

A Review of Angle-of-Attack Display Research From 1958–2014

Angela Campbell, Ph.D.

October 2019

DOT/FAA/TC-TN19/11

This document is available to the U.S. public through the National Technical Information Services (NTIS), Springfield, Virginia 22161.

This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.



U.S. Department of Transportation
Federal Aviation Administration

NOTICE

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof. The U.S. Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the objective of this report. The findings and conclusions in this report are those of the author(s) and do not necessarily represent the views of the funding agency. This document does not constitute FAA policy. Consult the FAA sponsoring organization listed on the Technical Documentation page as to its use.

This report is available at the Federal Aviation Administration William J. Hughes Technical Center's Full-Text Technical Reports page: actlibrary.tc.faa.gov in Adobe Acrobat portable document format (PDF).

Technical Report Documentation Page

1. Report No. DOT/FAA/TC-TN19/11		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle A Review of Angle-of-Attack Display Research From 1958–2014				5. Report Date October 2019	
				6. Performing Organization Code ANG-E272	
7. Author(s) Angela Campbell, Ph.D.				8. Performing Organization Report No.	
9. Performing Organization Name and Address U.S. Department of Transportation FAA William J. Hughes Technical Center Aviation Research Division Software and Systems Branch Atlantic City International Airport, NJ 08405				10. Work Unit No. (TRAIS)	
				11. Contract or Grant No.	
12. Sponsoring Agency Name and Address U.S. Department of Transportation FAA Northwest Mountain Regional Office Airplane & Flight Crew Interface Section 2200 S 216 th Street Des Moines, WA 98198				13. Type of Report and Period Covered	
				14. Sponsoring Agency Code AIR-671	
15. Supplementary Notes					
16. Abstract Loss-of-control inflight, which is often caused by excessive angle-of-attack (AOA), is a significant contributor to fatal commercial aircraft accidents. This report reviews the history of AOA indicators and their potential safety benefits and implementation challenges for transport category airplanes. An overview of the components in an AOA system is provided with past and current use of AOA systems. Additionally, a summary of publically available research on AOA indicator effectiveness is presented with literature ranging from the 1950s to 2014. Finally, the expected challenges associated with implementing AOA devices into commercial transport airplane flight decks are discussed.					
17. Key Words Angle-of-attack, angle-of-attack indicator, angle-of-attack sensor, loss-of-control, stall, stall warning, stall recovery, upset recovery, pilot training			18. Distribution Statement This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov .		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 42	22. Price

ACKNOWLEDGEMENTS

Thanks to John Stuber, Dr. Jeff Schroeder, Captain Phil Greco, and Dr. Robert “Buck” Joslin for their comments on the manuscript. Their insight and expertise greatly assisted with the development of this document.

TABLE OF CONTENTS

	Page
EXECUTIVE SUMMARY	ix
INTRODUCTION	1
AOA SYSTEM COMPONENTS	3
AOA Sensors and Transducers	3
Pivoted vanes	4
Differential-Pressure Tube	4
Null-seeking pressure tube	4
AOA Indicator Display and Stall Warnings	4
AOA SYSTEM APPLICATIONS	7
Military	7
General Aviation	8
Commercial Transport Stall Warning Systems	9
Boeing Stall-Prevention Systems	9
Airbus Stall-Prevention Systems	11
Other commercial AOA Systems	12
AOA INDICATOR EFFECTIVENESS LITERATURE SURVEY	15
Upset Avoidance/Recovery	15
20th Century Upset Avoidance/recovery research	15
21st Century Upset Avoidance/recovery research—	18
Stall Incidents With AOA Display Use	20
Stall Prevention and Recovery Effectiveness Summary	21
Diagnostics	22
Additional Benefits	23
AOA INDICATOR CHALLENGES	25
Aviation Community Perceptions	25
Training	25
Standardization of Displays	26
Cost	26
Technical Challenges	26

CONCLUSION

27

REFERENCES

28

LIST OF FIGURES

Figure		Page
1	C_L versus AOA	1
2	AOA sensors	3
3	Dial AOA indicator with degree units	5
4	Dial AOA indicator with normalized scale	5
5	Dial AOA indicator with color coding	6
6	AOA indexer	6
7	T-38 AOA system	7
8	F-16 AOA display system	8
9	Alpha systems AOA indicators	9
10	PLI	10
11	Boeing electronic PFD with PLI and speed tape indicator	11
12	Boeing AOA indicator option	11
13	CRJ 700 HUD with AOA indicator	13
14	Gulfstream PFD	14
15	NLR experimental PFD designs	20

LIST OF TABLES

Table		Page
1	Summary of 20 th century AOA indicator research	18
2	ASRS database stall incidents with AOA indicator usage	21
3	ASRS reports with AOA indicator used as a diagnostic tool	23

LIST OF ABBREVIATIONS

ADC	Air data computer
AOA	Angle of attack
ASRS	Aviation Safety Reporting System
CAST	Commercial Aviation Safety Team
CFR	Code of Federal Regulations
GA	General aviation
HUD	Head-up display
LOC-I	Loss of control-inflight
NLR	Netherlands Aerospace Centre
PFD	Primary flight display
PLI	Pitch limit indicator
SE	Safety enhancement
USAF	United States Air Force
V/STOL	Vertical/Short Takeoff and Landing

EXECUTIVE SUMMARY

Loss-of-control-inflight is the largest contributor to fatal commercial aircraft accidents. Excessive angle of attack (AOA) (i.e., the angle between the relative wind and the chord line of the wing) is the leading common factor in loss-of-control accidents. AOA is a crucial parameter because the aircraft will stall when the critical AOA is exceeded. Although the FAA has requirements under Title 14 Code of Federal Regulations (14 CFR) Part 25.1324 for AOA sensors to be heated, and AOA computations are used for a variety of equipments such as stall warning under 14 CFR 25.207, raw data AOA are not required to be displayed explicitly in the flight deck of Part-25 aircraft. Instead, pilots rely on other information such as stall speed or inferred AOA (estimated by differencing pitch attitude and flight path angles) to maintain control of the aircraft.

The report reviews the history of AOA indicators, their potential safety benefits, and implementation challenges. An AOA indicator is a flight instrument that informs the pilot of the aircraft's AOA relative to the critical AOA. Studies have suggested that the use of an AOA indicator can help pilots prevent or recover from upset conditions and can also be used to diagnose a pitot or static failure/degradation, which can manifest through presentation of unreliable or inaccurate airspeed or altitude information. After the particular failure/degradation has been diagnosed, an AOA indicator can be used with other gauges to maintain a safe airspeed, vertical rate, and attitude, helping to prevent excursion into unsafe operating conditions.

The military has the most widespread use of AOA indicators because they are viewed as an important tool for safely executing advanced maneuvers, and allowing for precise aircraft attitude control, such as landing on an aircraft carrier.

The literature survey revealed that the majority of research occurred prior to 1983; recent studies on AOA indicator effectiveness are limited. Early studies on AOA indicator effectiveness were focused on military and general aviation applications of AOA indicators. Many of the studies had inconclusive results on the ability of AOA indicators to prevent upsets; however, success was achieved in military applications. Moreover, evidence was found that AOA indicators were useful, in conjunction with other instruments, for the pilot to use during a pitot or static failure/degradation.

Very little published research was found regarding AOA effectiveness in transport category airplanes. One of the few available studies was conducted by NLR. The "box" type indicator similar to the pitch limit indicator (PLI) found on a Boeing Company aircraft was the most effective display for avoiding an upset. However, the overarching conclusion of the study was that AOA indicators had no measurable benefit, and the authors suggested that stall warning system design needs harmonization among commercial airliners. Additionally, a search of NASA's Aviation Safety Reporting System database was performed to identify safety incidents in which an AOA indicator was used by the flight crew. Eight reports were identified that demonstrated the use of an AOA indicator for stall recovery or as a cross-check in the event of an airspeed indicator failure.

With the safety benefits mentioned, the literature survey revealed some other potential operational benefits, such as helping pilots maintain proper attitude during takeoff and climb-out, improving

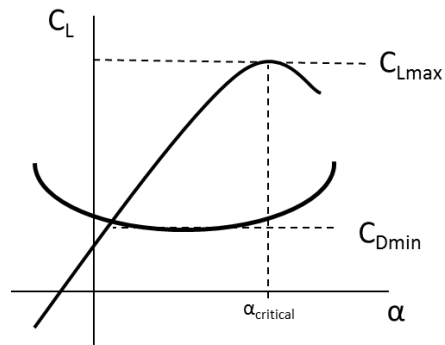
pilots' ability to fly a stabilized approach, and providing critical information during emergency maneuvers.

Some identified challenges include pilot training, technical issues, standardization, and cost. Pilot training is essential for the success of this technology. Practically every study on AOA indicator effectiveness stressed the importance of pilot training to realize the full benefits of the device. However, implementation and training do not come without cost. A comprehensive cost-benefit analysis is needed to warrant the induction of AOA indicators in commercial flight decks.

INTRODUCTION

Studies have shown that loss of control-inflight (LOC-I) is the largest contributing factor to commercial aircraft accidents, with excessive angle of attack (AOA) being the leading common factor in these types of accidents [1–3]. The Commercial Aviation Safety Team (CAST) Joint Safety Analysis Team defines loss of control (LOC) as a significant, unintended departure of the aircraft from controlled flight, the operational flight envelope, or unusual flight attitudes, including ground events [3]. The relatively high number of LOC accidents led the CAST to issue safety enhancement (SE) 207, which calls for the aviation community to “enable development, implementation, and certification of technologies that enhance flight crew awareness of airplane energy state and conditions likely to produce spatial disorientation” [4].

