An Experimental Study on Field Line and Field Concepts Based on the Unipolar Induction Problem

Authors: Zhang Xueliang, Zhang Xueliang

Date: 2024-02-27T20:07:12+00:00

Abstract

This paper demonstrates, through experiments on the relative motion of coils and magnets and through case analyses of numerous electromagnetic interactions, that Weber's original viewpoint on unipolar induction is correct. Furthermore, the experimental analysis also indicates that, compared with the concept of field, the concept of lines of force similarly plays an important role in explaining electromagnetic interactions.

Full Text

Preamble

An Experimental Study on Field and Field Line Concepts Based on the Unipolar Induction Problem

Zhang Xueliang

Institute of Electrical and Automation, Wuhu Institute of Technology, Wuhu 241000, China

Abstract

This paper, through experiments on relative motion between coils and magnets and analysis of numerous electromagnetic interaction cases, demonstrates that Weber's viewpoint on the unipolar induction problem was correct. Additionally, the experimental analysis in this paper shows that, compared to the concept of field, the concept of field lines plays an equally important role in explaining electromagnetic interactions.

Keywords: Electromagnetic Induction Law; Electromagnetic Interaction; Electromagnetic Field; Magnetic Field Lines; Electric Field Lines; Electromagnetic Waves; Lorentz Force

Classification: O441

When a magnet moves near a conductor, why is an electromotive force induced in the conductor? According to Faraday's law of electromagnetic induction, this occurs because of changing magnetic flux in a closed circuit. Maxwell extended Faraday's law, proposing that a vortex electric field is distributed in the space around a moving magnet. He maintained that at all points in space where magnetic field intensity changes with time, an electric field is generated, regardless of whether a conductor exists at those points. Einstein not only endorsed this view, but it also profoundly influenced the formation of his special relativity. In the opening of his paper "On the Electrodynamics of Moving Bodies," he wrote: "It is known that Maxwell's electrodynamics—as usually understood at the present time—when applied to moving bodies, leads to asymmetries which do not appear to be inherent in the phenomena. Take, for example, the reciprocal electrodynamic action of a magnet and a conductor. The observable phenomenon here depends only on the relative motion of the conductor and the magnet, whereas the customary view draws a sharp distinction between the two cases in which either the one or the other of these bodies is in motion. For if the magnet is in motion and the conductor at rest, there arises in the neighbourhood of the magnet an electric field with a certain definite energy, producing a current at the places where parts of the conductor are situated. But if the magnet is stationary and the conductor in motion, no electric field arises in the neighbourhood of the magnet. In the conductor, however, we find an electromotive force, to which in itself there is no corresponding energy, but which gives rise—assuming equality of relative motion in the two cases discussed—to electric currents of the same path and intensity as those produced by the electric forces in the former case."

What exactly causes the induced electromotive force in a conductor near a moving magnet? Let us follow Einstein's thought experiment and actually perform a test. The experimental conductive magnet is cylindrical in shape. The conductors are three hollow coils, L_1, L_2, and L_3, of identical length but different inner and outer diameters. Coil L_1's inner diameter is slightly larger than the cylindrical magnet's diameter, L_2's inner diameter is slightly larger than L_1's outer diameter, and L_3's inner diameter is slightly larger than L_2's outer diameter. The three coils are nested concentrically with aligned ends. Both the three coils and the cylindrical magnet can move relative to one another along the axial direction. Each coil is connected to a galvanometer G to form a closed circuit. The experimental principle is shown in Figure 1. During the experiment, the coil axis and magnet axis are maintained on the same line.

Experimental Observations

Figure 1: Electromagnetic induction experiment with a cylindrical magnet and three nested coils

1.1 All three coils are stationary while the magnet moves, or the magnet is stationary while all three coils move synchronously. When the magnet (or the three coils synchronously) moves toward or away from the coils (or magnet) at a certain speed, the galvanometer pointers connected to the three coils oscillate following essentially the same pattern, indicating that electromotive force is generated in all three coils.

1.2 The middle coil L_2 is stationary. When the inner and outer coils L_1 and L_3 move synchronously with the magnet relative to coil L_2, electromotive force is generated in coil L_2, while no electromotive force is produced in coils L_1 and L_3.

1.3 Coils L_1 and L_3 are stationary. When the middle coil L_2 moves synchronously with the magnet relative to coils L_1 and L_3, electromotive force is generated in coils L_1 and L_3, while no electromotive force is produced in coil L_2.

(Additional note: When the hollow coils have many turns and the magnet is strongly magnetic, a weak current may be observed in coils moving synchronously with the magnet. This current is an interference signal generated through transformer coupling from current flowing in the stationary coils. Determining whether it is transformer-coupled interference is straightforward—simply open the circuit of the stationary coil to verify.)

For the observation results of experimental step 1.1, explanations can be provided using either Faraday's law of electromagnetic induction or the Lorentz force law without any disagreement, so no extensive analysis is needed here.

The observations from experimental steps 1.2 and 1.3 are: when the magnet moves, electromotive force is induced in stationary coils that have relative motion with respect to the magnet, while no electromotive force is generated in coils moving synchronously with the magnet. Note that the stationary coils and those moving synchronously with the magnet are almost in the same space. According to Maxwell and Einstein's viewpoint, the induced electromotive force in stationary coils results from changing magnetic flux caused by the moving magnet (time-varying magnetic field), which generates a vortex electric field in the space around the magnet.

