REVISION LOG

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VERSION	EFFECTIVE DATE	DESCRIPTION OF REVISION(S)
001	2018.06	Module creation and release.
001.1	2023.04	Inclusion of Measurement Standards for clarification, page iv. Minor appearance and format updates.
002	2024.04	Regulatory update for EASA 2023-989 Compliance.
002.1	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 002.1 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.

Although there must always be at least some induced drag because wings have a finite thickness, designers attempt wherever possible to reduce this flow. The larger the wing aspect ratio, the less air disturbance is created at the tip. However, for most aircraft, there are both practical limits to maximum wing span for ground maneuvering and structural issues which mean that eventually, the weight penalty to adequately strengthen a long thin wing becomes excessive. The fact that aircraft carry most of their fuel in the wings is also a factor in wing design. Typical transport aircraft aspect ratios range between 6:1 and 10:1.

Other ways to reduce induced drag and tip vortex strength in a wing design are also based upon reducing the quantity air movement upwards at the wing tip by aiming to generate relatively more of the lift away from tips. Wing taper towards the tip assists this as does wing twist. The Boeing 767 is a example of a twisted wing. The inner wing is set at a higher angle of attack than the outer wing and thus generates proportionately more lift whereas the tip, at a very small angle of attack generates very little.

Winglets have also become popular, including both the usual up-turned versions and the Airbus 320 series two-way 'wingtip fence' versions. Well designed winglets can prevent about 20% of the airflow spillage at the tip, and therefore 20% of the induced drag. [**Figure 2-20**]

The effect of this is that induced drag is relatively unimportant at high speed in the cruise and descent where it probably represents less than 10% of total drag. In a climb, it is more important representing at least 20% of total drag. At slow speeds just after take off and in the 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,

Figure 2-20. Winglets help reduce induced drag.

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 airspeed, while induced drag, being a function of lift, is greatest when maximum lift is being developed, usually at low speeds.

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 the performance of a glider.

Knowing the best speed to fly is important in exploiting the best performance of a glider. Two of the key measures of a glider's performance are its minimum sink rate and its best glide ratio. These occur at different speeds. 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 the best speed to fly depends on the rate that the air is descending.

By measuring the rate of sink at various air speeds, data can be accumulated and plotted on a graph. The points on the graph are then connected by a line known as the polar curve. 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 2-21** 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. The best glide angle is the line with the least slope. In **Figure 2-22**, the line has been drawn from the origin to the point representing the best glide ratio. Note that the best glide ratio is shallower than the glide ratio for minimum sink.

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 2-23**], 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.

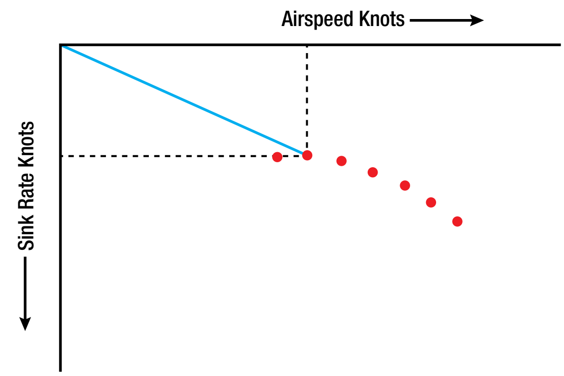

Figure 2-21. Polar curve showing glide angle for minimum sink.

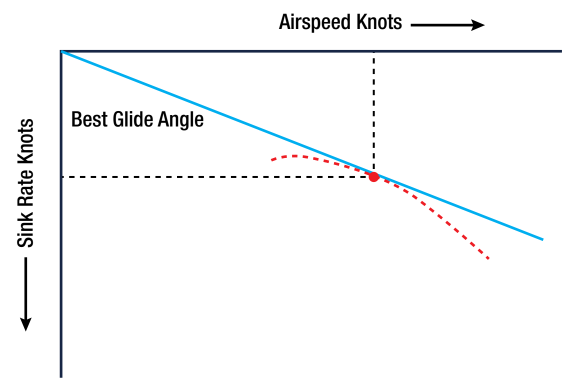

Figure 2-22. Polar curve showing glide angle for best glide.

Figure 2-23. 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