Airfoil Selection

Understanding and Choosing Airfoils for Light Aircraft

By Barnaby Wainfan

Preface to the Second Edition:

To call this a second edition is a bit of an exaggeration. It is essentially the original book, cleaned up a bit and formatted to take advantage of modern publishing technology. I have resisted the temptation to re-write and edit, and I believe the material has aged well. It is presented here as originally written, including the original forward.

It's hard to believe that it has been 17 years since this series of articles first appeared in KITPLANES. Fortunately, the physics of the air has not changed, so the material presented herein remains as relevant now as it was then.

This series of articles was the beginning of a career as an aviation writer for me. I have that career because Dave Martin, then editor of KITPLANES, was willing to take a chance and buy a series of articles from someone he then knew only as a voice on the phone. This started both a professional relationship and a friendship that endured to this day.

Barnaby Wainfan
Jan. 1, 2005

FORWARD

This book consists principally of a series of articles originally published in KITPLANES Magazine.

The articles are reproduced here as they appeared in the magazine with the exception of minor corrections and re-formatting. I have added appendices to the text of the original article series to give the reader some additional useful information which space did not permit to be included in the magazine article series.

These appendices include some properties of the atmosphere, a compilation of useful aerodynamic formulae and representative data for selected airfoils.

The purpose of the article series and hence of this book is to provide the reader with a basic understanding of airfoil geometry and how that geometry affects the aerodynamics of an airfoil and the characteristics of an airplane using that airfoil.

I hope that I have succeeded in this and that you, the reader will find this book useful and informative.

I give special thanks to KITPLANES and to Editor Dave Martin for his considerable help in making this possible.

Barnaby Wainfan

Jan., 1988

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Choosing Airfoils

Here's a primer on the process of picking the right airfoil.

One of the more important choices the designer of an airplane must make is what airfoil to use on the wing and tail surfaces of the airplane. The airfoil choice has a significant effect on the performance and flying characteristics of the airplane and should be made carefully. A working knowledge of airfoils and their characteristics is also useful to the prospective kit builder when evaluating a potential project before buying a kit.

The selection of an airfoil is, like everything in airplane design, a compromise. Choosing an airfoil to maximize performance in one part of the flight regime will usually hurt performance in another. For example, choosing an airfoil with very high maximum lift to get a low stall speed will usually also cause increased cruise drag. It is extremely important that the airfoil be chosen on the basis of the mission of the airplane. The airfoil requirements of an STOL bush airplane are very different from those of a fast cross-country machine.

There is no "magic airfoil". An airfoil that is appropriate for one airplane may be a very poor choice for another. It is unfortunate that, over the years, first one airfoil and then another becomes stylish. When an airfoil is in vogue, everyone wants his or her airplane to have it because it is new or "hi tech". It is quite common to read of a homebuilder changing the airfoil of a proven design because he believes that it will dramatically improve the airplane's performance. Such efforts usually end in disappointment. If the original designer did his job right, the airplane has an airfoil that is pretty well matched to its mission. Careful, knowledgeable modification may improve performance a few percent, but a simple airfoil change will not usually produce the hoped-for major change in performance.

An airfoil change can also affect the stability and handling of the airplane. It is not something to do lightly. Changing the airfoil is like changing any part of an existing design. The effects can be major and it should not be attempted without careful, knowledgeable analysis.

A case in point is the GAW-1 airfoil fad of several years ago. The GAW-1 was designed by NASA as an airfoil for use on relatively high-wing-loading, multi-engined aircraft. The drag of the GAW-1 airfoil was not particularly low but it was quite thick and had a high maximum lift coefficient. In theory, this combination would allow the designer to create a relatively light, high-aspect-ratio design with a high wing loading. The mediocre drag performance of the airfoil would be overpowered by the drag reductions achieved through high wing loading and high aspect ratio.

Unfortunately, many homebuilders responded to the publicity surrounding the GAW-l by changing the airfoil on their projects to the GAW-l without redesigning the wing to increase wing loading or aspect ratio. The airfoil switch usually resulted in a slower airplane. The homebuilt community was not the only culprit. At least one major airframe company used the GAW-l on a certified production airplane. Its performance was less than sparkling, due in part to a poor airfoil choice influenced by fashion rather than aerodynamics. The GAW-1 has been renamed the LS (1)-017 by NASA but it is still a poor choice for the airfoil of a light airplane.

