Angle of attack (AOA) is an aerodynamic parameter that is key to understanding the limits of airplane performance. Recent accidents and incidents have resulted in new flight crew training programs, which in turn have raised interest in AOA in commercial aviation. Awareness of AOA is vitally important as the airplane nears stall. It is less useful to the flight crew in the normal operational range. On most Boeing models currently in production, AOA information is presented in several ways: stick shaker, airspeed tape, and pitch limit indicator. Boeing has also developed a dedicated AOA indicator integral to the flight crew’s primary flight displays.
Since the early days of flight, angle of attack (AOA) has been a key aeronautical-engineering parameter and is fundamental to understanding many aspects of airplane performance, stability, and control. Virtually any book on these subjects, as well as basic texts and instructional material written for flight crews, defines AOA and discusses its many attributes.

AOA can be used for many indications on the flight deck to improve flight crew awareness of airplane state relative to performance limits. Dedicated AOA indicators have been used on military aircraft for many years, but this form of display has not been used often on commercial airplanes. On Boeing models currently in production, AOA is used to drive stall warning (stick shaker), stall margin information on airspeed indicators, and the pitch limit indicator (PLI) on the primary attitude displays. AOA information is combined with other data and displayed as an integral part of flight deck displays.

Recent accidents and incidents have resulted in new flight crew training programs for upset recovery and terrain avoidance, and these in turn have heightened industry interest in AOA as a useful flight parameter for commercial aviation.

The U.S. National Transportation Safety Board (NTSB) has recommended visual indication of AOA in commercial airplanes. This indication may take the form of a dedicated AOA indicator or other implementation, such as the PLI.

A dedicated AOA indicator shown on the primary flight display (PFD) recently has been developed in cooperation with airline customers. The new indicator is offered as an option on the 737-600/-700/-800/-900, 767-400, and 777 at this time. During the development of the new indicator, discussions with airlines, the NTSB, and U.S. Federal Aviation Administration (FAA) pilots and engineers provided a unique opportunity to examine potential uses of AOA and the many existing uses that have evolved in recent decades along with advances in display and indication technology.

This article discusses the following:

1. Basic principles of AOA.
2. Airplane performance and AOA.
3. AOA measurement.
4. AOA indications and flight crew procedures in current Boeing production models.
5. Design and uses of a separate AOA indicator.

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Aero性能

起飞。在旋转过程中，姿态角是关键参数，确保尾流清晰。如果噪声保持在低速下，不会受到地面效果和侧风的影响，并不需对计算机读数校准，AOA 将会提供有效信息。在起飞期间，没有单目标 AO A 能确保将空气动力学性能。

气动性能的一般规则是，如果鼻子保持下，将消耗掉所需的额外推力，所有发动机将丧失性能。如果鼻子下压，则在特定条件下，也将降低性能。如果鼻子上升并加速到更高的速度，从而降低性能，会导致近距离障碍物未被清除。

巡航。性能与飞行速度的关系，取决于发动机的性能。发动机的最小阻力点，与速度有关，但与 AO A 和马赫数有关。因此，最优的 AO A 将随马赫数变化。

Prima性能

停机坪。AO A 用于起飞时的判决。AO A 信息对飞行机组没有用处，这些参数必须考虑并计入指示器和相关机组程序。在飞行中，AO A 会提供有效信息。一旦飞机飞出地面效果，且无法受到侧风影响，AO A 将提供有效信息。
Those airplanes that do not account for the variation of stall speed with Mach number set the approach speed at the most conservative attitude. The speeds also allow for the most adverse CG (forward) that requires the most lift out of the wing, resulting in the highest stall speed and, therefore, the highest approach speed.

In addition, the approach speed cannot be smaller than a multiple of the minimum control speed in the landing configuration (V_{\text{mc}}). This speed is not significantly influenced by movement of the CG. So, during an approach at the aft CG, if the flight crew reduces speed to fly at the same AOA as required for the forward CG, an approach speed below the minimum control speed may result.

A further consideration is the clearance of the aft body from the ground at touchdown. Some airplanes, particularly those with high overhangs, have increased approach speeds to reduce the AOA and hence the pitch angle on touch-down. This provides adequate clearance between the body and the ground at the most critical CG.

