# Verification experiment of Faraday's law of electromagnetic induction based on radio frequency signals

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**[Abstract]** As a theoretically complete fundamental principle of electromagnetism for nearly two centuries, Faraday's law of electromagnetic induction states that the induction voltage in a metal coil is proportional to the number of turns in the coil and the rate of change of magnetic flux through a single turn. Recent research points out that Faraday's law of electromagnetic induction is only an engineering approximation formula， and that Lorentz's magnetic force theorem is the microphysical mechanism of electromagnetic induction. This verification experiment uses two induction coils, $C_A$ and $C_B$, of the same structure and size. Coil $C_A$ has a single-layer dense winding of 30 turns, and coil $C_B$ has a single-layer evenly spaced winding of 15 turns. The induction voltages of coils $C_A$ and $C_B$ are detected under low and high frequency signals, respectively. The experiment proves that: under low-frequency signals, Faraday's law of electromagnetic induction is an engineering approximation formula. However, under high-frequency (RF) signals, Faraday's law of electromagnetic induction is completely incorrect. Under RF signals, the coil induction voltage depends mainly on the relationship between the wire length and the RF wavelength, as well as the strength of the electromagnetic field radiation attenuation. The coil induction voltage has no direct relationship with the number of turns of the coil.

## 1. Introduction

In 1831, Faraday revealed for the first time through experiments that a changing magnetic flux in a metal coil could produce induction current and voltage in the metal coil.

As shown in Figure 1, a metal coil was connected in series with voltmeter V. When magnetic rod B was inserted or pulled out of metal coil C, coil C generated an induction voltage, and the pointer of voltmeter V deflected. The faster the insertion or withdrawal was, the greater the induction voltage generated by coil C. When the magnetic rod was stopped in the coil, there was no induction voltage in the coil, and the pointer of voltmeter V did not deflect.

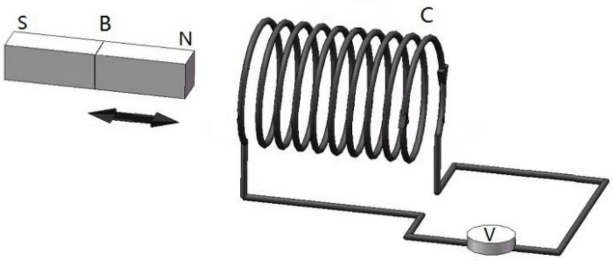



Figure 1 Electromagnetic induction in a metal coil

With a large number of experiments [1] [2] [3], Faraday revealed that the induction voltage generated in a metal coil is proportional to the number of turns in the coil and the rate of change of magnetic flux through a single turn. This conclusion is called Faraday’s law of electromagnetic induction. The induction voltage is expressed as:

$$\varepsilon = - n \frac{d\Phi_B}{dt}$$

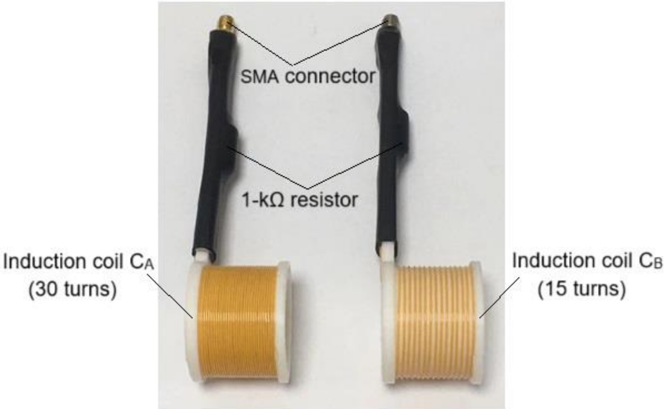
For nearly two centuries, Faraday's law of electromagnetic induction has been considered a universal fundamental principle of electromagnetism. According to Faraday's law of electromagnetic induction, the induction voltage of a coil is unaffected by the coil's shape [4] [5]. For two coils with same cross-sectional area and structure, the induction voltage is proportional to the number of turns of the coil.

Recent research [6] has pointed out that Faraday's law of electromagnetic induction is only an engineering approximation, while Lorentz's magnetic force theorem is the microphysical mechanism of electromagnetic induction. The following is the verification experiments of Faraday's law of electromagnetic induction under low-frequency and high-frequency signals.

## 2. Verification experiment of Faraday's law of electromagnetic induction

### 2.1 Experimental preparation

Two induction coils $C_A$ and $C_B$ with the same cross-sectional area and structure were used in the verification experiments. Fig. 2A is a photo of the induction coils, and Fig. 2B shows the structure schematic of the induction coils.



