Paper Plane Aerodynamics

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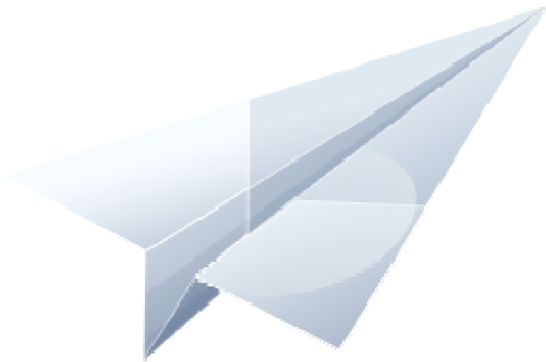

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Abstract

This paper takes into account a part of the elements affecting the flying distance of paper plane. We experimented and analyzed the effect of the angle of elevation, the location of the center of mass, the empennage and the aileron. These three factors influence the change of the angle of attack while the plane flies, thus influencing the flying distance.

Keywords: Paper plane; Angle of attack; Angle of elevation

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Nomenclature:

C_D	=	drag coefficient
C_L	=	lift coefficient
L/D	=	lift over drag ratio
L	=	lift force
D	=	drag force
G	=	gravity
R	=	resultant force
α	=	angle of attack
l	=	length of the airplane
b	=	wing span
S	=	planform area
ρ (ρ_∞)	=	density (of air)
V_∞, U_∞	=	airspeed
v	=	kinematic viscosity
Re	=	Reynolds number ($\mathrm{Re}=U_\infty \cdot l/v$)

Introduction

While planes have become a necessary mode of transportation of everyday life, paper planes are receiving far less attention. But the seemingly simple flight of a paper plane also includes numerous unsolved problems. Besides the akin problems faced by both paper planes and real planes, the former have some typical problems, including the relationship between the angle of elevation and the flying distance, the gradual decrease of flying speed, and the influence of humidity.

The study of these questions is a low Reynolds number aerodynamics study, which has not received much attention. Yet this kind of study is important because it can shed light on the study of Micro Air Vehicles (MAV). Not only will the paper plane inspire more innovative designs, its results can also be applied in a good deal.

In the following chapters, the discussion will focus on the flight as a whole rather than discuss each moment separately, because almost all the parameters are set before the plane is launched. Also, the differences between a paper plane and a real plane will be emphasized in the discussion.

General Theory

In order to simplify the research, the varying forces on the surface of the wings are synthesized into a single *resultant force R*, which can be divided into the lift force L, and the drag force D. When the plane moves in the air, it will be affected by these two forces, and a resulting *moment*. [3]

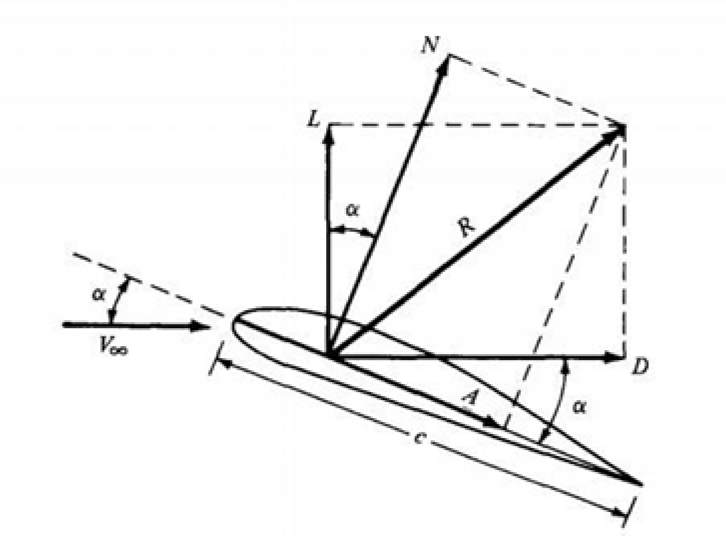
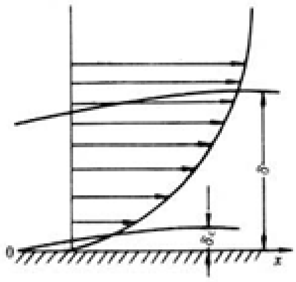


Figure 2.1 Force diagram

Considering the lift force, different theories can be applied, including the Kutta-rukefusiji theorem and Bernoulli's principle. Yet the underlying principle of all these theories is that the lift force is produced by the difference in velocity between the upper and lower surface of the wing. [4]

Besides the lift force, there are two different kinds of drag forces: the viscous drag and

the induced drag. [1] Viscous drag is caused by the viscidity of the air, as shown in the figure underneath. The figure shows that at the surface of the wing, the velocity of air is zero, and the velocity increases when gradually with the distance to the surface. In fact, the viscosity is caused by another two different drag forces: the *viscous friction* and the *viscous pressure resistance*. On the other hand, the induced drag can be described as a “price to pay for the lift force”. The induced force is caused by the vortices at the ends of the wings. [2]



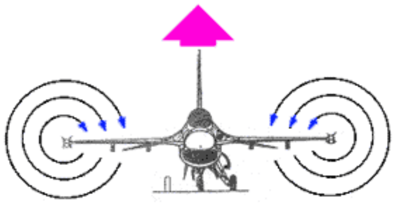


Figure 2.2 Airflow

Specific Theories and experiments

The following experiments are generally divided into two parts: the first three parts are intended to discuss the pneumatics of a paper plane, while the remaining parts address the stabilization and balance. In all the following experiments, the dihedral and the angle of center fold equal to zero.

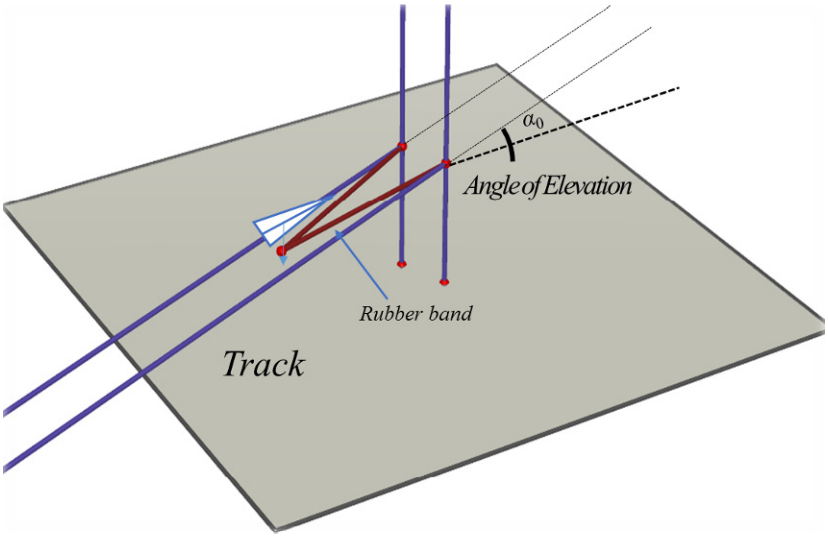
1. The Preliminary Experiment

Purpose: to select stable and simple plane models for further experiments

Procedure:

