AIRCRAFT DESIGN MADE EASY

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The following article, which is a first installement of a two-part article, describes a simple method for the preliminary design of an airplane of conventional configuration. This method will allow you to design an aircraft relatively easily with just a few sheets of paper, a pencil (and an eraser to make corrections!), plus a $10 calculator. No need for a computer, web link, or spreadsheets. The example chosen would fit into the proposed Light-Sport Aircraft category as defined in the FAA's proposed Sport Pilot / Light-Sport Aircraft category.

Basic Choices and Weights

This airplane is intended to carry two occupants (a pilot and one passenger) and the fuel required to keep the engine running at least the length of time we want to enjoy flying. The weight of each occupant is estimated at 190 pounds, and the fuel consumption at a rate of 6 gallons per hour (gph) per 100 hp installed.
Fuel weighs approximately 6 pounds per gallon, so 6 gallons of fuel will weigh 36 pounds, thus we'll need 36 pounds of fuel per hour endurance for 100 bhp. A practical airplane needs two to four hours' endurance, so let's choose three hours as our goal.
If the engine has 80 bhp, similar to the Rotax or Jabiru 2200, the weight of fuel required for three hours endurance will be:

3 (hours) x 36 (pounds) x .8 (bhp) = 86 pounds.

If the engine has 100 bhp, like the Rotax 912S or Jabiru 3300, the weight of fuel required for three hours endurance will be:

3 x 36 x 1 = 108 pounds.

Our two-seat airplane, equipped with a 100 bhp engine and 18 gallons of fuel (three hours endurance) will need a useful load of

$W_u = 2 \times 190 + 108 = 490$ pounds (488 to be exact).

If we want to carry baggage or if the weight of the occupants is heavier than 190 pounds (which is typical today because of the junk food we eat and the little physical exercise we practice), then we'll have to adjust W_u to what is required.

And, here's a warning about our engine selection. Never design a new airplane to be equipped with a new, unknown engine. You simply double the potential problems (we learned this from experience), and your fantastic design may become a failure because of an unreliable engine... or vice versa!
It's also important to carefully check the powerplant's weight, including engine, exhaust, coolers, coolant, oil, reduction unit, propeller, and other accessories. Is this weight within acceptable limits of today's technology -- that is, less than two pounds per hp? Also check the fuel consumption: Does it fit with our assumptions above?

Empty Weight (W_e)
Next we have to estimate the empty weight of our new airplane. We do this by choosing one of the columns in the following table.

	1	2	3	4	5	6
W_e/W_u	.8	1.0	1.2	1.4	1.7	2.0
W/W_u	1.8	2.0	2.2	2.4	2.7	3.0
W_e/W	.444	.500	.545	.583	.642	.667

– Column 1 is for a very basic airplane with a very good design.
– Column 2 or 3 equates with a simple airplane and a good design.
– Column 4 equates to a classic airplane, simple to build and with adequate strength.
– Column 5 or 6 equates to either a single-seat aircraft or a very strong (aerobatic?) airplane with heavy equipment and fairings. The design is compromised somewhat for ease of manufacturing.

Yes, this is a wide range of aircraft options! Let us not overestimate our design capability, especially if this is our first attempt at designing an airplane. Unless we are geniuses, most likely our airplane will end up heavier than anticipated. So, let's be humble when determining the maximum weight:

$$W = W_e + W_u = W_u\left[1 + {}^{W_e}\!/_{W_u}\right]$$

Choosing to be a modest designer, we pick column 4 as our guide to obtain our maximum weight:

$$W = 490\ (1 + 1.4) = 1{,}176 \text{ pounds}$$

This allows us an error of 1,232 pounds (the proposed weight for a Light-Sport Aircraft) minus 1,176 pounds, leaving us 56 pounds of "room for error," that is, being heavier than planned.
We could increase the useful load by 20 pounds to 510 pounds:

$$W_u = 490 + 20 = 510 \text{ pounds}$$

Then,

$$W = 510\ (1 + 1.4) = 1{,}224 \text{ pounds maximum weight}$$

That's pretty close to the proposed 1,232 pounds for a Light-Sport Aircraft.