The choice of airfoil should not be made at the outset of the design process. In other words, the designer should not sit down and say, "I am going to design an airplane with a GAW-1 airfoil". Instead, the first step is to define the mission of the airplane. At the very least, the stall speed and the cruise speed of the airplane should be specified. These two speeds define the basic compromise inherent in airfoil choice. If an airfoil with very low cruise drag is chosen it will usually not have a very high maximum lift coefficient, and the stall speed will rise. This can be compensated for by decreasing wing loading but the increase in wing area will increase parasite drag and may defeat the original goal of low cruise drag.

On the other hand, choosing an airfoil with a high maximum lift coefficient will drive the stall speed down and allow wing loading to be increased at the cost of higher parasite drag due to the airfoil. Somewhere in between these two extremes is an airfoil that will give an acceptable mix of high lift and low cruise drag. The details of the choice will depend entirely on what the airplane is expected to do. The designer must trade gains in one flight regime against penalties in another until a suitable compromise is reached.

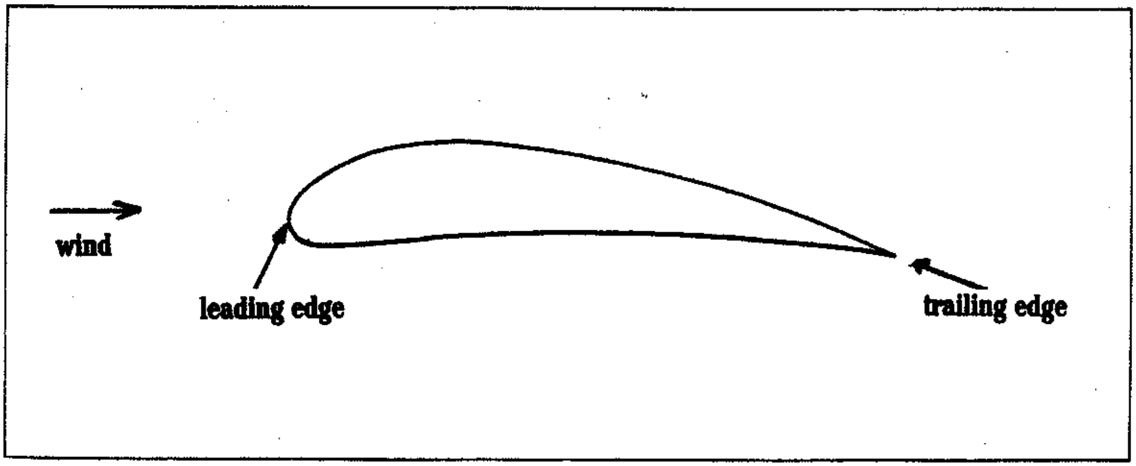
Before we can discuss the aerodynamic characteristics of airfoils, it is necessary to establish the definitions of some geometric and aerodynamic quantities that determine and describe the airfoils' aerodynamics.

The first area is geometry. An airfoil has several features of its geometry that have special significance to its aerodynamic and structural properties. Definitions of these follow.

The leading edge and the trailing edge:

Figure 1 shows the leading and trailing edges of the airfoil. The leading edge is simply the forward edge of the airfoil that encounters the oncoming airstream first.

The air leaves the airfoil at the trailing edge, which is the rearmost point of the airfoil. On most airfoils the trailing edge is sharp. While some squaring off of the trailing edge is often acceptable, rounding off the trailing edge will seriously degrade the airfoil's performance.

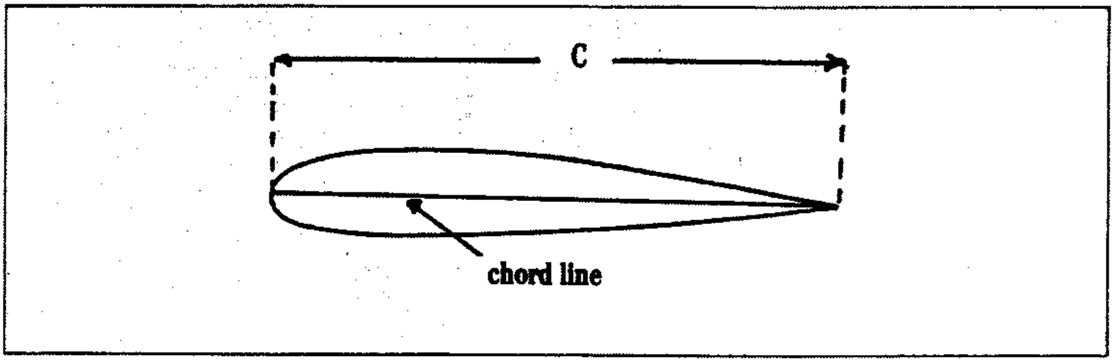


Illustrations: Barnaby Wainfan

Chord:

As shown in Figure 2, the chord line, called simply the chord of airfoil, is a straight line connecting the most forward point on the leading edge to the point of the trailing edge. Technically, the chord is defined as the longest straight line that can be drawn from the point of the trailing edge to any other point on the airfoil. The point farthest away from the trailing edge is, of course, the leading edge.

Figure 2.

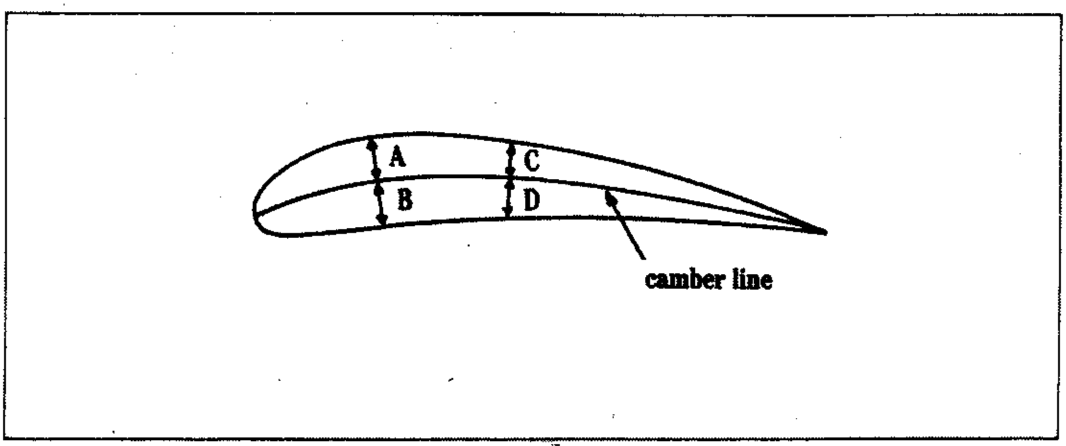


The length of the chord line is referred to as the chord of the airfoil and is represented in most equations by a capital letter C. All lengths used in the description of the aerodynamics and geometry of airfoils are expressed in terms of percent of the chord of the airfoil. For example, the thickness of the airfoil is always given in percent. If an airfoil has a thickness that is 12% of its chord, it is said to be a "12% airfoil".

Camber:

The camber line is a curve that connects the leading edge point and the trailing edge point of the airfoil. At each point along its length, the camber line is the same distance from the upper surface of the airfoil as it is from the lower surface. In other words, at any point along its length, a line drawn at 90° to the camber line, connecting the camber line to the airfoil upper surface will be the same length as a similar line connecting to the airfoil's lower surface. This is illustrated in Figure 3. The length of line A equals the length of line B and the length of line C equals the length of line D.

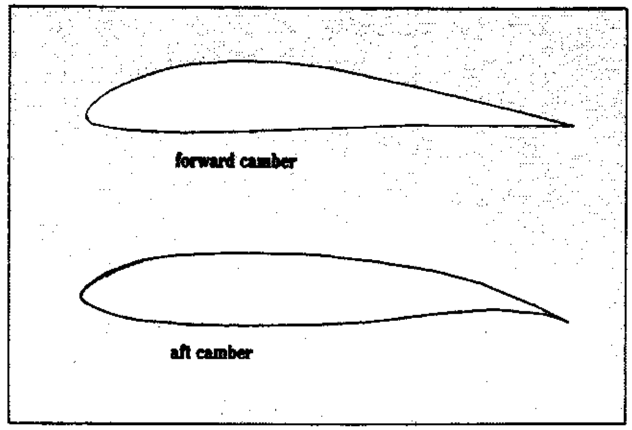
Figure 3.



The shape of the camber line has a major effect on the aerodynamic characteristics. The distance between the chord line and camber line is referred to as the local camber of the airfoil. Look at Figure 3 again. The distribution of local camber will determine the pitching moment that the airfoil generates and has a strong effect on its lift and drag. If the airfoil has its maximum local camber forward, it is said to have forward camber; if the maximum camber value is toward the trailing edge, it is said to be aft-cambered.
The difference is illustrated in Figure 4.