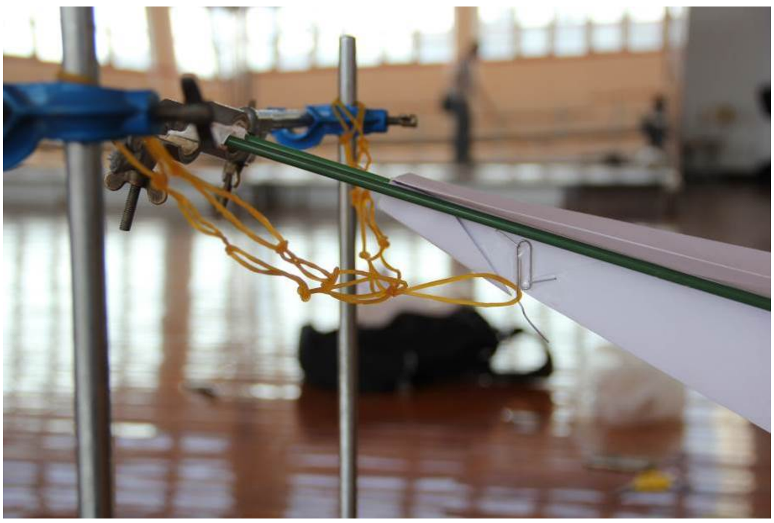
We use a self-made launcher to dart different kinds of planes at the same angle of elevation, with identical driving forces. We then compare the velocity, travel distance and its uncertainty.

Figure 3.1.1 Tested models



(a)

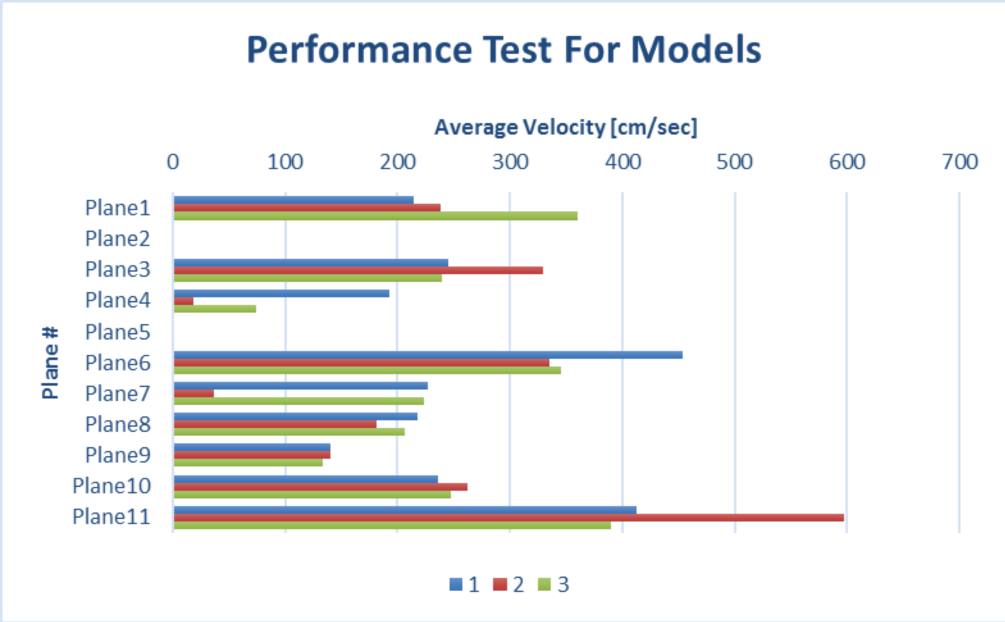
(b)



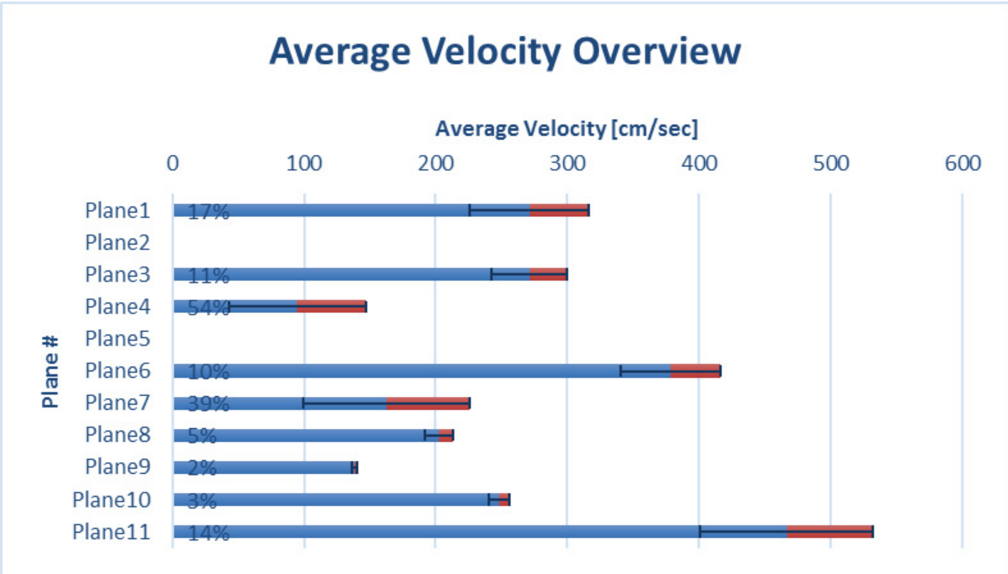
(c)

Figure 3.1.2 (a)(b)(c) Launcher

Data Overview:



(a)



(b)

Figure 3.1.3 (a) (b) Performance overview

Discussion:

While using eleven different plane models to conduct the experiment, we found out that Plane Two and Plane Five failed to fly at all, so that they have been excluded from any further experiments.

Result:

After comparing different the plane models, we have selected three of the simplest and most stable models: Plane One G（*Glider*）, Plane Six R *II*（*Revenger II*）and Plane Eleven R（*Revenger*）.