One contributing factor to LOC-I events is excessive AOA. AOA is the angle between the relative wind and the chord line of the wing [5] and is a critical parameter that defines the lift coefficient of the wing. As shown in figure 1, if AOA exceeds the critical AOA (the point of maximum lift coefficient) the aircraft will stall.



C_{Dmin} = Minimum drag coefficient, C_L = Coefficient of lift, C_{Lmax} = Maximum lift coefficient, α = Angle of attack, $\alpha_{critical}$ = Critical angle of attack

Figure 1. C_L versus AOA

AOA indicators have been identified as a possible mitigation strategy for the LOC-I risk. An AOA indicator is a flight instrument that displays the aircraft’s AOA as either a direct readout of the airplane’s AOA or a normalized unit of measure. A variety of display types exist, but most inform the pilot whether the AOA is within normal operating parameters, is approaching the critical AOA, or has exceeded the critical AOA. Studies have suggested that using an AOA indicator to supplement the primary flight instrumentation can help pilots prevent upset conditions or recover more easily if an upset has occurred [6].

Another advantage of AOA indicators is that they can be used to diagnose a complete pitot or static failure. Stall warnings in most commercial aircraft are dependent on airspeed/Mach number. In the event of a pitot or static failure, the Mach number calculation will not be correct and, consequently, the stall warning will be erratic. Having a true AOA indicator (i.e., the output on the display is not normalized) would help diagnose this problem (because it is not based on Mach number) and may help the pilot avoid or recover from an upset situation [7].

Currently, AOA indicators are not required in Part-25 aircraft, and some aircraft manufacturers, pilots, and other members in the aviation community question the added benefit that AOA indicators would provide versus current stall-protection systems. Those stakeholders consider current stall-protection systems to be sufficient; therefore, the addition of the AOA indicator is a potentially costly endeavor that would add unnecessary clutter to the flight instrument panel. Additionally, because commercial transports do not regularly operate at the edge of the flight envelope, it is not clear whether the inclusion of an AOA indicator would have additional benefits for commercial transports compared to the flight instruments currently found on flight decks. However, given the potential benefits of AOA indicators, the CAST included output 1 of SE 207, which calls on the aviation community to “assess the relative benefits associated with various methods of displaying angle-of-attack on the flight deck” [4].

Output 1-Action 1 of SE 207 calls for study, including the six following items:

1. Literature review of previous studies on the subject of AOA indicator effectiveness and the types of indicators available for display of AOA
2. Identification of quantitative standards to assess pilot recovery performance
3. Training and proficiency requirements for various indicators
4. Development of specific upsets and air data scenarios to assess
5. Performance of tests
6. Documentation of results in publicly available reports

This report aims to address item 1 of this list. The report will begin by covering the possible AOA sensor types and data formats for AOA indicators. Next, an overview of AOA display types is provided. The discussion will review the display type options and will discuss usage on past and current aircraft. Subsequently, studies that have evaluated the effectiveness of AOA indicators will be presented. The discussion will focus on the AOA indicators’ ability to help pilots prevent or recover for upset situation and diagnose pitot or static problems. Last, an overview of the expected challenges associated with the implementation of AOA indicators is provided.

AOA SYSTEM COMPONENTS

An assortment of AOA systems have been developed for military, general aviation (GA), and commercial transport applications. The indicators are available in a variety of data formats and display types that vary in complexity. Nonetheless, most AOA systems consist of four basic elements¹:

- Sensors that measure the AOA.
- Transducers that interpret the data from the sensors and make corrections (e.g., filter out turbulence).
- Indicators that (if installed) display the AOA data for the pilot on an integrated display (e.g. primary flight display [PFD]), standalone displays on the instrument panel or glare shield, or on a head-up display (HUD).
- Stall-warning devices that alert the pilot when the aircraft is approaching or has reached a stall condition. The stall-warning device must adapt the critical AOA setting based on aircraft configuration (e.g., landing gear, flaps) and other variables, such as icing.

This section will provide an overview of the variety of sensors, indicators, and stall-warning devices that are typically used. Additionally, some of the benefits and limitations of the devices are discussed.

AOA SENSORS AND TRANSDUCERS

Many AOA sensor devices have been developed since the beginning of flight ranging from a protractor and piece of string (used by the Wright brothers [8]) to sophisticated pressure sensor devices in use today. Currently, there are three primary types of AOA sensors in use: pivoted vanes (also known as an AOA vane), differential-pressure tubes, and null-seeking pressure sensors. Often, the pressure based sensors are referred to as probe type sensors. Examples of the sensors are shown in figure 2.

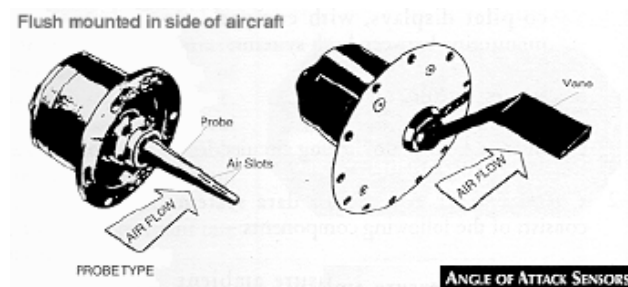


Figure 2. AOA sensors [6]

¹ Whereas sensors are still by far the most common way of measuring AOA, there are systems that calculate “derived” or “synthetic” AOA, which provide an AOA estimation based on data received from the air data computer and do not require an AOA sensor. These systems are relatively new and are not commonly used as a primary source of AOA data; however, there is interest in using these systems in-lieu of an AOA sensor, especially in GA airplanes and unmanned systems [11, 12, 13, 45, 46].

PIVOTED VANES—A pivoted vane is a small symmetrical airfoil winglet that is externally mounted to the fuselage and is free to rotate in the wind along an axis parallel to the vane’s length [14]. The vane is mounted to the shaft, and the rotation of the shaft is measured using a potentiometer. The measurements from the potentiometer are fed to the air data computer (ADC). The ADC interprets the data feed from the potentiometer and corrects the data for any errors that may be caused by airspeed and aircraft attitude, and then the data are displayed on the AOA indicator device [15].

Pivoted vanes have been employed on a variety of aircraft with Mach ranges from low subsonic to supersonic. This type of sensor can be sensitive to Mach number and the installation location on the aircraft [14]. Factors that may affect the AOA measured by the device include: distortion of the flow when the winglet is inclined to the flow (up-wash effect), asymmetry of the vane due to imperfections during manufacturing, and bending due to air loads [16].

The up-wash effect is dependent on the diameter of the boom support and the distance of the vane from the mounting point. These effects can be captured through testing, and the data can be corrected by the ADC. Similarly, the effect of bending can be captured through the wind tunnel, and the ADC can provide corrections based on other flight data, such as airspeed and environmental conditions.

DIFFERENTIAL-PRESSURE TUBE—A differential-pressure tube determines the AOA by measuring the pressure differential between two orifices at equal angles on either side of the tube [16]. As the angle of the sensor relative to the wind changes, the pressure differential between the two measurement locations will also change. The pressure differential is proportional to AOA [14].

This type of sensor has been implemented for a variety of aircraft types and speeds; however, accuracy can be influenced by Mach number, Reynolds number, tube shape, and the tube installation angle.

NULL-SEEKING PRESSURE TUBE—The null-seeking pressure tube is a device that extends out from the fuselage and has a number of slots that allow airflow to enter the interior of the device, which contains a number of movable paddles. As AOA changes, the pressure at each of the slots will vary. As a result, the paddles inside the devices will move to equalize pressure. The paddles are connected to a shaft, and the rotation of the shaft is measured using a potentiometer.

The advantage of this type of sensor is that, unlike the differential-pressure tube, the measurement is dependent on static pressure and is independent of total pressure and Mach number.

AOA INDICATOR DISPLAY AND STALL WARNINGS

AOA can be displayed in a number of different ways; specifically, the visual cues and units for the display vary widely. This section will provide a brief overview of AOA display types and the data formats that can be used.

The most basic type of AOA display is a circular dial like that shown in figure 3. Using this type of display, AOA can be represented a number of different ways, including actual degrees, normalized units, arbitrary units, or percentage of lift used [15].

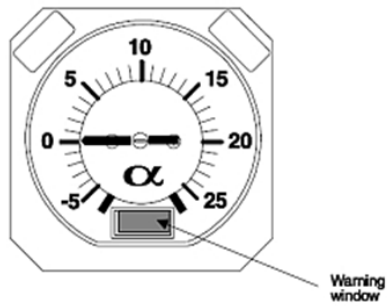


Figure 3. Dial AOA indicator with degree units [5]

The actual degrees format displays the true AOA (i.e., the angle between the relative wind and the reference line on the airplane or wing). Often, the readout will also show stall warning AOA levels. This type of display has the advantage of not requiring Mach number if only actual AOA is shown; however, Mach number is required to display the stall warning AOA.

Normalized units, as shown in figure 4, scale AOA from 0 to 1 where 0 corresponds to an AOA of 0 and 1 is the critical AOA. This type of display requires Mach number and aircraft weight so that the scale can be adjusted appropriately as the critical AOA changes. This type of display would provide erroneous data in the event of a pitot/static failure because the calculation is dependent on Mach number [6].



Figure 4. Dial AOA indicator with normalized scale [5]

A study in 1972 [17] indicated that pilots may prefer to have AOA displayed as the “percentage of lift used.” For example, if the indicator was reading 0.8, the pilot knew that there was 20% lift remaining. Many pilots felt that the information was more intuitive when displayed in this form.

