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The Worldwide Simplest and Oldest Motor: How does it operate?

Hermann Härtel

ITAP –Institute for Theoretical Physics and Astrophysics

University Kiel

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Abstract

Based on a publication of Assis, where the most straightforward and oldest motor is described, first constructed by Ampère, a simple experiment is added to demonstrate once again, why published explanations about its principle of operation and especial the kind how Newton´s 3rd principle is used has to be rejected. Ampère´s description of his motor and how it operates was explained in detail.

Keywords: Lorentz force, Newton´s 3rd law, Ampère´s law, Ampère´s motor.

INTRODUCTION

Due to the availability of rather strong permanent magnets, an effortless motor can be set up. It consists of 4 components: a 1.5 V battery, a cylindrical neodymium magnet, a ferrous pointed nail, and a short copper cable (fig. 1).

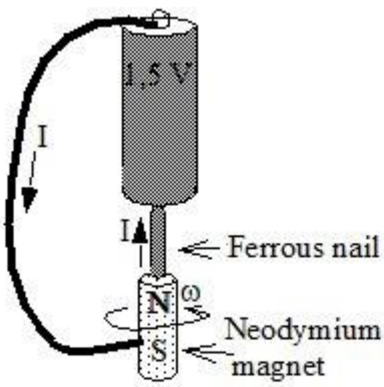

Figure 1. *The "simplest" motor*

After closing the circuit, the nail and magnet begin to rotate to the surprise of the audience, and this with an amazingly high rotational frequency (an estimated value of about five rpm). The current drawn from the battery through the nearly shorted circuit is between 1 and 2 A.

This motor is frequently demonstrated at various level schools and during open education events. Its principle of operation, however, has yet not been clearly explained and understood.

This paper is based on a publication of Assis (2012), where he presents the history of this motor, including the controversy between Ampère and Faraday about its principle of operation and where he questioned the recent related publications.

This paper adds a simple experiment to the discussion to show why some of the published explanations (Chiaverina, 2004; Schlichting & Ucke, 2004; Featonby, 2006) are not acceptable. It further questions the kind, how Newton´s 3rd law is applied in these publications to explain the operation of this motor. Finally, a short description of Ampère´s fundamental law and his explanation of how his motor operates is added.

Problematic Explanations

Figure 2 clarifies the explanation offered in one of the cited publications (Chiaverina, 2004).

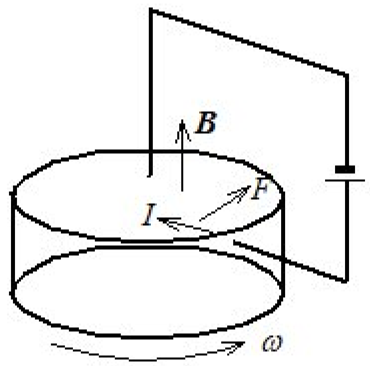

Figure 2. *Schematic representation of magnet and circuit together with an indication of the magnetic force F.*

The electric current passes through the magnet and its magnetic field. A magnetic force whose direction is given by the right-hand rule is applied to the flowing electrons, and - so it is said - this force transforms into a torque on the magnet and causes its rotation.

If the magnetic field would be "extrinsic", imposed from outside, then this explanation could seem to be just fine. However, both the magnetic field and the moving free electrons as partners of the interaction, according to the Lorentz force, are intrinsic to the magnet. Any action/reaction force, originating from these interacting partners are intrinsic and can never cause a rotation of the complete magnet.

The other cited publications follow the same type of argument as visualized in figure 2 and are all not acceptable

The controversy between Faraday and Ampère was about the same question: Can a body be set in rotation by internal forces? Ampère insisted that an external influence could only effect such a rotation, and he also provided a corresponding explanation derived from his force law. This explanation will be presented later.

The Experiment

The problem with the explanation, as mentioned earlier, shown in figure 2, can be demonstrated by a simple experiment.

If you put a slightly thicker metallic (but not magnetic) ring around the magnet (fig.3) with the ring firmly connected mechanically and electrically to the magnet, the contact point for the electric current is moved to an area with a much smaller magnetic field. This metallic ring does not change the electric current through the magnet, the magnetic field of the magnet remains the same, and thus also the effect of the magnetic force postulated inside the magnet should remain the same.

