Aerodynamics

Aerodynamics is a branch of dynamics concerned with studying the motion of air, particularly when it interacts with a solid object. Aerodynamics is a subfield of fluid dynamics and gas dynamics, with much theory shared between them. Aerodynamics is often used synonymously with gas dynamics, with the difference being that gas dynamics applies to all gases.

Overview

Understanding motion of air (often called a flow field) around an object enables the calculation of forces and moments acting on the object. Typical properties calculated for a flow field include velocity, pressure, density and temperature as a function of spatial position and time. Aerodynamics allows the definition and solution of equations for the conservation of mass, momentum, and energy in air. The use of aerodynamics through mathematical analysis, empirical approximations, wind tunnel experimentation, and computer simulations form the scientific basis for heavier-than-air flight and a number of other technologies.

Aerodynamic problems can be classified according to the flow environment. *External* aerodynamics is the study of flow around solid objects of various shapes. Evaluating the lift and drag on an airplane or the shock waves that form in front of the nose of a rocket are examples of external aerodynamics. *Internal* aerodynamics is the study of flow through passages in solid objects. For instance, internal aerodynamics encompasses the study of the airflow through a jet engine or through an air conditioning pipe.

Aerodynamic problems can also be classified according to whether the flow speed is below, near or above the speed of sound. A problem is called subsonic if all the speeds in the problem are less than the speed of sound, transonic if speeds both below and above the speed of sound are present (normally when the characteristic speed is approximately the speed of sound), supersonic when the characteristic flow speed is greater than the speed of sound, and hypersonic when the flow speed is much greater than the speed of sound. Aerodynamicists disagree over the precise definition of hypersonic flow; minimum Mach numbers for hypersonic flow range from 3 to 12.

The influence of viscosity in the flow dictates a third classification. Some problems may encounter only very small viscous effects on the solution, in which case viscosity can be considered to be negligible. The approximations to these problems are called inviscid flows. Flows for which viscosity cannot be neglected are called viscous flows.

History

Early ideas – ancient times to the 17th century

A drawing of a design for a flying machine by Leonardo da Vinci (c. 1488). This machine was an ornithopter, with flapping wings similar to those of a bird, first presented in his Codex on the Flight of Birds in 1505.

Humans have been harnessing aerodynamic forces for thousands of years with sailboats and windmills. Images and stories of flight have appeared throughout recorded history, such as the legendary story of Icarus and Daedalus. Although observations of some aerodynamic effects such as wind resistance (e.g. drag) were recorded by Aristotle, Leonardo da Vinci and Galileo Galilei, very little effort was made to develop a rigorous quantitative theory of air flow prior to the 17th century.

In 1505, Leonardo da Vinci wrote the *Codex on the Flight of Birds*, one of the earliest treatises on aerodynamics. He notes for the first time that the center of gravity of a flying bird does not coincide with its center of pressure, and he describes the construction of an ornithopter, with flapping wings similar to a bird's.

Sir Isaac Newton was the first person to develop a theory of air resistance, making him one of the first aerodynamicists. As part of that theory, Newton considered that drag was due to the dimensions of a body, the density of the fluid, and the velocity raised to the second power. These all turned out to be correct for low flow speeds.

Modern beginnings – 18th to 19th century

In 1738 The Dutch-Swiss mathematician Daniel Bernoulli published *Hydrodynamica*, in which he described the fundamental relationship among pressure, density, and velocity; in particular Bernoulli's principle, which is one method to calculate aerodynamic lift. More general equations of fluid flow - the Euler equations - were published by Leonhard Euler in 1757. The Euler equations were extended to incorporate the effects of viscosity in the first half of the 1800s, resulting in the Navier-Stokes equations.

Sir George Cayley is credited as the first person to identify the four aerodynamic forces of flight—weight, lift, drag, and thrust—and the relationships between them. Cayley believed that the drag on a flying machine must be counteracted by a means of propulsion in order for level flight to occur. Cayley also looked to nature for aerodynamic shapes with low drag. Among the shapes he investigated were the cross-sections of trout. This may appear counterintuitive, however, the bodies of fish are shaped to produce very low resistance as they travel through water. Their cross-sections are sometimes very close to that of modern low-drag airfoils.

Air resistance experiments were carried out by investigators throughout the 18th and 19th centuries. Drag theories were developed by Jean le Rond d'Alembert, Gustav Kirchhoff, and Lord Rayleigh. Equations for fluid flow with friction were developed by Claude-Louis Navier and George Gabriel Stokes. To simulate fluid flow, many experiments involved immersing objects in streams of water or simply dropping them off the top of a tall building. Towards the end of this time period Gustave Eiffel used his Eiffel Tower to assist in the drop testing of flat plates.

