Setup a Low-Speed Wind Tunnel

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Preface 前言

Since I want to design and manufacture my own drone, I need a way to test the basic dynamics performance of the drone by measuring drag and lift. I browsed my AP Physics textbook and had some basic ideas about my own wind tunnel.

A wind tunnel should be able to provide the following features so that people can make measurement with model plane in it:

- A stable air flow field that produces consistent measurements,
- Adjustable air flow to simulate low to high velocity,
- Method to measure aerodynamic indicators, such as force, moment and stability.

I also found related theories of aerodynamics.
I will illustrate the process and understanding of mine and every step to setup my test wind tunnel.

Laminar Flow and Turbulent Flow 层流和紊流

Air is a fluid, and the air flow can be classified as laminar flow and turbulent flow.

In laminar flows or streamlined flows, air particles move in layers as if there were virtual pipes that guide the stream.

Figure 1 shows (1) fluid flows steadily through a long, narrow, horizontal pipe of constant cross section. The particles move straightly and do not interreact with the particles in the adjacent layer.

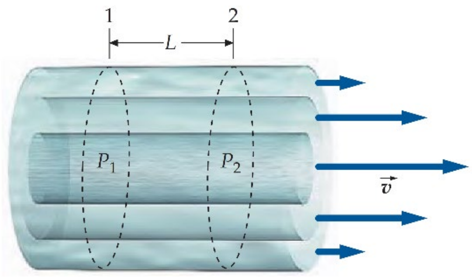

Figure 1: laminar flow

There is also turbulent flow. For example (2), in figure 2 you can find that the smoke from a burning cigarette rises in a regular stream, but the simple streamlined flow quickly becomes turbulent, and the smoke begins to swirl irregularly.


Figure 2: Turbulence flow

Scientists use Reynolds Number to characterize the conditions for laminar flow and turbulent flow. The Reynolds number of a flow (3), N_R, is defined by:

$$N_R = \frac{2r\rho v}{\eta}$$

Where

- v is the average speed of the fluid, (m/s)

- ρ is the density of the fluid, (SI units: kg/m^3)
- r is the radius of the tube, (m)
- η is the dynamic viscosity of the fluid ($Pa \cdot s$)

In general, high-speed flow tends to be turbulent (N_R>3000) and high viscosity fluids (N_R<2000) exhibit laminar flow. I want my wind tunnel to produce laminar flow. As I cannot change the viscosity of the air, a low-speed wind tunnel is preferred. To produce laminar flow, two factors should be considered: wind generation and shape of the tunnel.

Evaluate the Fan 风扇测试

An ordinary fan cannot be used for the wind tunnel because its diameter is not large enough, meaning it cannot create a large zone with uniform airflow, and the flow is not stable near the blade. Our family has a large air purifier (4) in which a large filter is installed (0.6m x 1.2m). As air flows through the filter element, it is expected to become more uniform and stable.

I hung 16 light strings on a cable and put the cable in front of the air purifier to determine whether the wind flow is stable. 7 of the 16 strings were displaced at an angle about (30±5)° from the vertical. By moving the cable up and down, I can detect the range in which the Laminar Flow is uniform.

Figure 3: FFU air purifier

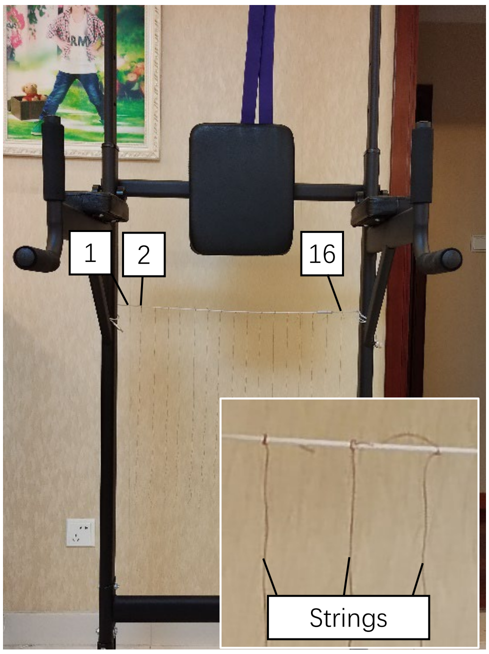

Figure 4: 16 Strings hanging on a cable.

A Wind Tunnel without Tunnel 无洞风洞

The test shows that the effective zone in front of the fan has dimensions of

$$L \times W \times H = 0.4 \times 0.7 \times 1.0\ (m)$$

in which the air flow is almost stable and uniform. Figure 5 shows the effective zone in front of the fan.

