Concept: AERODYNAMICS

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1. Definition

When objects move through air, forces are generated by the relative motion between the air and the surfaces of the object. Aerodynamics is the study of these forces, generated by the motion of air.

2. Introduction

Aerodynamics deals with the forces due to the motion of air and other gaseous fluids relative to bodies. Aerodynamic lift is generated perpendicular to the direction of the free stream as the reaction to the rate of change of momentum of air turning around an object, and, at high speeds, to compression of air by the object. Flow turning is accomplished by changing the angle of attack of the surface, or by using the camber of the surface in subsonic flight, or by generating vortices along the leading edges of swept wings. In flight at high speeds, the pressure changes generated when the oncoming flow is slowed down or accelerated around the object, causes large changes in density between different sides of the object, again resulting in a net change in momentum. The forces generated as a reaction to this rate of change of momentum, cause lift in high speed flight.

All lift generation is accompanied by some generation of drag forces opposing the motion of the object through air. Various mechanisms of drag generation have been identified. Achieving the highest possible ratio of lift to drag is a usual goal of aerodynamic design, except of course in cases such as parachutes and speed brakes where high drag is desired.

The behavior of air in motion can be described in general terms using physical theories at various levels, going from the dynamics of huge masses of air such as hurricanes, down to the tiniest scales of atomic motion. However it is unnecessary to use these general, all-inclusive theoretical descriptions to solve most problems. To design vehicles and predict their performance, we use several methods, each of which is restricted to a small range of parameters. Thus, for example, we divide the field of aerodynamics into categories based on the speed range of interest. The behavior of air flows changes depending on the ratio of the flow speed to the speed of sound. This ratio is called the Mach number. The speed of sound is the speed at which information propagates through a gas. So if the vehicle moves faster than the speed of sound, the air ahead of it cannot ”move away”: there is no way for it to ”know” of the approaching vehicle. This leads to the formation of ”shock” waves in the air ahead of the vehicle. Very close to a body surface, or at the interface between two streams of air moving at different speeds, we encounter friction. This leads to many strange and beautiful effects, producing the sinuous structures which make us want to keep looking at flowing streams for hours. Unfortunately, these things are quite difficult to calculate, so we argue that the primary effects of friction are confined to a region very close to the surface, called the ”boundary layer”. The boundary layer is a ”shear layer”. Likewise, the region between two streams of air, flowing at different speeds, is called a ”free shear layer” because no solid surface boundary is involved. Away from surfaces, the flow can usually be considered to the ”inviscid”: its almost as if viscosity does not exist there.

3. 3 Classification of speed ranges by relation to the speed of sound

Regimes of Mach number are classified as:

1. Incompressible; Low Speed Aerodynamics (0 ¡ M ¡ 0.33)
2. Subsonic (0.33 ¡ M ¡ Mcritical)
3. Transonic Aerodynamics (Mcritical ¡ M ¡ 1.2)
4. Supersonic Aerodynamics (1.2 ¡ M ¡ 4)
5. Hypersonic Aerodynamics (4 ¡ M ¡ ?)
6. Relativistic Aerodynamics, where the speed becomes comparable to the speed of light.

3.1. Low Speed Aerodynamics (0 ¡ M ¡ 0.33)

Here the speed range is from zero to roughly 1/3 the speed of sound. The speed of sound in the atmosphere is roughly 340 meters/second, so low-speed aerodynamics covers speeds of 0 to roughly 100 m/s. What is special about this range? The density of the air (mass per unit volume) does not change appreciably due to changes in velocity of this magnitude (i.e., from 0 to 0.3 times the speed of sound). The maximum variation in density is less than 5% of the value of density. Thus, in this speed range, the flow is said to be ”incompressible” (by changes in velocity!). With this assumption, we can treat air flow in a manner similar to water flow over a body. One primary simplification resulting from neglecting changes in density, is that the velocity field around an object can be completely described by considering just the fact that mass must be conserved. This can be done whether the flow problem is steady or time-dependent. Once this continuity equation is solved for the velocity field, the pressure at every point can be calculated directly using conservation of momentum. From the pressure distribution around the object, the net force can be resolved into lift, drag and side force, and the moments about the different axes can also be calculated.

