

Designing a Wind Tunnel

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Abstract

The purpose of this research paper is to condense the general knowledge of the design of a wind tunnel. By going through the individual parts of the structure of an open-return wind tunnel, a better understanding of how the wind tunnel is designed can provide researchers and students with better insight into aerodynamics. The paper goes through basic implementations and purposes of the honeycomb structure, the contraction cone, a force balancing system, the diffuser and the fan. An example design is provided.

I. Introduction

To create machines capable of flight, engineers had to understand how lift and drag forces worked instead of simply mimicking avian locomotion. Mimicry may provide an immediate solution, but it denies the option to optimize the efficiency of said mimicked systems. Hence a controlled test environment for wings and the like was created to learn about the flow of the air over the surfaces of wings. This controlled test environment takes the form of a wind tunnel [1]. It is one of the first steps towards creating usable and efficient flight machines.

Wind tunnels have two main types, open return and closed return. Closed return wind tunnels are self-contained; Airflow is made by using the fan and circulated in a loop structure using vanes, giving the wind tunnel a superior airflow quality as seen in figure 1. Open return wind tunnels in contrast only have one straight section without any vanes or corners. While closed return tunnels are more efficient for the fan as when air circulates through the tunnel, will require less power to move still air, the costs of setting up and maintenance for closed return tunnels are high; the cons outweigh the pros for homemade wind tunnels. Additionally, closed return tunnels are incapable of smoke visualization [2]. This is why I've opted to design an open return tunnel rather than a closed return tunnel.

Shown in figure 2, the structure of an open return wind tunnel consists of 3 distinct parts: The contraction, the test section and the diffuser. The contraction cone is an important component to create laminar flow while also increasing air velocity using Bernoulli's principle. The test section is where the object that needs its aerodynamics test is placed. The diffuser is integral in eliminating turbulence when fast flowing air is reintroduced to still air. [3]

National Aeronautics and Space Administration



Closed Return Wind Tunnel

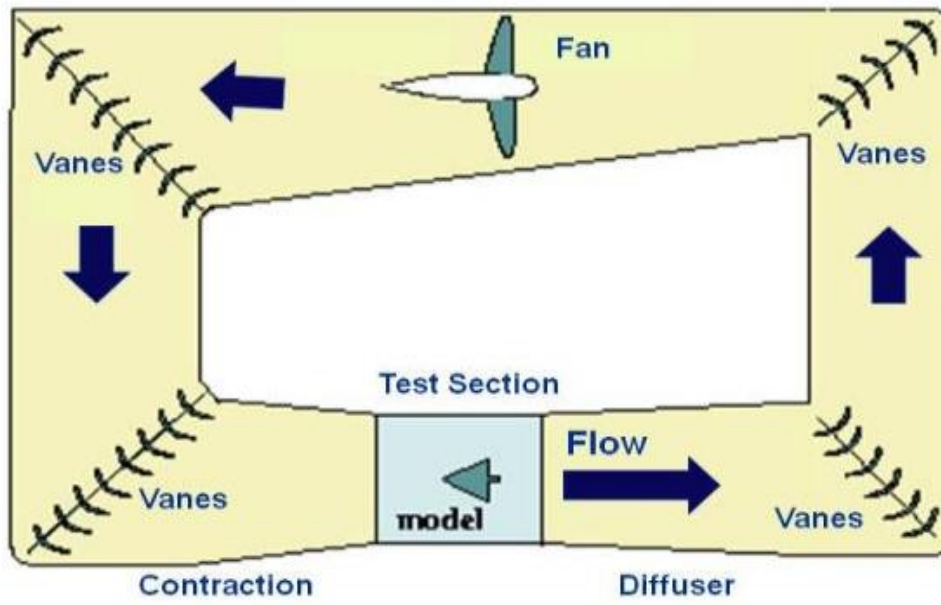


Fig. 1 NASA diagram of a close return wind tunnel [2]

