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Explaining Electromagnetic Induction using the Magnus Effect

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Abstract: According to Faraday's formula for electromagnetic induction, the mechanism by which induced electromotive force (EMF) is generated is unclear. This study proposes a possible mechanism by which the induced EMF is generated using a simple experimental setup. Herein, the angle of a circular coil made of copper wire is changed at every 15° (0°–360°) and brought close to the magnetic field at the center of the bar magnet to investigate changes in the EMF. The magnetic force lines are nearly straight and parallel at the center of the bar magnet. Moreover, at this position, the ↑ spin valence electrons are expected to align parallel to the bar magnet's north–south direction. Results showed that EMF varies with the angle and is distributed on the graph of $y = \sin\theta$, similar to the Magnus effect of airflow.

Keywords: Magnus effect; electromagnetic induction; magnetic flux density; Precession of electrons

1. Introduction

This study experimentally verifies whether the relationship between the electron's precession [1] and magnetic flux density resembles the relationship between airflow and the Magnus effect [2] shown in Figure 1a when the magnetic flux density is applied at different angles to the electron's precession axis. For the first verification, changes in the Magnus effect were examined by applying air currents at different angles (60°–330°) to a rotating styrene ball. Furthermore, this study investigated whether the electromotive force (EMF) generated when the magnetic flux density at different angles (from 0° to 360°) impinges on the electron's precession axis is the same as that in the Magnus effect. Regarding the precession of electrons, research at the University of Tsukuba has confirmed that ↑spin electrons in a magnetic field precess clockwise in the direction of the magnetic field. [1]
To this end, all the electrons in the coil should be aligned in the same direction, i.e., the magnetic field lines must be parallel for the electrons to be aligned in the same direction. At magnetic poles, the electrons are not aligned in parallel because the magnetic field lines radiate out from the magnetic pole (Figure 1b); however, if we focus on the magnetic field lines at the center of the bar magnet (Figure 1c), we can see that they are nearly parallel. In this position, I infer that all the valence electrons in the copper circular coil point in the same direction as the magnetic field lines if the coil is at a 90° angle to the bar magnet. Hence, I assumed that the electrons in the coil are not aligned until the coil reaches this position. Therefore, I experimented to measure the (EMF) by fabricating a device in which the coil always enters the magnetic field at the center of the bar magnet at an angle of 90° (Figure 1d). In this device, the bar magnets and coils move at the same angle, which indicates that the magnetic flux density hits the precession axis of the electrons at different angles of 15° intervals. Surprisingly, the experimental results were the same as those obtained for the Magnus effect of airflow. Although a simple

comparison of the macroscopic rotating ball and microscopic electron's precession is difficult, the induced EMF could be due to an interaction between the electron's precession and magnetic flux density.

2. Materials and Methods

2.1. Experiment 1

As depicted in the apparatus shown in Figure 1e, hard steel (with a high elastic modulus) connected to the motor by a coupling was passed through the styrene ball, fixed with an adhesive, and rotated. Then, a scale was used to measure the change in the Magnus effect as airflow hit the center of a rotating ball at different angles of incidence. The airflow hits the rotating styrene ball, the ball is tilted to one side because of the Magnus effect. Here, a scale was used to measure the displacement value of the inclination of the ball. The relational expression between the displacement width x (mm) of this hard steel wire and cN was $f(x) = 0.1451x$. Furthermore, cN was calculated by substituting the measured displacement into the aforementioned equation. Then, a graph of the Magnus effect for each angle was created. The styrene spheres were selected because they are light; thus, they are easily influenced by the Magnus effect. As shown in Figure 1f, by using coupling, (the device that connects the motor with the rigid wire), the styrene ball (diameter: 50 mm) and the rigid wire forming the rotation axis (diameter: 1.2 mm and length: 398 mm) were connected with a motor. The rotational speed of the styrene ball is 5,925.16 rpm; the wind speed from the blower is 20.4 m/s. A motor (MABUCHI RS-380PH) with a working voltage of 3.3 V was used. The airflow from the blower was applied to the center of the rotating styrene ball, and the displacement width was measured in the range of 60°–330° at an interval of 15°. I averaged the five measurements for each angle of incidence. The measurement range was set from 60° to 330° to prevent the blower from touching the rotating shaft. The rigid wire, protruded from the top of the styrene ball by approximately 3 mm (see "b" in Figure 1f). The maximum value of this displacement was measured using the scale set in front of the styrene ball. To determine the displacement amount of the tilt of the styrene ball, slow-motion shots were captured using an iPad; thereafter, the scale was read while slowly moving at the image.

