Hovering Dynamics of Spheres in Upward Airflow: Key Influences and Applications

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Abstract. The study investigates the hovering dynamics of spheres in upward airflow, focusing on key factors influencing their levitation characteristics. By conducting experiments with objects of varying mass, diameter, fluid velocity, and shape, the research aims to analyze the effects of these parameters on hovering height and stability. The levitation model is established through theoretical analysis, highlighting the equilibrium between drag force and gravity. Experiments involve the use of a hair dryer to generate upward airflow and track the motion of objects using Tracker software, capturing the levitation height and oscillation frequency under different conditions. Results indicate that increased mass reduces hovering height, while larger diameters enhance drag force, leading to higher levitation. The fluid velocity at the nozzle significantly impacts the hovering height, with higher speeds resulting in greater lift. Irregularly shaped objects exhibit unstable levitation due to asymmetric drag force distribution. The findings underline the importance of these factors in the stable hovering of objects and suggest potential applications in education, material classification, and fluid property testing. Future research is recommended to further explore the control and stability of levitating objects using advanced simulation techniques and control science methodologies.

Keywords: Levitation, aerodynamics, hovering characteristic.

1. Introduction

The study of hovering dynamics in spheres subjected to upward airflow is a widely recognized experiment in aerodynamics, often used to explore the principles of fluid dynamics and control systems. This setup, commonly involving objects such as balls levitated by air streams from devices like hair dryers or wind tunnels, serves as an illustrative example of how drag force interacts with gravity to maintain equilibrium [1]. These levitation experiments not only provide insights into basic aerodynamic principles but also have broader implications for educational purposes, material sorting, and even advanced control system designs.

Previous research on levitation experiments has primarily focused on controlling the position of levitated objects to ensure stability and precision. For instance, [2] Amirreza Tootchi et al. developed a model for a levitation system incorporating PID controllers to manage the ball's position, while [3] Shahin S. Nudehi et al. utilized a feedback loop to adjust the height of the ball by varying the input voltage to an axial fan. Although these studies emphasized control mechanisms, understanding the fundamental forces at play, particularly drag, remains crucial to optimize hovering behavior before integrating complex control systems [4]. Prior work, such as [5] Zachary Swartzwelder et al., has explored the physics of hovering under various conditions, yet a comprehensive analysis of key influencing factors like mass, diameter, and fluid velocity is still needed.

This research aims to fill this gap by systematically investigating the primary factors that influence the hovering characteristics of spheres in vertical jets, including mass, diameter, fluid velocity, and object shape. By employing the control variate method and utilizing Tracker software to record and analyze the positions of the hovering objects, the study provides detailed insights into how these factors affect hovering height and stability. The findings offer valuable references for applications in educational settings and industrial material classification, and suggest potential avenues for further research into control system integration and advanced simulation techniques [6, 7].

2. Theoretical Framework

2.1. Drag Force and Hovering Equilibrium

The ball's stable hovering is the result of the equilibrium between gravity and drag force:

$$F_D = W \tag{1}$$

The gravity of the object is easily described as

$$W = mg \tag{2}$$

m is the mass of the object, g is the acceleration of gravity. The drag force on the object is

$$F_D = \frac{1}{2}\rho v^2 A C_D \tag{3}$$

ρ is the density of air, v is the velocity of vertical air flow, A is the sectional area facing the flow, C_D is the drag coefficient. In most of the experiments, the object is a ball, so given the diameter D:

$$F_D = \frac{1}{8}\pi\rho v^2 D^2 C_D \tag{4}$$

C_D is a function to Reynold's number:

$$\mathrm{Re} = \frac{\rho v D}{\mu} \tag{5}$$

μ is the viscosity coefficient of air. In this experiment. The relationship between C_D and Re is depicted in Fig.1.

