Chapter 6
Pressure, Pressure, It's All About Pressure!

With the tools developed so far, the flow around an airfoil can be realistically described by the superposition of the uniform oncoming flow and many small vortices and sources with various strengths distributed along the mean line of airfoil. From a global perspective, the influence of the bound vorticity is to increase the air speed on the top of the airfoil and decease it on the underside. Every part of the vorticity sheet (see Fig. 3.2) has an influence on the flow field and the velocity (and speed) can be calculated everywhere it is desired. The energy equation (including the Bernoulli form) can be used to calculate the local pressure at any point where the velocity is known. Thus, the lifting forces can be determined and all that a wing structure designer might need is available. The pressure distribution from such a calculation is shown in Fig. 6.1. The pressure is above ambient under the airfoil and below ambient on the upper surface. The net lift force and any pitching *torques* (as they called by mechanical engineers) or *moments* (as they are called by aerodynamicists) are the quantities the airplane designer needs to integrate a wing design into that of an airplane design.

6.1 Forces and Moments

The totality of the distribution in Fig. 6.1 is the net lift force. Such a result is from a potential flow analysis consisting of only the uniform on-coming stream and the bound vorticity. The net force is upward. There is zero net force in the freestream direction: no drag. The structure at the physical point on the airfoil where this airfoil is attached (to the walls of a wind tunnel, for example) must deal with that force. For an arbitrary point on the airfoil, the pressure distribution will exert a torque about that point. If that point is near the leading edge, the torque is counterclockwise or nose-down and it is nose-up if near the trailing edge. There is one special point, generally between the leading and trailing edges, where the torque is zero and the whole of the pressure distribution can be summed as just a force. This is the *center*

R. Decher, *The Vortex and The Jet*,
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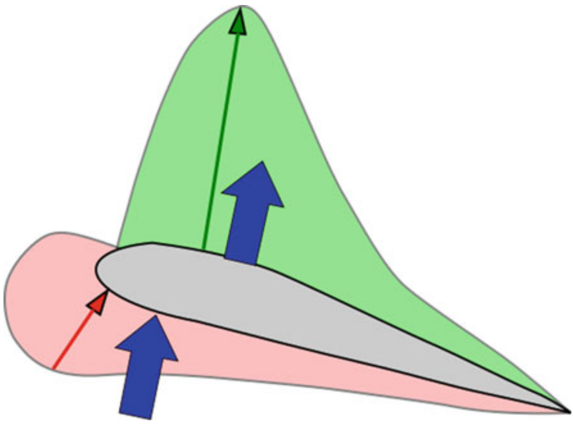


Fig. 6.1 A pictorial representation of the (static) pressure distribution on a typical airfoil at angle of attack. In green, local pressure is lower than ambient pressure; in pink, higher. The net upward lift force on the upper surface (upper blue arrow) is larger and acts on a point to the *rear* of a similar point (lower blue arrow) on the underside which causes the airfoil to exhibit a nose-down pitching moment

of pressure. Unfortunately for the airplane designer as we shall see, it turns out that the location of the center of pressure changes with changing angle of attack.

In general, both of these reactions (force and torque) are always present in varying amounts, no matter where the mounting point is located. There is, however, one point on the airfoil where the torque is nearly *independent* of the lift force. That point is called the *aerodynamic center* and is located one quarter chord back from the leading edge. This point's location on a wing relative to the airplane's center of gravity is central to the ability of the airplane to fly in level flight, provided that an additional balancing pitching moment, is provided by a horizontal stabilizer surface. In short, for steady, level flight, the designer must balance the inherent pitching moment associated with the airfoil shape, the moment exerted by the weight of the airplane relative to the aerodynamic center, and the moment exerted by the horizontal tail.

The fact that the pitching moment about the aerodynamic center is independent of angle of attack makes size, location, and orientation of the horizontal tail straightforward and thus eases the task of designing the airplane. Parenthetically, we note that the inherent pitching moment introduced by the airfoil shape is a direct measure of its camber. There is no moment about the aerodynamic center for a symmetric airfoil; one without camber.

What about these pitching moments? The pressure distribution on a normally (as shown in Fig. 6.1) cambered airfoil or wing typically results in a nose-down moment about the aerodynamic center. The location of the center of gravity relative to the aerodynamic center also results in nose-down moment. Thus, the moment to be provided by the horizontal tail must be nose-up from a *downward* force behind the wing. Yes, the force on the horizontal tail is downward, against lift. This function of the horizontal tail is difficult to discern in most images or displays because the angles of attack involved are small and orientation of the flow at the tail surface is heavily influenced by the flow behind the wing.

