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Research Article

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Analysis for Levitation of EHD and Electrostatic Propulsion Device in Direction of Gravity using Optical Flow Method

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Abstract

Electro hydro dynamic (EHD) and electrostatic propulsion devices have no moving parts and, in the air, operate on electrical energy. Thus, electric propulsion systems without moving parts such as propellers are expected to be developed in the future. EHD devices levitate in the direction opposite the direction of gravity when a high voltage is applied. In this study, detailed properties of the accurate propulsion direction, speed, and acceleration were clarified by imaging analysis. The analysis clarified that even if the orientation of the device was initially tilted from a horizontal line, the device was made to levitate vertically upward in the same direction as the direction of gravity, and a restoring force acts to return the orientation to a horizontal line during the levitation. These phenomena are very strange and different from those of drones with propellers. When the device levitates, the acceleration does not become constant immediately after the voltage is applied, but after passing through 0, it increases linearly in temporal duration of sub 0.1 s and saturates. The saturation of the acceleration changed with the input voltage.

In this study, we used optical flow analysis, which is a well-known and proven imaging analysis, to analyze the trajectory of an object using image analysis. Detailed levitation properties have not been analyzed until now. First, as a result of analyzing the free flight characteristics of a single plate electrode, a single unit that has been very well researched in many papers, it was revealed that the direction of propulsion changes from the lateral direction to the direction of gravity midway through. Analysis on the levitation property of a EHD device, which has a special structure with a large area on the ground at a triangular center, and a propulsion device revealed that the EHD device can only levitate in almost the same direction as gravity. The maximum acceleration of the EHD device in these experiments was estimated to be 7 m/s^2.

Keywords: EHD, Electrostatic, Optical-flow method

1. Introduction

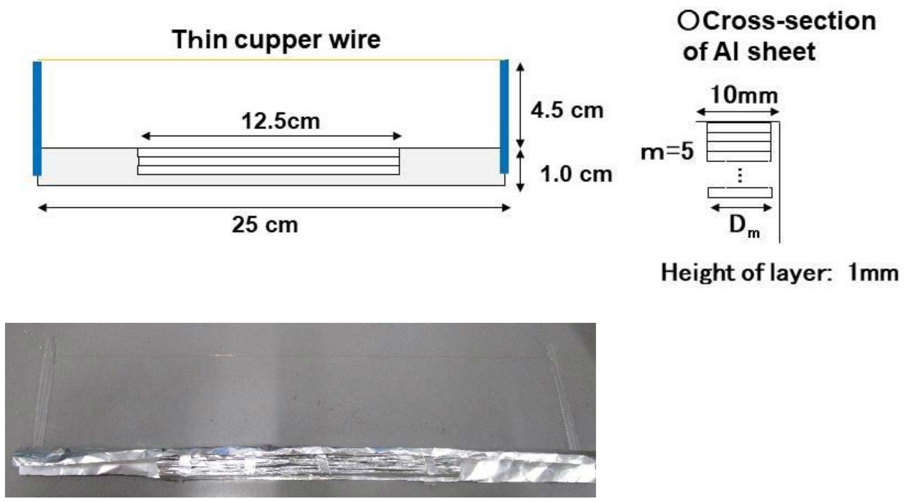
Electric propulsion systems without moving parts such as airplane and helicopter propellers are expected to be developed in the future. The advantage of such propulsion systems is that 1) there are no moving parts, so they are easy to maintain and 2) the propulsion efficiency may exceed that of the conventional engine.

From results of a series of thrust generation experiments testing the Brown effect at high voltage, the principle of ion craft was reported to be propulsion caused by the imbalance of electrostatic force and attraction caused by space charge [1,2]. Many experimental results from other papers support this finding [3-16]. It is considered that the propulsion principle is determined not by the ion wind but by the external electric field (applied voltage) and the amount of electric charge accumulated in the electrode. The principle of lifters has been widely researched.

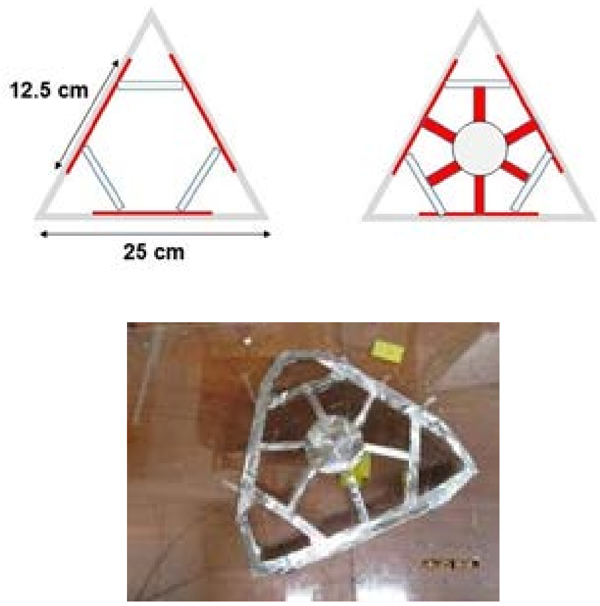
Up to now, many attempts have been made to explain the causes of levitation force analytically [5-8,10]. Methods have been discussed for improving levitation force, electric field distribution, and ion distribution characteristics for EHD and propulsion systems with static electricity [13-15]. However, detailed analyses for the levitation property have not been reported. On the other hand, the temporal dependence of the velocity and acceleration for EHD devices has been reported. The purpose of this study is to clarify the levitation characteristics of EHD propulsion devices, which have not been elucidated previously. Specific characteristics to be clarified are the temporal dependence of the relationship between acceleration and velocity, the direction of levitation connecting with gravity, motion properties, changes in the velocity and the acceleration, and how the levitation characteristics change when the starting point of the levitation is tilted for the input voltage. We obtained velocity and acceleration of EHD propulsion devices by analyzing using an optical flow method for the first time. The levitation properties of two triangular EHD devices with multiple electrodes and an EHD device with a central structure were clarified.