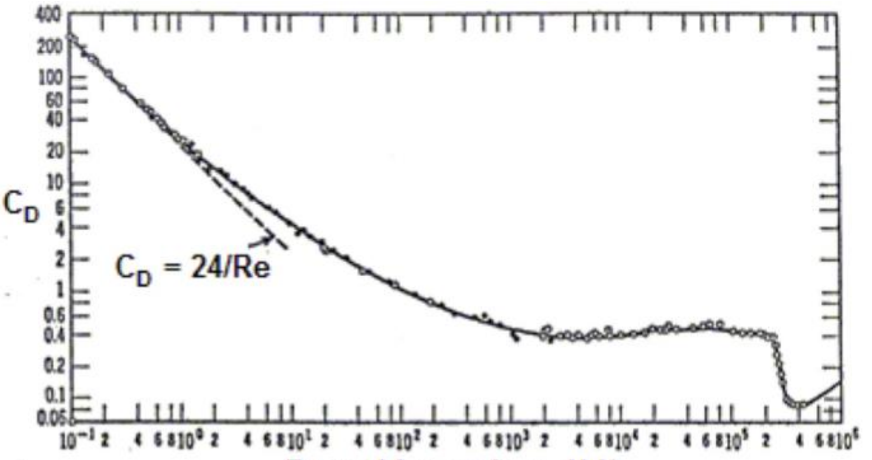

Fig. 1 Relationship between C_D and Re [8].

The flow generated by the dryer is turbulence which is determined by Reynolds' number. The distribution of flow velocity is related to the position from the exit y and the radius of the jet R. The y-component of fluid velocity profile is:

$$v_y(y,\ r) = v_{max}\exp\left(-\frac{r^2}{2\sigma^2}\right) \tag{6}$$

r is the distance to the center line, $\sigma(y)$ is the fluid velocity standard deviation, and v_{max} is the fluid velocity at the center line [9]. The maximum speed is.

$$v_x(x,\ 0)=v_{max}=\frac{5Vd}{y} \tag{7}$$

In this equation, $\sigma=y/10$, d is the diameter of the nozzle and V is the fluid speed at the exit of the nozzle. Under this condition, the fluid velocity distribution can be described as Fig.2.

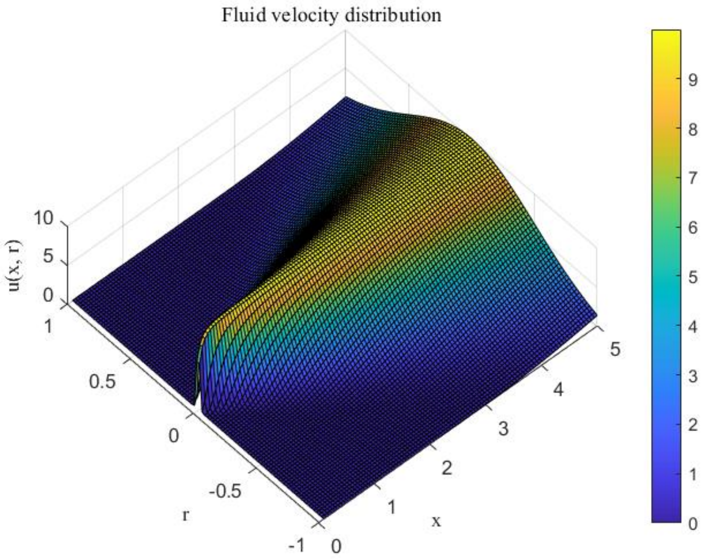

Fig. 2 Fluid velocity distribution ($V=10\ m/s$)(Photo credit: Original).

2.2. Key Influences on Hovering Characteristic

The most obvious hovering characteristic is the height y at which the object levitate [10]. Assuming that the object stays on the center line, according to (1), (2) and (6), the expression of y is:

$$y=5\sqrt{\frac{\pi}{8}}VdD\sqrt{\frac{\rho C_D}{mg}} \tag{8}$$

From this expression, it can be concluded that the hovering height is a function to fluid velocity at the exit V, the nozzle diameter d, the diameter of the ball D, the air density ρ, drag coefficient C_D, the mass of the ball or the object m, the acceleration of gravity g. In experimental cases, the variables d, ρ, C_D, g are constant, so this paper does not take them into consider.