Besides a numerical description of AOA, color coding is also often used on the indicator. For example, a green, yellow, and red color coding system can be used:

- Green: the aircraft is flying at a safe AOA
- Yellow: the aircraft is approaching the critical AOA

- Red: the aircraft is in immediate danger of an aerodynamic stall

The green-yellow-red color coding gives the pilot an intuitive reading of the aircraft state and allows for quick decision making (see figure 5). If the pilot notices the dial moving from the green to the yellow zone, the pilot should take action to lower the AOA. If the dial moves from the yellow to the red zone, the pilot needs to take immediate steps to reduce AOA. Further color coding and marking can be used to guide pilots to the optimum AOA for climb and approach.

Another common way to communicate AOA to the pilot is using symbols, as shown in figure 6. (This type of AOA indicator is often referred to as an AOA indexer.) A common approach is to use color-coded lines, dots, and chevrons to communicate AOA. A green colored symbol indicates a low/acceptable AOA. If the AOA is approaching the stall warning, yellow markings are illuminated. If the aircraft is approaching or has reached stall, red symbols are illuminated.

Typically, in commercial transports, AOA is rarely directly displayed. Instead, a pilot is alerted of an impending stall condition through at least two cues (i.e., visual, aural, tactile), as required by 14 CFR 25.1322. In the next section, the types of stall warning systems for commercial transport will be further explored with the AOA indicators that are used in military and GA applications.



Figure 5. Dial AOA indicator with color coding [5]



Figure 6. AOA indexer

AOA SYSTEM APPLICATIONS

AOA systems have been developed for military, GA, and commercial applications. AOA systems have gained the most traction in military applications; however, there is interest for using AOA indicators in GA and commercial applications. This section will provide an overview of existing AOA systems and indicators. The discussion will include information on aircraft types that use AOA indicators, indicator types, and commercial-transport stall warning systems.

MILITARY

AOA indicators have had widespread use in the military for decades because they are an important tool for safely completing maneuvers at the edge of the safe operating envelope. For example, AOA is used to perform landings on aircraft carriers because the procedure requires the aircraft to be flown on the “backside” of the power curve (high power, low airspeed). The military began assessing the benefits of an AOA display as early as the 1950s.

One of the early applications of AOA indicators in military aircraft was the AOA display for the T-38, which is shown in figure 7. The system included a dial indicator for each pilot that displays AOA as a percentage of maximum lift with an AOA indexer. The dial could be used for all phases of flight, and the indexer was configured for landing, or flaps were extended at least 5% with the landing gear up.

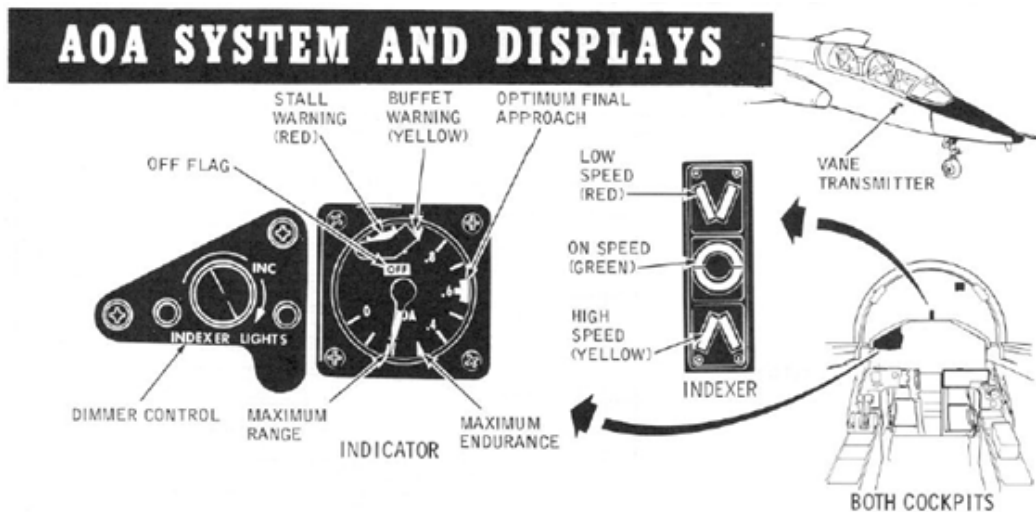


Figure 7. T-38 AOA system [6]

Another example of the military’s use of AOA displays is the AOA indicator found on the HUD of the F-18, in which AOA is displayed in true degrees. Furthermore, when the landing gear is extended, an AOA bracket appears. The bracket will move based on the velocity vector of the aircraft, and the center of the bracket indicates the optimal AOA. The F-18 also has an AOA indicator mounted next to the HUD, which operates when the landing gear are extended. The F-16 also has an AOA display system, shown in figure 8, similar to that of the F-18. It also consists

of an AOA bracket on the HUD display and an indexer. The F-16 AOA system displays true AOA along a vertical scale.

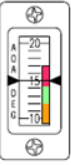



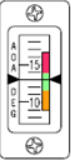

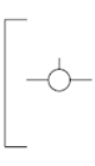
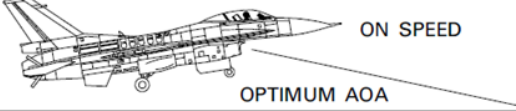
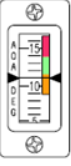


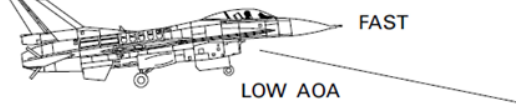
INDICATOR	INDEXER	HUD DISPLAY	ATTITUDE
 15	(RED) 		 SLOW HIGH AOA
 13	(GREEN) 		 ON SPEED OPTIMUM AOA
 11	(AMBER) 		 FAST LOW AOA

Figure 8. F-16 AOA display system [6]

Many other military aircraft have some variant of the AOA display systems that have been described. AOA indicators are considered to be crucial instruments that have been included on military flight decks for decades. For this reason, AOA displays on military aircraft have been extensively researched and are well developed.

GENERAL AVIATION

The use of AOA indicators in GA is a topic of increasing importance. In the past, AOA indicators were cost prohibitive in GA aircraft; however, because of competition, technological advances, and regulation changes, prices have rapidly dropped, making the addition of a stand-alone AOA indicator to an aircraft a feasible endeavor for GA aircraft owners.

A number of different AOA indicator manufacturers have entered the market. They include:

- Safe Flight
- Alpha Systems (shown in figure 9)
- ICON
- Bendix

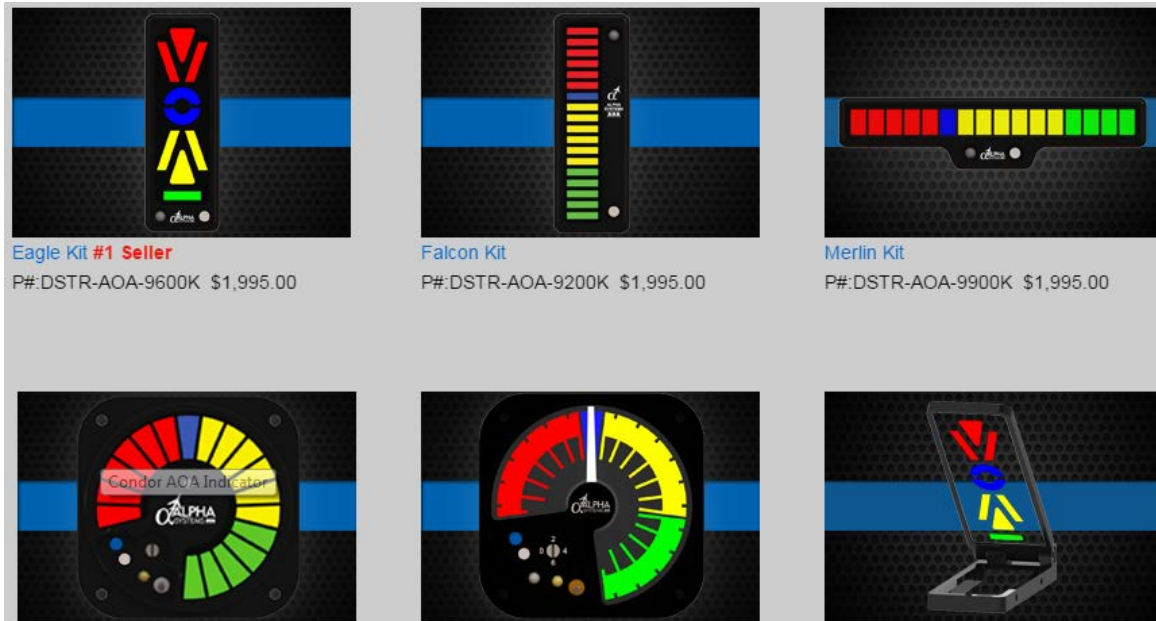


Figure 9. Alpha systems AOA indicators [9]

An assortment of AOA indicators with varying data types and displays are on the market for GA aircraft. Typically, the indexer type of AOA indicator is used in GA aircraft because of its low cost, simplicity, and ease of understanding. Adoption of AOA displays in GA flight decks is still in the early stages of widespread adoption; nonetheless, the relatively simple stall characteristics of straight-wing GA aircraft have led to the possibility of using low-cost AOA indicators as a stall risk mitigation strategy.

COMMERCIAL TRANSPORT STALL WARNING SYSTEMS

The types of AOA indicators discussed so far are rarely found on commercial transports (with the exception of a digital dial readout available on some Boeing models). Instead, stall warnings and stall margin are communicated to the pilot using other methods. Airbus and The Boeing Company have different flight deck design philosophies. On a Boeing aircraft, the information is provided to the pilot for decision-making. Conversely, stall avoidance in Airbus aircraft is primarily automatically controlled by the fly-by-wire system.

