

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 forces that may arise within finite-sized, non-closed, or transient current-carrying systems under specific configurations, which appear counter-intuitive from a classical mechanics perspective. Based on a systematic analysis of these phenomena, particularly the third form of "carrier asymmetry," we propose an innovative reactionless propulsion concept utilizing open-circuit coils. To resolve the fundamental momentum conservation challenge of this concept self-consistently within classical electrodynamics, we construct an original theoretical model—the "Virtual Wire." This model conceptually closes the physical open-circuit coil into a virtual loop by introducing an ideal massless wire segment. It thereby clearly links the apparent net thrust acquired by the device to the directed radiative momentum flux of the electromagnetic field resulting from the structural discontinuity. To investigate the physical implications of this theoretical model, we designed and implemented two experimental setups for preliminary observation. 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. Driven at a frequency of 100 MHz with an effective current of approximately 0.3 A, the experiment observed repeatable displacement indications consistent with the model's prediction, corresponding to an estimated net thrust on the order of 10^{-4} N. Error analysis and statistical tests indicate that this observed effect is not purely random. From phenomenological analysis and model construction to preliminary experimental exploration, this work aims to provide a self-consistent theoretical perspective and motivating 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.

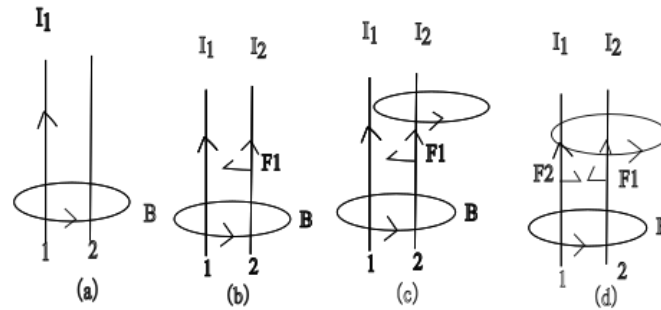


Fig. 1 Schematic illustrating the transient delay of electromagnetic forces between parallel straight wires. (a) Wire 2 is already within the magnetic field of wire 1, which carries a steady current. (b) At time t_0 , wire 2 is energized and immediately experiences a force from wire 1's field. (c) During 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.

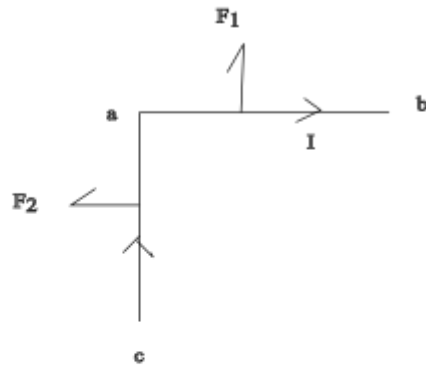


Fig. 2 Schematic illustrating the direction of Ampere forces between perpendicularly connected wires. Wires *ca* and *ab* are perpendicular and carry current. According to the Ampere force law, the force F_1 on wire *ca* is perpendicular to itself, and the force F_2 on wire *ab* is also perpendicular 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.

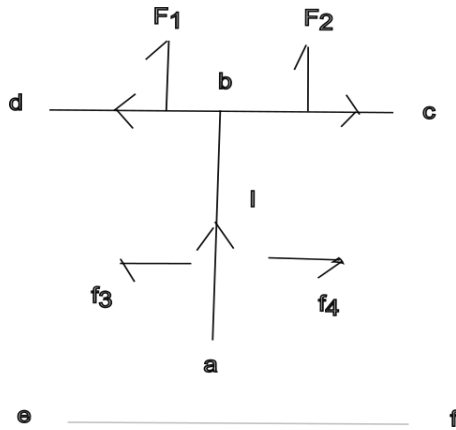


Fig. 3 Schematic of a three-wire structure illustrating "carrier asymmetry" in electromagnetic interaction. Wire *ab* is connected to two parallel wires *bd* and *bc* of equal length. When current flows as shown, wire *ab* exerts forces (F_1, F_2) on *bd* and *bc*, but the reaction forces f_3 and f_4 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 intentionally designing a geometrically incomplete current-carrying loop—i.e., an open-circuit coil (such as U-shaped or C-shaped coils)—to disrupt the internal self-balance of electromagnetic forces within the loop (Fig. 4). Theoretically, a net force arises on the remaining conductors. The essence of this force is the vector sum of the Lorentz forces experienced by the currents in these conductors within the asymmetric magnetic field generated by the entire coil configuration (including the virtual closed path introduced for analysis). The total momentum of the entire system (coil + electromagnetic field) is strictly conserved.