3.2. Subsonic Aerodynamics (0.33 ¡ M ¡ Mcritical)

Here the speed range is from about 1/3 the speed of sound, to about 0.8 times the speed of sound. When vehicles move in this speed range, the flow variations occurring over the vehicle surfaces involve substantial density variations. This effect must be taken into account in performing calculations, or the results obtained will be quite wrong. The upper limit of this regime is the flight Mach number where the local flow somewhere over the aircraft becomes sonic. This flight Mach number is called the ”critical Mach number”. It depends on the aircraft configuration, and the attitude at which it is flying. Flying faster than the critical Mach number makes the flow supersonic over some part of the aircraft. When this flow decelerates, shocks are produced, with a large increase in drag.

In the subsonic regime, calculating the pressure distribution requires solving for the velocity, pressure and density simultaneously, from the equations describing conservation of mass, momentum and energy. A much simpler practical approach for the small flow perturbations typical of good aerodynamic designs, is to find transformations of coordinate systems, so that a corresponding incompressible flow problem is solved, and the solution transformed back to the coordinates of the subsonic flow problem. This is made possible by identifying the dependence of all properties on the flight Mach number. The Prandtl-Glauert transformation allows engineers to relate pressure and lift coefficients at a subsonic Mach number for a given configuration, to the corresponding values under incompressible flow conditions.

3.3. Transonic Aerodynamics (Mcritical ¡ M ¡ 1.2)

Most of today’s airliners fly at speeds very close to the speed of sound. Today’s engines work very well in this regime, and today’s people want to reach their destinations quickly and as cheaply as possible. However, this is a very difficult flow regime to analyze, because the changes occurring over an aircraft flying at transonic speeds involve changes from ”supersonic” to ”subsonic” and back.

3.4. Supersonic Aerodynamics (1.2 ¡ M ¡ 4)

The behavior of flows moving faster than the speed of sound is very different from that of flows moving slower than sound. The simple explanation for this is that sound cannot propagate upstream in such flows; so these flows cannot ”know” of changes about to occur further downstream. Changes occur very suddenly, and through distinct flow features, rather than the curves and gradual changes of subsonic flows. The solutions to the conservation equations then take the form of waves, propagating at the speed of sound.

3.5. Hypersonic Aerodynamics (4 ¡ M ¡ ?)

Nothing magical happens at Mach 4, but given the decisions that designers make, Mach 4 is approximately the regime where hypersonic effects become a significant concern. As the Mach number increases, the changes caused by deceleration become very large. When a high-Mach number flow is stopped, say at the nose of a vehicle, the temperature, pressure and density increase by large amounts. This increase may be large enough that the properties of the air, such as the specific heat and even the molecular structure, change. This is generally considered to become significant above Mach 4. In the hypersonic regime, the disturbance caused by the aircraft is not felt until the vehicle is very close indeed: the "shocks" lie so close to the surface that the layer of air between the shock and the vehicle is quite thin. The concept of Mach number begins to lose significance as these changes occur, and engineers resort to descriptions in terms of "enthalpy" rather than Mach number to deal with flows at very high speeds. We can still take the flight speed and divide by the speed of sound in the undisturbed atmosphere, and arrive at a flight Mach number. For spacecraft re-entering the atmosphere without aerodynamic controls (such as the Apollo capsules) this "Mach number" was about 35; the Space Shuttle glides in at around Mach 25; meteors might come in at Mach number of a thousand or more.

3.6. Relativistic Aerodynamics

No human-built object has started flying in this range; however, it is easy to think about a star which is part of one galaxy encountering of another galaxy moving at a very different speed. Here the relative speeds may become a significant fraction of the speed of light. The flows inside the engines of spacecraft may reach such speeds, as engineers explore propulsion devices to power spacecraft towards other stars.

4. Classification of Flows according to properties of significance

Engineers often use terms which are most relevant to the methods which they are using to describe a particular problem and solve it. The following list is certainly not all-inclusive, but illustrates the reasoning behind the terms. The terms are not mutually exclusive. Thus, one speaks of a steady turbulent reacting flow, or an unsteady, high-temperature potential flow. One cannot speak of a laminar turbulent flow, or a steady unsteady flow, obviously.

4.1. Steady Flows

This term is used to describe situations where there is no rapid change in properties over time. For example, an aircraft cruising straight and level in the upper atmosphere, well above where any gust can reach it. When such situations are being analyzed, a lot of effort can be saved by neglecting terms in the equations which describe rates of change of the flow properties or forces at any point on the aircraft.