However, in revenue service, CG is rarely at the forward limit. So, if the approach speeds were flown on a daily basis by reference to a fixed approach AOA based on a margin above stall, at any CG aft of the forward limit, the probability of stall strike would be greater than the current practice of using approach airspeeds.

In addition, variations in thrust will affect the approach AOA-speed relationship.

From the discussion above, it can be seen that approach speed may be limited by many different requirements and that no single AOA can be targeted to ensure proper speed or landing attitude margins.

### Approach Speed

Approach speed is critical to landing performance and is established during the airplane certification process. It is determined not only by margin above stall speed but also may be increased by consideration of minimum control speed and stall clearance at touchdown.

Regulations require that the approach speed be no smaller than a specific multiple of the stall speed. Because stall speed is a function of Mach number, stall-limited approach speed will occur at a different AOA at different gross weights and attitudes (fig. 8).

Wind is a more fundamental consideration. For best fuel mileage in a headwind, the airplane should be flown faster than the speed for best range in still air; in a tailwind, it should be flown more slowly. Most modern flying airplanes have a flight management computer (FMC) that accounts for airplane, engine, and wind characteristics and can compute the optimal speed to be flown.

### AOA Indications and Flight

AOA is most useful to the flight crew when the airplane is at high angles of attack to show them the margin to stall or stall warning. All indications driven by AOA—stick shaker, PLI, and speed tape indications—are related to this important information.

An error in AOA corresponds to a much higher error in airspeed or gross weight at high speeds than at low speeds. For a mid-sized airplane, such as the 757-200, a 0.5-deg error in AOA results in the following errors:

<table>
<thead>
<tr>
<th>Flight condition</th>
<th>Speed error</th>
<th>Gross weight error</th>
</tr>
</thead>
<tbody>
<tr>
<td>High speed</td>
<td>30 kt</td>
<td>-30,000 lb</td>
</tr>
<tr>
<td>Takeoff/landing</td>
<td>20%</td>
<td>-6,000 lb</td>
</tr>
<tr>
<td>Stall warning</td>
<td>30%</td>
<td>*4,000 lb</td>
</tr>
</tbody>
</table>

*14 percent of maximum takeoff weight.

For the most part, the effects discussed above can be compensated for and, depending on the airplane, may be noted, however, that each correction has its own inherent uncertainty and can also cause erroneous readings. The input data is incorrect. In the philosophy of “keep it simple,” the fewer dependencies on other data, the more robust the AOA system will be. For example, Mach number affects the sensor calibration. While this relationship could be compensated for, this would make the sensor output dependent on good Mach information. If the airspeed data were inaccurate, the calculated Mach number and therefore the calibrated AOA reading would be incorrect. This would affect the usefulness of AOA in the event of an airspeed system failure. Note that because the sensors are located near the nose and the air data probe, conditions, such as radar or damage or loss, may cause erroneous measurement of AOA as well as airspeed.

### AOA Error Sources

- **AOA MEASUREMENT ERRORS**
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- **AOA in Speed and Gross Weight**
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must be in a form other than visual to be effective, even if the flight crew is not looking at the instrument panel. Beginning with early commercial jetliners, standard practice has been to equip these airplanes with a stick shaker as a means of warning stall. Some airplanes also have employed stick nudgers or stick pushers to improve stall avoidance and stall characteristics. All these indicators have been driven by an AOA threshold, which is usually a function of flap configuration, landing gear configuration, or both. Because of the effect of Mach number on stall AOA, the stall warning AOA typically was set at a conservative level to accommodate gross weight and altitude variations expected in the terminal area.

The early stall warning system thresholds were not set to be effective at cruise altitudes and speeds because they did not correct for Mach number (fig. 11). This kept the system simple. The stick shaker was set at an AOA effective for low altitudes but at too high a value for cruise. Fixed stall and buffet was found to give satisfactory warning at higher Mach numbers. Later stall warning systems used Mach number from the pitot or static air data system to adjust the stall warning AOA threshold down as Mach number increased. This provided the flight crew with a stall warning related to the actual available performance. However, it also made the stall warning system dependent on good pilot and static data, a factor that will be considered in the next section on the dedicated AOA indicator.

