Turbulence and Flying Machines

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This article is intended to introduce the young reader to the relationship between flight and fluid dynamics. It begins with a somewhat detailed discussion of what makes flight possible. Following this is a description of the effect of the nature of the flow on the drag. The connection between flow stability and drag-reduction, which is a topic of current interest in the aerospace industry, is discussed in the concluding section.

What Makes Flight Possible

It is obvious to most of us today that a body in flight must obey Newton's laws of motion. Leonardo da Vinci in the early 1500's had already realised that "a bird flies according to mathematical principles". Thus, if an aircraft is flying at constant altitude and constant speed, i.e., 'cruising', the upward force, or 'lift' L acting on it must balance its weight, W. In the line of motion of the airplane, we have a balance between the forward force, or thrust T applied by the engines and the drag force D due to the resistance of the air, i.e., under cruise conditions,

$$L = W \tag{1}$$

and

$$T = D \tag{2}$$

(*Figure* 1). We first discuss (1), and will take up the drag force in detail later.

The principle by which an airplane stays aloft is quite different from the mechanism by which a ship floats. The latter is based on hydrostatics: the weight of the ship is balanced by the upward force (buoyancy) due to the volume of water displaced (Archimedes principle). Man's early attempts to take off into the air were often based on the same principle: we are all familiar

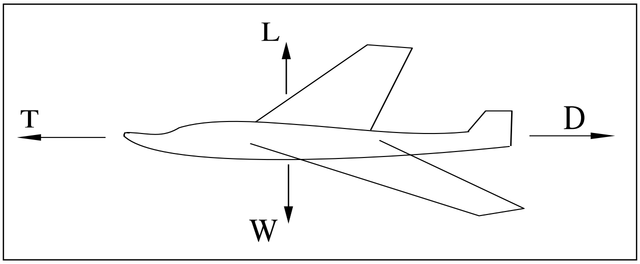

Figure 1. Forces acting on an aircraft.

with hot-air or helium balloons. A modern aircraft, however, is far heavier than the air it displaces. Staying airborne in this case is a dynamic process. In this article, for ease of expression, an aircraft moving forward in still air is replaced by an equivalent system in which the aircraft is thought of as being stationary with the wind rushing past it at the same speed. The wings of the aircraft are typically set at a small angle to the oncoming stream, as shown in *Figure* 2. Due to this angle-of-attack, the path traversed by the stream of air above the wing is different from that taken by the lower stream. The air above the wing travels faster on an average, i.e., it has more kinetic energy than the airstream upstream of the wing. This increase in kinetic energy must be compensated by a decrease in the pressure (Bernoulli's principle). Thus, the pressure above the wing has to be lower than the pressure upstream. Meanwhile the air flowing below the wing slows down on an average and this drop in kinetic energy is compensated by an increase in pressure. The difference in the pressures above and below the wing results in a relative vacuum above, which, if large enough, can lift the whole aircraft.

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Inherent in the above argument is the fact that two of the basic prerequisites for flight are airspeed and circulation. You make

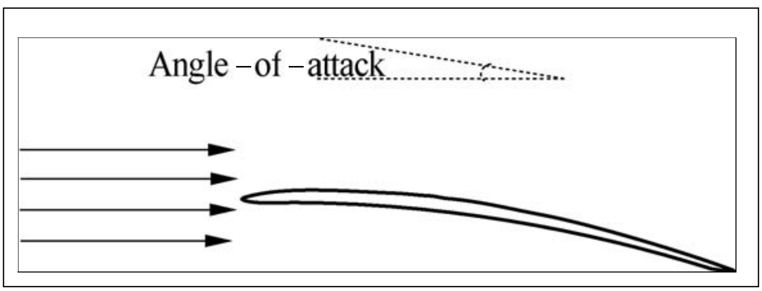

Figure 2. Angle-of-attack of wing section.