National Aeronautics and Space Administration



Open Return Wind Tunnel

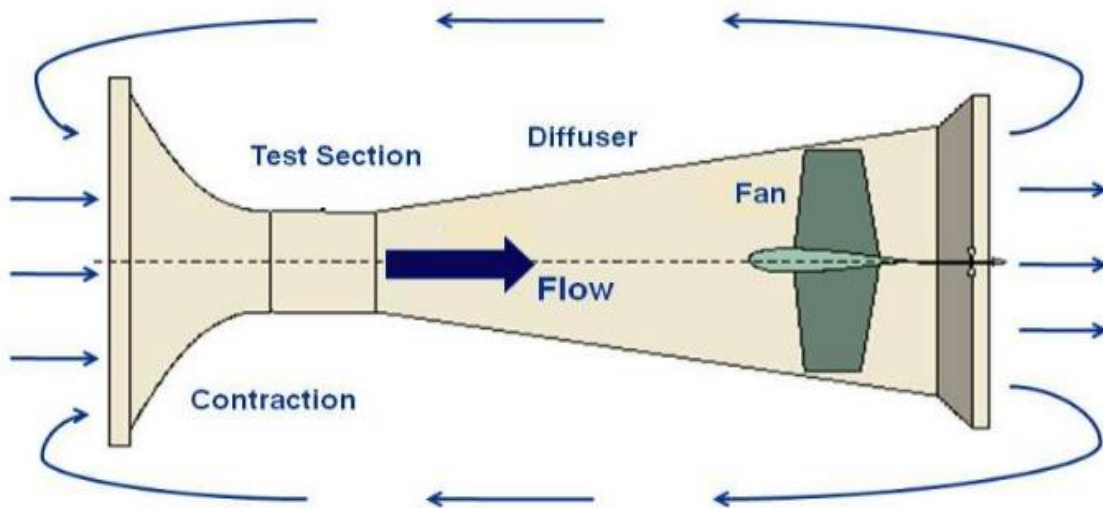


Fig. 2 NASA diagram of open return wind tunnel [3]

II. The Inlet

A. The Honeycomb Structure

A wind tunnel needs to have laminar flow travelling through the test section to have smooth, parallel and predictable movement. For repeatable test results, laminar flow is best because it is more predictable. Laminar flow can be achieved by having uniform airflow where all the air travels parallel and in the mean flow direction. Turbulent flow has more fluctuations in velocity and direction relative to the mean flow, creating chaotic changes in direction and velocity, meaning that it is unpredictable. The chaotic changes cause eddies in the airflow, this causes more drag, which leads to a less accurate simulation of the sky and reduces experimental accuracy. Eddies are the swirls or vortexes left caused by turbulent flow. [4]

The application of Reynold's number for scaled models can be done to translate simulated data of scaled model to full scale model, used in functional human-occupiable planes. You can calculate the Reynold's number of your tested object using the formula for Reynold's number through a pipe seen in Fig 8: U is the fluid velocity; L is the characteristic length (the diameter if it is a circle) and ν is viscosity.

$$Re = \frac{U \times L}{\nu}$$

Fig. 3 Formula for Reynold's number

Ratios like the Reynold's number, simply the inertial force divided by viscous force, provides a more concrete representation of airflow. To determine the flow characteristics of your wind tunnel, the transition Reynold's number of the pipe flows through your wind tunnel. This usually falls between 2300 to 3500. If the Reynold's number is <2300 , the flow can be seen as laminar, you can likely find this in drinking fountains or slow running faucets. The flow of water looks almost unchanging, void of turbulence; this is what your airflow is like if Reynold's number is <2300 . If the Reynold's number is >4000 , the flow is turbulent, this can be seen in fire hoses. The flow is violent and uncontrolled. As seen in figure 3, we want to achieve laminar flow as it is more predictable, when in contrast turbulent flow goes in unpredictable paths. In real conditions, laminar flow isn't always the case but, for experiments to be accurate and repeatable in wind tunnels, a controlled airflow is required. [5][6]

