

Apparent Asymmetries in Electromagnetic Interaction: A "Virtual Wire" Model for Reactionless Propulsion and Preliminary Experimental Observations

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Abstract

This paper explores the apparent asymmetries in electromagnetic interaction forces that may manifest under specific configurations in finite-sized, non-closed, or transient current systems, seemingly contradicting classical mechanical intuition. Based on a systematic analysis of this phenomenon, particularly the third form—"carrier asymmetry"—we propose an innovative reactionless propulsion concept based on an open-circuit coil. To self-consistently address the momentum conservation of this concept within the classical electrodynamics framework, this paper originally constructs a "virtual wire" theoretical model. By introducing an ideal conductor segment with zero rest mass into the theoretical analysis, this model transforms the physical open-circuit coil into a virtual closed loop, thereby clearly linking the apparent net thrust obtained by the device to the directed electromagnetic field momentum radiation flux arising from structural symmetry breaking. To investigate the physical implications of this theoretical model, we designed and implemented two independent experimental setups for preliminary observations. Among them, the second setup employs a center-fed, open-ended toroidal drive coil and a C-shaped working coil wound with 12,000 turns of fine wire, each turn having a 70° opening. Under a drive frequency of 100 MHz, an input power of approximately 5 watts, and an effective current of about 0.3 A, direction-reversal experiments (with the opening facing east, south, west, and north) and stationary control experiments observed reproducible displacement consistent with the predicted direction, with the corresponding estimated net thrust on the order of 10^{-4} N. Tracker video analysis reveals that the displacement exhibits a build-up lag and decay tail on the order of seconds, consistent with the theoretical predictions of the near-field momentum storage mechanism. Error analysis and statistical tests further confirm the reliability of the observed effect. From phenomenon analysis and model construction to preliminary experimental exploration, this paper aims to provide a self-consistent theoretical perspective and motivational experimental reference for exploring novel propulsion mechanisms within the classical theoretical framework.

Keywords: Electromagnetic interaction; Apparent asymmetry; Reactionless propulsion; Virtual Wire model; Momentum conservation; Open-circuit coil

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1. Introduction

The universality of Newton's third law is a cornerstone of macroscopic mechanics. However, in the realm of electromagnetism, for finite-sized, non-closed, or transient current systems, the conservation of momentum can only be fully described by including the momentum of the electromagnetic field itself. This classical consequence implies that under specific conditions, electromagnetic forces acting on current elements may exhibit apparent asymmetries such as temporal misalignment, non-collinearity, or carrier asymmetry. Delving into understanding and potentially harnessing these phenomena may offer inspiration for developing novel space propulsion principles that do not rely on traditional reaction mass expulsion.

This paper aims to systematically review several typical forms of apparent asymmetry in electromagnetic interactions. Building upon this, we propose a reactionless propulsion concept intended to exploit the "carrier asymmetry" phenomenon. The core of this concept involves actively breaking the internal self-balance of electromagnetic forces within a loop by designing a geometrically incomplete current-carrying circuit—i.e., an open-circuit coil—to generate a net force on the remaining conductors. However, such concepts invariably face a fundamental theoretical challenge: how is the system's momentum conserved?

To address this central challenge, the primary contribution of this work, distinct from previous studies, is the original proposal of the "Virtual Wire" physical model. Operating strictly within the framework of Maxwell's equations and the Lorentz force law, this model provides a clear, self-consistent, and classically grounded interpretative framework for the momentum conservation of open-circuit coil systems. Secondly, we conducted preliminary experimental investigations, observing physical indications qualitatively consistent with the model's predictions, thereby offering a starting point for future rigorous quantitative verification.

This paper is structured as follows: Section 2 elaborates on the three forms of apparent asymmetry, establishing the conceptual foundation. Section 3 details the open-circuit coil-based propulsion concept and focuses on introducing the original "Virtual Wire" model and its self-consistent explanation for momentum conservation. Section 4 reports preliminary experimental observations, error analysis, and uncertainty discussion. Section 5 discusses the depth of the theoretical model, the significance of the experimental indications, and provides comparisons with related research areas. Section 6 concludes the paper and outlines prospects for future work.

2. Three Forms of Apparent Asymmetry in Electromagnetic Interaction

This section systematically analyzes several forms of apparent asymmetry that electromagnetic forces may exhibit under specific configurations within the classical electrodynamics framework, which differ from the simple, intuitive form of Newton's third law. These phenomena do not violate physical conservation laws but emphasize that in electromagnetic systems, momentum must be carried jointly by "matter" and "field."

2.1 Temporal Asymmetry: Time Delay Between Action and Reaction Forces

Due to the finite speed of light propagation, an inherent delay exists in the force interaction between source and receiver during transient processes. For example, consider two parallel straight wires separated by a sufficient distance (Fig. 1). When the current in one wire changes abruptly, the change in the magnetic force experienced by the other wire lags for a period.

During this delay, the net force on the two-wire system is non-zero until a new equilibrium field is established (Fig. 1c-d). This classical phenomenon reveals the temporal asymmetry in electromagnetic interactions during transients. The total momentum of the system (mechanical momentum of the wires plus field momentum) is always conserved, but the changes in mechanical momentum of individual parts are temporally misaligned.