However, the distribution of vortex electric fields should be continuous and diffuse within a certain range. Therefore, for experimental step 1.2, the electric field exists only in the space where stationary L_2 is located, yet there is no electric field at positions L_1 and L_3, which are located inside and outside L_2 and moving synchronously with the magnet. For experimental step 1.3, the electric field exists only in the space where stationary L_1 and L_3 are located, yet there is no electric field at the position of L_2, which is sandwiched between them and moving synchronously with the magnet. This is clearly untenable. Moreover, when all three coils are stationary and only the magnet moves in the same manner at the original position, electromotive force is generated in all three coils. If a vortex electric field truly exists in the space around a moving magnet, then the only possible explanation is that another electromotive force exists in coils moving synchronously with the magnet that cancels out the first one. There is a basis for this canceling electromotive force. According to Faraday's view, the magnetic field lines of a moving magnet are stationary and do not move with the magnet. Therefore, based on this view, coils moving synchronously with the cylindrical magnet along the axial direction would cut these stationary magnetic field lines, inducing an electromotive force in the coils that is always equal in magnitude and opposite in direction to the electromotive force generated by the vortex electric field, thus completely canceling it. If this explanation holds, then the problem becomes the unipolar induction issue of whether the magnet's magnetic field lines move with the magnet.

The author has already drawn conclusions from verification experiments on the unipolar induction problem: a moving magnet carries its magnetic field lines with it 【2】【3】【4】. Here, let us briefly verify the unipolar induction problem again. In the above experiment, the cylindrical conductive magnet is changed from its original axial back-and-forth motion to unidirectional constant-speed rotation about its central axis. When a closed circuit is formed by contacting the rotating magnet surface at appropriate positions through sliding contacts and wires, a direct current flows through the circuit, indicating that a DC induced electromotive force is generated. This is Faraday and Weber's original unipolar induction experiment. Weber's view was that magnetic field lines move with the magnet, and it is the stationary wires in the laboratory cutting these magnetic field lines that induces the DC electromotive force. Faraday held the opposite view, believing that conductors on the rotating magnet cut stationary magnetic field lines to induce electromotive force, and that the rotating cylindrical conductive magnet becomes a DC power source. Returning to the coil-magnet relative motion experiment, when the cylindrical magnet and coils move synchronously back and forth along the axial direction, if we adopt Faraday's view of stationary magnetic field lines and combine it with the magnetic field line distribution around the cylindrical magnet shown in Figure 2, coils moving synchronously with the magnet should cut magnetic field lines and induce electromotive force that cancels the electromotive force generated by the vortex electric field mentioned earlier. If this explanation holds, then according to the same Faraday view, conductors on the cylindrical magnet moving back and forth along the axial direction should also cut magnetic field lines and induce alternating electromotive force in the circumferential direction around the axis within the magnet. However, it is well known that the magnetic flux or magnetic field intensity inside a magnet does not change with the magnet's motion. According to Faraday's law of electromagnetic induction or Maxwell's view, no vortex electric field is generated inside a moving magnet, so no electromotive force caused by vortex electric fields is produced. Therefore, the electromotive force induced by cutting magnetic field lines in the magnet would not be canceled, and eddy currents should be generated in the magnet. When the magnet moves at a relatively high frequency for some time, there should be noticeable temperature rise. However, in reality, the magnet shows no temperature increase, indicating that no eddy currents or induced electromotive force exist in the magnet. (This can also be directly verified by winding a coil on the magnet.) This also shows that in coils moving synchronously with the magnet, there is no canceling electromotive force generated by cutting stationary magnetic field lines, and therefore no electromotive force caused by vortex electric fields exists in the coils. This further confirms the verification conclusion that magnetic field lines move with the magnet.

Figure 2: The section view of the magnetic field line distribution around the cylindrical magnet (cut open along the rotation axis)

Incidentally, in the unipolar induction experimental state, according to Faraday's view, even if a DC electromotive force is induced on a constantly rotating cylindrical conductive magnet, the direction distribution of the electromotive force is similar to that of a battery—it cannot form a current loop by itself. A closed circuit must be formed through sliding contacts and stationary wires to produce current. Therefore, it is plausible that the magnet does not heat up during prolonged rotation in the unipolar induction state. (The generation of unipolar induction electromotive force has been analyzed in detail in reference [4] and will not be discussed further here.) However, the situation is different when the cylindrical magnet moves back and forth along the axial direction. If conductors on the magnet indeed cut magnetic field lines to induce electromotive force, the direction of this electromotive force should be vortex-like around the axis, so eddy currents should be generated. Yet experiments show that no eddy currents are produced.

If we adopt the conclusion that magnetic field lines move with the magnet and analyze the above experimental observations using the Lorentz law based on this conclusion, what results do we obtain? Combining with the magnetic field line distribution around the magnet shown in Figure 2, we can see that as long as there is relative motion between the coil and the magnet (the perpendicular component of magnetic field lines), there exists an interaction of the coil cutting magnetic field lines, and electromotive force will be induced in the coil. Otherwise, no electromotive force will be induced. In experimental steps 1.2 and 1.3, coils moving synchronously with the magnet have no relative motion with respect to the magnet's magnetic field lines, do not cut magnetic field lines, and therefore no electromotive force is induced in the coils. Whether the magnet moves while the coil is stationary, or the coil moves while the magnet is stationary, it is essentially the same regarding induced electromotive force—the key is whether relative motion exists between the magnet and the coil. This is completely different from Einstein's assumption and eliminates the asymmetry problem in electromagnetic interactions that Einstein described.

