Research on Aerodynamic characteristics of Lightweight Spheres Suspended in Vertical Airflow

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Abstract. Experimenting to obtain data about the drag force is usually difficult and expensive. In this paper, an experiment is conducted using a hair dryer as a provision of a controllable airflow, and two ping pong balls as the object in an airflow to find out the factors that affect the stability of an object in an airflow by using the control variate method and use the turbulent jets theory to calculate the drag force. The result of this experiment is that when the balls have the same mass, as the wind speed increases, the vertical stability of the ball becomes better and the horizontal stability becomes better as well. When the wind speed is the same, as the mass of the ball increases, the vertical stability of the ball becomes better. The equations to calculate the drag force are correct and can simulate and calculate the result of the track of an object. The value of this experiment is that it provides an easy way to experiment with the drag force.

Keywords: Drag force, Experiment, Hair dryer; Light sphere, Control variate method.

1. Introduction

When an object moves in contrast to a fluid, the object is subject to a resistance related to the speed of movement and parallel to the direction of movement, usually called flow resistance. If the fluid is a gas, it is sometimes called wind resistance or wind pressure.

In engineering, the phenomenon of flow resistance is very common: the hull in the water or people swimming in the water should be water-resistant; construction, buildings, or poles in the wind in the lateral pressure of atmospheric air flow; parachute in the air resistance; cars and trains are also blocked when running at high speed. What is the generation mechanism of this flow resistance? What are the factors involved? How should the size be calculated?

In general, textbooks, when talking about flow resistance, it is said that it should be measured by experiments, but in addition to some schools that have conditions to do quantitative experiments in wind tunnels, most schools cannot do quantitative experiments in flow resistance. So, in the paper, a hair dryer has been used to simulate the experiment in wind tunnels to find out how an object moves in an airflow, and how the track of the sphere changes because of the change of the drag coefficient with the different wind speeds.

Because a sphere is a basic object, the result of a sphere can easily be deducted from objects like cars and airplanes.

Many experiments have been conducted to measure and calculate the drag force, but these experiments are usually difficult and expensive and need equipment like a wind tunnel which is difficult to obtain.

Qing [1] experimented to study the relationship between the force of the solid object and the shape and the relative velocity, in that experiment, an air resistance coefficient tester was built instead of a hair dryer to provide steerable airflow.

Qi [2] used the plane measurement method to measure the wind drag force for bicyclists.

Ruan [3] conducted experiments using a method of measuring the windward area of a vehicle by using a digital camera and computer data processing to calculate the wind drag force of a vehicle.

Dong [4] used a different method called the two-stage test method to calculate the drag force of a vehicle. The two-stage test method is a way that can accurately calculate the drag force of a vehicle.

Wu [5] used the two-stage coast-down testing method to calculate the drag force and the drag coefficient of a vehicle accurately.

All these experiments have some materials that are difficult to obtain. In this paper, the experiment uses materials that are easy to obtain: a hair dryer and two ping-pong balls. However, the cost of using these experiments is that the measured data can have a deviation, and because of the limits of ping pong balls, not every factor can be considered in this experiment.

To minimize the deviation this experiment should have many repetitions and to include more factors, every factor that can be included by a ping pong ball should be considered.

This is an experiment that uses ping pong balls and a hair dryer, using the control variate method to find out the factors that affect the stability of an object in airflow and use the turbulent jets theory and the 'Tracker' software to analyze the data and calculate the drag force. will be the main method in this experiment. The result of this experiment can also be applied to the majority of objects in an airflow and this experiment will provide an easy way to experiment with the drag force.

2. Method

2.1. Experimental Settings

This experiment required one hair dryer with different wind speeds and two of the same ping pong balls.

To measure the diameter and the weight of the two ping pong balls, an electronic scale and a vernier caliper are used to make sure that the measurement is accurate. The precision of the electronic scale is g, and the precision of the vernier caliper is mm. The diameters are measured to be 37.0mm and the weights are measured to be 2g. By putting some water in one ball, one weighs 6g, so now the only difference between the two ping pong balls is that their weights are different, which conformed to the control variate method.