When this negative lift by the tail is not desired, (because it counteracts the wing lift and thus involves a drag increase) a control surface in front of the wing, called a "canard" can provide an upward (lifting) force. The rather uncommon implementation of horizontal control surface in front of the wing in modern aircraft requires artificial (electronic) stabilization because the configuration is not naturally stable in a flying airplane. The word "canard" is French for the bird "duck" and why? You should have asked the person who coined the description watching Alberto Santos-Dumont fly in 1906!

Note the distinction between flight *equilibrium* where all forces and torques are balanced, and *stability* that involves a *return to an equilibrium* for changes in attitude. For a well-designed airplane to fly in steady level flight, equilibrium is required and stability is desirable. With the horizontal control surface in front of the wing, the tendency is for an increase in the angle of attack on the wing to increase further due to the torques and forces so that the pilot has to react and counter this angle of attack increase. In flying their airplanes with forward control surfaces, the Wright brothers were able to do this with their skill. With the horizontal control surface at the rear, changes in condition naturally return to the state before the change so that the flight is stable, i.e., the airplane can be flown "hands off" the controls in the cockpit. The subject of airplane stability is a subject onto itself and not a concern for this development of the forces involved in establishing equilibrium.

6.2 Data for a Simple Airfoil

At this point in the development of the story it might be useful to look at the performance data taken in a wind tunnel test for a simple airfoil. The data is shown in a form that will become clear further on when we take up the subject of dynamic pressure as a quantity for normalizing forces and moments.

A presentation of experimental airfoil data also has to include a notation that portrays the importance of air viscosity. Thus, values of Reynolds number are generally noted. The role of viscous friction and Reynolds number per se is examined in detail further on (Chap. 7), so that the graphs of Fig. 6.2 should be viewed as nominal.

A beautiful compendium of airfoil data is given in a NACA technical report no. 824 dated 1945 (Summary of Airfoil Data) and made widely available by Abbott and von Doenhoff in the classic book on the *Theory of Wing Sections* that every student of aerodynamics encounters. This book is also a good follow-on to this writing with more mathematical details. To illustrate the general nature of the behavior of a simple cambered airfoil and allow the conclusion that the understanding developed so far is quite good, the performance data of a NACA 2412 is shown in Fig. 6.2. The airfoil is similar to the symmetric example (NACA 0012) used in the illustrations later in this story. The appellation of the NACA 2412 is descriptive and means that it cambered by 2% at the 40% chord point and is 12% thick. The percentages quoted are of the chord length. The profile is shown in the second part of the figure. The data given for such a summary of airfoil performance includes lift, drag, and pitching moment about the aerodynamic center as well as the moment about the quarter chord. The

