34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

# Study on Technology of High-Frequency Pulsed Magnetic Field Strength Measurement

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***Abstract*—High-frequency transient weak magnetic field is always involved in researches about biomedical engineering field while common magnetic-field sensors cannot work properly at frequencies as high as MHz. To measure the value of MHz-level weak pulsed magnetic-field strength accurately, this paper designs a measurement and calibration method for pulsed magnetic-field. In this paper, a device made of Nonferromagnetic material was independently designed and applied to pulsed magnetic field measurement. It held an accurately relative position between the magnetic field generating coil and the detecting coil. By applying a sinusoidal pulse to the generator, collecting the induced electromotive force of the detector, the final magnetic field strength was worked out through algorithms written in Matlab according to Faraday's Law. Experiments were carried out for measurement and calibration. Experiments showed that, under good stability and consistency, accurate measurement of magnetic-field strength of a sinepulse magnetic-field can be achieved, with frequency at 0.5, 1, 1.5 MHz and strength level at micro-Tesla. Calibration results carried out a measuring relative error about 2.5%.**

## I. INTRODUCTION[1]

Nowadays technology on magnetic field strength measurement have made great progress and been widely applied to industry, agriculture, science of national defense and biomedical engineering[1-3]. In recent decades, repetitive Transcranial Magnetic Stimulation (rTMS) played more and more critical roles in cranial nerve and brain research while pulse magnetic field (PMF) involved in rTMS is of microsecond level. Accurate measurement of this magnetic field strength would help researchers get an idea about the real magnetic field strength when performing a rTMS, that will be helpful in rTMS experimental analysis, as well as in a safety consideration.

There are several methods in PMF measurement. Most PMF detecting and measuring technologies are focusing on strong pulsed magnetic field (sPMF) used in atom structure research and weak pulsed magnetic field (wPMF) at nanosecond level conducted in transformer substation, but when it comes to wPMF in medical instruments application they cannot meet demands[3-8]. Comparing to magneto-optical effect method used for sPMF, electromagnetic induction method based on Faraday's Law is more feasible for wPMF measurement, which has advantages of wide measuring range and high sensitivity without any constraint in signal frequency. So this paper demonstrated a study on measuring method for wPMF with frequency range of 0.1-1.0 MHz based on Faraday's Law of electromagnetic induction, which mostly involved in medical fields such as rTMS in clinical application.

## II. METHOD

### A. Principle

According to Faraday' Law of electromagnetic induction, if a detecting coil with turns N and transverse section area S is placed in a target magnetic field with strength **B**, keeping the center axis of the coil parallel to direction of this magnetic line of force, when magnetic flux through coil changes, an induction electromotive force $\xi$ or its integrated signal $\Psi$ will be generated in the coil[6-8]. Based on above, there are three for the detecting coil requirements to meet[8,10]: (1) its transverse section area should be small enough to approach a point in the target field; (2) its impact on the target field should be as tiny as possible; (3) its central axis should be strictly parallel to the magnetic field direction.

### B. Pulsed magnetic field measurement

Based on demonstration above, a method and technology on pulsed magnetic field measurement was studied here, which contained PMF generation, measurement and calibration.

A single-period sine voltage signal was generated from AFG3252 function generator, amplified through power amplifier HSA4101 and then applied to calibration device designed here so as to generate a pulsed magnetic field[10,11].

This calibration device of the PMF measurement device made from non-ferromagnetic material consists of two I-shaped bobbins of different size and one concentric cursor shaft with scale. The larger bobbin of diameter 15.00cm is to produce PMF and the smaller one of diameter

*Research supported by NSFC (81127003) and NSFC(81171424)
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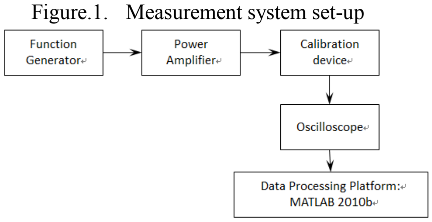
1.28cm is for PMF detection and measurement and fixed onto the cursor shaft through a couple of fastening screws. The minimum scale of cursor shaft is 0.5cm and its diameter is 1.00cm. This device ensures that the detecting coil will be strictly placed at the central of the targeted PMF so as to make the measurement feasible and reliable.