2. The Measurement of Aerodynamic Parameters

Purpose: to measure the pneumatic parameters of Glider, Revenger and Revenger II, including their lift coefficients and drag coefficient.

Procedure:

We use a simplified wind tunnel to measure the lift force and drag force of a certain wing at different angle of attack, then calculate the lift coefficient and the drag coefficient which are summarized in a graph. Digital Information System Lab (DIS) was used to measure the lift and drag.

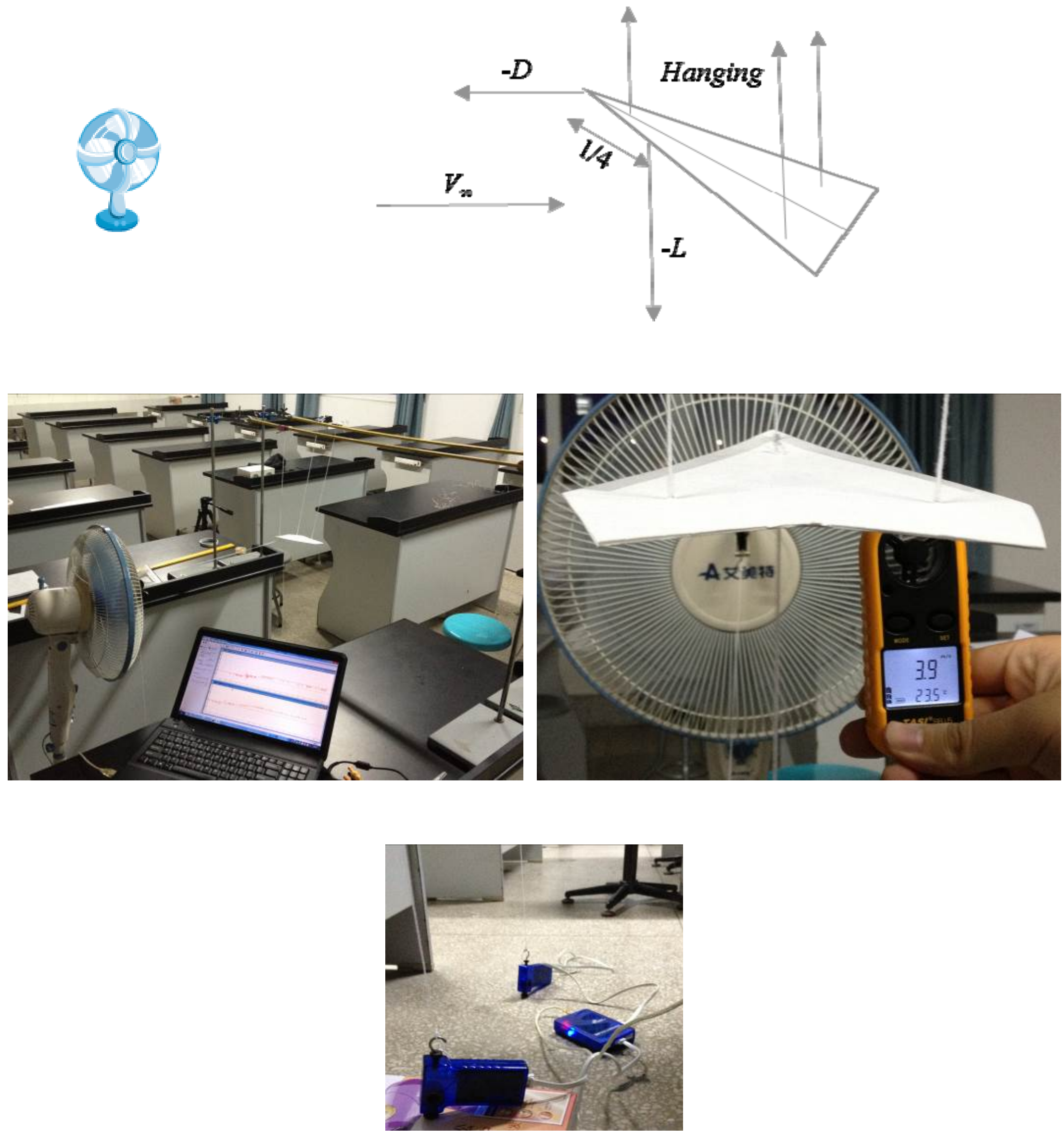


Figure 3.2.1 Wind tunnel setup and data collector (Airspeed: (4.0±0.1) m/s)

Analysis:

The lift coefficient C_L, the drag coefficient C_D and the *focus of moment* m_{z_0} *coefficient* are the three fundamental parameters of a wing. Since the wing of a paper plane is always symmetrical, the latter equals to zero.

In measuring the lift force and the drag force, we used DIS (Data Input Supervisor) and a simplified wind tunnel as shown beneath. Because m_{z_0} equals zero, the *focus of moment* coincides with the center of pressure. [7] These two points coincide at first quarter of the wing cord, where the moment caused by the lift force and the drag force is zero. For this reason, it is the perfect point to measure the lift force and the drag force.

After measuring the forces, the following equations allow us to derive the results. [3][6]