The hair dryer used has two different wind speeds, to measure the wind speeds of the hair dryer, the method following has been used.

By using the hair dryer blows air into a plastic bag, then the wind speed can be calculated with equation (1):

$$U = \frac{V}{\frac{\pi}{4}D^2 \cdot t} \tag{1}$$

Where U is the wind speed, m/s; V is the volume of the plastic bag, m^3 and can be measured by using the measuring cup pouring a certain amount of water into the bag; D is the diameter of the hair dryer, m; t is the time that the hair dryer needs to fill in the plastic bag, s.

Using this method, the wind speeds are calculated to be 6 meters per second, and 3 meters per second and the area of the hair dryer is $4cm^2$. By using the control variate method, the strong wind is first to be used to blow up the light ball, then the strong wind is used to blow up the heavy ball and then the week wind is used to blow up the light ball, at last the week wind is used to blow up the heavy ball and the whole process of this experiment is filmed. The process for the experiment has been repeated 10 times. The process is shown in Figure 1.

Because the weak wind was not strong enough to blow up the heavy ball, the ball fell on the ground immediately after the ball was placed on the airflow. That leaves only three experiments to be calculated.



(a) (b) (c)

Figure 1. Pictures of the process of the experiment, different wind speeds with different weights of ping pong balls. (a) Strong wind with light ball; (b) Strong wind with heavy ball; (c) Weak wind with light ball.

Then the three videos of these different processes are uploaded to the 'Tracker' software. By using this software, the data and the track of the ping pong ball can be obtained.

And with these data the vertical stability and the horizontal stability can be calculated by comparing the distance of the ping pong ball moving vertically and horizontally in every frame with the average distance in each experiment, to find out which factors can make a light sphere more stable.

2.2. Theoretical basis

This phenomenon can be explained by the turbulent jet's theory.

The distance between the hair dryer and the ping pong ball can be compared with the theoretical distance that can be calculated using equations:

$$u(x,r) = U_{max}\exp(-\frac{r^2}{2\sigma^2}) \tag{2}$$

Where x is the downstream distance along the jet (measured from the virtual source), or is the cross-flow distance (from the center line), U_{max} is the jet speed at the center line, and σ(x) is the fluid velocity standard deviation. The maximum speed is

$$u(x,0) = U_{max} = \frac{5 \cdot U \cdot d}{x} \tag{3}$$

The fluid standard deviation is σ = x/10. d is the diameter of the jet.

The drag force on an object is the component of the total hydrodynamic force in the same direction as the main fluid flow. In dimensionless terms, the drag force is requested as the drag coefficient, C_D, and the equation to calculate the drag coefficient is [6]:

$$C_D = \frac{2F_D}{\rho U^2 A} \tag{4}$$

Where F_D is the drag force, ρ is the fluid density, U is the speed of the flow and A is the superficial area. For the case of a sphere, the drag coefficient has been extensively studied.

3. Results

3.1. Experimental results and data analysis

In the first set of experiments, a strong wind is used to blow up the lightweight ball. Through trajectory tracking software, A periodic change is obtained in the vertical motion of the balls. After the periodic change stabilized, the average distance was calculated. The center of the mouth of the hair dryer is defined as the origin of coordinates, the diameter of the ping pong ball in the video is defined as 37.0mm, and then the track of the ping pong ball is recorded frame by frame in the software, a graph and a table are formed, that gave the data that showed the distances between the ping pong ball and the mouth of the hair dryer vertically and horizontally.

For the first situation, a ball (mass is 2g, velocity is 6 meters per second), x refers to the vertical distance between the ball and the mouth of the hair dryer its unit is cm, and y represents the horizontal amplitude and its unit is also cm. The results are shown in Figure 2.