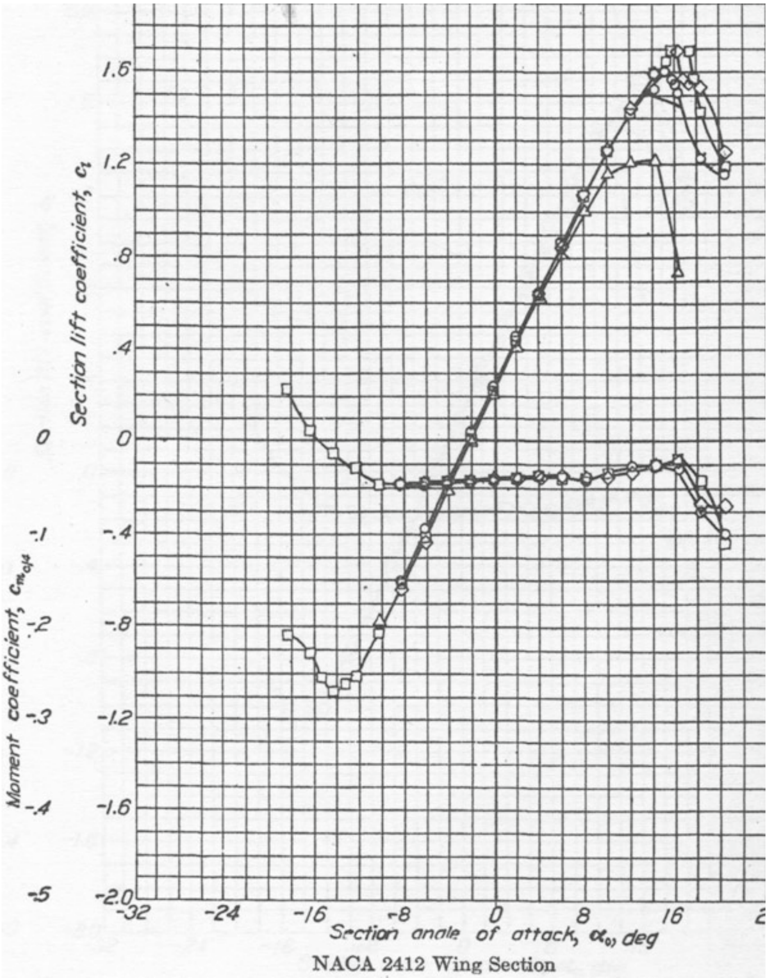
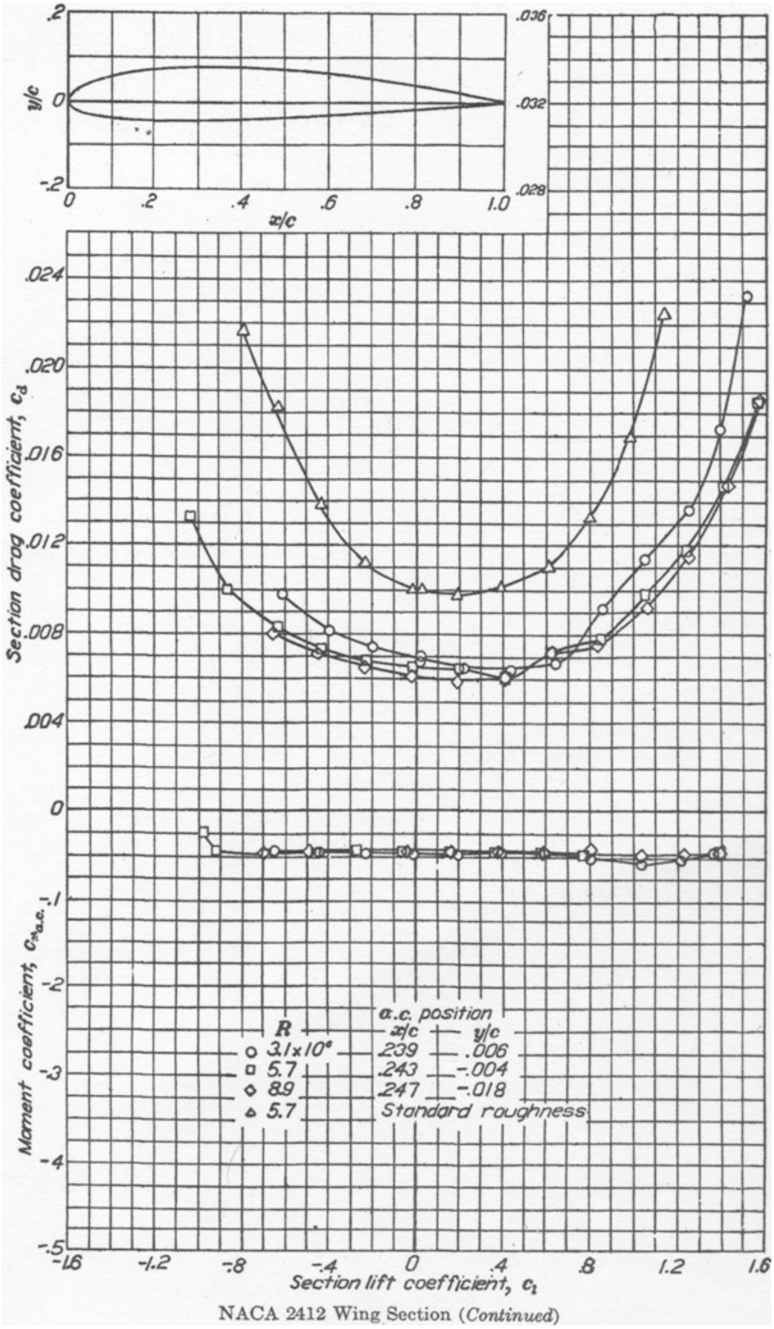


Fig. 6.2 Performance of a cambered airfoil. The first plot is of lift and moment about the 1/4 chord. The second plot is of drag in in the form of a drag polar and the moment about the aerodynamic center (lower curve). Reynolds numbers (***R***) indicated are in the millions. The reference to standard roughness is to highlight realistic performance contrasting with data obtained with a smooth wind tunnel model (NACA)



NACA 2412 Wing Section (*Continued*)

Fig. 6.2 (continued)

2412 airfoil illustrates the non-zero nature of the moment about the aerodynamic center for a cambered airfoil. The moment coefficient about the aerodynamic center of the symmetric 0012 airfoil is zero. An examination of the data allows a number of conclusions to be drawn.