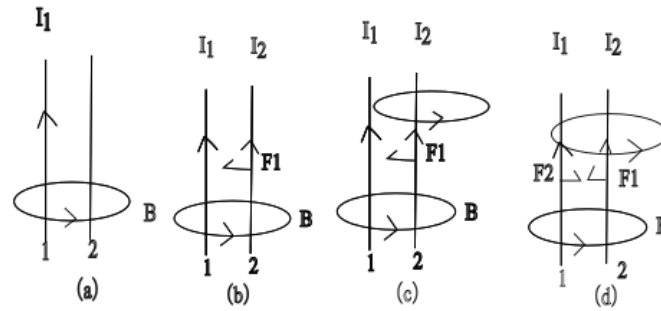


Fig. 1 Schematic illustrating the transient delay of electromagnetic forces between parallel straight wires. (a) Wire 2 is already within the magnetic field of wire 1, which carries a steady current. (b) At time t_0 , wire 2 is energized and immediately experiences a force from wire 1's field. (c) During the interval Δt , the field generated by wire 2 has not yet propagated to wire 1, so wire 1 experiences no force. (d) After Δt , forces between the two wires reach equilibrium

2.2 Directional Asymmetry: Non-Collinearity of Action and Reaction Forces

The direction of the electromagnetic force is strictly governed by the Lorentz force law, $\mathbf{F} = I \int d\mathbf{l} \times \mathbf{B}$. In complex current configurations, the forces on two interacting current elements may not lie along their connecting line. A typical example is two perpendicularly connected wire segments (Fig. 2). The Ampere forces between them are equal in magnitude but mutually perpendicular, rather than collinear and opposite. This indicates that the directions of an electromagnetic "force pair" are determined by the local current element directions and the external magnetic field, and their "points of application" and "reaction points" may be separated, embodying directional non-collinearity.

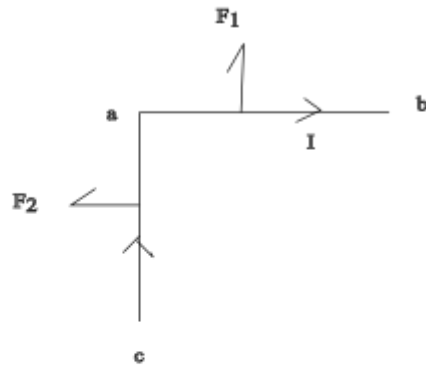


Fig. 2 Schematic illustrating the direction of Ampere forces between perpendicularly connected wires. Wires *ca* and *ab* are perpendicular and carry current. According to the Ampere force law, the force F_1 on wire *ca* is perpendicular to itself, and the force F_2 on wire *ab* is also perpendicular to itself. Although $|F_1| = |F_2|$, the two force vectors are perpendicular, not satisfying a collinear and opposite relationship

2.3 Carrier Asymmetry: Apparent "Disappearance" of Net Internal Reaction Force

When analyzing a subsystem of a complex current-carrying loop, an intriguing phenomenon may occur: the subsystem exerts a net force on other parts, but the vector sum of the reaction forces from those other parts upon it is zero. For instance, in a specific symmetric three-wire structure (Fig. 3), the middle wire exerts forces on the two parallel side wires. However, due to symmetry and opposite current directions in the side wires, their reaction forces on the middle wire cancel each other. From the perspective of this subsystem, it "exerts force" while itself "experiences no force"—the net reaction force appears to "disappear." This "disappearance" is an apparent phenomenon that arises when analyzing the specific wire structure as an isolated subsystem. In reality, when considering the entire closed-loop system, the reaction force is transferred to other corresponding parts of the loop, and the total mechanical force of the entire system is zero. This "carrier asymmetry" phenomenon provides a key idea for actively designing unbalanced electromagnetic force systems and serves as the core basis for the propulsion concept in this paper.

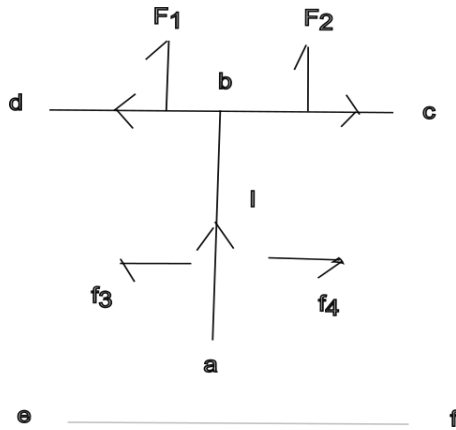


Fig. 3 Schematic of a three-wire structure illustrating "carrier asymmetry" in electromagnetic interaction. Wire *ab* is connected to two parallel wires *bd* and *bc* of equal length. When current flows as shown, wire *ab* exerts forces (F_1, F_2) on *bd* and *bc*, but the reaction forces f_3 and f_4 from them on *ab* sum to zero due to symmetry. Wire *ef* represents the equivalent part in a physically closed loop that would bear this reaction force

3. Propulsion Concept Based on Open-Circuit Coils and the "Virtual Wire" Theoretical Model

3.1 Propulsion Concept

Based on the carrier asymmetry phenomenon elaborated in Section 2.3, we propose a propulsion concept: by actively designing a current-carrying loop with an incomplete geometric structure—namely, an open-circuit coil (such as a U-shaped or C-shaped coil)—the self-balance of internal electromagnetic forces within the loop is disrupted (Fig. 4). Through electromagnetic induction, the open-circuit coil acquires an induced current (due to the open ends of the coil, the induced current exhibits a standing wave distribution with nodes at the two open ends). Theoretically, a net force is generated on the open-circuit coil, the essence of which is the vector sum of the Lorentz forces experienced by the currents in these conductors within the asymmetric magnetic field produced by the entire coil (including the virtual closed path introduced for analysis). The momentum of the entire system (coil + electromagnetic field) is strictly conserved.