$$C_L = \frac{L}{q_\infty S}$$

$$C_D = \frac{D}{q_\infty S}$$

While $q_\infty = \frac{1}{2}\rho_\infty V_\infty^2$

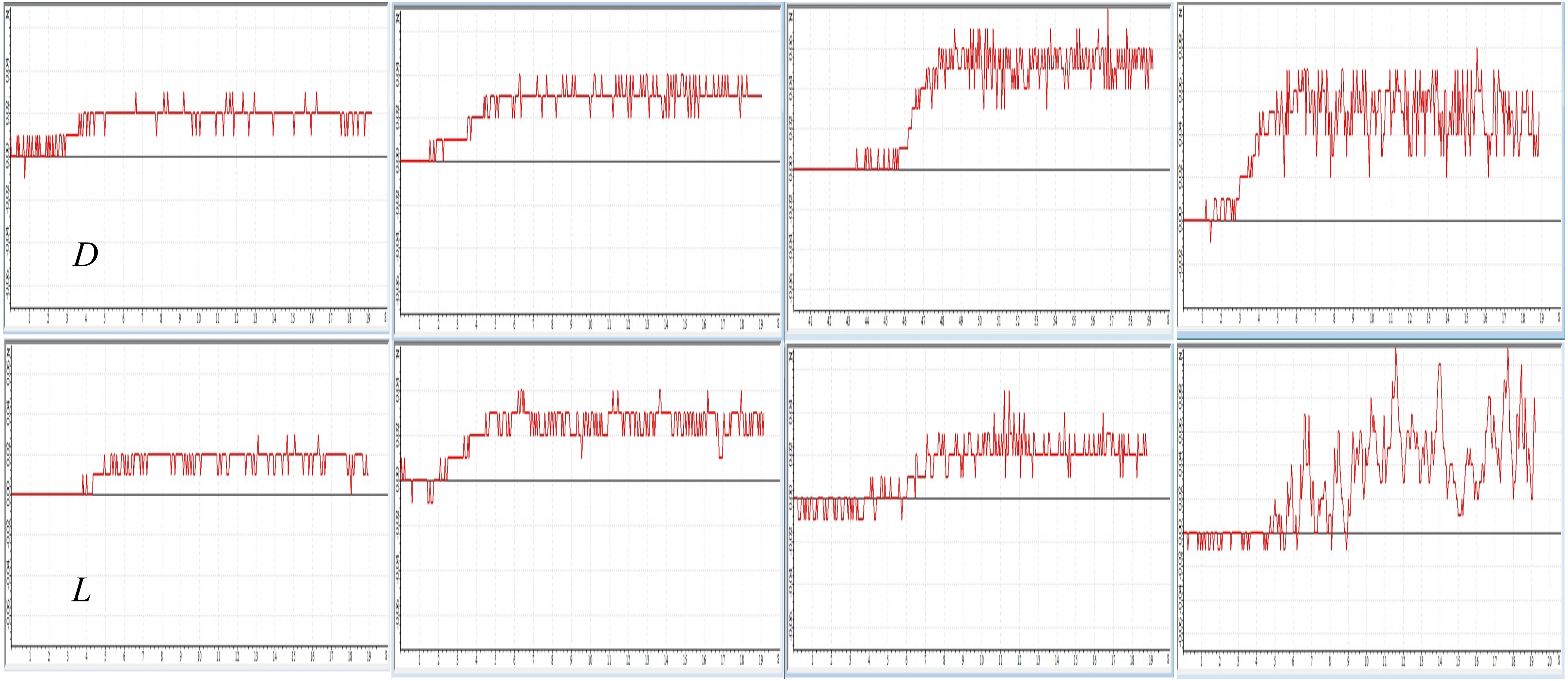
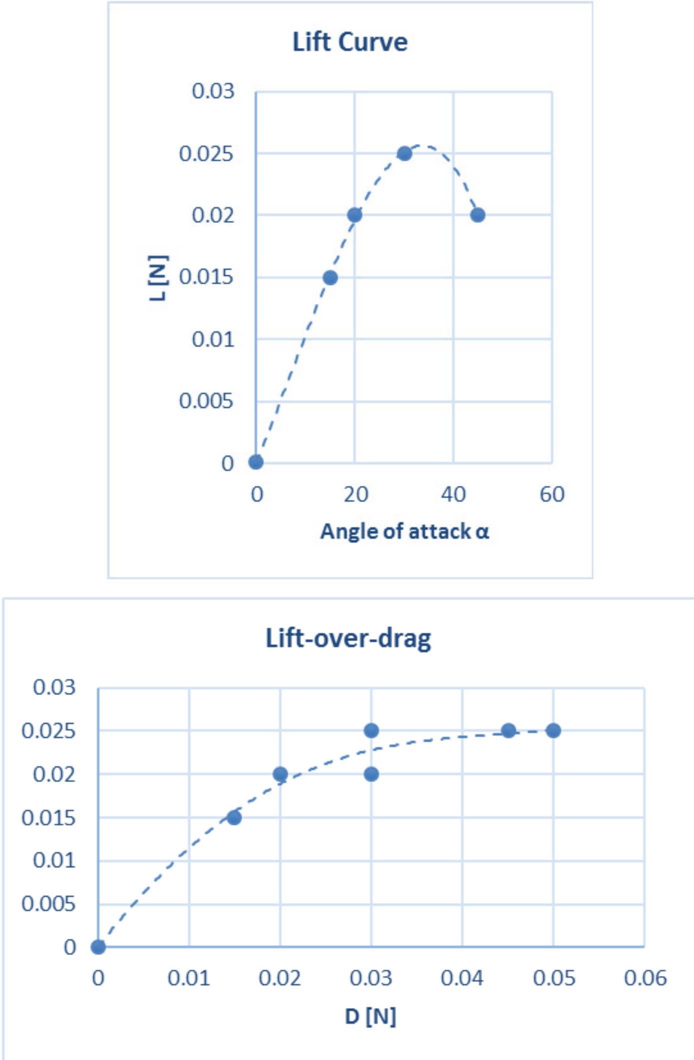
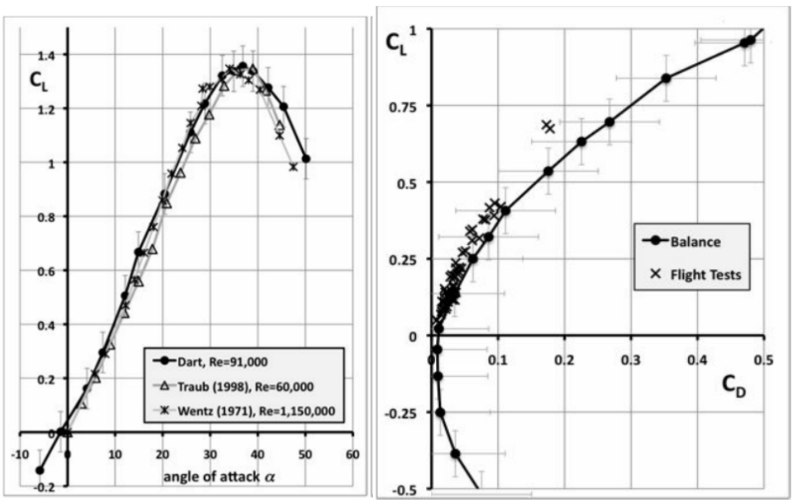


Figure 3.2.2 Graph of Lift and Drag (Uncertainty+|0.02N)
NOTE: i. *Due to the limitation of DIS, the scale of each graph might vary slightly;*
ii. *In the last case, the oscillation went up tremendously, so we had to abort further measurements.)*

The figures beneath show the relationship between α, L and D (or C_L and C_D) [5]:



(a) Our result



(b) Data from [5]

Figure 3.2.3 Lift curve and Lift coefficient-over-drag coefficient plot

We compare our results with other existing results. Possibly due to the instability of the set up, the drag was substantial while the lift was small; however, we still observed the same pattern of curve.