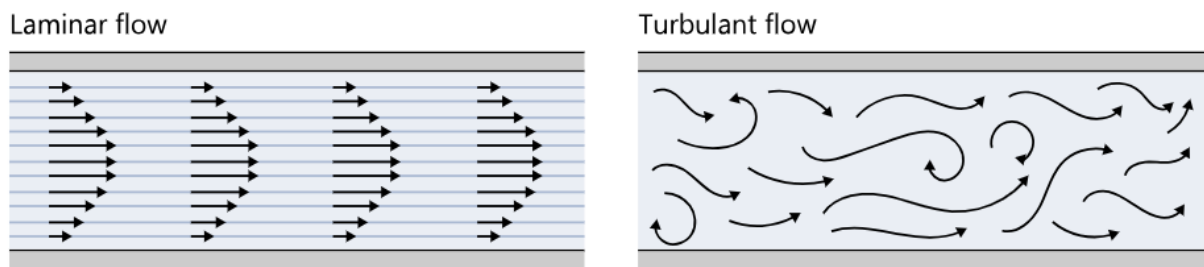
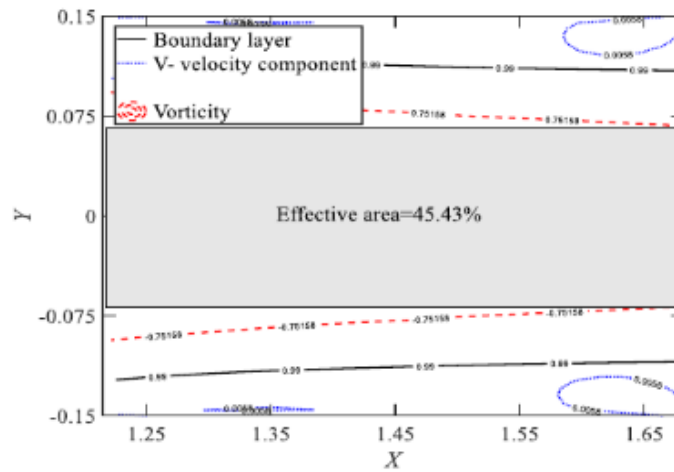
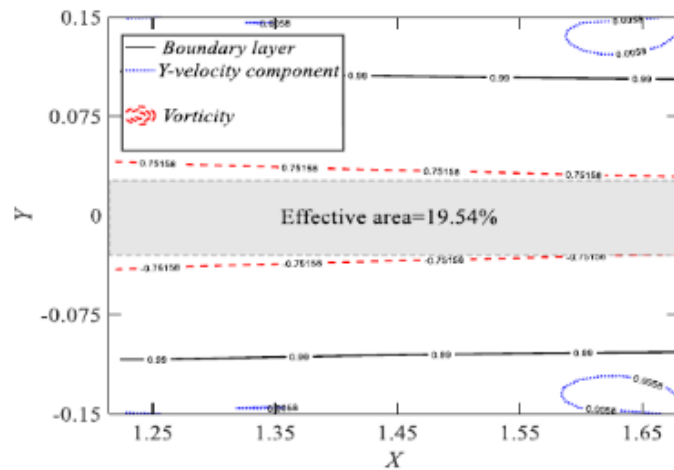


Fig. 4 Diagram representing laminar flow and turbulent flow [4]

According to Hudhaifa Hamzah, et al, the honeycomb structure at lower porosity, more closed area, gives the wind tunnel straighter air flow, more uniform. But at the cost of less efficiency due to power being lost to drag induced by the larger surface area. The fan used in the wind tunnel would have to work harder to get an equal air velocity to the honeycomb structure if it had higher porosity. Porosity is the ratio of surface area lost to holes and surface area that are filled; The empty space rather than being one continuous hole, it is a series of individual holes with solid spaces in between. The study used porosity levels of 0.85 to 0.9825. The honeycomb structure also allows the wind tunnel to have a more effective flow area. The study showed that the effective flow area was a wind tunnel with and without a honeycomb structure was 45.43% and 19.54%, respectively. But also, the power lost was 3.84 and 1.472, respectively. [7]



(a) With honeycomb



(b) Without honeycomb.

Fig. 5 Diagram representing the effective flow area [7]

B. The Contraction Cone

According to professor Durmuş, S. et al, the contraction cone needs to consider the main parameters, contraction curve profile, convergent angle, contraction cone length, contraction ratio, diffuser length, diffuser angle, and diffuser area ratio. The conclusion drawn from their studies is that a contraction cone 2 times the inlet hydraulic radius is the most optimal. [8]

The contraction cone is shaped so that air flows as smoothly as possible into a smaller cross-sectional area. Through Bernoulli's principle, the static pressure from the entrance of the contraction cone with a larger cross-sectional area to the smaller cross sectional area decreases, meaning that the mean flow velocity in the smaller cross-sectional area increases. This allows the wind tunnel to exhibit a more realistic environment with high wind speeds. It is not the contraction cone itself that increases the air velocity but the difference in cross sectional area. The contraction cone only reduces turbulence.

The recommended ratio of cross-sectional area of contraction cone to test section is 6:1 or 12:1, the boundary layer will be negligible and provide better quality flow. [10]

First, the contraction curve profile needs to be decided. There are many proposed shapes like the Fifth-order polynomial curve by Bell and Mehta. The shape has to be engineered to keep the boundary layer of travelling air from growing too large and to lower turbulence intensity on the shape being tested. Researchers try to make the curve profile have the smoothest transition from the large surface area that air enters from to the smaller sectional area of the test section. This curve profile goes hand in hand with the length of the contraction cone. A smooth curve prevents flow separation from happening. Flow separation happens when the pressure increase is large due to the flow decelerating too much due to the shape of the curve, leading to the flow being pushed back. Since the fluid motion is still happening, the flow can't reverse, forcing it to detach from the surface [8]. A good curve profile will maintain flow uniformity that was formed by the honeycomb structure; It does not create the uniformity itself.