BOEING STALL-PREVENTION SYSTEMS—On Boeing aircraft, AOA information is provided to the pilot in the form of a stall warning or stall margin through the stick shaker, PLI, and speed tape. The stick shaker mechanism is an artificial tactile stall warning that alerts the pilot, with a visual cue, that the aircraft is approaching the critical AOA by mimicking the effects of pre-stall aerodynamic buffeting. In some cases, the stick shaker mechanism is accompanied by a stick pusher that assists the pilot in lowering the AOA. The stick shaker mechanism is reliant on Mach number in most Boeing aircraft, so it will only properly function with valid pitot and static data. Another limitation of the stick shaker is that it is a binary warning; that is, it indicates only whether the aircraft is near stall. It gives the pilot no indication of whether he/she is approaching a dangerous AOA or if AOA is changing.

A PLI used on Boeing aircraft is a visual representation of stall warning margin.² An example of a PLI is shown in figure 10. The margin is communicated using three components on the PFD: the pitch scale, the airplane symbol, and the PLI. The pitch scale is displayed as a vertical axis that ranges from approximately -30 degrees to +30 degrees pitch. The pitch scale is limited to ± 30 degrees because during certain maneuvers, such as terrain avoidance, the pitch of the aircraft could get very high before the stall warning is reached if the maneuver is entered with sufficient speed. In this case, AOA margin should not be the primary focus of the crew. The airplane symbol location indicates the actual pitch of the aircraft at a given moment. The PLI shows the pitch that will trigger the stall warning; therefore, the space between the airplane symbol and the PLI is the stall warning margin. Unlike the stick shaker, the PLI provides the pilot stall margin situation awareness before reaching the stall warning. The stall warning schedules are Mach dependent (like the stick shaker); therefore, a functional pitot and static system is needed for the system to properly function.

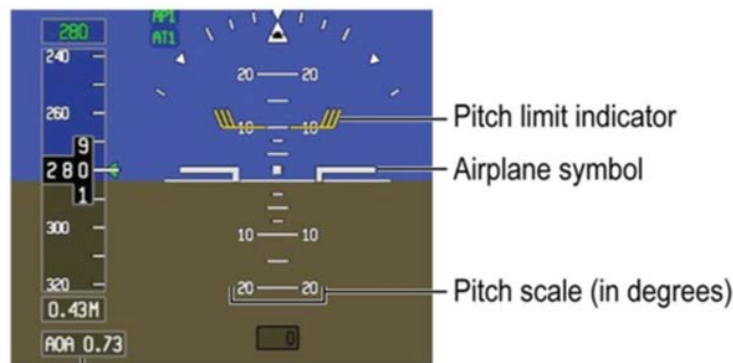


Figure 10. PLI [10]

Boeing also displays AOA/stall information using speed tape indications, as shown in figure 11. The speed tape has an amber band, which indicates when the aircraft is approaching the stall warning activation. Like the PLI, the speed tape indication provides the pilot with stall margin situation awareness, which provides forewarning of a deteriorating situation.

² Note that the Boeing PLI shows the margin to stall warning, not stall. The pitch limit indicator on Airbus aircraft shows the pitch limit for tailstrike.

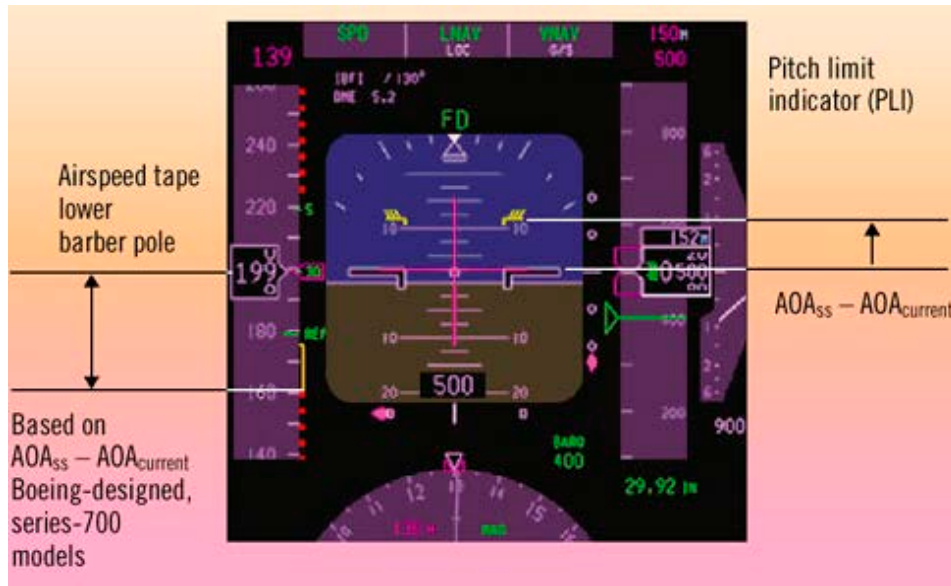


Figure 11. Boeing electronic PFD with PLI and speed tape indicator [7]

With the standard stall systems described, Boeing has an option for an AOA gauge on certain models (737-600/-700/-800/-900, 767-400, and 777). With this option, AOA is displayed on an electronic dial with degree units, as shown in figure 12. The red marker shown in the figure is used to indicate the point that the stall warning will be activated, and the green band shows the optimal AOA when the aircraft is in the approach configuration.

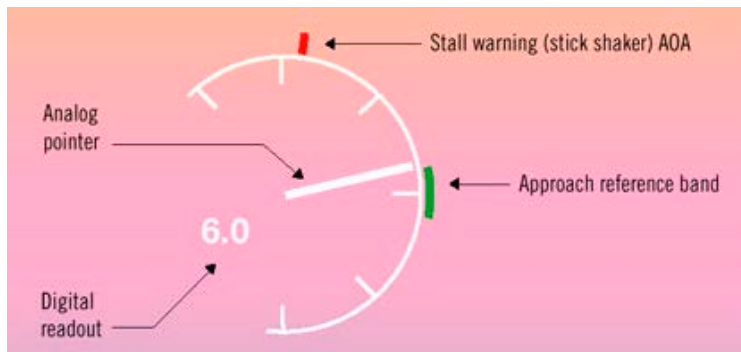


Figure 12. Boeing AOA indicator option [7]

With Boeing’s newest series of aircraft—the B787—some changes to stall protection were made. The B787 makes use of envelope protection to reduce the probability that the aircraft will approach or enter a stall. In the event of an instrumentation failure that causes airspeed data to become erroneous, the B787 uses a synthetic airspeed system. The synthetic airspeed is generated using AOA and inertial data to estimate the airspeed and show the estimation on the PFD [20]. This approach does not require the pilot to interpret AOA data and provides airspeed data in a form that is familiar to the pilot.

AIRBUS STALL-PREVENTION SYSTEMS—Airbus mitigates the stall risk by building safeguards, which are dictated by the Airbus control laws, into their aircraft with a fly-by-wire

system. When an Airbus aircraft is operating under “normal law” AOA information and stall warnings are not present because protections in the system will not accept control inputs from the pilot that would stall the aircraft. Additionally, when the aircraft is in normal law, the alpha-floor function is activated, which is an auto-thrust mode that applies takeoff/go-around thrust if the aircraft approaches stall speed. The protections put in place in normal law make it extremely unlikely that the aircraft will stall; however, the system can falter due to system failures or extreme environmental conditions. For example, if there is simultaneous failure in several key systems, the aircraft control system will receive erroneous data, which could lead to a stall. (When these situations occur, the aircraft should enter alternate law.)

As with normal law, Airbus aircraft can be operated in alternate, direct, or mechanical laws. In these cases, the AOA envelope protections are deactivated, and the pilot could potentially stall the aircraft. Under alternate law, stall warnings are activated. If the aircraft enters a high AOA, the flight control system will attempt to restore a safe AOA. However, the pilot can override the command using his/her sidestick. The pilot is also alerted with audio stall warning messages. Similar to Boeing, some Airbus models also show the stall warning speed on the PFD speed scale [21].

The Airbus 340 has an optional AOA indicator. The display is a circular dial with actual degrees and a digital warning banner directly below the dial.

OTHER COMMERCIAL AOA SYSTEMS—Most stall warning systems on commercial transports resemble the Boeing and Airbus systems, though some regional jets offer an AOA indicator option. For example, as shown in figure 13, the CRJ 700 has an AOA indicator option available for the head-up guidance system developed by Rockwell Collins [22]. It is a digital dial similar to the option on some Boeing aircraft, but it is included on the HUD instead of the PFD. The system also displays an AOA limit symbol when the AOA reaches 80% of the stick-shaker activation point.