An induction electromotive force would be detected by detecting coil of the calibration device. Then an oscilloscope was used for data acquisition, and MATLAB 2010b was used for data processing. Eventually the magnetic field strength value will be calculated. Figure.1 showed the whole measurement system set-up.

Figure.1. Measurement system set-up




*C. Data processing*

Data processing was performed on MATLAB 2010 platform. It was divided into three parts. The first two parts demonstrated that how the actual measured value of magnetic field $B_d$ was calculated, and the third one explained the estimation of the real PMF strength value.

One is data pre-process, filtering and truncation included, the other is integration and solving for magnetic field strength **B** using coil parameters.

*1) Data pre-processing*

Frequency domain spectrum analysis was performed firstly on collected data $V_d$. According to its frequency-amplitude response, frequency range distribution was derived, and then corresponding digital filter parameters were confirmed to wipe off noises[9,15,16]. In this case when a 1MHz sine pulse stimuli was used, the cut-off frequency of filter was set to 2MHz.

Data collected contained not only induction electromotive force but also noises. Although high frequency noise was wiped off after filtering, low frequency noise was still there, such as base line floating, which means that the output did not equal to zero when the input did. This would result in one basic increment at each integration step and eventually brought about base-line error which cannot be ignored. Therefore, data truncation was done to minimize integration range so as to lessen base-line error. Due to experimental experience, let truncation window width τ be (1±10%)×T, where T is signal period. On the basis of electromagnetic induction Law, Ψ was derived through calculation after $V_c$ integrated.

*2) Calculation of magnetic field strength **B***

Common integral methods are analogical integration and digital integration[12-14]. As analog components like amplifier, capacitance and resistance are not ideal element, and always affected by multiple factors[13,14], while the core section of digital integration is the algorithms so it has the advantages of stability and consistency.

Choosing an integral algorithm should obey rules below: low sampling frequency and simple structure. Common digital integral algorithms include compounded rectangular formula, trapezium formula and Simpson formula and so on[9]. Their z-transfer functions are as follow:

$$H_R(z) = \frac{T}{z-1} \tag{1}$$

$$H_T(z) = \frac{T(z+1)}{2(z-1)} \tag{2}$$

$$H_S(z) = \frac{T(z^2+4z+1)}{3(z^2-1)} \tag{3}$$

Taking the phase-frequency responses into consideration, it is trapezium integrator and Simpson integrator that have better linear consistency while response of rectangular integrator will reduce as f increases. Considering both algorithm complexity and phase-frequency response, trapezium integrator is adopted here. Error $E_S$ induced by it has an order of $O(h^2)$, where h is integration step length, and in this study, $h=1\times10^{-9}$ s.

*3) Estimation of real PMF strength value*

For frequency response of common magnetic field detectors cannot meet the demands of high frequency PMF measurement, here we designed a estimation and calibration method. On the basis of IEEE standard [10], there are two methods on magnetic detector time domain calibration: (1) using measuring value from standardized magnetic field sensor for calibration; (2) using theoretical calculated value in standardized reference magnetic field for calibration. The second method is adopted in this paper and magnetic field detecting device developed here is used right to generate a standardized reference magnetic field.

On the basis of Biot-Savart Law,

$$\boldsymbol{B} = \frac{\mu_0}{4\pi}\int_c \frac{I \cdot \mathrm{d}\boldsymbol{l} \times \boldsymbol{r}_0}{r^2} \tag{4}$$

where $\mu_0$ denotes permittivity in vacuum and $\boldsymbol{r}_0$ denotes vector pathway from where the current source is to where the magnetic field strength needs to be determined, magnetic field strength at the center of the current-carrying coil is known to be $\boldsymbol{B} = \frac{\mu_0 I}{2R}$. When coil diameter is fixed, ***B*** is only determined by *I*.

There are two ways to get current in driving coil I: (a) simulating the circuit with differential formula

$U(t) = (L + L_0)\frac{\mathrm{d}i}{\mathrm{d}t} + (R + R_0)i$ and solving for I[9,15,17]; (b) deriving voltage on current-limiting resistance through oscilloscope and solving for I by Ohm Law.

