Flying Angle of Attack

There's a lot more to be gained from understanding angle of attack than just determining stall margins. AOA is the most important single factor for obtaining maximum endurance, maximum specific range and most economical cruising performance./Dan Manningham

IN THE SPRING of 1907, Wilbur Wright suggested in a letter to his brother that they consider the advantages of an angle-of-attack indicator. "We can," he wrote, "put on a vane to show (when) our angle of incidence is six or seven degrees, and climb without any attempt to estimate from looking at the ground."

The terminology has changed since 1907, but never having been misled by a tradition of airspeed indicators, these two astute aerodynamicists knew that a pilot's single most useful piece of information would be angle of attack, that critical angle between the wing chord line and the relative wind (Figure 1). Unfortunately, those aviators who immediately followed Orville and Wilbur did not understand angle of attack. Thus, 68 years later, most of us have not yet caught up with the Wrights.

In subsonic flight, any given angle of attack will produce specific and predictable values of lift and drag coefficients. Those lift and drag coefficients (C_L and C_D) versus angle of attack for a theoretical aircraft are shown in Figure 2. For any given speed, an increase in AOA will produce an increase of lift up to C_L Max. Beyond that point, separation and stall occur. Conversely, each AOA will produce a specific value of C_D.

Angle of attack, therefore, is the basic parameter of all subsonic flight. In fact, angle of attack, along with equivalent airspeed, directly defines the aerodynamic condition of the airplane regardless of weight, altitude, attitude, load factor or bank angle. As an approach cue it is unsurpassed, and in cruising flight it offers a precise yet simple means of optimizing endurance or range.

The Measurement

For useful cockpit information, AOA is measured by a fuselage-mounted probe to avoid airflow disturbances. Those probes fall into two basic categories: (1) mechanical vanes or tabs that align themselves with the local airflow, and (2) ported sensors that detect the airflow's direction by sensing differential pressures. Any differential is transmitted through the ports to an internal paddle blade, creating pneumatic torque, which aligns the sensor with the airflow. All of these probes are null-seeking devices designed to measure the free-stream airflow, independent from aircraft pitch angle. When that information is transmitted to the cockpit, it can be displayed in several different fashions. Some indicators are graduated in actual angles. Others use arbitrary units, symbols or a simple "fast-slow" presentation. One manufacturer, Teledyne, has taken a different approach to AOA presentation that they call "normalization" (Figure 3).

Normalization is a basic mathematical process in which raw data is adjusted to produce a more uniform standard. Normalized AOA is essentially a linear display of the values between AOA for zero lift and AOA for maximum lift (C_L Max). Because of the near-linear relationship between lift and AOA, normalized angle of attack can be interpreted as the ratio of the actual lift to the mass available lift for the flap setting in use. An indicator reading of 0.5 in this instance would

You could say AOA = pitch angle + flight path angle, but it's easier to describe angle of attack as the difference between where you're pointed (pitch angle) and where you're going (flight path).

