Ampère's motor: Its history and the controversies surrounding its working mechanism[a]

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Abstract

In 1822 Ampère created a new kind of motor when he succeeded in spinning a cylindrical magnet around its axis by connecting it to a battery generating a steady current. Nowadays it is easy to present such a motor in the classroom utilizing a neodymium magnet, a D battery, a steel nail, and a short piece of copper wire. Although it is very simple to observe the rotation, the explanation of this effect is still under dispute. This work presents the history of this motor including the controversy between Ampère and Faraday, as well as the modern explanation based on the field concept. We emphasize the positive outcomes to be gained in the classroom by presenting this device to students.

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I. INTRODUCTION

The importance of presenting history of science and hands-on experiments in the classroom is well known.[1] Experiments are especially appropriate when they can be done with low-cost equipment and when the observed effects are impressive. In this work we discuss a device that has been aptly called "the simplest motor."[2,3] It has also been called a "homopolar motor."[4–7] Beyond exploring the simplicity of this device, we emphasize here the fascinating history of this motor, which goes back almost 200 years. There was an important controversy between Ampère and Faraday about the working mechanism of this instrument. Their opposing points of view can also be contrasted with the modern explanation based on the field concept. These different interpretations for the same observed effect can be easily explored in the classroom.

II. THE SIMPLEST MOTOR

Students are always fascinated by motors. One of the simplest electrical motors, which can be easily demonstrated in the classroom, has only four components: a cylindrical neodymium magnet; a D cell or similar battery; a steel nail or screw; and a short piece of copper wire. See Fig. 1.

The nail is attracted by the strong magnet and its head sticks to one flat side of the magnet. The nail becomes magnetized. Its tip is attracted to the ferromagnetic bottom of the battery. By holding the battery in our hand, the nail and the magnet remain attached to one another below the battery, in a vertical orientation. The gravitational pull of the Earth is balanced by the magnetic interaction. One end of the wire is held to the top of the battery. When the other end of the wire touches the circular side of the magnet, the circuit is closed, and a steady current flows through the magnet. Immediately the magnet and the nail begin to spin together very quickly around the vertical axis. This rotation does not take place when the other end of the wire touches the center of the free flat side of the magnet.

III. EXPLANATION BASED ON THE FIELD CONCEPT

The typical explanation for this motor can be illustrated as in Fig. 2.[2,3,5,8]

The magnet produces a magnetic field $\vec{B}$ which is essentially homogeneous inside the magnet, pointing parallel to its axis. According to the Lorentz force, each radial current element $id\vec{\ell}$ of length $|d\vec{\ell}|$ and current intensity i experiences a force $d\vec{F}$ given by

$$d\vec{F} = id\vec{\ell} \times \vec{B}. \tag{1}$$

The direction of this force is given by the right-hand rule, being orthogonal to the magnetic field and to the current. This force generates a torque upon the magnet which makes it turn around its axis. For the situation of Fig. 1, this torque causes the magnet to rotate in a counter-clockwise direction when viewed from above, as shown in Fig. 2.

IV. HISTORY OF THIS MOTOR

In order to understand the path leading to the discovery of Ampère's motor, it is important to discuss the first electric motor in the history of physics, presented by Faraday (1791–1867).[9,10] Following Oersted's historical discovery (1820) of the deflection of a magnetized needle by a nearby long straight wire, Faraday began to devote himself to the study of electromagnetism. In September 1821 he created what is normally considered as the first electric motor.[11] Figure 3 shows schematic representations of his two kinds of motor. In both cases there are glass cups filled with mercury. A steady current flows along the wire, passes through the mercury and along the magnet. In Fig. 3(a) the upper pole of the magnet rotates around the vertical current-carrying wire fixed in the laboratory. In Fig. 3(b) the lower extremity of the inclined wire rotates around the vertical magnet fixed in the laboratory.

