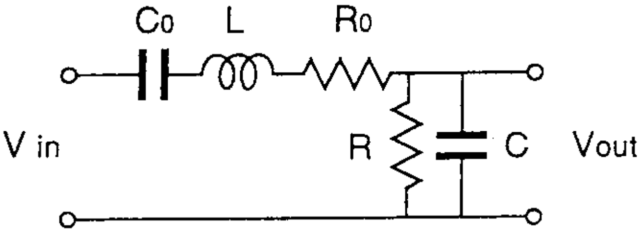
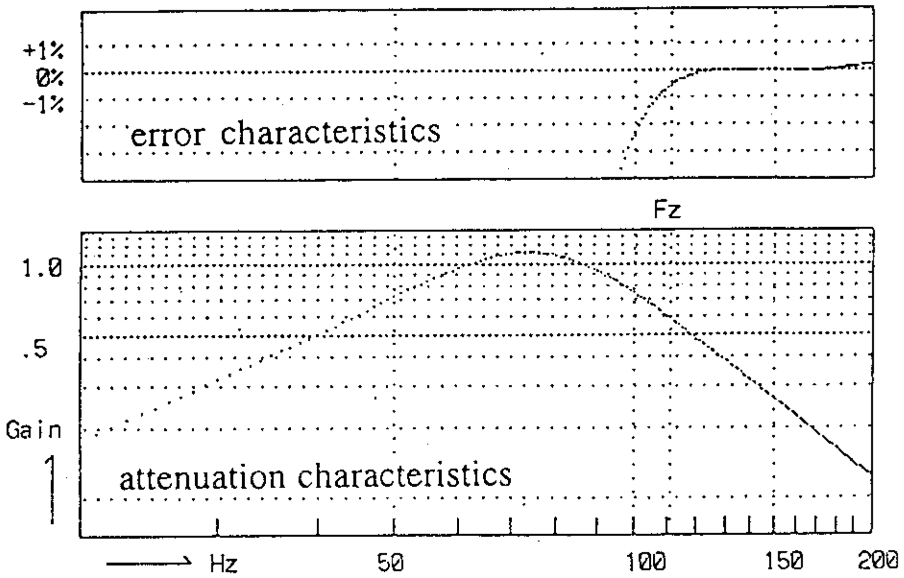


Fig. 4 Equivalent circuit for the numerical calculation.

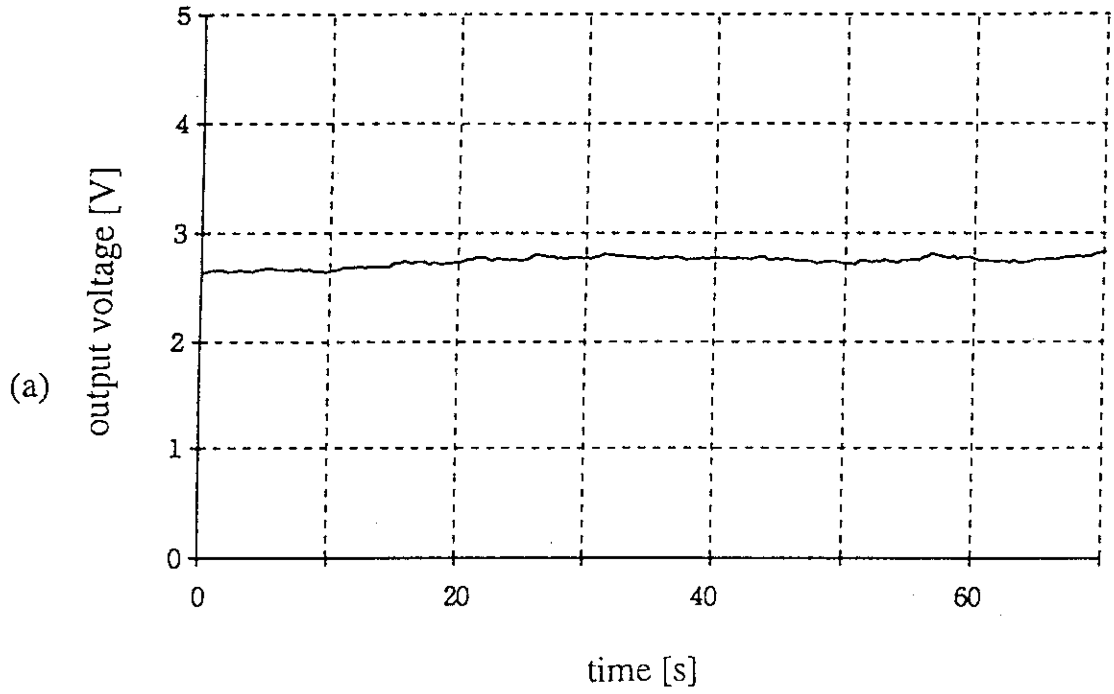
L=20H C=.15μF C0=.33μF R=6400Ω Fr=110.877Hz



