Effect of Weight on Drag and Airplane Performance
12/24/09

In flying RC models, weight is not your friend. Given two planes with identical airframes, engines, and props (the only difference being one is heavier than the other), the light one always seems to fly better. The heavy one is harder to take off, more difficult to land, and can be very "mushy" in the air. The basic reason for this is that weight causes drag which can affect performance in all flight regimes.

The type of drag resulting from weight is called induced drag. Unlike normal drag that intuitively is a resistive force due to the friction of the air moving over the airframe surfaces, induced drag is produced in the act of generating lift.

This article discusses the basic aerodynamic forces acting on an airplane in flight with an emphasis on drag. Some basic drag equations will be presented and some numbers "crunched" for those readers who need a more quantitative description of induced drag. For all the others, don't get hung up in the math. Try to understand the concepts.

Basic Aerodynamics:

There are 4 basic forces acting on an airplane in flight:

Drag (D): This is a generic term used to describe the resistance to the motion of a plane flying through the air. Although there are many different types of drag acting on an airplane, they fall into two basic types: Parasitic Drag (D_p) and Induced Drag (D_i). Parasitic drag is a resistive force produced by friction and pressure forces acting on airframe surfaces. Induced drag is a resistive force produced during the generation of lift by the wing. Total Drag (D_T) is simply the sum of parasitic drag and induced drag.

Thrust (T): This is the force produced by the engine to overcome the total drag forces acting on the airframe.

Weight (W): This is the total flying weight of the plane.

Lift (L): This is the lifting force produced by the wing. In simple terms, a wing is shaped such that the velocity of the air over the top surface is greater than that on the bottom surface. This causes the pressure on the top surface to be less than that on the bottom surface. This small pressure difference acting over the entire wing area produces an upward force large enough to defy gravity and keep the plane in the air.

For any plane in straight and level flight at some speed V, whether they are models or the real thing, $T = D$ and $L = W$. If T is greater than D, the plane will accelerate until the drag force matches the thrust force produced by the engine; if T is less than D the plane will slow down until the drag force equals the thrust produced. If L is greater than W, the plane will climb; if L is less than W, the plane will descend.

Parasitic Drag:

Parasitic drag is the resistive force produced by friction and pressure forces acting on an airframe and can be expressed as follows:

$$D_p = K_1 V^2$$

Where: D_p is the parasitic drag
K_1 is a constant for a given airframe
V is the velocity of the airframe through the air

From this relationship, you can see that parasitic drag is strongly affected by the speed of the plane. If you double the speed of the plane, parasitic drag increases by a factor of 4.

Induced Drag:

Induced drag is the resistive force acting on an airframe as a direct result of generating lift. The best way to understand the concept of induced drag is to picture a wing of finite length hanging out in the air with the air travelling over the surfaces. The pressure on the bottom surface is greater than the pressure on the top surface resulting in lift. The same pressure difference that causes lift causes air to spill over the wing tip from the bottom of the wing to the top. Wing tip vortices are formed. Their impact on the wing (a general downward flow of air) is greatest at the tips, but their effect is felt over the entire span of the wing. The downward flow of air on the wing surface (downwash) has a component of flow opposite the direction of flight of the plane that causes a resistive force to the forward motion of the plane.

Induced drag is a strange, non-intuitive force:

1. Unlike parasitic drag that increases with increased speed of the plane, induced drag increases as the speed of the plane decreases. It is much larger than parasitic drag at low speeds. This can be a serious consideration when you're trying to take off or land a plane with marginal power.
2. Induced drag is significantly affected by wing geometry. Long narrow wings produce a smaller induced drag force. Gliders have long narrow wings to minimize the significant induced drag force produced at the slow speeds they fly at. (See 1. above.)
3. Induced drag is affected by air density, but not in a way you expect. It becomes greater at <u>lower</u> densities. This means that planes designed to fly at high altitudes must consider high induced drag forces in their design. If you look at the wings of a U2 spy plane or a B-52 bomber, you will see long narrow wings to minimize the large induced drag forces that can be generated at their operating altitudes.
4. Induced drag is significantly greater with increasing weight. Where parasitic drag is proportional to velocity squared, induced drag is proportional to the weight of the plane squared.