Without proof, because we have not developed the mathematics, one can state that the linear slope of the lift curve (lift vs. angle of attack) observed agrees very well with theoretical calculation, i.e., one without consideration of viscous effects. The drag is very small compared to the lift with a maximum value of *lift to drag ratio* on the order of about 150 for a smooth two-dimensional airfoil model. The moment about the aerodynamic center is numerically negative (nose down) and constant for most of the angle of attack range. The aerodynamic center location is given as close to the quarter chord, varying slightly with friction effects. The theory gives the location as exactly the quarter chord. All this is to say that the modeling, in the minds of aerodynamicists and the mathematical one, is very good, especially at modest angles of attack.

The NACA 4-digit series of airfoils is an early (in the history of aviation) design and has been supplemented by many others, especially for drag reduction. The National Advisory Committee on Aeronautics no longer exists as such and current generation of airplane builders largely develop airfoil sections for their special needs using modern computational aerodynamics. The treasure of information gathered by NACA in its early years and summarized in the text above is nevertheless a valuable resource.

6.3 Calculation Iterations Toward Realism

The performance results from wind tunnel tests can be calculated to some degree. The key to doing it successfully involves modelling the behavior of the boundary layer accurately. The pressure distribution on the surfaces of an airfoil allows an examination of the equations of motion for the air in the boundary layer of the airfoil subject to the freestream pressure field. These, to a large degree, allow of the calculation of shear (resistive) forces contributing to drag. The boundary layer alters the effective shape of the airfoil. It is not hard to conclude that accurate determination of these flow phenomena is something of an iterative process involving the given hard surface shape, calculation of the effective shape alteration due to viscous effects and recalculation of the field with the new shape, specifically the changes brought about by air's viscous nature. Probably more than once. Modern analysis of the forces acting on a body like an airplane is not straightforward. It requires the use of powerful computers to be done well.

While the description so far has been limited to two dimensions, a real airplane is a three-dimensional object. The tools available for analysis are similar but they are more demanding because the field is large with three dimensions and three velocity components. Extension of our understanding to three dimensions does not greatly impact the physics of flight through air at a fundamental level. There are, however, important exceptions that involve vorticity. One important aspect of such three-dimensionality is the trailing vortex system.

6.4 Vorticity Provides More Than Lift, It Adds to Drag!

An interesting fact about a vortex is that it cannot end in space. It must end against a boundary or form a closed loop. An example of a vortex ending on a boundary might be a whirlpool in water or a tornado ending on the ground (see Figs. 2.7 or 8.1). Since there are no boundaries in the air through which we fly, the bound vortex on a wing must be a component of a closed loop. Indeed, the wing tips are the front ends of vortices trailing all the way back to a starting vortex left at the airport when the pilot rotated the airplane to begin flight. Together, these elements form a closed vortex "ring". The starting vortex, often illustrated as a line vortex, is actually a sheet (like our spread-out spaghetti bundle) because the airplane cannot be made to develop lift instantaneously.

Figure 6.3 is a view of a much simpler ring. Naturally, over time, the vortex dissipates into randomized turbulence and ultimately to heat when it decays to the molecular level. At that time the vortex will have ceased to exist. More interesting details concerning smoke rings will arise in connection with the nature of the fluid jet, the subject to be taken up in Chap. 9.

The wing tip vortex is, in actuality, a wrapped-up bundle of vorticity shed from the entirety of the span of the wing and not only at the wing tip, especially when flaps are deployed on the wing. This bundle is initially a sheet because the wing, being finite in length, contributes lift to a decreasing degree as one proceeds from the wing root to the wing tip. Figure 5.1 illustrates this idea. The tip generates no lift because

Fig. 6.3 A closed vortex ring with entrapped smoke (Andrew Vargas, Wikimedia, Creative Commons file: http://flickr.com/photo/45665234@N00/2891056110)

the tip allows the upper and lower surface pressures to be equalized by flow from the bottom to the top. As the wing produces *decreasing* amounts of lift toward the tip, it sheds to the rear an *increasing* amount of vorticity which then bundles into a more organized vortex. It may take a few chord lengths for the vortex to appear as a well-defined, symmetric, tornado-like structure.

The flow between the two trailing vortices is downward (see Figs. 2.3 and 6.5), consistent with the downward momentum imparted to the freestream flow as required by Newton's force law. The net effect is that the far field velocity *upstream* is also turned *downward* causing the finite length wing of an airplane to experience flying into a *descending* head wind. This means that the flight lift force vector experienced at the wing is not vertical but is rotated to the rear. In effect, the lift force has a component acting as a drag.

The wing's bound vortex (or better, its distributed vorticity) contributes an upward share to the flow ahead of the wing and adds to the downwash behind it. These velocities play no role on the orientation of the lift force. The vortex cannot interact with itself. The net effect of these influences on the flow ahead of the wing is rather small because the vorticity distributed along the chord and span is modest in length. In a sense, the bound vortex length is shorter than the span of the wing. That makes the relative contribution to the downwash near the wing by the semi-infinite trailing vortex system dominant in its influence.