L= 20 H C= .15 μF C0= .33 μF R= 6400 Ω Fr= 110.877 Hz

F	Gain	Vout	error%	direct%
20	.273319	.0132308	-98.6769	-97.6331
30	.4256	.0463553	-95.3645	-94.6746
40	.596487	.115498	-88.4502	-90.5325
50	.785652	.237698	-76.2302	-85.2071
60	.969324	.422305	-57.7695	-78.6982
70	1.08256	.641953	-35.8047	-71.0059
80	1.06595	.825603	-17.4396	-62.1302
90	.949861	.931109	-6.88908	-52.071
100	.807337	.977034	-2.29656	-40.8284
110	.67865	.993772	-.622824	-28.4024
120	.5732	.998905	-.109548	-14.7929
130	.488943	1	0	0
140	.421572	.99996	-3.97955E-03	15.9763
150	.367181	.999811	-.0189101	33.1361
160	.322734	.999862	-.0138086	51.4793
170	.285968	1.00016	.0162155	71.0059
180	.255207	1.00068	.0675565	91.716
190	.229204	1.00135	.134547	113.609
200	.207016	1.00212	.211894	136.686

Fig. 5 An example of numerical calculation result with a circuit shown in Fig. 4.



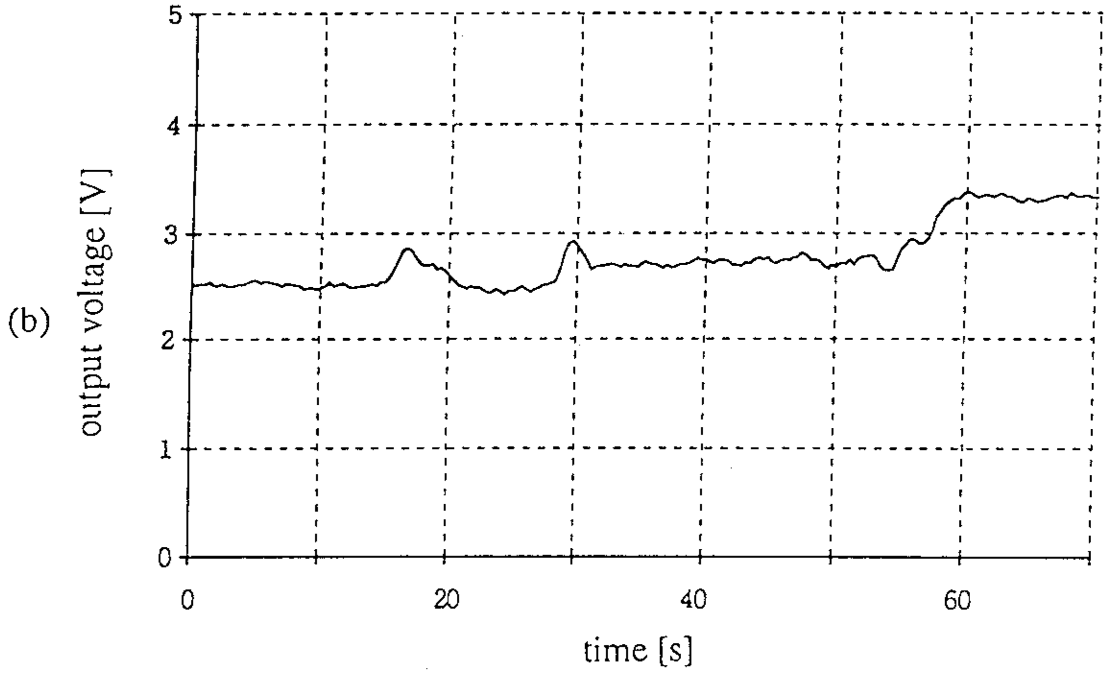


Fig. 6 Comparison of the output voltages with (a) and without (b) a compensation circuit for rotation speed fluctuation.

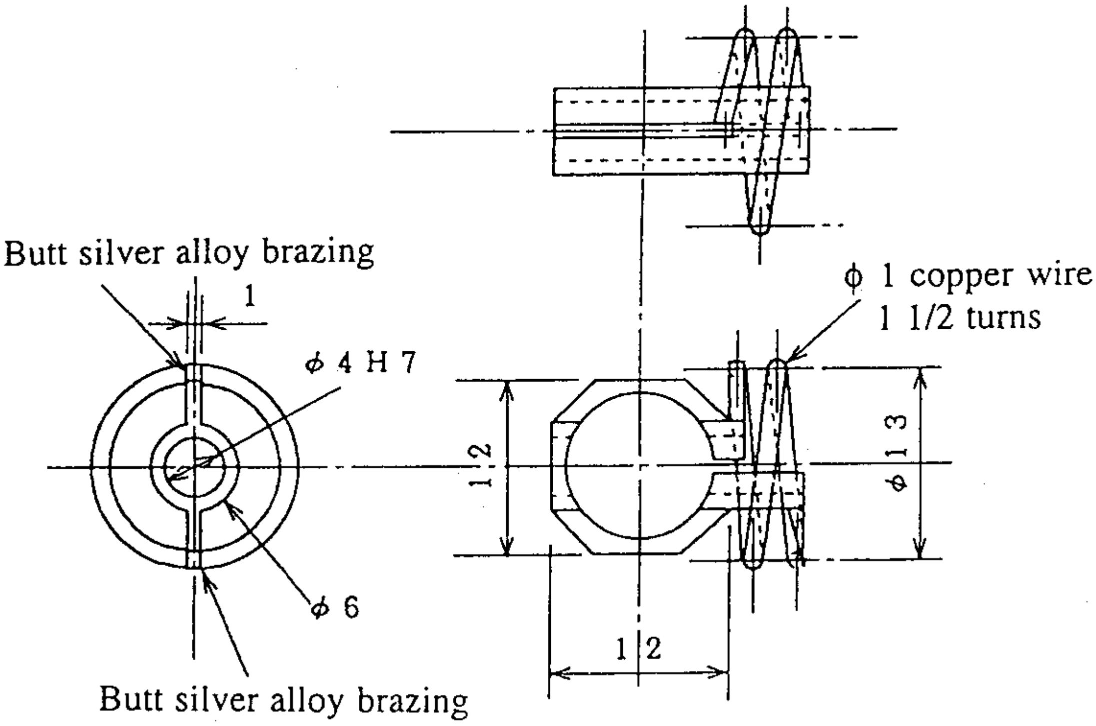


Fig. 7 Drawing of the detection head of a transformer-coupled rotating magnetic probe.