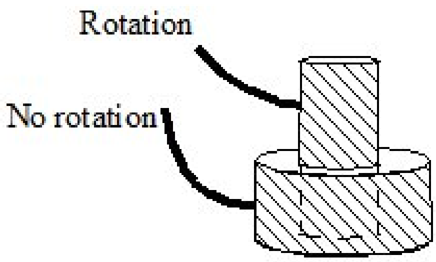

Figure 3*. Arrangement for moving the contact point to the outside.*

The experimental result is clear. Already with an aluminum ring with a wall thickness of 1mm, it is slightly more difficult to affect a rotation. With a wall thickness of 5 mm, no rotation can be induced. There is a video available on the net showing this experiment (http://www.astrophysik.uni-kiel.de/~hhaertel/Videos/Einfachster-Motor.mp4)

Applicability of Newton´s 3rd law

Taking the proposition of Newton´s 3rd law seriously, it should be clear from the outset that internal forces alone cannot cause the rotation, but that external action is required. Such an explanation based on the Lorentz force in connection with this motor has been published (Wong 2009). The explanation presented there sets the focus on an interaction between the drifting free electrons in the external circuit near the contact point and the rather strong magnetic field at this area outside the magnet. Figure 4 illustrates this explanation.

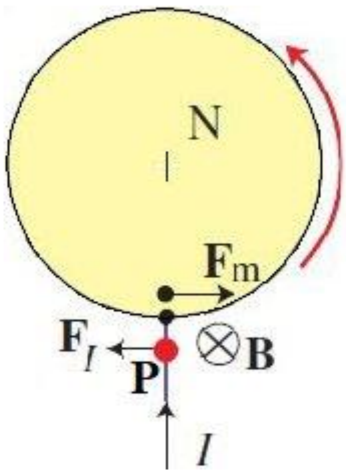

Figure 4. *Top view of the magnet indicating the action and reaction forces (see text)*

Consider the current at point P, marked in red. There, due to the magnetic field B, directed into the page, the magnetic force F_I acts on the drifting free electrons inside the wire. According to Newton´s action/reaction principle, and according to the author´s argument, there exists a force F_m of equal strength inside the magnet, pushing the magnet in the opposite direction. Due to the torque formed by F_I and F_m, the magnet rotates in the indicated direction (and the conductor - if free- would rotate in the opposite direction).

This explanation, presented by Wong, is unsatisfactory because it just refers to the action/ reaction principle without attending any further details. These details would have to refer to both interaction partners, on the one hand, the permanent magnet with its magnetic field, caused by internal microscopic currents or spins, and on the other hand, the external current with its surrounding magnetic field.

Assuming that such an interaction would be the source of two forces in the opposite direction acting on the free electrons on both partners, an open question remains: How could these forces, strictly only acting on moving electrons, be transferred to the core of the conductor and the permanent magnet, respectively?

In the case of a long and thin conductor like the wire at point P in figure 4, such a coupling between the free electrons and the metallic wire is conceivable. The flowing electrons, when crossing the magnetic field of the permanent magnet, experience a force proportional to (v x B) and are diverted sideways. Since they cannot leave the wire (neutrality must be maintained), there will be a pile-up of surface charges producing an electric field. This electric field couples the surface charges with the metallic wire by some kind of contact forces and could pull the wire sideways.

In the case of the permanent magnet, the situation is different. The source for a force applied to the magnet can only come from the external current and its magnetic field, it cannot come from its magnetic field. If so, this would contradict Newton´s „action/reaction "principle.

To find such a force, a situation like in figure 5 can be studied as a first approach where a current-carrying solenoid is being traversed by an external current, assuming the same magnetic field outside.

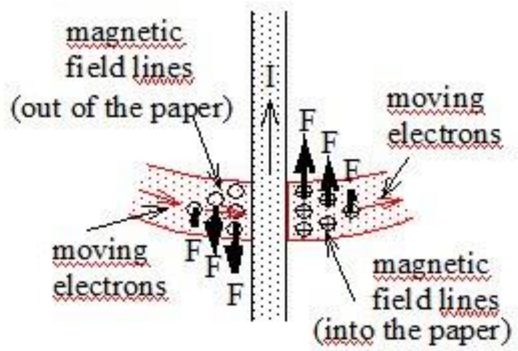

Figure 5. *Magnetic forces on a current-carrying solenoid due to the magnetic field of a traversing external current.*

As shown in figure 5, two forces of opposite direction will be applied to the flowing electrons in the solenoid due to the magnetic field of the external current. Such a pair of forces, if they could be transferred from the flowing electrons to the solenoid, would just cause the two currents to align. These forces cannot cause the magnet to rotate around its axis of symmetry.