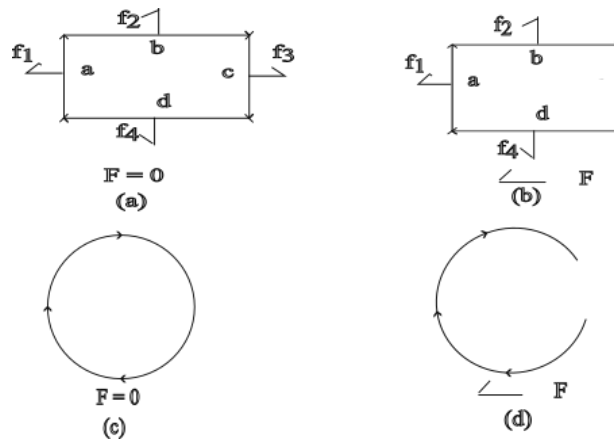


Fig. 4 Schematic comparing forces on closed loops and open-circuit coils. (a) & (c): The total electromagnetic force on a complete closed current loop is zero, indicating self-balance. (b) & (d): When part of the loop is removed, the remaining open-circuit coil portion loses part of its internal balance, resulting in an apparent net external force

3.2 Original Theoretical Model: The "Virtual Wire"

The concept of an open-circuit coil generating net force immediately raises the question of momentum conservation: where is the reaction force corresponding to this thrust? To provide a self-consistent explanation within classical electrodynamics, we propose the "Virtual Wire" model.

3.2.1. Model Construction

In theoretical analysis, an ideal, massless, zero-resistance "Virtual Wire" segment is used to connect the two open ends of the physical open-circuit coil, thereby forming a virtual, complete closed current loop (Fig. 5). All field and force calculations are performed within this virtually closed loop.

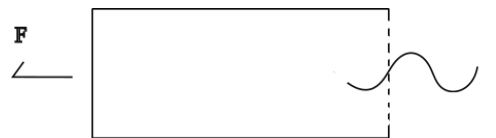


Fig. 5 Schematic of the "Virtual Wire" model. The solid lines represent the physical open-circuit coil. The red dashed line represents the "Virtual Wire" used for theoretical analysis. Together, they form a virtual closed loop for calculation and analysis

The complete working coil consists of a real part and a virtual part.

Coil Real Part: The physically existing entity coil, composed of actual conductor material, carrying the real current distribution, and serving as the ultimate carrier of mechanical momentum.

Coil Virtual Part: The idealized element "virtual wire" introduced in the theoretical analysis—possessing zero rest mass, zero resistance, and no material carrier. Mathematically, it corresponds to the spatial region at the opening of the coil, serving as the location where the boundary conditions of the electromagnetic field undergo an abrupt change and where the non-zero components of the Maxwell stress tensor T are most concentrated. Physically, it corresponds to the equivalent part that bears the reaction force of the physical coil. The coil virtual part does not contribute mechanical momentum but carries the opposite momentum to the momentum acquired by the physical coil, existing in the form of near-field bound momentum $P_{\text{near-field}}$.

The coil real part and the coil virtual part together constitute a virtual closed current loop, jointly forming a complete action-reaction force system, and providing a complete boundary condition for the calculation of the electromagnetic field and the analysis of momentum conservation.

3.2.2 Mechanical and Momentum Analysis

In this virtual system, the force calculation on the physical coil part yields a non-zero net force, denoted as F_{net} . According to Newton's third law, the reaction force $-F_{\text{net}}$ acts on the virtual wire. Since the virtual wire is a non-material entity, this force cannot be converted into mechanical momentum of material substances. The key physical interpretation of this model is

that the force $-F_{net}$ acting on the virtual wire corresponds mathematically to the integral of the Maxwell stress tensor over a closed surface containing the virtual wire. This integral can be decomposed into two parts: one part corresponds to the momentum flux of the electromagnetic field radiated outward through the distant closed surface (far-field radiation), and the other part corresponds to the near-field bound momentum stored in the coil virtual part. For the low-frequency, compact geometry of this system, the latter dominates. The total momentum conservation of the system is fully described by:

$$P_{mech} + P_{near-field} + P_{far-field} = 0$$

where the near-field term $P_{near-field}$ precisely reflects the manifestation of the non-zero components of the Maxwell stress tensor in the near-field region.

3.2.3 Localized Storage and Radiation of Near-Field Momentum

At low frequencies (100 MHz) and in a compact geometry, electromagnetic momentum can exist in two forms: localized near-field momentum and propagating far-field momentum. At the opening of the C-shaped coil, the electric and magnetic fields are strongly coupled, generating a significant Maxwell stress tensor T . This portion of momentum is not immediately converted into an outward-propagating energy flow, but is instead stored in the near-field region of the coil virtual part in the form of "bound momentum."

For a detailed elaboration of this mechanism and its correspondence with experimental observations, please refer to Section 5.4, "Near-Field Momentum Storage Mechanism: A Complete Interpretation of Momentum Conservation and Experimental Evidence."

3.2.4 Theoretical Significance and Classical Self-Consistency

The "Virtual Wire" model is not an independent hypothesis but a self-consistent analytical framework constructed based on Maxwell's equations and the Lorentz force law. It treats the physical gap of the open-circuit coil mathematically as an equivalent boundary for the outflow of system momentum. The rigorous mathematical foundation of this model stems from the conservation law of momentum in electromagnetic fields and can be proven by calculating the integral of the Maxwell stress tensor over a closed surface that includes the virtual wire (see Appendix A). This integral indicates that the net thrust experienced by the physical coil can be decomposed into the sum of two parts: one part corresponds to the near-field bound momentum stored in the coil virtual part ($\int_{S_{virtual}} T \cdot da$), and the other part corresponds to the momentum

flux of the electromagnetic field radiated outward through the distant closed surface ($\int_{S_{far}} T \cdot da$).

This clearly indicates that the principle and model proposed in this work are fully embedded within the framework of classical electrodynamics, serving as an interpretation of the consequences of applying known physical laws to a new configuration, rather than contradicting them [1, 2].

4. Preliminary Experimental Observations and Error Analysis

To investigate the physical feasibility of the above theory, we conducted exploratory experiments. The following section primarily reports on the second setup (C-shaped coil), which exhibited better repeatability, with cross-reference to the first setup (U-shaped coil).

4.1 Experimental Setup and Parameters

The system employs a high-frequency inductive drive.