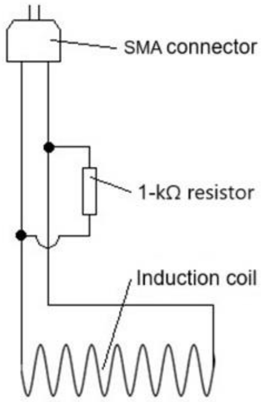




Fig. 2A Photo of induction coils Fig. 2B Schematic of induction coils

The induction coils are wound with 0.72 mm enameled wire with a mid-diameter of 31.8 mm and a height of 22 mm. Coil $C_A$ is dense winding 30 turns with a single-layer, and its wire length is 3 m. Coil $C_B$ is uniformly spaced winding 15 turns with a single-layer, and its wire length is 1.5 m. The output of both induction coils $C_A$ and $C_B$ is a female SMA connector with a 1-kΩ non-inductive resistor in parallel. The induction voltage of the coil is input to the oscilloscope through an RF cable; the RF cable is Oriental-Xupu RM141-BNC-J/SMA-JG with a length of 100mm and the oscilloscope is Ding-Yang SDS822X HD digital oscilloscope. As shown in Figure 3.

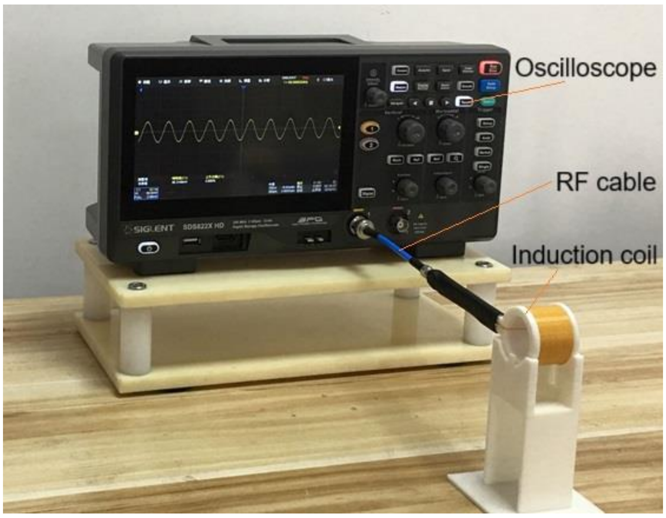



Fig. 3 Photo of oscilloscope with induction coil

In the experiment, the input of the induction voltage does not use a standard oscilloscope probe. Consequently, the oscilloscope does not directly indicate the measured value of the coil's induction voltage; rather, it shows the peak-to-peak display value of the induction voltage. However, the peak-to-peak display value is proportional to the actual measured value of the induction voltage. In this experiment, the concern is the ratio between the induction voltages of coils $C_A$ and $C_B$. Therefore, the experiment directly uses peak-to-peak display value of the induction voltage for numerical comparison.

### 2.2 Verification experiments under low frequency signals

The experiment utilizes a Helmholtz coil, which can form a uniform alternating magnetic field with equal magnetic induction intensity in its central region. The Helmholtz coil in this experiment has two coils on the left and right, with an inner diameter of 180 mm and an outer diameter of 286 mm. A uniform magnetic field area of 50 mm x 50 mm x 50 mm in the center of the Helmholtz coil can be formed, and its magnetic field error is less than 0.5%.

The Helmholtz coil is powered by a sinusoidal AC power supply with the frequency set to 50 Hz and the RMS values of the voltage set to 25 V and 50 V. The induction coils $C_A$ (30 turns) and $C_B$ (15 turns) are placed sequentially on a positioning seat in the center region of the Helmholtz coil. The central axis of the Helmholtz coil coincides with the central axis of the induction coils, as shown in Fig. 4.

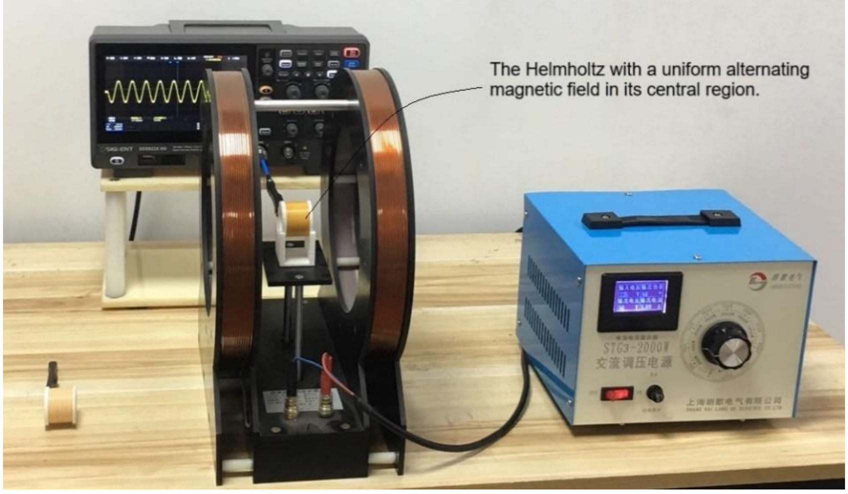



Fig. 4 Induction voltage of coil under low frequency signals

The peak-to-peak display values of the induction voltages in the coils are obtained by the oscilloscope, and the corresponding experimental data are presented in Table 1.