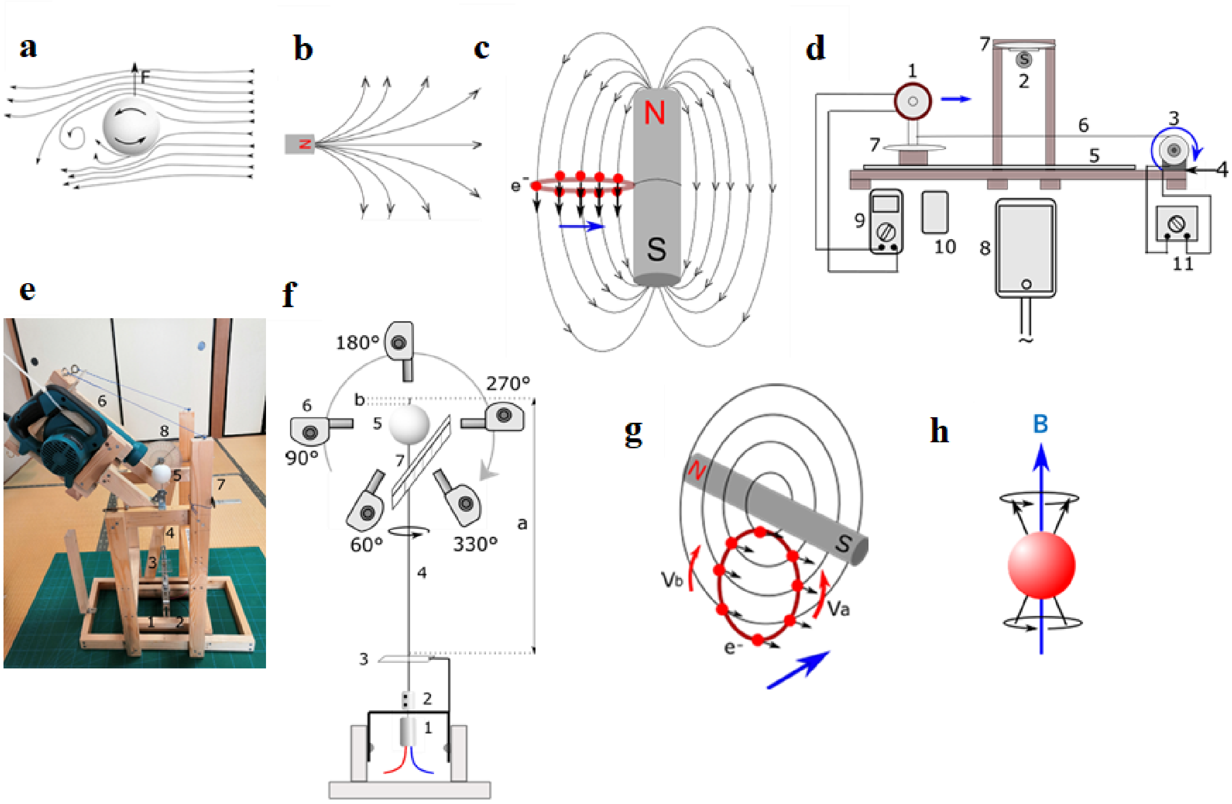

Figure 1. Induced electromotive force (EMF) and Magnus effect. **(a)** Magnus effect, **(b)** N pole magnetic field lines **(c)** Red balls, black arrows, and blue arrows indicate electrons in the coil, the direction of electrons, and the direction of the coil motion, respectively. **(d)** Apparatus to measure EMF depending on the incident angle of the coil into the magnetic field. 1: coil, 2: bar magnet, 3: take-up pulley, 4: gearbox with built-in motor, 5: roller stand, 6: kite string, 7: protractor, 8: iPad, 9: digital direct current (DC) voltmeter, 10: smartphone timer, and 11: DC power supply. The distance between right below the center of "2" and the upside center of "1" is 29 mm. **(e)** Equipment for verifying the Magnus effect via airflow. **(f)** Schematic of **(e)**. 1: motor, 2: coupling, 3: support plate, 4: hard steel wire, 5: styrene ball, 6: blower, and 7: scale. In Figure 1e, 8 is a protractor; a = 335 mm and b = 3 mm. **(g)** Red arrows Va and Vb show the EMF generated at the frontside and backside of the coil, respectively. The measured EMF is equal to Va − Vb. **(h)** Electrons in precessional motion in a magnetic field.