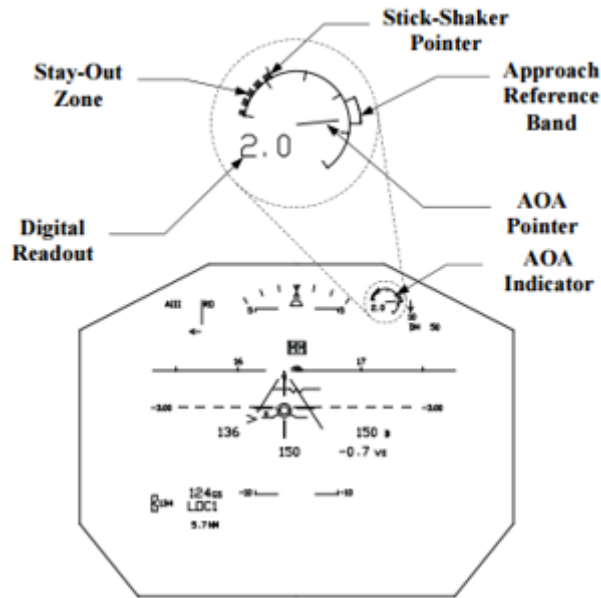


Figure 4-25:
Approach Modes Attitude Symbols

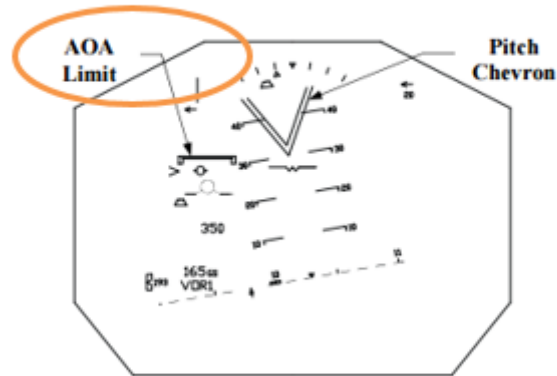


Figure 4-26:
Approach Modes Attitude Symbols

Figure 13. CRJ 700 HUD with AOA indicator [6]

The Cessna Citation X Model 750 has an optional AOA indicator and indexer. The indicator has a normalized scale and contains colored coding to alert the pilot of a normal, approaching critical, and stall AOA.

Gulfstream offers a normalized 0-1 display where 0 corresponds to 0 lift and 1 is the stick shaker activation. As shown in figure 14, the indicator is found on the PFD below the airspeed tape. The color of the text displaying AOA will change from white for normal operations to amber when approaching stall, and to red when the aircraft is stalled.



Figure 14. Gulfstream PFD [6]

AOA INDICATOR EFFECTIVENESS LITERATURE SURVEY

As discussed in the introduction, the possible safety benefits of AOA indicators include energy state awareness/upset recovery and diagnosis of air data system failures. In the past 60 years, a number of studies have been performed on the usage and effectiveness of AOA indicators. The majority of the studies took place before 1983; little research has been performed in recent years. As early as the 1950s, research demonstrated the ability of AOA indicators to help pilots prevent or recover from upset situations. Several studies have also indicated that AOA indicators could aid pilots in the diagnosis of static or pitot problems because AOA may not be dependent on Mach number.

More recent research has been conducted by Boeing and Netherlands Aerospace Centre (NLR) regarding the inclusion of AOA displays in commercial transports. A Boeing report published in 2000 highlighted the potential uses for a separate AOA indicator in their aircraft [7]. Some potential benefits they identified are:

- Improved stall margin situation awareness and flight crew training.
- AOA backup indication following pitot or static system failure.
- Reference during upset recovery, windshear escape, and terrain avoidance maneuvers.
- Indication of maximum L/D or range, detection of weight errors, and a check for fuel consumption during cruise.
- Cross-check to detect weight or configuration errors on approach to reduce the probability of tail strikes on landing.

In this section, the possible benefits of AOA indicators will be explored in more detail, and the findings in published studies on AOA indicator effectiveness will be discussed.

UPSET AVOIDANCE/RECOVERY

AOA is a critical parameter in upset avoidance and recovery because it is a direct indication of how the wing is flying. By providing AOA information to the pilot, he/she can assess whether aircraft stall margin is increasing, decreasing, or staying approximately the same. This information has the potential to increase the pilot's situational awareness and improve his/her ability to avoid or recover from an upset. An advantage of AOA indicators versus airspeed for avoiding a stall is that unlike airspeed, AOA indicators provide stall prediction under accelerated G loads [6]. Multiple studies have been conducted over the past 60 years. In this section, the research conducted in the 20th century will be reviewed, and more recent research conducted in the 21st century will be discussed.

20TH CENTURY UPSET AVOIDANCE/RECOVERY RESEARCH—Research on AOA display effectiveness began nearly 60 years ago with military experiments. One of the first studies on AOA indicators was performed on the United States Air Force (USAF) Advanced Flight Instrument Panel (1958). During this early AOA indicator study, it was found that pilots found only the AOA parameter useful after training. The report recommended technical improvements to the indicator (such as making it less sensitive to turbulence) and implementing AOA indicator training.

Subsequently, the United States Navy started to include AOA indicators in their aircraft in response to a number of accidents attributed to excessive AOA when attempting to land on aircraft carriers [22, 23]. Navy research concluded that the addition of an AOA indicator in the flight deck [24]:

- virtually eliminated accidents caused by premature rotation on takeoff,
- provided stall warning at high altitudes when executing maneuvers involving high g forces, and
- allowed for flights with maximum range and endurance.

The FAA conducted a study in 1968 to assess the use of AOA indicators in private pilot certification training [25]. The experiment consisted of two groups. One group was trained to use an AOA indicator in conjunction with airspeed, and the other group used only airspeed. Each pilot was evaluated on measures such as time to first solo, number of hours, and overall performance. The results on these measures showed no significant difference between the two groups of students. Nonetheless, the group using the AOA indicator did have superior performance in slow flight, the downwind leg of normal landings, and final approach for short-field landings. The report also noted that students trained to use the AOA indicator seemed to have a more complete understanding of basic aircraft aerodynamics.

In 1969, Forrest conducted a study similar to the FAA research on the effect of AOA indicators on pilot training [24]. During the experiment, student pilots were broken into two groups. One group was trained on the use of an AOA indicator and the other was not; then, the student pilots' ability to complete a set of maneuvers was evaluated. The results showed no statistical difference between the two groups' ability to complete the maneuvers; however, the author notes that the influence of an AOA indicator on a student pilot's ability to complete the maneuvers was likely very low because pilots at this stage primarily rely on out-the-window scan and cues rather than instruments to fly the aircraft. Based on this outcome, the author believed that a similar study should be conducted on students training for an instrument rating.

In 1971, NASA conducted a study on the effectiveness of using AOA as a control parameter in GA aircraft. The study focused on the effect of using AOA in lieu of airspeed to control the aircraft. The report noted that the advantages of using AOA as a PFD are:

- AOA is a direct measure of stall margin that is independent of weight.
- AOA responds more quickly than airspeed to the pilot's control inputs.

The study concluded that when pilots used AOA (instead of airspeed) as a primary instrument, they performed either the same or in some cases worse than when using airspeed as a primary instrument. The only time that AOA showed an advantage over airspeed was when a well-trained pilot (in the use of AOA) was landing the aircraft. The AOA indicator enabled the pilots to select an approach trim condition using a single reference, providing a constant stall margin before flare and resulting in consistent flare and float characteristics regardless of weight and flap settings. However, when the aircraft was landing at a light weight with full flaps, using AOA often caused the airspeed to fall below the recommended approach speed and resulted in a reduction in lateral control.

During low-speed maneuvering, pilots noted that although their performance may not be altered by the AOA display, they did find the information desirable. Every pilot in the study agreed that AOA was useful as a stall-warning reference. In general, the conclusion was that AOA was not useful as a primary flight control parameter, but did show the potential to be used as a supplementary parameter to airspeed with proper training. Most pilots in the study agreed that they would like to see both airspeed and AOA displayed.

In the conference proceedings of AGARD (Advisory Group for Aerospace Research and Development) No 106 (1972) on Handling Qualities Criteria, it is noted that the usefulness of inclusion of AOA on the cockpit display was “demonstrated on V/STOL configurations during the transition flight phase, on carrier based aircraft which must operate close to their maximum potential, and prototype test aircraft which demonstrate compliance with the Civil Airworthiness Stall Requirements.” [26]

Also during 1972, the USAF developed a report on their research on AOA indicator effectiveness [17]. The study was conducted after the USAF lost 35 T-38s in stall related accidents. It was the USAF’s belief that if AOA indicators were used, many of the accidents could have been avoided. The study showed that the AOA indicator proved to give accurate and adequate stall margins for the pilots. Almost all the pilots in the study agreed that AOA was a more useful parameter than airspeed to recover from a stall. The AOA indicator also was effective during the approach and landing phases of flight by helping the pilot ensure that he/she maintains an acceptable stall margin. The majority of the pilots in the study remarked that they believed that the AOA indicator improved their ability to properly control the aircraft during approach, landing, and maximum performance maneuvers. Another outcome of the study was that the pilots preferred having AOA data displayed as percent lift available rather than percent of AOA available or arbitrary units.

Table 1 provides a summary of the research that was described in this section. The table cells are color coded to show whether the study showed results in favor of AOA indicators, showed results that AOA indicators have no benefit, or showed inconclusive results. The table showed that three of the studies had conclusive results in which AOA indicators provided tangible benefits for upset avoidance/recovery, diagnostics, or operations. Typically, the benefits of AOA indicators were most apparent in military applications. This most likely occurred because of the advanced flight maneuvers used in military operations. Studies focused on GA tended to show fewer positive results or had inconclusive results. One of the primary reasons cited for this outcome was GA pilots’ lack of familiarization with flight instruments.