Table 1: Comparison of peak-to-peak display values of the induction voltages in coils $C_A$ (30 turns) and $C_B$ (15 turns) under low-frequency signals.

| Induction Coils/ Voltages（rms） | Peak-to-peak display values（$V_{PP}$） |
|---|---|
| $C_A$ / 50Hz/ 25V | 86mV |
| $C_B$/ 50Hz/ 25V | 170mV |
| $C_A$/ 50Hz/ 50V | 172mV |
| $C_B$/ 50Hz/ 50V | 340mV |

From Table 1: The ratio of peak-to-peak display values of induction voltage between coil $C_A$ (30 turns) and coil $C_B$ (15 turns) is about 2, which means that the induction voltage of the metal coil is proportional to its number of turns. It can be concluded that at a low-frequency signal of 50Hz, the experimental results are approximately consistent with Faraday's law of electromagnetic induction.

### 2.3 Verifications experiments under high frequency (RF) signals

Sine waves at frequencies of 50 MHz and 100 MHz are produced by a signal generator. These waves are then passed through a 100 Ω non-inductive resistor and applied to a current-carrying circular ring with a diameter of 100 mm to create high-frequency sinusoidal magnetic fields at 50 MHz and 100 MHz. Induction coils $C_A$ and $C_B$ are placed sequentially on a positioning seat in the magnetic field to ensure uniformity of the alternating magnetic field environment. The central axis of the current-carrying circular ring coincides with that of the induction coils, and the distance between the current-carrying circular ring and the induction coil is 20 mm along the axial direction. The experimental photo is shown in Fig. 5.

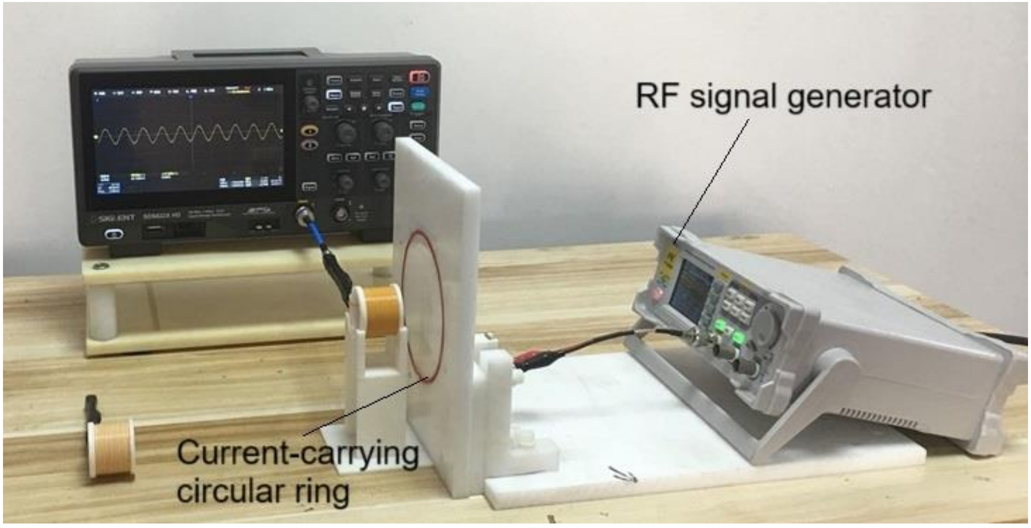



Fig. 5 Induction voltage of coil under RF signals

The peak-to-peak display values of the induction voltages in coils $C_A$ (30 turns) and $C_B$ (15 turns) are obtained by an oscilloscope, and the corresponding experimental data are showed in Table 2.

Table 2: Comparison of peak-to-peak display values of the induction voltages in coils $C_A$ (30 turns) and $C_B$ (15 turns) under RF signals.

| Induction Coils/ Frequencies/ Voltages （$V_{PP}$） | Peak-to-peak display values （$V_{PP}$） |
|---|---|
| $C_A$ / 50MHz/5V | 60.8mV |
| $C_B$/50MHz/5V | 52.3mV |
| $C_A$/ 100MHz/3V | 63.2mV |
| $C_B$/ 100MHz/3V | 98.6mV |

From Table 2: Under 50 MHz/5V RF signals, the ratio of peak-to-peak display values of induction voltage between coil $C_A$ (30 turns) and coil $C_B$ (15 turns) is 1.16, which is much lower than the ratio of the number of turns between coil $C_A$ (30 turns) and coil $C_B$ (15 turns). Therefore, under 50 MHz RF signals, Faraday's law of electromagnetic induction is incorrect.

Under 100MHz /3V RF signals, the peak-to-peak display value of induction voltage in coil $C_A$ (30 turns) is 63.2 mV, which is lower than the peak-to-peak display value of induction voltage in coil $C_B$ (15 turns) of 98.6 mV. The experimental result is completely opposite to Faraday's law of electromagnetic induction. Therefore, under 100 MHz RF signals, Faraday's law of electromagnetic induction is completely incorrect.

Based on the above verification experiments, it can be concluded that Faraday's law of electromagnetic induction is not a theoretically complete fundamental principle. Under low-frequency signals, Faraday's law of electromagnetic induction is an engineering approximation; under high-frequency (RF) signals, Faraday's law of electromagnetic induction is completely incorrect.

### 2.4. Experimental analysis

N/A