Additionally, computer based imaging analysis has made remarkable progress in recent years [17-20]. A method was proposed for image recognition used in facial recognition, autonomous driving, etc. using computer vision (inputting image information into a computer and processing it to extract the necessary image information). One example is tracking an actual moving object in an image space. In this paper, we used the well-known optical flow analysis as a tool for analyzing the trajectory of objects in images [17,18]. We will discuss the merits of the analysis for position, velocity, and acceleration here. IC devices are usually used to measure the acceleration of an object and send information wirelessly. However, the disadvantages are 1) the levitation force of the EHD device is small, and the measurement device is too heavy to be mounted. Furthermore, because the EHD device is made to levitate by applying a high voltage, the machine has a high possibility of malfunctioning or being damaged. This computer analysis of images does not require the loading of heavy objects for measurement and, although it is an estimate, position, velocity, and acceleration can be measured without contact.

2. Experimental Set Up



(a)



(b)

Figure 1. EHD propulsion devices. (a) One unit EHD device. (b) Triangle EHD device.

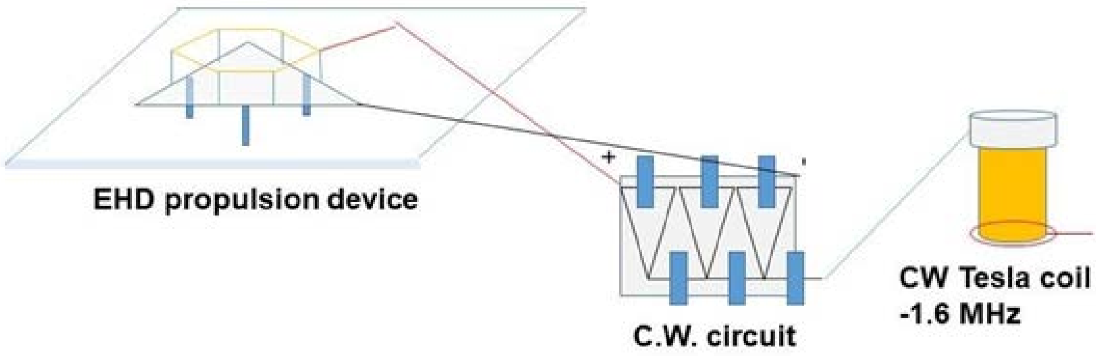


Figure 2. Experimental setup.

The used EHD propulsion devices are shown Fig.1. The parameters for EHD propulsion devices used in this analysis are shown in Table 1. Fig. 1(a) shows single unit EHD device, and (b) shows an EHD device with a star-shaped multi-electrode in the middle. (c) is a photograph of (b). In the figure, red indicates that the structure is multi-electrode. Ten layers of electrodes are used in the frame, and five layers of electrodes are used in the central star. Three places are connected to the desk with wires about 10 cm long. The used Al foil was 11 µm thick.

The experimental setup and the connection of high voltage source to EHD propulsion device are shown Fig.2.

Three multi-layered electrodes are set at the three red parts one by one. The devices are made of aluminum foil. The electrode was 25 cm long. Lm is set to 12.5 cm. The maximum output voltage of the used DC rectified power supply in this experiment was 30 kV. A Cockcroft-Walton rectifier with three-stage driving by a single output wire of Tesla coil operating CW mode was used to obtain DC high voltage output. The output frequency of the TC was 1.9 MHz. We can rectify the output signal from TC by connecting only a single wire. The gap length was chosen to be 4.5 cm. The used ultra-thin wire (50 µm thick) was connected to the + electrode, and the long plate electrode was connected to - electrode. The reason for using the ultra-thin wire is to enable low voltage operation. The EHD devices can operate up to be 30 kV.

The optical flow method is widely known as an analysis method that estimates position, velocity, and acceleration. The optical flow method expresses the motion of an object in a digital image as a vector and is mainly used for detecting moving objects and analyzing their motions. The analysis in this code extracts image feature points and tracks multiple feature points in the image. The advantage of this method is that the EHD device is applied with a high voltage and is difficult to contact, so the position, velocity, and acceleration of the object can be estimated by calculation without contact, which is highly effective. In this study, we attempted to analyze the position, velocity, and acceleration of a moving object using the Lucas-Kanade method, which is widely used among optical flow methods. In the video analysis, the kernel size was set to an appropriate value. The temporal resolution of the mpeg video was 25-30 fps. We wrote the Python code and used OpenCV, which is an open source library for image analysis. The parameters for used optical flow method in these analysis are shown in Table 2.

The image method will be explained. First, after converting the color image to grayscale, corner detection was performed, and feature points were tracked using the Lucas Kana method. The image position in the height direction was extracted.

Using the above optical flow method, we attempted to analyze the characteristics of two types of EHD devices in horizontal and oblique levitation.

Type 1	Length: 25cm Weight 1.2g	Number of multi-layered electrodes 3 Number of layer 10 Width of electrodes: 10mm
Type 2	Length :25cm Weight 1.7g	Number of multi-layered electrodes 3 Number of layer 10 Number of center electrodes 6 Number of layer 5 Width of electrodes: 10mm

Type 3.	Length :25cm Weight 2.2g	Number of multi-layered electrodes 3 Number of layer 10 Number of center electrodes 12 Number of layer 5 Width of electrodes: 10mm

Table 1. Type of EHD propulsion device.

Used Computing Library Spatial resolution number Programing Code: Parameter of Shi-Tomasi corner detection	OpenCV 1280 x 720 Python Max Corners = 7 Quality Level = 0.01 Minimum Distance = 10 Block Size: 3
Parameter of Lucas-Kanademe method	WinSize = (30,70) Max Level = 2

Table 2. Parameter for Calculation

3. Results

The experimental results for the calculated optical flow are shown in Fig.3. The red curved line is the trajectory at the feature points of the EHD device. The unit, which consists of a single aluminum foil plate, first moves sideways after power is applied. After that, it immediately changed its levitation direction vertically, which is the same as the direction of gravity. The two trajectories indicate reproducibility.

The analyzed velocity and acceleration in the horizontal direction is shown in Fig.4. The input voltage of the lower power supply was of 20V, the current was 0.5A, and the input high voltage was 20kV. The maximum lateral acceleration was 1.5m/s^2. The acceleration in the longitudinal direction was 4.5 times higher than that in the horizontal direction. In other words, it is difficult to propel the vehicle horizontally with the same power consumption. It became clear that the aircraft had strange flight characteristics. The lateral acceleration quickly changed to vertical acceleration.