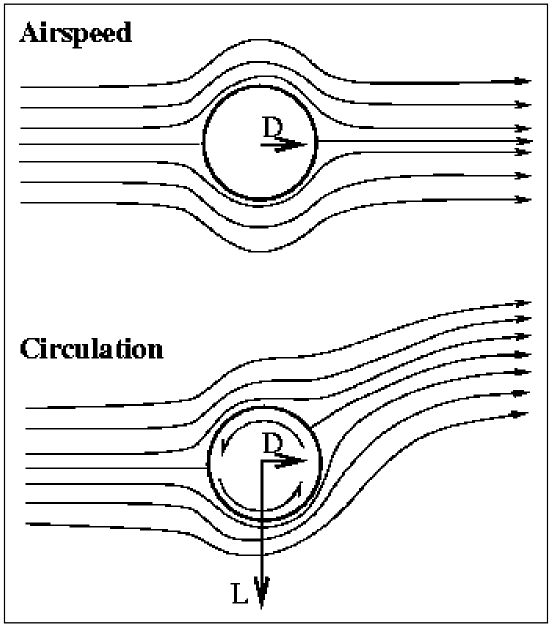

Figure 3. Generation of lift.

use of this thrilling twosome every time you stun your opponent in table-tennis with a top-spin. If you take one look at *Figure* 3, it is immediately clear why: the rotation of the ball decelerates the flow of air above it, and accelerates the air below. This causes lower pressure on the underside which is basically a downward lift. The trajectory of the ball is therefore different from that it would follow if it were not spinning in that the downward motion is earlier and sharper than your opponent is ready for (if he or she is new to the game!). A top-spin can ensure that the ball lands on the table while a ball hit with the same forward speed without spinning could sail over the edge, costing you a point.

What the ball achieves by rotating, a wing section achieves just by its shape: a net circulation is created by the mechanism described in the above paragraph. The next time you are in a moving vehicle, you can convince yourself of the creation of lift by extending your hand (very carefully!) out of the window and keeping it at a small angle to the oncoming stream of air. Almost all the lift experienced by an airplane comes from the wings; the body contributes most of the weight of course, but very little to the lift. The lift therefore can be taken to be proportional to the

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wing surface, S. If ρ is the density of air, and V_f is the forward speed of the aircraft, the lift is given by

$$L \propto \rho \, V_f^2 \, S.$$

As the aircraft climbs higher into the atmosphere, the density of air decreases. This means that the plane has to fly faster at higher altitudes in order to produce enough lift to balance its weight.

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There is a third basic prerequisite for flight: control. It is not enough merely to be airborne, it is crucial to be able to descend when desired, apart from being able to choose one's course. All modern aircraft have three-axis control, as shown in *Figure* 4. It is relevant here to mention that deflecting the elevators enables the pilot to pitch the aircraft up or down while the rudder helps him turn it in the horizontal plane, i.e., about the yaw axis. The ailerons on either side can be deflected differently from each other to make the aircraft roll. For example, a downward displacement of the left aileron causes the airplane to roll to the right. In *Figure* 4 the elevators have been deflected downwards, giving rise to a 'nose-down' moment about the pitch axis.

Delaying Turbulence

In the last few decades, flying machines have proliferated to the extent that some corridors in the sky (e.g. several trans-Atlantic

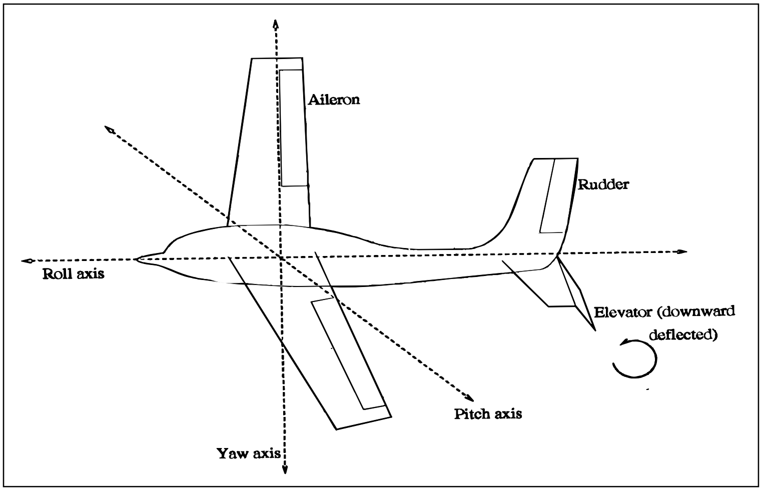

Figure 4. Example of moment created by deflection of control surface.