2.2. Experiment 2

The magnetic force lines at the center of the bar magnet were almost parallel and aligned in the same direction (Figure 1c). Therefore, all electrons in the coil were presumed to be aligned in nearly the same direction. Furthermore, as indicated by the blue arrow in Figure 1g, the electrons in the coil proceeding to the center of the bar magnet were considered to generate an upward EMF at this position (Figure 1g) due to the interaction between the electron's precession and magnetic flux density. The upward EMF is generated in both the front and end parts. However, as the front part of the coil was closer to the center of the magnet and the magnetic force was stronger, a stronger EMF was considered to be generated there. The EMF measured by the voltmeter corresponded to the difference in the EMFs between the front part of Va and the end part of Vb. Based on these results, a new experimental apparatus (Figure 1d) was constructed. This experimental device allows coils at different angles to pass through the center of a bar magnet. Using this apparatus, the experiments were conducted for 0°–360° at 15° intervals to verify how the EMF changes depending on the incident angle of the coil in the magnetic field. A bar magnet (total length: 110 mm) was prepared by stacking 23 circular neodymium magnets (diameter: 20 mm, thickness: 4.8 mm, and magnetic flux density: 1225 G). The magnetic flux density (G) was 92.2 G at a distance of 37 mm from the center of the bar magnet. The coil used was made by winding a copper wire (diameter, 0.26 mm) 100 times (diameter, 58 mm; coil width, 12 mm; coil thickness, ~0.5 mm). The distance from the center of the bar magnet to the center of the top of the coil (a) was 29 mm (Figure 2a). Using a gearbox with a built-in motor, the coil was placed on the roller stand and passed under the center of the bar magnet at a speed of 23.97 mm/s. I used a DC digital voltmeter to measure the EMF (mV) corresponding to the moment the tip of the coil reached just below the center of the bar magnet (Figure 2a). The resolution and accuracy of the voltmeter were 0.1 mV and ±(0.1% + 1), respectively. I calculated the average value based on 5 measurements for each angle. I found that this digital voltmeter displays the measured value on the LCD display 4 times per second (every 0.25 seconds), so the display is delayed by 0.25 seconds. As a result, measuring the value at 0.25 s after reaching just below the center of the bar magnet was essential. Therefore, using the slow-motion application (SloPro) on the iPad, a video was shot on the same screen using a smartphone timer that can display up to 1/1000 s and a voltmeter. After shooting, the motion on the screen was observed in slow motion; the time at the moment when the tip of the coil reached just below the center of the bar magnet was confirmed using a timer, and the value (mV) of the voltmeter was read 0.25 s later. Both the bar magnet and circular coil could rotate 360° and a protractor was set at each instrument to confirm the angle. As shown in Figures 2b1, b2, and b3, which are top views of Figure 1d, the voltmeter value (mV) was always measured 0.25 s after the moment the coil entered the magnetic field of the bar magnet at right angles, with the coil and bar magnet adjusted at the same angle. The measured angle range was 0°–360°; I measured the EMF every 15°. The measurement timing is when the tip of the coil reaches just below the center of the bar magnet and the coil becomes perpendicular to the bar magnet. (Figure 2c). It is expected that the electrons in the coil were always aligned in the same direction, as indicated by the red arrow, due to the magnetic field at this position. Accordingly, the electrons in the coil were aligned on a straight line ("a" in Figure 2c) and facing the same direction, and all electrons were subjected to the motion of the magnetic flux density, as indicated by the black arrow from the same direction. I believe that this would cause an upward EMF similar to the Magnus effect of air currents. The main body, various mounting fixtures, screws, and nuts were made of wood, aluminum, and brass. Although these materials do not affect the magnetic field, the roller stand shown in Figure 1d (5) was made of iron. However, since the bar magnet is far away from the roller stand, I thought the effect would be minimal.

