REVISION LOG

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VERSION	EFFECTIVE DATE	DESCRIPTION OF REVISION(S)
001	2015.01	Module creation and release.
002	2016.07	Format update and minor content revisions.
003	2018.07	Refined content sequencing to Appendix 1.
003.1	2023.04	Inclusion of Measurement Standards for clarification, page iv. Minor appearance and format updates.
004	2024.01	Regulatory update for EASA 2023-989 Compliance.
004.1	2025.05	Relocated topic Polar Curve from Submodule 3 to Submodule 2. Corrected answer to question 4-6.

Module was reorganized based upon the EASA 2023-989 subject criteria. Enhancements included in this version 004.1 are:

8.1 *Atmospheric Density* - added content.
8.1 *Water Content* - added content.
8.2 *Free Stream Flow* - rewrite.
8.2 *Aerodynamic Contamination* - added content.
8.3 *Aircraft Performance* - rewrite.
8.4 *Shock Waves* - added new figure.

initial climb, it is of maximum importance and may produce as much as 70% of total drag. Finally, when looking at the potential strength of wing tip vortices, theory on induced drag must be moderated by the effect of aircraft weight. Induced drag always increases with aircraft weight.

WAVE DRAG

Wave drag is a force, or drag that retards the forward movement of an airplane, in both supersonic and transonic flight, as a consequence of the formation of shock waves.

Wave drag is caused by the formation of shock waves around the aircraft in supersonic flight or around some surfaces of the aircraft while in transonic flight. In cruise, most civil jet aircraft fly in the Mach .75 to .85 speed range. Shock waves are typically associated with supersonic aircraft, however, they also form on an aircraft traveling at less than the speed of sound.

This occurs on the aircraft where local airflow is accelerated to sonic speed and then decreases back to subsonic speed. A shockwave (and associated wave drag) forms at the point the airflow becomes subsonic. This is common on aircraft airfoils. As the aircraft continues to accelerate, the area of the wing experiencing supersonic flow increases. The shockwave moves further back on the wing and becomes larger. Boundary layer separation also increases with the increase in speed and if the speed is allowed to increase beyond the limiting Mach number, severe buffeting, Mach tuck or "upset" (loss of control) may occur. Shock waves radiate a considerable amount of energy, resulting in drag on the aircraft. This wave drag can be reduced by incorporating one or more aerodynamic design features such as wing sweep, ultra thin wings, fuselage shape, anti shock bodies and super critical airfoils.

DRAG AND AIRSPEED

Parasitic Drag increases with the square of the airspeed, while induced drag, being a function of lift, is greatest when maximum lift is being developed, usually at low speeds. **Figure 2-23** shows the relationship of parasitic drag and induced drag to each other and to total drag.

There is an airspeed at which drag is minimum, and in theory, this is the maximum range speed. However, flight at this speed is unstable because a small decrease in the speed results in an increase in drag, and a further fall in speed. In practice, for stable flight, maximum range is achieved at a speed a little above the minimum drag speed where a small speed decrease results in a reduction in drag.

POLAR CURVE

A *polar curve* is a graph which contrasts the sink rate of an aircraft with its horizontal speed. It is used mainly to illustrate performance of a glider.

Knowing the best speed to fly is important in exploiting the performance of a glider. Two of the key measures of a glider's performance are its minimum sink rate and its best *glide ratio*, also known as the best glide angle. These occur at different speeds. Knowing these speeds is important for efficient cross country flying. In still air the polar curve shows that flying at the minimum sink speed enables the pilot to stay airborne for as long as possible and to climb as quickly as possible. But at this speed, the glider will not travel as far as if it flew at the speed for the best glide. When in sinking air, the polar curve shows that best speed to fly depends on the rate that the air is descending. The optimal speed to fly for best cross country speed may often be considerably in excess of the speed for the best glide angle to get out of the sinking air as quickly as possible.

By measuring the rate of sink at various air speeds a set of data can be accumulated and plotted on a graph. The points can be connected by a line known as the polar curve. Each type of glider has a unique polar curve. The curve can be significantly degraded with debris such as bugs, dirt, and rain on the wing. Published polar curves will often be shown for a clean wing in addition to a dirty wing with bug splats represented by small pieces of tape applied to the leading edge of the wing.

The origin for a polar curve is where the air speed is zero and the sink rate is zero. In **Figure 2-24** a line has been drawn from the origin to the point with minimum sink. The slope of the line from the origin gives the glide angle, because it is the ratio of the distance along the airspeed axis to the distance along the sink rate axis.