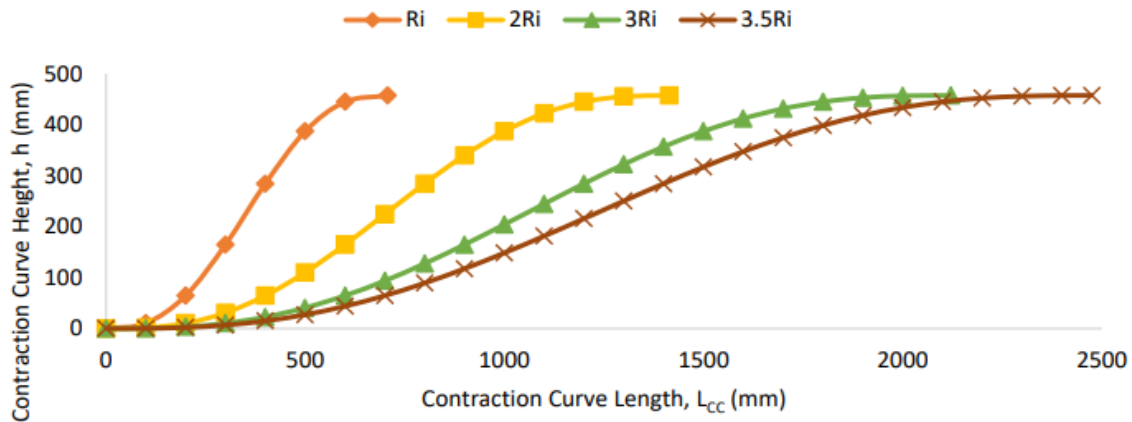


Fig. 6 Contraction cone profiles with different lengths obtained with the 5th order polynomials proposed by Bell and Mehta [8]

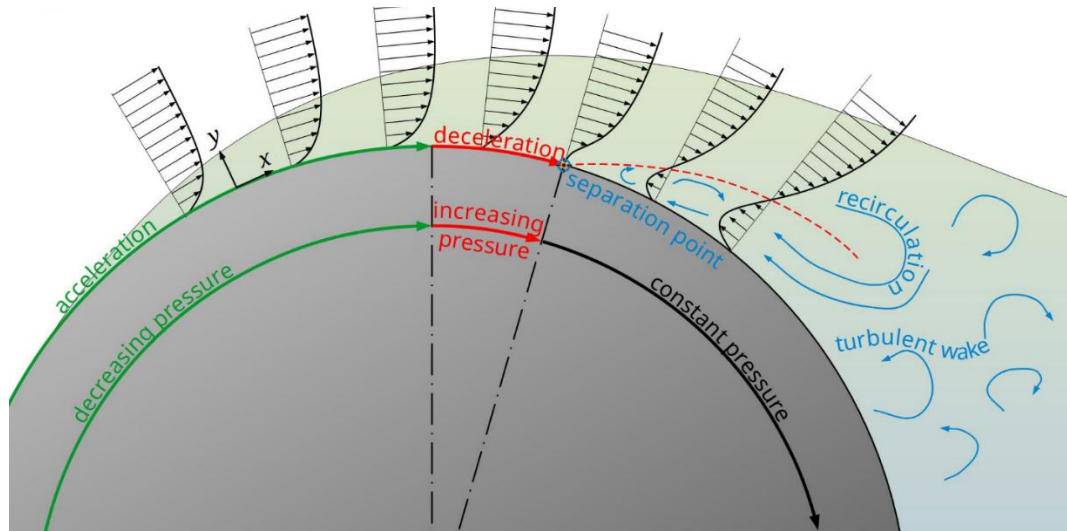


Fig. 7 Diagram of flow separation from Tec Science [9]

III. Test Section

A. NACA Airfoils

Wind tunnels are used to simulate and control as best as possible the conditions of an open sky. In doing so, the possibility of experimenting with lift and drag forces that affect an aerial vehicle, in others words an aircraft, are opened to us. The part that most concerns an aircraft's ability to fly would be its wings. Therefore, it is important to understand the most applied airfoil system, the NACA airfoils.