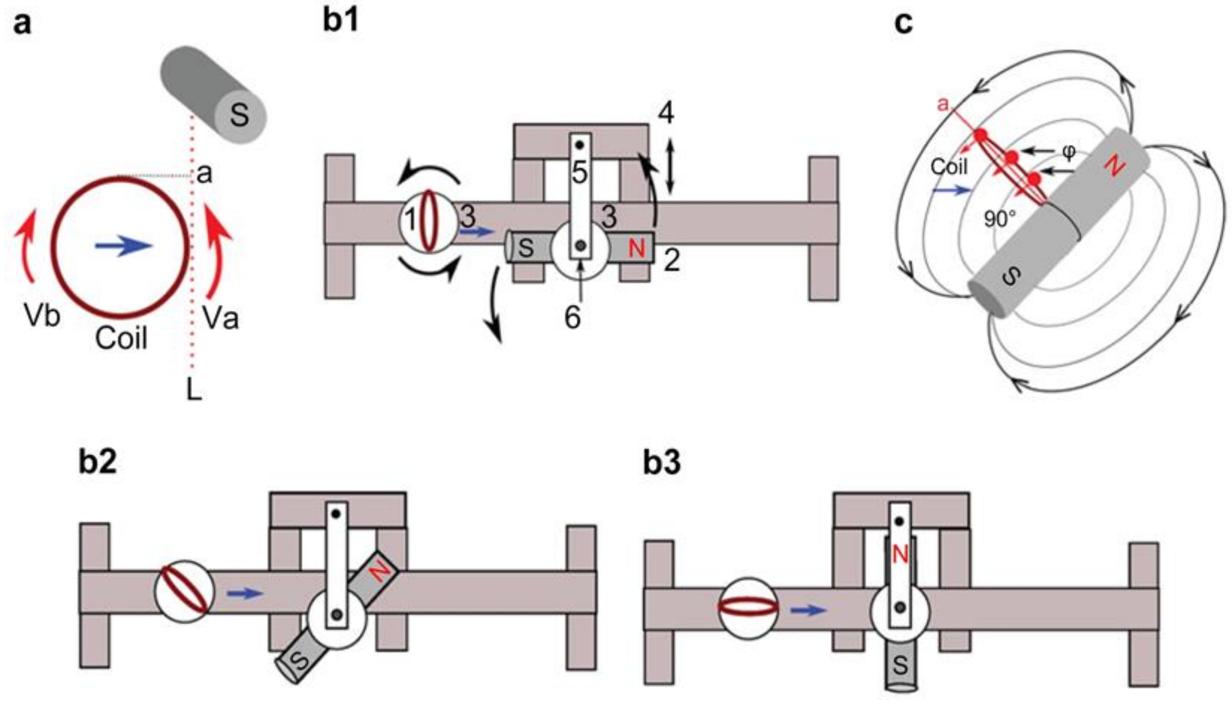

Figure 2. Angle of the coil proceeding toward the magnetic field and the angle of the magnet. **(a)** Measurement position of the EMF of the coil. **(b)** Top view of Figure 1d with 1: coil, 2: bar magnet, 3: protractor, 4: magnet mounting base movable, 5: aluminum fitting, 6: screw, and the blue arrow representing coil movement. b1: coil entering at 0°, b2: coil entering at 45°, and b3: coil entering at 90°. **(c)** The red balls, red arrows, black arrows, and blue arrows show the electrons within the coil, the direction of electrons, the direction of magnetic flux density, and coil motion, respectively.

3. Results

3.1. Experiment 1

Table 1 shows the Magnus effect data for each angle obtained in Experiment 1. Figure 3a shows a graph obtained by dividing the value obtained this way using the value 2.1185 at 90°. The solid line represents the graph for $y = \sin\theta$. The Magnus effect peaks at 90° (Figure 1f); however, at 180°, i.e., directly above the Styrofoam ball, it is nearly zero. Beyond that position, the Magnus effect begins to reverse and the displacement reaches a maximum at 270°.