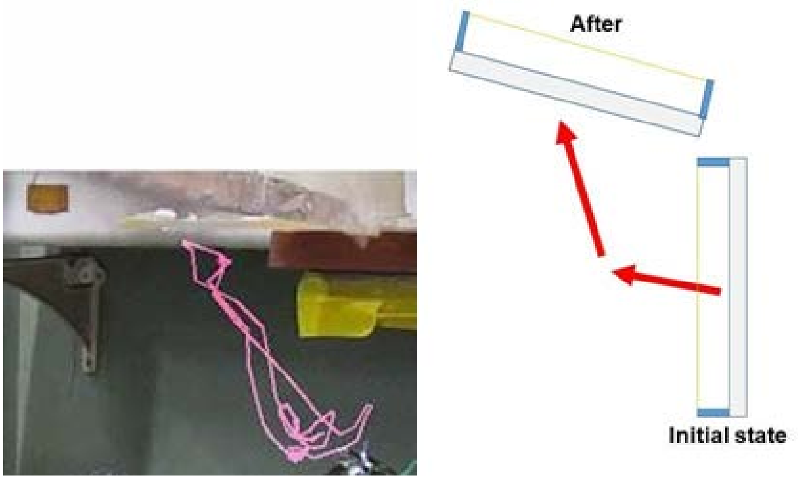
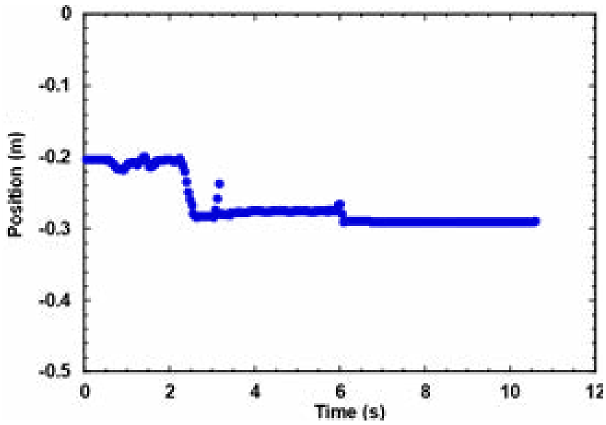


Figure 3. Experimental result of calculation by optical flow.

(a)



Wide

(b)

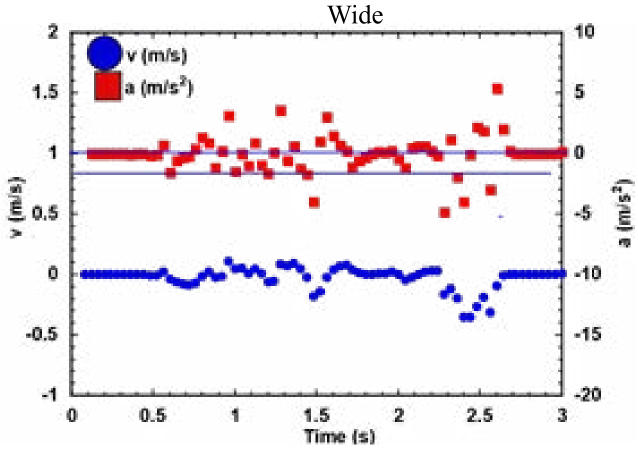


Figure 4. Velocity and acceleration in the horizontal direction. (a) Position, (b) Velocity and acceleration

Triangle Unit

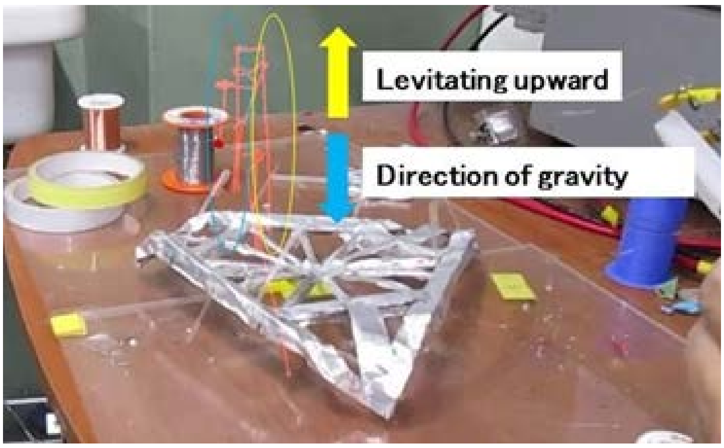


Figure 5. Experimental result of calculated optical flow.

Next, we show the experimental results when the EHD device is placed horizontally. Fig. 5 shows an example of the results of analysis using moving images of an EHD device with a central structure when it levitates. Here, Type 3 EHD device was used in this experiment. In the experiment, the EHD device was lifted straight up. The levitation direction was the exact opposite of the gravity direction, and the angle between the levitation direction and the gravity vector was almost 0 degrees. Although it was tilted 0.1 mrad from the desktop in the initial state, the device kept horizontal and slowly rose. Velocity changes with applied voltage. When the voltage is low, it becomes unstable.

Next, Figs. 6 and 7 show experimental results in the case of tilting arrangement with Type 1 and Type 2 EHD devices, respectively. Both devices levitated in an oblique direction and then ascended while changing their orientation to return to the horizontal direction. This was true even when the input voltage changed.

In the case of the Type 1 EHD device as shown in Fig. 1(b), the unit levitates straight in the direction determined by the structure. A certain amount of distance was necessary for the posture to become horizontal. Compared with the EHD device, the frame EHD device turned out to have better property of floating straight as shown in Fig.6. Eventually, the posture became parallel to the surface of the desktop.

Type 2 EHD device was used in this experiment as shown in Fig.7. Both devices levitated in an oblique direction and then ascended while changing their orientation to return to the horizontal direction. It was the same even if the input voltage changed.