A more precise way to measure resistance is to place an object within an artificial, uniform stream of air where the velocity is known. The first person to experiment in this fashion was Francis Herbert Wenham, who in doing so constructed the first wind tunnel in 1871. Wenham was also a member of the first professional organization dedicated to aeronautics, the Royal Aeronautical Society of the United Kingdom. Objects placed in wind tunnel models are almost always smaller than in practice, so a method was needed to relate small scale models to their real-life counterparts. This was achieved with the invention of the dimensionless Reynolds number by Osborne Reynolds. Reynolds also experimented with laminar to turbulent flow transition in 1883.

By the late 19th century, two problems were identified before heavier-than-air flight could be realized. The first was the creation of low-drag, high-lift aerodynamic wings. The second problem was how to determine the power needed for sustained flight. During this time, the groundwork was laid down for modern day fluid dynamics and aerodynamics, with other less scientifically-inclined enthusiasts testing various flying machines with little success.

A replica of the Wright Brothers' wind tunnel is on display at the Virginia Air and Space Center. Wind tunnels were key in the development and validation of the laws of aerodynamics.

In 1889, Charles Renard, a French aeronautical engineer, became the first person to reasonably predict the power needed for sustained flight. Renard and German physicist Hermann von Helmholtz explored the wing loading (weight to wing-area ratio) of birds, eventually concluding that humans could not fly under their own power by attaching wings onto their arms. Otto Lilienthal, following the work of Sir George Cayley, was the first person to become highly successful with glider flights. Lilienthal believed that thin, curved airfoils would produce high lift and low drag.

Octave Chanute provided a great service to those interested in aerodynamics and flying machines by publishing a book outlining all of the research conducted around the world up to 1893.

Practical flight – early 20th century

With the information contained in Chanute's book, the personal assistance of Chanute himself, and research carried out in their own wind tunnel, the Wright brothers gained enough knowledge of aerodynamics to fly the first powered aircraft on December 17, 1903. The Wright brothers' flight confirmed or disproved a number of aerodynamics theories. Newton's drag force theory was finally proved incorrect. This first widely-publicised flight led to a more organized effort between aviators and scientists, leading the way to modern aerodynamics.

During the time of the first flights, Frederick W. Lanchester, Martin Wilhelm Kutta, and Nikolai Zhukovsky independently created theories that connected circulation of a fluid flow to lift. Kutta and Zhukovsky went on to develop a two-dimensional wing theory. Expanding upon the work of Lanchester, Ludwig Prandtl is credited with developing the mathematics behind thin-airfoil and lifting-line theories as well as work with boundary layers. Prandtl, a professor at the University of Göttingen, instructed many students who would play important roles in the development of aerodynamics, such as Theodore von Kármán and Max Munk.

Design issues with increasing speed

Compressibility is an important factor in aerodynamics. At low speeds, the compressibility of air is not significant in relation to aircraft design, but as the airflow nears and exceeds the speed of sound, a host of new aerodynamic effects become important in the design of aircraft. These effects, often several of them at a time, made it very difficult for World War II era aircraft to reach speeds much beyond 800 km/h (500 mph).

Some of the minor effects include changes to the airflow that lead to problems in control. For instance, the P-38 Lightning with its thick high-lift wing had a particular problem in high-speed dives that led to a nose-down condition. Pilots would enter dives, and then find that they could no longer control the plane, which continued to nose over until it crashed. The problem was remedied by adding a "dive flap" beneath the wing which altered the center of pressure distribution so that the wing would not lose its lift.

A similar problem affected some models of the Supermarine Spitfire. At high speeds the ailerons could apply more torque than the Spitfire's thin wings could handle, and the entire wing would twist in the opposite direction. This meant that the plane would roll in the direction opposite to that which the pilot intended, and led to a number of accidents. Earlier models weren't fast enough for this to be a problem, and so it wasn't noticed until later model Spitfires like the Mk.IX started to appear. This was mitigated by adding considerable torsional rigidity to the wings, and was wholly cured when the Mk.XIV was introduced.

The Messerschmitt Bf 109 and Mitsubishi Zero had the exact opposite problem in which the controls became ineffective. At higher speeds the pilot simply couldn't move the controls because there was too much airflow over the control surfaces. The planes would become difficult to maneuver, and at high enough speeds aircraft without this problem could out-turn them.

These problems were eventually solved as jet aircraft reached transonic and supersonic speeds. German scientists in WWII experimented with swept wings. Their research was applied on the MiG-15 and F-86 Sabre and bombers such as the B-47 Stratojet used swept wings which delay the onset of shock waves and reduce drag. The all-flying tailplane which are common on supersonic planes also help maintain control near the speed of sound.