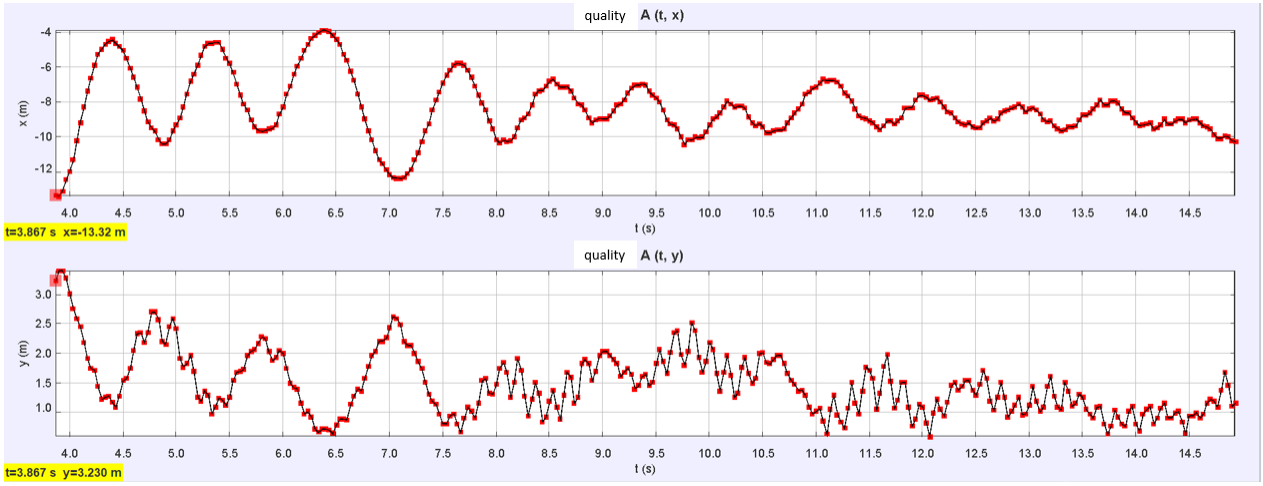

Figure 2. The track of the light ball in the heavy wind.

The same methods and principles were used to calculate the vertical distance and the horizontal amplitude for the experiment with heavy balls and strong wind. But in the experiment with the light ball with the light wind, x is the horizontal amplitude and y is the vertical distance. The results are shown in Figures 3 and 4.