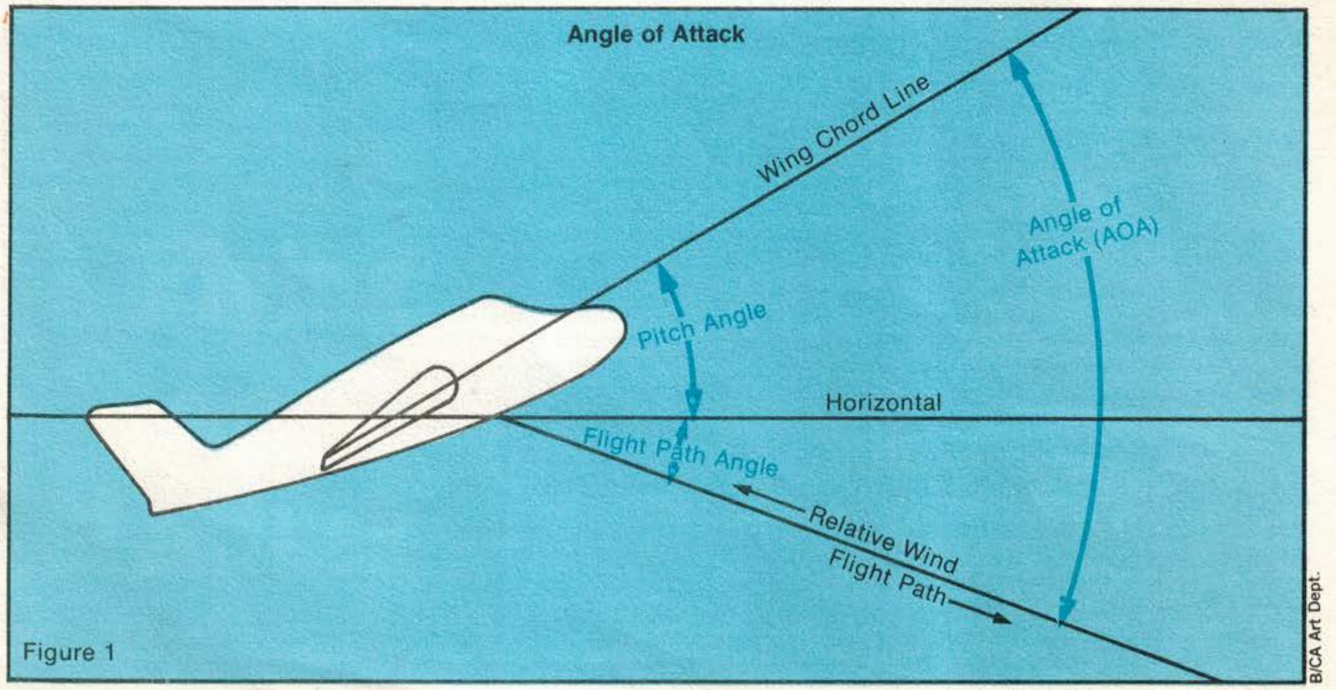

Figure 1

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mean that the lift was 50 percent of the maximum available for the existing flap setting and airspeed.

When the raw data is normalized and effectively flap-compensated, any given cockpit indication will have the same practical meaning for all configurations and for all models of airplanes.

Approach

During the approach, primary consideration is necessarily given to maintaining minimum speed with adequate stall margin. Convention and regulation have established 130 percent of the stalling IAS as an appropriate target. It works, despite the fact that IAS is an indirect and imprecise way to measure that critical stall margin.

Airfoils do not stall from lack of speed. They stall at some easily determined angle of attack, which is independent of weight, load factor, attitude or speed. Under steady-state conditions, it is possible to establish the speed at which that critical angle will be reached, but the speed is only a secondary indication of the actual determinant. As a result, the use of indicated airspeed during the approach allows for compound errors in calculation and interpretation that can substantially reduce that 30 percent margin.

If, for instance, your V_{REF} is 130 knots, you might presume you're maintaining a 30-knot margin above the stall. In fact, several operational factors can detract from that margin even though the airspeed indicator never shows less than 130. A few of the more obvious are:

- Excess landing weight from inaccurate fuel gauges, unknown payload or mathematical error will raise the stall speed above your calculated figure because higher weights require higher angles of attack for a given airspeed. And the wing only cares about angle of attack.
- Turns during the approach will subtly increase the G-loading, which has the same effect as increasing the gross weight, a requirement for more angle of attack.
- Airspeed instrument errors are not at all uncommon, especially at higher angles of attack, because of static system errors. If the error, for whatever reason, causes the instrument to read high, your margin is proportionately reduced.

In the extreme case, where several errors are compounded during a single approach, that 30 percent margin can be reduced to near zero.

Angle of attack simply does not allow for such errors. The wing will stall at one fixed AOA value under all con-