The penalty associated with force rotation is called *induced drag* because it is induced by (or perhaps better said, associated with) the presence of the trailing vortex system. In practice, the drag can be reduced (though not eliminated) by the use of high aspect ratio wings, such as those of a glider. Roughly stated, the aspect ratio is the ratio of wing-span to chord.[1] A higher aspect ratio wing is slenderer and involves greater skin surface of the wing hence larger skin friction drag. A compromise is always made for a practical airplane design. Elements of the compromise involve speed, fuel consumption, and practical aspects like airport gate access for a commercial airliner.

Figure 6.5 illustrates the use of a conceptual model to aid in understanding the flow configuration. The picture of the trailing vortex shows an approach used in classical texts on aerodynamics to "prove" that one half the of the ultimate downwash velocity appears at the location of the bound vortex and is used to explain the nature of induced drag. The method is well suited for students because the velocity variation along the centerline of the picture can be written in terms of a simple algebraic equation that can be plotted to make the point.

It must be evident, however, that the model fails in a number of respects to illustrate the reality of the situation. For example, the trailing system's induced velocity near the wingtips is certainly incorrect because the downwash velocities associated with the trailing vortices there would be unrealistically large. This is doubly so because the sharp turn of the line vortex is not observed in nature. Finally, it must be recognized that in reality the trailing vortex does not persist as a straight or nearly straight line. The vortex itself is unstable in shape. This matter is not serious for modeling purposes,

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[1] Technically, Aspect Ratio is (wing-span squared)/wing area. See Appendix C.

however, because the evolution is spread out over space. Figure 6.3 illustrates the phenomenon.

A better model is needed. The tip of the wing cannot support lift. The span-wise lift distribution must be zero at the tip and finite closer to the centerline where the fuselage might be. Just as the vorticity is distributed along the chord, it is also distributed along the span. As one looks from airplane centerline to wing tip, the decreasing lift must shed an increasing amount of vorticity into the stream as a sheet. Such a model softens the singularity at the wing tip. Yet, we observe that downstream of the wing the vorticity does bundle into a fairly well-organized line vortex (see Fig. 6.4). Adaptive modeling is again called for. A better model is shown in Fig. 6.6. The model involves a multitude of smaller loops of vorticity better reflecting the span-wise lift distribution. The loops are not shown in the figure (because the figure would be too complex) but the span-wise variation of the shed vorticity is shown as region D.

In classical aerodynamics, the variation of the vorticity of the trailing system shown in Fig. 6.6 is used to determine the lift distribution to give minimum induced drag. That variation turns out to be an elliptical one, meaning that when plotted along the span, the line representing lift is an ellipse (region A). That condition is attained when the downwash at the wing is uniform (shown as region C in the figure). That result might be an expected one for any other distribution for a given lift requires a greater investment in energy to bring it about. Such a model analysis was the basis for an elliptic wing planform of the Supermarine Spitfire designed and used in WW II. In practice, tapered wings are easier to build and perform nearly as well.

While Fig. 6.6 shows a rectangular wing (B), the lift distribution may be made elliptical by twisting the wing and forcing the wing to operate with a varying distribution of angles of attack.

The model that leads to the conclusions about uniform downwash assumes, for analysis purposes, that the vortex sheet extends far downstream unchanged. That

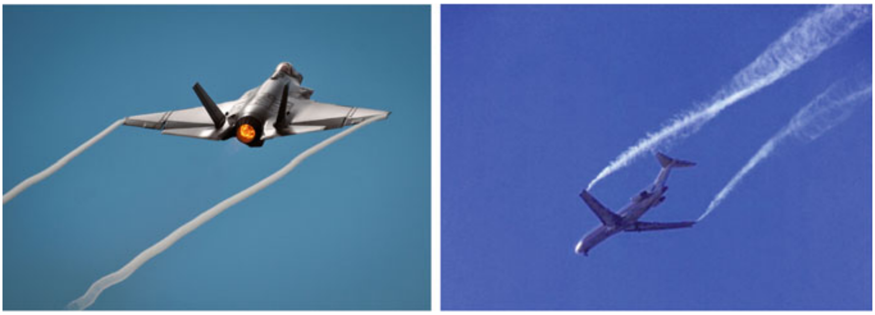

Fig. 6.4 Left: A fighter plane with trailing vortices made visible by the condensation of moisture in the air. Near the center of the vortex core the high velocity leads to locally low temperatures and condensation (US Air Force) photo. Right: The vortex nature of the flow is well illustrated with smoke injection at the wing tip on a test airplane. The airplane is a Boeing 727. The smoke injection ports are visible in Fig. 2.2. (NASA Dryden Research Center)

eases the mathematics but is not an accurate reflection of reality because the sheet bundles into a line vortex far downstream as described above. Perhaps the use of the spaghetti noodle bundle is appropriate again here, but the noodles would have to have been cooked to twist into a line vortex! Approximate models are, nevertheless, useful to gain insight into the flow kinematics and to obtain some degree of certainty about the magnitude of the effects involved on what is really wanted: a good measure of the actual induced drag associated with a specific design.