There is no argument known why this conclusion should not hold for the currents inside a permanent magnet. Whatever the path of the electric current is from the rim of the magnet to its central axis, a permanent rotation around this axis cannot be expected.

DISCUSSION

How does this little motor operate? The previous considerations have shown that the Lorentz force does not help to find an answer to this question. What is needed is an interaction between the external conductor and the magnet in the form of attraction/repulsion forces to explain the observable rotation.

An answer to this question can be found in the work of Ampère, first published in 1822. As Assis has reported (Assis 2012), Ampère presented in 1822 for the first time a motor where a cylindrical permanent magnet rotated around its axis of symmetry. Ampère gave an explanation based on his newly developed law about the interaction between current elements (the original Ampère´s law). Figure 6 shows a schematic representation of this motor.

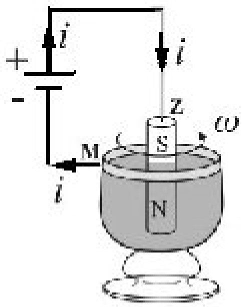

***Figure 6**. (a) A schematic representation of Ampère's motor*

The permanent magnet S-N is floating in mercury and can freely rotate around its axis. The external current enters the arrangement at point Z and leaves it at M. The little motor of figure 1 is a modern development of Ampère's motor. The essential building blocks are the same: a cylindrical magnet that can freely rotate around its axis and an external electric circuit, entering the magnet at its center and leaving it at its rim or vice versa. Therefore, both devices should be explained in the same way.

To follow Ampère's explanation, described below, the following points are helpful to know:

1. Ampère believed that all phenomena of natural magnetism were due to an interaction between electric currents. To explain the effect of permanent magnetism, he postulated the existence of microscopic electric currents inside the magnetic material.

2. Ampère insisted that all forces occurring in nature must be governed by Newton's principle of "action equals reaction" in its strict form, i. e. that there can only be equally attractive and repulsive forces whose line of action coincides with the connecting line of the interacting partners.

3. Ampère succeeded in formulating a law - based on his experiments and using various newly developed measuring devices to study this interaction. This law allowed him to make quantitative statements about the interaction between two DC elements at any orientation in

space. This law was relatively well received at that time, as evidenced by the following quotation from a statement by Maxwell

„The experimental investigation by which Ampère established the law of the mechanical action between electric currents is one of the most brilliant achievements in science. The whole, theory, and experiment, seems as if it had leaped, full-grown and fully armed, from the brain of the 'Newton of Electricity.' It is perfect in form and unassailable inaccuracy, and it is summed up in a formula from which all the phenomena may be deduced. Which must always remain the cardinal formula of electrodynamics."

4. In modern vector notation, Ampère's force dF between 2 current elements Ids and I'ds' at a distance r and with r_0 as a vector of unit magnitude pointing along r is given by:

$$dF = -\frac{\mu_0}{4\pi} II' \frac{r^0}{r_2} [2(d\vec{s} \cdot d\vec{s}') - 3(r^0 \cdot d\vec{s})(r^0 \cdot d\vec{s}')]$$

For the simple case of two current elements, lying in the same plane, the following four rules follow from this law, which are helpful to understand Ampère´s explanation:

1. Parallel directed current elements attract each other
2. Anti-parallel directed current elements repel each other.
3. Current elements flowing in the same direction repel each other.
4. Current elements flowing in the opposite direction (in separate circuits) attract each other.

Rules 1 and 2 are consistent with the well-known rules about magnetic forces between parallel oriented current-carrying conductors.

Rules 3 and 4 do not exist in classical electromagnetism. Since an electric current contributes no magnetic force in its flow direction or opposite to it, no statements can be made in the frame of classical electromagnetism about any interaction between current elements oriented as indicated in rules 3 and 4.

In respect to rule 3, however, there is a relation to classical electromagnetism. It is known that current-carrying circuits tend to extend. This can be explained by the rule that in a closed circuit, all parts with currents flowing in anti-parallel direction do repel each other (see figure 7).

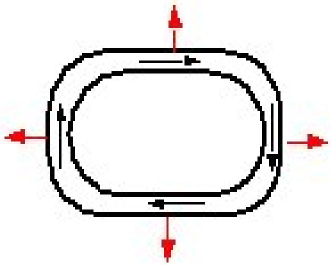

Figure 7. *Magnetic forces between oppositely oriented circuit elements*

Therefore, there should be certain longitudinal stress present in all closed current carrying circuits. Such stress could also be explained by rule 3 mentioned above. For rule 4, however, no relation can be found to any rule within the frame of classical electromagnetism.