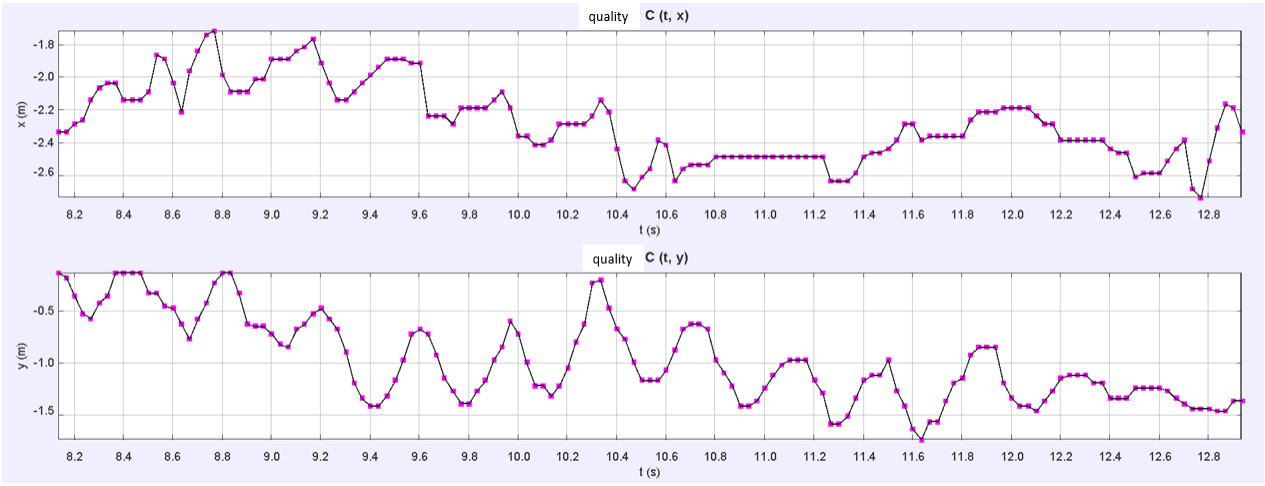

Figure 3. The track of the heavy ball in strong wind

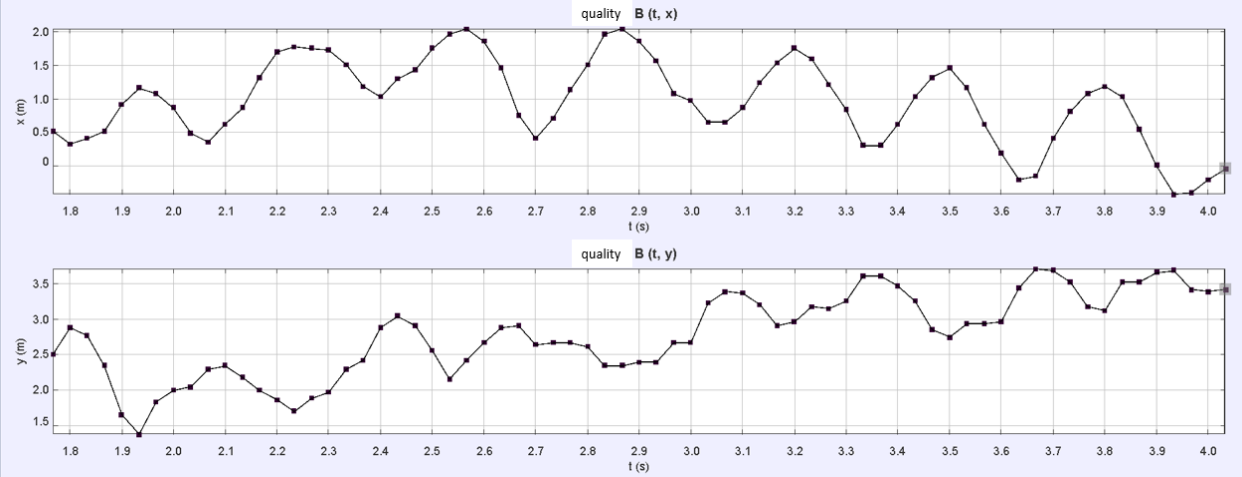

Figure 4. The track of the light ball in weak wind

Then, according to the principle of control variables, two conclusions' graphs Figures 5, 6, and 7 are shown. When experimenting, different comparisons have been set up, which can control the mass of the balls and the wind speed, to draw a more comprehensive conclusion.

When the balls have the same mass, as the wind speed increases, the vertical distance anomaly of the strong wind is 2.3×10^{-4} cm, the vertical distance anomaly of the weak wind is 5.6×10^{-4} cm. The horizontal amplitude anomaly of the strong wind is 1.2×10^{-5} cm, the horizontal amplitude anomaly of the weak wind is 1.4×10^{-2}cm, the vertical stability of the ball becomes better, and the horizontal stability becomes better as well, as the wind becomes stronger. The result is shown in Figures 5 and 6.

When the wind speed is the same, as the mass of the ball increases, The vertical distance anomaly of the heavy ball is 1.8×10^{-4} cm, the vertical distance anomaly of the light ball is 2.3×10^{-4}cm. the vertical stability of the ball becomes better. The result is shown in Figure 7.

