Parasite Drag

by David F. Rogers
http://www.nar-associates.com

How many of you still have a Grimes rotating beacon on both the top and bottom of the fuselage? If you don't have a Grimes beacon, then it probably has been replaced by a similar beacon. Have you ever wondered how much drag those beacons generate and by how much they reduce your speed? I did and conducted some wind tunnel tests to find out. Let me share the results with you. They are rather interesting and show that, as always, details count.

Some background

First, recall that a subsonic aircraft experiences two types of drag, parasite drag and induced drag, also called drag due to lift. The Grimes beacon generates parasite drag.

All parasite drag is the result of viscosity. Vicosity is the stickiness of a fluid, e.g., maple syrup is stickier, and more viscous, than water which is stickier, and more viscous, than air. Parasite drag results from either skin friction drag or pressure drag. Skin friction drag results from the friction generated by the molecules of air as they move over the surface of a body. Pressure drag results when the molecules of air separate from the surface of a body and create a turbulent wake. The pressure in the turbulent wake at the rear of a body is lower than the pressure at the front of a body. The result is a net force in the direction of the flow, i.e., pressure drag.

Basically, there are two types of aerodynamic bodies, streamline bodies, e.g., airfoils, and blunt or bluff bodies, e.g., a sphere or a Grimes beacon. Streamline bodies aligned with the airflow experience mostly skin friction drag. They have small turbulent wakes and thus little pressure drag. Blunt bodies experience mostly pressure drag. They have large turbulent wakes over the rear portions of the body. The larger the wake the larger the pressure drag. Blunt bodies also experience skin friction drag on the forward portions of the body, but the amount of skin friction drag is small compared to the pressure drag. To reduce the total drag on a blunt body, the size of the turbulent wake must be reduced.

A turbulent wake is caused by separation of the boundary layer from the body. The boundary layer is that very very thin, but very important, viscous layer of air right next

Figure 1. Grimes beacon mounted in the wind tunnel. The yarn tufts show the turbulent wake. Notice the tuft on the tunnel floor behind the beacon.

to the surface of the body. In this thin boundary layer, the air velocity increases from zero at the surface to the free stream velocity, i.e., flight velocity, at the boundary layer edge. At typical cruise flight conditions enjoyed by a Bonanza the boundary layer thickness is significantly less than 0.1 in. Hence, the velocity changes very rapidly through the boundary layer.

There are two types of boundary layers—laminar and turbulent. Laminar boundary layers are rather delicate. Almost any small imperfection in the body surface, e.g., bugs or a little bit of surface roughness, will cause transition to a turbulent boundary layer. Furthermore, laminar boundary layers are very sensitive to increases in pressure in the flow direction. Even small pressure increases cause the laminar boundary layer to separate from the surface. The result is a turbulent wake. Here, note that a turbulent boundary layer is quite a different phenomena from a turbulent wake. In a turbulent boundary layer any turbulence is very small scale, i.e., microscopic in scale. In a turbulent wake the turbulence is large scale, i.e., macroscopic in scale. The turbulence in a turbulent wake can be seen with something as simple as a tuft of yarn taped to the body, as shown on the Grimes beacon in Figure 1. The turbulence in a boundary layer cannot be seen without the use of special instrumentation.

On a nominally cylindrical or spherical body, i.e., a blunt body, such as the Grimes beacon, the maximum velocity, and the lowest pressure, in the flow around the body occurs at the shoulder point, 90° from the upstream flow direction. Downstream of the shoulder point the pressure begins to increase. A laminar boundary layer is unable to handle even a small amount of this increasing pressure. As a result, the flow separates from the body just behind the shoulder point and forms a large wide turbulent wake (see Figure 2a). This large wide turbulent wake results in a large amount of pressure drag. On the other hand, a turbulent boundary layer is able to handle a larger amount of the increasing pressure on the rear of the body before it separates from the body. Consequently, a smaller turbulent wake is formed resulting in lower pressure drag (see Figure 2b). Thus, to decrease the overall pressure drag on a blunt body it is desirable for the boundary layer to transition from an initial laminar boundary layer to a turbulent boundary layer *before* the shoulder point. The exact same principle is used to make golf balls fly further—the dimples force an early transition to a turbulent boundary layer.