NACA airfoils have many series, including 1 to 16 different series. Most commercial aircraft or modern aircraft follow the structure of modified series 4-digit and 5-digit or the 6-digit series. The modified 4-digit series is structured: The first digit is the percentage of maximum camber, if it is a 2 then it is 2% camber. The second digit is the max camber position, if it's a 4 it's 40%. The last two digits determine the maximum thickness, 12 means 12% thickness. The percentage is of the chord of the airfoil. Put it all together and you get the NACA 2412. [11]

For the 5-digit series: The first digit is the design lift coefficient when multiplied by $3/2$, for example 2 gives a design lift coefficient of 0.3. The second and third digit is the camber position, for example 30 means the position of maximum camber is at 15% of the chord. The final two digits determine maximum thickness in percentage of the chord. Put it together and you have the NACA 23012. [11]

For the 6-digit series: The first digit is the series the NACA airfoil belongs to. The second digit is the location of minimum pressure in percentage of the chord, 3 means minimum pressure at 30% of the chord. The digit after the dash is the design lift coefficient, 2 is 0.2. The last two digits are the thickness in percentage of the chord, 15 is 15% thickness. Put it together and you get the NACA 63-215. [11]

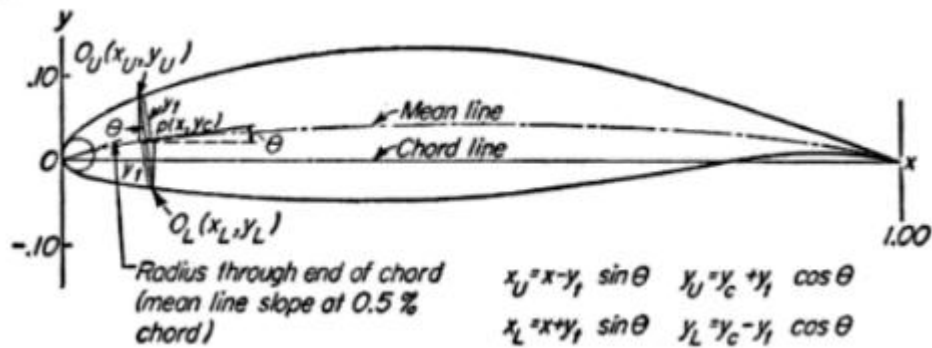


Fig. 8 NACA airfoil geometrical construction [11]

The blockage ratio or blockage effect is another factor to keep in mind; it is best to keep it under 10% for results to not be affected. The blockage ratio is the distortions in airflow caused by the contact surface area of the tested model. The ratio compares the cross-sectional area of the test section and the front 2D area of the model. If the ratio goes over 10%, the simulation of free air will be disrupted. With the wind tunnel intended replication of the open sky, meaning no constraints are present like the wall, the blockage ratio will cause abnormalities in resulting lift or drag forces, the wind tunnel needs to yield accurate results. [12]

B. Measurement Systems

There are 4 main forces to be aware of in aerodynamics, lift, drag, thrust and weight. They act on the aerodynamic object from its center. Weight is the force that pulls the aerodynamic object towards the ground. Lift is the force perpendicular to the ground, generated by pressure distribution over the surface. Thrust is the force that comes from propulsion systems, it drives the aerodynamic object forward to generate lift. Drag is the force that acts opposite the direction the aerodynamic object is moving in. [13]

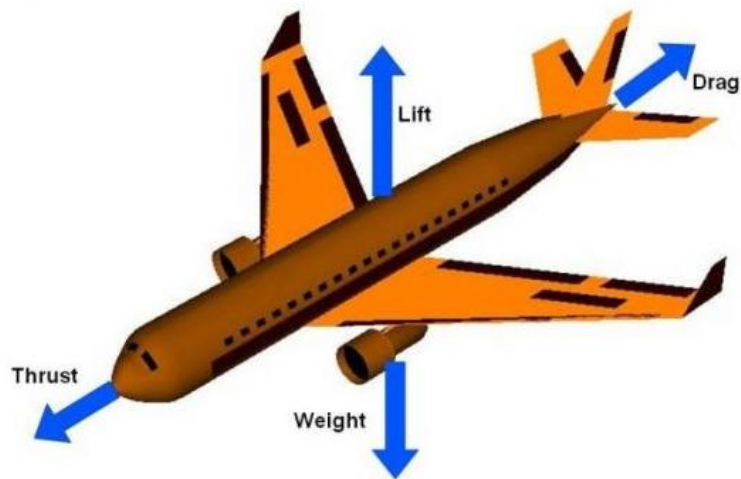


Fig. 9 NASA diagram of the force balance [13]

Force balances are the most basic measuring instrument used in wind tunnels testing. 6 main components are measured: Lift, drag, side (forces) and pitch, roll, yaw (moments). The one-component balance seen in Fig 10 only measures lift. For most experiments, only 3 components, lift, drag and pitch, are needed. [14][15]