3. Influencing Factors

The influence of factors on hovering characteristic are tested by experiments. The tools used in the experiments includes a hair dryer with a high speed mode and a low speed mode, different types of balls and objects, and a camera to record the motion of the objects. Before the key experiments, the flow rate of different mode of the dryer are tested in a pre-experiment. A bag with the volume of 10L is put at the nozzle with the air pulled out and the bag wrapped tightly to the nozzle not allowing any air out. After turning on each mode, the time for the dryer to fill the bag is measured thus working out the flow rate of the dryer under each speed mode. The result is that it takes 1.49 s to fill the bag under high speed mode and 2.05s to fill the bag under low speed mode. Given that the diameter of the dryer outlet is 5 cm, the velocity of the flow from the dryer can be calculated:

$$V_{high}=3.418\ m/s \tag{9}$$

$$V_{low}=2.484\ m/s \tag{10}$$

The ball in the experiments includes a standard Ping Pong ball and different balls made of clay, differing in size, shape and mass. In the experiment of examining the relationship between hovering characteristic and volume of the object, the ball is stuffed with small objects with higher density at the center in order to keep the mass of the ball as the same while raising the mass of the ball. In the experiment of testing the hovering stability and shape of the object, the shape of the clay ball is changed into an oblate sphere with a same value of mass.

In the experiments, a software Tracker is used to analyze the position of the hovering object. Tracker can measure the actual distance between objects by calculating the proportion of the distance on the image with the length of a known length object on the image. Therefore, by inputting a known actual length in the image of the video (specifically the diameter of the nozzle), the height of the hovering object to the nozzle can be precisely measured. Additionally, by recording video of the hovering process, the hovering characteristic as a function to time starting from the point when the dryer is turned on, which is also an important reference for hovering stability.

3.1. Mass

The factor of mass can affect the value of the gravity of the object resulting in the change of equilibrium height. In the experiment, two balls with a same volume are prepared. Both of the ball has a diameter of 40 mm, but one weighs 3g, the other weighs 2g (Fig. 3.). The dryer is fixed to a chair, pointing upwards.

Fig. 3 A 9 grams black ball (left) and a 3 grams Ping Pong ball (right) with the same volume (Photo credit: Original).

When the dryer is on under the high speed mode (in order to ensure an obvious phenomenon), the sphere is placed at the nozzle and be blown up inside the jet, trying to keep it levitating. The position of the ball in this process is recorded, and is revealed in Fig.4 and Fig.5.

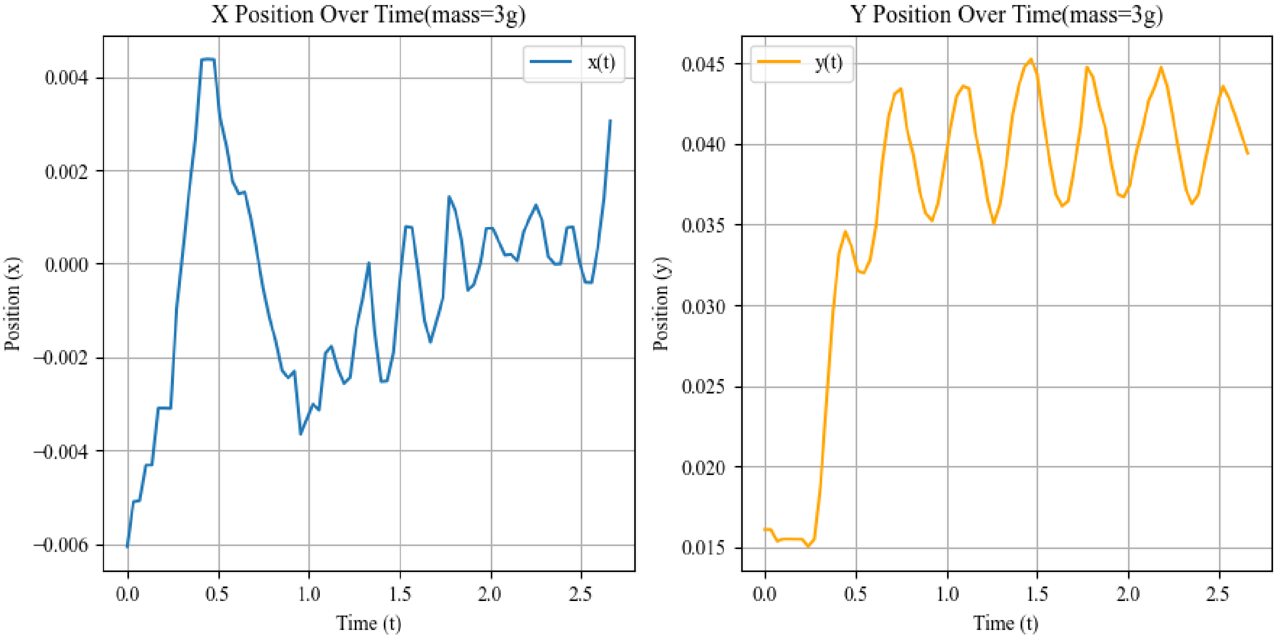

Fig. 4 Position of the ball as a function to time(mass=3g) (Photo credit: Original).