The maximum value of the local camber is an important parameter in the evaluation of the airfoil. The camber is always expressed in percent of chord. If, for example, an airfoil has as the maximum value of local camber 2% of the chord, that airfoil is said to have 2% camber.

Figure 4.



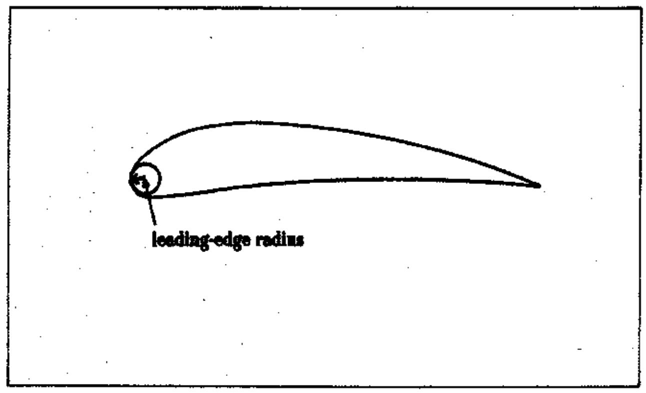
Thickness-to-chord ratio (T/C)

The thickness of the airfoil is expressed in percent of the chord. It is represented in equations and in the discussion that follows by the expression **T/C** or thickness-to-chord ratio. The maximum value of **T/C** is used to characterize the airfoil. An airfoil with a maximum **T/C** of 17% is called a 17% airfoil.

Leading-edge radius:

The leading-edge radius of the airfoil is the radius of a circle that is tangent to the leading edge of the airfoil and matches the curvature of the airfoil at the leading edge. See Figure 5.

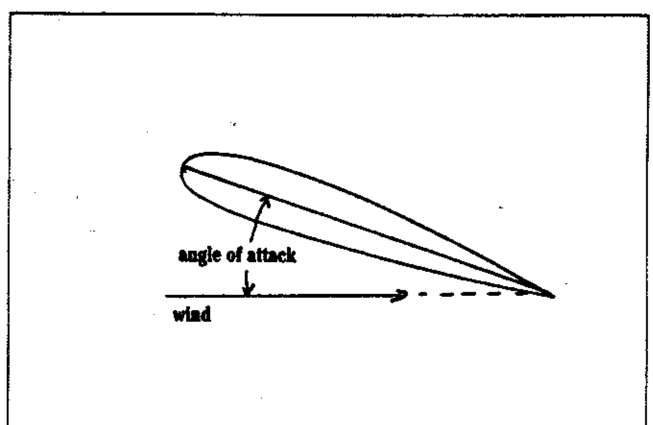
Figure 5.



Angle of attack:

Although it is not strictly speaking part of the geometry of the airfoil itself, the angle of attack is an important geometric parameter in the discussion of airfoils. The angle of attack is the included angle between the free airstream and the chord line of the airfoil. It is positive if the airfoil is nose up relative to the wind and negative if the airfoil is nose down relative to the wind. Angle of attack is represented in equations by the Greek letter alpha α. it is also represented by the abbreviation AOA. Angle of attack is illustrated in Figure 6.

Figure 6.



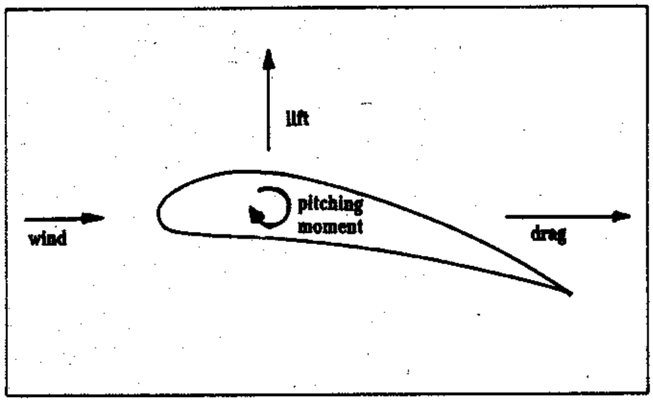
Aerodynamic Forces:

As an airfoil moves through the air, it generates two forces and one moment. It is these forces and this moment that the designer must consider when choosing an airfoil.

