Model Testing of a Sub-Sonic Wind Tunnel

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Abstract-A subsonic wind tunnel was designed for laboratory use. The design is for an open-circuit, closed-test-section wind tunnel that is about 9 ft. by 3ft, and can be taken apart for storage and transportation. The wind tunnel is designed mainly for use in fluid mechanics laboratory and this justifies the size, the material and equipment specifications and, the cost. Each of the sections are designed and constructed independently and then assembled. Models of different shapes and sizes can be tested to study the aerodynamic forces interacting. Major results obtained from the study are: Lift and Drag forces, coefficient of lift (CL) and coefficient of drag (CD) and Reynolds' number. Other parameters include: volumetric flow rate, static and dynamic pressures, Mach number, flow velocity, density, angle of attack, flow area, air foil chord and span. The Continuity equation and Bernoulli's equation were useful in determining some parameters in the design.

***Keywords*: Axial fan, Contraction cone, Dynamic Similarity, Lift and Drag, Prototype.**

I. INTRODUCTION

Wind engineering is a field that has been evolving over centuries. The first step in wind engineering was over 350 years ago when Torricelli invented the barometer to measure air pressure (Cochran 4). There have been many changes over the years, but at its core wind engineering is based on using measurements of actual wind flows to predict the forces transferred to engineering structures and machines. However, wind tunnels are now finding use in non-traditional applications, such as simulating the forced airflows required to cool electronic systems. As the functionality of modern electronic systems increase, power dissipation levels also increase and forced air-cooling is required to maintain operating temperatures below present maximum levels, so that reliable and safe operation is maintained. While fans and air blowers are typically used to provide this airflow, thermal designers require input data to aid the design process so that the thermal performance of electronic components, Printed Circuit Boards (PCBs) and heat sinks are known. Such empirical data is obtained using low speed wind tunnels and an excellent review of the issues surrounding wind tunnel design for such applications has been presented by Westphal (1997).

Wind tunnels have been used for over 100 years. In fact, the Wright brothers used one to help them figure out how to build the world's first successful aircraft, the *Wright Flyer*.

Today, wind tunnels are used by NASA, Boeing, Northrop Grumman, and every other organization that makes aircraft and spacecraft. In fact, NASA AMES, in Moffet Field, California, has the most wind tunnels than any location in the world, and also has the largest wind tunnel on Earth! Wind tunnels are also used for educational purposes. For instance, schools use them to demonstrate how planes fly. They are also used in research projects, as students design aircraft models and test their performance.

One hundred years ago, in the fall of 1902, Wilbur and Orville Wright tested their most successful glider at the Kill Devil Hills camp, near Kitty Hawk, North Carolina. This was not an impromptu event, it followed more than a year of testing wing sections in their homemade wind tunnel, back in Dayton, Ohio. The glider's performance confirmed calculations based on the wind tunnel data. Their ultimately successful venture provides a useful model for science teachers, students and researchers to emulate [12]

During the spring of 2001, a group of State College Area School District and Penn State University faculty (along with a volunteer pilot from US Airways) met to discuss ways to enhance instruction in a third and fourth grade unit, called Air and Aviation. A specific goal of these meetings was to find classroom strategies that would help students to visualize abstract concepts of flight, such as lift and drag. One idea seemed feasible, to create a small, inexpensive device that would illustrate Bernoulli's principle in a way that third graders could understand. The device began as a small wind tunnel, similar to that developed by the Wright brothers, which would allow "correctly" shaped paper airfoils (plane wings) to fly. That same device ended up being an efficient teaching tool with numerous applications. Potential uses of our wind tunnel device (nicknamed the "Bernoulli box"), range from discovery and guided learning of qualitative aspects of lift to the possibility of adding instrumentation for quantitative studies.

The objective is to design and construct a low speed wind tunnel which can help to measure aerodynamic forces (lift and drag forces) for instructional purposes, conduct wind tunnel testing on models of various shapes and sizes and simulate airflow using spring scales and compare with experimental results in order to enhance the understanding of aerodynamic design and air flow through across the model.