In general terms, the induced drag acting on an airframe can be expressed as follows:

$$D_i = K_2W^2/d(AR)V^2$$

Where: D_I is the induced drag
K_2 is a constant for a given airframe
W is the flying weight of the plane
d is the air density
AR is the aspect ratio of the wing (how long/narrow)
V is the speed of the plane

Total Drag:

Total drag is just the sum of parasitic drag and induced drag. The total drag on an airframe can be expressed as follows:

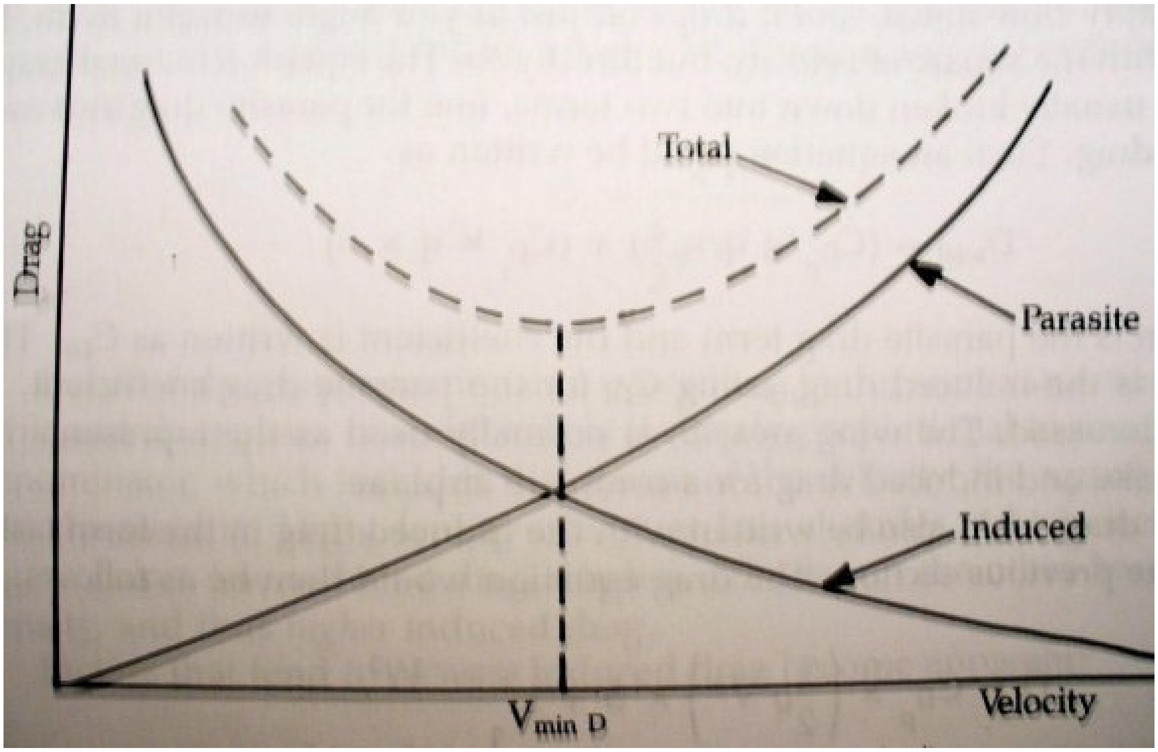
$$D_T = K_1V^2 + K_2W^2/d(AR)V^2$$

For a given plane flying at a given altitude, this equation can be simplified to the following:

$$D_T = K_1V^2 + K_3W^2/V^2$$

Typical Drag Curves for an Airframe:

The last equation for total drag is hard to use in evaluating drag forces on our models. However, if you look at a typical plot of parasitic, induced and total drag versus velocity, using a few assumptions, there are many useful things you can learn about how weight affects model performance. Shown below is such a typical plot.