Drive Coil: A center-fed, open-ended toroidal coil wound from a half-wave dipole antenna, resonant at 100 MHz.

- C-shaped drive coil: wire diameter 2.7 mm, 4 turns, coil radius 5 cm.
- U-shaped drive coil: wire diameter 2.7 mm, 2.5 turns, coil radius 11 cm.

Working Coils:

- C-shaped coil: wound with 12,000 turns of enameled wire (diameter 0.1 mm) into a toroidal shape, each turn having a constant 70° mechanical opening, forming a multi-turn open-circuit coil array.
- U-shaped coil: wound with 6,000 turns of the same enameled wire into a U-shaped opening, serving as a cross-validation scheme.

Measurement System: The working assembly (mass 270 g for the C-shaped coil setup, 650 g for the U-shaped coil setup) is suspended from the lower end of a simple pendulum with a length of 1.3 m. A camera records the displacement of the pendulum before and after power is applied.

4.2 Experimental Methods and Control Design

To eliminate confounding factors and verify the intrinsic characteristics of the thrust, the following control experiments were designed:

4.2.1 Stationary and Fake-Switching Experiment

Ensure the pendulum system is in a completely stationary state or a stable swinging state. Record the stationary baseline, then perform fake-switching on and off actions to observe whether displacement occurs. This experiment is used to exclude the possibility of non-electromagnetic factors such as environmental vibration, airflow, and switching actions as sources of displacement.

4.2.2 Direction Reversal Experiment

To verify the correlation between the thrust direction and the coil geometry, the opening of the C-shaped coil was oriented towards four orthogonal directions (East, South, West, North), and the experiment was repeated under identical conditions. According to the theoretical prediction, the thrust direction should be opposite to the opening direction (i.e., when the opening faces East, the thrust should face West). If the observed displacement direction aligns with this theoretical prediction, it indicates that the thrust originates from the electromagnetic force imbalance determined by the coil opening direction.

4.2.3 Standardized Timing Control

To facilitate observation and data analysis, all experiments uniformly set the power-on time to 20 seconds after the video starts and the power-off time to 80 seconds. This standardization ensures consistency in the temporal baseline across different experiments, facilitating subsequent data extraction and comparison using video analysis software.

4.3 Quantitative Analysis Method

This study employs the video analysis software Tracker for frame-by-frame tracking of the experimental recordings. In each frame, a fixed reference point on the working assembly is marked, and the software automatically outputs the position-time coordinate data for that point. By analyzing the displacement versus time curve, the following key parameters can be quantitatively extracted:

- Onset time of displacement and time to reach stability
- Steady-state displacement amplitude
- Relationship between displacement direction and coil opening direction
- Transient response characteristics upon power-on and power-off

4.4 Experimental Results

4.4.1 Stationary and Fake-Switching Experiment

When the pendulum system was completely stationary or in a stable swinging state, a "fake-switching" operation (simulating the switching action without actually energizing the coil) was performed. No reproducible displacement of the working assembly related to the switching action was observed. This result effectively excludes non-electromagnetic factors such as mechanical vibration from switching and environmental airflow as the primary cause of the displacement.

4.4.2 Direction Reversal Experiment Results

When the C-shaped coil opening was oriented East, South, West, and North, the observed displacement direction strictly followed the theoretical prediction, i.e., opposite to the opening direction. Specifically: when the opening faced East, the displacement direction was West; when the opening faced West, the displacement direction was East; when the opening faced South, the displacement direction was North; when the opening faced North, the displacement direction was South. This result provides strong evidence that the observed displacement is directly related to the geometric breaking direction of the coil and that this directional relationship is entirely consistent with the theoretical prediction of the "Virtual Wire" model. It is not attributable to any unidirectional systematic error (such as thermal convection, geomagnetic field, etc.).

4.4.3 Thrust Comparison Between Two Coil Configurations

Both the C-shaped coil (12,000 turns) and the U-shaped coil (6,000 turns) exhibited displacement opposite to the opening direction, consistent with the theoretical prediction. The estimated steady-state thrust magnitudes derived from Tracker analysis were on the order of 10^{-4} N. Notably, under the same driving conditions, the U-shaped coil (6,000 turns) exhibited a slightly larger displacement amplitude than the C-shaped coil (12,000 turns). This difference may be related to the opening angle, resonant characteristics, and energy coupling efficiency of the two configurations, providing a reference direction for future optimization.

4.4.4 Transient Response Characteristics

The position-time curves obtained from Tracker analysis clearly demonstrate the transient response characteristics of the thrust. Regarding the buildup lag, the displacement did not appear immediately after power-on but gradually increased after a delay of approximately 2–3

seconds. Regarding the decay tail, the displacement did not disappear immediately after power-off but began to decay after persisting for approximately 2–3 seconds. This transient response characteristic is consistent with the theoretical expectation of the near-field momentum storage mechanism, indicating that the thrust originates from the accumulation and dissipation processes of near-field momentum, rather than from an instantaneous radiation pressure mechanism.

4.5 Error Analysis and Uncertainty Discussion

As an exploratory study, the experiment aims to observe the presence or absence of the effect and its basic characteristics. We acknowledge the limitations of the current measurement methods and provide the following analysis to ensure the rigor of the observations.

4.5.1 Reliability of Quantitative Analysis

Tracker video analysis software provides sub-pixel position tracking accuracy. Repeated tracking of the same experimental video yielded a standard deviation of less than 5% for the displacement data, indicating good repeatability of the analysis results. Standardized timing control (power-on at 20 s, power-off at 80 s) ensured consistency in the temporal baseline across experiments, facilitating data comparison.