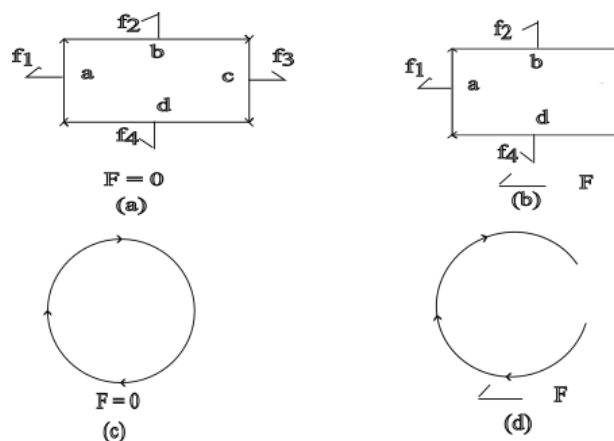


Fig. 4 Schematic comparing forces on closed loops and open-circuit coils. (a) & (c): The total electromagnetic force on a complete closed current loop is zero, indicating self-balance. (b) & (d): When part of the loop is removed, the remaining open-circuit coil portion loses part of its internal balance,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

3.2.2 Mechanical and Momentum Analysis

Within this virtual system, calculating the forces on the physical coil part yields a non-zero net force, denoted as F_{net} . According to Newton's third law, the reaction force $-F_{net}$ acts upon 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 $-F_{net}$ on the Virtual Wire precisely corresponds to the **directed radiation** of electromagnetic energy and momentum through the coil opening acting as a "channel." The time rate of change of the momentum flux carried by this radiation field equals $-F_{net}$ in magnitude and direction.

Therefore, the total momentum conservation of the system is expressed as:

$$\frac{d}{dt}(P_{mech,coil}) = F_{net} = -\frac{d}{dt}(P_{field, radiated})$$

where $P_{mech,coil}$ is the mechanical momentum of the physical coil, and $P_{field, radiated}$ is the total momentum of the electromagnetic field radiated directionally through the opening.

3.2.3 Theoretical Significance and Classical Self-Consistency

The "Virtual Wire" model is not an independent hypothesis but a self-consistent analytical framework built upon Maxwell's equations and the Lorentz force law. It treats the physical gap of the open-circuit coil as an equivalent boundary for momentum outflow in the mathematical treatment. The rigorous mathematical foundation of this model stems from the momentum conservation law of the electromagnetic field, which can be demonstrated by calculating the integral of the Maxwell stress tensor over a closed surface enclosing the Virtual Wire (detailed in Appendix A). This integral shows that the net thrust on the physical coil equals the flux of electromagnetic field momentum radiating outward through a distant closed surface. This clearly indicates that the principles and model proposed here are fully embedded within the

classical electrodynamics system, representing an interpretation of the consequences of applying known physical laws to a new configuration, rather than contradicting them [1,3].

4. Preliminary Experimental Observations and Error Analysis

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

4.1 Experimental Apparatus and Parameters

The system employed a high-frequency inductive driving method.

- **Drive Coil:** A toroidal coil fabricated by winding a half-wave dipole antenna resonant at 100 MHz, fed at the center with open ends. Specifications: wire diameter 2.7 mm, 5 turns, perimeter per turn ~30 cm.
- **Working Coil:** A C-shaped open-circuit coil, placed coaxially with the drive coil for strong coupling. It was wound with 12,000 turns of enameled wire (diameter 0.1 mm) into a toroidal shape. The key feature is that each turn is not a closed ring but has a constant 70° mechanical opening, making the entire working coil essentially a multi-turn array of open-circuit toroidal coils.
- **Measurement System:** The assembly comprising the drive and working coils (total mass 270 g) was suspended from the lower end of a simple pendulum with a length of 1.3 m. A video recording device captured the minute displacement changes of the pendulum before and after power application, from which the thrust was estimated.