Some things to note about the curves presented above:

1. Note how fast induced drag increases with reduced velocity and how fast parasitic drag increases with increased velocity.
2. Total drag, being the sum of parasitic and induced drag, is shown as the dashed curve. Note that total drag is a minimum where parasitic drag equals induced drag. The velocity where minimum drag occurs is $V_{min\ d}$. Any velocity other than $V_{min\ d}$ will result in a higher drag on the airplane. For maximum endurance and optimum fuel use flying at $V_{min\ d}$ is the right thing to do.
3. For velocities less than $V_{min\ d,}$ induced drag governs and behaves as expected. High drags can result at low velocities in this region.
4. For velocities greater than $V_{min\ d}$, parasitic drag governs and behaves as expected. The greater the speed of the plane, the greater the drag force produced. Max speed attainable in the plane would be dependent on the size of the engine and its ability to overcome drag forces.

Weight/Drag Analysis for a Typical Model:

Using the above drag curves with some simplifying assumptions, you can do some useful performance evaluations for the types of models we fly in RC.

Let's say we have two identical .60 size airplanes. The only difference in the two is that one weighs 7 pounds and the other weighs 8 pounds. Note that this is a difference in weight of 14%. Let's see if some conclusions can be drawn on plane performance for straight and level flight, takeoffs and landings using the typical drag curves shown above.

<u>Straight and Level Flight</u>: Assume that both planes are flying at $V_{\text{min d}}$. How much greater will induced and total drag be for the heavier plane?

Using the equation for induced drag, you can get the ratio of induced drag for the two planes:

$$D_{i8}/D_{i7} = W^2 \text{ Heavy plane}/W^2 \text{ Light plane}$$

Where: D_{i8} is the induced drag of the 8 pound plane
D_{i7} is the induced drag of the 7 pound plane

The ratio of drags for our 2 planes is therefore 64/49 or 1.30. In other words, the induced drag on the 8 pound plane is 30% higher than the 7 pound plane.

Since at $V_{\text{min d}}$, parasitic drag equals induced drag, total drag will equal 2 times the induced drag and the total drag for the 8 pound plane will also be 30% greater than for the 7 pound plane.

Because thrust is equal to total drag in straight and level flight, the only way both planes can be flying at the same speed is if either the 7 pound plane is flying at part throttle or the 8 pound plane has a bigger engine.

<u>Takeoff Performance</u>: During the takeoff roll, both the 7 pound plane and the 8 pound plane will be travelling at speeds less than $V_{\text{min d}}$. In this region of the drag curve, parasitic drag is small, induced drag is very large, and a large part of total drag is composed of induced drag. Induced drag and total drag can be very much larger than minimum drag in this region of the drag curve so we know that total drag for the 8 pound plane during takeoff will be at least 30% greater than the total drag for the 7 pound plane. Assuming both the 7 pound plane

and the 8 pound plane have the same size engine, the 8 pound plane will dissipate more of its power to induced drag and less power will be available to accelerate the plane to takeoff speed. As a result, the takeoff roll of the 8 pound plane will be longer and may need to be "horsed" into the air if it's able to get airborne at all. A larger engine may be needed to get the same takeoff performance as the 7 pound plane.

Landing Performance: During the landing approach just prior to touchdown, both the 7 pound plane and the 8 pound plane will be travelling at speeds less than $V_{\text{min d}}$. In this region of the drag curve, parasitic drag is small, induced drag is very large, and a large part of total drag is composed of induced drag. Induced drag and total drag can be very much larger than minimum drag in this region of the drag curve so we know that total drag for the 8 pound plane during the landing approach will be at least 30% greater than the total drag for the 7 pound plane.

For the 8 pound plane, unless the throttle is increased during landing approach to provide additional thrust to compensate for the 30% increase in induced drag, the speed of the 8 pound plane will dissipate more rapidly than the 7 pound plane. The 8 pound plane will tend to land like a brick compared to the 7 pound plane. Landing of the 8 pound plane will require flying the plane to the ground as a result.

Conclusions:

Weight has a major impact on RC plane performance in all flight regimes. Small increases in weight significantly impact drag which may or may not be compensated for by the power available from the engine. Flying a heavier model will be more difficult and may result in increased damage to the airframe. The bottom line is if you are building a new plane do everything possible to minimize weight. This includes using light density wood, minimizing glue where possible, and finishing the model with materials having the lightest possible weight. When balancing the plane, shift internal components where possible to eliminate unnecessary balance weight.

May the Force (drag) be with you!
Steve Grabowski