Faraday sent a small model of the apparatus to several scientists, including Ampère. In this pocket apparatus the inclined wire rotates around a fixed magnetized piece of metal. Recently Hottecke made a historical reproduction of this motor and discussed didactic implications of this instrument.[12]

Faraday informed Ampère about his discovery in October 1821. In his first paper describing this device Faraday mentioned the following:[9,10]

> Having succeeded thus far, I endeavoured to make a wire and a magnet revolve on their own axis by preventing the rotation in a circle round them, but have not been able to get the slightest indications that such can be the case; nor does it, on consideration, appear probable.

André-Marie Ampère (1775–1836) had also begun working with electromagnetism after Oersted's discovery. His approach was completely different from those of Oersted and Faraday. Ampère was creating a whole new area of research which he coined "electrodynamics."[13–17] He wanted to explain all magnetic and electromagnetic phenomena only in terms of interactions between electric currents. To this end, he supposed the existence of microscopic or molecular electric currents inside magnets and considered that these currents were responsible for their magnetic effects. He was also the first to predict and to observe torques and forces between current carrying wires, without the presence of any magnet. His main goal was to find a force law between current elements, from which he could explain the interactions between two currents, between a current and a magnet, and between two magnets. He succeeded in 1822.[18–20]

Faraday tried to rotate a magnet around its axis utilizing a steady current but did not succeed. He also considered that this effect did not appear probable. Ampère, on the other hand, based upon a preliminary version of his force law between currents elements, predicted the existence of this effect. He was also the first to demonstrate the rotation of a magnet around its axis utilizing a steady current, performing the experiment between November and December 1821. He presented it to the Academy of Sciences in January 1822.[13,19]

A simplified version of Ampère's motor is shown in Fig. 4. The cylindrical magnet NS floats vertically in liquid mercury with the help of a counter-weight CW in its lower end. At the upper end there is a cavity Z filled with mercury. A steady current i goes down vertically along the conductor DZ, leaving laterally through GF. There is a metallic ring GH floating in the mercury. In this configuration the magnet rotates around its axis.

V. AMPÈRE'S EXPLANATION

Ampère's electrodynamic conception was based upon a force describing directly the interaction between two current elements acting along the straight line connecting them, always complying with Newton's action and reaction law.[19–23]

In order to explain the working mechanism of his motor, Ampère considered essentially the interaction between the microscopic currents of the magnet (responsible for its magnetic properties) and the macroscopic current due to the battery flowing *externally* to the magnet.

A schematic representation of his device is shown in Fig. 5.

Ampère predicted the rotation of the magnet about its axis utilizing his concept of action and reaction between current elements. In particular, he considered the interaction between the macroscopic current i flowing in the circuit connected to the battery and the microscopic currents i' flowing around the molecules of the magnet.

Ampère presented an explanation of the working mechanism of his motor with a diagram similar to our Fig. 6.

The internal circle $mn'Tn$ represents a cross section of the cylindrical magnet as seen from above. The tangential current i' represents the net microscopic or molecular current of the magnet which, according to Ampère, is responsible for its magnetic effects. The region between the internal and external circles is filled with mercury. The external circle $Mcfc'$ represents the metallic ring floating in mercury around the magnet. The radial current i along the radius ZmM is the macroscopic electric current flowing along the circuit when it is connected to the battery. It enters the magnet from its upper end, leaving the magnet radially. The main point to be emphasized is that the portion Zm of this radial current i passes inside the magnet, while the portion mM flows in the mercury outside the magnet.

Ampère's explanation runs as follows:[13,16,17]

> Let ZM be one of these currents [from the external circuit]. The Zm portion does not act upon the [microscopic] electric currents of the magnet. The mM portion attracts mn' and repels mn. These combined forces make the magnet turn around its axis in the $n'mn$ direction. Similar forces are exerted simultaneously upon all points of the magnet, so that it turns indefinitely around itself.[24]

These forces are illustrated in Fig. 7(b). Ampère is here considering only the most relevant forces between the external radial current i along mM and the internal microscopic tangential current along nmn'. The portion mM attracts the portion mn' and repels the portion nm. The net effect of these combined forces is a torque upon the magnet making it turn around its axis in the $n'mn$ direction.