Result:

With the figure of lift-over-drag curve, it is now easy to find the angle of stall (approximately 37°), the maximum of lift-dray ratio $K_{\max}$ (approximately 4.9), and the optimum angle of attack α_{opt} (approximately 12°).

3. The Relationship between Angle of Elevation and Distance

Purpose: to detect the relationship between angle of elevation and distance.

Procedure:

In order to find out the relationship between angle of elevation and distance, we dart planes at different angles of election and measure the traveling distances, which are summarized in a figure.

Data Overview:

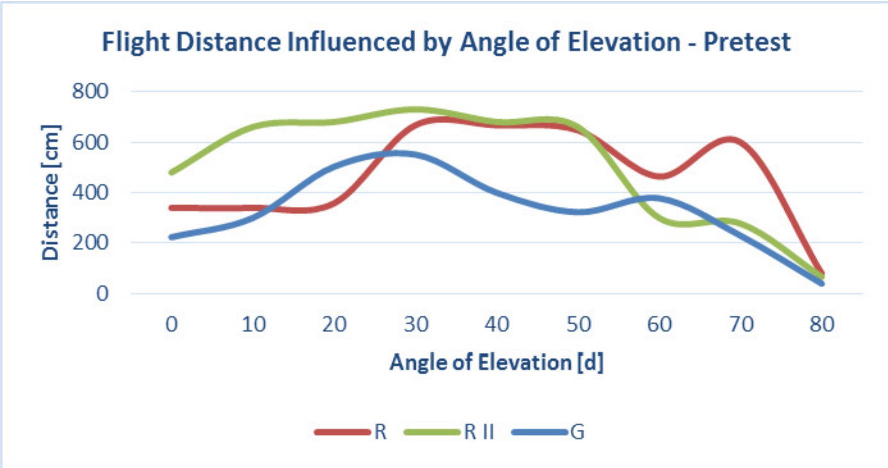


Figure 3.3.1 Effect of angle of elevation - pretest

Analysis:

In the above figure, we discovered that the fluctuations of the curves were significant. After a re-examination of the launcher, we came to the conclusion that any tiny increase of the launching force would result in a nonlinear increase in the flying distance, thus affecting our experiment. In order to verify our conjecture, we added another experiment to detect the relationship between projecting force and flying distance (shown in the figure below).

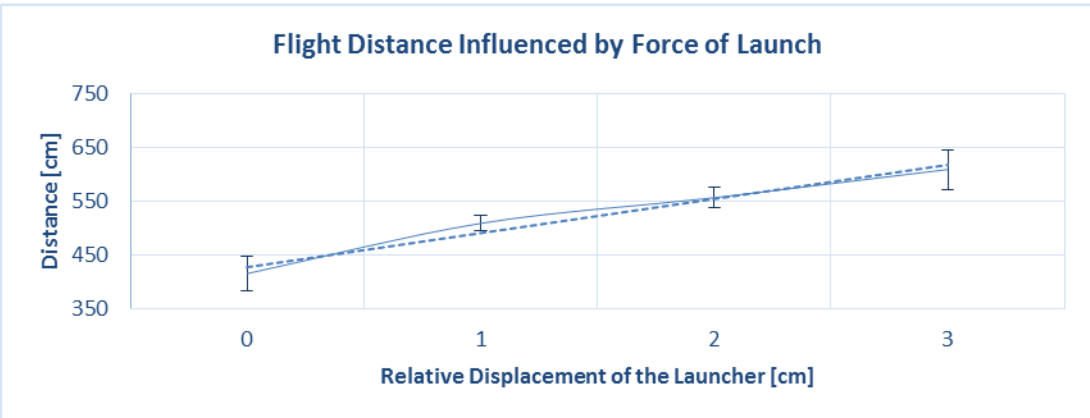


Figure 3.3.2 Effect of force of launch

Through measuring the relative displacement of the launcher and the flying distance, we

observed that the flying distance was in direct proportion to the launching force, so that our first conjecture may not be tenable.

Then we tried to propose another conjecture to explain the fluctuation found in the experiments; we realized that just on the day before we conducted our experiment, it rained, and the rain had persisted for more than two days. Considering this fact, we argue that maybe the humidity of the air added another factor to the experiment, thus causing the results to fluctuate. Considering this, we conducted the experiment on another sunny day and got the following figure:

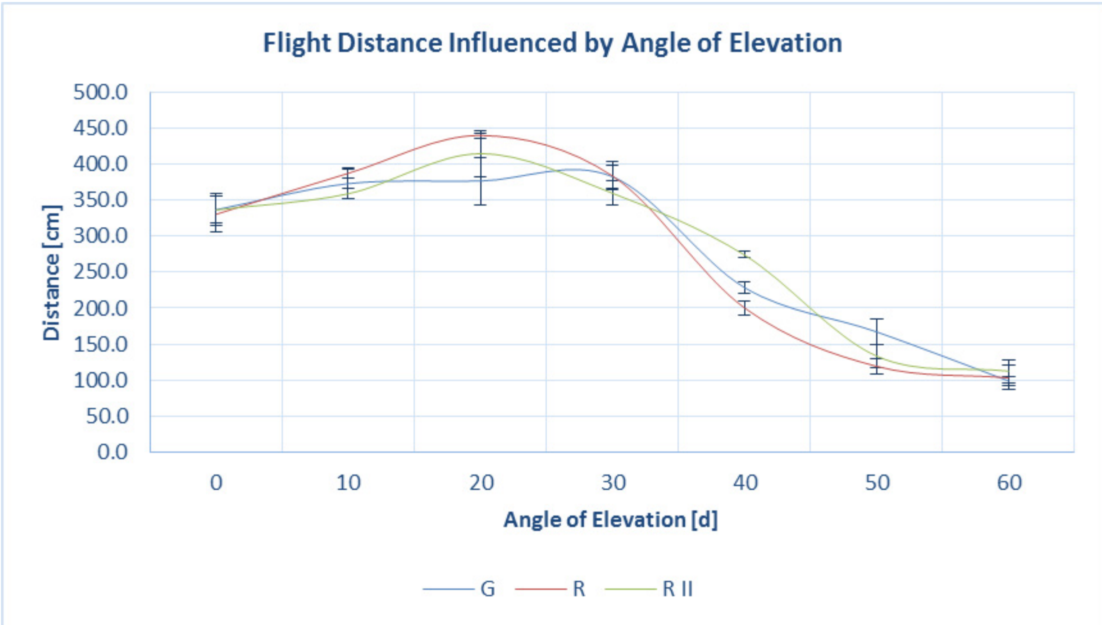


Figure 3.3.3 Effect of angle of elevation

It is easy to see the difference in these two examples. The conjecture about the weather as an influential factor is therefore confirmed, and of course the factor of humidity requires further research.