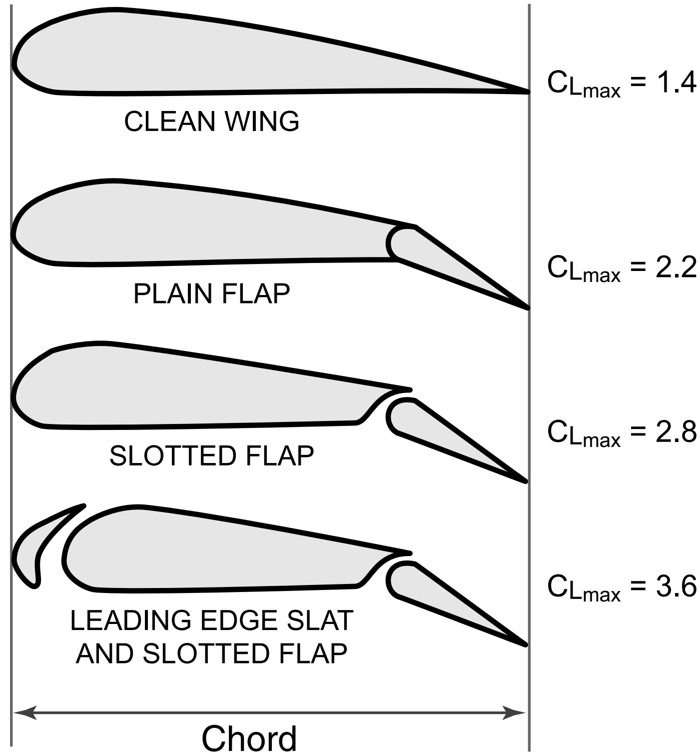
Landing Speeds and Wing Area

Having selected the weights, we now have to select the maximum stall speeds. The proposed Light-Sport Aircraft category prescribes these as:

V_{SO} = 39 knots = 45 mph (flaps down)
V_S = 44 knots = 50 mph (clean configuration)

At these speeds, the airplane will be easy and relatively safe to land, which is one of the purposes of creating the Light-Sport Aircraft category.
If you are interested in designing an experimental category aircraft that exceeds the performance parameters of a Light-Sport Aircraft.. .and you are a good pilot.. .you could go up to a V_{SO} of 60 mph. But, be aware that above this speed, the energy generated becomes so large that there is very little chance of survival in the case of a landing accident.
Next, we have to know the airplane's maximum lift coefficient (C_L) for both configurations -- flaps down and flaps up (clean). The lift coefficient will depend on the wing planform, Reynolds number, airfoil roughness, and center of gravity (CG) position.

Without going into complicated theories (and then finding out that practically built wings may have lift coefficients quite different than from the theory) we make a reasonably good estimate with the following configuration of wing sections with full-span flaps:



For a simple design, we choose a simple, plain flap, and we do not forget that the flap portion of the wing is only about one-half of the wingspan (the ailerons occupy the outboard one-half span approximately).

$$C_{L\text{flaps down}} = 1/2\ C_{L\text{no flaps}} + 1/2\ C_{L\text{with flaps}}$$
$$= [1.4/2] + [2.2/2] = .7 + 1.1 = \mathbf{1.8}$$

and

$$C_{L\text{clean}} = 1.4$$

With these values we find the required *wing area* (ρ) to meet the selected stall speed requirements:

$$W = \rho \times q \times C_{Lmax}$$
$$\text{where } q = \frac{\rho V^2}{2} = \frac{V^2}{19.77} = \frac{V^2}{391}$$

(q is in PSF, pounds per square foot, when V is in mph)

Or $\rho = \dfrac{W}{qC_{Lmax}}$ and for

V= 50 mph $\qquad q = \dfrac{50^2}{391} = 6.4$ psf

$$\rho = \frac{1{,}232}{6.4 \times 1.4} = 137 \text{ feet}^2 \text{ (clean airplane)}$$

$$V = 45 \text{ mph} \qquad q = \frac{45^2}{391} = 5.18 \text{ psf}$$

$$\rho = \frac{1{,}232}{5.8 \times 1.8} = 132 \text{ feet}^2 \text{ (clean airplane)}$$

If our design has to fit in the Light-Sport Aircraft category, our wing area must be 137 square feet. Again, we have to make choices:

– High or low wing?
– Tricycle or taildragger gear?
– Tractor or pusher configuration?
– Open or enclosed cockpit?
– Your imagination is the limit!