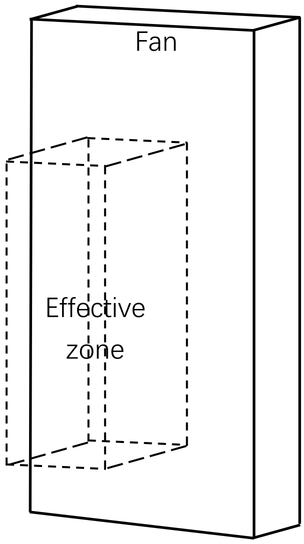

Figure 5: Effective zone

Figure 6 is the top view of the drisplaced strings. 7/16 strings are displaced, and they are almost parallel with each other. However, the strings are not perfectly in parallel, as string No. 6 is at a 3 ° angle to the rest of the parallel strings. The wind field generated by the fan and filter is not enclosed in a tunnel, so I thought the strings could be closer to being parallel if walls were added.

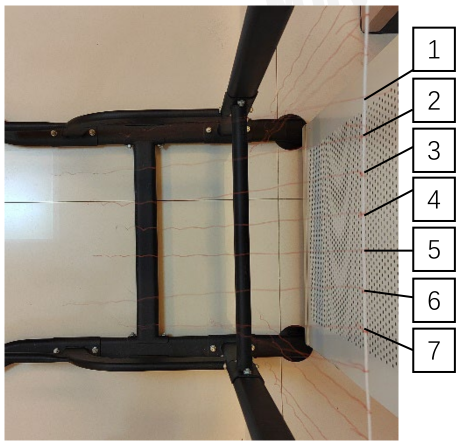

Figure 6: Top view of strings

Since the ground is a wind barrier, only a right wall, a left wall, and a ceiling is needed to create the tunnel. The outcome was totally unexpected. Installing a ceiling has minimal effect on the wind field, but installing a wall degrades the uniformity of the wind field. Figure 7 shows that the installation of right wall makes string No. 5, No, 6 and No. 7 more displaced to the right. The installing both walls produces the same effect. After trying multiple configurations of different distances between the flow and the walls, I gave up.

Figure 7: string swift to the right

This remains a trivial problem, as a 3° displacement is not a big issue. An exposed wind field with an almost uniform laminar flow is perfect for me to evaluate my drone. Therefore, I can say I have built a wind tunnel without tunnel. It reminds me a similar Chinese Phrase “不射之射”(5).

Drag and Lift 阻力和升力

I want to measure (or compare) the two most important coefficients for any airfoil/airplane, C_D and C_L. C_D is the coefficient of drag, defined by $C_D = \frac{D}{\frac{1}{2}\rho u^2 S}$ (6). C_L is the coefficient of lift, defined by $C_L = \frac{L}{\frac{1}{2}\rho u^2 S}$ (6). Here, D is the drag force and L is the lift force, ρ is the fluid density, u is the flow speed, and S is the relevant surface area (6). Figure 8 shows a segment of airfoil that is attached to a mount which hangs on 4 strings. When steady wind flows over the airfoil, drag force is along the -y direction while lift force is along the -x direction. Because the gravity is along the z direction, the strings will tilt and have displacements Dx and Dy and a vertical component of length of the string Z. We can measure Dx, Dy, and the string length L. $Z = \sqrt{L^2 - D_x^2 - D_y^2}$. The ratio between Dx, Dy, and Z is the same as the ratio between lift, drag, and mg. We can measure mg, so we can derive the lift and drag.