Table 1. Summary of 20th century AOA indicator research

Study	Military/ GA/ Commercial?	Upset avoidance/ recovery	Diagnostics	Other AOA benefits	Notes
USAF Advanced Flight Instrument Panel (1958)	Military			<ul style="list-style-type: none"> • Allowed for flights with maximum range and endurance 	
FAA GA Study (1968)	GA			<ul style="list-style-type: none"> • Superior performance in slow flight, the downwind leg of normal landings, and final approach • AOA training improved pilots' understanding of aerodynamics 	
Forrest GA Study (1969)	GA			<ul style="list-style-type: none"> • No statistical difference could be found for any metrics 	<ul style="list-style-type: none"> • Author believed the study needed to be repeated with instrument rated pilots
NASA GA Study (1971)	GA			<ul style="list-style-type: none"> • In general, pilots using AOA performed the same or, in some cases, worse when using AOA as a primary flight parameter 	<ul style="list-style-type: none"> • Pilots did find AOA information desirable
USAF (1972)	Military			<ul style="list-style-type: none"> • Qualitative data showed that pilots believed the AOA indicator improved their ability to properly control the aircraft 	

■	Author concluded that AOA indicators provided a benefit
■	Author concluded that AOA indicators do not provide a benefit
■	Inconclusive results
	Benefit category was not studied

21ST CENTURY UPSET AVOIDANCE/RECOVERY RESEARCH—Based on the success of AOA indicators in military aircraft in the 1960s and 1970s, many experts believed that AOA indicators would become commonplace in commercial transports [27, 28]; however, this was not the case. In recent years, the usefulness of AOA indicators is again becoming an important debate. Whereas some pilots resist the addition of an AOA display to the flight deck, others promote the change. As discussed in Air Safety Week, Captain Ron Rogers proclaims that AOA is “the most useful piece of information that you can get.” [29]

The best practice for recovering from a stall is to immediately lower the AOA [18, 30–34]. AOA indicators could increase situation awareness regarding AOA, improving stall recovery. However, some caveats to AOA indicators should be considered when developing training requirements. For

example, a Boeing report [7] recognized the potential AOA indicator benefit of improved situation awareness and flight crew training. Their report stressed that for AOA indicators to be useful, pilots must be properly trained in when and how to use them. As a result, they provided four key points to emphasize in AOA indicator training:

- AOA is the most useful in high-AOA, low-speed parts of the flight envelope; it is less useful at normal speeds.
- Airspeed and Mach are still the primary sources for performance data for reasons of precision, regulatory basis, system redundancy, and integrity; therefore, if the AOA indicator is used, flight crews should cross-check with other instruments, just as they would with airspeed.
- The AOA approach reference green 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. Because approach speed in some cases can also be determined by issues not related to or sensed by AOA, increasing or decreasing approach speed 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.

Another potential use for AOA indicators is as a reference during upset recovery, windshear escape, and terrain avoidance maneuvers. Windshear and terrain avoidance require immediate change in pitch attitude and thrust followed by monitoring the situation and further increases in pitch if required. The AOA indicator can assist a pilot in avoiding the stall warning area during this type of maneuver; however, care must be taken if the aircraft enters this type of maneuver at high speeds because monitoring AOA alone could result in an extremely high pitch attitude [7].

NLR recently conducted research on AOA indicators for commercial transports [35]. They devised a simulation study to compare a variety of AOA and stall warning displays for the PFD with regard to the pilot's ability to recover from an upset and diagnose a failed airspeed indicator. The four PFD types evaluated are shown in figure 15. One baseline PFD was used that was representative of PFD currently found on commercial airliners. The second PFD had a digital dial version of an AOA indicator similar to the option available on certain Boeing aircraft. The third PFD had a "box" pitch guidance (somewhat representative of Boeing's PLI). The last PFD had a too fast/too slow indication of the speed tape. The study found no statistical difference between the pilots' performance between the baseline PFD and separate AOA indicator. The study did find that the "box" pitch guidance did increase recognition of reduced AOA margin in an unreliable airspeed scenario, and it performed marginally better in a low-altitude stall scenario. The conclusion of the study was that no measurable benefit of a separate AOA indicator was found; however, the researchers did suggest that stall warning system design does need harmonization among commercial airliners.

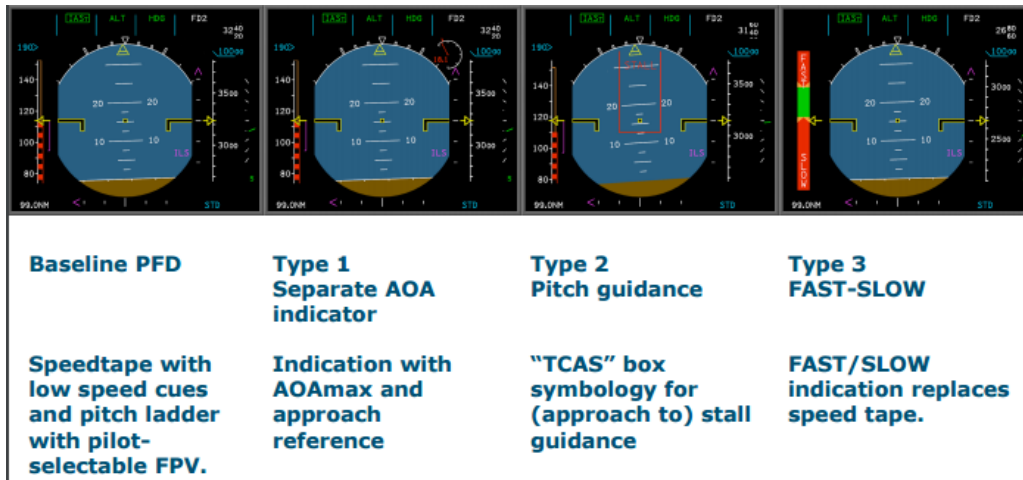


Figure 15. NLR experimental PFD designs [35]

STALL INCIDENTS WITH AOA DISPLAY USE

The NASA Aviation Safety Reporting System (ASRS) was searched to determine whether AOA indicators helped stall prevention or recovery in any of the reported incidents. Six reports, which are summarized in table 2, were found that mention the use of an AOA indicator in a stall prevention or recovery incident. In several instances, the AOA indicator offered a secondary stall warning to complement the stick shaker and aural warnings. In one of the records, the AOA indicator alerted the pilot of a degraded stall margin so the pilot was able to take action before other stall alerts were activated.

Table 2. ASRS database stall incidents with AOA indicator usage [36]

ASRS Report Number	Aircraft type	Synopsis	Role of AOA indicator
1046945	Lancair IV	Icing conditions caused the airplane to fly close to a stall	The AOA indicator turned red, and an aural warning was given to the pilot alerting the pilot of an impending stall
841092	Rockwell North American Civil Twin Jet	An encounter with changing weather conditions caused the aircraft to approach stall	The pilots were alerted by buffeting and a red AOA indicator of the impending stall
837808	Learjet 35	During a climb to a higher cruising altitude, the crew experienced a degraded climb performance and was not able to maintain the new cruise altitude	During the climb, the AOA indicator alerted the pilots that they were approaching stick shaker
727371	IAI1125 (Astra)	The crew experienced engine icing while climbing to FL410, causing a power deficit	The AOA indicator went to the yellow arc, indicating a degraded stall margin. Following this indication, the crew took immediate action to lower the AOA
647238	PC-12	A pitot input failure led to an unexpected autopilot disconnect and degraded airspeed. The result was a stall warning	The AOA indicator confirmed that the aircraft was nearing a stall condition
575640	C560	The crew climbed the aircraft too high for the aircraft's gross weight. This led to a slowing airspeed and stall warning	The AOA indicator confirmed the pilot's suspicion that the stall margin was degraded and a stall would occur unless immediate action was taken.

STALL PREVENTION AND RECOVERY EFFECTIVENESS SUMMARY

To summarize, studies have shown AOA indicators have the potential to reduce LOC-I accidents, but few conclusive results were found. Although commercial transports have audio and stick shaker warnings, these systems only provide a binary indication of approach to stall that is triggered at a set stall margin. Indirect stall margins are presented using a barber pole on the speed

tapes; however, these devices may present inaccurate information if key systems have failed. AOA indicators may provide pilots with additional stall margin information, which could alert the pilot of a developing stall situation. Furthermore, the AOA provides the pilot with critical information between the stick shaker and aerodynamic stall points, which can improve pilot stall margin situation awareness [6].

DIAGNOSTICS

Another important feature of an AOA indicator is its potential to help a pilot avoid an upset situation during a static/pitot failure. In the event of erroneous or conflicting altitude and airspeed indicators, an AOA indicator can serve as a cross-check to diagnose the problem. The research conducted in regard to AOA indicator effectiveness as a diagnostic tool is limited. The USAF study from 1972 that was previously discussed did demonstrate the AOA indicator's ability to help pilots recover the aircraft in the event of an airspeed indicator failure.

If the aircraft is equipped with an AOA indicator that displays actual degrees, the indicator can be used as an additional cross-check to diagnose a pitot or static system problem. Furthermore, it can assist the pilot in maintaining favorable flying conditions. Nonetheless, if the AOA indicator is to be used in this situation, pilots need to be trained in proper procedures. Control should be maintained using pitch attitude and using AOA as a cross-check. Attempting to follow AOA too closely without stabilizing pitch could result in an oscillatory flight path.

In 2013, a study on AOA effectiveness in the event of an airspeed indicator malfunction was performed by Boesser as a Master's Thesis at Embry-Riddle Aeronautical University [30, 37]. In this study, GA pilots were asked to perform a landing of a Cessna 172 aircraft using a simulator. The pilots were divided into two groups. One group flew the aircraft with no AOA indicator, and the other group was trained to use the AOA indicator and had it available during the simulations. During the trials, the pilots were presented with an airspeed indicator malfunction. (The indicator got stuck at 70 knots during the approach.) The study found that the group using the AOA indicator had more success maintaining the correct airspeed during the airspeed indicator failure and also had less deviation from the proper glideslope. Furthermore, participants using the AOA indicator had fewer instances of activating the stall horn.

Lastly, as previously mentioned, the 2014 NLR study did show that the box type of indicator did improve pilots' ability to recognize a reduced stall margin in the event of a failed airspeed indicator. In summary, this potential benefit of AOA indicators warrants further study. The few studies performed show that it is probable that the AOA indicator could help a pilot avoid an upset in the potentially dangerous situation of a pitot/static failure.