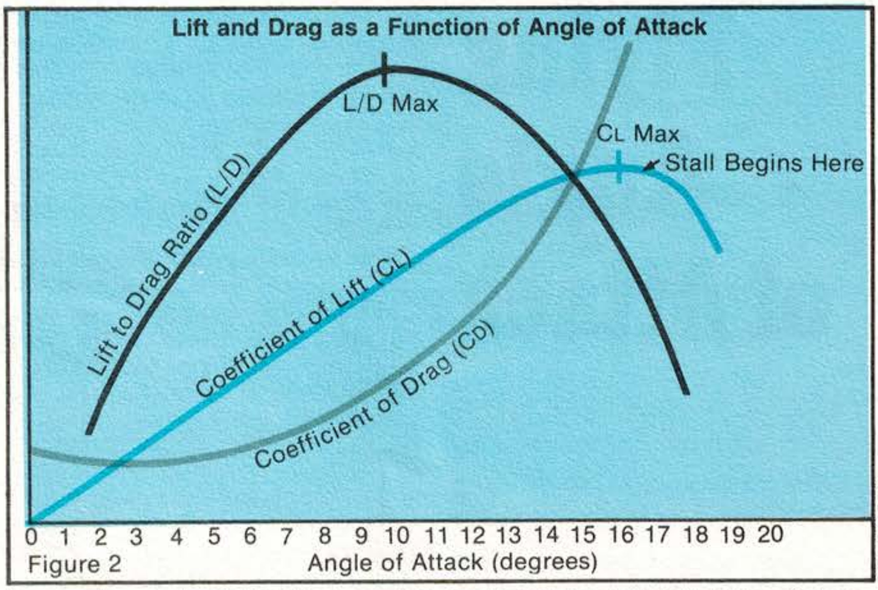

Figure 2

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For any given angle of attack there are corresponding values of lift and drag coefficients. C_D has no specific maximum. C_L reaches maximum just prior to that gross airflow separation popularly called "the stall." The ratio of lift to drag, L/D, is a classic measure of the airfoil's efficiency.

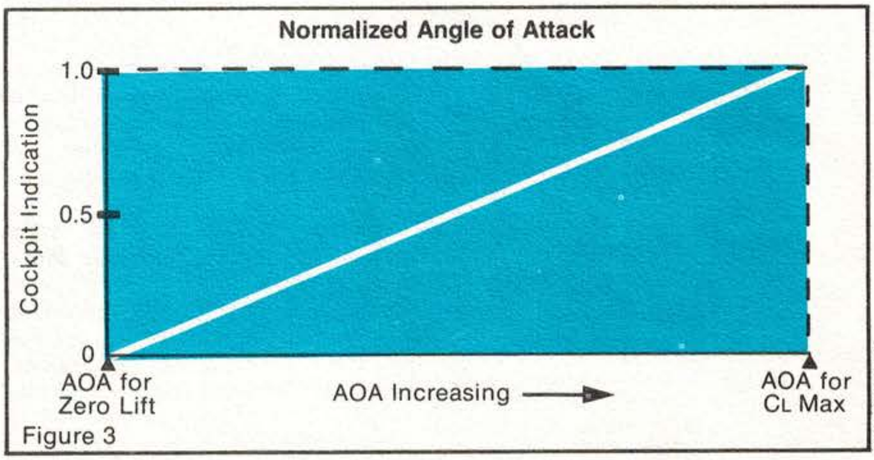

Figure 3

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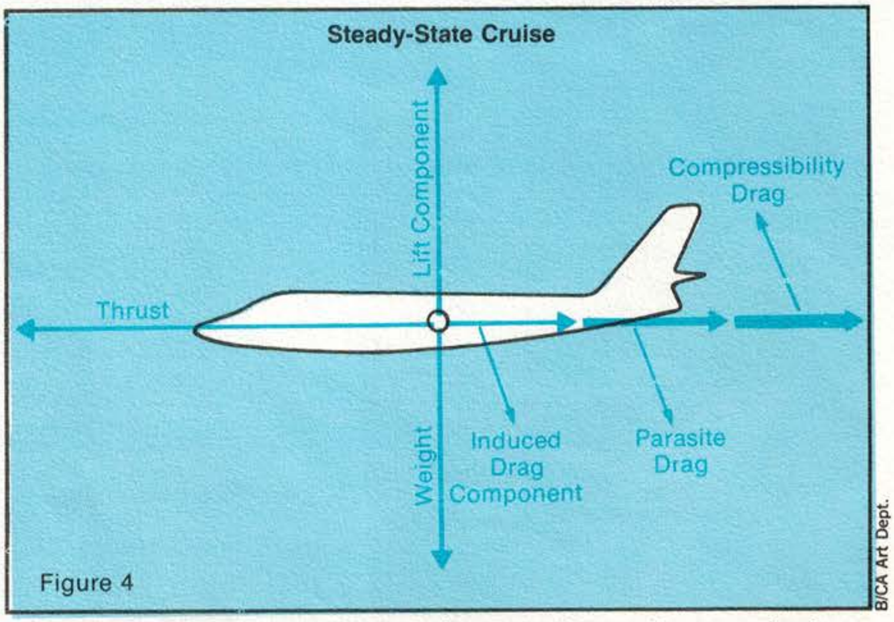

Figure 4

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In straight and level, unaccelerated flight, the four cardinal forces acting on an aircraft are equal. Any inequality between lift and weight will result in acceleration or deceleration until the two forces become balanced.