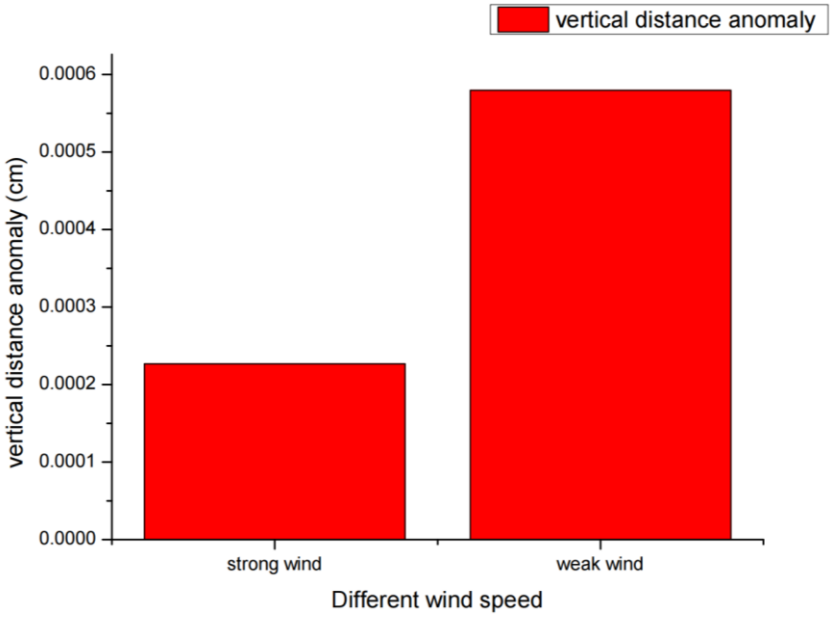

Figure 5. The vertical distance anomaly of the strong wind and weak wind

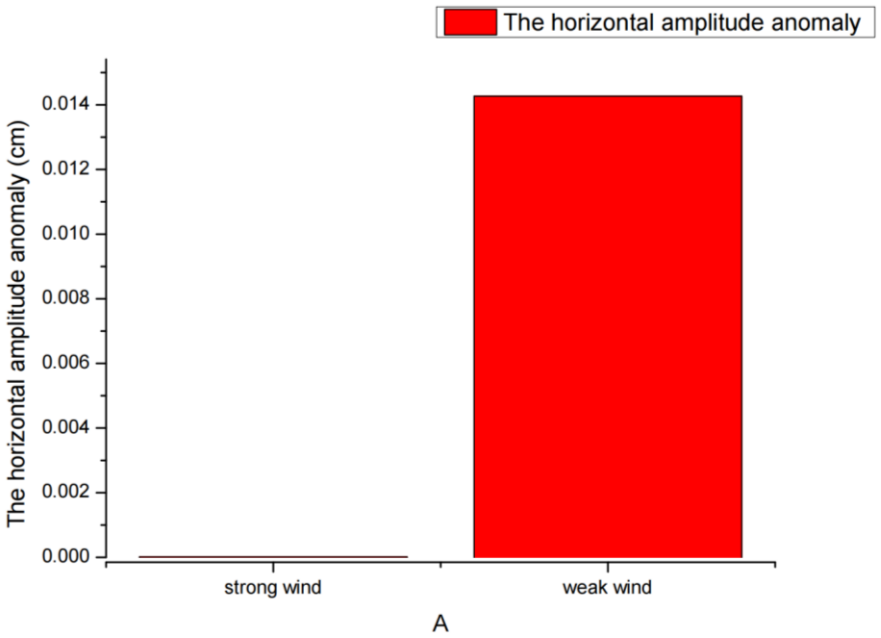

Figure 6. The horizontal amplitude anomaly of strong wind and weak wind

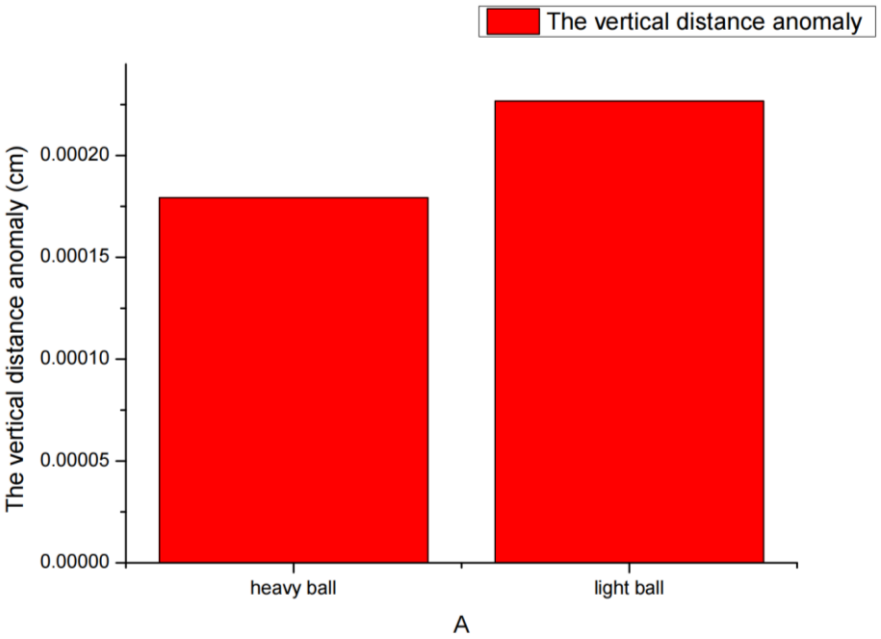

Figure 7. The vertical distance anomaly of heavy ball and light ball

In the first experiment, $U_{max} = 6m/s$, d=2.3cm, D=3.7cm, ρ=1.2kg/m^3, value $C_D$as 1.5, $F_D = 2 \times 10^{-3} \times 9.8 = 0.0196N$. By the simultaneous equations of (3) and (4), x can be calculated to be 0.0825. The average distance between the ball and the mouth of the hair dryer obtained during the first experiment is 0.0873, which is very close to the theoretical calculation of 0.0862. Therefore, the experimental results have well-validated the theory.

3.2. Discussion

According to the problems in the experiment and the differences between the experimental results and the data obtained by theoretical calculation, combined with the knowledge learned, the following parts have been discussed and concluded.

When the balls have the same mass, as the wind speed increases, the vertical stability of the ball becomes better, and the horizontal stability becomes better as well.

When the wind speed is the same, as the mass of the ball increases, the vertical stability of the ball becomes better.

When the theoretical distance between the ball and the outlet calculated is different from the actual measured distance, there are several reasons:

(1) Unstable wind speed.

(2) The center of the sphere is not in the vertical position of the mouth of the hair dryer.

(3) The fluid temperature from the hair dryer is higher than the room temperature, which causes

(4) The density of the air becomes different.

(5) The wind speed measured by Equation (1) is not accurate, because the time is difficult to be measured accurately.

(6) The direction of the wind is not perfectly vertical.

(7) Not enough repetitions

In this experiment, Equations (3) and (4) have been proved to be correct and can simulate and calculate the result of the track of an object. With these equations, questions about how to make the air resistance smaller for vehicles and aircraft can be solved. The smaller the superficial area of the vehicle and aircraft that is facing the airflow, the smaller the air resistance is [7-8].