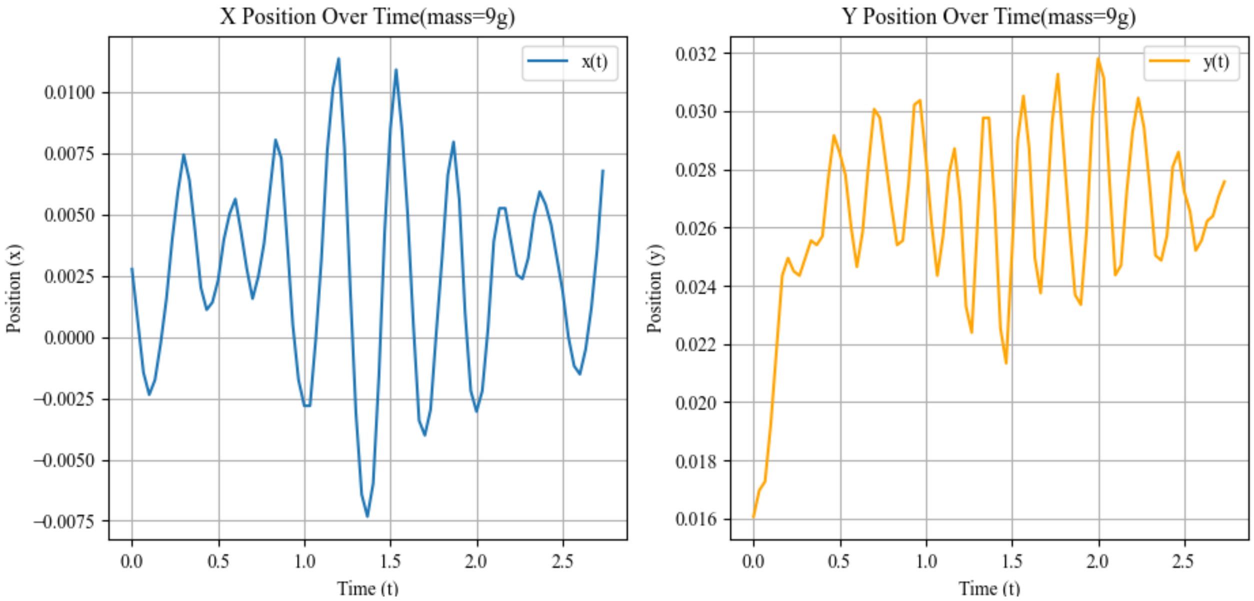

Fig. 5 Position of the ball as a function to time(mass=9g) (Photo credit: Original).

From the result, it can be figured out that the position of objects or the ball levitated is in the state of periodically vibration after the levitation become stabilized. According to Fig.4 and Fig.5, the height of the ball is around 0.040 cm at the oscillation frequency of $\omega \approx 18.85\ rad/s$ for 3g Ping Pong ball and 0.027cm at the oscillation frequency of $\omega \approx 29.32\ rad/s$ for the 9g clay ball, which is in accord with (7) that the levitation height y will decrease when the mass of the ball m increases. The increase of mass results in increase of the gravity value W in equation (2). Therefore, the value of drag force F_D needed to balance the gravity increase. To achieve a higher drag force, the ball's height is smaller where the velocity is big enough to generate a higher drag force to support the ball.

3.2. Diameter

To measure the relevance between levitation height and volume or diameter of the ball, two balls with a same weight of 4g but with different volumes (one is 3.2cm diameter, the other is 2.8cm diameter) are prepared (the heavier one is stuffed with a small object with higher density which is placed at the center of the ball to maintain the mass center). The operation in 3.1 is repeated while using Tracker to analyze the height and comparing the result of different volumes (diameters). As show in the fig. 6.