In summary, neither Maxwell's view that changing magnetic fields generate vortex electric fields nor Faraday's law of electromagnetic induction can provide satisfactory explanations for the above experiments. However, the Lorentz law based on magnetic field lines moving with the magnet can easily and naturally provide reasonable explanations. Does this indicate that Faraday's law of electromagnetic induction does not perfectly reflect the essence of electromagnetic interaction?

2 Extended Lorentz Force and Its Electromagnetic Waves

If we accept the conclusion that magnetic field lines move with the magnet and combine it with Lorentz's law, we form a Lorentz force (law) based on magnetic field lines moving with the magnet. When examining numerous electromagnetic interaction cases from the perspective of this new Lorentz law, one finds that it can provide natural and reasonable explanations for almost all encountered cases—something Faraday's law of electromagnetic induction and other viewpoints cannot achieve. This suggests that the true cause of electromagnetic induction or electromagnetic interaction is not the change in magnetic flux described by Faraday's law, but rather the relative motion between charges and magnetic field lines. Therefore, this paper refers to the new Lorentz law based on magnetic field lines moving with the magnet as the Extended Lorentz Force (law).

The Extended Lorentz Force is defined as the force acting on a charge when it moves relative to the perpendicular component of magnetic field lines (magnetic field B). Whether the charge moves relative to the magnetic field lines or the magnetic field lines move relative to the charge, the electromagnetic interaction effect is equivalent. The expression for the Extended Lorentz Force F is identical to the original Lorentz force:

$$F = qvB\sin\alpha \quad (1)$$

where v is the relative velocity between charge q and magnetic induction intensity B (magnetic field lines), and α is the angle between the charge's motion direction and the magnetic induction intensity B direction. The expression for induced electromotive force E also remains unchanged:

$$E = \int (V \times B) \cdot dl \quad (2)$$

where V is the relative velocity between the line segment conductor l and the magnetic field lines (magnetic induction intensity B).

According to the Extended Lorentz Force, in a stationary magnetic field, the force acting on a moving charge is the original Lorentz force. In a moving magnetic field, a stationary charge also experiences a force. In a moving magnetic field, a moving charge simultaneously experiences two forces: one is the original Lorentz force from the charge moving in the magnetic field, and the other is the force generated by the magnetic field's motion. Usually, these two forces are not in the same direction. The direction of the Extended Lorentz Force acting on a charge and the direction of induced electromotive force can be determined using conventional methods unchanged.

Although the Extended Lorentz Force is proposed based on the experimental conclusion that a magnet's magnetic field lines move with the magnet, it should apply not only to magnetic field lines established by molecular currents in magnets but also to magnetic field lines established by other charge motion patterns. Charges moving at constant velocity under electric fields or steady currents excite static magnetic fields. Uniformly moving charges or steady currents do not carry their surrounding magnetic field lines forward with them—the magnetic field lines are stationary; otherwise, static magnetic fields could not be obtained. However, moving current-carrying wires and moving electromagnets can carry magnetic field lines just like moving magnets. Therefore, the Extended Lorentz Force also applies to electromagnetic interactions caused by relative motion between electromagnets and conductors. Accelerated charges under electric fields or changing currents excite electromagnetic waves. The direction of electromagnetic wave motion is perpendicular to the charge motion direction. The magnetic and electric field lines constituting electromagnetic waves are moving, with their motion direction perpendicular to the charge motion direction. The Extended Lorentz Force should also apply to electromagnetic interactions of electromagnetic waves.

From the perspective of the Extended Lorentz Force, the generation and propagation mechanism of electromagnetic waves differs from Maxwell's electromagnetic waves. Assuming that a medium capable of propagating electromagnetic waves exists in vacuum, this medium can interact with charges to establish electric field lines between positive and negative charges. Under the action of electric or magnetic fields, moving charges generate a magnetic field composed of closed magnetic field lines surrounding themselves, with the plane of these closed magnetic field lines perpendicular to the charge's motion direction. If the charge moves at constant velocity (steady current), the resulting magnetic field lines (magnetic field) are stationary, and the magnetic field intensity near the charge can be approximately determined using the Biot-Savart-Laplace law or Biot-Savart formula. If the electric field changes or a changing electric field causes charge acceleration (changing current), electric and magnetic field lines with varying density will be produced. These density-varying electric and magnetic field lines will vibrate like a longitudinal wave medium and propagate outward at the speed of light in a direction perpendicular to the electric field lines or perpendicular to the charge's motion, forming electromagnetic waves.