For the following explanation given by Ampère, it may be helpful to note that there is a continuous transition from rule 3 to rule 4 as a function of the angle between two planar current elements. Figure 8 demonstrates this transition from attractive to repulsive interaction, depending on the angle between planar current elements.

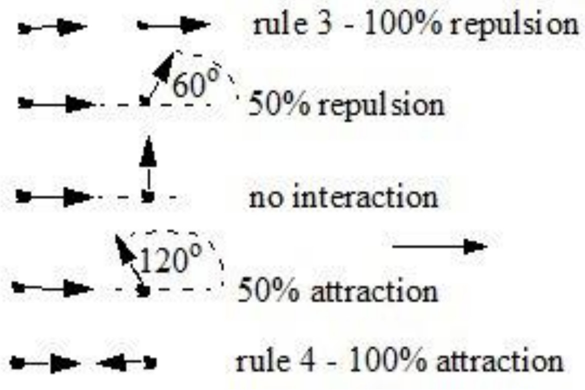

Figure 8*. The transition between rule 3 and rule 4*

These rules 3 and 4, based on Amperes force law and later confirmed by Weber´s law of force (published in 1846) are helpful to understand Ampère‘s explanation regarding the operation of his motor (see fig.9)

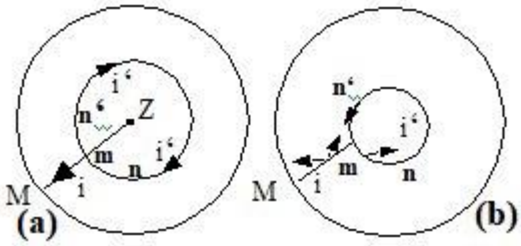

Figure 9. *(a) The arrows indicate the tangential microscopic current i' of the magnet and the radial macroscopic current i flowing outside the magnet.*
(b) The arrows indicate the attractive forces of action and reaction acting between i' in the portion m-n 'and i, and the repulsive forces of action and reaction between i 'in the portion n-m and i.

The current i' is the solenoidal current as a result of microphysical currents. As already mentioned, such currents were introduced by Ampère as a source of natural magnetism.

In his explanation described in figure 9, Ampère is pointing to sections of currents to both sides of the crossing point as the sum of single current elements. The current elements in such sections have oppositely directed velocity components relative to the external current (the partner of interaction). Due to rule 3 and 4 such oppositely directed flow directions lead to either attractive or repulsive forces

Figure 10 shows how rules 3 and 4 can be helpful to understand Ampère's explanation about the principle of operation of his motor.

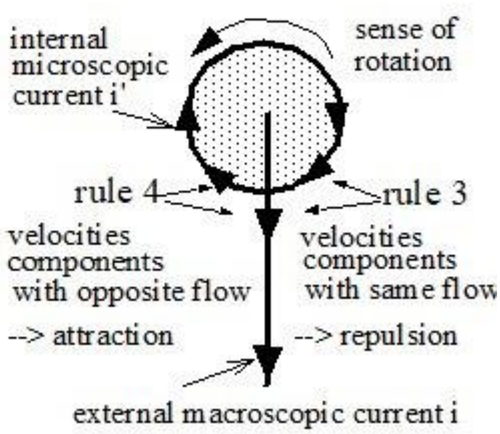

Figure 10*. Exemplification of Ampère's explanation of how his motor works*

The interaction forces between the elements of the two circuits vary inversely with the square of their distance and have, therefore, their origin close to the crossing point.

Applying rules 3 and 4 to the velocity components of the flowing electrons on the two opposite sides leads to the needed oppositely directed forces between the oppositely located sections to explain the rotation of the little motor.

For a detailed description, how these four rules can be derived from Weber´s fundamental Law of Electrodynamic by using only graphical means and qualitative arguments (see Härtel 2018). For a treatise about Weber´s work and a confirmation of this derivation in modern notation (see Assis 1994).

FURTHER PLANS

The problems with generally acceptable explanations continue if the little motor is used as a generator. By rotating the magnet, a voltage is induced between its rim and its axis. This effect is called Unipolar Induction and has been discussed for almost 200 years, ever since Faraday raised this problem in the 1830s. Different authors present different points of view when comparing many different experiments, and no consensus has been reached after 200 years. In a following-up paper, it will be tried to add some constructive arguments to this discussion on the base of own new experiments.

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