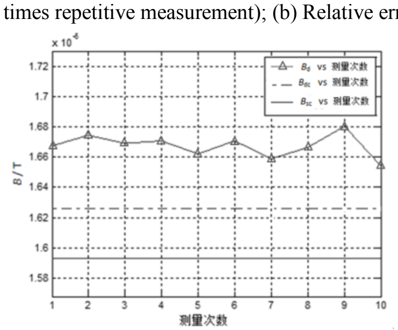
## III. RESULTS

A function generator TEK AFG3252 was used to generate 1 MHz sine pulsed voltage signal with amplitude of 0~±5 V. Signal was applied to detecting coil in this magnetic field measuring system after amplified through power amplifier NF HSA0401 and then recorded by digital oscilloscope TEK TDS2012b. Driving coil in the calibration device used for magnetic field generation had a diameter $D_s$ of 15.00 cm and turns $N_s$ of 5, and detecting coil used for magnetic field signal collection had a diameter $D_d$ of 1.28 cm and turns $N_d$ of 9. Vertical distance between the two coils was set to 0cm, that is, the detecting coil was right in the center of the driving coil.

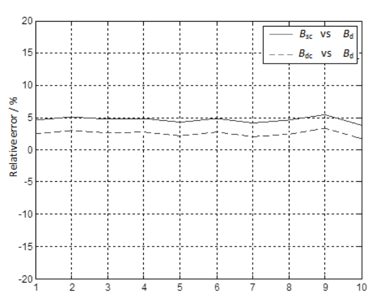
### *A. Repetitive measurement*

Experimental parameters were set as follows: driving voltage $V_{spp}$=50.0 V, its frequency f =1.0 MHz, equivalent resistance R=62.1 Ω and 10 measurements were performed repeatedly. (As shown in Figure.2)

Figure.2. Measurement result of magnetic field strength. (a) Magnetic field curve(10 times repetitive measurement); (b) Relative error curves




(a)




(b)

As shown in Figure.2, $\boldsymbol{B}_d$ denotes actual measured value of magnetic field calculated from data collected in detecting coil. $\boldsymbol{B}_{sc} = \frac{\mu_0 I_{sc}}{2R}$, where $I_{sc}$ denotes coil current derived by solving circuit differential equation when inductance of the circuit is 6.2μH . $\boldsymbol{B}_{dc} = \frac{\mu_0 I_{dc}}{2R}$, where $I_{dc}$ denotes coil current directly measured in the circuit. $\boldsymbol{B}_{sc}$ is smaller than $\boldsymbol{B}_{dc}$ as shown in Figure.2 (b), therefore we know that $I_{sc}$ is smaller than $I_{dc}$. Considering that circuit electrical characteristics vary with environment, $\boldsymbol{B}_{dc}$ was taken as estimation of real magnetic field strength, and then relative error curve was plotted as Figure.2 (b), where $\eta = \frac{\boldsymbol{B}_d - \boldsymbol{B}_{dc}}{\boldsymbol{B}_{dc}} \times 100\%$, which implied that the measuring method showed a good consistency and stability with η stayed at about 2.5%.

### *B. Measurements under different driving voltage*

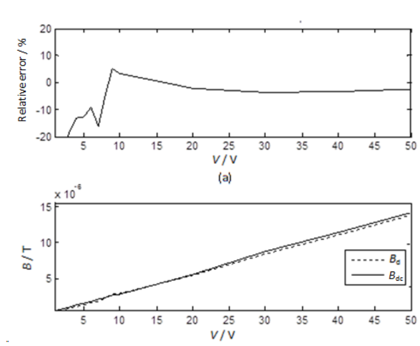
Experimental parameters were set as follows: driving frequency f=1.0MHz and $V_{spp}$ varies from 1.0 V to 50.0 V. Induction electromotive force signal and were collected by oscilloscope as TABLE.I.