The known Biot-Savart magnetic field formula for a straight current is:

$$B = k\frac{I}{r} \quad (3)$$

Multiplying both sides of the above equation by $2\pi r$ yields Ampere's magnetic circulation law formula:

$$2\pi rB = 2\pi kI \quad (4)$$

In the above two equations, k is a constant. The product $2\pi rB$ is called the circulation of magnetic induction intensity B. From equations (3) and (4), we know that DC current produces closed magnetic field lines (magnetic field B) surrounding the current-carrying wire. The magnetic induction intensity B (magnetic field line density) at a point distance r from the wire is proportional to the current I flowing in the wire and inversely proportional to the distance r. The magnetic field lines distributed around the wire are denser closer to the wire, meaning the magnetic induction intensity B is greater, and vice versa. The greater the current, the larger the range over which magnetic field lines extend. Obviously, the magnetic field lines at distance r from the current-carrying wire are not established instantaneously out of nothing. According to the principle that like magnetic field lines repel each other, it is not difficult to imagine that the magnetic field lines surrounding the wire begin at positions close to the wire and gradually expand outward as the current in the wire increases from zero and its density gradually increases. Conversely, as the current in the wire gradually decreases, the magnetic field line density gradually becomes thinner and contracts toward the wire. The magnetic field lines around the wire change with the increase or decrease of current in the wire, expanding and contracting in the direction perpendicular to the current. If the current direction in the wire reverses, the magnetic field line direction also reverses, but the pattern of expansion and contraction with current increase and decrease remains unchanged. Assuming that equations (3) and (4) also apply to changing currents (accelerated moving charges), then when periodic alternating current flows in the wire, such as sinusoidal current, the magnetic field lines will vibrate like a longitudinal wave medium in the direction perpendicular to the current, forming the magnetic field line wave component of electromagnetic waves and propagating outward at the speed of light. However, due to the non-open circuit structure, the propagation distance of magnetic field line waves from such circuits is very limited.

When a plate capacitor charges and discharges, the changing charging/discharging current not only generates vibrating magnetic field line waves around the charging/discharging wires but also produces vibrating magnetic field line waves in the peripheral space between the capacitor plates where the electric field changes (Maxwell's displacement current). Additionally, the establishment and variation process of electric field lines (electric field) between the capacitor plates is similar to that of magnetic field lines. During charging, as the charge on the plates gradually increases, the density of electric field lines between the plates gradually increases. During discharging, as the charge on the plates gradually decreases, the density of electric field lines between the plates gradually becomes thinner. The arrow direction of electric field lines points from the plate with positive charge accumulation to the plate with negative charge accumulation. The same applies when charging/discharging in reverse. If the excitation source for charging/discharging is periodic AC power, the electric field lines between the plates will also vibrate. When the structure and shape of the capacitor plates are appropriate, the vibrating electric field lines will propagate into space at the speed of light, forming the electric field line wave component of electromagnetic waves. This means that changing electric fields (displacement current) generate both magnetic field line waves and electric field line waves. If the wires connecting the plates are moved to one side of the capacitor as shown in Figure 3, and the inner sides of the plates are expanded as much as possible toward space, the electromagnetic waves composed of electric field line waves and magnetic field line waves will propagate into space more easily.

Figure 3: Expanding plate capacitor to facilitate emission of electric field line waves into space

The electromagnetic waves based on the Extended Lorentz Force differ from Maxwell's electromagnetic waves in that: 1) Changing currents excite magnetic field lines; changing electric fields (displacement current) excite both electric field lines and magnetic field lines. Electric field lines and magnetic field lines vibrate individually, both propagating at the speed of light to constitute electromagnetic waves. The vibration and propagation of these two types of field lines are determined by the inherent properties of the medium constituting these field lines and the accelerated moving charges, similar to the vibration propagation of sound waves in air, and do not require alternating excitation between magnetic and electric fields. 2) Magnetic field line waves and electric field line waves are perpendicular to each other, and their vibration directions and wave propagation directions are perpendicular to the vibration direction of the source charge. From the perspective of the vibration direction of the two types of field lines and the wave propagation direction, electromagnetic waves should belong to longitudinal waves, but from the perspective of the wave propagation direction and the vibration direction of the source charge, electromagnetic waves should belong to transverse waves. Strictly according to wave definitions, electromagnetic waves are neither transverse nor longitudinal waves.

3 Explanation of Typical Electromagnetic Interaction Cases Using Extended Lorentz Force

Here we list several typical electromagnetic interaction cases and analyze and explain them using the Extended Lorentz Force perspective. When analyzing with the Extended Lorentz Force perspective, it is necessary to understand both the distribution of magnetic field lines in the experimental magnet's peripheral space and the relative position between the magnetic field lines and the interacting conductor.

3.1 Relative Translation Experiment Between Magnet and Conductive Ring

Figure 4 shows a schematic diagram of the magnet and conductive ring experiment. In the figure, L is a closed rectangular conductive ring with a galvanometer G connected in series. Assuming the magnet volume is relatively large and the rectangular conductive ring area is sufficiently small compared to the magnet pole area, the magnetic field lines in the central region between the two poles can be considered as a uniformly distributed homogeneous magnetic field region. The motion during the experiment is translation, meaning the rectangular conductive ring plane remains perpendicular to the magnetic field lines.