The simple models outlined in Figs. 6.5 and 6.6 are simplifications of the real world. Modern computers allow much more detailed representations of the flow around a winged airplane. The improvements allow incorporation of span-wise and chord-wise lift distributions. Also available for inclusion are better descriptions of the flow field associated with the coalescence of the vorticity sheet from the wing into a trailing line vortex pair that exert influence on one another.

The modeling exposed in this discussion and that of the related propeller discussion in Chap. 9 owes a lot of the original thinking to Ludwig Prandtl, the German

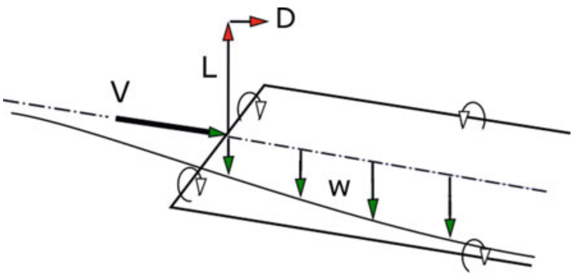

Fig. 6.5 Simplified sketch illustrating induced drag at mid span from the rotation of the oncoming flow vector by the wing's trailing vortex system. On the wing-bound vortex, the downwash on the centerline has half the value experienced at the far right. The oncoming stream (V) is therewith rotated downward (green arrowhead) and the lift force vector (L) is rotated to the rear, contributing to drag (D). The vectors (oncoming air speed (**V** + **w**) and the resulting force, **L** + **D**) are 90° apart. Far to the right (at the airport) would be a "starting vortex" closing the loop

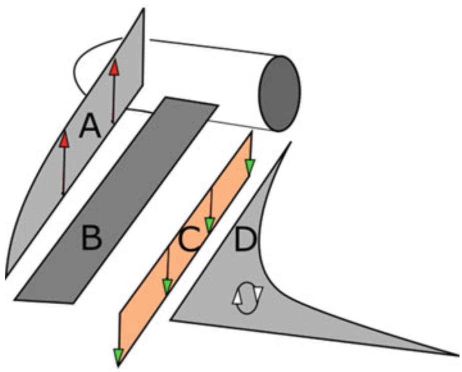

Fig. 6.6 A more realistic model of trailing vortex system (D) from a wing (B) with distributed lift. Noted are the lift (A) and downwash (C) distributions. In the far-field to the right, the distributed vorticity (D) shed as a sheet bundles into an organized line (trailing) vortex further downstream

aerodynamicist who did much of the pioneering work in the early in the twentieth century. His understanding was furthered by Hermann Glauert, the British aerodynamicist. Both individuals left their marks on the field with the latter well known to aerodynamics students for his book "*The Elements of Aerofoil and Airscrew Theory*." It was, for a time, required reading, including for this student. A simple summary of a quantified description of induced drag is given in Appendix C.

6.5 Flight in Ground Effect

The model of a bound vortex with trailing vortices can be used effectively to describe flight in so-called *ground effect*. The details are left for the serious student, but the essence is that the ground in proximity of a flying wing is a flat, rigid surface. Aerodynamically such a rigid surface is obtained with a second bound and trailing vortex system on the other side of the surface. That way an impenetrable surface results from the addition of the two vortex systems. The system "below the ground", so to speak, induces a velocity field that reduces induced drag. A pilot in an airplane approaching the ground for landing typically feels the reduction of drag as a small net forward acceleration.

6.6 Dynamic Pressure and Those Convenient and Pesky Coefficients

When we look at the pressures that sum up to lift, we are concerned with only that part which results from the motion of the air. When flight speeds were slow, the Bernoulli form of what we now call a flow energy equation was simple. It involved the dynamic nature of motion in a single term, the *dynamic pressure*, $\frac{1}{2}\,V^2 \frac{1}{2}\,\rho V^2$ given its own symbol, q.

Since the pressure differences from atmospheric pressure are of primary interest, one would expect that all pressures on an airfoil can be related to the dynamic pressure. This indeed the case. Thus, to simplify life, aerodynamicists express all pressures from any calculation related to airfoils in a non-dimensional way as a *pressure coefficient*[2] written as

$$C_p = \left(p - p_{in\,the\,freestream\,far\,away}\right)/q$$

This coefficient is the quantity displayed in Fig. 6.1: negative above the airfoil and positive below.