The natural transition of a laminar boundary layer to a turbulent boundary layer is governed by a parameter called the Reynolds number. The Reynolds number is usually

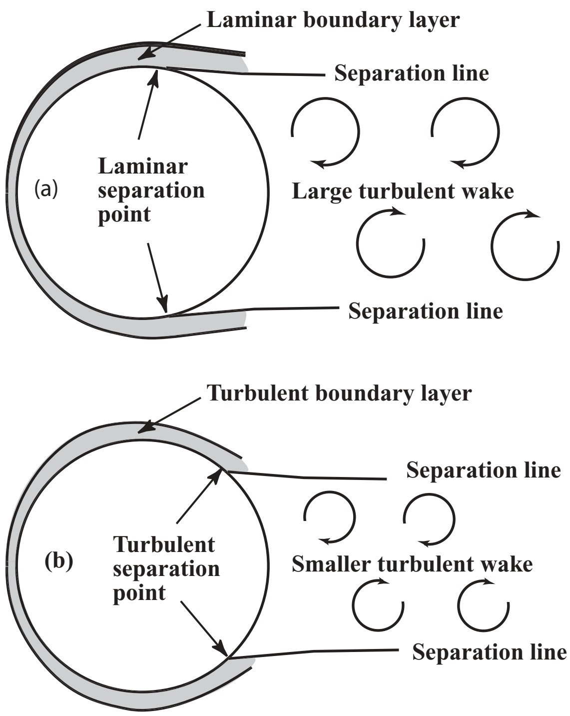

Figure 2. Figure 2. Laminar and turbulent boundary layer separation on a blunt body.

characterized as the ratio of the inertia forces to viscous forces. Simplistically, here, inertia forces equate to pressure forces. The Reynolds number is given by

$$\text{Reynolds number } Re = \frac{\rho V \ell}{\mu} = KV$$

where ρ is the density, V is the velocity, ℓ is some length characteristic of the body and μ is the dynamic viscosity. All else being equal, the Reynolds number is proportional to the velocity, as shown by the expression KV where K is a constant. The larger the Reynolds number, the more likely that the laminar boundary layer will naturally transition to a turbulent boundary layer *before* the shoulder point is reached. Hence, it is more likely that separation will yield a smaller wake with a smaller pressure drag.

Experimental Setup

The drag experiments were performed in the United States Naval Academy Closed-Circuit Wind Tunnel (CCWT). The model was mounted 0.015 in. above a boundary layer splitter plate in the 54×38×94 in. long test section as shown in Figure 1. The splitter plate is offset 2.75 in. from the test section floor. Hence, a new boundary layer develops at the leading edge of the splitter plate. Thus, the model is not operating in the tunnel wall boundary layer. The maximum Reynolds number achievable in the test section is 1.4 million per foot. Incidentally, neither the tape nor the yarn tufts seen in Figure 1 were attached to the Grimes beacon when the drag was measured. The beacon dome was clean.

Aerodynamic forces and moments are measured by a six-component external compact platform balance located beneath the wind tunnel test section. The model is mounted directly to the balance and does not touch the test section walls or the splitter plate. The standard deviation in measured drag over a 15 minute test period at constant flow conditions is ±0.03 lbs. The standard deviation in drag is ±0.0003 lbs. The test section is instrumented with pressure and temperature transducers to obtain real-time flow velocity and air denstiy.