Lift is the force that directly opposes the weight of an object and holds it in the air. It is a mechanical aerodynamic force produced by the motion of the object through the air. It acts through the centre of pressure of the object and is directly perpendicular to the flow direction. There are several factors which affect it's magnitude. It is generated by the difference in velocity between the solid object and the fluid. There must be motion between the object and the fluid: no motion, no lift. It makes no difference whether the object moves through a static fluid, or the fluid moves past a static solid object. Lift acts perpendicular to the motion. Drag acts in the direction opposed to the motion [10]
Lift occurs when a moving flow of gas is turned by a solid object. The flow is turned in one direction, and the lift is generated in the opposite direction.

Drag is the aerodynamic force that opposes an object's motion through the air. It is thought of as aerodynamic friction, and one of the sources of it is the skin friction between the molecules of the air and the solid surface of an automobile. It is a mechanical force which generated by the interaction and contact of a solid body with a fluid (liquid or gas). It is not generated by a force field, in the sense of a gravitational field or an electromagnetic field, where one object can affect another object without being in physical contact. For drag to be generated, the solid body must be in contact with the fluid. If there is no fluid, there is no drag. It is generated by the difference in velocity between the solid object and the fluid. There must be motion between the object and the fluid. If there is no motion, there is no drag. It makes no difference whether the object moves through a static fluid or whether the fluid moves past a static solid object [4].
For a gas, the magnitude of drag depends on the viscosity of the air and the relative magnitude of the viscous forces to the motion of the flow, expressed as the Reynolds number. Along the solid surface, a boundary layer of low energy flow is generated and the magnitude of the skin friction depends on conditions in the boundary layer [3].

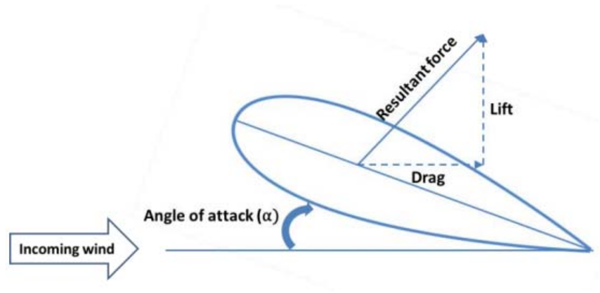

Figure 1: Drag and Lift components of the aerodynamic force (10)

The angle of attack is the angle at which relative wind meets an airfoil. It is the angle that is formed by the chord of the airfoil and the direction of the relative wind or between the chord line and the flight path. The angle of attack changes during a flight as the pilot changes the direction of the aircraft. It is one of the factors that determine the aircraft's rate of speed through the air.

The angle of attack is related to the amount of lift. Lift will increase as the angle of attack is increased up to the point (usually around 17 degrees) where the aircraft stalls, the critical angle of attack [5]

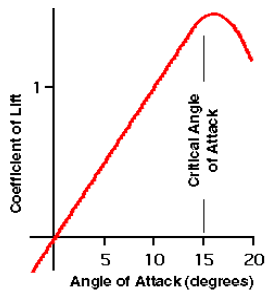

Figure 2: Curve showing relationship between AOA and coefficient of lift (Skybrary.aero)

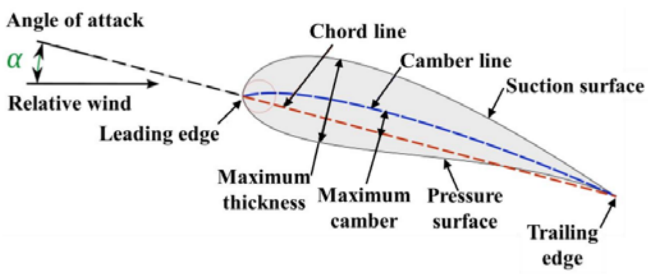

Figure 3: Diagram showing a detailed airfoil [11]

II. METHODOLOGY

2.1 *Wind Turnel*

The main features of the Wind Tunnel are: Axial fan, Contraction cone, Diffuser assembly, Stripper, Entrance Cone, Lift and Drag, Angle of Attack.