Figure 7 also shows the reaction forces exerted by the microscopic current i' acting upon the external macroscopic current i. By action and reaction, the microscopic currents of the magnet must exert an opposite torque upon the macroscopic currents flowing in the mercury outside the magnet.

It is possible to understand qualitatively the directions of the interactions represented in

Fig. 7(b) utilizing Ampère's force between current elements. To facilitate the comprehension of modern readers, this force is expressed here in vector notation and in SI units:[21–23]

$$d^2\vec{F}^A_{21} = -\frac{\mu_0}{4\pi} i_1 i_2 \frac{\hat{r}_{12}}{r^2_{12}} \left[2 \left(d\vec{\ell}_1 \cdot d\vec{\ell}_2 \right) - 3 \left(\hat{r}_{12} \cdot d\vec{\ell}_1 \right) \left(\hat{r}_{12} \cdot d\vec{\ell}_2 \right) \right] = -d^2\vec{F}^A_{12} \ . \tag{2}$$

In this expression $d^2\vec{F}^A_{21}$ is Ampère's force exerted by the current element $i_2 d\vec{\ell}_2$ located at $\vec{r}_2$ acting upon the current element $i_1 d\vec{\ell}_1$ located at $\vec{r}_1$; the constant $\mu_0 = 4\pi \times 10^{-7}$ kg m C^{-2} is the vacuum permeability; $r_{12} = |\vec{r}_1 - \vec{r}_2|$ is the distance between the two current elements; and $\hat{r}_{12} = (\vec{r}_1 - \vec{r}_2)/r_{12}$ is the unit vector pointing from $i_2 d\vec{\ell}_2$ to $i_1 d\vec{\ell}_1$.

It is important to point out that this force complies with the principle of action and reaction, namely, $d^2\vec{F}^A_{21} = -d^2\vec{F}^A_{12}$. Moreover, this force is always along the straight line connecting the two current elements, that is, along the direction of $\hat{r}_{12}$. This means that the force complies with Newton's action and reaction law in the strong form. The same happens with Newton's law of gravitation and with the electrostatic force between two point charges.

The essence of Ampère's explanation is that only the macroscopic current i flowing *externally* to the magnet exerts a torque upon the internal microscopic currents i' of the magnet. By action and reaction, the microscopic currents must exert an opposite torque upon the external macroscopic currents.

VI. FARADAY'S EXPLANATION

Ampère sent his paper to Faraday, who presented another explanation of Ampère's motor in his reply of February 02, 1822.[19] Faraday made essentially an analogy with his own motor in which a wire rotated around a fixed magnet, as in Fig. 3(b).

Faraday's interpretation about the working mechanism of his own motor was that "it was evident that each pole had the power of acting on the wire by itself."[9] Moreover, to Faraday this interaction was not along the straight line connecting them, but had a transverse direction which produced a rotational motion. In the case of Fig. 3(b), for instance, the south pole of the magnet would exert a force upon the current which was coming down along the wire. This force would be orthogonal to the paper, as if it were leaving the paper towards the reader.

Faraday decided to apply the same concept to explain Ampère's motor. But now, instead of supposing the magnetic pole acting upon a current flowing in the external wire, he supposed that the magnetic pole would act upon currents flowing inside the magnet. Faraday's explanation of Ampère's motor is shown in Fig. 8. The steady current enters the cylindrical magnet from above through the mercury drop. The black dot represents the south pole of the magnet, while the arrows indicate the current flowing through the magnet and in the surrounding mercury.

Faraday's explanation of Ampère's motor runs as follows:[25]

> The rotation of the magnet seems to me to take place in consequence of the different particles of which it is composed being put into the same state by the passing current of electricity as the wire of communication between the voltaic poles, and the relative position of the magnetic pole to them. Thus the little arrows may represent the progress of the electricity. Then any line of particles parallel to them except that line which passes as an axis through the pole (represented by a dot) will be in the situation of the revolving wire and will endeavour to revolve round the pole and as all the lines act in the same direction or tend to go one way round the pole, the whole magnet revolves.