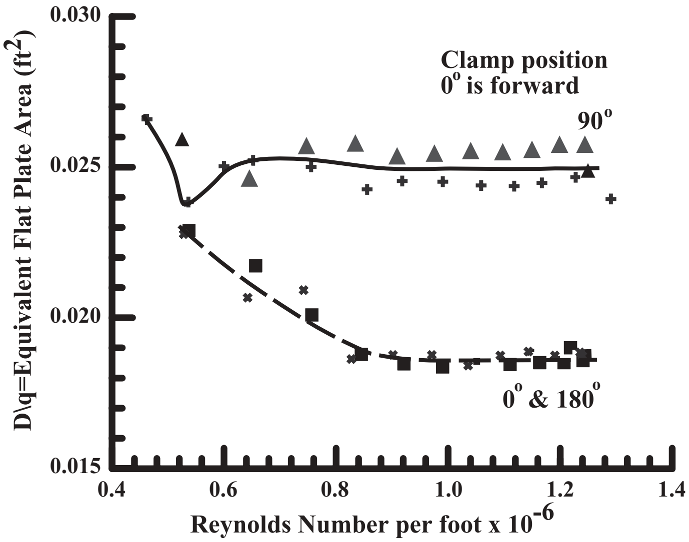

Figure 3. Equivalent flat plate area for a Grimes beacon as a function of Reynolds number.

Experimental Results

Recall that the equivalent parasite flat plate area, f, is given by $f = C_D S$ where C_D is the drag coefficient of a flat plate perpendicular to the free stream, typically taken to be 1.0, and S is the wing planform area. Recall also that the drag of the body is given by

$$Drag = D = C_D q S \qquad \text{or} \qquad \frac{D}{q} = C_D S = f$$

where q is the dynmanic pressure given by $q = 1/2\,\sigma\rho_{\text{SL}}V^2$. Here, ρ_{SL} is the air density at sea level and σ is the ratio of the density at a specific altitude compared to sea level, i.e., $\sigma = \rho/\rho_{\text{SL}}$.

Figure 3 shows the equivalent flat plate area, or D/q, of the Grimes beacon as a function of the Reynolds number. Four sets of data points are shown representing different positions of the clamping nut and bolt. Zero degrees represents the clamping nut and bolt at the front of the beacon. The two lower data sets represented by the cross and the square are for the clamp at the 0° and 180° positions, i.e., at the front and the rear of the beacon. The shape of the lower curve is typical of the drag of a blunt body. The large values of drag to the left of the figure, i.e., at lower Reynolds numbers, represent laminar boundary layer separation at or near the shoulder of the beacon resulting in a large turbulent wake and associated large pressure drag. As the Reynolds number, and flow velocity, increase to the right in the figure, natural transition to a turbulent boundary layer occurs on the front of the body and boundary layer separation is delayed until further back on the rear of the body. The result is a smaller turbulent wake, a smaller pressure drag and hence a lower total drag. What is interesting is that the results for the clamp located at the front, 0°, and back, 180°, of the beacon are essentially the same. This result is attributed to the fact that at the front of the beacon the clamp is positioned in the stagnation region with nearly zero flow velocity and hence generates little drag. Similarly, when the clamp is located at the rear of the body little drag results because of the low velocities in the wake.

The two upper sets of data represented by the triangles and the plus signs are for the clamp at 90° left and right from the 0° forward position. The difference in the results is attributed to the fact that on one side the head of the bolt is facing into the flow and on the other the nut, which creates greater turbulence, is facing into the flow. Little things make a difference. Of even more importance is the fact that the nut and bolt fixture, which is about 1/4 in. on a side, increases the drag at flight Reynolds numbers by 1/3, i.e., from an equivalent flat plate area, f, of 0.0186 ft^2 for the 0° and 180° positions to 0.0250 ft^2 at the ±90° positions.

Intermediate clamp fixture locations between 0° and 90° exhibit increasing drag, as shown in Figure 4, representative of the increasing flow velocity from the front of the beacon back to the shoulder. Clamp fixture locations between 90° and 120° exhibit rapidly decreasing drag which smooths out as the aft position is approached.