Lift:

The first force the airfoil generates is ***lift,*** which is defined as a force acting at right angles to the airstream. It is important to understand that lift acts normal to the airstream and not normal to the wing chord. Lift is the force we want the airfoil to generate to hold the weight of the airplane up against gravity.

Figure 7.



Drag:

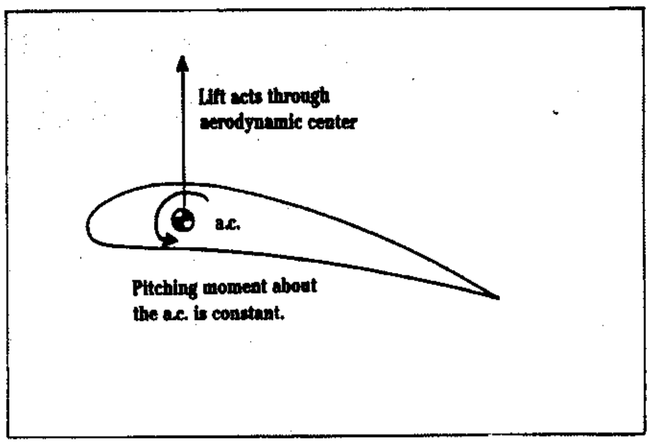
Drag is defined as an aerodynamic force that acts parallel to the airstream. It is a force tending to pull the airfoil downstream. Like lift, drag is defined relative to the airstream direction, not relative to the chord of the airfoil.

Pitching moment.

In addition to producing lift and drag, the airfoil also produces a torque that tends to twist the nose up or down. This torque exists even when the airfoil is at an angle of attack where no lift is produced. Not surprisingly, it is called the zero-lift pitching moment. It is usually represented by MO. Pitching moment can be a very important parameter for the designer to consider because it has a strong impact on the trim drag of the airplane and the structural loads on the wing. See Figure 7.

Aerodynamic Center:

Figure 8.



The ***Aerodynamic center*** is defined as a point on the chord about which the pitching moment does not change with angle of attack. Another way of looking at it is that the aerodynamic center is the point on the chord where the lift acts. The aerodynamic center of an airfoil at subsonic Mach numbers is at or near 25% of the chord. The aerodynamic center does not move as angle of attack changes as long as the airfoil is not stalled. See Figure 8.

There is an older way of keeping track of lift and pitching moment. The lift and pitching moment can be mathematically combined, yielding a lift and a "center of pressure (CP)" on which the lift acts. At first this seems attractive because the zero-lift pitching moment drops out of the equation. In fact, the use of the CP concept is highly misleading. The modern and proper way of considering the lift and pitching moment on an airfoil is to use the concept of the aerodynamic center: The lift always acts at the aerodynamic center and the pitching moment about the aerodynamic center is constant. The zero lift pitching moment is often called the pitching moment about the aerodynamic center (C_{Mac}).

Aerodynamic Coefficients:

Now let's discuss the aerodynamic coefficients: C_L, C_D and C_M.

The forces being generated by an airfoil are dependent on several factors. These include the shape of the airfoil, chord, angle of attack and the airspeed and altitude at which the wing is flying. This large number of variables makes comparing airfoils by looking at physical forces very difficult. For purposes of comparison and calculation, aerodynamicists have developed a system to describe the characteristics of an airfoil strictly in terms of its shape and its angle of attack. The characteristics are put into what is called nondimensional form. That is, a form independent of the physical dimensions of the airfoil is used.

The nondimensional numbers describing the characteristics of the airfoil are called aerodynamic coefficients and there is one for each force and moment. To put the force into nondimensional form, it is necessary to divide it by a quantity proportional to the size of the airfoil and a quantity determined by the speed and altitude.

For size, we use the wing area. Wing area is represented in equations by the letter S.

The quantity determined by speed and altitude is called the "dynamic pressure" and it is a measure of the amount of pressure the airflow can exert on a surface. The dynamic pressure is represented by the letter Q and is defined as follows:

$$Q = 1/2 \times \rho \times V^2$$

V is the airspeed in feet per second.
(To convert miles per hour to feet per second, multiply by 1.47.)

ρ (Greek letter Rho) is the density of the air at the altitude at which the plane is flying. It can be found in a Standard Atmosphere Table and has units of slugs/ cubic foot. (A slug is an English unit of mass.)