3.1.1 Place the rectangular conductive ring in the central homogeneous magnetic field region of the magnetic pole (for observation convenience, the conductive ring is drawn proportionally larger in Figure 4). In this case, whether the conductive ring is stationary and the magnet moves, or the magnet is stationary and the conductive ring moves, no current flows in the conductive ring. Explanation: In both cases, there is relative motion between the conductive ring and magnetic field lines, and the conductive ring cuts magnetic field lines. However, the cut magnetic field lines are divided into two types: one type enters the conductive ring interior after being cut by some part of the wire, and the other type leaves the conductive ring interior after being cut by another part of the wire. Because the number of these two types of magnetic field lines cut per unit time is equal, the induced electromotive forces in the closed conductive ring loop are equal in magnitude and opposite in direction, completely canceling each other out. Alternatively, the net number of magnetic field lines cut by the conductive ring per unit time is zero, so the induced electromotive force in the conductive ring is zero and no current is generated.

3.1.2 Place the conductive ring near the magnet edge where the magnetic field distribution is non-uniform. In this case, whether the magnet is stationary and the conductive ring moves away from or toward the magnet, or the conductive ring is stationary and the magnet moves away from or toward the conductive ring, current will be generated in the conductive ring. Figure 4: Electromagnetic induction due to the relative motion between a magnet and a rectangular wire-frame

Explanation: In both cases, there is relative motion between the conductive ring and magnetic field lines, and the conductive ring cuts magnetic field lines. Due to the non-uniform distribution of magnetic field lines, the number of magnetic field lines entering the ring interior from outside after being cut per unit time is not equal to the number leaving the ring interior after being cut per unit time.

In other words, the net number of magnetic field lines cut by the conductive ring per unit time is not zero, so the induced electromotive force in the conductive ring is not zero, and therefore current is generated.

3.2 Transformer

Figure 5 shows a schematic diagram of transformer structure, where M represents the iron core and L_1, L_2 denote the primary and secondary windings. As is well known, when a sinusoidal AC voltage u_1 is applied to the primary winding L_1 and a sinusoidal current i_1 flows through it, a sinusoidal AC voltage u_2 of the same frequency is induced in the secondary winding L_2. Based on equations (3), (4) and the previous analysis, because current i_1 flows through it, each turn of coil L_1 establishes magnetic field lines surrounding itself. The direction of these magnetic field lines changes with the current direction in the wire, and their density varies with current magnitude, expanding and contracting in a direction perpendicular to the wire. The vibrating magnetic field lines enter the iron core enclosed by L_1, interact with the circular currents in the core, and excite additional magnetic field lines. Since magnetic field lines form closed loops and the iron core has low magnetic reluctance with magnetic flux-concentrating properties, as long as the transformer core dimensions are appropriate and the core is not saturated, the expansion and contraction vibrations of magnetic field lines excited by the primary winding and core will be confined within the range determined by the core columns. These expanding and contracting vibrations of magnetic field lines will cut across the wires of other coils wound on the core columns.

Figure 5: The structure of a transformer

The cutting interaction between magnetic field lines and primary winding L_1 wires generates self-induced electromotive force in L_1. The cutting interaction with secondary winding L_2 wires generates mutual inductance electromotive force in L_2, achieving voltage transformation and energy conversion. The vibration propagation of magnetic field lines in the transformer is shown in Figure 6, where thin solid lines represent vibrating magnetic field lines.

Figure 6: The vibration and propagation of magnetic field lines of a transformer

3.3 Betatron

Remove the secondary winding from the transformer shown in Figure 5, change the iron core cross-section to circular, open a moderate air gap in the middle of the iron core column where L_1 winding is located, and divide the L_1 winding into two equal parts wound on the iron core columns above and below the air gap. This device becomes an AC electromagnet. When coil L_1 is powered by sinusoidal AC current, based on the previous analysis, the magnetic field lines in the air gap generated by coil L_1 and the circular currents in the iron core will expand and contract vibrate between the outer edge and central part of the iron core with changes in the current in L_1. This radial vibration of magnetic field lines can accelerate electrons entering the air gap. However, the moment when electrons enter the circular orbit in the air gap must be synchronized with the sinusoidal current in coil L_1. The time period during which electrons are accelerated must be a specific interval in each cycle of the sinusoidal current, during which the direction of magnetic field lines and their motion direction should be determined—for example, whether the magnetic field lines point upward or downward, and whether their motion direction is inward or outward. Electrons entering the air gap for acceleration simultaneously experience two forces: one is the Lorentz force from the charge moving in the magnetic field; the other is the accelerating force obtained by electrons due to the motion of magnetic field lines. The directions of these two forces are perpendicular to each other. (If this paper is fortunate enough to be read by friends engaged in betatron design and manufacturing, I hope they can help the author verify the above analysis through an experiment: move the excitation coil of the electromagnet in the betatron from the original air gap column to another column, change the injection position of moving electrons into the air gap, and observe whether the modification affects electron acceleration.)

3.4.1 Two Straight Wires with Steady DC Current at Close Distance

The magnetic field distributed around a wire carrying steady current is composed of stationary magnetic field lines (here we temporarily ignore the transient process of establishing steady current in the wire and the stationary magnetic field lines around it). Two current-carrying wires experience forces in the magnetic field established by each other. According to the left-hand rule, wires with current in the same direction attract each other, while wires with current in opposite directions repel each other.