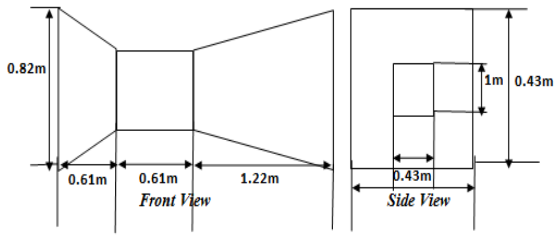

Figure 4: Schematic diagram of the designed wind tunnel

The construction of the Subsonic Wind Tunnel involves many operations which includes; cutting, turning, sawing.

2.2 The Contraction Cone

Using a ratio of 7:1 for the contraction cone at both ends.

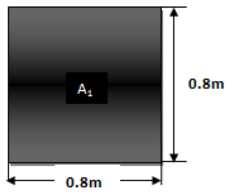

Figure 5: Entrance section of the contraction cone

$$\boldsymbol{A_1 = (L \times B)m}$$

Where A_1 is the area at the entrance of the contraction cone

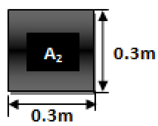

Figure 6: Exit section of the contraction cone

$$\boldsymbol{A_2 = (L \times B)m}$$

Where A_2 is the area at the exit of the contraction cone.

Contraction Cone Ratio

$$\frac{\mathrm{A_1}}{\mathrm{A_2}}$$

A reduction in area causes increase in the velocity at the other end of the contraction cone.

Applying the continuity equation;

$$\text{AV=constant}$$

$$A_1V_1 = A_2V_2$$

$$\frac{V_2}{V_1} = 7.11$$

For a wind speed of 72.72km/h in the test section, i.e.$V_2 = 20.2m/s$

$$V_1 = 2.8m/s$$

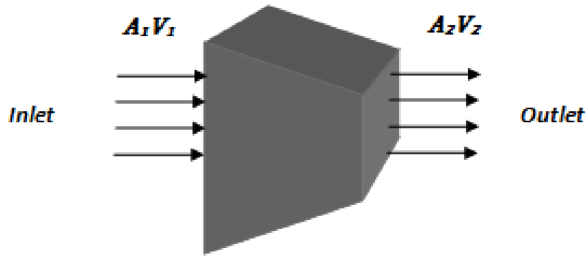

Figure 7: Diagram showing fluid flow across the wind tunnel contraction cone

2.3 The Drive Section

$$\omega = \frac{2\pi N}{60}$$

$$V_2 = \omega r$$

$$V_2 = \frac{\pi DN}{60}$$

Where r and D represent the radius and diameter (in meters) of the axial fan blade respectively.

ω represents the angular velocity in rad/s and, N is the revolution per minute of the axial fan.

Using a fan blade diameter of 11 inches (0.275m);

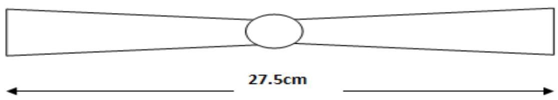

Figure 8: Diagram showing an arm of the axial fan blade

To determine the rpm of the axial fan to be used, given the following;

Axial fan blade diameter, D = 0.275m

$$V_2 = \frac{144 \times 1000}{3600}$$

$$= 40\ m/s$$

$$V_2 = \frac{\pi DN}{60}$$

$$V_2 = \frac{0.275\pi \times 1400\text{rpm}}{60}$$

$$V_2 = 20.16m/s$$

Wind speed in the test section, V_2 20.2m/s = 72.72km/h

2.4 The Test Section

Where A_3 is the area of the test section

$$A_3 = 0.18m^2$$

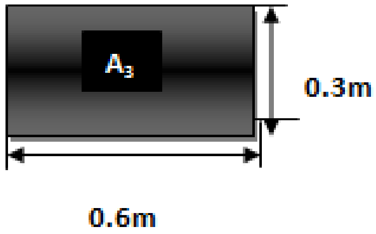

Figure 9: Diagram showing a section of the test section

Hence, flow rate Q = Test section area, $A_3 \times Velocity\ of\ fluid\ moving\ across\ the\ test\ section, V_2$

$$Q = A_3 V_2$$

Therefore, the fluid flow rate across the wind tunnel test section is**.** $\boldsymbol{Q = 3.64m^3/s}$