To nondimensionalize a force and put it in coefficient form, we divide the force in pounds by the dynamic pressure (Q) and a reference area, in this case the wing area.

Lift:

The lift coefficient is equal to the lift in pounds divided by the wing area and the dynamic pressure.

$$C_L = L/(S \times Q)$$

or

$$CL = L/(S \times 1/2 \times \rho \times V^2)$$

This equation can be rewritten to give the following:

$$L = 1/2 \times \rho \times V^2 \times S \times C_L$$

The equation allows us to calculate lift in pounds if we know the wing area, lift coefficient, airspeed and altitude. It is called the basic lift equation and will prove important in our later discussion of airfoil characteristics.

Drag:

The drag coefficient (C_D) is definedsimilarly to the lift coefficient.

$$C_D = D/(S \times Q)$$

The drag in pounds can be determined from the equation:

$$D = 1/2 \times \rho \times V^2 \times S \times C_D$$

Pitching moment:

The definition of the pitching moment coefficient (C_M) is a little different from the definition of C_L and C_D. A moment has the units of a force times a distance, so it is necessary to divide it by a reference length as well as a reference area and dynamic pressure to nondimensionalize it.

The reference length used is the wing chord (C). Pitching moment coefficient is defined by:

$$C_M = M/(S \times Q \times C)$$

If C_M is positive, the moment is nose up and if it is negative, the moment is nose down. Most airfoils have negative pitching moment about the aerodynamic center.

The pitching moment coefficient of the airfoil is presented in the form of C_M about the aerodynamic center (C_{MAC} or about the quarter chord ($C_{M\ c/4}$).

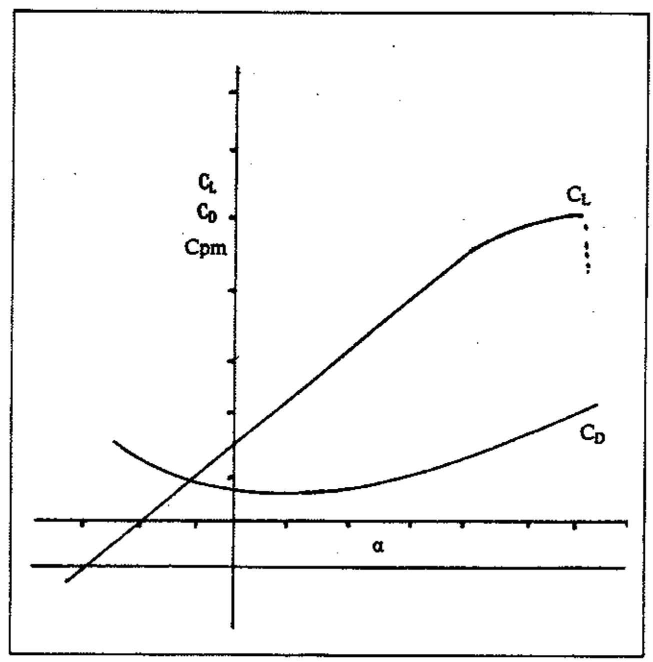
Presenting Data:

When an airfoil is tested in a wind tunnel, its measured characteristics are tabulated in the form of lift, drag and pitching-moment coefficients. This information is usually presented in series of plots that enable the designer to use the data efficiently.

The first type of plot presented is of a coefficient against angle of attack. These are typically shown on one set of axes as in Figure 9. The variation of lift coefficient (C_L), drag coefficient (CD) and pitching moment coefficient (C_M) with angle of attack are all shown in Figure 9. This type of plot is very useful, particularly in determining the stall speed, trim characteristics, and required wing incidence of an airplane.

It is possible to use the C_L vs. AOA and C_D vs. AOA curves to calculate the airplane's performance, but the procedure is awkward. The angle of attack at which an airplane flies is determined by several things and not all of them are related to the airfoil. What the designer can calculate directly is the lift coefficient (C_L at which the airplane is flying at any airspeed and altitude. It is therefore common to plot C_D against C_L. This type of plot has C_D on one axis and C_L on the other and is referred to as the airfoil's drag polar or polar plot. The polar is by far the most useful form of airfoil data for the calculation of airplane performance.

Figure 9.