The following question may arise in the mind of the reader: "Does the presence of a boundary layer cause a pressure measurement made on a surface to differ from the

[2] The symbol C_p is the same as the specific heat but the context makes distinction evident.

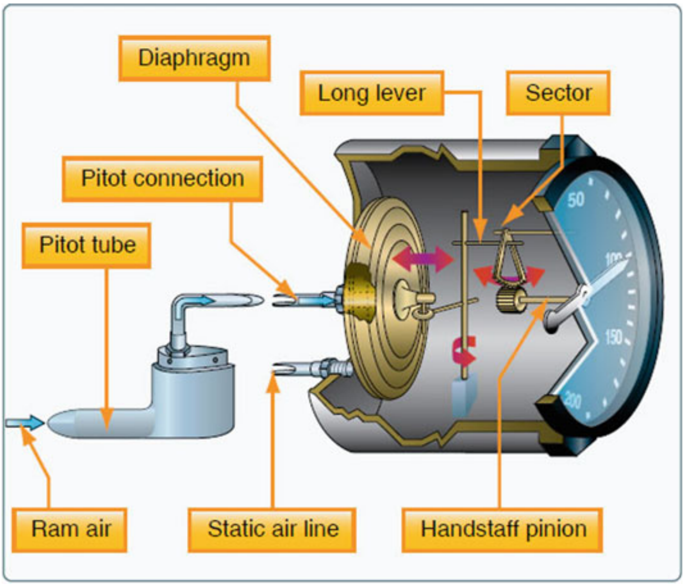

Fig. 6.7 Cross-section of a bellows type Indicated Air Speed instrument connected to a pitot probe (image courtesy of *Flight Literacy*)

pressure calculated from consideration of the inviscid freestream flow field?" The answer is that the difference is extremely small. Figures 6.1 and, for example, 7.2 in the next chapter rely on the premise that the pressures are identical. The argument for that truth is made in Appendix B and involves the invocation of Newton's second law of motion.

6.7 The Pitot Probe and Dynamic Pressure

There are two operational aspects of the dynamic pressure of interest to the pilot of an airplane. The first is that dynamic pressure plays an important role in determining the loads experienced by the surfaces of an airplane. These cannot be allowed to exceed the design values lest a structural failure be risked. The second is that dynamic pressure has to be large enough for flight to be possible. Stated another way, one could ask: When can the airplane accelerating down a runway be rotated to present a positive angle of attack on the wings and thereby lift off the airplane the ground?

Dynamic pressure is relatively easy to measure and is the basis for telling a pilot of his flight situation, the airplane's speed in particular and, more importantly, whether the wing can operate effectively. The determination of dynamic pressure is typically

Fig. 6.8 Pitot probe under the leading edge of a Cessna 172. The ports for measuring static pressure are on the airplane fuselage (Photo: Ronald Parker)

made with an instrument (Fig. 6.7) consisting of a bellows[3] wherein stagnation pressure air is fed to its inside and the outside is exposed to static pressure. The deflection of the diaphragm responding to the pressure *difference* allows a connected needle to display dynamic pressure on a dial. At modest speeds, the difference between the total (also called stagnation or ram) pressure and the static pressure is the correct value of the dynamic pressure. In very old airplane instruments, the information might have been displayed as deflection of a liquid in a glass U-tube where one end of the "U" is connected to the pitot probe and the other is left open, exposed to the nearly static pressure in the cockpit. That turned out to be awkward in a number of ways in that the pressure is hard to read, the fluid could be spilled (when flying upside down), and the reading depends on the g-forces experienced. Dial instruments were quickly developed and adopted. Ever more commonly today, the pressure signals are fed to transducers that generate an electrical signal used to display the information on an electrical instrument.

The stagnation pressure is measured by a probe like that shown in Fig. 6.7, also shown on Fig. 6.8. It brings the flow to rest on the relatively blunt nose. For the best measurement, the probe should be positioned at a location where it is exposed to clean flow. Locating it at a place where it faces true freestream pressure is often impractical, however, because the pressure field around an airplane is large, reaching out distances of many feet. The underwing location of the probe on a general aviation airplane in Fig. 6.8 is a reasonably good location. On commercial airliners, the probe is typically located near the nose of the airplane.

Similarly, the static pressure should be measured far from the airplane so that its pressure field associated with and surrounding the airplane is not involved in the measurement. Again, in a practical setting, a local measurement can be made on the probe itself by means of ports (small holes) near the elbow of a pitot probe

[3] A bellows is a set of two flexible diaphragms that separate when the pressure inside is raised relative to outside.