2.5 Reynolds Number

Known:

Fluid velocity across test section $V_2 = 20.2m/s$

Length of test section l=0.6m

Kinematic viscosity of air,

$$v = 1.4146 \times 10^{-5} m^2 s^{-1}$$

$$\text{Reynolds no, } \mathrm{R_e} = \frac{\text{fluid velocity across test section } \mathrm{V_2} \times \text{length of test section 1}}{\text{kinematic viscosity of air v}}$$

$$\mathrm{R_e} = \frac{\mathrm{Vl}}{\mathrm{v}}$$

$$\mathrm{R_e} = 8.56779 \times 10^5$$

Therefore, the Reynolds no. for this wind tunnel; $\mathrm{R_e} = 8.56779 \times 10^5 > 50{,}000$**.** This large value signifies that flow is turbulent.

2.6 Mach Number

$$\text{Mach no.} = \frac{\text{wind speed in the test section}\mathrm{V_2}}{\text{Speed of sound in air } \mathrm{V_{sound}}}$$

Given;

Wind speed I the test section $V_2 = 20.2m/s$

Speed of sound in air $V_{sound} = 340m/s$

Therefore,

$$\text{Mach no} = \frac{\mathrm{V_2}}{\mathrm{V_{sound}}}$$

Mach no =0.06

The ratio of the speed of air in the test section to the speed of sound in air is 1:17

2.7 The Diffuser Assembly

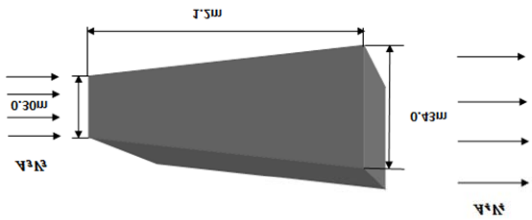

Figure 10: Diagram showing a section of the diffuser assembly

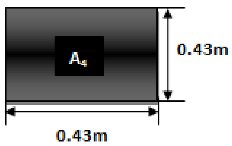

Figure 11: Diagram showing the front view of the 17" end of the diffuser assembly

To find the velocity at the 17 square inch end of the diffuser, we also apply continuity equation;
Let A_3 be the area of the diffuser end that connects to the test section $=A_2$
Let A_4 be the area of the diffuser end that constitutes the drive section
Let V_3 be the velocity of air emerging from the test section $=V_2$
Let V_4 be the velocity of air emerging from the 17" end of the diffuser
Known;

$$A_3 = 0.09\text{m}^2$$
$$A_4 = (0.43 \times 0.43)\text{m}^2$$
$$A_4 = 0.185\text{m}^2$$
$$V_3 = 20.2\text{m/s}$$
$$V_4 = ?$$
$$A_3V_3 = A_4V_4$$
$$V_4 = 9.8\text{m/s}$$

2.8 Pressure Calculations

Let P_b be the pressure of air emerging from the larger end of the diffuser
Let P_a be the pressure of air entering the smaller end of the diffuser
Let V_a be the velocity of air entering the diffuser

Let V_b be the velocity of air leaving the diffuser

To calculate the pressure difference, we apply equation below

$$\mathrm{P_b} - \mathrm{P_a} = \frac{1}{2}\mathrm{P}(\mathrm{V_a^2} - \mathrm{V_b^2})$$

$$\Delta P_{ab} = 0.191'1KPa$$

Therefore, the pressure difference across the diffuser is 0.19kPa.