Table 1. Data of Magnus effect due to airflow for each angle.

Angle	Displacement (mm)	cN	With 90° as 1
60	11.0	1.5961	0.7534
75	13.8	2.0024	0.9452
90	14.6	2.1185	1.0000
105	14.2	2.0604	0.9726
120	11.6	1.6832	0.7945
135	9.2	1.3349	0.6301
150	6.9	1.0012	0.4726
165	4.8	0.6965	0.3288
180	0.7	0.1016	0.0480
195	−4.7	−0.6820	−0.3219
210	−7.0	−1.0157	−0.4794
225	−10.2	−1.4800	−0.6986
240	−12.4	−1.7992	−0.8493
255	−14.4	−2.0894	−0.9863
270	−14.6	−2.1185	−1.0000
285	−13.6	−1.9734	−0.9315
300	−12.4	−1.7992	−0.8493
315	−10.2	−1.4800	−0.6986
330	−6.6	−0.9577	−0.4521

3.2. Experiment 2

Table 2 shows the EMF (mV) data for each angle obtained from Experiment 2. Figure 3b shows a graph obtained by dividing the value obtained this way using the value 0.348 at 90°. The solid line is the graph of $y = sin\theta$. The EMF was almost zero at 0°, maximum at 90°, and almost zero again at 180°. Thereafter, the values became negative, reaching a maximum at 270° and almost 0 at 360°.

Table 2. Experimental data of the EMF at each angle at the center of the bar magnet.

Angle	Electromotive force (mV)	With 90° as 1	Angle	Electromotive force (mV)	With 90° as 1
0	0.004	0.011	195	−0.086	−0.247
15	0.112	0.322	210	−0.168	−0.483
30	0.176	0.506	225	−0.252	−0.724
45	0.230	0.661	240	−0.290	−0.833
60	0.320	0.920	255	−0.326	−0.937
75	0.330	0.948	270	−0.334	−0.960
90	0.348	1.000	285	−0.300	−0.862
105	0.338	0.971	300	−0.286	−0.822
120	0.320	0.920	315	−0.220	−0.632
135	0.218	0.626	330	−0.138	−0.397
150	0.172	0.494	345	−0.040	−0.115
165	0.066	0.190	360	0.026	0.075
180	0.010	0.029			

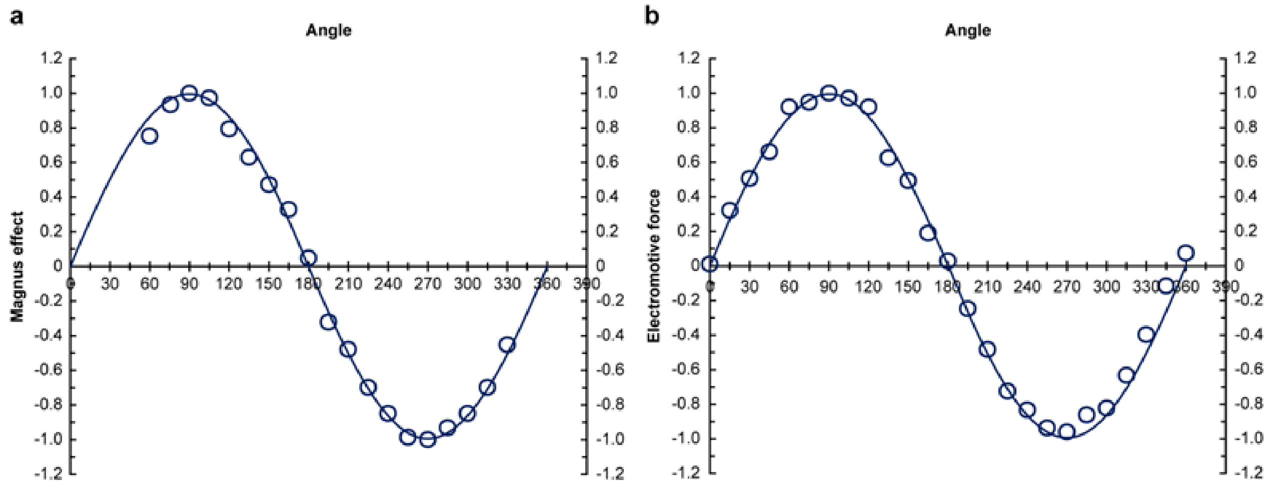

Figure 3. Graphs from experimental data. (a) Magnus effect due to air flow at each angle. The open circles show the values where the measured values were divided by that at 90°. The solid line shows the graph represented as $y = sin\theta$. (b) EMF at the center of the bar magnet at each angle. The open circles show the values where the EMF at each angle was divided by the value at 90°. The solid line shows the graph represented as $y = sin\theta$.

