Airfoil Selection

By: Bill Husa

Recently there has been a rash of activity relating to the selection or design of wing airfoils. In this article, I will attempt to clarify some of the issues associated with the airfoil selection process, especially as it relates to the general aviation and homebuilt arena. In short, it seems that too much effort is being spent on the selection of sections and that the criteria used are not always realistic or applicable to the small airplane.

About fifteen years ago I had the good fortune to work with a chief aerodynamicist who some years back was the lead for the A-4 Skyhawk program. One day, when I was trying to make a bit more than I should have of selecting an airfoil, he related to me the following story.

During the wing design phase of the Skyhawk development, a junior engineer was assigned the task of designing the airfoil section for the delta planform. After about four weeks of no reports, the lead engineer went to visit the wind tunnel where this individual was working, only to find him almost buried in reams of computer output and hand calculations, as he was trying to tweak the last bit of infinitesimal performance from the wind tunnel model.

Somewhat upset by the engineer's lack of progress and understanding of the problem, the chief engineer replaced the highly optimized model in the tunnel with a piece of one-inch plywood. The wood was cut to the same planform shape as the “optimized” wing and the leading edges were rounded. No other embellishments or refinements were incorporated. The plywood was then instrumented in the same way as the original model and run through the same test scenarios.

The results were enlightening in that all the plywood values were, for all practical purposes, virtually identical to that of the highly optimized model. The exercise was done in order to show the junior engineer (and later myself) that the choice of airfoil in many applications is not all that critical and for the most part is not worth the expense of starting from scratch.

Granted, the example uses a delta planform which is not very sensitive to airfoil shape, but over the years I've found that the same argument holds true for many applications in the general aviation arena, especially for the smaller, light aircraft most commonly encountered in the homebuilt industry. Our company (Orion Technologies) designs aircraft for this sector of the market. We have file folders big enough to choke a mule, stuffed full of various airfoil shapes and design reports, in addition to publications and papers dealing with the subject. Out of all that data how many have we used over the last fifteen years or so? Maybe seven or eight.

Since much has been written about airfoils and their characteristics, I'll try to approach the question of selection from a different, more practical perspective.

First, what does an airfoil do? When built into a wing planform it keeps your airplane airborne, right? Right. Will any practical airfoil do that? Yes. So what's the big deal in selecting one that works for you?

To start with, you must have an idea of what you want your airplane to do, how it should perform, and how it should handle. You should also know how a particular airfoil affects the various aspects of your airplane's design. To help with the process, I have assembled a table, which compares some the more critical characteristics of some of the more common airfoils used for small aircraft. These are the initial values that are needed in order to make a logical selection. The numbers represent the airfoils' two-dimensional values: pitching moment coefficient; maximum lift coefficient (unflapped); and lift-to-drag ratios for three different lift coefficient values.

The first value, pitching moment coefficient about the aerodynamic center (where the value does not vary with the change in angle of attack), is a function of the pressure distribution (camber line) along the chord. In general, you can see that the higher the maximum lift coefficient of the section, the higher its pitching moment. During cruise, the horizontal tail must provide necessary down lift in order to balance the nose down tendency caused by this value therefore, the higher the section pitching moment, the higher the trim drag. Notice that some of the new airfoil shapes (NLF, LS, GAW) developed supposedly for general aviation, have pitching moments almost ten times that of some of the older sections. When examining these shapes, it is important to remember that NASA’s definition of general aviation is a King Air, not a Glasair. These sections were optimized for the higher wing loads encountered on the upper end of the general aviation spectrum.

An additional effect of too much pitching moment is that if the airplane is not designed with a sufficiently large tail, or a tail located adequately aft (sufficiently large tail volume coefficient), the allowable CG envelope may be limited. The forward limit of the CG envelope is determined by the elevator's power to flare the airplane in a landing configuration **<u>in ground effect</u>**. If the trim requirement due to the wing pitching characteristic is high, the forward CG limit may have to be positioned further aft to assure that the elevator has sufficient power to provide flare control at minimum speed during a landing. It is therefore beneficial to select an airfoil with minimal section pitching characteristics.

The next number, the maximum lift coefficient, represents the highest lift that the section can deliver without using flaps. Generally, this is not as important as some make it to be since most airplanes have flaps available for landing.

High lift airfoils are however advantageous on commuter type aircraft, where a higher wing loading provides better cruise performance. This is demonstrated in the last three columns of the table. Most small aircraft fly with a relatively low wing loading thus resulting in a cruise lift coefficient of around .15 to .25. At these values, the lift-to-drag ratios are rather low - in the range of about twelve to twenty (pounds of lift to one pound of drag). Increasing the cruise lift coefficient (designing a smaller wing) to .4 or better, gives the airplane a “l/d” ratio two to four times that as for the same airplane with a lower planform loading.