$V_R$ indicated voltage value measured on the current-limiting resistance. Current in coil $I_{dc}$ and magnetic field strength $\boldsymbol{B}_{dc}$ can be derived from $V_R$. $\boldsymbol{B}_{dc}$ would be used to calibrate $\boldsymbol{B}_d$. Figure.3 demonstrated that relative error of $\boldsymbol{B}_{dc}$ and $\boldsymbol{B}_d$ was large when $V_{spp}$<10.0 V while it was stably at about 2.5% with $V_{spp}$>10.0 V. The reason was when driving signal was much too small the output of detecting coil was also small and covered by noises. Hence, minimum driving value $V_{min}$ should be above 10.0 V to meet the demands of measurement.

TABLE I. VOLTAGES ON THE CURRENT-LIMITING RESISTANCE WITH DIFFERENT DRIVING VOLTAGES

| $V_{spp}$ / V | $V_R$ / V | $V_{spp}$ / V | $V_R$ / V | $V_{spp}$ / V | $V_R$ / V |
|---|---|---|---|---|---|
| 1.0 | 1.6 | 6.0 | 5.2 | 20.0 | 15.4 |
| 2.0 | 2.2 | 7.0 | 6.0 | 30.0 | 24.4 |
| 3.0 | 3.0 | 8.0 | 6.8 | 40.0 | 31.6 |
| 4.0 | 3.8 | 9.0 | 7.6 | 50.0 | 39.2 |
| 5.0 | 4.4 | 10.0 | 7.84 | | |

Figure.3. Measured magnetic field curves with different driving voltages. (a)Relative error curve; (b) Measured and calibrated magnetic field curve



*C. Measurements under different frequencies*

Experimental parameters were set as follows: $V_{spp}$ = 50.0 V. Data were collected separately at 0.5、1.0、1.5 MHz, five times repetitive measurement at each frequency. After a series of data processing, relative error η was calculated by comparing the final averaged calculated magnetic field strength value $\mathbf{B}_d$ with the standard calibration value $\mathbf{B}_{dc}$. Results are shown in TABLE.II. From data in this table the conclusion can be derived that this measuring system maintains a good stability, consistency and frequency response at range of 0.5-1.5 MHz.

TABLE II. MEASUREMENT OF MAGNETIC FIELD WITH DIFFERENT DRIVING FREQUENCIES

| f / MHz | $B_d$ / μT (5 measurements) | | | | | $B_{dc}$ / μT | η / % |
|---|---|---|---|---|---|---|---|
| | *1* | *2* | *3* | *4* | *5* | | |
| 0.5 | 15.59 | 15.61 | 15.70 | 16.19 | 16.59 | 16.45 | –3.2 |
| 1.0 | 13.81 | 14.31 | 13.61 | 13.80 | 13.81 | 14.16 | –2.21 |
| 1.5 | 12.03 | 12.14 | 12.19 | 11.72 | 12.01 | 12.14 | –1.02 |

## IV. DISCUSSION

High frequency weak magnetic field measurement plays a truly important role in biomedical engineering field, while as a common element of magnetic field sensor, Hall element didn't have a enough satisfying frequency response. As a result, here electromagnetic induction method was adopted for magnetic field measurement and calibration.

This paper designed a measuring and calibrating method on weak pulsed magnetic field at microsecond level. As target signal is weak, experiments require precise manipulation. Hence, a set of calibration device was designed independently to precisely control relative horizontal and vertical position between detecting coil and driving coil. Experiments showed that measured magnetic field value brought into correspondence with its real value nicely.

There still exists some defect: firstly the targeted signal is narrow-band, while signal collected through oscilloscope is whole-band. Inevitable attenuation occurs during signal filtering, which has already been proved in experiment result analysis. Data processing indicated that total measurement errors mainly came from data filtering, therefore more attention should be paid on designing an ideal narrow-band filter with excellent frequency response. Secondly, restricted by experimental equipment used, signal with frequency beyond 2 MHz or amplitude larger than 120.0 V cannot be accurately measured.

As mentioned above, a magnetic field strength measuring method has been established for application in high frequency weak pulsed magnetic field in this paper. And experiments demonstrated that with this method precise measurement and calibration can be achieved. Then more work should be taken into consideration in errors and frequency response analysis to achieve higher precision. System integration and digitization will be completed and get through tests in metering departments, then be put into practical application.

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