It should be noted from figure 10 that the stall warning schedule does not follow the buffet boundary at very high Mach numbers. The buffet here is caused by Mach buffet, or too high a speed. Setting the stall warning system to activate at this point may lead the flight crew to forget the airplane is near stall and increase, rather than decrease, speed.

Pitch limit indicator. The PLI originally was developed as part of an industry effort to add windshear escape training. Because stall warning is primarily a function of AOA, the PLI shows AOA margin to stall warning, even though it is part of the pitch attitude display (fig. 11). Because the distance from the airplane symbol to the PLI is calculated from the difference between the AOA of the airplane and the AOA at which stall warning will occur. This provides the flight crew with good situational awareness, enabling them to monitor airplane attitude in pitch and roll relative to the horizon, while simultaneously showing whether the airplane is approaching its minimum AOA. In general, when the airplane symbol and the amber PLI bars meet, the stall warning system will activate. However, the PLI also is limited to 30 degrees of pitch attitude, regardless of AOA. If AOA or AOA margin to stick shaker were to be used as the first and primary focus of the flight crew during windshear escape or terrain avoidance procedures, extremely high pitch attitudes could be reached before stall warning if the maneuver is entered with sufficient speed. Therefore, the PLI shows the lesser of either margin to stick shaker, or 30 degrees of pitch.

Because stall AOA is a function of Mach number, a PLI on airplanes with fixed stall warning schedules would display an excessively large margin at typical cruise Mach and altitude. To avoid this misleading display, PLI was available only with flaps extended when it was introduced in the mid-1980s. Later airplanes have employed stall warning schedules that adjust the stall warning threshold as a function of Mach number. The design of the 777, 717, and 767-400ER has taken advantage of this and will display the PLI full time when flaps are down, as well as when flaps are up if speed or load factor causes stall margin to decrease to an AOA within 1.3 g of stall warning.

Work is currently under way to introduce this type of PLI indication on other models. Recent changes to the 757 and 767 enable the PLI to be displayed with flaps up.

Speed tape indications. Soon after the introduction of the PLI, a vertical scale airspeed indicator was developed and added to electronic flight displays. This offered the opportunity to display and place airspeed-related data such as minimum or maximum airspeed, stall warning speed, or reference speeds on the airspeed instrument (fig. 11). All Boeing models currently in production have this capability. Of particular interest are the minimum speed amber and red bands, or barber pole. At low speeds on Boeing-designed airplanes currently in production, these indications are based on sensed AOA and the AOA margin to stick shaker. At higher Mach numbers, most airplanes with fixed AOA stall warning schedules show margins to stick shaker or margin to initial buffet, whichever corresponds to the highest speed. On these airplanes, the margin to buffet at higher Mach numbers is calculated by the FMC. On newer models, such as the 777 and 767-400, the amber and red bands show margin to stall warning at all times because the stall warning schedule generally follows the initial buffet boundary at higher speeds up to cruise. The position of the amber and red bands is always a function of AOA margin to stall warning. The speed tape is designed to provide the flight crew with situational awareness of the flight envelope. It shows the crew where the airplane speed is relative to the limits (i.e., maximum placard speeds or minimum stall warning speed, as well as the maneuvering capability available).

Digital reference bands. The PLI originally was developed as part of an industry effort to address windshear escape training. Because stall warning is primarily a function of AOA, the PLI shows AOA margin to stall warning, even though it is part of the pitch attitude display (fig. 11). Because the distance from the airplane symbol to the PLI is calculated from the difference between the AOA of the airplane and the AOA at which stall warning will occur. This provides the flight crew with good situational awareness, enabling them to monitor airplane attitude in pitch and roll relative to the horizon, while simultaneously showing whether the airplane is approaching its minimum AOA. In general, when the airplane symbol and the amber PLI bars meet, the stall warning system will activate. However, the PLI also is limited to 30 degrees of pitch attitude, regardless of AOA. If AOA or AOA margin to stick shaker were to be used as the first and primary focus of the flight crew during windshear escape or terrain avoidance procedures, extremely high pitch attitudes could be reached before stall warning if the maneuver is entered with sufficient speed. Therefore, the PLI shows the lesser of either margin to stick shaker, or 30 degrees of pitch.