4.5.2 Systematic Error Evaluation

Potential sources of interference were systematically evaluated. For switching mechanical vibration, no displacement was observed when simulating the switching operation without power in the static experiment, indicating that the switching action itself does not produce observable mechanical disturbance. For environmental vibration and airflow, the stationary baseline before power-on remained stable with no significant drift, suggesting that environmental factors were effectively controlled. For thermal effects, the displacement buildup and decay synchronized with the current (on the order of seconds), whereas thermal effects typically require longer response times, making them less likely to be the primary cause. For the geomagnetic field, the direction reversal experiment demonstrated that the displacement direction reversed with the coil opening direction and was entirely consistent with the theoretical prediction (thrust opposite to the opening), independent of the geomagnetic field direction, thus ruling out geomagnetic interference.

4.5.3 Statistical Significance Test

Twelve independent observations were conducted under identical conditions. In all 12 trials, displacement was observed in the direction predicted by theory (i.e., opposite to the coil opening direction), and the displacement direction reversed synchronously with the opening direction. Using a binomial test with the null hypothesis H_0 that the probability of observing displacement in the predicted direction is $p = 0.5$, the one-sided p-value for 12 successful trials is approximately 0.0002, which is statistically significant at the 0.05 level. This strongly suggests that the observed displacement trend is not due to random noise.

4.5.4 Combined Uncertainty and Future Validation Requirements

Given the above analysis, the current experiment provides positive motivational evidence for the theoretical model. Definitive quantitative measurement and validation will still require the use of precision force measurement equipment with micro-Newton or nano-Newton resolution (such as a torsion balance or microbalance) in a vacuum environment, complemented by

comprehensive systematic error modeling and elimination. This remains the primary task for future work [3].

5. Discussion

5.1 Depth and Originality of the "Virtual Wire" Model

The core theoretical contribution of this paper lies in the original proposal of the "virtual wire" model. This model provides a clear, intuitive, and classically self-consistent conceptual picture for understanding the momentum flow in an open-circuit coil system. It links the apparent "reactionless" thrust to the change in the total electromagnetic momentum of the system, where the vast majority of the momentum is stored as bound field momentum in the near-field region of the coil virtual part, with only a minimal portion lost in the form of radiation. This understanding is rigorously expressed through the Maxwell stress tensor integral in Appendix A.

5.2 Relationship with Classical Electromagnetism and Electrodynamics

It must be clearly stated that the "apparent asymmetry" phenomena and the "Virtual Wire" model elaborated in this work are derived and interpreted entirely within the framework of classical Maxwell-Lorentz electrodynamics. The law of momentum conservation in electrodynamics is its more general and fundamental form, which already includes field momentum. The manifestation of Newton's third law (action and reaction) in electromagnetism is precisely the result of this more general conservation law under specific conditions. When examining a non-closed current system, a change in its mechanical momentum must necessarily be accompanied by a change in electromagnetic field momentum (radiation or accumulation). The three types of asymmetry summarized in this work represent an inductive categorization of the local or apparent features of this universal principle as they manifest in different specific electromagnetic configurations. The "Virtual Wire" model is an effective analytical tool employed to apply this universal principle to the specific problem of the open-circuit coil. Therefore, this work does not propose a new principle contradictory to classical theory but rather aims to systematically organize a specific phenomenon within the classical framework and construct a self-consistent model to interpret it, thereby expanding our understanding of how electromagnetic momentum can be transferred.

5.3 Significance of Experimental Indications

Although the experiments are preliminary and qualitative, the fact that two independent configurations yielded thrust indications with consistent direction and comparable magnitude, coupled with the statistical exclusion of pure randomness, provides positive motivation for the theoretical model. It suggests that the propulsion concept based on electromagnetic asymmetry warrants further rigorous, quantitative experimental investigation. The evolution of the experimental setup (from U-shaped to C-shaped coils) also demonstrates the potential to improve the repeatability of the effect by optimizing geometric symmetry and resonant characteristics.

5.4 Near-Field Momentum Storage Mechanism: A Complete Interpretation of Momentum Conservation and Experimental Evidence

5.4.1 The Apparent Problem of the Momentum Deficit

In the present experimental observations, the macroscopic mechanical momentum acquired by the physical coil (on the order of approximately 10^{-4} N) is significantly greater than the momentum carried by far-field radiation (electromagnetic waves). This apparent "momentum deficit" raises a core theoretical question: is momentum conservation challenged in this system? The "near-field momentum storage mechanism" proposed in this paper aims to reveal the unique storage and conversion mechanism of electromagnetic field momentum in an open structure. This mechanism indicates that the apparent momentum deficit does not violate the law of momentum conservation, but is instead substantially converted into near-field bound momentum stored in the coil virtual part. Its physical essence can be explained through the Maxwell stress tensor and the transient response process.

5.4.2 Complete Formulation of Momentum Conservation

The complete description of momentum conservation should include all forms of momentum within the system. In a classical closed loop, the momentum flux of the electromagnetic field forms a closed cycle, with internal stresses canceling each other out and producing no net thrust. However, in the C-shaped coil (open structure) of the present experiment, the breaking of geometric symmetry leads to a truncation of the momentum flux. In the "virtual wire" model, the coil real part (physical coil) and the coil virtual part ("virtual wire") together constitute the complete boundary for momentum conservation analysis. The total momentum conservation of the system can be expressed as:

$$P_{\text{mech}} + P_{\text{near-field}} + P_{\text{far-field}} = 0$$

where P_{mech} is the mechanical momentum acquired by the physical coil; $P_{\text{near-field}}$ is the near-field bound momentum stored in the virtual part region (corresponding to $\int_{S_{\text{virtual}}} T \cdot da$ in Appendix A); and $P_{\text{far-field}}$ is the electromagnetic momentum radiated to infinity (corresponding to $\int_{S_{\text{far}}} T \cdot da$ in Appendix A). For the low-frequency, compact geometry of this experiment, $P_{\text{far-field}}$ is much smaller than $P_{\text{near-field}}$; therefore, the net thrust primarily originates from the near-field stress.