4.2 Experimental Results

With the C-shaped coil setup, repeatable displacement indications consistent with the model's predicted direction were observed. Analysis of the video footage yielded an estimated average net thrust of:

$$F_{\text{exp}} \sim 1.0 \times 10^{-4} \text{ N}$$

This magnitude is roughly consistent with the indications from the first U-shaped coil setup, providing preliminary cross-validation from different experimental configurations.

4.3 Error Analysis and Uncertainty Discussion

As an exploratory study, the experiment aimed for qualitative observation of the effect's existence rather than precise metrology. We fully acknowledge the limitations of the current measurement method and performed the following analysis to ensure observational rigor.

4.3.1 Limitations of Observation

The displacement estimate was based on manual interpretation of video footage, with a resolution limit on the order of $10^{-4}m$. Consequently, this experiment is essentially a qualitative observation of the presence/absence and direction of displacement, incapable of providing high-precision quantitative data. Furthermore, systematic errors could be introduced by thermal effects, air convection, and environmental micro-vibrations.

4.3.2 Error Control and Randomness Test

Error control and assessment of randomness were addressed as follows:

- (1) Environmental Stabilization:** Experiments were conducted in a maximally static environment, away from large metal objects to minimize stray electromagnetic interference.
- (2) Thermal Effect Check:** Coil temperature was monitored before and after operation, confirming negligible Joule heating-induced air convection during the brief tests.
- (3) Baseline Verification:** Prolonged observation of the unpowered assembly showed no spontaneous displacement.
- (4) Orientation Independence Test:** The spatial orientation of the assembly was altered; powered tests confirmed the displacement direction remained consistent with the model, independent of installation.

Under the stringent adherence to the above conditions, we performed 14 independent observation trials. All 14 trials exhibited visible displacement in the direction predicted by the theory.

To quantitatively assess whether this series of consistent observations was purely coincidental, we employed a Binomial test. The null hypothesis H_0 was set as the probability $p = 0.5$ of observing a positive displacement in a single trial (i.e., completely random outcome). Given 14 independent trials all showing positive displacement, the calculated one-sided p-value is approximately 0.001, well below the conventional significance level of 0.05. This result strongly suggests, statistically, that the observed displacement trend is not due to pure random noise. However, it must be explicitly stated: statistical significance is not equivalent to proof of a physical effect. It merely indicates the observation is non-random, but the fundamental physical origin of the minute displacement (i.e., whether it indeed stems from the proposed electromagnetic mechanism) remains to be ultimately confirmed by excluding all potential systematic errors (such as unidentified mechanical vibrations, subtle airflows, or other electromagnetic interactions). The core value of this qualitative experiment lies in providing a positive, preliminary indication that warrants further rigorous quantitative testing.

4.3.3 Combined Uncertainty and Future Verification Requirements

Given the aforementioned limitations, the current experiment cannot serve as evidence for quantitatively validating the theoretical model. Instead, it should be regarded as a positive, motivating preliminary indication. It suggests that the proposed physical concept merits investigation using more precise methods. Therefore, definitive quantitative measurement and verification must be accomplished using micro- or nano-newton resolution force measurement devices (e.g., torsion balance, precision balance) within a vacuum environment, accompanied by comprehensive systematic error modeling and elimination. This is the foremost task for future work [2].

5. Discussion

5.1 Depth and Originality of the "Virtual Wire" Model

The core theoretical contribution of this work is the original proposal and establishment of the "Virtual Wire" model. It provides a clear, intuitive, and classically self-consistent conceptual picture for understanding momentum flow in open-circuit coil systems. It directly links the apparent "reactionless" thrust to a calculable radiative flux of electromagnetic field momentum.

The model's mathematical foundation (Appendix A) is firmly rooted in the momentum conservation law expressed via the Maxwell stress tensor, demonstrating its classical intrinsic nature.