Analyzing the trajectory of flight, we found two typical patterns: (1) parabola-like; and (2) smooth gliding curve. Generally the first type of flight results into a short duration in the air and a short flight distance, and occurs when the angle of elevation is either too large or too small. The gliding pattern appears when the angle of elevation is moderate, and leads to a high performance.

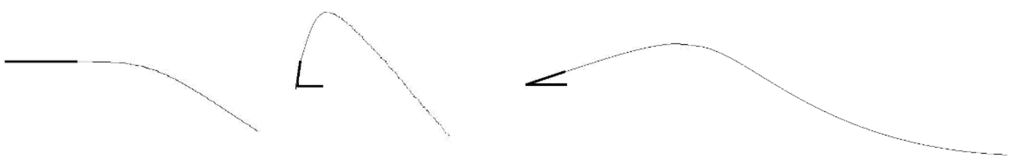


Figure 3.3.4 Flying trajectory

Result:

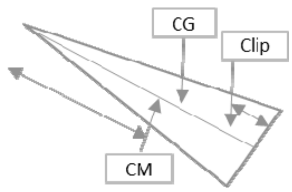
The plane reaches the furthest distances when the angle of elevation is approximately 20°. Additionally, humidity is a factor to be considered when analyzing the flying patterns of paper planes.

4. The Influence of the Centre of Mass

Purpose: to find out the relationship between the center of mass and flying distance, and then draw figures for different flying conditions when the center of mass is different.

Procedure:

We use clips to adjust the location of the center of mass, and measure the dependence of the flight distance on the location of the center of mass, in comparison with the geometrical center.



CM = center of mass

CG = center of geometry

Figure 3.4.1 Center of mass and center of geometry

NOTE: *this triangle is only part of the wing*

Data Overview:

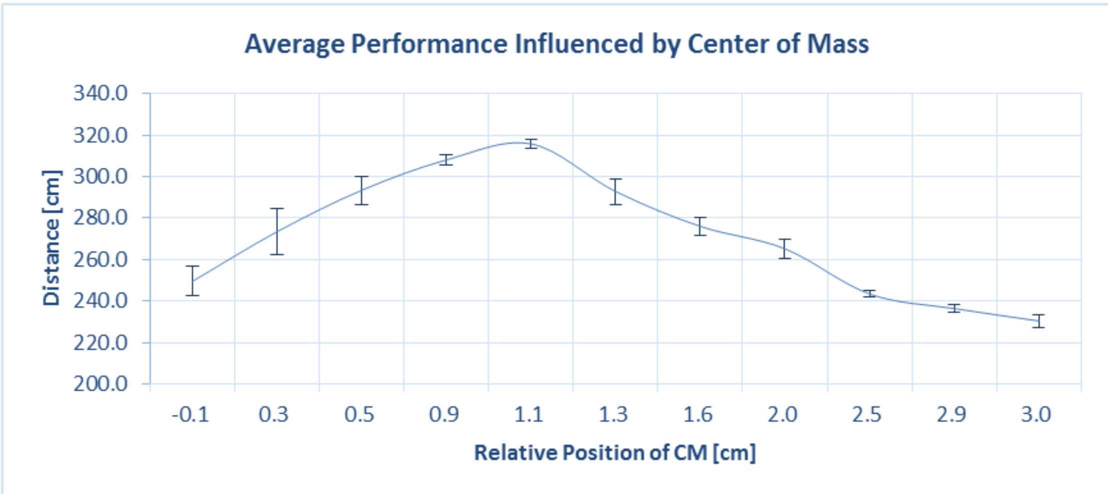


Figure 3.4.2 Effect of different center of mass

Flying Trajectory:

(a) Flying Trajectory – Centre of Mass near the Nose

(b) Flying Trajectory – Centre of Mass near the End

Figure 3.4.3 (a) (b) Effect of center of mass on flying trajectory

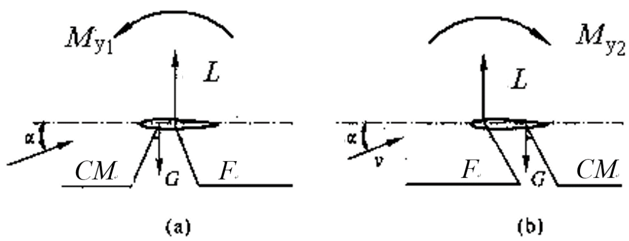
Discussion:

While conducting the experiment, we found that a modification of the center of mass results in an instability of flying, so that we reduced our previously applied projecting force.

Result:

When the center of mass is located near the midpoint of the wing cord, the plane reaches the furthest distance. Besides, when the center of mass is near the nose of the plane, it drops down easily; when the center of mass is near the end of the plane, it rises up and then stalls, sometimes resulting in an undulating flight.

Analysis:



CM	=	center of mass
F	=	focus of the wing

Figure 3.4.4 Force diagram of wings

From the result, we can observe that the plane reaches the furthest distance while the center of mass is behind the focus of the wing. The plane can achieve the furthest distance because when the center of mass is near the end of the plane, the resulting moment will raise the nose of the plane, as shown in the figure on the right above. In a certain range, this raise causes the angle of attack to be closer to the optimum angle of attack (12°); therefore, the flight distance can increase.

On the other hand, the midpoint of the wing may not be the best place to locate the center of mass if the plane is to achieve stabilization. According to the existing theory of UAV (unmanned aerial vehicle) aerodynamics, locating the center of mass behind the focus causes instability. [7] It is said that when the angle of attack increases, the lift force increases, while the moment of the focus remains constant, so the resulting moment on the plane increases, finally causing the stall.

However, this situation cannot be applied directly to paper planes. Since paper planes do not have power supplies, the decrease of their speed will result in the decrease of pitch up moment, so even the angle of attack increases, the total moment may still remain the same. Considering this, it is still in debate that whether the plane can be stable and balance when the center of mass is behind the focus.

5. The Influence of the Aileron

Purpose: to find out the relationship between the angle of ailerons and the flying distance, including the deflection distance.

Procedure:

We define the angle of aileron to be positive when the aileron is lifted up, negative when it is down. In the first experiment, the angles of the ailerons on both wings are adjusted to the same degrees, while on the second experiment, they are adjusted to opposite degrees.