3.4.2 Two Straight Wires with AC Sinusoidal Current at Close Distance

The magnetic field lines surrounding wires carrying AC sinusoidal current are not stationary; the magnetic field lines vibrate and propagate around the wire, and their density and direction change with the current in the wire. Moving charges in the wire simultaneously experience two forces: one is the Lorentz force generated by charges moving in the magnetic field, which is the attractive or repulsive force between the two wires; the other is the force generated by cutting between the wire and moving magnetic field lines, which acts along the wire direction and results in induced electromotive force in the wire—this is the induced electromotive force of a transformer. Whether the force is attractive or repulsive, and whether the induced electromotive force reduces or enhances the original voltage in the wire, depends on whether the currents in the two wires are in phase or out of phase. The transient process that must be experienced when establishing steady current in the two wires mentioned above is similar to the case of AC current in the two wires here.

3.5 Interaction Force Between Two Charges Observed from Different Reference Frames

This is another example of whether electromagnetic induction phenomena are symmetric when observed from different reference frames. Suppose there are two positive charges q_1 and q_2 on a train moving at constant speed, separated by distance r and stationary relative to the train. For an observer on the train, the interaction force between these two charges is only the repulsive Coulomb static electric force. But what does an observer outside the train, stationary relative to the tracks, see? The traditional view holds that the two moving charges generate a magnetic field, so in addition to the Coulomb static electric force, there is also electromagnetic interaction force between the charges. The magnitude of the electromagnetic force is proportional to the train's running speed relative to the tracks. To reconcile the so-called different observation results of the two observers in different reference frames, people need to use relativistic effects for balancing treatment or explanation. According to the Extended Lorentz Force viewpoint, an observer in the stationary track reference frame can indeed measure a magnetic field generated by charges moving with the train through measuring instruments, but this is caused by relative motion between charges in the measuring instrument and charges on the moving train, and cannot be taken as evidence that the two charges on the train truly generate a magnetic field and electromagnetic interaction force. The Extended Lorentz Force viewpoint holds that only charge motion caused by electric or magnetic field forces can generate magnetic field lines or magnetic fields, while charge motion caused by other means cannot generate magnetic field lines or magnetic fields. This viewpoint can avoid asymmetry phenomena in electromagnetic interaction observations from different reference frames. This can actually be verified using this example. Imagine placing a sensitive indicating magnetic needle near the charges on the moving train; an observer on the train would certainly observe no deflection of the indicating magnetic needle. Could an observer in the track reference frame observe deflection of the indicating magnetic needle? Therefore, the nature of electromagnetic interaction forces does not change with the choice of different observation reference frames.

Some of the above examples are commonly used in textbooks to prove Faraday's law of electromagnetic induction. Some examples cannot be satisfactorily explained using Faraday's induction law alone and require the Lorentz force to provide reasonable explanations. There are also many examples that cannot be reasonably explained even by combining Faraday's law of electromagnetic induction with other viewpoints, such as unipolar induction, the Trouton-Noble experiment, the quadrupole cylindrical magnet induction experiment for verifying unipolar induction, and the dipole spherical magnet induction experiment. These experimental cases can also be easily explained naturally and reasonably using the Extended Lorentz Force viewpoint without assistance from other viewpoints. Additionally, the concepts of field and field lines were proposed by Faraday. The Extended Lorentz Force shows that electromagnetic force is a force generated by relative motion between magnetic field lines and charges, and is an interaction force between physical entities. The above experiments and example analyses also demonstrate that compared to the concept of field, the concept of field lines seems to describe the world more simply and closer to reality.

4 On Faraday's Law of Electromagnetic Induction and Maxwell's Electromagnetic Waves

If we accept the viewpoint that a magnet's magnetic field lines move with the magnet, observing and thinking about electromagnetic induction cases of magnets reveals that the moment when electromotive force is induced in a conductor does not necessarily accompany changes in magnetic flux, but must accompany relative cutting motion between some part of the conductor or wire segment and the perpendicular component of magnetic field lines. In the dipole induction and quadrupole induction experiments conducted to verify unipolar induction, cases completely inconsistent with Faraday's law appear: the amplitude (absolute value) of sinusoidal induced electromotive force in a closed circuit increases as the magnetic flux change per unit time decreases, and decreases as it increases. This experimental result can be easily explained by the Extended Lorentz Force. In fact, using the Extended Lorentz Force can almost naturally and reasonably explain all electromagnetic induction and electromagnetic interaction problems the author has encountered so far. In comparison, Faraday's law of electromagnetic induction is much inferior. This raises a series of questions: Is the Extended Lorentz Force closer to the essence of electromagnetic interaction than Faraday's law of electromagnetic induction? Could Maxwell's equations be not so perfect and also have flaws? How do we explain the fact that Faraday's law of electromagnetic induction has been very practical and played a huge role in human social development and progress? How was Maxwell able to accurately predict electromagnetic waves and their propagation speed, as well as that light is electromagnetic waves, based on two circulation law equations? How do we explain the great success achieved by these two great scientists?

First, we must affirm that Faraday's law of electromagnetic induction is already very close to the essence of electromagnetic induction, which is why it is highly practical. Based on Faraday's law of electromagnetic induction, people have designed and manufactured numerous power generation, electric motor, and various practical electrical devices, bringing tangible benefits to humanity. This is because Faraday's law of electromagnetic induction and the equations of the Extended Lorentz Force are basically interchangeable and convertible when solving practical problems, yielding the same calculation results. From a practical standpoint, the effects of the two laws in solving practical problems are consistent, and in some cases, calculations using Faraday's induction law are even more convenient. From a purely practical perspective, there is no difference between what Faraday's law of electromagnetic induction and the Extended Lorentz Force can provide people, which may be the main reason for the success of Faraday's law of electromagnetic induction.