4.2. Unsteady Flows

Obviously, unsteady means "not steady", but it also means a lot more. Many situations of "not steady" can be made "steady" by appropriately changing coordinates. For example, an aircraft flying around in circles can be considered to be flying a steady, "coordinated turn", with the flow properties not changing at any point on the craft. The rotor blade of a helicopter hovering steady in still air also sees the same flow properties from instant to instant. Now if the aircraft starts rising or sinking, or stays in the coordinated turn long enough to burn a lot of fuel and thus require changes to the control surfaces and engine thrust, or if the helicopter starts flying forward very slowly, there is a small rate of change of properties encountered, but this is slow enough to be broken up into several stages of steady flow. Likewise, if a wing flaps up and down very slowly, its attitude and the forces on it, change with time, but this can be analyzed by breaking the flapping motion into several steady steps and ”joining the dots” of the answers at each step. On the other hand, an aircraft wing encountering a gust is a situation which requires ”unsteady aerodynamics”. A helicopter rotor in moderate forward flight speed encounters substantially different flow conditions within each revolution. A shock forming at the inlet of a jet aircraft, and then disappearing, causes large unsteady effects. The flapping motion of an insect’s wings is an extreme case of unsteady aerodynamics. In all these cases, the fact that there is a high rate of change has an important bearing on the result.

4.3. Inviscid Flows

To describe flows which are away from surfaces, one can simplify the theory and neglect the influence of viscosity of the fluid. Such descriptions are adequate for situations where the flow velocity and the size dimensions are large. The resulting methods are adequate to explain most of the lift forces (forces perpendicular to the freestream direction) on vehicles; they can also explain the formation of parts of the drag forces, but not all.

4.4. Potential Flows

When viscosity is neglected, and the effects of any rotation and shear in the flow are replaced by mathematical artifacts known as ”singularities”, the behavior of the rest of the flow can be analyzed by methods similar to those used to analyze electric fields and magnetic fields. These methods of ”potential theory” are very powerful: they are used to do the initial calculation of the air loads on the wings, rotors and fuselages of most airplanes flying today, and also to analyze what happens when the flow is unsteady.

4.5. Viscous Flows

When flow close to a solid surface, or near any boundary where there is relative motion, is analyzed, the effects of fluid viscosity become important. So, analyses of such regions of flows must use equations which include the terms describing the effects of viscosity.

4.6. Laminar Flows

Generally used in analyses of ”viscous flow” problems, this term means that the flow is ”smooth”, and resembles layers of fluid with slightly different velocities. In such flows, the effects of forces due to viscosity are significant, when compared to the effects of the inertia of the fluid motion. In other words, the "Reynolds number" which describes the ratio of inertial forces to viscous forces, is not very large (it still can be of the order of 100,000, but probably not 1 million.) In describing such flows, it is possible to arrive at an answer to the question: "what will the velocity be at this point one second from now?" to a high degree of accuracy: unlike "turbulent flows", described below.

4.7. Turbulent Flows

When there is some source of shear between different regions of fluid, and the Reynolds number is extremely high (on the order of a million or more), flows become turbulent, with the velocity, flow direction, and all associated properties fluctuating from instant to instant. Analyses of such flows must thus account for the results of such fluctuations, which include increased skin friction drag, reduced occurrence of flow separation and its drag, different rates of heat transfer between the flow and vehicle surfaces, the generation of noise, faster mixing between different fluid streams, and faster propagation of flames through gases.

4.8. High Temperature Flow

Over a narrow range of temperature, the properties of air, such as its specific heat, molecular composition etc. can be assumed to hold constant. We generally don't even worry about this issue in most of aerodynamics. However, there are situations where the changes in temperature are large, and hence we have to include detailed models of how gas properties change with temperature, in solving such problems. An example is the shock wave in front of the nose of the space shuttle as it comes down through the atmosphere. If we ignored the changes in gas properties in analyzing the change of temperature through this shock, we would get ridiculous results: we would predict temperatures which do not occur except in nuclear explosions!! As seen above, its not the actual "highness" of the temperature that matters for this definition: its the fact that the temperature can change over a large range.

4.9. Reacting flow

If the chemical reactions occurring in the flow are significant to the changes in flow properties, one has to include them in the analysis. For example, a "flame" is a reacting flow, where there is a large and rapid release of heat occurring during a chemical reaction. The molecular composition also changes, of course, during the chemical reaction. The flow in the combustion chamber of a rocket is a reacting flow. However, the flow in the nozzle of the same rocket, though it is glowing hot, may or may not be classified as a reacting flow: this depends on whether the composition changes substantially in the nozzle.