Figure 9 provides a representation of Faraday's explanation. The letter S represents the south pole of the magnet. The crosses represent the downward currents flowing inside the magnet. The arrows indicate the tangential forces exerted by the south pole upon the internal currents. According to Faraday, these supposed internal forces would exert a net torque upon the magnet, making it turn in the counter-clockwise direction when seen from above.

VII. CONTROVERSY: AMPÈRE VERSUS FARADAY

Ampère immediately saw that Faraday's explanation violated Newton's third law of action and reaction. Faraday supposed that the magnetic pole of the magnet was acting upon internal currents and exerting tangential or transverse forces upon them. This internal torque would produce the rotation of the magnet. Ampère was very explicit about this aspect in his reply to Faraday, dated July 10, 1822:[26]

> As the action is always equal to the reaction, a fundamental and clear principle of physics states that it is impossible that a rigid body be put into any kind

of motion, due to a mutual action between two of its particles, as this action produces upon the two particles two equal forces which tend to move the body in opposite directions. From this it follows that, when the particles of a magnet traversed by an electric current which puts them into the same state as the conducting wire act upon the pole or upon any other portion of the magnet, there cannot result from this [interaction] any motion in this body, in the same way that the ensemble of a magnet and a conducting wire cannot move when they are rigidly connected together. From this observation, the rotation of a floating magnet around its axis can only be explained as I did in the Memoir of May of the *Annales de Chimie et de Physique*, which I sent to you recently through M. Dorckray of Manchester.[27]

VIII. BOOTSTRAP EFFECT WITH THE MODERN INTERPRETATION BASED UPON THE FIELD CONCEPT

The modern explanation of Ampère's motor based upon the field concept was presented in Section III. It is different from Ampère's original interpretation and also different from Faraday's model. In order to reconcile Faraday's viewpoint with the modern interpretation it would be necessary to avoid the magnetic pole concept and to suppose the torque to originate in forces acting upon internal radial horizontal currents. In order to reconcile Ampère's viewpoint with the modern interpretation it would be necessary to deal only with the interaction between current elements, avoiding the magnetic field concept.

While Faraday believed that the magnetic pole was acting upon vertical currents flowing inside the magnet, the modern explanation is based upon the magnetic field acting upon internal radial horizontal currents. Despite this distinction, the modern explanation shares a very important similarity with Faraday's own interpretation. According to both explanations, the torque acting upon the magnet arises due to the interaction between internal components within the magnet. According to Faraday, the pole of the magnet is acting upon internal currents flowing within the magnet. Analogously, according to the modern interpretation, the magnetic field due to the magnet is acting upon internal currents flowing within the magnet.

In the same way that Ampère rejected Faraday's original explanation, he certainly would reject the modern interpretation based upon the field concept. After all, both explanations are based upon a so-called bootstrap effect—that is, a self-sustaining torque that proceeds without external help.

IX. THE OPPOSITE TORQUE ACTING UPON THE EXTERNAL MACROSCOPIC CURRENT

Ampère's explanation for his motor, on the other hand, complies with Newton's third law. His force law between two current elements is always along the straight line connecting them, as was seen in Eq. (2).[19,20] By considering Ampère's force applied to his motor, it is concluded that the torque upon the magnet must be exerted by the current flowing along the external circuit. By action and reaction, the magnet must exert an opposite torque upon this external circuit.

Is it possible to observe this opposite torque acting upon the external circuit? In defense of his points of view, Ampère quoted experiments by Davy showing the motion of mercury in the opposite direction to the motion of the magnet.[28] Nowadays these opposite torques acting upon the external circuit in Ampère's motor can be easily observed. To this end, it is necessary to fix the magnet and the battery in the laboratory, while allowing the external circuit to rotate relative to the ground. Extremely simple devices have been proposed in the literature showing the action of this opposite torque. When free to move, the external circuit rotates relative to the ground. If the magnet in Ampère's motor runs in the clockwise direction, the external circuit will move in the counter-clockwise direction when free to move. These experiments can be easily performed with a mobile external copper wire.[4,7,8,29,30] A very interesting alternative is to use a simple aluminum foil tube to close the circuit.[6]

X. APPLICATION IN THE CLASSROOM

Many interesting topics can be addressed in the classroom with this extremely simple device:

- This motor is extremely simple to build. It runs very fast, fascinating and surprising students and experts.