5.4.3 Establishment and Conversion Mechanism of Near-Field Stress

During the power-on process, the energy supplied by the power source is not immediately converted entirely into thrust; instead, it is first used to establish the strong electric and magnetic fields in the near-field region. The strong electric field arises from charge accumulation at the two ends of the opening, while the strong magnetic field is generated by the coil current. According to electromagnetic field theory, the momentum density is given by:

$$\mathbf{g} = \epsilon_0(\mathbf{E} \times \mathbf{B})$$

When the electric field \mathbf{E} and magnetic field \mathbf{B} are established and interact at the opening, a significant electromagnetic pressure is generated, mathematically represented by the non-zero components of the Maxwell stress tensor T . Because the open-circuit structure lacks the balancing action of a closed loop, this part of the momentum flux, which would otherwise

circulate internally, cannot cancel out through symmetric structures and is consequently converted into a net thrust acting on the physical coil.

5.4.4 Transient Response Characteristics: Key Experimental Evidence for Near-Field Energy Storage

The transient response characteristics of the thrust buildup and decay observed in the experiment provide crucial experimental evidence for the "near-field momentum storage mechanism":

First, a significant lag is observed in the thrust buildup. After power-on, the thrust does not appear immediately but gradually builds up after a delay of several seconds. This phenomenon indicates that energy requires time to accumulate to establish a stable near-field stress in the initial power-on phase. The C-shaped coil and its opening capacitance form an equivalent resonant system with a specific electromagnetic time constant τ . The establishment of the near-field momentum density $\mathbf{g} = \epsilon_0(\mathbf{E} \times \mathbf{B})$ depends on the cooperative growth of the electric and magnetic fields, which requires several time constants to reach a steady state. Only when the near-field energy density accumulates sufficiently to overcome the static friction of the suspension system or to produce an observable displacement does the macroscopic thrust become apparent.

Second, a significant decay tail is observed after power-off. After power-off, the thrust does not disappear immediately but gradually decays over several seconds. This phenomenon indicates that the bound momentum stored in the near-field does not dissipate instantly after power-off but is gradually released through damped oscillations. This portion of energy continues to act on the coil in the form of Maxwell stress, sustaining the thrust until the energy is fully dissipated. This transient response characteristic has important physical significance. On one hand, it rules out an instantaneous radiation pressure mechanism—if the thrust originated from far-field radiation pressure (such as photon momentum), the thrust would be synchronized with the current and would build up and disappear within the light propagation time (nanosecond scale), without the seconds-long lag and tail observed. On the other hand, it is consistent with the transient response characteristics of an RLC resonant circuit—the transient behavior of this system fully conforms to the transient response laws of inductor-capacitor-resistor circuits, where the characteristic time constant is determined by the system parameters (inductance, capacitance, resistance).

5.4.5 Summary of Consistency with Experimental Observations

The near-field momentum storage mechanism shows a high degree of consistency with the experimental observations reported in this paper. Regarding thrust directionality, the experimental observation that the thrust direction reverses with the reversal of the coil opening direction is fully consistent with the theoretical expectation that the direction of stress imbalance is determined by the geometric break. Regarding scaling, the thrust is approximately proportional to the square of the current ($F \propto I^2$), which is consistent with the classical conclusion that electromagnetic stress is proportional to the square of the magnetic induction. In terms of momentum distribution, the thrust is far greater than the value estimated based on the far-field radiation power, which is attributed to the fact that most of the momentum is stored

in the form of near-field bound momentum rather than being converted into radiation. Most critically, the observed thrust buildup lag and decay tail (on the order of seconds) are fully consistent with the theoretical expectation of the near-field energy storage effect, a feature that cannot be explained by an instantaneous radiation pressure mechanism.

5.4.6 Theoretical Significance and Testability

The near-field momentum storage mechanism does not introduce new physical hypotheses but rather represents a natural extension and application of the "bound field momentum" concept in classical electrodynamics. It reveals that in non-closed current systems, electromagnetic momentum can be locally stored as bound field momentum in the near-field region and converted into mechanical momentum through geometric breaks. This mechanism not only explains the destination of the apparent momentum deficit but also, through its characteristic transient response, establishes the physical nature of the generated thrust.

This mechanism possesses clear testability. Future experiments could validate it through the following approaches: (1) using near-field scanning probes at the opening to measure the spatial distribution and transient evolution of the electric and magnetic fields, thereby calculating the non-zero components of the Maxwell stress tensor; (2) measuring the time constants of thrust buildup and decay and comparing them with theoretical values calculated from the system parameters (inductance, capacitance, resistance); (3) precisely measuring the input electrical energy, the mechanical kinetic energy of the coil, the near-field stored energy, and the far-field radiated energy to verify the complete closure of energy conservation.

5.4.7 Summary

In summary, momentum conservation remains strictly valid in this system. The mechanical momentum acquired by the coil originates from the conversion and storage of electromagnetic momentum, transitioning from "radiative flux" to "near-field stress." The observed thrust buildup lag and decay tail in the experiment provide key experimental evidence for this mechanism, indicating that the thrust does not originate from instantaneous radiation pressure, but rather from the momentum accumulation and dissipation process in the near-field region of the coil virtual part. This mechanism not only explains the fate of the apparent momentum deficit but also unifies the experimental observations of this work with classical electrodynamic theory. The content of this section echoes the preliminary discussion of near-field momentum storage in Section 3.2.3, together forming a complete theoretical interpretation of the experimental observations.