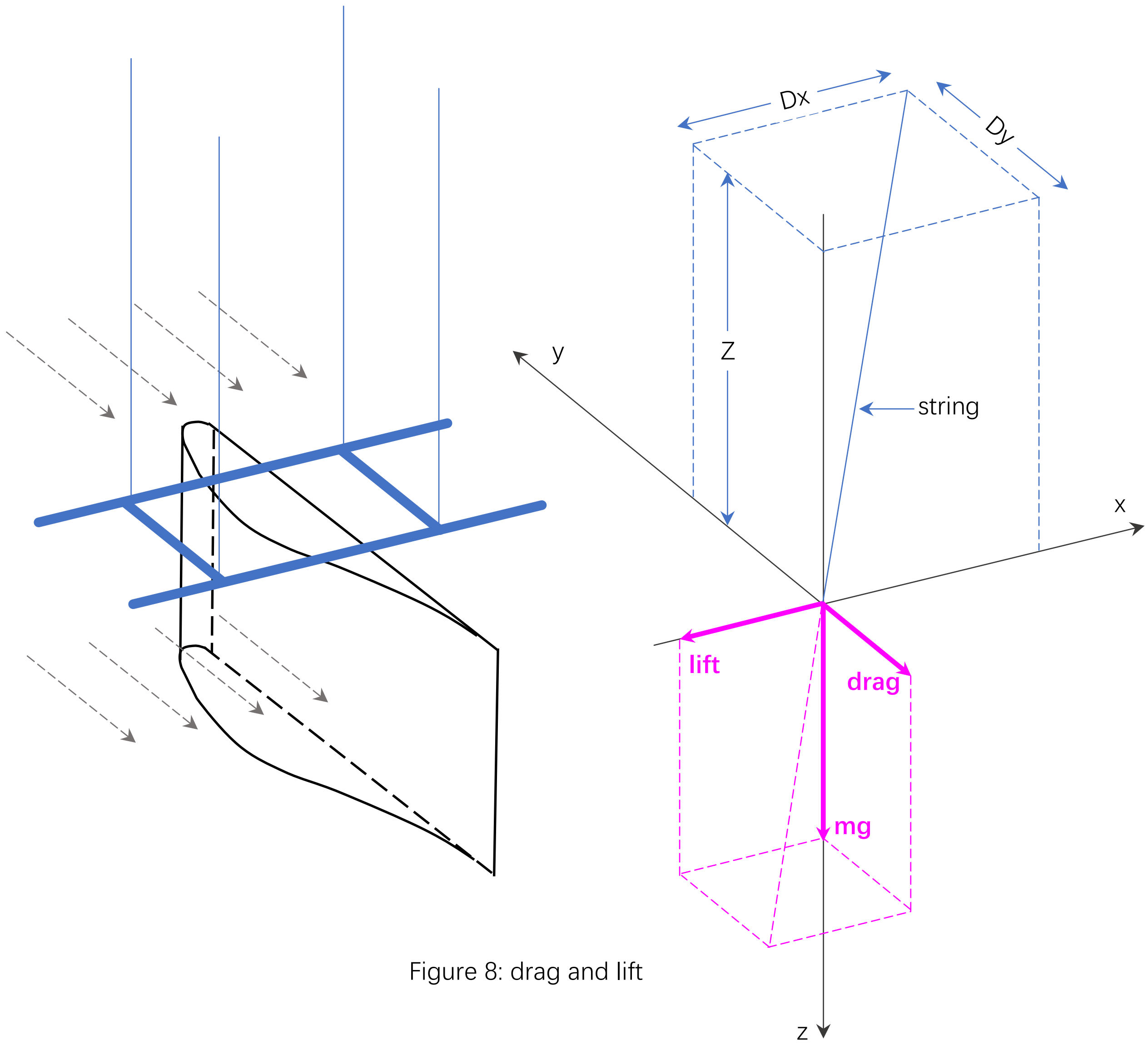

Figure 8: drag and lift

Figure 9: a sample airfoil and the test bench

Figure 9 shows the sample airfoil, its frame, and the test bench.

Moment Produced by Aerodynamic Force 风力的力矩

After the airfoil is correctly set up in the wind tunnel, the strings tilt gradually until it reaches an equilibrium position. The airfoil also rotates clockwise or counterclockwise to different angles of attack (top view) where it stays in equilibrium. Therefore, the aerodynamic forces exert a net moment on the airfoil. Figure 10 shows that only when the AOA (Angle of Attack) is -7°, -17° and 23° respectively, the system can reach its equilibrium position.