Calculating the dynamic pressure at each end of the diffuser, according to equation 2.4;

$$q_a = \frac{1}{2}PV_a^2$$

$$q_a = 58.838Pa = 0.059KPa$$

To find the total pressure, we apply equation

$$P_0 = p + q$$

Static pressure of air p is known to be 101.309kPa

Therefore, total pressure at diffuser entrance;

$$P_{0a} = 101.559KPa$$

Also, the total pressure of air leaving the diffuser;

$$P_{0b} = (101.309 + 0.059)KPa$$

$$P_{0a} = 101.368KPa$$

III. PRINCIPLES OF MODEL TESTING

Wind tunnel models is divided into rigid models and aero elastic models. Rigid models are mostly used for measuring the forces, moments and pressures. Aero elastic models are used for measuring the deflections, stresses in static models and oscillatory forces in dynamic models.

Model scale has to be chosen based on the following;

- Geometrical similarity
- Dynamic similarity
- Blockage ratio considerations in the wind tunnel test section

The model has to be sufficiently rigid and should be geometrically scaled down for required dimensions to meet geometric similarity. Because the situations or conditions, the prototype will encounter in its field of operation is different from the conditions in the wind tunnel. To this extent the test conditions are not representative to the field conditions. To have dynamic similarity, the Reynolds number of the prototype has to be equal to the Reynolds number of the model under test in the wind tunnel. The cross sectional area of the model should not exceed 5% of the cross sectional area of the wind tunnel. Scale of the model is chosen based on the test section size of the wind tunnel. In general, experiments in wind tunnels cannot be done at full scale Reynolds number, but in practice model Reynolds number is made to be similar with prototype. For a realistic simulation of the full-scale condition to be obtained, both the tip speed ratio and Reynolds number are ought to be the same for the full scale and the wind-tunnel turbines.

3.1 Geometric Similarity

One of the most important requirements of models is that there should be geometric similarity between the model and the prototype. By geometric similarity it is meant that the ratios of corresponding dimensions in the model and the prototype should be the same.

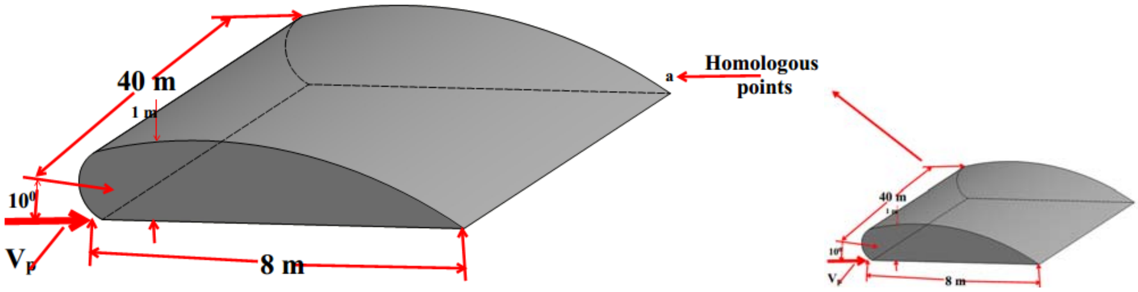

Figure.12: Geometric Similarity in Model Testing (Mdp.eng.cam.ac.uk)

3.2 Dynamic Similarity

Equally important as the geometric similarity is the requirement of dynamic similarity. In an actual flight, when the body moves through a medium, forces and moments are generated because of the viscosity of the medium and also due to its inertia, elasticity and gravity. The inertia, viscous, gravity and elastic forces generated on the body in flight can be expressed in terms of fundamental units. The important force ratios can be expressed as non-dimensional numbers. For example,

- Reynolds number (Re) = Inertia force/Viscous force
- Mach number = Inertia force/Elastic force
- Froude number = Inertia force/Gravity force

The principle of dynamic similarity is that a scale model under same Reynolds number and Mach number will have forces and moments on it that can be scaled directly. The flow patterns on the full scale body and the model will be exactly similar

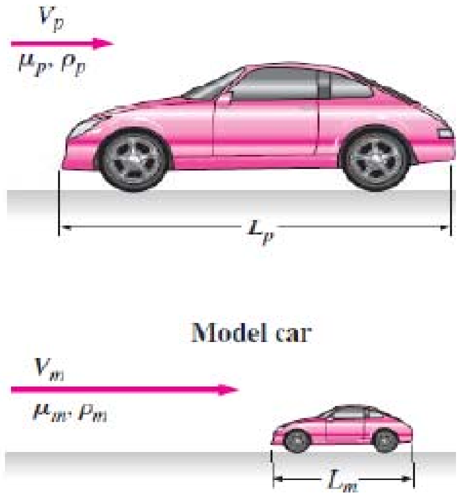

Figure. 13: Showing model of a car and its prototype (Geometric similarity between a Prototype car of length Lp and a model car of length Lm.). (Mdp.eng.cam.ac.uk)