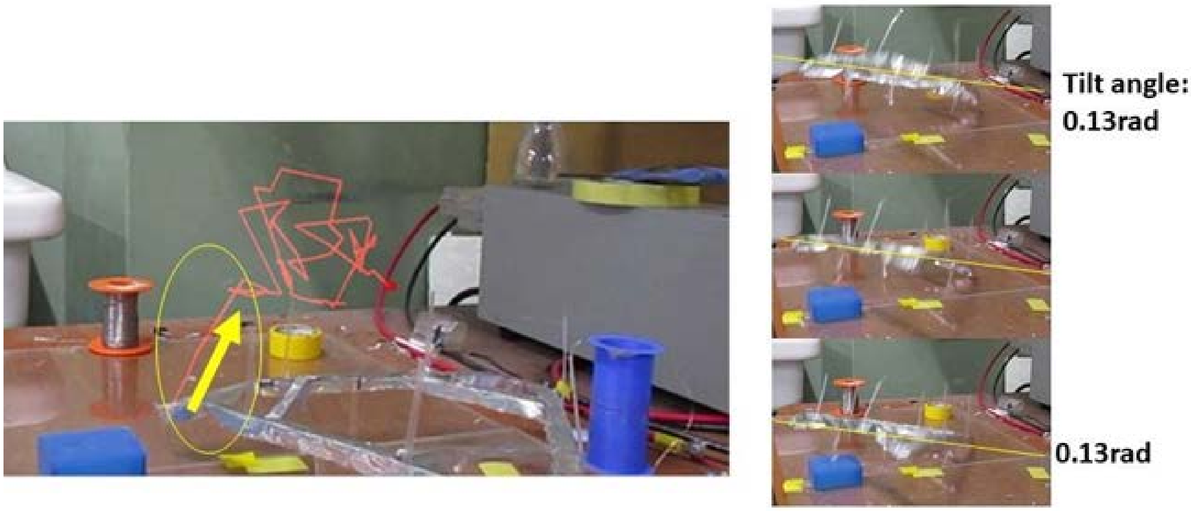


Figure 6. Analyzed result for levitation of triangle EHD device (Type 1).

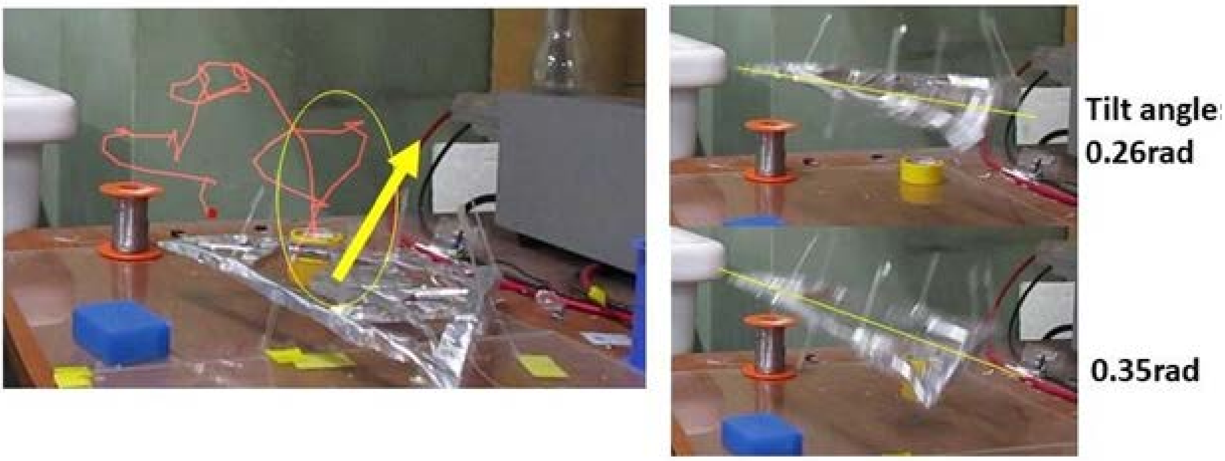
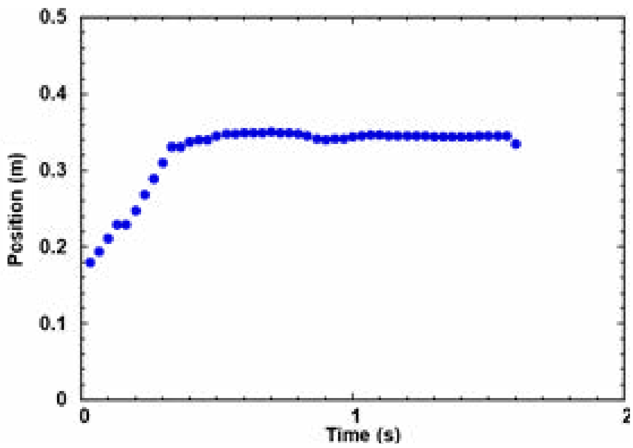


Figure 7. Analyzed result for levitation of triangle EHD device (Type 2).

(a)



(b)

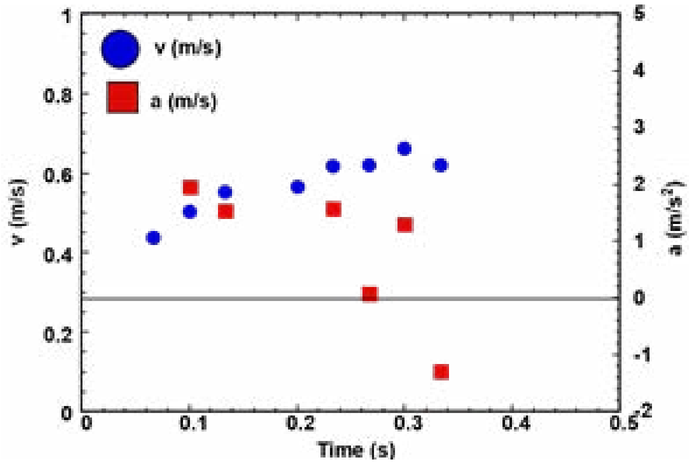
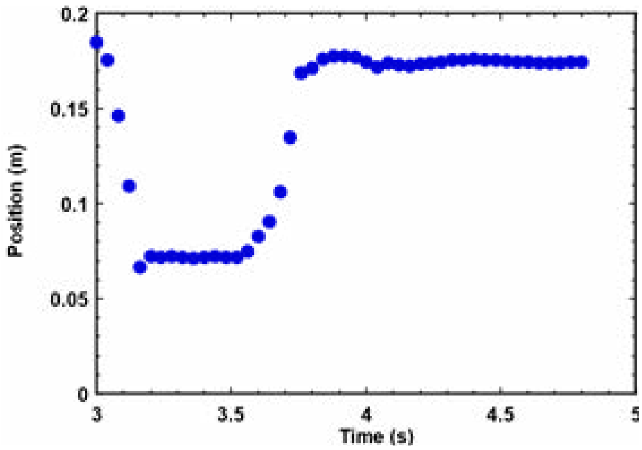


Figure 8. Analyzed results. (a) Position. (b)Velocity and acceleration.