Keep in mind that unless you are designing this wonderful new airplane just for yourself, it needs to be rather conventional if you want to sell it to the flying community, which tends to be very conservative. This means that a potential customer will simply walk away from your fantastic airplane shaking his head because unconsciously he is afraid of new things, new concepts, even changes from the usual. Fear arises when we meet the unknown and don't have enough inner security.

Performance

To estimate the maximum level full-throttle speed of our aircraft, we simply calculate:

$$V_H = 160 \sqrt[3]{\frac{bhp}{\rho + 100}}$$ for a comfortable, wide side-by-side two-seater

$$= 160 \sqrt[3]{\frac{100}{137 + 100}}$$ = 120 mph for the above example

Or,

$$V_H = 180 \sqrt[3]{\frac{bhp}{\rho + 100}}$$ for an average design

$$= 180 \sqrt[3]{.422}$$ = 135 mph in our example

Or,

$$V_H = 200 \sqrt[3]{\frac{bhp}{\rho + 100}}$$ for a very clean design

$$= 200 \times .75 = 150 \text{ mph}$$

Because the proposed light-sport aircraft category limits the maximum level flight speed to 115 knots, or 132 mph, we will be quite happy with the "average design."

The usual 75 percent power setting cruise speed at sea level will be:

$$.9 \times V_H = .9 \times 132 = 119 \text{ mph}$$

The cruise speed will increase to

$$.9\, V_H = 125 \text{ mph}$$

at 7,000 or 8,000 feet where we will have 75 percent power at full throttle. Above this altitude the cruise speed will decrease (unless we have a turbo charger!), and we will fly very close to the indicated stall speed when we reach the airplane's ceiling.

Calculating Takeoff and Landing Performance

A simple way of estimating whether our airplane will have good takeoff and climb performance is to calculate the wing loading (W/S) and power loading (W/bhp) and multiply:

$$\frac{W}{\rho} \times \frac{W}{bhp} = P$$

if P is smaller than 200 $\frac{\text{pounds}^2}{\text{ft}^2 \text{ bhp}}$

The above performance parameters outlined for weight and speed are acceptable. The smaller "p" is, the better the takeoff and climb will be.

In our example:

$$P = \frac{W}{\rho} \times \frac{W}{bhp} = \frac{1232}{137} = 9 \times 123 = 110$$

This airplane will take off like a charm!

We can easily estimate the rate of climb (V_Z):

$$V_Z = \frac{7000}{W/bhp} \times \sqrt[4]{AR}$$ in fpm when W is in pounds.

With $AR = \frac{b^2}{\rho}$ = the aspect ratio of our wing

If we choose b = 30 feet in our example

$$AR = \frac{b^2}{\rho} = \frac{30^2}{137} = 6.57$$

Which gives us a mean aerodynamic chord (MAC):

$$MAC = \frac{\rho}{b} = \frac{137}{30} = 4.56 \text{ feet}$$

$$\text{And } V_Z = \frac{7000}{1232/100} \times \sqrt[4]{6.57} = 910 \text{ fpm (approx.)}$$

The service ceiling will be close to:

$$Z_{max} = 16 \times V_Z = 16 \times 910 = 14{,}000 \text{ feet}$$

(approximately) for our example.

Note: It is quite informative and worthwhile for our education to vary the BHP of our engine in the above calculations and then compare V_H, V_Z, and Z_{max}. We may then decide to reduce the installed power and save some weight (fuel, empty airplane, and maximum weight)! That's part of the never-ending process of compromising when designing an aircraft.

Helpful Hint: To calculate the cubic root with an inexpensive calculator having only the square root function, we can interpolate from the following table:

a	=	.2	.25	.3	.35	.4	.45	.5
$\sqrt[3]{a}$	=	.58	.63	.67	.70	.74	.77	.79

This concludes this first installment in designing our own airplane. In the next installment we'll continue looking at controllability and stability and yaw and roll.

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