- It is a low-cost device. Neodymium magnets are easily found nowadays in many schools and shops.
- It has a very interesting history, going back to Ampère and Faraday in 1821–22.
- There is a fascinating and documented controversy between two fathers of our modern electromagnetic theory. The different paradigms can be compared and explored.
- There are different explanations for this effect. Ampère's interpretation is based upon the action and reaction between internal microscopic currents and external macroscopic currents. Faraday's interpretation and the modern explanation based upon the field concept, on the other hand, require a bootstrap effect. That is, the magnet (its pole or its own magnetic field) acts upon internal currents and generates a torque upon the magnet.

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[24] Soit ZM un de ces courans, la portion Zm est sans action, d'après ce qui a été dit précédemment, sur les courans électriques de l'aimant; la portion mM attire mn' et repousse mn; ces deux forces reunis tendent à faire tourner l'aimant sur lui-même dans le sens $n'mn$; des forces semblabes s'exerçant simultanément sur tous les points de l'aimant, il tourne sur lui-même indéfiniment.

[25] L. d. Launay (editor), *Correspondence du Grand Ampère* **3** (Gauthier Villars, Paris, 1943).

[26] L. d. Launay (editor), *Correspondence du Grand Ampère* **2** (Gauthier Villars, Paris, 1936).

[27] D'après ces faits, j'ai déterminé un principe fondamental et évident en physique, c'est que, l'action étant toujours égale à la réaction, il est impossible qu'un corps solide soit mû en aucune manière par une action mutuelle entre deux de ses particules, parce que cette action produit sur les deux particules deux forces égales qui tendent à mouvoir le corps en sens opposés. D'où il suit que, quand les particules d'un aimant, traversées par un courant électrique qui les met dans le même état que le fil conducteur, agissent sur le pôle ou sur toute autre partie de l'aimant, il ne peut en résulter aucun mouvement dans ce corps, pas plus que l'assemblage d'un aimant

et d'un fil conducteur ne peut se mouvoir quand ils sont invariablement liés ensemble. D'après cette observation la rotation autour de son axe d'un aimant flottant ne peut plus guère être expliquée que comme je l'ai fait dans le mémoire inséré dans le cahier de mai des *Annales de Chimie et de Physique* et que je vous ai envoyé dernièrement par M. Dorckray de Manchester.

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FIGURE CAPTIONS

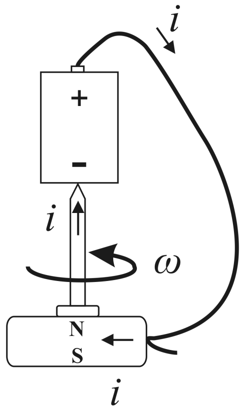

FIG. 1. The simplest motor. When a steady current i flows through the circuit, the magnet and the nail spin together relative to the ground with an angular velocity ω.

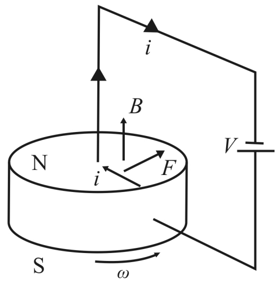

FIG. 2. Force $\vec{F}$ exerted upon the magnet utilizing the magnetic field $\vec{B}$ of the magnet acting upon a radial current i.