Similar to the stall incidents, the NASA ASRS database was searched for reports in which an AOA indicator was used in the case of an airspeed indicator failure. Two reports (summarized in table 3) were found in which a pilot used the AOA indicator as a cross-check to determine that an airspeed indicator was unreliable.

Table 3. ASRS reports with AOA indicator used as a diagnostic tool [36]

ASRS Report Number	Aircraft type	Synopsis	Role of AOA indicator
1322272	B737	The captain's airspeed indicator malfunctioned shortly after takeoff.	After the captain announced "airspeed unreliable," the FO used the AOA indicator to cross-check and determine that the aircraft was in a normal flight regime
1083592	DC-10	An 18 KTS discrepancy was detected between the captain's and FO's airspeed indicators.	A cross-check with the standby ASI and AOA indicator on the HUD confirmed that the FO's airspeed indicator was correct

ADDITIONAL BENEFITS

Although the primary goal of this literature survey is to ascertain the safety benefits of AOA indicators, operational benefits may also be realized. In a study by Fishel et al. in 1958, AOA indicators were installed in the flight deck for an experiment assessing the low speed stall characteristics of jet transports [38]. One of the conclusions of the study was that pilots discovered having an AOA indicator helped them maintain proper attitude during takeoff and climb-out. By maintaining proper attitude, large AOA's (caused by over-rotation) that produce considerable drag could be avoided. Work by Barton demonstrated that AOA indicators were also useful for maintaining proper aircraft attitude during the landing phase of flight [6].

Another possible benefit of AOA indicators is improving pilots' ability to fly a stabilized approach. An article written in 1966 suggested that AOA indicators could reduce the number of accidents cause by high sink rates and touchdown short of the runway [27]. The position of the author was that if a constant and correct AOA was held on approach, all other parameters would fall into place, which would improve the accuracy of the pilot while simultaneously reducing workload.

The FAA funded the Center of Excellence for General Aviation—that is, Partnership to Enhance General Aviation Safety, Accessibility, and Sustainability (PEGASAS)—an experiment to determine whether AOA indicators assist GA pilots in performing a stabilized approach [39]. The study consisted of 84 participants that completed 507 approaches. A 2X2 experimental design was used for which the factors were "AOA training was provided" and an "AOA indicator was available in the flight deck." No statistically significant difference between the four groups was found. One group that was not trained to use the AOA indicator but was provided the instrument in the flight deck actually had more difficulty maintaining a stabilized approach than the other three groups on a simulated engine-out approach. The authors cited that a possible reason for this

occurrence was that the indicator was distracting (i.e., the pilots spent too much time trying to decipher the information rather than focusing on the approach).

AOA indicators could also provide pilots with critical information during emergency maneuvers. One notable example is the crash of American Airlines flight 965. This accident was classified as controlled flight in terrain caused by navigation errors. The investigation revealed that once the ground proximity warning system was engaged, the pilot pulled up to the point that the stick-shaker was activated. At that point, the pilot reduced pitch. The investigation concluded that if an AOA indicator had been present, the pilot could have flown the aircraft closer to the critical AOA. This would have produced a higher climb rate and would have increased the probability that the aircraft would have cleared the terrain [40]. As a result, the National Transportation Safety Board issued recommendation A-96-94 to “Require that all transport-category aircraft present pilots with AOA information in a visual format, and that all air carriers train their pilots to use the information to obtain maximum possible airplane climb performance.” [41]

In summary, many studies over the past six decades have demonstrated that AOA displays can provide valuable information when the aircraft is operating at the boundaries of the flight envelope or when the envelope has been exceeded. In general, the studies suggest that AOA displays are highly beneficial when other data sources, such as airspeed, are not accurate. Early military studies suggested that AOA displays are also useful for stall recovery. In contrast, GA studies on AOA indicators had less success in proving that AOA indicators significantly altered stall-recovery performance.

Although lessons can be learned from the military and GA studies, the findings may not be directly applicable to commercial transports. Military aircraft routinely perform advanced maneuvers at the extremes of the flight envelope that would never be intentionally performed in a commercial transport; therefore, the stall avoidance and recovery advantages of AOA indicators found in the military studies may not be fully realized for commercial transports. Conversely, the GA studies found limited benefits for AOA displays; however, GA pilots often have little experience using flight instruments. Consequently, the performance of the GA pilots is likely not representative of highly trained commercial pilots. Because the results of the military and GA studies may not be directly applicable to commercial transports, and the research available on AOA displays for commercial transports is limited, further research is needed to determine the benefits of AOA displays in commercial transport flight decks.

AOA INDICATOR CHALLENGES

As discussed in the previous section, AOA indicators have a number of potential benefits; however, those benefits cannot be realized without addressing the challenges associated with implementation. Technical, training, and cost challenges are all associated with the implementation of AOA indicators. Some of those issues will be discussed in this section. Certainly, this will not serve as a comprehensive list of the challenges to be faced but will pose some key questions/issues that need to be addressed through research and debate.

AVIATION COMMUNITY PERCEPTIONS

One of the key issues is the debate among the aviation community about whether AOA indicators should be included on the PFD. There are questions within the community about whether the existing stall protection systems on transport category airplanes are sufficient or whether AOA indicators would offer any added value. Many experts feel that current stall protection systems adequately mitigate stall risk and the addition of an AOA indicator would unnecessarily add clutter to the PFD. Other safety experts and pilots feel that AOA indicators could significantly improve safety. When speaking about the Air France Flight 447 crash, Captain Chesley Sullenberger stated: “We have to infer angle of attack indirectly by referencing speed. That makes stall recognition and recovery that much more difficult. For more than half a century, we've had the capability to display angle of attack in the flight decks of most jet transports, one of the most critical parameters, yet we choose not to do it.” [42]

As shown earlier in the literature review, few studies have been performed assessing the benefits of AOA indicators for commercial transport airplanes. Objective research on AOA indicator effectiveness is needed to properly determine whether AOA indicators offer additional benefits to existing stall protection systems.

TRAINING

In a number of studies on AOA indicator effectiveness, the need for proper pilot training was highlighted. Without proper training, experiments often showed that AOA indicators have little benefit (or in some cases a detrimental effect). Even in the first AOA indicator study performed in 1958, the author noted that the test pilots found the AOA indicator useless until they were properly trained. After training, pilots who originally opposed the AOA indicator began to see the benefits [6].

To implement the use of AOA indicators, guidelines for pilot training must be carefully crafted. The pilot training must address proper use of the AOA indicator, including upset avoidance/recovery and diagnostics. Past studies on AOA indicator training have emphasized that pilots should be trained to use AOA as a supplementary parameter and not a replacement for airspeed.

Research and SME input will be needed to formulate training guidelines. Any proposed training guidelines should be supplementary to existing upset training recovery guidelines, such as the Airplane Upset Recovery Training Aid [31], guidelines from the Upset Prevention & Recovery Training Association [30], FAA Advisory Circular (AC) 120-111 [33], AC 120-109A [34], and the International Civil Aviation Organization (ICAO) manual on upset prevention and recovery

training [18]. Experiments using simulators need to be crafted to test training programs to find the most effective guidelines.

STANDARDIZATION OF DISPLAYS

AOA can be displayed in a number of different units and display types. This poses the question of whether AOA presentation in the flight deck should be standardized. For example, one possible research question is: Should AOA displays show true AOA or normalized units? Experimentation is needed to determine whether certain display configurations are more effective than others. This may lead to the need for standardization to realize the maximum benefits of AOA indicators [35]. Future standards could build on existing standards for displays such as SAE AS8046 section 4.2 [43] and ASTM F3011-13 section 5 [44].

COST

As in any practical problem, cost is an issue. Possible sources of cost include research into safety benefits, changes to the PFD, adding instrumentation to the aircraft, creating and implementing training programs, and developing policies/guidance of AOA indicator design and implementation. The cost/benefit for all stakeholders (including operators, manufacturers, the flying public, and regulatory agencies) must be considered.

TECHNICAL CHALLENGES

Integrating an AOA indicator in a modern flight deck will pose a number of technical challenges. First, the stall characteristics of Part-25 aircraft are much more complex than that of a GA aircraft. The lift curve slope for straight-winged aircraft is steeper, and the break is more pronounced; therefore, the principal stall characteristic for GA aircraft is a pitch break. Conversely, this is not the case for Part-25 aircraft. Additionally, the stall point for Part-25 aircraft is dependent on Mach number and effects caused by configuration, thrust, spoilers, and asymmetric flaps [5, 43]. The large number of parameters that contribute to identifying the stall point of a Part-25 aircraft could make systems more complex, possibly introduce new avenues for failure or false alerts, and impose difficulties on the design of an AOA display.

Another complication is that the AOA indicator might show conflicting information to instruments found on the PFD when a rapid change in AOA occurs. A raw data AOA indicator would respond quickly to a change in AOA. Conversely, stall margin information currently found on the PFD is often based on smoothed AOA data and will take time to show changes in AOA. Therefore, the two instruments might provide the pilot with conflicting information. The consequences of this effect need to be carefully studied to mitigate negative outcomes.

CONCLUSION

Over the past 60 years, a number of angle of attack (AOA) indicators have been developed, implemented, and studied. The key feature of AOA indicators is their ability to mitigate the risk of loss of control-inflight accidents. AOA is such an important parameter because it is a direct indication of lift coefficient of the wing and, therefore, provides stall margin information. Because AOA is independent of speed, it can also be used to help diagnose a pitot/static system failure.

AOA can be displayed in the flight deck in a variety of ways, such as dials or color-coded AOA indexers. The most common application for AOA indicators is in military airplanes because the indicators are useful when performing maneuvers at the extremes of the flight envelope. AOA indicators are currently gaining popularity in the general aviation (GA) community because of recent reduction in prices and relaxed regulatory hurdles.