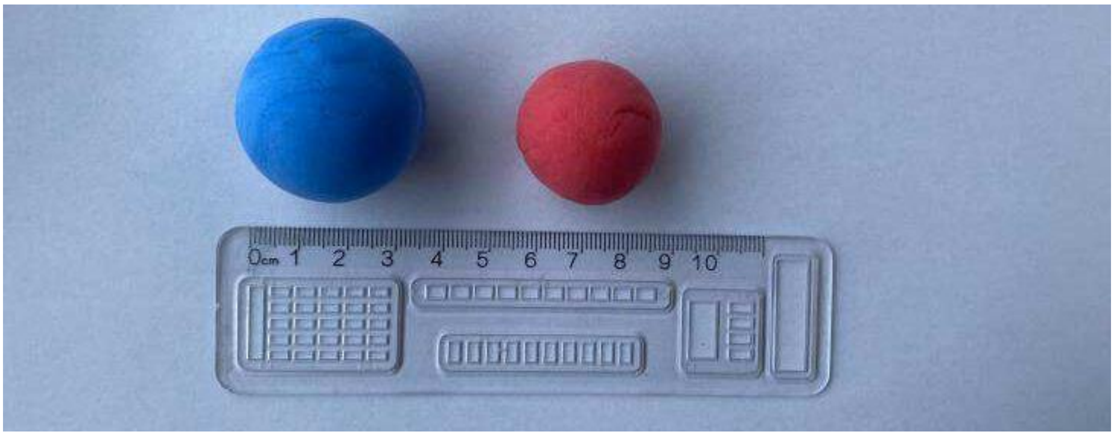

Fig. 6 A 4 grams blue ball with 3.2cm diameter (left) and a 4 grams red ball with 2.8cm diameter (right) (Photo credit: Original).

The trace of the levitation is recorded in the following Fig.7 and Fig.8. (Photo credit: Original).

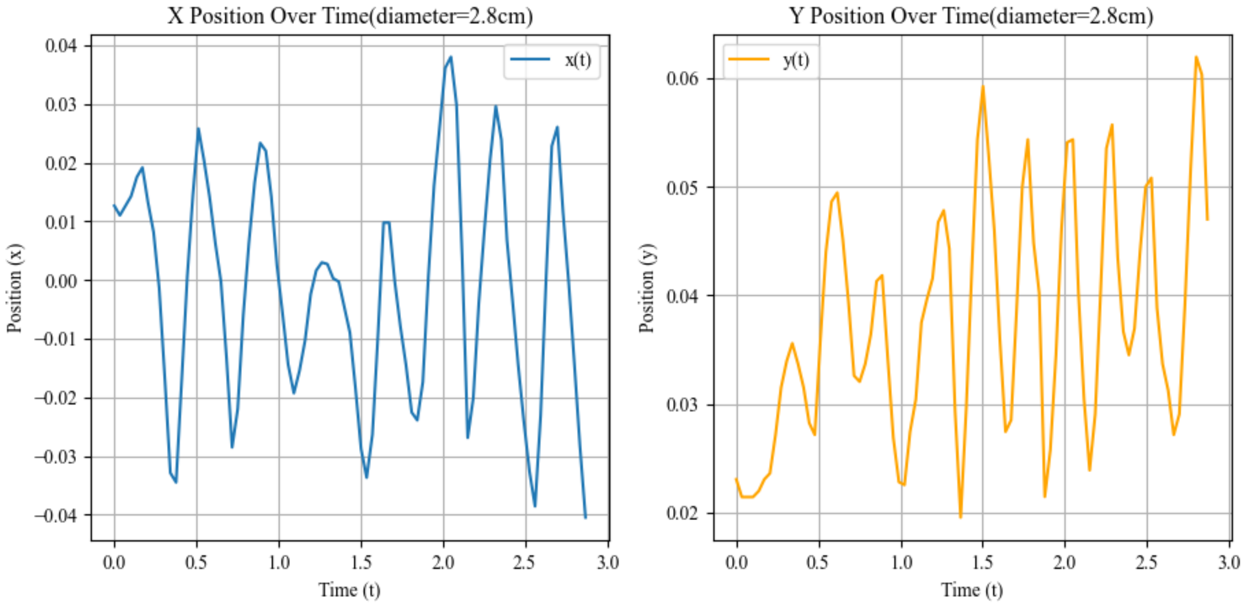

Fig. 7 Position as a function of time(diameter=2.8cm) (Photo credit: Original).