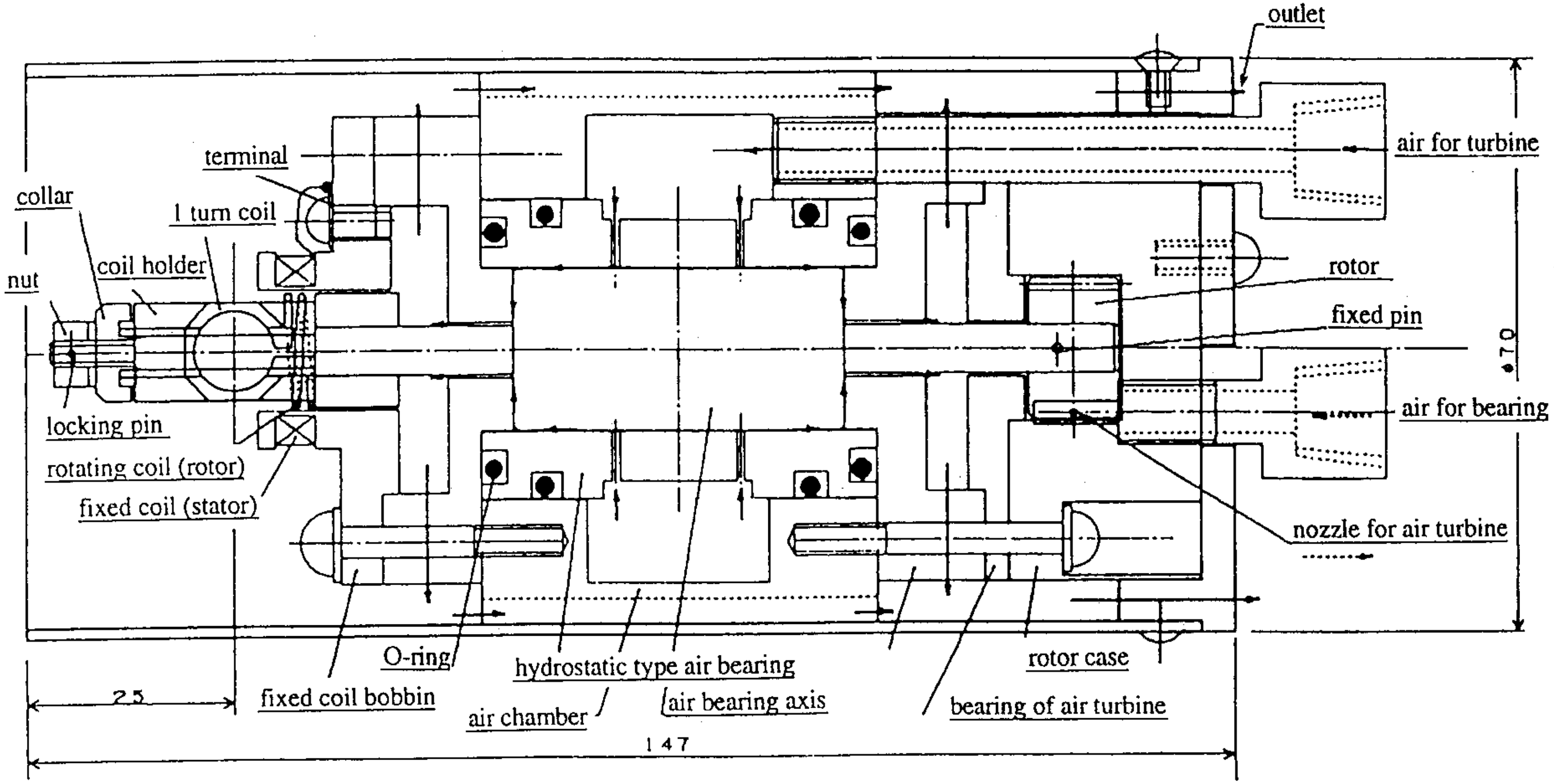


Fig. 8 Drawing of transformer-coupled rotating magnetic probe.