Figure 8 shows the analysis results of the position, velocity, and acceleration of the EHD with the central structure, which corresponds to Type 3. Input voltage was 30 kV. The device slowly ascends with increasing speed while remaining level. Speed increased proportionally. Acceleration seemed constant. The maximum acceleration was 2 m/s^2. When the gravitational acceleration was 9.8 m/s^2, the acceleration direction reversed and became around 1/5 of the gravitational acceleration.

(a)



33V

(b)

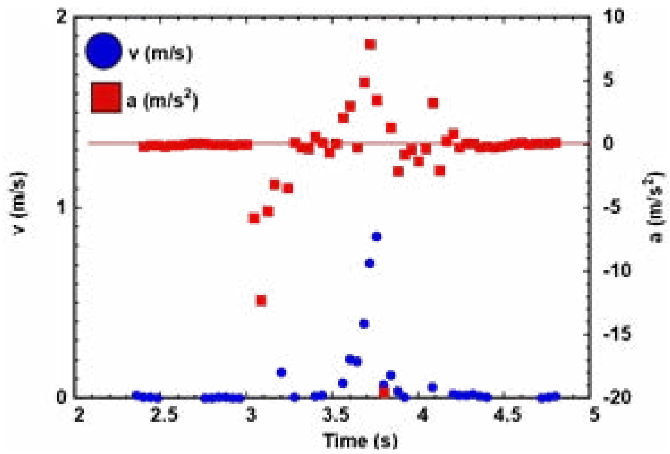
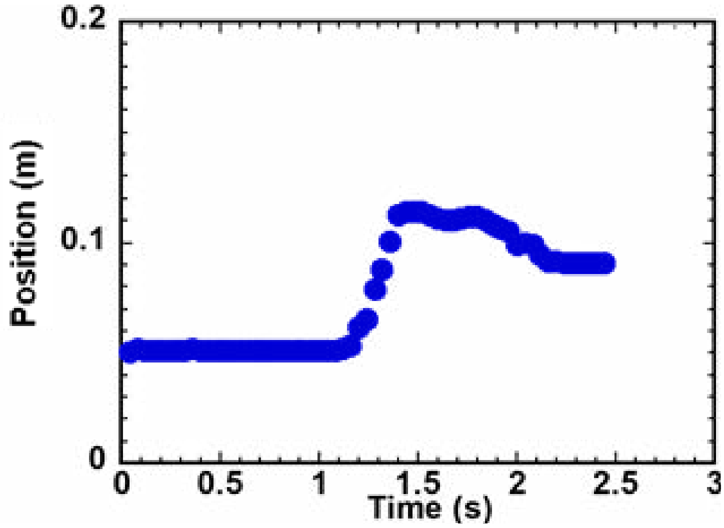


Figure 9. Analyzed results. (a) Position. (b)Velocity and acceleration.

The analysis results of velocity and acceleration are shown. Fig. 9 shows the analysis results of the position, velocity, and acceleration of the EHD with the central structure, which corresponds to Type 1. Input voltage was 30 kV. Device slowly ascends with increasing speed while remaining level. Speed increased proportionally. Acceleration seemed constant. Fig. 9 shows the analysis results of the position, velocity, and acceleration of the triangular EHD. Input voltage was 30 kV. Device acceleration varied from 0 to 8 m/s^2. The maximum velocity was 0.9 m/s.

(a)



26V

(b)

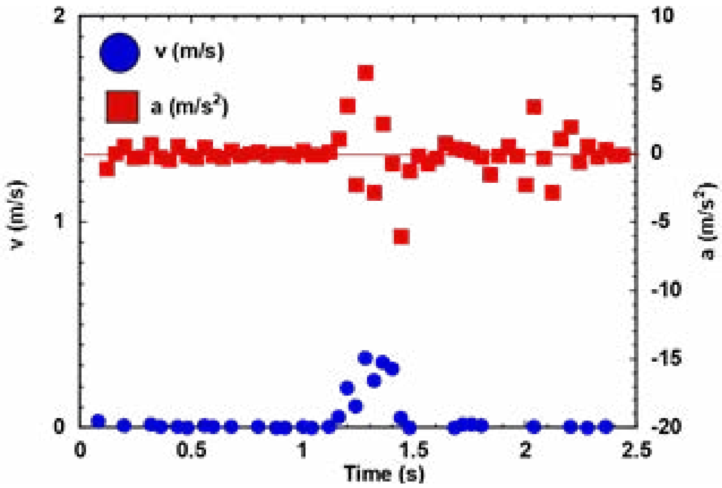
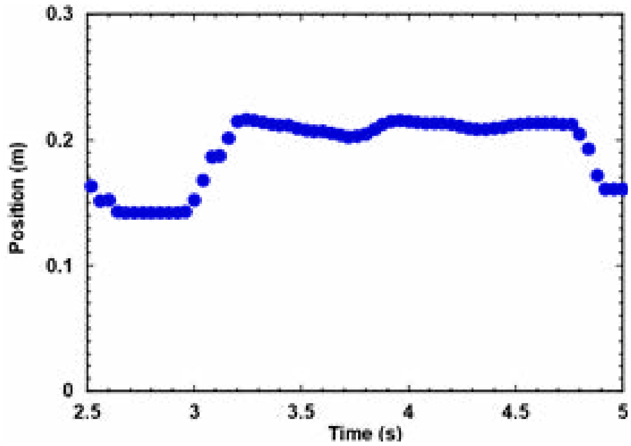


Figure 10. Analyzed results. (a) Position. (b)Velocity and acceleration.