Designing an aircraft wing for reduced drag can be done at two levels: eliminating 'form drag' and reducing 'skin-friction'.

routes) have become quite crowded: pilots actually have to follow three-dimensional traffic rules such as lane-flying! In this scenario, fuel efficiency becomes extremely important, since even a small fraction of fuel saved per flight can translate into billions of dollars of revenue per year for a large airline company. We therefore turn our attention to the horizontal component of the force balance (2). On a long flight, cruise conditions are held for a major fraction of the time. Since the thrust demanded of the engines is primarily that required for countering the drag force, it is obvious that any reduction in drag reduces fuel consumption. Designing an aircraft wing for reduced drag can be done at two levels: eliminating 'form drag' and reducing skin-friction.

Form drag occurs when a flying object behaves like a sudden obstacle in the path of the oncoming air, resulting in the flow separating from the body surface. This is followed by the formation of large eddies and results in massive energy losses. By streamlining and cambering the wing cross-section (*Figure* 5), most designers ensure that the form drag is eliminated over most of the wing surface for a range of flight conditions including cruise. A topic of great interest to present-day aircraft designers is the reduction of skin friction over wing surfaces. This friction is caused by the viscous nature of air: the layer of air in contact with the wing surface is at rest (no-slip condition), while the air far away from the surface maintains a speed related to V_f and the

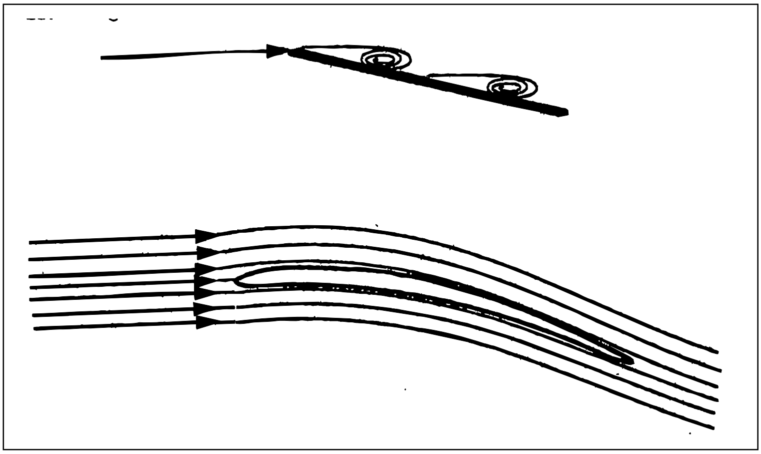

Figure 5. Elimination of form drag.

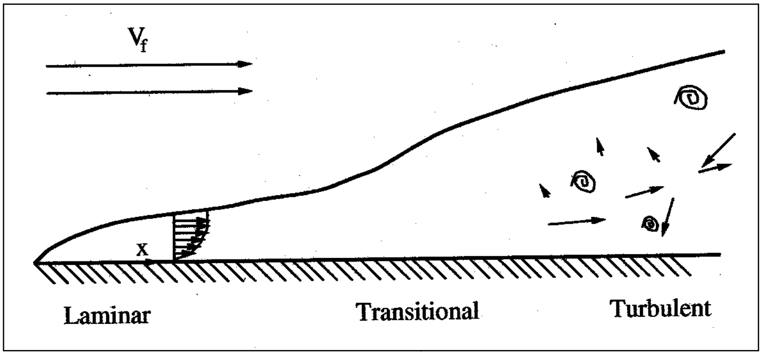

Figure 6. Boundary layer over a wing surface.

airfoil shape, as discussed in the previous section. Close to the surface, successive layers of air get slowed down due to the action of viscosity as the flow proceeds downstream. There is now a thin but growing 'boundary layer' close to the surface in which the velocity of air varies with height (*Figure* 6).