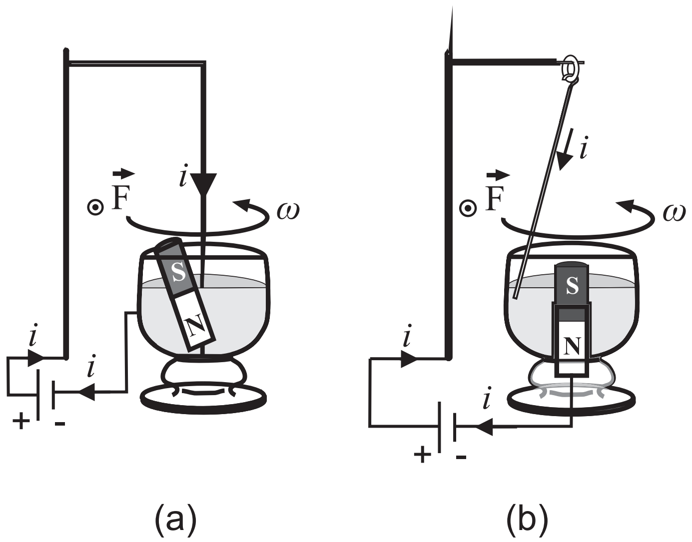

FIG. 3. Simplified representations of Faraday's motors. (a) The upper pole of the magnet rotates around the vertical wire fixed in the laboratory. (b) The lower extremity of the wire rotates around the fixed magnet.

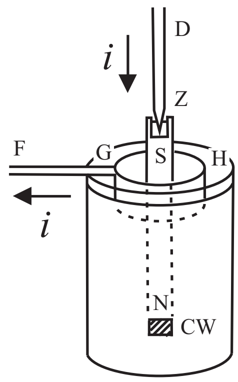

FIG. 4. Simplified version of Ampère's motor.

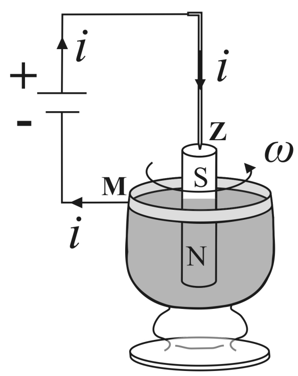

FIG. 5. A schematic representation of Ampère's motor.

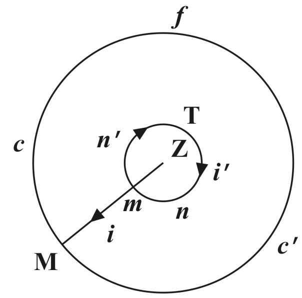

FIG. 6. The microscopic tangential current i' of the magnet and the external radial current i flowing inside (Zm) and outside (mM) the magnet nmn'.

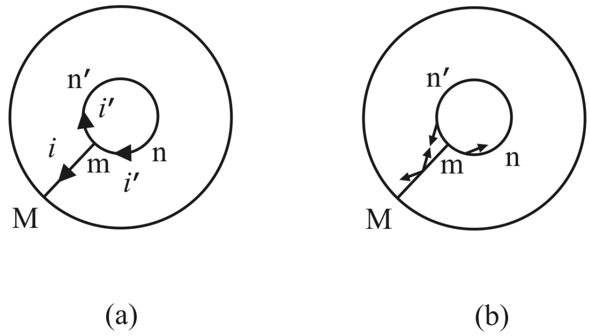

FIG. 7. (a) The arrows indicate the tangential microscopic current i' of the magnet and the radial macroscopic current i flowing outside the magnet. (b) The arrows indicate the attractive forces of action and reaction acting between i' in the portion mn' and i, and the repulsive forces of action and reaction between i' in the portion nm and i.

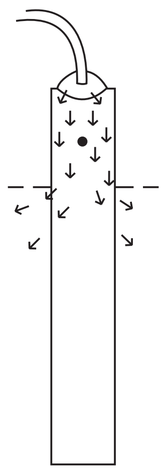

FIG. 8. Faraday's explanation of Ampère's motor.

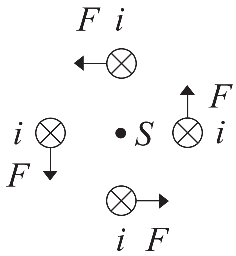

FIG. 9. Forces F exerted by the south pole S upon the internal currents i coming down through the magnet.