5.2 Relationship with Classical Electromagnetism and Electrodynamics

It must be unequivocally stated that the "apparent asymmetry" phenomena and the "Virtual Wire" model elaborated in this paper are derived and interpreted entirely within the framework of classical Maxwell-Lorentz electrodynamics. The law of momentum conservation in electrodynamics is its more general, fundamental form, which already incorporates field momentum. The manifestation of Newton's third law (action-reaction forces) in electromagnetism is a specific consequence of this more general conservation law under particular conditions. When examining a **non-closed** current system, changes in its mechanical momentum are necessarily accompanied by changes in electromagnetic field momentum (radiation or accumulation). The three asymmetries summarized herein are an induction of the **local or apparent features** exhibited by this universal principle under different specific electromagnetic configurations. The "Virtual Wire" model serves as an **effective analytical tool** for applying this universal principle to the specific problem of open-circuit coils. Therefore, this work does not propose a new principle contradicting classical theory. Instead, it strives to systematically delineate a specific phenomenon within the classical framework and construct a self-consistent model to interpret it, thereby extending our understanding of electromagnetic momentum transfer mechanisms.

5.3 Significance of Experimental Indications

Although the experiment is preliminary and qualitative, observing thrust indications of consistent direction and similar magnitude from two independent setups, coupled with statistical testing excluding pure randomness, provides **positive motivation** for the theoretical model. It indicates that the propulsion concept based on electromagnetic asymmetry warrants investment in the next steps of rigorous, quantitative experimental research. The evolution of the experimental setup (from U-shaped to C-shaped) also demonstrates the potential to improve effect repeatability by optimizing geometric symmetry and resonant characteristics.

5.4 Comparative Analysis with EmDrive and Mach Effect

5.4.1 Comparison with EmDrive

EmDrive relies on microwave radiation pressure within a closed resonant cavity, and its theories often invoke hypotheses outside the standard model [4-6]. This skepticism is supported by a major independent replication effort, the SpaceDrive project, which found no conclusive evidence for such thrust under stringent error-controlled conditions [7]. In contrast, this study is based on an open, macroscopic current loop. Its thrust mechanism originates from the classical Lorentz force, offering a clear physical picture. The "Virtual Wire" model provides a closed theoretical explanation from first principles that is self-consistent with momentum conservation. Moreover, its key prediction (the existence of a directed Poynting vector flux at the coil opening) offers clear testability in future experiments.

5.4.2 Comparison with Mach-Effect Propulsion

Mach-effect propulsion attempts to generate net thrust through transient variations in inertial mass, involving frontier and controversial areas such as general relativity [8,9]. This study is

strictly confined to the realm of **classical electrodynamics**, involving no spacetime geometry, mass variation, or non-local effects. The driving force is purely electromagnetic, resting on a solid theoretical foundation.

In summary, unlike research reliant on unconfirmed physical effects, this work proposes a research pathway that is rooted in classical theory, features a clear model, and is amenable to verification by traditional experimental methods.

5.5 Engineering Application Prospects and Challenges

Based on the theoretical model, we can prospect the potential engineering applications of this concept, while simultaneously emphasizing that this remains theoretical speculation urgently requiring experimental validation.

If the effect is confirmed by future precise experiments, it may offer unique advantages in spacecraft propulsion: no need to carry and expel reaction mass, making it suitable for long-duration orbital missions, deep-space exploration, and precise attitude control of microsatellites. Scaling analysis from 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 a given input power, optimizing the design (e.g., achieving resonance utilizing coil self-inductance and gap capacitance) to increase the operating current is a key pathway to enhancing thrust efficiency and energy conversion rate. Theoretically, if engineering challenges allow safely raising the operating current to the order of hundreds of amperes while maintaining efficient electromagnetic coupling and heat dissipation, the net thrust could potentially reach the **Newton level**, which would be of substantial practical value.

However, achieving this goal faces significant engineering challenges: Ohmic losses and thermal management under high-frequency, high-current conditions; control and efficiency of the radiation field; material and structural optimization, among others. **All these prospects are predicated on first confirming the existence of this physical effect through precise quantitative experiments.** The present work merely provides a starting point for this long journey.