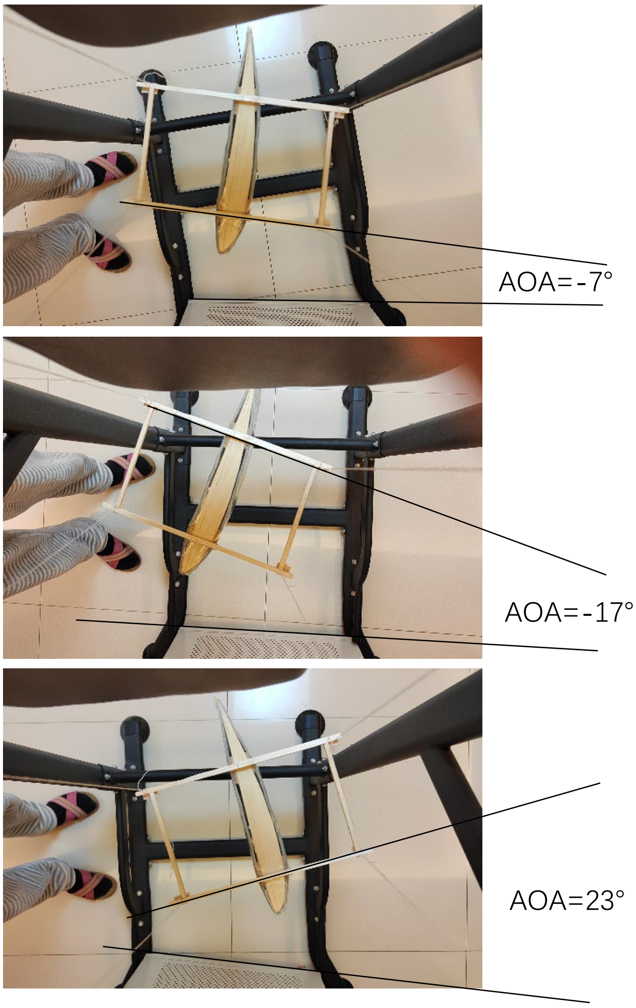

Figure 10: rotation of the airfoil.

- Test Condition:

Airfoil type	Clark Y
Airfoil weight	44 g
Cord	274 mm
Span	307 mm

Table 1: Airfoil information

String length		885 mm		Air Density	1.184 kg/m3
Temperature		25 °C		Air Dynamic Viscosity	1.849 x E-5 Pa·s
Wind speed		2.6±0.5 m/s		Reynolds number	51112

Table 2: Test Condition

Note: In calculation of Reynolds number, 2r=0.307m.

- Lift and drag test

string length = 885 mm, airfoil = 44 g							
AOA(°)	Dx (mm)	Dy (mm)	z (mm)	lift (mN)	C_L	drag (mN)	C_D
-7	-39	35	883.4	-19.04	-4.41E-02	17.08	3.96E-02
-17	-64	86	878.5	-31.41	-7.24E-02	42.21	9.73E-02
23	62	24	882.5	30.29	7.02E-02	11.73	2.72E-02

Table 3: lift and drag of different AOA

Note: The accuracy of lift, C_L , Drag and C_D are all ±8/274=±3%, where 274 is the cord length.

- Net moment of aerodynamic forces

Figure 11 shows the rotation θ of the airfoil and mount in the wind flow. The dimensions of the mount are represented by x and y.

Dimension of Fixture	
x (mm)	215.0
y (mm)	140.0
$d = \sqrt{x^2 + y^2}$ (mm)	256.6
R_{cm}=d/2 (mm)	128.3

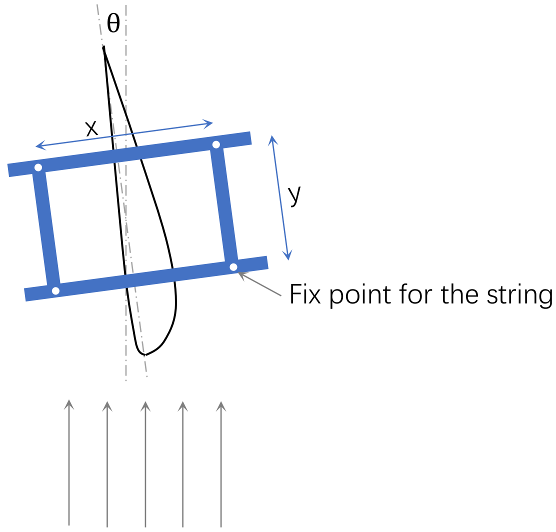

Figure 11: rotation measurement.

Moment of airflow

AOA(°)	Rotation (°)	$Disp_{xy}$ (mm)	z (mm)	mg (mN)	T_{xy} (mN)	M (mN·m)
-7	-17	-38.06	883.4	431.2	-18.578	-9.533
-17	-24	-53.73	878.5	431.2	-26.375	-13.534
23	7.5	16.79	882.5	431.2	8.205	4.210

Table 5: Moment due to the airflow

Note: $Disp_{xy}$ is the displacement of the fix point for the string in x-y plane.

$Disp_{xy} = R_{cm}\theta$

z is the vertical length of the string

T_{xy} is the tension's horizontal component in x-y plane. $\frac{Disp_{xy}}{T_{xy}} = \frac{z}{mg}$

M is the moment of airflow $M = 4 \times T_{xy} \times R_{cm}$

Analysis and Conclusion 分析与总结

Really not expected result but can still get some output:

1. This system can calculate drag, lift and moment due to airflow in 3 AOAs when the wind speed is 2.6m/s. In any other AOA, as the system is not stable, a measurement cannot be implemented.
2. In other wind speed, some other AOA can achieve some stable condition.

Any way this is the first step for me to have a try in aerodynamic studies. I will discuss how to decrease the interference from the moment and get more a stable condition in the next paper.

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目录