4. Discussion

The Magnus effects due to air flow at each angle (Experiment 1) were distributed on the graph of $y = sin\theta$ in the range of 60°–330° (Figure 3a). Furthermore, the EMF in the central part of the bar magnet at each angle seems distributed on the graph of $y = sin\theta$ in the 0°–360° range (Figure 3b). These results indicate that when airflow hits a rotating sphere and also when a magnetic flux density hits a electron's precession axis, the same mechanism works. The results described so far show that when airflow hits the rotating sphere by changing the incident angle against the rotation axis of the sphere, the Magnus effect changes. Furthermore, the EMF changes when a magnetic flux density with a different incident angle hits the electron's precession axis.

These phenomena can be explained based on Figure 4a, in which the black arrows represent the magnitude of the magnetic flux density at each incident angle against the electron. Even when the incident angle is different, all the magnitudes of the magnetic flux density are equal because the speed of the coil is the same. The bold red arrows, which show the direction of electrons, indicate that the direction of the electrons is toward the right, i.e., the direction of the magnetic field. Considering that the electron's precession rotate clockwise relative to the direction of the magnetic field, EMF is considered to be generated via the phenomenon estimated to be the Magnus effect in the forward direction, as shown by the blue arrow. The EMF generated by the phenomenon estimated to be the Magnus effect becomes largest when the magnetic flux density hits the electron’s precession axis at 90°. The phenomenon that can be speculated as the Magnus effect seems to be related to the component striking at 90° to the electron’s precession axis. Each red arrow in a, b, c, and d represents the magnitude of the magnetic flux density of the component that hits the electron’s precession axis at 90° (downward in Figure 4a). The magnitude of the magnetic flux density is the largest at 90° for “a,” and it is expected to be the smallest at 0° for “d.” Additionally, the magnitude is expected to be expressed by $sin\theta$. When the magnitude of a magnetic flux density that hits an electron is attenuated according to $sin\theta$, the EMF can also be assumed attenuated according to its ratio. Therefore, the changes in the EMF of electrons are estimated to be distributed on the graph of $y = sin\theta$, similar to changes in the Magnus effect for airflow.

Furthermore, this phenomenon can be inferred to be the Magnus effect due to the magnetic flux density acting on the electron precession axis, and it applies to Fleming's right-hand rule. Comparing Figures 4b and 4c, these two cases are estimated to represent the same phenomena. When the electron aligns in the direction of the magnetic field and when it is rotating precession clockwise by looking toward this direction, the magnetic flux density moves relatively downward according to the upward motion of the coil (conductor) (Figure 4b). At that moment, EMF is generated via the Magnus effect, and electrons move backward. Because the electric current is reversed with respect to the motion of electrons, the current flows to the front. Based on these considerations, the phenomenon estimated to be the Magnus effect of electrons can also be considered to be expressed by Fleming’s right-hand law (Figure 4c). Further, we considered whether the Lorentz force acting on electrons moving in a magnetic field can be explained by the phenomenon estimated to be the Magnus effect of electrons. Let us compare Figure 4d with Figure 4e. Let the electron in Figure 4d move in the direction of the back in the magnetic field pointing to the right side. Because the electric current is reversed with respect to the motion of electrons, the current flows to the front. The thin black arrows pointing to the right represent the magnetic field direction. The electron will change its trajectory by receiving the upward Lorentz force. This Lorentz force is presented in Figure 4e, i.e., Fleming’s left-hand law. Because the electron in Figure 4d is moving backward, the magnetic flux density relatively moves to the front, as shown by the thin blue arrows. If the electron’s precession is rotating clockwise with respect to the magnetic field direction, the electron will gain the upward force via the phenomenon estimated to be the Magnus effect of this moving magnetic flux density. Therefore, both the Lorentz force and Fleming’s left-hand law could be explained by the phenomenon estimated to be the Magnus effect of the electron’s precession rotation and moving magnetic flux density.