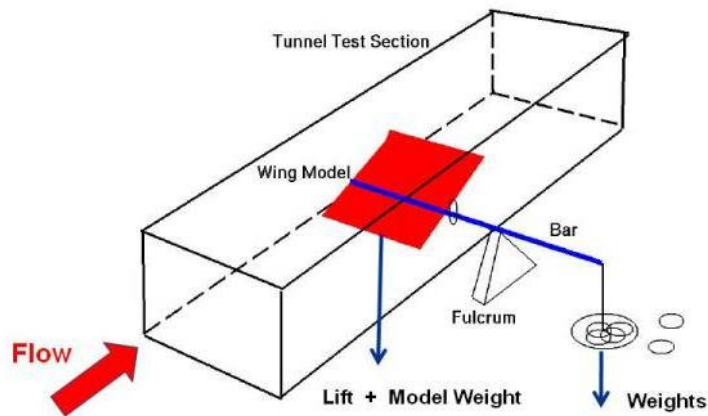


Fig. 10 NASA diagram of the force balance [14]

The overall structure of the one-component force balance uses a lever system. A bar is placed on a fulcrum; the wing model is attached to one end of the bar inside the tunnel. Weights are attached using strings on the other end to balance out the forces applied on the bar. In this set-up, the wing model is faced downwards to create lift in the same direction. To measure the lift force generated, more weights are added until the bar is balanced; the added weight is the magnitude of generated lift force. For set-ups with a positive attack angle, facing upwards, remove the weights until the bar balanced; the amount subtracted is the generated lift force [14]. For additional information on the flow, it is possible to visualize it by introducing smoke to the airflow.

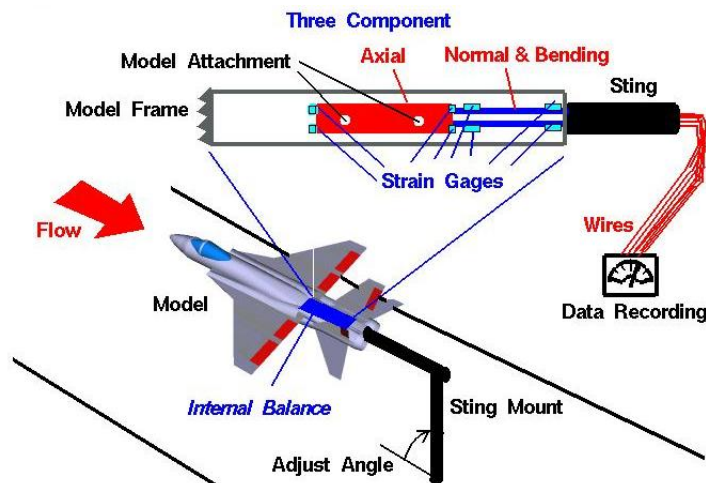


Fig. 11 NASA diagram of an internal force balance [15]

The three-component balance seen in Fig 11 measures lift, drag and pitch. The set-up consists of a sting that houses a three-component force balance attached to an idealized fighter jet model. The three-component balance detects the axial force and normal force and bending along the axes perpendicular to the axial and normal axes. The axial force acts parallel with the length of the model; in this situation it is compressing the model due to the airflow going towards the model. The normal force is the perpendicular force to the axial force, it goes upwards. These measurements derive the lift, drag and pitch of the model at a particular airflow and attack angle. Values are received from strain gages placed on the balance. These gages are electrical resistors that change resistance according to how stretched they are. Wires carry electricity to the gages and carry resulting signals back to recording devices for analysis. The model must face parallel to the airflow to eliminate side forces. [15]

C. Lift / Drag Coefficient

The lift coefficient is used to predict the lift that will be produced under different conditions. Referring to the equation for the lift coefficient, the lift force can be predicted for a different set of density (r), velocity (V) and wing area (A). [16]

$$C_l = \frac{L}{r \times V^2 / 2 \times A}$$

Fig. 12 Equation for the lift coefficient provided by NASA [16]

Drag is the resultant of two forces, shear stress and pressure stress. Shear stress comes from forces acting parallel with the surface of an object. It is caused by friction against a fluid's viscosity. Pressure stress comes from forces acting perpendicular to the surface of an object. The drag coefficient tells you how much an object interacts with the friction/drag of the air. It can be used to compare the drag force between objects of different sizes, speeds and shapes. For accurate comparisons, the conditions of viscosity and compressibility must match. [17]

$$C_d = \frac{D}{r \times A \times V^2 / 2}$$

Fig. 13 Equation for the drag coefficient provided by NASA [17]

IV. The Outlet

A. The Diffuser

Just like how the contraction cone decreases static pressure for a high velocity flow, the diffuser recovers static pressure and slows the air velocity after air has passed through the test section. With equalized pressure, the airflow out from the wind tunnel will not crash into the still open air, preventing flow reversal and reduce turbulence throughout the wind tunnel. The general shape of the diffuser is the length of expanding cross sectional area.