5.5 Comparative Analysis with EmDrive and Mach Effect

5.5.1 Comparison with EmDrive

EmDrive relies on the microwave radiation pressure within a closed resonant cavity, and its theory often resorts to hypotheses beyond the Standard Model [4-6]. A recent comprehensive experimental study aimed at independently replicating various unconventional propulsion effects pointed out [7] that, under strictly controlled error conditions, such thrust could not be confirmed. In contrast, this study is based on an open macroscopic current loop, where the thrust mechanism originates from the classical Lorentz force and achieves momentum conversion through the near-field momentum storage mechanism, providing a clear physical picture. Through direction reversal experiments (four orthogonal directions) and static control

experiments, this work systematically eliminates environmental interferences. The observed thrust direction is strictly opposite to the coil opening direction, in complete agreement with the theoretical prediction of the "Virtual Wire" model, and exhibits unique transient response characteristics—features that sharply contrast with the mechanisms of EmDrive and similar concepts that rely on instantaneous radiation pressure.

5.5.2 Comparison with Mach-Effect Propulsion

The Mach effect attempts to generate thrust through transient changes in inertial mass, involving frontier areas such as general relativity, which remain highly controversial [8, 9].

This study is strictly confined to the realm of classical electrodynamics, involving no spacetime geometry or mass changes. Its driving force is purely electromagnetic, resting on a solid and reliable theoretical foundation.

In summary, unlike research relying on unconfirmed physical mechanisms, this work proposes a research pathway that is rooted in classical theory, features a clear model, and is testable through conventional experimental methods.

5.6 Engineering Application Prospects and Challenges

Based on the theoretical model, we can speculate on the potential engineering applications of this concept, while emphasizing that these are merely theoretical projections that urgently require experimental validation.

If the effect is confirmed by future precision experiments, it may offer unique advantages in the field of spacecraft propulsion: no need to carry and expel propellant, making it suitable for long-duration orbital missions, deep-space exploration, and precise attitude control of microsatellites. From scaling analysis, the model predicts that the net thrust is approximately proportional to the square of the current in the working coil ($F \propto I^2$). Therefore, for the same input power, increasing the operating current through optimized design (e.g., achieving resonance via the coil's self-inductance and gap capacitance) is a key pathway to enhancing thrust efficiency and energy conversion rate. Theoretically, if engineering could safely increase the operating current to the 100-ampere level while maintaining efficient electromagnetic coupling and heat dissipation, the net thrust could potentially reach the Newton level, which would have substantial practical value. Future research could explore replacing the drive coil with a magnetron and the working coil with a waveguide to significantly increase the system's propulsion power.

However, achieving this goal faces enormous engineering challenges, including ohmic losses and thermal management under high-frequency, high-current conditions, control and efficiency of the radiation field, and optimization of materials and structures. All such prospects are built upon the prerequisite that the physical effect itself is first confirmed through precise quantitative experiments. The current work only provides the starting point for this long journey.

6. Conclusion

This paper systematically analyzes the apparent asymmetries in electromagnetic interactions under specific configurations and, based on this, proposes a reactionless propulsion concept utilizing an open-circuit coil. To address the momentum conservation issue inherent in this concept, the original "Virtual Wire" theoretical model is established, which self-consistently unifies the apparent net thrust with the directed radiation of electromagnetic field momentum

within the framework of classical electrodynamics. Through direction reversal experiments (four orthogonal directions), static control experiments, and Tracker video analysis, a repeatable displacement opposite to the coil opening direction was observed, in complete agreement with the theoretical prediction of the "Virtual Wire" model, with an estimated magnitude of approximately 10^{-4} N. The displacement exhibits a buildup lag and decay tail on the order of seconds, consistent with the theoretical expectation of the near-field momentum storage mechanism and ruling out the possibility of instantaneous radiation pressure. Statistical tests further confirm the reliability of the observed effect, providing positive motivational evidence for the theory. However, the current experiments are limited to qualitative observations; definitive quantitative validation awaits future studies utilizing ultra-high vacuum environments and precision force measurement equipment.

The primary value of this research lies in proposing a clear, falsifiable theoretical model and analytical framework, opening a calculable and testable path for exploring novel propulsion mechanisms within the realm of classical physics. Future work should prioritize the quantitative validation of the effect, numerical simulation of the model, and experimental investigation of the thrust scaling relationships.

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Author Contribution

Li Yong: Conceptualization, Methodology, Theoretical derivation, Experimental design and execution, Data analysis, Writing – original draft, Writing – review & editing. As an independent researcher, the author is solely responsible for all aspects of this work.

Competing interests

The author declares no competing interests.

Data Availability

The video recordings of the preliminary experimental observations supporting the findings of this study are openly available in the Zenodo repository at <https://doi.org/10.5281/zenodo.19246776>. The authors confirm that the data supporting the findings of this study are available within the article.

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Appendix A: Detailed Force-Field Integration Derivation for the Virtual Wire Model

This appendix aims to provide a rigorous mathematical foundation for the "Virtual Wire" model proposed in Section 3.2 of the main text. We will demonstrate that for an open-circuit coil, the net mechanical force it acquires equals the integral of the Maxwell stress tensor over a closed surface containing the "Virtual Wire," and this force is directly related to the field momentum flux radiated through the coil gap.

A.1 Theoretical Basis: Maxwell's Equations and Momentum Conservation

In classical electrodynamics, the closed system comprising charge-current distributions and the electromagnetic field obeys a local momentum conservation law. This law is expressed by the Maxwell stress tensor T [1, 2]. In vacuum, the rate of change of the system's momentum density is:

$$\frac{\partial}{\partial t} p_{\text{mech}} + p_{\text{field}} = \nabla \cdot T \quad (A1)$$

where p_{mech} is the mechanical momentum density, $p_{\text{field}} = \epsilon_0 E \times B$ is the electromagnetic field momentum density. The Maxwell stress tensor T is a second-rank tensor with components:

$$T_{ij} = \epsilon_0 \left(E_i E_j - \frac{1}{2} \delta_{ij} E^2 \right) + \frac{1}{\mu_0} \left(B_i B_j - \frac{1}{2} \delta_{ij} B^2 \right) \quad (A2)$$

For all charges and currents within a finite volume V , the total electromagnetic force F on them (i.e., the rate of change of mechanical momentum) can be transformed via Gauss's divergence theorem into an integral over any closed surface S enclosing that volume:

$$F = \frac{dP_{\text{mech}}}{dt} = \oint_S T \cdot da \quad (A3)$$

Here da is the area element vector, pointing outward from the surface. Equation (A3) is the core of this derivation: it states that the total force on matter within any volume is entirely determined by the state of the electromagnetic field on the boundary of that volume.