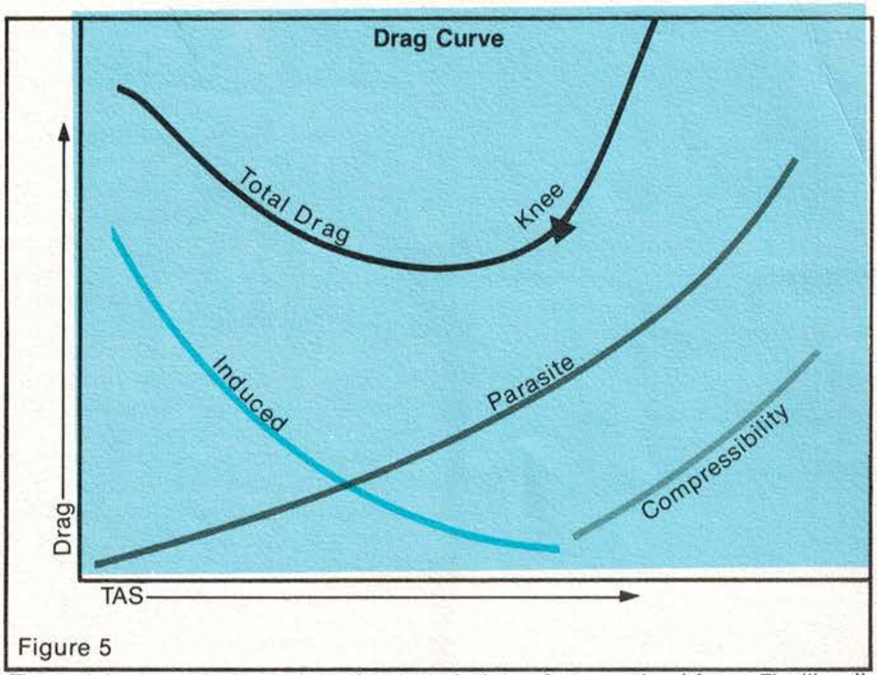

Figure 5

The total drag curve is the mathematical sum of all drag forces on the airframe. The "knee" is that point at which compressibility effects cause a major departure from the basic drag curve.

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ditions, so angle of attack provides a direct and continuous indication of the aircraft's reserve maneuvering capability.

In general an approach made at the angle of attack corresponding to 60 percent maximum lift will ensure that adequate stall margins are maintained. When this information is available, IAS is relegated to a position of secondary importance during the approach, although it resumes a primary status for deceleration on the ground.

Clearly AOA is superior to IAS as a means to determine stall margins, especially during approach. Indeed, it is in this very phase of flight that AOA has been most widely accepted. There are, however, several other areas where AOA is far superior to anything else in the cockpit. Two of those areas are endurance and range optimization, especially in jet-powered aircraft.

Maximum Endurance

Level, unaccelerated flight involves steady-state conditions in which lift is equal to the airplane weight and engine thrust is equal to total drag (Figure 4). Drag, under these circumstances, can be viewed as the major factor defining an airplane's performance. Endurance, range, climb and maneuvering performance are all based on relationships involving the airplane drag curves.

The total drag of an airplane in cruise is the sum of three different types of drag:

- *Induced drag* is the undesirable but unavoidable consequence of the development of lift. It is actually a component of the lift vector that acts parallel and opposite to the flight path. Induced drag is highest at low speed and declines as speed increases.
- *Parasite drag* is the force of air resistance to the aircraft's frontal area. It is called "parasite" because it is produced by surfaces that do not contribute to lift. Parasite drag increases with speed.
- *Compressibility drag* is the consequence of shock-wave buildup on the airframe as the aircraft approaches the speed of sound. Every airplane has a critical Mach number, which is that speed at which airflow over some point on the wing first reaches sonic speed. Above the critical Mach number, shock waves grow and drag increases greatly. If the plane goes fast enough, compressibility will cause a departure from the basic drag curve (Figure 5).