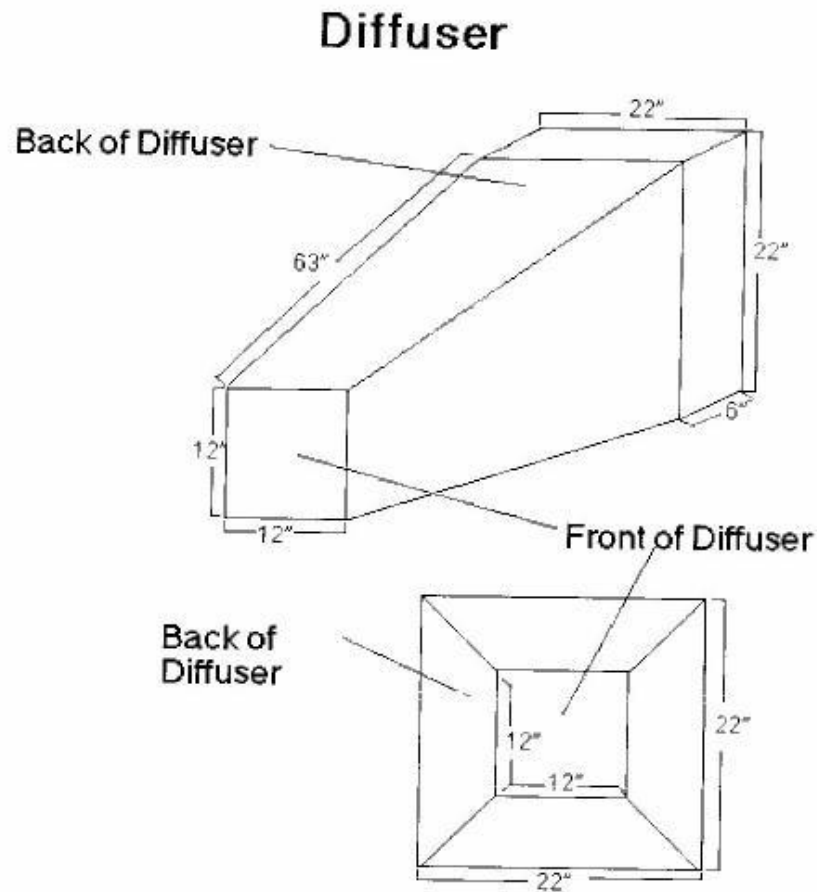


Fig. 14 NASA diagram of the diffuser for their Wandering Wind Tunnel project [18]

B. The Fan

The fan that pulls air in to allow air to circulate the wind tunnel is placed at the very end of the diffuser. By placing the fan there, turbulence caused by the spinning blade is prevented from being introduced directly into the wind tunnel. Instead of pushing the air in using the spinning blades, which inhabit turbulence due to sudden change in the velocity caused by low pressure cavities in the blades, pulling air in from the back will reduce the effect.

When choosing a fan for your wind tunnel, there are measurements that need understanding. The first metric is volume flow, meaning how much volume of air is displaced by the fan per unit of time. This is measured in cubic feet per minute (CFM). The second metric is the rotational speed of the fan, measured in rotations per minute (RPM). [19]

It is recommended that a wind tunnel uses Axial Flow fans instead of centrifugal fans: Axial fans provide uniform high airflow with better energy efficiency than centrifugal fans. The key differentiator is that axial fans propel air parallel to the shaft, the blades spin perpendicular to the direction of airflow. Centrifugal fans do the opposite, their blades spin with the direction of airflow, which is directly pushing volumes of air in a direction to create airflow in that same direction. Referring to Fig 7, axial fans displace air at low pressure, which is ideal when a high air velocity

is essential for experimental purposes with a wind tunnel. Additionally, axial flow fans create more uniform air flow, this is due to its parallel airflow direction. The air is pulled straight through the wind tunnel in one axis, reducing any potential turbulence that may result from violent directional changes that a centrifugal fan causes. A wind tunnel doesn't necessarily need 830,000 m³/h as the table says the flow rate can go up to. University level research will only need around 70,000 m³/h. It is best to use formula $V = Q/A$ to determine the best fitted fan, where V is the air velocity, Q is the volumetric flow rate and A is the cross-sectional area of your wind tunnel. [20]

Feature	Axial fan	Centrifugal fan
Airflow direction	Straight-through (parallel to shaft)	90° angle (radial discharge)
How air moves	Air is drawn in line with the shaft and propelled outward in the same direction	Air is moved radially thanks to centrifugal force generated by the impeller
Air volume	Higher (large volumes)	Lower vs axial at same size (more focused)
Max flow rate	up to 830,000 m ³ /h	up to 500,000 m ³ /h
Pressure capability	Lower	Higher
Max static pressure	up to 5,000 Pa	up to 25,000 Pa
Best performance	High airflow in low pressure conditions	Higher pressure airflow against resistance
Typical use cases	Ideal when low-pressure, large volumes of clean air must be moved	Effective in systems like filtration, ducts, dust/fume extraction
Size/weight	More compact and with a simpler structure	Heavier construction and more complex structure

Fig. 15 Table comparing Axial fans and Centrifugal fans [20]

Your fan choice will be important as it will be the primary part of the wind tunnel that causes air to circulate.