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The skin friction coefficient c_f (a suitably non-dimensionalised measure of the skin friction) depends sensitively on the type of flow within this boundary layer – i.e. whether the flow is laminar, turbulent or transitional. For the present discussion, it is sufficient to say that laminar flow is steady, streamlined and gives rise to lower levels of skin-friction than turbulent flow, which is highly unsteady, vortical and supports higher c_f , as shown schematically in *Figure* 7. Here x is the distance from the leading edge along the wing surface. In a majority of commercial aircraft

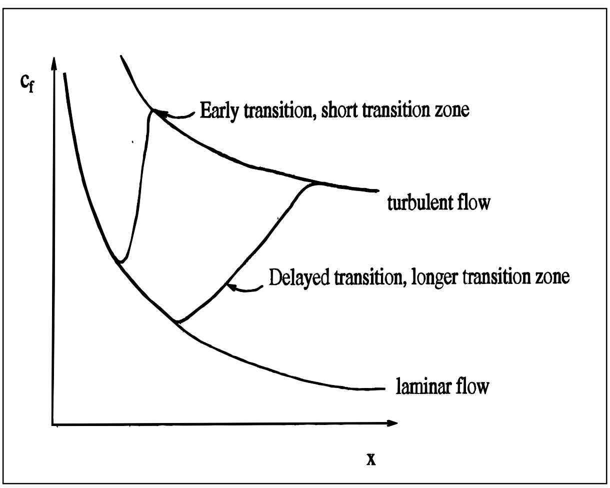

Figure 7. Boundary layer over a wing surface.

In the last decade or two, the design of natural laminar flow airfoils, i.e., wing sections which will support laminar flow over a substantial fraction of their surface, has become increasingly important.

today, the boundary layer flow over most of the wing is turbulent. This is because, at high speeds, laminar flow is often unstable and difficult to maintain. It is however clear from *Figure* 7 that laminar or transitional flow at a given location is preferable to turbulent flow, since the corresponding drag is then lower. The drag is proportional to the area under the curve shown in *Figure* 7. The case where the onset of transition is delayed and the transition zone is longer is thus more fuel-efficient than the other case shown in which transition occurs closer to the front of the wing (leading-edge) and the flow quickly becomes fully turbulent. In the last decade or two, the design of natural laminar flow airfoils, i.e., wing sections which will support laminar flow over a substantial fraction of their surface, has become increasingly important.

Although it is now almost a century after flying machines were first proved to be viable, it is often difficult even today to predict theoretically what fraction of the flow over the wing will be laminar and what fraction transitional. The kind of flow that will prevail over the wing depends on a host of parameters such as how uniform the external flow is, what is the curvature of the surface and so on. In this discussion we will take up the effect of only two parameters: the local acceleration or deceleration of the external flow, and a dimensionless quantity called the Reynolds number, given by

$$R = \rho xV/\mu \qquad (4)$$

where ρ and μ are the density and viscosity of air respectively, and V is a representative velocity scale. Holding all other parameters constant, the flow is laminar at low Reynolds numbers and turbulent at high Reynolds numbers. Thus, the boundary layer is usually laminar close to the leading edge of the wing, i.e., at low x, and undergoes transition to turbulence downstream.