This was the primary reason for the development of the GAW, the NLF, and the LS series of airfoils. These high lift sections enable larger airplanes to have smaller, high aspect ratio wings. The high maximum lift coefficient enables them to maneuver without the risk of stalling. For example, assuming a smaller wing was installed using an older airfoil: The benefits of high C_l cruise would still be realized but, if the cruise lift coefficient is .4, and the maximum C_L of the wing is 1.0, then, for a given airspeed the aircraft would stall if a maneuver in excess of 2.5 G's was attempted. Using a section with a maximum C_l of 2.0 gives the aircraft a potential maneuver capability of almost 5 G's (minus losses due to three dimensional effects of course).

Due to their high pitching moments, however, these new airfoils were not meant to be used on the smaller, private airplanes.

You can of course install a small wing on your airplane if you want to, but you may run into a few problems such as where do you put the fuel or the landing gear? Assuming the span is about the same as your original wing, the fuel volume will be proportional to the square of the chord, this means that if you put on a smaller, high aspect ratio wing, say one-half the average chord of the original wing, you will end up with one-fourth the fuel volume. Due to this consideration and others (structural and landing speed requirements, for example), smaller aircraft generally have larger wings than considered optimum for cruise. Taking this information and looking at the table, you will notice that for the most part these new airfoils do not have good “l/d” ratios at low wing loads – even an old Clark Y (2412) in many cases has better performance and handling characteristics.

A secondary, but as important, feature of the “l/d” ratio is the airplane’s climb performance. During ascent, the wing is flying at a lower speed and therefore at a higher lift coefficient. The rate of climb is a function of the excess horsepower available so, the lower the drag, the more power is available to gain altitude. Maximizing the “l/d” characteristics of the wing is an important component of this relationship. If you examine the database for the majority of the standard airfoils, you can see that the sections generally have a low drag count for only a small range of lift coefficient values. To maximize climb performance it is preferred that the low drag range or “bucket” (not to be confused with the laminar bucket) extends over the widest possible extent of lift coefficients.

Examining several conventional sections, one can predict how each will behave in a climb situation. Looking at the c_d/c_l plot of the standard Clark Y (2412), we can see that the drag curve flattens out on the bottom and extends over a substantial range of lift coefficient values. The plot is rather flat from c_l values of -.15 to about .5. After this point, the drag curve rises relatively gradually. From a climb performance perspective, this would make the airfoil behave well on lightly loaded wings where the climb lift coefficient would not exceed about .6.

If we examine the 23012 section, it too has a relatively flat drag curve, extending from a c_l value of .13 to just about .8. There is a sharp drag rise below a lift coefficient of .13 but on the opposite end, the curve again rises gradually as on the 2412. This section would therefore be applicable to a wing with a somewhat higher loading than in the previous case.

A more demonstrative example of performance degradation is the rather popular 64-415 section, used on several production aircraft including the Grumman Yankee, the Twin Commanchee, DHC Beaver, and the Barracuda, among others. The low drag characteristics extend only over a narrow range of lift coefficients (.15 to .6). At the extremes of this range, the plot increases sharply, doubling the drag values in only three lift counts (.6 to .9).

Currently, we commonly use the family of sections developed for light aircraft by Harry Riblett. To compare the characteristics of this family of airfoils, we can examine one we used recently, the 35A415. First, the low drag range is relatively extensive, covering lift coefficient values from .05 to nearly 1.0. The drag curve then climbs gradually, rather than increasing in a nearly vertical jump. This results in a very benign performance envelope with little penalty for higher climb attitude lift coefficients. Coupled with good lift characteristics and a gentle stall, this airfoil would be excellent for a variety of airplanes and performance envelopes.

Now a bit more on handling. A number of airfoils get an additional amount of lift by having a cusp located near the trailing edge (rear loaded airfoil). This works well for generating lift but it does two things which are not as desirable; first of all it gives the airfoil a higher pitching moment coefficient; second, it makes control surfaces feel heavy, making the airplane seem somewhat sluggish or heavy-handed. Both things can be fixed but with some penalties.

The most common way to counter the pitching moment is to reflex the flap trailing edge up a few degrees, thus changing the aft loaded characteristics of the section. One problem though, by reflexing the flap you have also reduced the lift (for a constant angle of attack) that section generates. Since the section is still basically the same, the drag level is also the same, so what you have done in the end is created an airfoil with a much lower “l/d”. Furthermore, if you reflexed the flap and not the aileron, you have reduced the lift carried at the root. This action increases the loading at the tip, thus causing an outboard loaded wing, which may be more susceptible to tip stall.