V. Example Design

Using the design considerations, I've created a Fusion 360 drawing of a wind tunnel. This draw excludes the fan and measurement system; it is only the shell of a wind tunnel. I designed this wind tunnel with the scale of a testable wind tunnel so it will be large for a homemade wind tunnel you can keep on your desk. Though, this should be the general shape of a wind tunnel. Due to size constraints, some corners had to be cut like in the ratio of the cross-sectional area of the test section and contraction cone is not 1:6 but 1:4. I can't make the contraction cone larger or otherwise there will be no space to keep the wind tunnel. I can't shrink the test section either as my hand would barely fit, making it hard to set-up measurement systems and the stand that holds up the airfoil.

It will be inevitable that you meet road bumps in the process of designing and making a wind tunnel.

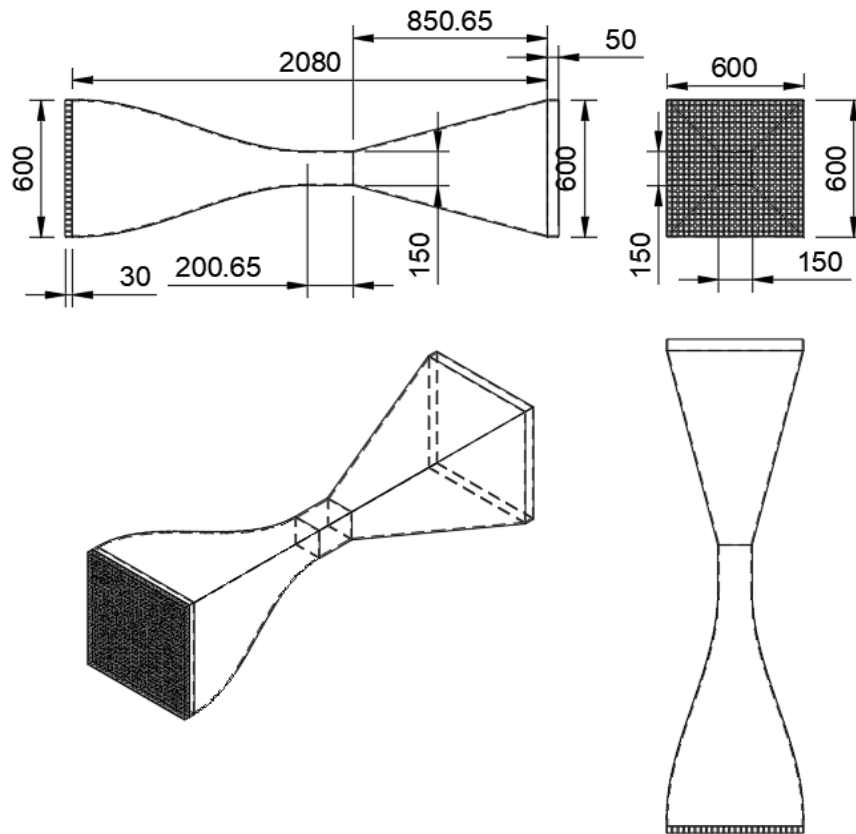


Fig. 16 Fusion 360 drawing of a wind tunnel designed by me; the measurements are in mm.

VI. Conclusion

Wind tunnels have been an essential tool in the field of aviation technology, and they continue to be with countless research and developments done to design. To mimic the conditions of the open sky, many factors are accounted for, and the design of a wind tunnel is built around these core factors. Such as the boundary layer caused by the walls of the wind tunnel or the blockage ratio that distorts the simulation of an open sky in the wind tunnel. Tools that help translate the test results from a wind tunnel are Reynold's number and the drag and lift coefficient. The honeycomb structure and the contraction cone and the diffuser ensure flow uniformity to create repeatable test conditions. Force balancing is one of many ways to measure forces and moments generated by the test model. The diffuser will decelerate the air velocity to prevent airflow reversal and reduce turbulence. All parts of the wind tunnel design are done to ensure a controllable, laminar airflow. All for the sake of an accurate and repeatable experimental environment in the field of aerodynamics.

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