In most commercial transports, AOA is not directly displayed in the cockpit; rather, stall warnings such as the stick shaker, stick pusher, pitch limit indicator, and other visual, tactile, and aural cues are used. Debate remains about whether an actual AOA indicator would be useful in commercial transports because of the number of stall warning systems and envelope protection that are already present in the flight deck.

Several studies have been conducted on the effectiveness of AOA indicators, but most of the research was focused on military and GA applications. The studies often focused around determining the effectiveness of AOA indicators with respect to upset avoidance and recovery and/or pitot/static failure diagnostics. In general, the findings were not conclusive. In military studies, there was an improvement in a pilot's ability to perform advanced maneuvers with training; however, a pilot would be unlikely to encounter the extreme conditions tested in a commercial airliner. Very little conclusive evidence was found that AOA indicators significantly improved a pilot's ability to avoid or recover from an upset in GA applications. Nonetheless, the studies assessing a pilot's ability to maintain control during an airspeed indicator failure did show some promising results. In most of the studies, the researcher concluded that pilot performance during a pitot/static failure was improved with an AOA indicator.

In addition to the effectiveness studies, reports from the NASA ASRS database cited several examples of AOA indicators being used for stall prevention/recovery and to diagnose an airspeed indicator failure. The examples from the database demonstrate operational use of AOA indicators in relation to real-world scenarios and could be used to develop follow-on simulator studies.

The information reviewed for this literature study found that AOA indicators do provide some potential benefits in the military and GA communities, but further evaluation is needed to determine the effectiveness of AOA indicators for transport category airplanes. Additionally, many challenges need to be addressed, such as training, standardization, cost, and integration into the flight deck. To address these challenges, carefully crafted experiments need to be conducted to provide objective evidence on the effectiveness and best practices for AOA indicators in commercial transports.

REFERENCES

1. Boeing. (2016). "Statistical Summary of Commercial Jet Airplane Accidents: Worldwide Operations 1959-2015," Aviation Safety: Boeing Commercial Airplanes, Seattle, WA.
2. Lambregts, A., Nesemeier, G., Wilborn, J., and Newman, R. (2008). *Airplane Upsets: Old Problem, New Issues*. Presented at the AIAA Modeling and Simulation Technologies Conference and Exhibit, Honolulu, HI.
3. CAST JSAT Report. (2000). JSAT Loss of Control Results and Analysis.
4. CAST. (2014). ASA - Research - Attitude and Energy State Awareness Technologies
5. Anderson, J. D. (2008). *Introduction to Flight* (6th ed.) Hackett, M. (Ed.), New York, NY: McGraw-Hill.
6. NASA Report. (2014). Review of Research on Angle-of-Attack Indicator Effectiveness (NASA/TM-2014-218514).
7. Cashman, J. E., Kelly, B. D., and Nield, B. N. (2000). Operational use of angle of attack on modern commercial jet airplanes. *Aero Magazine*, 12.
8. Pope, S. (2011). The Missing Instrument. *Flying Magazine*.
9. Alpha Systems AOA. (2016). Retrieved from: <http://www.alphasystemsaoa.com/>. [Accessed 27 September 2016].
10. Basic Air Data. (2016). *In Flight Angle of Attack Usage*. Retrieved from: <http://www.basicairdata.eu/knowledge-center/measurement/in-flight-angle-of-attack-usage/>. [Accessed 27 September 2016].
11. Colgren, R. D., Frye, M. T. and Olson, W. M. (1999). *A Proposed System Architecture for Estimation of Angle of attack and Sideslip Angle*. Presented at the AIAA Guidance, Navigation, and control Conference and Exhibit, Portland, OR.
12. Euston, M., Coote, P., Mahony, R., Kim, J. and Hamel, T. (2008). *A complementary filter for attitude estimation of a fixed-wing UAV*. Presented at the 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems, Nice, France.
13. Lai, Y. C. and Jan, S. S. (2011). Attitude estimation based on fusion of gyroscopes and single antenna GPS for small UAVs under the influence of vibration. *GPS Solutions*, 15(1) 67–77.
14. Watson, J. (2013). *Aerospace Sensors*, Nebylov, A. (Ed.) New York, NY: Momentum Press.

15. U.S. Department of Transportation: FAA (2014). *Aviation Maintenance Technician Handbook*, 15 May 2014. [Online]. Retrieved from https://www.faa.gov/regulations_policies/handbooks_manuals/aircraft/amt_airframe_handbook/media/ama_Ch10.pdf. [Accessed 3 June 2015].
16. NACA Report. (1958). Summary of Methods of Measuring angle of Attack on Aircraft (NACA TN 4351).
17. USAF Report. (1972). ATC Angle of Attack Training (AD0757243).
18. ICAO Report. (2014). Manual on aeroplane upset prevention and recovery training. (Doc 10011, AN/506).
19. NASA Report. (1964). A Review of the Stall Characteristics of Swept Wings. (NASA TN D-2373).
20. Dodt, T. (2011). Introducing the 787. Retrieved from: <http://www.isasi.org/Documents/library/technical-papers/2011/Introducing-787.pdf>. [Accessed 15 September 2016].
21. Airbus. Response to Stall Warning Activation at Takeoff. Retrieved from: http://www.airbus.com/fileadmin/media_gallery/files/safety_library_items/AirbusSafetyLib_-FLT_OPS-TOFF_DEP-SEQ08.pdf. [Accessed 23 February 2016].
22. Rockwell Collins Flight Dynamics. (2002). *HGS Pilot Guide for the Bombardier CRJ700*. Portland, OR.
23. Dunn, R. (2011). The AOA Indicator: Small Device, Huge Impact. *The Naval Safety Center's Aviation Magazine*, 9–10.
24. FAA Report. (1969). Angle of Attack Presentation in Pilot Training. (FAA-DS-69-6).
25. FAA Report. (1968). Evaluation of Angle of Attack Instrumentation in the Training of Student Pilots for Private Pilot Certification. (FAA-DS-68-19).
26. Advisory Group for Aerospace Research & Development. (1972). "AGARD Conference Proceedings No. 106 on Handling Qualities Criteria."
27. Unknown (1966). Attack Angle Device Seen Aid to Piloting. *Aviation Week & Space Technology*, 67–73.
28. Tuomela, C. H. (1965). "Angle of Attack as an Aid to Flying," in SAE National Aeronautic Meeting. DOI: 10.4271/650250
29. Air Safety Week (1999). "Angle of Attack Displays Could Enhance Safety." Retrieved from http://findarticles.com/p/articles/mi_m0UBT/is_34_13/ai_55550142/

30. Brooks, R., Ransbury, P. and Stowell, R. (2014). Addressing on-aeroplane upset prevention & recovery training: Primary considerations for the safe and effective delivery of UPRT. Retrieved from: <http://www.UPRTA.org> .
31. Carbaugh, D., Rockliff, L. and Vandell, B. (2008). Airplane upset recovery training aid revision 2. Retrieved from: https://www.faa.gov/other_visit/aviation_industry/airline_operators/training/media/AP_UpsetRecovery_Book.pdf.
32. FAA. (2008). Airplane upset recovery: High altitude operations. Airplane Upset Recovery Training Aid Team, Revision 2. Retrieved from: http://www.faa.gov/other_visit/aviation_industry/airline_operators/training/media/Appendix_3-E_HighAltOperations.pdf .
33. FAA Report. (2015). Upset Prevention and Recovery Training. (AC 120-111).
34. FAA Report. (2015). Stall prevention and recovery training. (AC 120-109A).
35. Karwal, A. (2014). *Angle-of-attack display in modern commercial aircraft - Do we need that?*. Paper presented at the ICAO LOC-I Symposium, Montreal, CAN.
36. NASA. Aviation Safety Reporting System. Retrieved from: <https://asrs.arc.nasa.gov/>. [Accessed 2 June 2017].
37. Boesser, C. T. (2013). *The Effects of Angle-of-Attack Indication on Aircraft Control in the Event of an Airspeed Indicator Malfunction* (Thesis). Embry-Riddle Aeronautical University, Daytona Beach, FL.
38. Fischel, J., Butchart, S., and Robinson, G. (1958). *Flight studies of problems pertinent to low-speed operation of jet transports*. Presented at the NSAS Conference on Some Problems Related to Aircraft Operation, Langley Field, VA.
39. FAA Report. (2018). Angle of Attack Equipment in General Aviation Operations. (DOT/FAA/TC-18/28).
40. NTSB. (1996). Safety Recommendation A-96-90.
41. FAA. "NTSB Recommendations, American Airlines Flight 965," [Online]. Available: http://lessonslearned.faa.gov/American965/NTSB_recommendations.pdf. [Accessed 2 June 2017].
42. Thomson, J. (2013). *Situation Awareness and the Human-Machine Interface*. Retrieved from: http://www.safetyinengineering.com/FileUploads/Situation%20awareness%20and%20HMI_1369663651_2.pdf. [Accessed 31 August 2015].

43. SAE AS 8046: SAE International: 1992: Minimum Performance Standard Angle of Attack Equipment.
44. ASTM Standard F3011-13 “Standard Specification for Performance of Angle of Attack System” ASTM International, West Conshohocken, PA, 1992, www.astm.org.
45. Lie, P. (2014). *Synthetic air data estimation: a case study of model-aided estimation* (Dissertation). University of Minnesota, Minneapolis, MN.
46. Morelli, E. A. (2012). Real-time aerodynamic parameter estimation without air flow angle measurements. *Journal of Aircraft*, 49(4) 1064–1074.