The key to Maxwell's accurate prediction of electromagnetic waves back then was his correction and extension of two laws. First, because Ampere's magnetic field circulation law encountered contradictions when applied to plate capacitor charging/discharging circuits, Maxwell boldly and creatively introduced displacement current I_d (changing electric field) to obtain the corrected Ampere-Maxwell magnetic field circulation law. The original magnetic field circulation law changes from equation (4) to:

$$2\pi rB = 2\pi k\left(I + \frac{\Delta\Phi_E}{\Delta t}\right) \quad (5)$$

where K is the Coulomb's law constant determined through actual measurement, I is conduction current, and $\frac{\Delta\Phi_E}{\Delta t}$ is displacement current I_d, which is also the changing electric field between the capacitor plates during charging/discharging. Second, Faraday's law of electromagnetic induction states that the magnitude of induced electromotive force e in a closed loop is proportional to the rate of change of magnetic flux passing through the closed loop, expressed as:

$$e = -\frac{\Delta\Phi_B}{\Delta t}$$

where $\frac{\Delta\Phi_B}{\Delta t}$ is the rate of magnetic flux change. Regarding Faraday's law of electromagnetic induction, Maxwell extended it to believe that a vortex electric field E exists in the space around a changing magnetic field, and that electromagnetic induction law should hold regardless of whether an actual circuit exists, and that the vortex electric field E always exists. Assuming the volume range of magnetic flux change in vacuum is axisymmetric with the central line as the axis, if this volume is cut open along the direction perpendicular to the axis, the outer edge of the cross-section is a circle. Then the induced electromotive force e caused by magnetic flux change can also be expressed using the vortex electric field E. Because the distance around the magnetic flux change volume is $2\pi r$, $e = 2\pi rE$. Therefore, through extension of Faraday's law of electromagnetic induction, Maxwell obtained the Faraday-Maxwell electric field circulation law, expressed as:

$$2\pi rE = -\frac{\Delta\Phi_B}{\Delta t}$$

Considering the general case, the path encircling conduction current, displacement current, or magnetic flux change volume should not be limited to circular shapes but can be any shape. For plate capacitor charging/discharging circuits where conduction current I is zero, the two circulation law expressions can be rewritten as【5】:

$$\sum B_{\parallel} l = \frac{1}{c^2}\frac{\Delta \Phi_E}{\Delta t} \quad (8)$$

$$\sum E_{\parallel} l = -\frac{\Delta \Phi_B}{\Delta t} \quad (9)$$

where $B_{\parallel} l$ and $E_{\parallel} l$ represent the magnetic and electric field circulation components of line element l respectively; $\sum$ denotes summation over the entire loop; c is a constant with velocity dimensions, determined by actual measurements. The establishment of equations (8) and (9) means electromagnetic waves are about to emerge. Equation (8) shows that a time-varying electric field in peripheral space excites a vortex magnetic field; equation (9) shows that a time-varying magnetic field in peripheral space excites a vortex electric field. Because the vortex magnetic or electric field generated in peripheral space is created from nothing, it must also be a time-varying field. Therefore, the excited vortex magnetic field in peripheral space will further excite a vortex electric field, and the excited vortex electric field in peripheral space will further excite a vortex magnetic field, inevitably resulting in alternating excitation of magnetic and electric fields that expands and propagates into peripheral space. Thus Maxwell predicted the existence of electromagnetic waves. Note that the two circulation law equations (8) and (9) have only one dimensional constant c, whose unit is velocity, determined by actual measurements, and its value happens to be the same as the known speed of light at that time. Therefore, Maxwell concluded that the propagation speed of electromagnetic waves is the speed of light c, and further predicted that "light (including heat radiation and other forms of radiation, if any) is itself an electromagnetic disturbance in the form of waves…". Today, deriving Maxwell's predictions from equations (8) and (9) seems very natural and not complicated because we already know the results. However, in that era, being able to correct Ampere's magnetic field circulation law, extend Faraday's law of electromagnetic induction, obtain equations (8) and (9), and make a series of great predictions based on these two equations required extraordinary intelligence.

However, from today's perspective, since Faraday's law of electromagnetic induction is not the real cause of electromagnetic induction and its expression should be considered an equivalent operational formula for the Extended Lorentz Force, Maxwell's extended equation (9) can hardly be perfect. The magnet-coil electromagnetic induction experiments described earlier also demonstrate this. The author has two questions here: 1) According to equations (8) and (9), a periodically vibrating magnet in space should also be an electromagnetic wave source even without other conductors present. However, such an electromagnetic wave source has not been proven to exist to date. According to the unipolar induction verification conclusion or the Extended Lorentz Force viewpoint, magnet motion can carry magnetic field lines (magnetic field) with it, but this is not equivalent to charge motion that can generate magnetic fields or electromagnetic waves under magnetic or electric field action. 2) Maxwell's electromagnetic waves propagate through alternating excitation of changing electric fields and changing magnetic fields. This means that any point within the electromagnetic wave coverage range can be considered an electromagnetic wave source, and each point emits electromagnetic waves into surrounding space. This also implies that within the electromagnetic wave coverage range, electromagnetic wave receivers should have no shadow as long as they are not completely shielded. In reality, shielding materials or corresponding substances can easily create shadows for electromagnetic waves and light. However, the electromagnetic waves based on the Extended Lorentz Force viewpoint do not require alternating excitation of electric and magnetic fields for propagation. The propagation of electromagnetic waves is similar to the sparse-dense vibration propagation of sound waves, and its propagation characteristics are determined by the inherent properties of the electromagnetic wave propagation medium. In the absence of other media, electromagnetic waves propagate linearly and unidirectionally outward from the emission source.