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which is related to the second objective above, that the indicator be useful when pitot or static data, and therefore Mach calculations, are unreliable because of blockage or a fault in the system. The point of a normalized indicator in this condition would be to make the indicator unusable.

The nonnormalized design, the position of the needle is a function only of sensed AOA. The red tick mark for stall warning may behave erratically in a pitot or static failure state, as may stick shaker, P/II, and speed tape amber and red bands. However, the AOA needle and digits will remain stable, and the indicator itself still will be useful as a backup for unreliable airspeed, provided the AOA varies are within the normal range of its operation.

A variety of potential uses for AOA were examined during the design of the new AOA indicator:

- Improved situational awareness and flight crew training.
- AOA backup indication following pitot or static system failures.
- Reference during upset recovery, wind shear escape, and terrain avoidance maneuvers.
- Indication of maximum L/D or range, detection of weight errors, and checking fuel consumption during cruise.
- Reference during upset recovery, windshear escape, and terrain avoidance maneuvers.
- Cross-check to detect weight or configuration errors on approach to reduce the probability of stall strikes on landing.
- AOA can be used for some of these purposes, but it does not work as well for others. From the standpoint of flight operations, some of the goals can be met with certain caveats that are discussed below.

Imperfect situational awareness and flight crew training. There is a desire to use AOA information to increase the flight crew's understanding of the physics of flight and their general awareness of the state of the wing during normal and nonnormal conditions. Within certain limitations, this display provides this indication in a clear, unambiguous format. The degree to which AOA can be used to increase knowledge and awareness depends, of course, on the approach taken by the airline in training its flight crews and on the use of this indicator in training scenarios for nonnormal procedures. Some of the limitations are discussed below.

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Pilot or static system failure requires the flight crew to take several fundamental steps to resolve the problem (see "Euminous Flight Instrument Information," Aero. no. 8, Oct. 1998):

- Recognize an unusual or suspect indication.
- Keep control of the airplane with basic pitch and power skills.
- Take inventory of reliable information.
- Find or maintain favorable flying conditions.
- Get assistance from others.
- Use checklist.

Recognition of a problem will be accomplished by instrument scanning and cross-check practices or crew alerts, depending on the design of the system in the airplane. In this respect, AOA instruments can be useful as an additional cross-check.

Present procedures for unreliable airspeed call for flying the airplane by reference to the pitch attitude display, it does not provide protection against high pitch attitudes if the indicator is used as the flight crew's primary focus or target during such maneuvers.

For upset recovery, either the P/II or the red stall warning mark on the AOA indicator may be used to assess the margin to stall warning.

Indication of maximum L/D or range, detection of weight errors, and a check of fuel consumption during cruise. As shown in the section on airplane performance, AOA is not the appropriate parameter for optimizing cruise flight, because of the strong influence of Mach number on airplane performance. Because AOA is not very sensitive to speed or weight changes at cruise speeds, even large gross weight errors may not be detectable. A 0.5-deg error in AOA is equivalent to 30,000 lb on a 777-200, or approximately 14 percent of the maximum takeoff weight.

Cross-check to detect weight or configuration errors on approach to reduce the probability of stall strikes on landing. AOA can be used during approach as an extra cross-check for errors in configuration, weight, or reference speed calculation. Proximity of the AOA to reference speed on the airspeed tape can be used in a similar manner because it is based on AOA margin to stick shaker.

However, for either method, the errors must be large enough that they are not masked by other factors.

Normal variations in AOA as a result of the regulatory requirements on approach speed, as well as those caused by differences in thrust, CG, sidestick, and the installed accuracy of the AOA measurement systems may act together to mask all but large errors in weight or configuration. These factors are taken into account in determining the size of the green approach reference band. To keep the size of the green band from becoming too large, these variations were root-sum-squared because of the low probability that they would all add in the same direction at any one time. The resulting green band is about 2 deg wide for the 777 and 3 deg for the 737. The band is centered on a nominal gross weight, mid-CG, no sidestick, a 3-deg glide slope, and no system error. A 20,000-lb error on a 757, corresponding to approximately 10 percent of maximum landing gross weight or about a 40 percent error in payload, yields a change in AOA of about 1 deg. So, it can be seen that even relatively large weight errors may not be enough to move the needle out of the green band. Conversely, it is also possible that flying at the proper speed and configuration may yield an AOA that is outside the reference band.