The Role of Instabilities

The reason that transition occurs is that the flow responds to disturbances, becomes unstable and changes in character. This process can be thought of as the typical sequence of events an observer sitting within the boundary layer will witness as he moves downstream. Now, the atmosphere contains different kinds of disturbances and these can exist in certain forms within the boundary layer. The internalisation by the boundary layer of external disturbances is known as its 'receptivity'. Understanding receptivity is practically a separate sub-field of research and will not be discussed here. All we need to know right now is that different disturbances can exist within the boundary layer. At low x, the flow, in addition to being laminar, is also *linearly stable*. This means that any small disturbance introduced into the flow by the environment will die down. Somewhat downstream, it may be seen that disturbances whose frequencies lie within a particular small range begin to amplify as they are convected downstream. This streamwise growth continues for quite a distance at the end of which the amplitude of the disturbances has reached a critical level. At this point, there is interaction between different growing modes and new modes are created. These interactions give rise to small regions or 'spots' of turbulence. The region downstream of the birth of these spots is called the transition zone, which contains turbulent spots in a laminar background. Turbulent spots grow as they move downstream in the transition zone because they destabilise the laminar flow they come into contact with. Different spots merge with each other to form patches of turbulence until far downstream there are no regions of laminar flow left. The flow is now fully turbulent. This sequence is shown in *Figure* 8, where we are looking at the surface of the wing from above.

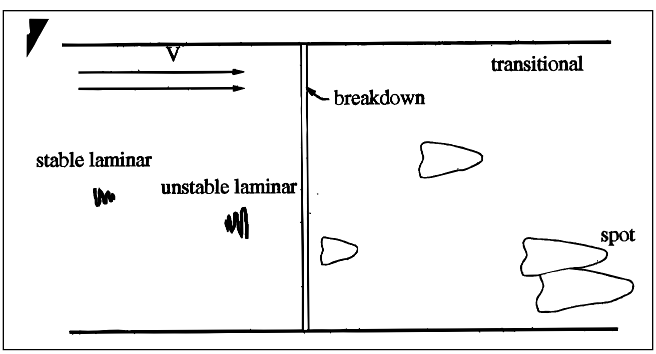

Figure 8. Boundary layer flow undergoing transition to turbulence.

We have seen that for saving on fuel, a designer would like to ensure laminar flow over as great a fraction as possible of the wing surface. Since it is an instability of the laminar flow that drives the flow to turbulence, the design of a non laminar flow (NLF) airfoil involves ensuring a stable laminar boundary layer for as great a distance as possible. There are several methods that can be adopted to stabilise the flow, such as judiciously applying suction at the wing surface or blowing from the surface into the boundary layer. The simplest way to make the flow more stable is to design the shape of the airfoil appropriately. The shape determines the flow outside the boundary layer: roughly speaking, a local acceleration results in a stabler laminar boundary layer while a local deceleration destabilises the flow. However, maintaining a rapidly accelerating flow over a good part of the wing may give rise to abrupt deceleration somewhere downstream, which can have disastrous consequences. A detailed explanation of various flow scenarios is beyond the purview of this article: the point here is to make the reader aware that there are several design requirements which often make contradictory demands on the airfoil shape. The designer must therefore choose the optimum shape which maintains a stable flow over as large a fraction of the wing as possible. A prerequisite for the designer is a knowledge of whether a given flow is stable or not. Although boundary layer stability has been studied by many people throughout the second half of this century, it is only in the nineties that a consensus has emerged among various workers and the stability of the flow is beginning to be understood. This is because the problem has proved to be mathematically as well as computationally very complicated. There are many exciting aspects of stability which are currently being researched, such as the effect of three-dimensionality. Anyone wishing to know more about this area is welcome to contact the author.

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Suggested Reading

[1] **S Dhawan, *Bird Flight*, Council for Scientific and Industrial Research, New Delhi, 1988.**

[2] **A C Kermode, *Flight without formulae*, Sterling Book House, (fifth edition - updated by Bill Gunston), 1994.**

[3] **V Radhakrishnan, From square sails to wing sails, *Current Science*, 73, No. 6, 503–516, 1997.**

[4] **V Radhakrishnan, Locomotion: dealing with friction, *Current Science*, 74, 826–840, 1998.**

[5] **H Tennekes, *The simple science of flight*, MIT Press, Cambridge, Massachusetts, 1996.**

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