Airplanes: Why and how they fly?

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Abstract:

This paper will present the basics of how and why airplanes are able to fly, describing Bernoulli's Equation and other simple equations of fluid dynamics. It will demonstrate how simple models of wings tested in a wind tunnel are directly related to the wings used in airplanes of all sizes. A discussion on viscous flows and how Bernoulli's equation is not the only factor that determines how an airplane flies, will also be given. In conclusion, it will include practical work done in modeling airfoils in a wind tunnel.

Introduction:

Starting with the Flyer I, constructed and tested by the Wright Brothers, on December 17, 1903; studies in aerodynamics depend on experiments in fluid dynamics and various simulations of models. Wind tunnels play a vital role in aerodynamic simulations, though the role of computers is increasing at a fast pace. This paper will concentrate on how wind tunnels are used extensively to model airfoils and wing designs.

Basic Aerodynamic Concepts and Variables:

This section presents an introductory description of some of the basic terms used later to describe the theory of wing design.

Steady Flow: A flow is said to be steady is the state of motion remains unchanged at any place within the fluid. The motion itself need not be uniform. The fluid particles that move through a given point at different times exhibit similar behavior. Thus the flow of the fluid particles is curved.

Streamlines: The direction of the velocities of the flow of the fluid particles are given by tangents to the curve. These curves are called streamlines. Streamlines give information on the magnitude of the velocity. Along each streamline the product of the velocity, density and cross sectional area is always a constant. This is called the condition of continuity, which is required for flight.

Bernoulli's Equation [1]

Bernoulli's equation is considered the most famous equation of fluid dynamics, as it presents a relation between pressure and velocity in an inviscid, incompressible flow. It also holds true for compressible flow (which is more relevant when try to model supersonic airplanes; in air streams that are viscid and compressible).

The derivation is beyond the scope of this paper, and can be read in any elementary book on Fluid Dynamics. It is sufficient to say that Bernoulli's Equation follows directly from Newton's second law, when applied to incompressible fluids. It states

$$\frac{V^2}{2g} + h + \frac{p}{\gamma} = H \quad = \text{constant along a streamline} \qquad (1)$$

The first term ($V^2/2g$) is the height that a free falling body must fall from to acquire a speed V. The pressure head (p/γ) is the difference of pressures at the height ($V^2/2g$) and ground level. This term can be easily modeled as an integral to account for compressibility of the fluid. The constant H is sometimes referred to as "Total head". It is a constant for a particular streamline. Aerodynamics generally deals with a region of constant pressure and velocity. Thus H can be viewed as a constant for the field of flow.

Dynamic Pressure [1]

Consider a uniform flow in which some streamlines pass over the flow and some below the flow. These two groups are separated by one streamline that splits as it hits the air flow. Let the point where it splits be S. A direct application of Bernoulli's equation gives the following result

$$P_s - P = \frac{\rho V^2}{2} \quad = \text{ Dynamic Pressure} \qquad (2)$$

Thus we can define dynamic pressure as the difference in pressures P_s and P at two points along the streamline which have velocities 0 and V respectively. The point S is sometimes known as "Stagnation point". The calculation of the velocity of an air stream using a Pitot tube is based on this relation.

<u>How does a wind tunnel work?</u>

A wind tunnel operates at wind velocities that are much lower than the speed of sound and where the airflow can be considered as *incompressible*. Thus it is sometimes called a low-speed wind tunnel. Simulations involve sucking an uniform stream of air over a test section, where a wing design is mounted. The wing is connected to a beam balance or strain gauges (on the outside of the tunnel) to measure lift and drag forces. Since, the air stream is incompressible; we do not need to worry about density. Bernoulli's equation provides us with a simple relationship between the pressure and velocity.

We are able to use a small wing model to model the actual wing. For example if the length of the real wing is 100% the model, then all are calculations need to be corrected by a factor of 100 for the actual wing. However, it is important to note that the shape and structure should be similar. This desired dimensionless similarity is given by

$$\mathrm{Re} = \frac{Ul\rho}{\mu} = \frac{Ul}{v} \tag{3}$$

Re = Reynolds Number, U = velocity, l = length, ρ = density, μ = dynamic viscosity / pressure, v = kinematic viscosity (For standard air pressure and 59 degrees F, take this to be $1.57 * 10^{-4}$ ft^2/sec). Using Re tells us that we can change the air properties, wind speed or model length, using the appropriate Re for the full-size wing.

Now we need dimensionless values for drag and lift that were determined in the wind tunnel experiments so that they can be applied to real airplanes, after correction using Re. These are calculated by dividing the empirical values for Drag (D) and Lift (L) by the product of the dynamic pressure calculated using Bernoulli's equation and the area of the test model.

References:

[1] Richard Von Mises, *Theory of Flight,* Dover Publications, Inc. New York.

[2] Anderson, John D. Jr. *Fundamentals of Aerodynamics,* 2nd. Edition, McGraw Hill Publications