Another factor that also affects the drag coefficient is the shape and angle of the object. There have been researches that show that in the same wind speed, a flat object suffers from a greater wind drag and a streamlined body suffers from a relatively small wind drag. So, a vehicle and an aircraft should apply a more streamlined body to have less wind drag [1]. Different angles of an object affect the drag coefficient. As the wind angle increases, the average resistance coefficient of the square column decreases and increases, the average lift coefficient increases and then decreases [9]. So, the wings of an aircraft should use an angle of 2.85°to have a better lift force and a smaller drag force [10]. Based on the conclusion drawn in the experiment, two vehicles with the same shape, the heavier the vehicle is, the more stable the vehicle is.

4. Conclusion

In this paper, to find out what the factors that make ping pong balls steady in an airflow, and to prove that the equation of the drag force is correct, a hair dryer is used to provide a controllable airflow instead of a wind tunnel, a ping pong ball is used as the object in the airflow, to obtain data and graphs, the “tracker” software is used. After the experiment can the conclusion be drawn: When the balls have the same mass, as the wind speed increases, the vertical stability of the ball becomes better, and the horizontal stability becomes better as well.

When the wind speed is the same, as the mass of the ball increases, the vertical stability of the ball becomes better. The equations to calculate drag force have been proven to be correct and can simulate and calculate the result of the track of an object. This experiment provides an easier way to conduct experiments about airflow when a wind tunnel is difficult to obtain, but because of the limitations of this experiment, not every factor has been included. So, in the future, more similar experiments should be conducted to have more complete data about the movement of an object in an airflow.

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