A.2 Force Analysis of the Open-Circuit Coil and Construction of the Virtual Closed Surface

Consider a U-shaped open-circuit coil carrying a current $I(t)$ (see Fig.4(b)). To calculate its force, we follow the idea of the "Virtual Wire" model:

A.2.1. Connect the open ends A and B of the coil with a virtual, massless ideal wire segment, thereby forming a virtual closed loop C_{virtual} .

A.2.2. The object of analysis now is the virtual closed system composed of the physical wire and the virtual wire.

A.2.3. Choose a closed integration surface S . This surface closely follows the surfaces of both the physical and virtual wires, completely enveloping them, and closes at a distance (schematically shown in Fig.6).

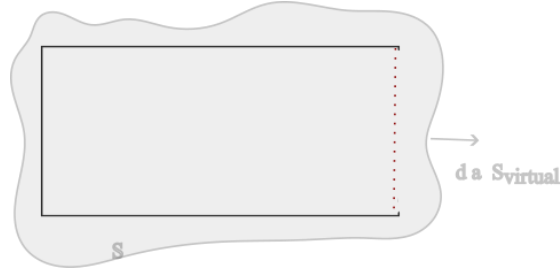


Figure. 6 Schematic diagram of the virtual closed surface S used for the force-field integration in the "Virtual Wire" model. The surface S closely follows the surfaces of the physical U-shaped coil (solid black line) and the virtual wire (red dashed line) bridging the gap, and closes at a distance to enclose the entire system under analysis

A.3 Calculation of Net Force via Stress Tensor Integration

For this virtual closed system, applying formula (A.3). The matter contained within the system is the physical wire. Therefore, the integral $\oint_S T \cdot da$ gives the force F_{total} , which is the total electromagnetic force acting on the physical wire, i.e., the observed net thrust.

We decompose the closed surface S into three parts:

- * S_{real} : The part closely following the surface of the physical wire.
- * S_{virtual} : The part closely following the surface of the virtual wire.
- * S_{far} : The part connecting and closing the surface at a distance, typically taken as a sphere at infinity.

Thus:

$$F_{\text{net}} = \oint_S T \cdot da = \int_{S_{\text{real}}} T \cdot da + \int_{S_{\text{virtual}}} T \cdot da + \int_{S_{\text{far}}} T \cdot da \quad (A4)$$

* For the far-field surface S_{far} : In the radiation zone, the electromagnetic field decays as $1/r$, the stress tensor T decays as $1/r^2$, while the area element da grows as r^2 . If the radiation field were isotropic, its integral at infinity might be zero. However, the key point is that the radiation field of an open-circuit coil is not isotropic. Due to the presence of the gap (the virtual wire location), its radiation pattern may have a net momentum flow along the normal direction of the virtual wire. Therefore, $\int_{S_{\text{far}}} T \cdot da$ is not necessarily zero; it actually represents the total rate at which field momentum radiates outward from the entire system.

* For the virtual wire surface S_{virtual} : The virtual wire is ideal and massless, containing no real charges or currents. Therefore, the net force acting on the virtual wire itself must be zero. This means the stress on the inside and outside of the virtual wire must balance. According to action-reaction, the force exerted by the "outer surface" (S_{virtual}) of the virtual wire on the interior "vacuum" equals the reaction force exerted by its "inner surface" on the interior of the system. Therefore, the integral $\int_{S_{\text{virtual}}} T \cdot da$ has the physical meaning of the force exerted by

the virtual wire on the interior of the system (i.e., the physical coil). This is precisely the source of the "thrust" defined in our model that drives the physical coil.

A.4 Final Formulation of Momentum Conservation and Model Interpretation

Substituting the above analysis into (A4) and noting that the contributions from the ideal conductor surface S_{real} cancel out when calculating the overall net force (as tangential electric fields are zero and magnetic fields are perpendicular to the surface), we obtain:

$$F_{\text{net}} = \int_{S_{\text{virtual}}} T \cdot da + \int_{S_{\text{far}}} T \cdot da \quad (\text{A4}')$$

Equation (A4') is the precise quantitative formulation of the "Virtual Wire" model, where:

- * $\int_{S_{\text{virtual}}} T \cdot da$ corresponds to the stress integral over the virtual wire surface, physically representing the near-field bound momentum stored in the coil virtual part.
- * $\int_{S_{\text{far}}} T \cdot da$ corresponds to the stress integral over the far-field surface, physically representing the electromagnetic field momentum flux radiated to infinity.

In a general electromagnetic system, these two terms together contribute to the net thrust experienced by the physical coil. For the low-frequency, compact geometry of this experiment, because the system dimensions are much smaller than the radiation wavelength, the radiation efficiency is extremely low, and $\int_{S_{\text{far}}} T \cdot da$ is much smaller than $\int_{S_{\text{virtual}}} T \cdot da$. Therefore, the net thrust primarily originates from the near-field stress contribution.

Thus, the "Virtual Wire" is not merely a conceptual bridge but corresponds mathematically to the critical part of the system boundary through which momentum flows out. The coil opening (where the virtual wire sits) is the geometric origin that breaks field symmetry and generates a non-zero net radiation momentum flux. This derivation firmly anchors the physical picture of the model in the conservation laws of classical electrodynamics.

It is worth noting that the above derivation gives the net force under steady-state conditions. During transient processes, the dynamic response of the system is governed by differential equations determined by the inductance LL and capacitance CC , which explains the time delay observed in the experiments.