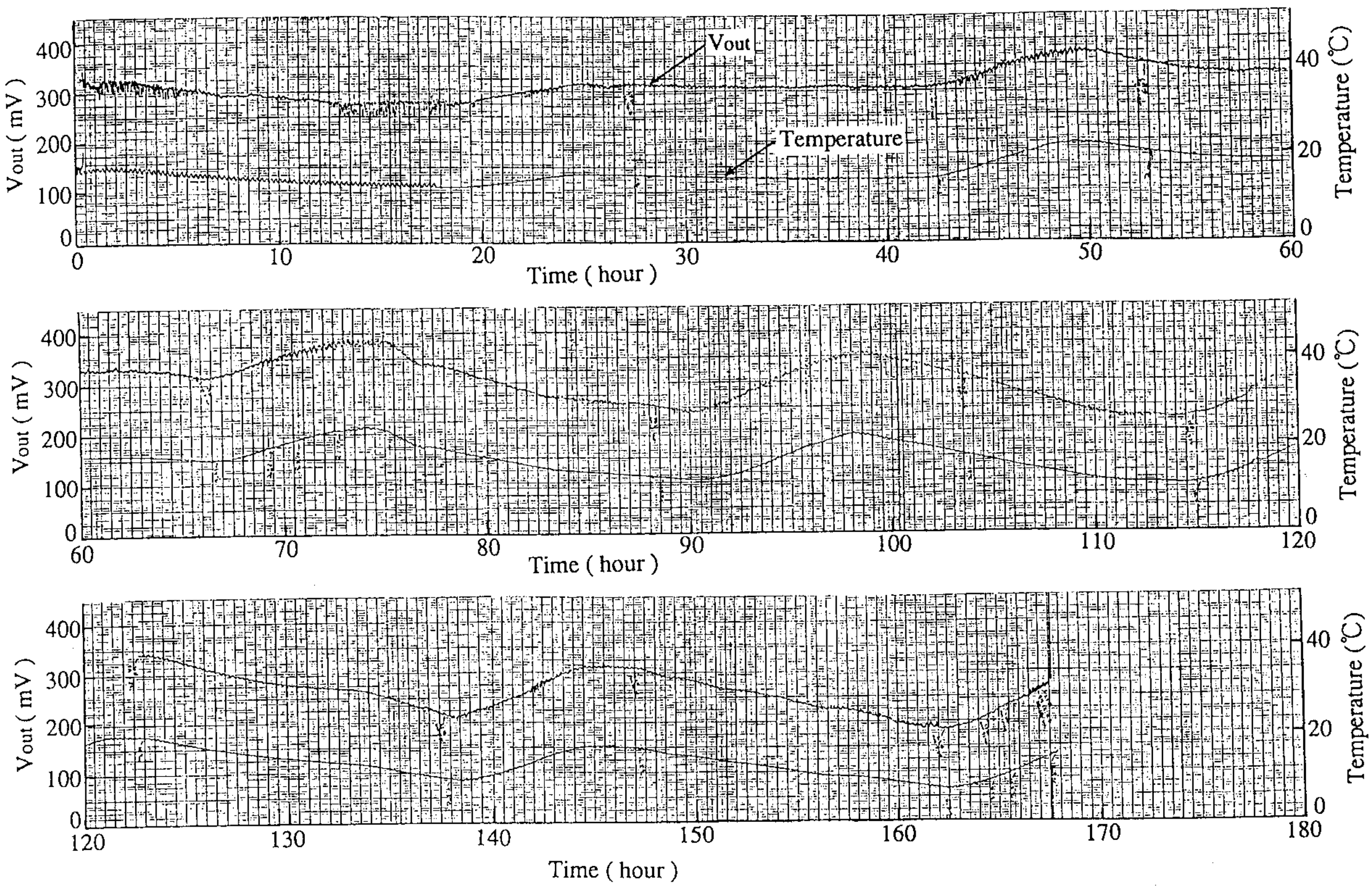


Fig. 9 The full recorded chart of output voltage from magnetic probe system and the room temperature for the long time test. The signal shows a drift of one-day cycle due to the change of the room temperature, which can be cancelled with a rotation frequency compensation circuit.