30V

(a)



30V

(b)

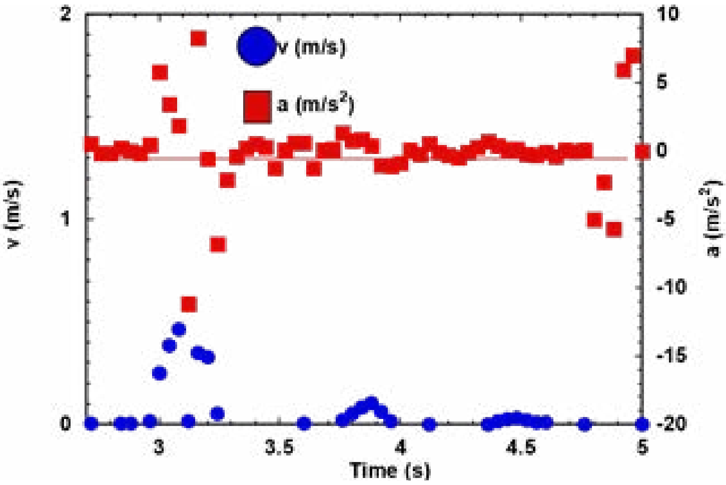
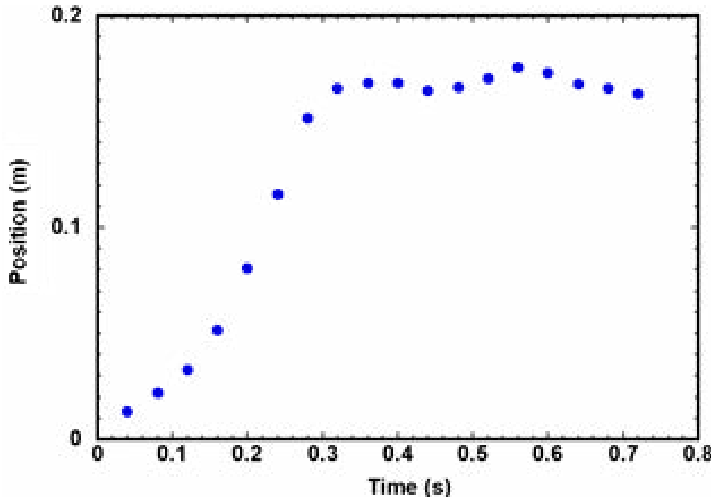


Figure 11. Analyzed Results. (a) Position. (b)Velocity and Acceleration.

34V

(a)



34V

(b)

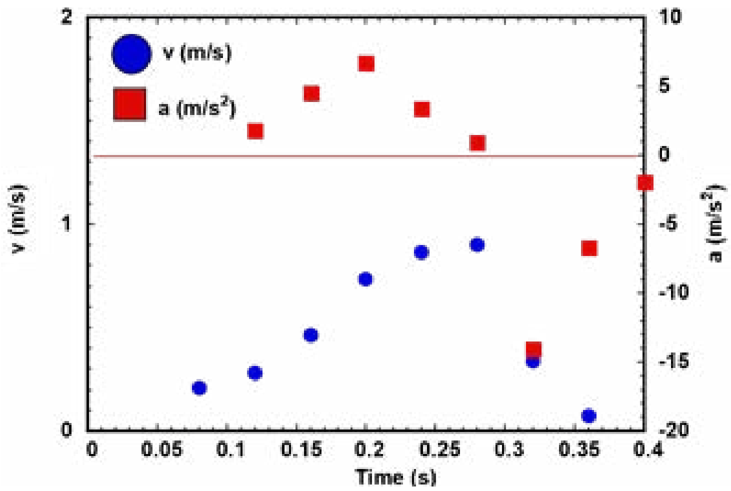
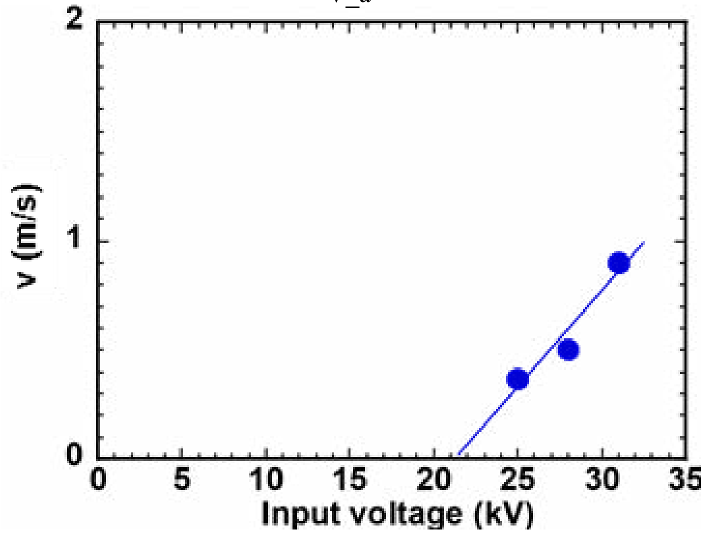


Figure 12. Analyzed results. (a) Position. (b)Velocity and acceleration.

Figures 10, 11, and 12 show the analysis results of the position, velocity, and acceleration for different input voltages of an EHD device having a central structure, which corresponds to Type 2. In Fig. 10, the input voltage was 25 kV. Acceleration varied from 0 to 2 m/s^2. The maximum velocity was 0.4 m/s. Fig. 11 shows the analysis results of the position, velocity, and acceleration of the EHD with the central structure, which corresponds to Type 2. Input voltage was 30 kV. The device slowly ascends with increasing speed while remaining level. Speed increased proportionally. Acceleration seemed constant. In Fig. 11, the input voltage was 28 kV. Acceleration varied from 0 to 5 m/s^2. The maximum velocity was 0.65 m/s. Fig. 12 shows the analysis results of the position, velocity, and acceleration of the EHD with the central structure. Input voltage was 30 kV. The device slowly ascends with increasing speed while remaining level. Speed increased proportionally. Acceleration seemed constant. In Fig. 12 the input voltage was 30 kV. Acceleration changed from 0 to 7 m/s^2. The maximum velocity is 0.9 m/s.