The second fix that is often used is to fill in the cusp. This does a good job of reducing control forces but, as mentioned in the previous paragraph, it also reduces the lift generated for a given angle of attack. The bottom line is, if you have to modify the section (or wing) geometry in order to make the airplane fly right, you have chosen the wrong airfoil. On the other hand however, if you already have the airfoil set and tooled, it is cheaper to make these quick fixes than to retool for a different section. At that point however, don't complain if the airplane does not perform as well as you expect.

Now a bit about laminar airfoils. Contrary to some opinions, laminar airfoils are good sections, applicable to many classes of airplanes. The idea that a laminar section stops flying when it is wet or contaminated with bugs is false. All the contamination does is trip the boundary layer from laminar to turbulent a little earlier along the chord than normal. This results in a small increase in drag and a slight change in the center of pressure position.

In canard aircraft this change of center of pressure position causes increased stick forces, sometimes to the point where the pilot has a hard time pulling back hard enough to keep the nose up. The airfoil however does not stop flying; it's just that the control system has insufficient lever authority to counteract this shift of pressure.

As far as performance is concerned, a dirty laminar section will generally have a lower drag count than a turbulent airfoil with the same amount of contamination. In the case of published data, the numbers for contaminated airfoils (standard roughness) are not realistic to the operation of most small aircraft, unless of course you plan on flying through a swarm of locusts. The roughing medium used for the wind tunnel analysis is equivalent to about forty grit sandpaper, far from what most private airplanes see in actual service.

So, after all this what do I recommend? For most low speed applications, say, less than 130 mph, you probably do not need anything fancier than the good old standbys, the 2412, the 4412, even the 23012 if you can tolerate a somewhat sharper stall. All are very predictable sections and due to their large leading edge radii, work very well with most flap configurations. If you need more thickness for structural reasons or fuel capacity, you can use the 15% versions, maybe even 18% at the root. Twelve to fifteen percent thick sections will yield the highest “l/d” values for wing loading up to about 20 psf; 18%, however, is still O.K. and gives you a lighter structure along with more fuel capacity.
Above 130 mph, I start looking at the laminar sections. My favorite has been the 747A315, which I have used with great success on several configurations. Although it does not have a high unflapped C_l, it does have a very low pitching moment, good stall characteristics, and some of the lowest drag numbers in the table. It also doesn't seem to have the leading edge separation tendencies of the more classical laminar sections like the 63- to 66- series.

For application of laminar sections, I would recommend picking up a copy of Harry Riblett's publication "GA Airfoils". In it is a good write-up on the history and characteristics of the sections and some excellent suggestions for modification, which make the shapes more suitable for general aviation applications. Today, we tend to use these sections more than any others in our work.

If you plan to go over about 350 mph, careful consideration has to be given to the wing design and airfoil selection process. At these speeds, compressibility becomes a factor, the best examples of which were the effects encountered by the P-38 in WW-II. As the airplane picked up speed (in a dive), the relative airflow over the wing approached the speed of sound, at which point the center of pressure shifted aft (at subsonic speeds the center of pressure is around the quarter chord; supersonically it is at about the 50% chord). This rearward C_p motion increased the nose down pitching moment while at the same time increasing the control forces required to deflect the surfaces. If the pilot did not correct the situation quick enough, the effect built on itself, well past the point of pilot controllability. Eventually this “tuck under” problem was fixed with dive brakes, but not before a number of pilots lost their lives.

Designing a wing for this flight envelope requires careful consideration of the airfoil, the wing shape and the effect of the fuselage on the wing airflow, all beyond the scope of this article. If you are developing an aircraft that will operate at these speeds, you will have to consult with someone who is well versed in this arena of flight.

Airfoil Section Characteristics
Two dimensional properties only
Reynold’s Number = 6,000,000
Lift coefficient values for l/d characteristics: .1, .4, .6