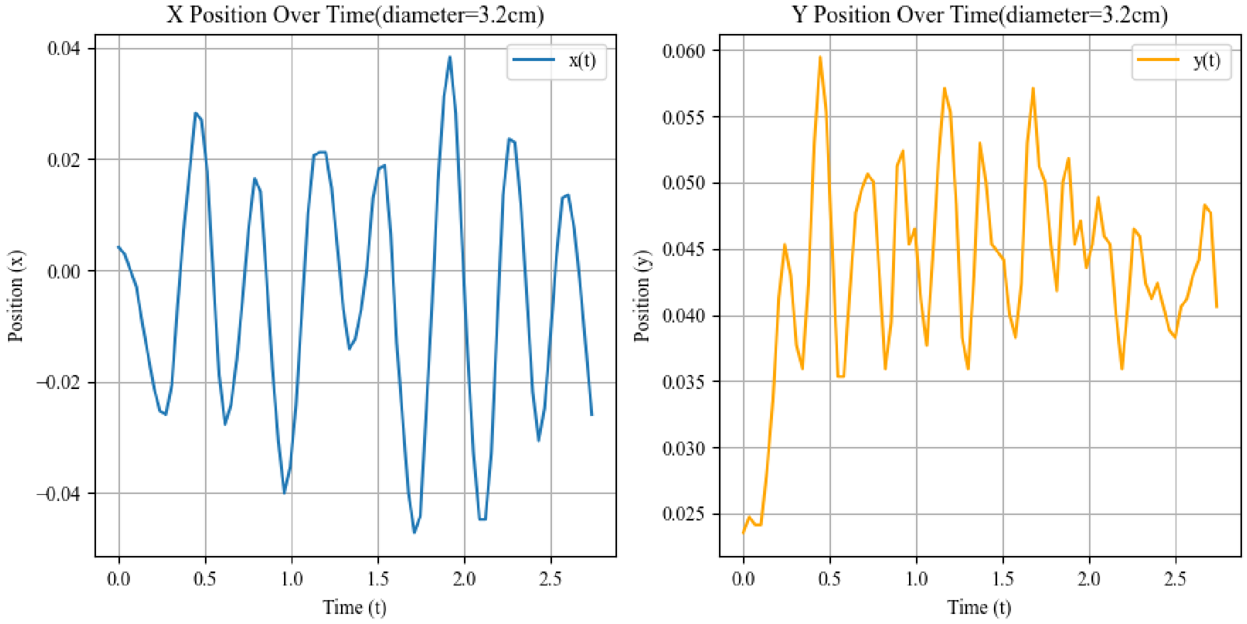

Fig. 8 Position as a function of time(diameter=3.2cm) (Photo credit: Original).

It can be observed that, with the same weight, the levitation height is around 0.040 cm at the oscillation frequency of $\omega = 21.89\ rad/s$ for the 2.8cm diameter ball and 0.045cm at the oscillation frequency of $\omega = 25.86\ rad/s$ for the 3.2cm diameter ball. This result indicates that as the diameter of the ball increases, the levitation height y will also increase when the ball weights are the same. This is the result of increased drag force F_D because of the increase of diameter, as equation (3) described. As the drag force increases because of the ball's diameter which is a property of the ball itself, the ball can be supported at a higher position in the jet where fluid velocity is smaller to form a balanced drag force to the ball's gravity.

3.3. Fluid velocity at the nozzle

In this experiment, the same Ping Pong ball is put under different speed mode of the dryer. The operation in 3.1 is repeated again. The experiment of Fig.4 is repeated as it is the result of a ball put under the high speed mode. The trace of levitation ball under low speed mode is revealed in the following Fig.9.