Since drag must always be overcome with thrust, you can think of the total drag curve as a "thrust required" curve, and since thrust in a jet engine is directly proportional to fuel flow, we could just change the name from drag curve to "fuel flow versus speed" curve (Figure 6). Naturally, minimum fuel flow will occur at the lowest point on the curve. At that point total drag is at a minimum, so thrust required is minimized. This low point on the drag curve is found at one specific AOA. That AOA is the same one that produces maximum lift for minimum drag as indicated by L/D Max in Figure 2. In other words, the angle of attack that generates optimum lift for minimum drag is most efficient and will produce maximum endurance. This figure is essentially independent of weight and altitude, so, for any given circumstance, operation at the AOA for L/D Max will afford the most efficient holding or loitering profile, without regard to any other factor.

Two powerplant considerations in jet aircraft demand high altitude for maximum efficiency:

- The lower inlet air temperatures associated with high altitude are conducive to efficient turbine operations.
- Engine efficiency (specific fuel consumption) is substantially enhanced by operating at or near the optimum engine speed. At low altitudes, turbine engines are efficient at some power setting far above that necessary to maintain level, optimum L/D flight; in other words, the engine and airframe are maximized at very different speeds. At higher altitudes those desirable, efficient power settings are more nearly suited to the airframe optimum of L/D Max.

Still, at any given combination of altitude, weight and temperature, maximum endurance can be achieved by simply flying the airplane at the AOA known to produce L/D Max. It just couldn't be simpler. One point on one indicator can be used for efficient holding under all circumstances. And that's pretty nice when you consider how busy you are in most holding situations.

But endurance is just a matter of establishing the lowest possible fuel flow to keep the airplane in level flight. Range is something else.

Maximum Range

Best range is, by definition, the farthest distance traveled per unit of fuel consumed. In your car you call it mileage and express it in terms of miles per gallon. In airplanes it is called specific range (SR) and stated as nautical miles per pound of fuel (nm/lb.). Maximum specific range (MSR) is that ultimate and elusive ideal at which the airframe/engine combination is traveling the greatest possible distance for each pound of kerosene consumed. There are several ways for the pilot to achieve MSR, but none is more simple than good cockpit AOA information. MSR is, in the final analysis, achieved at one AOA.

Traditionally, efficient cruise profiles are shown in terms of step climbs and reduced Mach schedules, with variables for temperature, weight, altitude and power setting. These charts normally do an excellent job of presenting the cockpit variables that result from operation at one specific angle of attack. In fact, when you use this type of information, you are really maintaining that

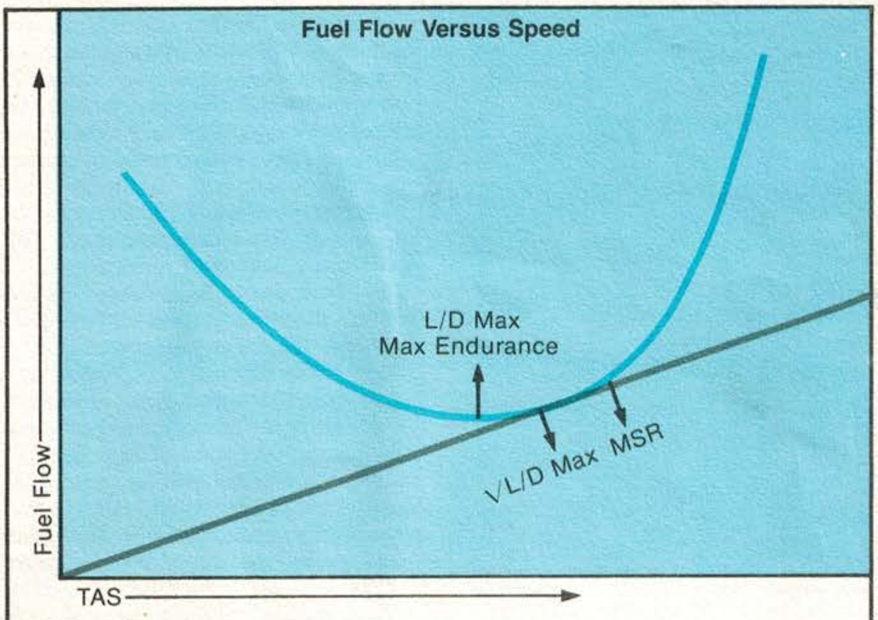

Figure 6

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AOA by reference to the results it produces. Accurate AOA information can replace all of those secondary references and allow the pilot to establish optimum cruising conditions with very little work and almost no potential for error. Let's see how that works.