4.10. Non-equilibrium flow

This is another of those "when did we assume that? revelations. In most problems in aerodynamics, we assume that we have "equilibrium" in the flow. The rates of collisions between molecules are high enough that we can assume, for example, that the temperature and pressure in the flow in a nozzle adjust instantly to changes in the nozzle geometry. In some flow situations, the changes in properties may be so large and so sudden that the flow has moved a significant distance before there is complete adjustment of the temperature and the chemical composition. This occurs in lasers, for example, where the medium is kept out of equilibrium. Non-equilibrium phenomena can cause important differences to the pressure distribution and hence the pitching moment on a high-speed aircraft, like the Space Shuttle at re-entry. Calculations of nozzle geometry and heat transfer for rocket engines and vehicles such as the X-33 also require non-equilibrium considerations.

4.11. Multiphase flow

Sometimes, flows may include changes between solid, liquid and gas states, and may also include substantial amounts of material of different phases flowing along together. For example, as compressed air at room temperature is expanded through the throat of a supersonic wind tunnel, some of the constituent gases may begin to liquefy, and droplets of oxygen or nitrogen might form in the flow. The flow over the leading edge of a rotor blade operating under icing conditions may involve the formation of ice particles near the surface.

4.12. Rarefied flow

In the upper reaches of the atmosphere, the density of the air becomes so low that air cannot be assumed to be a continuous medium or ”continuum”. The flow analysis must include consideration of this fact. Since collisions between molecules become rare, it is smarter to regard the flow as being composed of many balls bouncing off the surface of the vehicle. Plasma When the gases in the flow are ionized (electrons leave many atoms, so that there is a high concentration of positive ions and free electrons), the flow behavior can be modified, and forces generated, using magnetic fields. Such flows are called plasmas.

4.13. Buoyant flow

These are probably the most common flows of air in the atmosphere: flows driven by the changes in their density due to heating or cooling, making them lighter or heavier than surrounding fluid. In most aerodynamics problems, we can neglect buoyancy effects because the flow velocities and the inertial effects are so large; however, buoyancy is a driver of atmospheric flows. Gliders, obviously, take advantage of buoyant flows when they rise on ”thermals”.

5. Advanced

Elsewhere on EXTROVERT you will find an abundance of in-depth content on aerodynamics.

6. Supersets

Fluid dynamics, Aeromechanics

7. Subsets

Hydrodynamics: this is mostly incompressible flow aerodynamics, with effects of buoyancy becoming important since it deals mostly with forces developed in liquids which are about a thousand times more dense than air. The speed of sound in liquids is very high, so that flows with speed comparable to the speed of sound are very rarely encountered.

Gas dynamics, which deals primarily with phenomena occurring over a wide range of Mach number.

Other subsets are listed under the classifications given above.

8. Calculators/Applets

Hyperlinks are not given, because today Internet Search Engines and people have become quite adept and very quick at locating what they want, given some idea of what they should be seeking.

1. Standard atmosphere calculators
2. Shock calculators
3. Prandtl Meye expansion calculators
4. Conical Flow calculators based on the Taylor-McColl scheme
5. The Wolfram CDF site (see under EXTROVERT Tools), where there are several example projects.

9. 10 Analytical Codes

1. The XFOIL code developed by Professor Drela at MIT calculates 2D airfoil aerodynamics at low speed, including the effects of boundary layers. This works well in the linear regime of lift curve slope, but caution must be exercised in interpreting results beyond stall (as someone once remarked at an AIAA meeting, we try to keep our airplanes from stalling, so this is no criticism at all).
2. The Eppler code is extensively used in sailplane design (as is the XFOIL code)

3. The Murman-Cole Transonic Small Disturbance airfoil aerodynamics code is efficient enough to run on personal computers. There are many subsequent versions from other researchers that solve various issues.

4. Full Potential equation solvers are also efficient enough to be run on personal computers, and can deal with many aspects of subsonic and transonic flows, but have serious problems once strong shocks occur, or when flow separation occurs.

5. Euler solvers are based on a large finite difference grid, and hence the resources required grow explosively as the grid size increases.

6. Codes based on the Moretti scheme of solving the unsteady conservation equations to obtain steady solutions for blunt-body flows.

7. Navier-Stokes codes. These typically require high-speed computers such as the National Supercomputer facilities at various centers.

10. Notes:

Low Speed Aerodynamics. Ebook at adl.gatech.edu/extrovert High Speed Aerodynamics. Notes in the user password-controlled portions of adl.gatech.edu/extrovert

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