Practical Effects

At typical cruise conditions, e.g., 6000 ft. at 165 knots true airspeed on a standard day, the flight Reynolds number per foot is 1.5 million. From Figure 3 note for Reynolds numbers per foot greater than one million, the equivalent flat plate area, $f = D/q$, is constant. Using these values we can calculate the additional drag generated by the Grimes beacon. Specifically, with the clamping fixture located at 180°, where the equivalent flat plate area is 0.0186 ft^2, the drag is

$$\begin{aligned} Drag = D &= \frac{D}{q}q = fq = f\frac{1}{2}\sigma\rho_{\text{SL}}V^2 \\ &= (0.0186)(\frac{1}{2})(0.8357)(0.002378)((1.69)(165))^2 \\ &= 1.44\,\text{lbs} \end{aligned}$$

which you might say is not worth bothering about.

However, my aircraft, as many others, actually has two Grimes beacons, with one located on the top of the fuselage and the other on the bottom. In fact, the beacon on the bottom has a lens that is larger than the one in the top beacon. The drag of the bottom beacon can be obtained by multiplying the drag of the top beacon by the ratio of the projected frontal areas to give

$$Drag_{\text{bottom}} = 1.8Drag_{\text{top}} = (1.8)(1.44) = 2.6\,\text{lbs}$$

where 1.8 is the ratio of the projected frontal areas. Thus, the total drag of the two Grimes beacons is a bit over four pounds. That much drag is significant. Here is why. Drag is

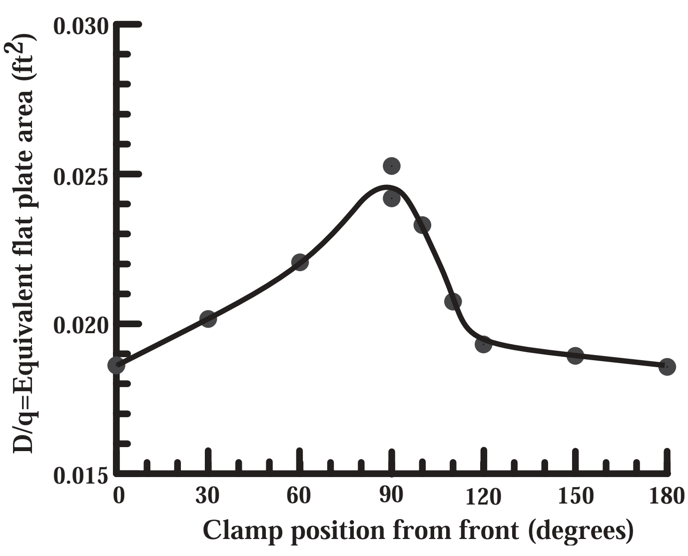

Figure 4. Equivalent flat plate area for a Grimes beacon as a function of clamp position.

thrust horsepower required divided by velocity. At 6000 ft. at 165 knots true airspeed, (TAS), 158.5 thrust horsepower, Thp, is required. Thus, the total aircraft drag is

$$Drag = \frac{550\,\text{Thp}}{1.69\,\text{TAS})} = \frac{(550)(158.5)}{(1.69)(165)} = 312.6\,\text{lbs}$$

where 1.69 and 550 are conversion factors. The four pounds of drag generated by the Grimes beacons represents **1.3% of the total drag** of the aircraft. That is **not** insignificant. The drag attributed to the Grimes beacons results in an increase is thrust power required to achieve the same true airspeed of approximately two horsepower. For the same thrust power required, the increased drag results in a decrease in true airspeed of approximately one knot. The fuel required to achieve the same true airspeed is increased by approximately $^1/_4$ gallon per hour, which results in a decrease in range for a four hour flight at typical cruise conditions (burning 13 gph) of approximately 12.5 nm. A decrease in climb performance also results. Add up all the little increases in drag due to antennas, Grimes beacons, partially open cowl flaps and gear doors, etc. and little things really do make a difference.

Acknowledgements

The Grimes beacon was graciously provided by Kevin O'Halloran of Beechparts. It took so long to get the data that Kevin probably thought I'd forgotten where the beacon came from. Thanks Kevin.