6. Conclusion

This paper systematically analyzes the apparent asymmetries in electromagnetic interaction under specific configurations and, based on this, proposes a reactionless propulsion concept utilizing open-circuit coils. To resolve its momentum conservation challenge, the "Virtual Wire" theoretical model is originally established, successfully and self-consistently unifying the apparent net thrust with the directed radiative momentum of the electromagnetic field within the classical electrodynamics framework. Preliminary experiments observed repeatable displacement indications qualitatively consistent with the model's prediction, and statistical testing indicated their non-random nature, providing positive motivation for the theory. However, the current experiment is limited to qualitative observation; definitive quantitative verification awaits future implementation using ultra-high vacuum environments and precision force measurement equipment.

The primary value of this study lies in proposing a clear, falsifiable theoretical model and

analytical framework, opening a calculable and testable pathway for exploring novel propulsion mechanisms within the domain of classical physics. Future work should prioritize the quantitative verification of the effect, numerical simulation of the model, and experimental investigation of thrust scaling relationships.

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Statements and Declarations

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Competing interests

The author is an independent researcher and declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. A patent application related to the conceptual design in this work has been filed (Application Number: CN202511853769.2). This intellectual property activity represents a potential future interest but does not constitute a current financial competing interest regarding the publication of this fundamental research.

Data Availability

The video recordings of the preliminary experimental observations, which support the qualitative findings of this study, are openly available in the Zenodo repository at <https://doi.org/10.5281/zenodo.18310064>. An early version of this manuscript has been posted as a preprint on the Research Square platform under the DOI: <https://doi.org/10.21203/rs.3.rs-8617166/v1>.

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.

Additional Declarations for Individual Researcher

The author confirms that this independent research was conducted adhering to accepted ethical principles of scientific inquiry. All experimental activities were performed by the author in a private capacity.

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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 [2, 3]. 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).

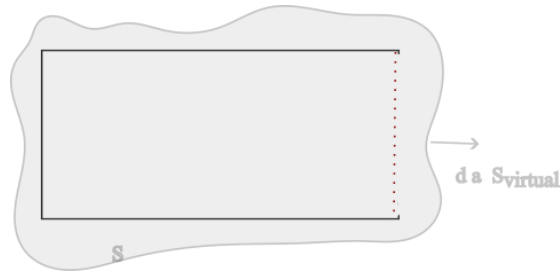


Figure. 6 Schematic diagram of the virtual closed surface S used for the force-field integration in the "Virtual Wire" model. The surface S closely follows the surfaces of the physical U-shaped coil (solid black line) and the virtual wire (red dashed line) bridging the gap, and closes at a distance to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

A.3 Calculation of Net Force via Stress Tensor Integration

For this virtual closed system, applying formula (A.1). 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:

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

- * 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 rearranging, we obtain:

$$F_{\text{netForce on physical coil}} = \underbrace{\int_{S_{\text{virtual}}} T \cdot da}_{\text{Force exerted by virtual wire}} = - \underbrace{\int_{S_{\text{far}}} T \cdot da}_{\text{Momentum flux carried away by radiated field}} \quad (A4')$$

In deriving (A4'), we utilized the fact that on the surface of an ideal conductor S_{real} , the tangential electric field is zero and the magnetic field is perpendicular to the surface; the contribution of this part to the integral mainly relates to internal stresses within the coil and cancels out when calculating the overall net force.

Equation (a4') is the precise quantitative formulation of the "Virtual Wire" model:

1. The first equality, $F_{\text{net}} = \int_{S_{\text{virtual}}} T \cdot da$, shows that the net thrust acting on the physical coil is exactly equivalent to the Maxwell stress integral over the virtual wire surface. This provides a strict mathematical definition for the concept of the "virtual wire exerting a force."

2. The second equality, $F_{\text{net}} = - \int_{S_{\text{far}}} T \cdot da$, embodies global momentum conservation.

The mechanical momentum gained by the physical coil is exactly balanced by the electromagnetic field momentum flowing out through the surface at infinity S_{far} . The negative sign indicates opposite directions.

Therefore, 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 [2].