Airfoil Shape	Drag Coefficient Values			Max. $C_{m.ac}$	L/d @ C_l = .1	L/d @ C_l = .4	L/d @ C_l = .6	Max. Section C_l
	C_l = .1	C_l = .4	C_l = .6					
0009	.0057	.0060	.0068	0.0	17.54	66.67	88.23	1.32
0010-34	.0043	.0065	.0076	0.0	23.26	61.53	78.94	.75
0012	.0058	.0066	.0076	0.0	17.24	60.61	78.94	1.59
1412	.0058	.0060	.0068	-.025	17.24	66.67	88.23	1.57
2412	.0065	.0061	.0071	-.04	15.38	65.57	84.50	1.69
4412	.0064	.0063	.0062	-.09	15.63	63.49	96.77	1.64
23012	.0061	.0063	.0065	-.013	16.39	63.49	92.31	1.76
63-212	.0045	.0045	.0063	-.035	22.22	88.89	95.24	1.58
63-412	.0056	.0048	.0052	-.075	17.85	83.33	115.38	1.73
63-415	.0052	.0052	.0055	-.07	19.23	76.92	109.09	1.64
64-412	.0059	.0046	.0051	-.073	16.94	86.96	117.64	1.67
64-415	.0052	.0050	.0051	-.07	19.23	80.00	117.64	1.60
64A212	.0046	.0045	.0072	-.04	21.74	88.89	83.33	1.50
64A215	.0045	.0048	.0071	-.037	22.22	83.33	84.50	1.50
65-212	.0040	.0051	.0072	-.035	25.0	78.43	83.33	1.46
65-412	.0055	.0042	.0053	-.07	18.18	95.23	113.21	1.61
65-415	.0046	.0042	.0045	-.068	21.74	95.23	133.33	1.58
66-212	.0033	.0056	.0076	-.03	30.30	71.43	78.94	1.45
66-415	.0057	.0039	.0042	-.074	17.54	102.56	142.85	1.57
747A315	.0050	.0044	.0048	-.012	20.00	90.90	125.00	1.36
747A415	.0063	.0044	.0048	-.03	15.87	90.90	125.00	1.42
GAW-2	.0072	.0055	.0070	-.10	13.89	72.73	85.71	2.04
NLF(1)-0215F	.0074	.0064	.0046	-.13	13.51	62.50	130.40	1.72
NLF(1)-0416	.0063	.0058	.0053	-.10	15.87	68.96	113.21	1.87
LS(1)-0413	.0085	.0080	.0080	-.11	11.76	50.00	75.00	2.07

GA(PC)-1	.0073	.0073	.0072	-.045	13.70	54.79	83.33	1.80
The following are a sample of Harry Riblett's sections for general aviation								
GA30-312	.0060	.0060	.0070	-.055	16.67	66.67	85.71	1.59
GA30-315	.0065	.0070	.0075	-.055	15.38	57.14	80.00	1.67
GA30-412	.0065	.0065	.0070	-.07	15.38	61.53	85.71	1.70
GA30-415	.0070	.0070	.0075	-.07	14.28	57.14	80.00	1.80
GA35-312	.0060	.0055	.0060	-.055	16.67	72.72	100.00	1.58
GA35-315	.0060	.0060	.0065	-.055	16.67	66.67	92.30	1.70
GA35-412	.0070	.0055	.0060	-.072	14.28	72.72	100.00	1.65
GA35-415	.0060	.0060	.0065	-.073	16.67	66.67	92.30	1.82
GA37-312	.0060	.0055	.0055	-.06	16.67	72.72	109.09	1.54
GA37-315	.0055	.0055	.0055	-.06	18.18	72.72	109.09	1.68
GA37-412	.0070	.0052	.0055	-.072	14.28	76.92	109.09	1.61
GA37-415	.0065	.0058	.0058	-.072	15.38	68.96	103.44	1.78

The accompanying table format provides probably the clearest comparison of the listed airfoils. Looking at the numbers we can quickly examine the values and trends, and determine which section would be best for an anticipated flight envelope. The chart can also be used to establish performance comparisons between aircraft.

About ten years ago, when the kit of the Questair Venture was becoming popular, Stoddard-Hamilton (Glasair) was desperately trying to figure out why the Questair configuration was so much more efficient than their Glasair III. It was not uncommon for the new aircraft to easily outdistance the Glasair, on substantially less horsepower. In an industry where an extra mile per hour can result in bragging rights and a few extra sales, this difference in performance was hurting some of the company's projected sales figures.

Looking at the published performance and geometry figures for both aircraft (Jane's 1993 – 1994) and extrapolating, where necessary to get the sea level values, we can determine the lift coefficients for each of the aircrafts' cruise condition. For the Questair Venture this yields a value of .208. If we look at the above table (the Questair use a 23015 at the root and a 23010 at the tip) and approximate the performance with the 23012 section, we see that the "l/d" comes to 33.55.

For the Glasair, the same calculation yields a cruise lift coefficient value of .13. The aircraft used the LS(1)-0413 section so for the same flight condition, its wing generates an "l/d" value of 16.56, or less than half of the Venture. To compound the problem, to counter the heavy stick forces of the selected airfoil, early in the development the company filled in the trailing edge cusp, thus decreasing the lift performance further. In short, this was a terrible selection on the part of the original designer.

Please note: the above example is a simplification. For calculating the effects of a new design one must examine the three dimensional characteristics of the wing in question, converting the applicable data to account for the finite wing geometry. Two-dimensional data is rarely accurate for an actual wing. The example was given only for discussion purposes.

In short, the selection of the right airfoil is important and depends on the part of the flight envelope the designer wishes to enhance. Almost anything will fly, given sufficient power, stability and luck. The trick is to make it fly well. Airfoil selection is an important part of this process but there is nothing magic about it, nor does it need to be expensive. Call around, some designers might even be able to give you ideas for candidate sections for free. Good luck.