V_a

(a)



V_a

(b)

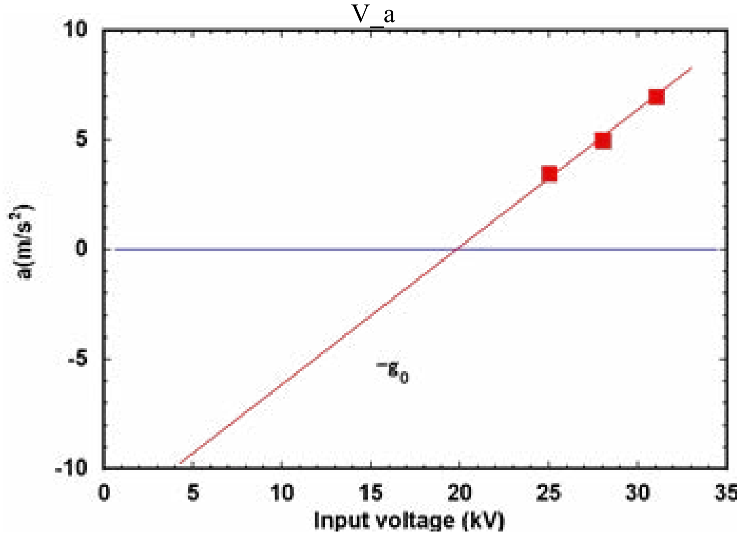


Figure 13. Analyzed Results. (a) Velocity and (b) Acceleration as a Function of Input Voltage.

Figure 13(a) shows the velocity vs. input voltage in an EHD device with a central structure, and Figure 13(b) shows the analyzed results by estimating the acceleration. Regarding the graph of acceleration against input voltage in Figure 13(b), if you draw a line to -g_0 (g_0 is the acceleration of the earth gravity), there seems to be a levitation force generation threshold at 5 kV.

4. Discussion

In this paper, we conducted dynamic analyses for the levitation of a propulsion system by EHD and electrostatic electricity. The results revealed that a propulsion system with EHD and electrostatic electricity has very unique levitation properties. EHD devices levitate in the direction opposite to the direction of gravity when a high voltage is applied. Detailed properties of the accurate propulsion direction, speed, and acceleration were clarified by imaging analysis at this time. The analysis clarified that even if the orientation of the device is initially tilted from a horizontal line, the device was made to levitate vertically upward in the same direction as the direction of gravity, and a restoring force acts to return the orientation to a horizontal line during the levitation. These phenomena are very strange and different from those of drones with propellers.

4.1 Direction of Levitation

We describe these phenomena. Analysis of the free levitation property of a single plate-shaped electrode unit, which has been well studied in previous papers, revealed that the direction changes from the horizontal direction to the direction of gravity. The two optical flow trajectories in the analyzed image show reproducibility. Comparing the initial horizontal acceleration and the later vertical acceleration, the vertical acceleration is large, so it is concluded that the object eventually floated above gravity.

The levitation properties of the EHD device with only a frame were that it flew and went straight regardless of the direction of gravity. On the other hand, the levitation properties of an EHD device with a central structure were almost the same in the direction of gravity and the direction of flight. The levitation properties of a specialized EHD device increased metal surface area revealed that even if the flight distance is short, the device can levitate almost completely in the same direction as gravity. In other words, these experiments have shown that increasing the area of the EHD device relative to the ground causes it to be strongly propelled in the direction of gravity.

It became clear that the direction in which gravity is applied to the EHD device and the direction in which it floats are exactly opposite. The angle between the direction of gravity and the direction of propulsion is less than 10 mrad and almost the same direction. Wires and electrodes are circular. The positive wire of the EHD device is a perfectly continuous cylindrically symmetrical structure.

The experiment also revealed that the triangular EHD device with only the frame has high straightness and low resilience, while the EHD device with the structure at the center has strong resilience to move in the direction opposite to this gravity.

As for the effect on the tilt of the device, when the EHD device was placed almost horizontally and levitated, it rose in the vertical direction opposite to gravity as shown in Fig. 14(A). Triangle unit and EHD device had the same characteristics. Even when the initial tilt angle of the device was as small as several mrad, the device rose vertically upward, which is exactly opposite to gravity, as shown in Fig. 14(B). Experiments have revealed that when the initial tilt angle of the device is large, the device levitates diagonally once and then tries to return to the horizontal direction, as shown in Fig. 14(C). Here, the device vibrates and becomes unstable.

4.2 Standing Time of Acceleration in Levitation

For the levitation, it became clear that the acceleration first reached its maximum value over a period of 0.1 s and then decreased rapidly. This is thought to be related to the physics of generating propulsive force. If the generated ions were the cause of propulsion, more air would enter, so the propulsive force and acceleration would increase, and acceleration would take time to occur, with a time constant of several seconds. Assuming that the device is levitating due to the reaction of the secondary air movement, the time constant of 0.1 s is too short. The observed phenomena in these experiments are the exact opposite. The conditions around the metal may change. Regarding the charging time of the metal, the voltage application time depends on the charging time of the CW rectification circuit. Charging time is proportional to the product of frequency and capacitor. Since the frequency is 1 Mz, the charging time is considered to be less than 1 ms. Also, the delay in the levitation time of EHD devices cannot be explained. Also, a short rise time means the generation of a high-intensity magnetic field. It is thought that the generation of the levitation force may be connected to the magnetic field. New experimental proposals and results are expected in the future. In the future, experiments will need to be conducted to understand these phenomena in detail.

4.3 Amount of Acceleration

Acceleration changed gradually during applying voltage. It is thought that the reason the acceleration takes time is that some states of the metal itself and its surroundings change. The acceleration changed from $-g_0$ to a positive value similar to g_0 via 0. Here, it was found that the acceleration changes in a slow time of the order of 0.1 seconds when it changes from 0 to positive. Experiments show that the acceleration increases linearly and then saturates and becomes constant. The experimental results suggest that there is a device input voltage threshold for the acceleration to decrease.