IV. RESULTS & DISCUSSION

4.1 Result

In Table 1, it is seen that at A=0.0234m^2 and A=0.0266m^2, C_D remains unchanged with a value of 0.106. This follows from the fact that at low speeds, C_D is approximately constant. Therefore, increasing the area increases the resistance to air and progressively causes the air moving across the airfoil to move at low speeds.

The table shows the result for the lift and drag forces we got from the design and construction of subsonic of a wind tunnel.

Table 1: Table of calculated lift and Drag for Model 1 from experiment

Forces (N)	***V (ms^{-1})***	***t(sec)***	***m (kg)***	***Results***
Lift	***20.2***	***60***	***0.002***	***0.00067N***
Drag	***20.2***	***60***	***0.050***	***0.017N***

In Table 2, it is seen that as the angle of attack θ is increased CL and CD also increase up to θ=18^0 and then decrease at θ=20^0.

Table 2: Table of calculated lift and Drag for Model 2 from experiment

Forces (N)	***V (ms^{-1})***	***t(sec)***	***m (kg)***	***Results***
Lift	***20.2***	***60***	***0.025***	***0.0084N***
Drag	***20.2***	***60***	***0.065***	***0.022N***

Table 3: Table of calculated lift and Drag for Model 3 from experiment

Forces (N)	***V (ms^{-1})***	***t(sec)***	***m (kg)***	***Results***
Lift	***20.2***	***60***	***0.030***	***0.0101N***
Drag	***20.2***	***60***	***0.082***	***0.028N***

Table 4: Table of calculated lift and Drag for Model 4 from experiment

Forces (N)	*V (ms^{-1})*	*t(sec)*	*m (kg)*	*Results*
Lift	***20.2***	***60***	***0.037***	***0.0125N***
Drag	***20.2***	***60***	***0.091***	***0.031N***

Table 5: Table of calculated lift and Drag for Model 5 from experiment

Forces (N)	*V (ms^{-1})*	*t(sec)*	*m (kg)*	*Results*
Lift	***20.2***	***60***	***0.042***	***0.0141N***
Drag	***20.2***	***60***	***0.125***	***0.0420N***

4.2 Discussions

Calculations were performed as described in the design work in section 3.3 above. For all calculations; static pressure **p** equals 101.309kpa, density $\boldsymbol{\rho}$ 1.2252835 kg/m^3 and temperature equals 288k.

The wind tunnel is designed to operate at Mach number 0.06 with a test section area of $0.18m^2$, flow velocity V across the test section is 72.72km/h (20.2m/s). The Reynolds' number for this wind tunnel is 8.56779×10^5. Since the Reynolds's number is greater than 50,000, this signifies that flow is turbulent. This value differs from the value obtained from simulation 8.56830×10^5, because of dimensional variations and obstructions to airflow across the wind tunnel.

The volume flow rate was calculated as $3.64m^3/s$. Since the area, density and temperature are fixed, this flow rate depends only upon the pressure. Any increase in pressure will result in a linear increase in flow rate.

For the wind tunnel to operate at Mach 0.06 (This Mach number signifies a very low compressibility of air which results in an insignificant tendency for any change in density); the test section is required to have an area of $0.18m^2$, and a dynamic pressure of 0.25kpa will occur in the test section. Any increase in test section area will result in an increase in Reynolds' number.

The important similarity parameter for compressibility is the Mach number, defined as the ratio of air velocity to the speed of sound. Aerodynamic forces depend on the compressibility of the air or fluid. At low speeds, the density of the fluid remains fairly constant.

The ratio of the speed of air in the test section to the speed of sound in air was calculated to be 1:17.

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