Despite imperfections, Faraday's law of electromagnetic induction and Maxwell's equations have played an extremely huge role in promoting human civilization progress and technological advancement because they are already very close to the essence of electromagnetic interaction. Undoubtedly, no amount of praise for these two great scientists would be excessive.

5 Conclusion

The author has written three articles on verification experiments for the unipolar induction problem. Originally, I thought that as long as someone recognized the verification conclusions introduced in the articles, they would subsequently ask what these conclusions mean, think deeply, and inevitably feel, like the author, that Faraday's law of electromagnetic induction might have deficiencies and develop the same ideas as the author, thus making this article unnecessary for the author to write. However, after the three articles were published, no feedback was received. Perhaps everyone is not interested in the remaining unipolar induction problem, or perhaps they think that in this day and age, using a rotating magnet to study electromagnetic fields is not worth considering. But the author does not think so. As is well known, although Maxwell's equations have been around for more than a hundred years, they are not outdated and are still being decorated magnificently. Let us not forget the basic conditions on which the equations were established at that time. Although Maxwell was a person of extraordinary intelligence, his equations and theories were not created out of thin air. Maxwell's equations first summarized and generalized the achievements of predecessors, and secondly, incorporated his own great ideas through extending and correcting the theoretical achievements of predecessors, resulting in two circulation law equations that led to Maxwell's great predictions. Undoubtedly, every equation supporting Maxwell's equations was based on the experimental foundation of predecessors. Today, in terms of experimental conditions for similar unipolar induction experiments, although our ordinary people's basic knowledge of electromagnetic theory and experimental conditions cannot compare with professional experts in the electromagnetic field, we are certainly stronger than our predecessors like Faraday. Therefore, as long as we are willing, everyone, like the author, is qualified and has the conditions to study and verify the problems studied by Faraday and Weber back then, including the unipolar induction problem they left behind to this day. In fact, these verification experiments are very convenient to implement, low in cost, and easy to reproduce observation results. Regarding what conclusions should be drawn from the verification experimental observations, as long as everyone is willing, they can participate in the discussion, present their own viewpoints, and more easily reach correct conclusions.

Since this paper involves three famous scientific giants, the author feels very uneasy. The reason for the involvement is that all three giants' theories are related to Faraday's law of electromagnetic induction. The conclusion drawn from the author's verification experiments on the unipolar induction problem is that a magnet will drive magnetic field lines with it. This conclusion not only negates Faraday's viewpoint on the unipolar induction problem but also indirectly demonstrates the imperfection of Faraday's law of electromagnetic induction. Maxwell firmly believed in Faraday's law of electromagnetic induction and extended it into an electric field circulation law. Einstein must have firmly believed in the Faraday-Maxwell electric field circulation law, and this law must have had a significant influence on the formation of his special relativity thought, which can be confirmed from his famous paper that solemnly proposed that imagined electromagnetic induction experiment at the beginning. It is unimaginable that three famous scientific giants would make errors on the same electromagnetic induction problem. There must be errors on the author's part. However, due to the author's limited knowledge, perhaps having gotten into a dead end without realizing it. I hope this paper can be fortunate enough to meet enthusiastic people who can repeat the author's verification experiments, help the author point out errors, and provide criticism. The author would be extremely grateful.

References

[1] Albert Einstein. On the Electrodynamics of Moving Bodies. Compiled by Fan Dainian, Zhao Zhongli, and Xu Liangying.

[2] Zhang Xueliang. Explaining the Unipolar Induction Problem Through a Two-Pole Spherical Magnet Experiment. ChinaXiv:2023.00166v2, 2023.9.15.

[3] Zhang Xueliang. Quadrupole Rotor Magnet Induction Experiment and Unipolar Induction Problem. ChinaXiv:202303.00166v1, 2023.3.16.

[4] Zhang Xueliang. Multi-Pole Induction Experiment Based on Unipolar Induction Problem. ChinaXiv:2019.00050, 2019.5.8.

[5] (USA) U. Haber-Schaim et al. Physics Volume 3 [M]. Beijing: Science Press,

1978.09.

[6] Liang Baohong. General Physics Volume 2, Part 2 [M]. Beijing: People's Education Press, 1979.

(Corresponding author: Zhang Xueliang E-mail: dqxzxl@163.com)

Author Contribution Statement:

- Zhang Xueliang: Proposed research ideas, designed research plans; data acquisition, provision, and analysis; conducted experiments; drafted the paper; revised the final version of the paper.

Note: Figure translations are in progress. See original paper for figures.