The acceleration is large when the EHD device is nearly stationary. It was found that when the device is moving, i.e., to the ground has a relative velocity, the acceleration and force decrease in the levitation. When the device is fixed, the generated force can be explained by the imbalance of force due to static electricity, but this experimental analysis shows that the propulsive force is not generated by simple static electricity, but may be caused by other forces in the future. A theoretical explanation of levitation force generation will most likely be required. The effect only affects metals (devices). The surroundings do not have affections. It was found through experiments that a voltage threshold of the generation levitation force exists and that the phenomenon cannot be observed unless the charge density is above a certain level.

Tests were also conducted on pulsed EHD device operation by pulsing the applied voltage, but there was no particular difference in the levitation property, except that the rise time of the speed and acceleration was faster.

4.4 Dependency of Velocity Owing to Metal Area

The maximum speed of the EHD device should be increased by increasing the scale of the device by one or two orders of magnitude. Here, in this experiment, the maximum speed of the device was 1 m/s and the acceleration was 7 m/s^2. Higher speeds can be achieved because the acceleration increases in proportion to the area of the device, thus, it increases the levitation force. As for the decreasing acceleration, it is considered that high speed can be maintained because acceleration decreases in the levitation, but the speed increases.

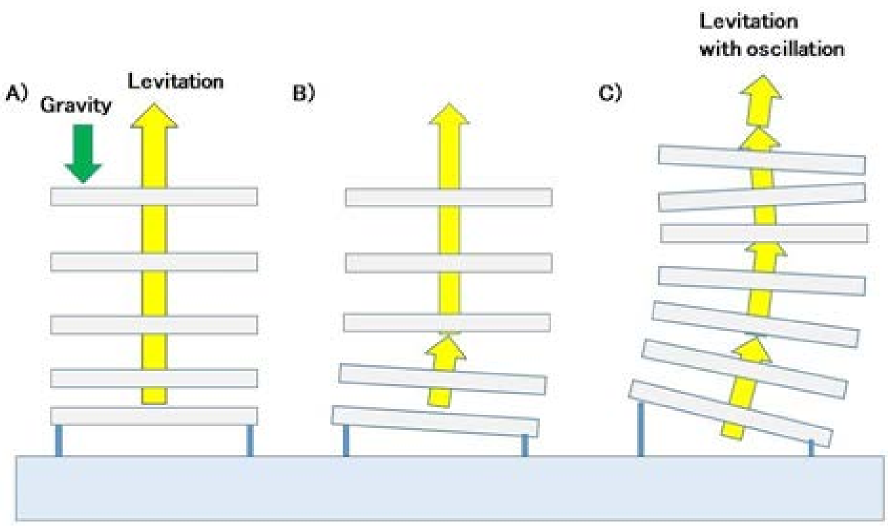


Figure 14. Differences in levitation properties due to differences in device orientation.

Data Availability
No data were used to support this study.

Conflicts of Interest
The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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References

1. T. T. Brown. (1960). "Electrokinetic Apparatus". U.S. Patent N°2949550.
2. T. T. Brown. (1962). "Electrokinetic Generator". US patent N°30224300.
3. http://www.jlnlab.com/
4. http://www.blazelabs.com/
5. M. Tajmar. (2004). "Biefeld–Brown Effect: Misinterpretation of Corona Wind Phenomena". *AIAA Journal 42*(2).
6. Zhao, L., & Adamiak, K. (2005). Numerical analysis of forces in an electrostatic levitation unit. *Journal of Electrostatics, 63*(6-10), 729-734.
7. Zhao, L., & Adamiak, K. (2006). EHD gas flow in electrostatic levitation unit. *Journal of electrostatics, 64*(7-9), 639-645.
8. Martins, A. A., & Pinheiro, M. J. (2011). Modeling of an EHD corona flow in nitrogen gas using an asymmetric capacitor for propulsion. *Journal of electrostatics, 69*(2), 133-138.
9. Ianconescu, R., Sohar, D., & Mudrik, M. (2011). An analysis of the Brown–Biefeld effect. *Journal of Electrostatics, 69*(6), 512-521.
10. Chen, M., Rong-De, L., & Bang-Jiao, Y. (2013). Surface aerodynamic model of the lifter. *Journal of Electrostatics, 71*(2), 134-139.
11. Canning, F. X., Melcher, C., & Winet, E. (2004). Asymmetrical capacitors for propulsion (No. NASA/CR-2004-213312).
12. Wilson, J., Perkins, H. D., & Thompson, W. K. (2009). An investigation of ionic wind propulsion (No. NASA/TM-2009-215822).
13. M. Eiant and R. Kalderon. (2014). AIP advances 4, 077120-1-20.
14. Masuyama, K., & Barrett, S. R. (2013). On the performance of electrohydrodynamic propulsion. Proceedings of the Royal Society A: Mathematical, *Physical and Engineering Sciences, 469*(2154), 20120623.
15. Saiki, T. (2015). Enhanced EHD and Electrostatic Propulsion Devices Based on Polarization Effect Using Asymmetrical Metal Structure. *Journal of Electrical and Electronic Engineering, 3*(4), 76-86.
16. T. Saiki. (2019). "High-voltage Pulse Generation Using Electrostatic Induction in Capacitor", *Int. J. of Electrical Components and Energy Conversion, 5*(2), Dec. pp.20-29.
17. Serres, J. R., & Ruffier, F. (2017). Optic flow-based collision-free strategies: From insects to robots. *Arthropod structure & development, 46*(5), 703-717.
18. Horn, B. K., & Schunck, B. G. (1981). Determining optical flow. *Artificial intelligence, 17*(1-3), 185-203.
19. Ma, C., Yang, F., Li, Y., Jia, H., Xie, X., & Gao, W. (2021). Deep trajectory post-processing and position projection for single & multiple camera multiple object tracking. *International Journal of Computer Vision, 129*, 3255-3278.
20. Royden, C. S., & Moore, K. D. (2012). Use of speed cues in the detection of moving objects by moving observers. *Vision research, 59,* 17-24.