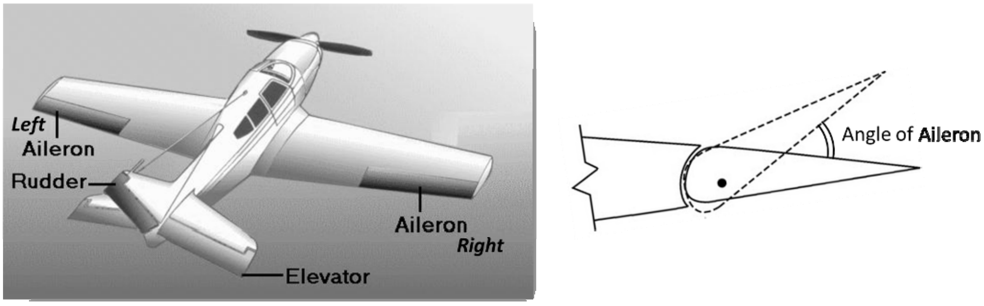
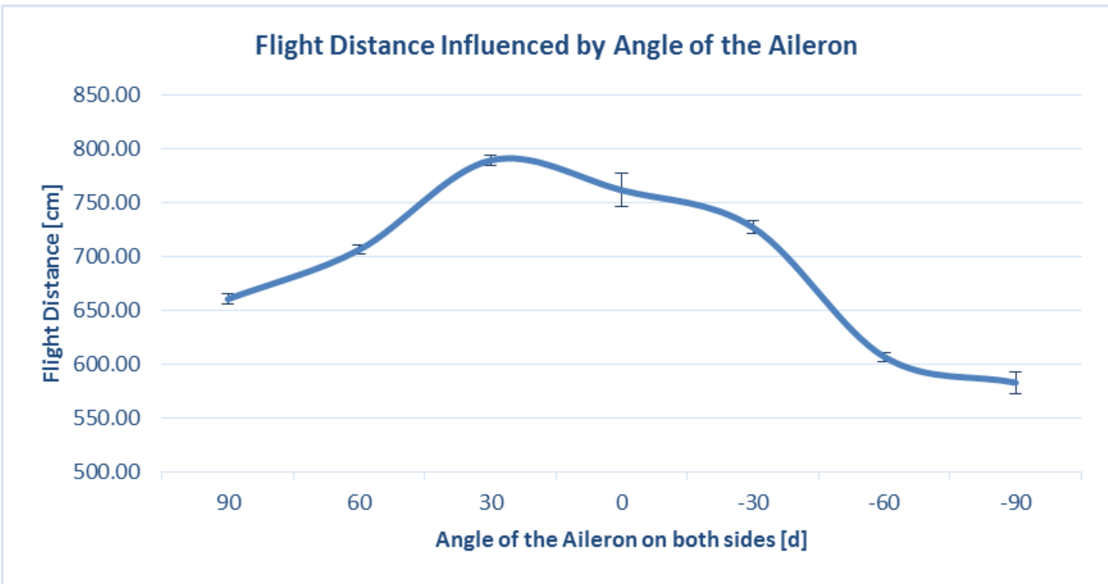
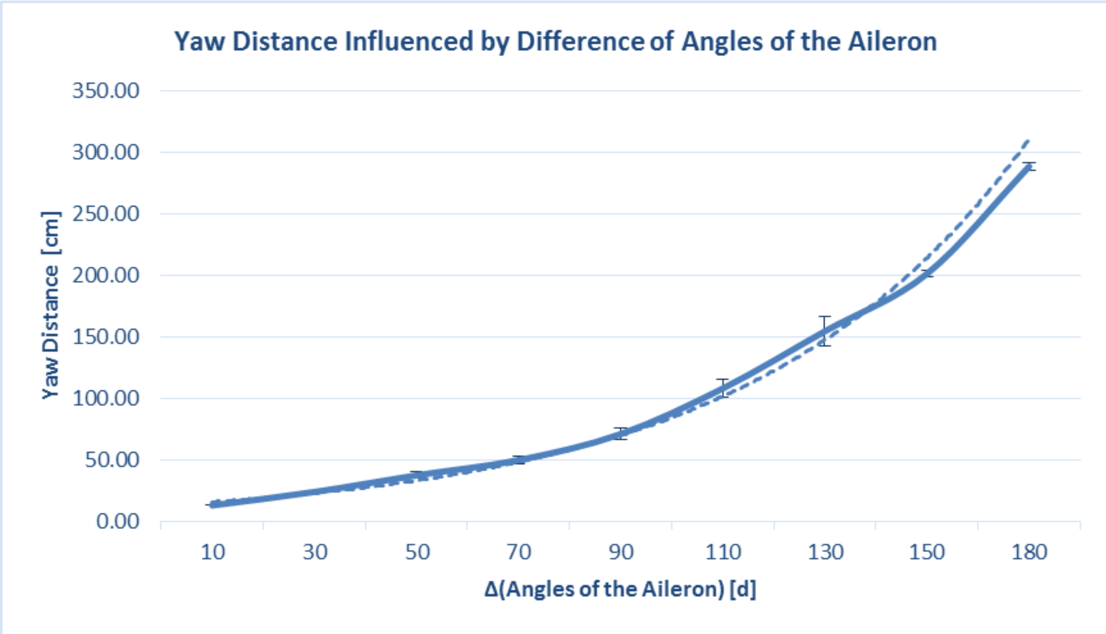


Figure 3.5.1 Angle of Aileron

Data Overview:



(a) Effect of the same angle of Aileron on both sides



(b) Effect of the difference of angles of Aileron on each side

Figure 3.5.2 Effect of Aileron

Result:

In real-life situations, the ailerons on both wings seldom go up or down at the same time as in our first experiment. If they do, then raising the aileron to the same degrees seems to have the same effect as a relocation of the center of mass. This phenomenon will be discussed in the next experiment.

Regarding the second experiment, the influence of the ailerons is similar to that observed in the case of real planes: while the difference in the angles becomes larger, the plane’s lateral displacement increases.

6. The Influence of the Empennage

Purpose: to compare the flying distance with and without the empennage, using the famous model of DC-3.