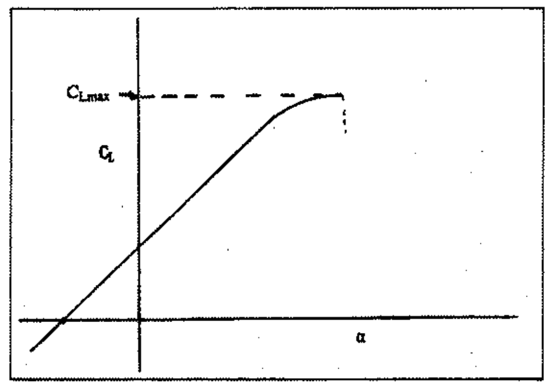


Interpreting the Data:

C_L vs. AOA:

A typical plot of lift coefficient (C_L) vs. angle of attack (α) is shown in Figure 10. Several important things can be learned about the airfoil from reading this curve. The first is the maximum lift coefficient (C_{Lmax} that the airfoil can develop. C_{Lmax} is the lift coefficient at which the airfoil stalls. The higher C_{Lmax} is, the lower will be the stall speed of an airplane using the airfoil. C_{Lmax} can be read off of the C_L -vs.-AOA plot directly as shown in Figure 10.

Figure 10.



A second useful characteristic that can be determined from the C_L vs. AOA plot is the angle of attack at which the airfoil stalls. This is simply the angle of attack at which the airfoil is at its maximum lift coefficient.

The angle of attack at which the airfoil has zero lift is the point at which the curve of C_L vs. AOA intersects the X-axis of the plot.

The lift coefficient at any angle of attack can be read from the C_L vs. AOA plot. This information is particularly important when deciding the incidence angles at which flying surfaces are to be attached to the fuselage.

The lift coefficient vs. angle of attack plot is useful in determining the stall characteristics and incidence angles, but it gives the designer no information about the drag of the airplane and hence is not useful in calculating the performance of the airplane.

C_D vs. AOA:

Drag characteristics of the airfoil are presented in two forms. One of these is a plot of the drag coefficient (C_D) against the angle of attack. This form of data presentation is difficult to use for airplane performance calculations because the angle of attack at which the airplane is flying is a function of some variables that depend on the planform of the airplane as well as its wing loading and airfoil. It is much easier to use the airfoil's drag polar plot to calculate performance.

Drag Polar (C_D vs. C_L):

The polar plot is of C_D vs. C_L as shown in Figure 11. The polar is much easier to use than the C_D vs. AOA plot because it is easy to determine the lift coefficient at which the airplane is flying. From the basic lift equation we have:

$$W = = 1/2 \times \rho \times V^2 \times S \times C_L.$$

Solving for C_L gives:

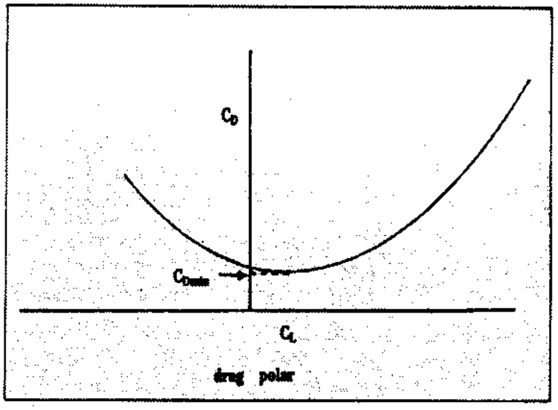
$$C_L = 2 \times W/(C_L \times V^2 \times S)$$

Note: quantities must be in consistent units; V must be in feet per second and W must be in pounds. ρ has units of slugs/cubic foot and can be found in a standard atmosphere table.

To calculate C_L we need to know only the airspeed, the wing loading (W/S) and the density of the air at the desired altitude (ρ).

Once C_L is known the drag coefficient of the wing can be read off of the polar plot directly. Note that the drag read from the airfoil polar is parasite drag only and does not include induced drag. This is because the induced drag is a function of the wing planform and is independent of the choice of airfoil. This will not be a problem in the use of the airfoil polar to select an airfoil.

Figure 11.



The polar can tell us some useful things about the airfoil. In particular, we can determine what the minimum drag coefficient of the airfoil (C_{Dmin}) is, and we can determine at what lift coefficient the airfoil has its minimum drag. This will prove important in the process of selecting an airfoil for an airplane. By using the drag polar, the designer can choose an airfoil that is at or near its minimum drag when the airplane is flying at its cruise speed, This is done by calculating the cruise lift coefficient of the airplane by the process described above and choosing an airfoil that has its minimum drag at this lift coefficient.