A whole series of lines could be drawn from the origin to each of the data points, each line showing the glide angle for that speed. However, the best glide angle is the line with the least slope. In **Figure 2-25**, the line has been drawn from the origin to the point

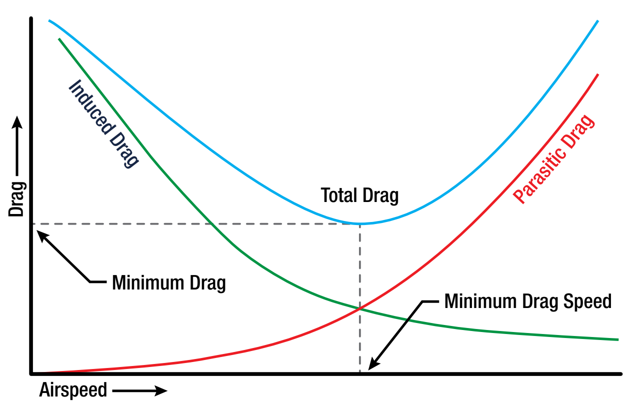

Figure 2-23. Different types of drag versus airspeed.

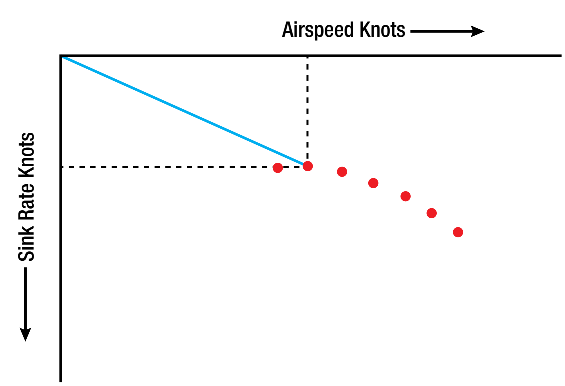

Figure 2-24. Polar curve showing glide angle for minimum sink.

representing the best glide ratio. The air speed and sink rate at the best glide ratio can be read off the graph. Note that the best glide ratio is shallower than the glide ratio for minimum sink. All the other lines from the origin to the various data points would be steeper than the line of the best glide angle. Consequently, the line for the best glide angle will only just graze the polar curve, e.g. it is a tangent.

AERODYNAMIC CONTAMINATION

All discussion of aerodynamic behavior of airfoils assumes that the aircraft airfoils are free of contamination. Some of the most common forms of contamination are ice, snow and frost. Each of these, if accumulated on the aircraft, will reduce its capacity to develop lift. Ice commonly changes the shape of the airfoil which disrupts airflow and make it less efficient. Snow, ice, and especially frost, alter the smooth even surface that normally promotes laminar airflow. Laminar airflow is required to set up the pressure differential between the lower and upper wing surfaces that creates lift. All snow and ice must be completely removed from any aircraft before flight. Frost must also be removed. While it appears insignificant, the disruption to airflow caused by frost is possibly the most dangerous.

If ice is allowed to accumulate on the aircraft during flight [**Figure 2-26**], the weight of the aircraft is increased while the ability to generate lift is decreased. As little as 0.8 millimeter of ice on the upper wing surface increases drag and reduces aircraft lift by 25 percent.

Other common forms of airfoil contamination, particularly on laminar flow airfoils, include insects, paint chips, and even simple dirt. Any debris affecting the airflow over a wing or any other airfoil such as a propeller or helicopter rotor blade, even if appearing insignificant, can significantly affect the lifting qualities of that wing.

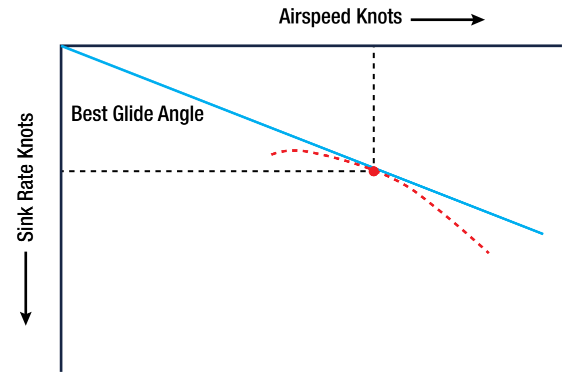

Figure 2-25. Polar curve showing glide angle for best glide.

Figure 2-26. Inflight ice formation adds weight, increases drag and reduces lift.

SUBMODULE 4 PRACTICE ANSWERS

Answer 4-1
increases

Answer 4-2
Mach number.

Answer 4-3
To delay the onset of compressibility effects.

Answer 4-4
To reduce drag, primarily at transonic speeds.

Answer 4-5
Oblique shock waves

Answer 4-6
Until new materials are developed to withstand the friction heat developed at hypersonic speeds, the only practical solution is to increase altitude (to thinner air) or to reduce speed.

Answer 4-7
increases
decreases.

Answer 4-8
shock waves