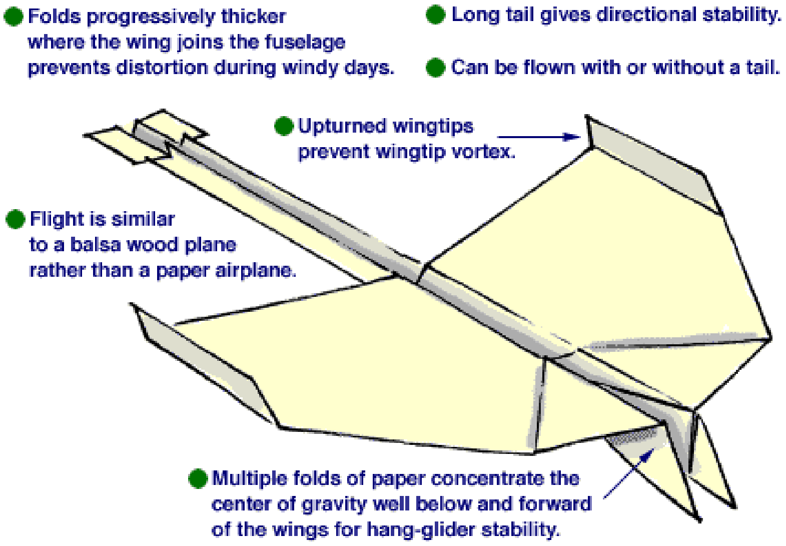


Figure 3.6.1 DC-3

Data Overview:

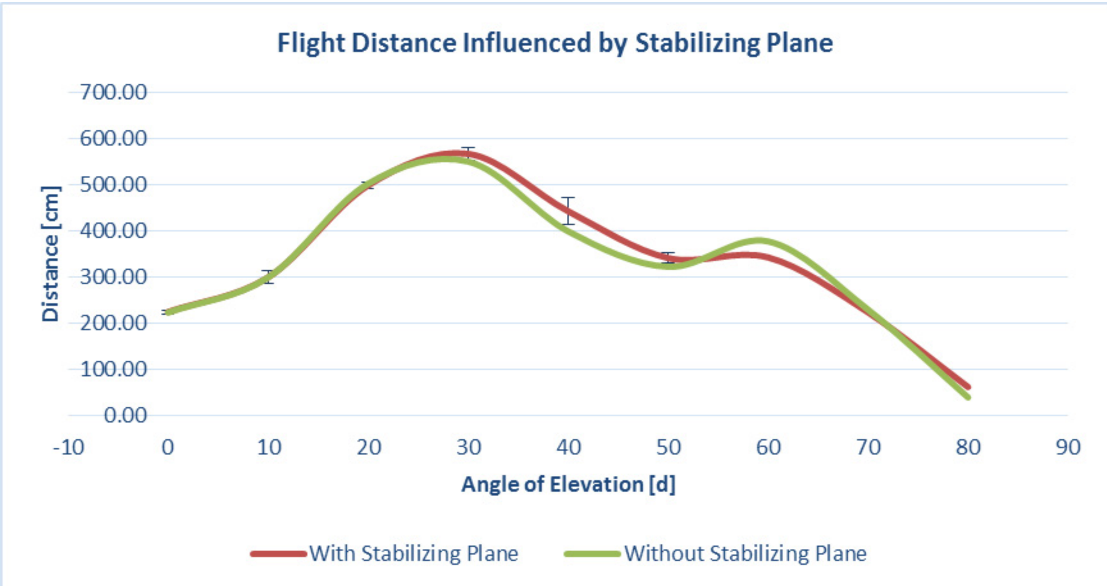
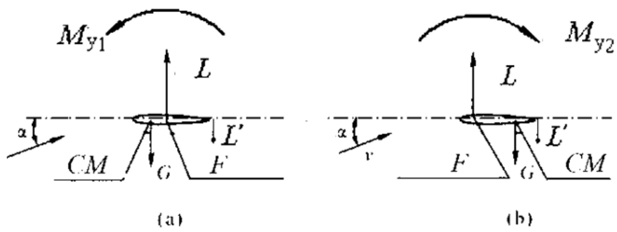


Figure 3.6.2 Effect of Stabilizing Plane

Analysis:

The flight distance seems not affected by the addition of a stabilizing plane; this is easy to understand since stability is not directly related to traveling distance. The situation is different, however, when adding the factor of wind. The wind power is akin to an engine's power, only in a rather inconstant way. This additional power is causing the plane to lose the state of balance, and in this situation the function of the empennage is required.

For the plane we used in this experiment, the plane DC-3, its center of mass is in front of the focus, as shown on the left figure beneath. In the wind condition, when the angle of attack increases, it is easy to see that the pitch down moment increases as well, and the plane is able to reverse into the previous state. Also, in relative to the center of mass, the moment of the wing's lift force and that of the empennage's force cancel each other, so that the plane achieves a balance even in windy conditions.



CM	=	center of mass
F	=	focus of the wing

Figure 3.6.3 Force diagram of wings (with the effect of empennage)

Conclusion

The plane can fly the further while the angle of attack during the flight is closer to the optimum angle of attack (approximately 12°). This angle of attack during the flight can be directly affected by the angle of elevation and the location of the center of mass: when the angle of elevation is approximately 20° and the center of mass is at the midpoint of the wing cord, the plane achieve the optimum change pattern of the angle of attack, and fly the furthest.

The empennage and the aileron can affect the angle of attack during the flight indirectly. The aileron change the flying direction; the empennage can help to stabilize and balance the plane, especially in wind condition.

A Plane of Mine

After conducting the experiment above, we designed our own paper plane. It has a center of mass near the nose, a relatively small aspect ratio, and can travel about thirty meters when there is no wind.

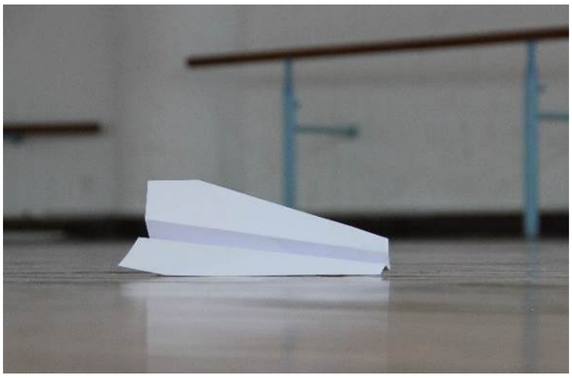


Figure 5.1 A Plane of mine

Suggestion for Further Research

The humidity of the air should be regarded an important factor to be taken into account when discussing the parameters of a paper plane. Furthermore, this factor may have an innate relation to the question: "why people exhale at the nose of the plane before flying it?"

The performance of a certain wing shape will increase as a function of the Reynolds number, and when the Reynolds number reaches a certain point, the performance of the wing increases even exponentially. [4] This sudden increase should be studied in detail to determine which wing shape is theoretically the best, and how it influences the choice of the optimum initial speed.

Acknowledgements

We thank the support of Xiamen Foreign Language School and Xiamen University.

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