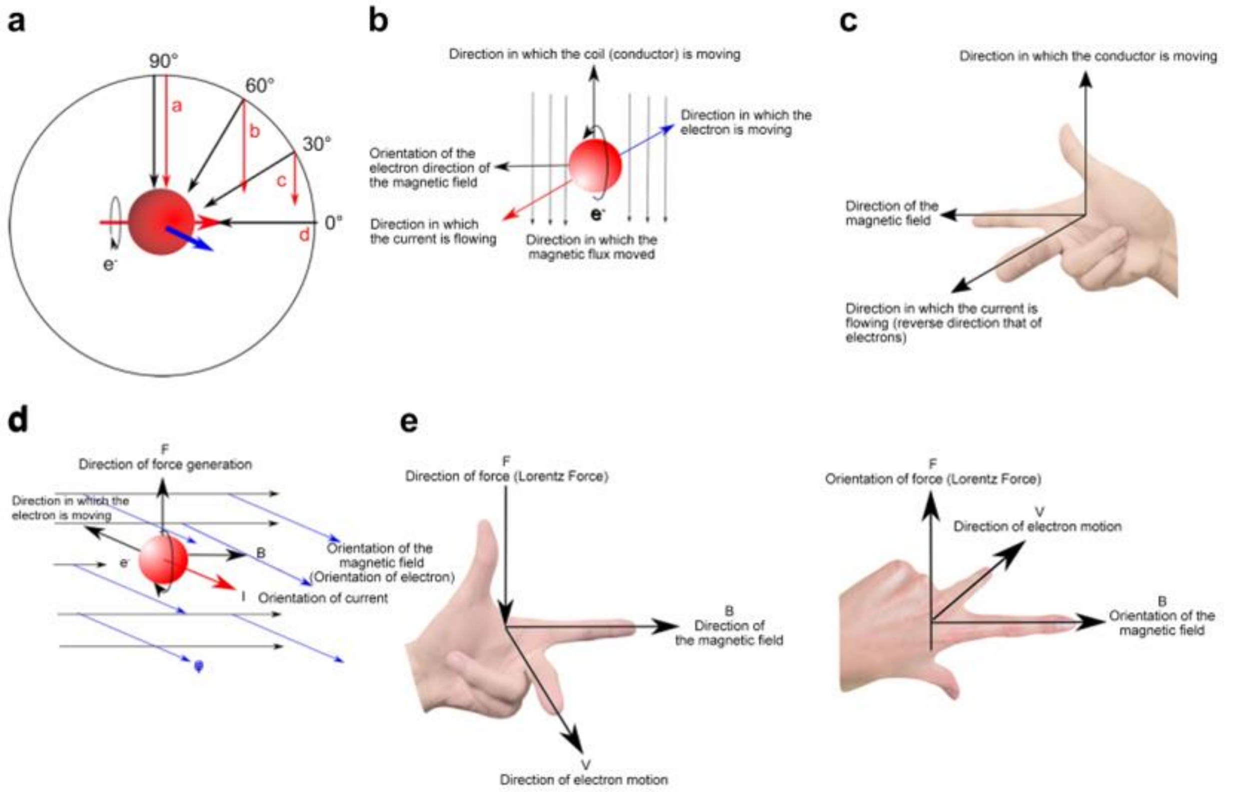

Figure 4. Contrasting the Magnus effect and the movement of electrons. **(a)** Change in the EMF of electrons. **(b)** The direction of electron motion when the coil moves in the magnetic field. The red ball is a precessing electron. The black arrow in the upward direction indicates the direction in which the coil is moving. The black arrow in the left direction is the direction of the magnetic field. The thin black arrow pointing downward is the direction in which the magnetic flux density is moving. The blue arrow indicates the direction in which the electron is moving. **(c)** Fleming's right-hand law. **(d)** The red ball is a precessing electron. The black arrow in the back direction is the direction in which the electron is moving. The black arrow in the right direction is the direction of the magnetic field. The blue arrow pointing front side represents the movement of the magnetic flux density. The black arrows in the upper direction show the orientation of force. **(e)** Fleming's left-hand law (in cases of the electron) at the front and back.