Figure 13 illustrates how errors can be

**KEY POINTS TO REMEMBER IN TRAINING**

- AOA is most useful in high-AOA, low-speed parts of the envelope. It is least useful at most normal speeds.
- Airspeed and Mach are still the primary sources for performance data for reasons of precision, regulatory basis, system redundancy, and simplicity. Therefore, if the AOA instrument is used, flight crews should cross-check with other instruments, just as they would with airspeed.
- The AOA approach reference band may be used as a cross-check for configuration errors, reference speed calculation errors, or very large errors in gross weight. Normal variations in AOA measurement dictate the width of the green band. Also, because approach speed in some cases can be determined by issues not related to or sensed by AOA, increasing or decreasing approach by targeting the center of the green band can result in inappropriate approach speeds.
- Pulling to stick shaker AOA from a high-speed condition without reference to pitch attitude can lead to excessive pitch attitudes and a higher probability of stall as a result of high deceleration rate.
- Pitot or static system failure requires the flight crew to take several fundamental steps to resolve the problem (see "Euminous Flight Instrument Information," Aero. no. 8, Oct. 1998).
- Recognize an unusual or suspect indication.
- Keep control of the airplane with basic pitch and power skills.
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**AERODYNAMICS UNDER VARIOUS CONDITIONS ON APPROACH TO LANDING**

<table>
<thead>
<tr>
<th>Weight error</th>
<th>0</th>
<th>23,000</th>
<th>16,000</th>
<th>23,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>CG</td>
<td>mid</td>
<td>mid</td>
<td>mid</td>
<td>mid</td>
</tr>
<tr>
<td>Speed</td>
<td>76</td>
<td>5</td>
<td>6</td>
<td>75</td>
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<tr>
<td>Speed brake</td>
<td>down</td>
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<td>down</td>
</tr>
<tr>
<td>CG</td>
<td>mid</td>
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<td>Speed</td>
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Cross-check to detect weight or configuration errors on approach to reduce the probability of stall strikes on landing. AOA can be used during approach as an extra cross-check for errors in configuration, weight, or reference speed calculation. Proximity of the AOA to reference speed on the airspeed tape can be used in a similar manner because it is based on AOA margin to stick shaker.
AERO

For these and other reasons, the AOA indicator can be used as an additional means to check for large errors in weight or configuration, but it should not be used as a substitute for current procedures to establish approach speeds and verify configurations. To determine the approach speed based solely on placing AOA in the green band can cause situations of excessively high or low approach speeds, depending on a variety of circumstances.

SUMMARY

AOA is a long-standing subject that is broadly known but one for which the details are not broadly understood. While AOA is a very useful and important parameter in some instances, it is not useful and is potentially misleading in others.

- The relationship between AOA and airplane lift and performance is complex, depending on many factors, such as airplane configuration, Mach number, thrust, and CG.
- AOA information is most important when approaching stall.
- AOA is not accurate enough to be used to optimize cruise performance. Mach number is the critical parameter.
- AOA information currently is displayed on Boeing flight decks. The information is used to drive the PLI and speed tape displays.
- An independent AOA indicator is being offered as an option for the 737, 767-400, and 777 airplanes. The AOA indicator can be used to assist with unreliable airspeed indications as a result of blocked pitot or static ports and may provide additional situation and configuration awareness to the flight crew.

MILITARY APPLICATIONS

AOA has been used as a primary performance parameter for years on some military aircraft, particularly on fighters. There are many good reasons for this. In general, fighters operate more often at the extremes of the envelope, often flying at minimum lift for minimum radius turns. For other applications, AOA is less critical to the pilot (usually single-place) workload, giving simple targets for approach to all flight levels. However, AOA accuracy is crucial for approach to aircraft carriers, where it is important to maintain a consistent approach attitude for each landing. Use of this technique during approach on commercial jet airplanes would be contrary to the pitch commands provided by the flight director bars, and to the speed hold mode of the autothrottle, which is often used during approach.

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