Going back to Figure 6, you can see that maximum specific range will be achieved at that point on the curve where speed divided by fuel flow is at a maximum. We could compute specific range for each point on the curve in order to determine the most favorable one, but MSR can be found more simply by pivoting a straight edge at the origin until it is tangent to the curve. This tangent on the drag curve *is* MSR and corresponds to the AOA that produces the mathematical relationship of $\sqrt{L/D}$ Max. In subsonic performance, $\sqrt{L/D}$ Max occurs at one particular value of AOA and, like its relative, L/D Max, is unaffected by weight or altitude.

Operational considerations dictate one simple modification to MSR and its corresponding angle of attack, especially in swept-wing and turbine-powered aircraft. Since the drag curve is quite flat near the tangent, there is only a small sacrifice in fuel for a relatively large increase in speed. And because the curve is so flat, speed, stability and ride quality are greatly improved by any shift toward a steeper portion of the curve. For these two reasons, the accepted practice is to move along the curve to the right until specific range has decreased one percent from the maximum. That point, 99 percent MSR, is normally designated long-range cruise (LRC). The tradeoff is generally from five to 15 percent increase in speed, with markedly better speed stability, for a one percent loss in range.

Once again, this delicate balance is achieved at one fixed value of angle of attack. When you know that angle, and can accurately read it in flight, it is possible to establish LRC with reference to just one instrument and without any Mach schedules or complex charts. Airplanes with very large weight variations (the G-II, for example) may need to make minor AOA adjustments. Due to engine characteristics, MSR is always achieved at the highest altitude at which $\sqrt{L/D}$ Max can be sustained with maximum cruise power.

Compared to the traditional cruise charts, angle of attack offers at least the following advantages:

- A greatly simplified means of establishing the most economical cruising or holding conditions.
- A more precise reference that does not suffer from the inaccuracies of temperature, weight and speed calculations.
- An excellent cross-check of all other performance indications.

If it sounds good, it works even better. Modern angle-of-attack indicating systems are accurate, durable, lightweight and inexpensive. And best of all, they are very easy to fly.

Total Control with AOA

Beginning with the initial departure climb, AOA can provide safety and efficiency throughout most of the flight profile (as even Wilbur knew). Climb at L/D Max will produce maximum climb for obstacle clearance with or without all engines operating, while preserving an excellent margin above stall. During initial departure, it is necessary to maintain minimum control speed by reference to IAS since V_{MC} is a function of directional control, although there will probably not be much conflict.

There is, however, one serious restriction to the use of AOA during that initial climb. If you fixate on the AOA indicator as the airplane accelerates, the flight profile could become a series of ever larger phugoids. Here's why:

When the airplane accelerates, angle of attack is progressively reduced as the speed builds. If the profile were flown strictly by reference to AOA, you would instinctively increase pitch to maintain the AOA value as the airplane accelerated. Then when the airspeed dropped at that higher pitch angle, it would be necessary to push over in order to maintain that fixed AOA. If your fixation were absolute, this pitch cycle could well progress to disastrous levels. Naturally, the solution is to maintain a routine instrument cross-check using attitude information as the primary reference.

Throughout the enroute climb after speed has stabilized, this same AOA will afford optimum performance right on up to cruising altitude.

For cruise, the best range/speed compromise can be achieved by satisfying two simple propositions:

- Select the highest altitude at which long-range-cruise AOA can just be maintained with maximum cruise thrust. Any altitude higher or lower will detract from specific range.
- Step climb as soon as the fuel burns down to the point where the next higher available altitude satisfies that first proposition.

Strong winds during climb and/or cruise will dictate some adjustment to zero-wind angles of attack for optimum specific range. Such adjustments are severely restricted by compressibility and engine considerations in jet aircraft, so it is difficult to dictate any universal rules. In general, winds under about 75 knots do not require any adjustment, although experience in type is the very best guide. When an adjustment is indicated, it too can be established or cross-checked by reference to AOA information.

In any instance of turbulence, AOA will provide an accurate measure of the aircraft's reserve maneuvering capability and stall margin. During the approach, AOA is unexcelled for safety and precision.

It has always been easy to sell safety to pilots, and it's been even easier to sell economy to the boss. When the angle of attack story gets around, everyone is going to be sold. ☐