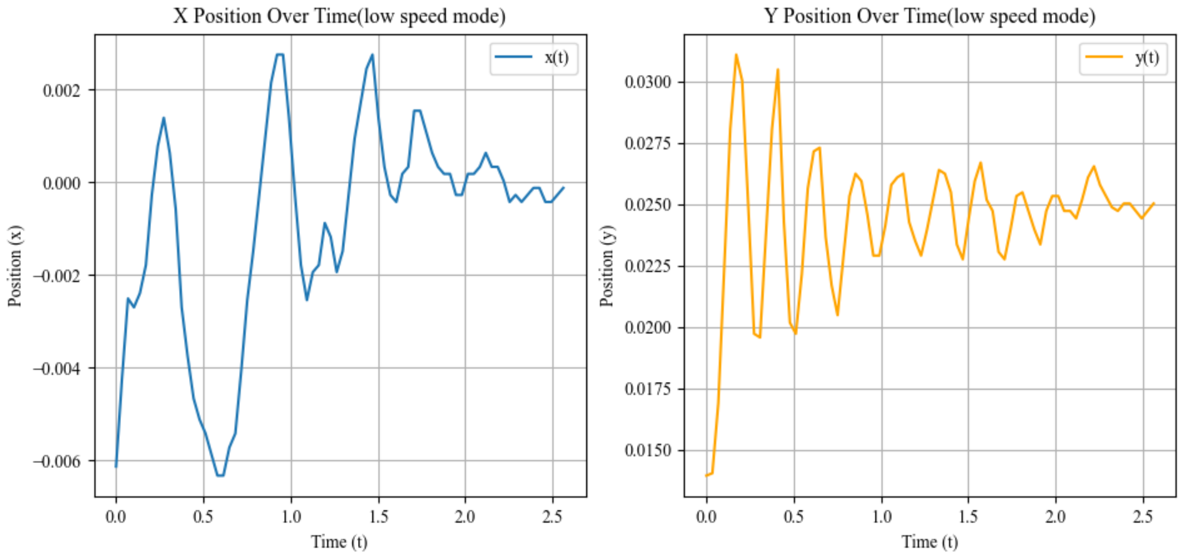

Fig. 9 Position as a function to time (low speed mode) (Photo credit: Original).

From the figures, it can be known that the height of the ball is around 0.040 cm at the oscillation frequency of $\omega \approx 18.85\ rad/s$ under high speed mode and 0.024cm at the oscillation frequency of $\omega = 27.83\ rad/s$. As the speed of the fluid increases, the levitation height will also increase because a higher speed can provide greater drag force as equation (3) suggested.

3.4. Shape

Two shapes of objects are used to test the stability of levitation. The object used is a slightly squeezed sphere with the weight of 3g. The object is put in the jet to test whether the shape of the object can affect its levitation stability. The result is that the object can not be steadily levitated in the jet because the object is manually made by clay which means that it is not symmetric and does not have a smooth surface. These properties influence the formation and distribution of the drag force on the sphere. The trace of the changed shape sphere is recorded in Fig.10.

Fig. 10 Position trace of the slightly squeezed ball (Photo credit: Original).

To further take research into the relationship between shape and hovering stability, it is better to use more perfectly shaped objects or using computer simulation to analyze the variation of drag force. It is also plausible to measure the stability using knowledge in control science and engineering.

4. Future Implications

For the future research, the hovering characteristic can be further analyzed from control science aspect because the hovering traces can be analyzed as a time domain characteristic function which can be transformed to figure out the feasibility of the whole control system.

For the application prospect, the experiment was originally designed for education, so further analysis can help improve experiment equipment to achieve better educational effect. The research of hovering characteristic can also be put in industrial use of material classification in which different particles or objects can be sorted by changing fluid velocity according to the objects' mass and volume properties. Further research can be carried our in particle or even molecular extent, and the hovering effect can also be used to test fluid properties.

5. Conclusion

This study systematically analyzed the hovering dynamics of spheres in upward airflow, emphasizing the effects of key factors such as mass, diameter, fluid velocity, and shape on levitation height and stability. Through theoretical modeling and controlled experiments, the equilibrium between drag force and gravity was explored, demonstrating how variations in mass and diameter directly influence the drag force and consequently the hovering height. Increased mass was found to lower hovering height, while larger diameters improved drag force, leading to higher and more stable levitation. The experiments also highlighted the significant impact of fluid velocity at the nozzle on lift generation, with higher velocities enhancing levitation. Irregularly shaped objects exhibited unstable hovering due to asymmetric drag force distribution, underscoring the importance of symmetry in achieving stable levitation. These findings provide valuable insights into the fundamental principles governing hovering dynamics and offer practical implications for educational demonstrations, material classification, and fluid property testing. Future research should focus on refining the control and stability of levitating objects using advanced simulation techniques and control science methodologies. Incorporating computational fluid dynamics (CFD) simulations could provide a deeper understanding of complex airflow patterns and their interactions with various object shapes. Further exploration into the impact of material properties and surface roughness on drag forces could also enhance the precision of hovering models. Expanding this research to include more diverse object geometries and environmental conditions would help to broaden the applications of hovering dynamics in fields such as industrial sorting, particle characterization, and aerodynamic testing, ultimately contributing to the development of more efficient and adaptable levitation systems.

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