Fig. 6.9 Pitot tube on a Lockheed Martin F-35. This is typically a temporary installation for flight test purposes. This rig measures a number of aerodynamic and attitude parameters. The static measurement is made along the long probe even when flight speed is supersonic [Photo: Wikimedia Commons File:CF-1 flight test.jpg (cropped)]

or it is taken from a static pressure port located somewhere on the airplane. Any inaccuracy in both these measurements is either ignored (because it is negligibly small) or accounted for by a calibration. Such a calibration is usually established with prototype test aircraft with a long nose probe (Fig. 6.9) or on a long, thin trailing tube behind the test airplane. In either case, the goal of the calibration is to measure the true pressure of the environment as if the airplane was not present and relate that measurement to the pressure actually measured at the locations deemed practical. The calibrations are then built into the display of pressure by adjustments on the instrument or mathematically for display in digital form.

Dynamic pressure is important for assuring that the wing can generate the necessary lift force while staying within the structural load limits. It may be measured in pounds per square inch, inches (or millimeters) of mercury, Newtons per square meter, or other units. The call-out of such abstract quantities are not convenient for the pilot. He or she deals with speed. Fortunately, a speed can be inferred or calculated from the dynamic pressure provided the air density is known. An easy solution is to build into the pressure measuring gage the density of standard sea-level air and display the pressure as a speed by marking the dial appropriately. Traditionally, the speed determined this way is measured in knots (nautical miles per hour, reminding us of a tradition established by mariners).

By these means, the pilot can think of dynamic pressure as a speed. The instrument that displays the dynamic pressure is an *indicated airspeed* indicator (Fig. 6.10). The numerical value shown on the gage is that of the airplane as if it was flying at sea level on a standard day. When flight is at higher altitudes, the indicated speed shown on the instrument will be smaller than the *true airspeed* whose accurate determination would have to include data about the local air density where the airplane is flying (or trying to fly!). This value of the local density can be determined from measurements of temperature and pressure of the airplanes' environment with application of the ideal gas law ($pv = RT$) since density is $1/v = p/RT$. Such measurements are quite

Fig. 6.10 Simple display in an airplane instrument panel showing indicated air speed. In the U.S., this speed is traditionally given in knots (nautical miles per hour). The green zone is safe operation range, yellow requires smooth air, and red tab is the not-to-exceed speed for concerns of structural damage to the airplane. The white range is for operation with flaps, such as during takeoff or landing. More complex versions of such a dial are common (Wikimedia Commons: Marek Cel, file: Airspeed indicator.svg)

commonly made on aircraft for many purposes so that true air speed may be obtained from proper instruments or a hand calculation.

A good illustration of the role of dynamic pressure is in connection with takeoff from an airport. Independent of whether the airport is a high altitude or sea level, the indicated speeds necessary for the pilot to rotate the airplane for lift off are identical. Indication on the gage in the lowest reading in the green zone (Fig. 6.10) is where the pilot can initiate rotation. With flaps lowered, he or she can do it earlier in the takeoff roll (the white zone). The ground rolling speed is higher for the mountain runway takeoff. At the 130 knots mark, the pressure measured is on the order of a half a pound per square inch, one inch of mercury, or 0.035 atmospheres. A commercial airliner in cruise would experience about 4 times this dynamic pressure or double an indicated speed, around 280 knots with a maximum of about 350 knots. The upper end of the white zone is where flaps must be retracted because there is a risk of their failing to stay with the airplane due to excessive structural loads. The yellow and finally red lines display other structurally imposed speed limits on the airplane.

The pilot would also want to know how fast he is going relative to the ground so that he can navigate accurately. Within the airplane, however, the best speed determination is that of *true air speed*, the speed of progress within the air mass around the airplane. Wind will inject a difference between the true and ground speeds. Nowadays ground speed is often obtained from GPS (Global Positioning Satellite) information obtained as input to navigation systems. From such systems, wind information is easily deduced. GPS systems are common in general aviation aircraft and are uniformly installed in all commercial aircraft.

The pitot probe and the associated indicated air speed indicator remain a fixture on most subsonic aircraft such as general aviation aircraft and commercial airliners. No matter how sophisticated the pressure measurements may be made and displayed, flight safety consideration usually require the pitot probe and its instrument as a backup resource.

So far, the discussion of flight speed(s) has not addressed what is the best speed for an airplane to travel? Maximum speeds are always interesting from a general viewpoint, but operators of airplanes usually consider economic issues as a more important concern. The achievement of long range with minimal use of fuel is paramount for commercial airline operators and the designers of the airplanes. General aviation flyers are often similarly concerned with the fuel consumption and the issue of the related cost. The speeds that allow addressing this goal is where the discussion to follow will have to take us.