5. Conclusions

Collectively, the results indicate that the EMF generated in the coil moving in the magnetic field is caused by the Magnus effect, which is the interaction between a electron's precession and the magnetic flux density hitting it. Dr. Yoshida's group at the University of Tsukuba observed that the electron's precession clockwise when viewed from the magnetic field's direction. [1]

It can be inferred that the interaction between the precessing electrons and the magnetic flux density causes an effect similar to the Magnus effect, causing the electrons to move.

In the precession of electrons, each point of the electron moves in a circular motion, and I believe that the Magnus effect occurs when the electron moves in a circular motion in the direction opposite to the direction in which the magnetic flux density collides. (Figure 5)

Therefore, the Magnus effect may occur alternately before and after the electron, and the electron may be moving.

Anyone can easily make this experimental device and conduct experiments, so I would like researchers to replicate this experiment and confirm that the published data is correct.

If you have a different opinion than mine, I would appreciate it if you could let me know.

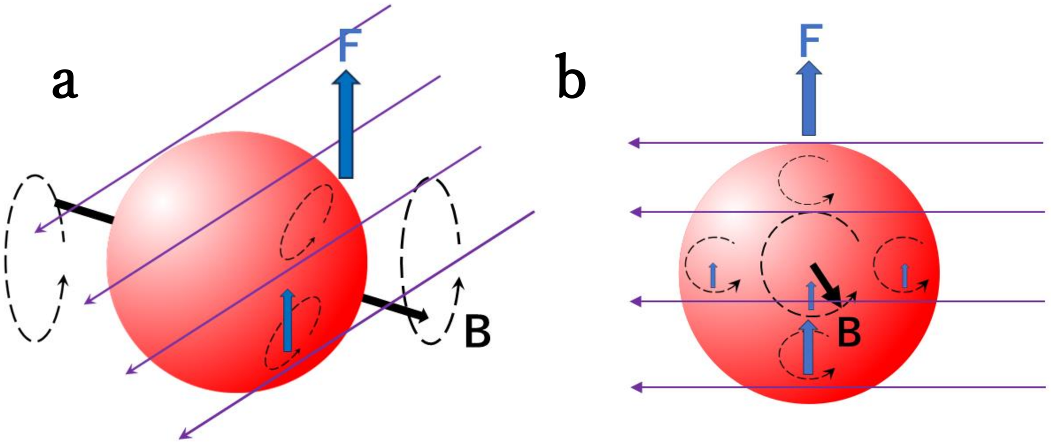

Figure 5. Hypothetical diagram of the Magnus effect acting on precessing electrons. **(a)** Side view. The thick black arrow is the precession axis, which precesses clockwise around the dotted black circle. The purple arrow to the left indicates the movement of magnetic flux density. The small black dotted circles show the circular motion of each point of the electron, which collides with the magnetic flux density at the bottom of the electron, creating a blue upward Magnus effect that lifts the electron upward. **(b)** Front view. The thick black arrow is the precession axis. The purple arrow to the left indicates the movement of magnetic flux density. The black dotted circle represents the circular motion of each point of the electron. The blue arrow pointing upwards is the Magnus effect. The bottom of the electron collides with the magnetic flux density, producing an upward Magnus effect in blue. The upper part of the electron also collides with the magnetic flux density, but the magnetic flux density escapes upward, so no Magnus effect occurs.

References

1.Yoshida, S.; Aizawa, Y.; Wang, Z.H.; Oshima, R.; Mera, Y.; Matsuyama, E.; Oigawa, H.; Takeuchi, O; Shigekawa, H. Probing ultrafast spin dynamics with optical pump-probe scanning tunneling microscopy. *Nature Nanotechnology* **2014**, 9, 588–593.

University of Tsukuba paper (Japanese)

https://www.tsukuba.ac.jp/images/92a9444fccb085f99705b353bb27a6cd.pdf

2.Muto, M.; Watanabe, H.; Tsubokura, M.; Oshima, N. Negative Magnus effect on a rotating sphere at around the critical Reynolds number. *J. Phys. Conf. Ser* **2011,** 318, 032021.