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The effects of using an angle of attack system on pilot performance and workload during selected phases of flight

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Abstract

In-flight loss of control (LoC-I) is the number one fatal accident category for light airplanes.The most common type of LoC-I accident involves a stall/spin and inadequate airspeed management and is frequently cited as a causal factor.An aircraft stalls when the critical angle of attack is exceeded and this may occur at any indicated airspeed, hence the use of airspeed as an indication to the proximity to stall is unreliable.This is of particular importance during the take-off, approach and landing where stall margins are reduced.Military aircraft commonly use angle of attack (AoA) devices to indicate proximity to the stall and these have been in continuous use for almost 60 years.More recently, with the simplification of light airplane design approval requirements, an increasing number of AoA designs are appearing on the market, installed in light airplanes to complement airspeed indication and stall warning systems, to notify pilots of proximity to the stall.This paper reviews a selection of current types of AoA devices and presents the preliminary results of practical flight testing and flight simulation experiments to investigate the effects of using an AoA on pilot performance and workload during selected phases of flight.The results have implications for the operational use of current AoA devices and future AoA design.

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*Keywords:*Angle of attack; Loss of control; Workload; Stability

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1. Introduction

1.1. History

In April 2011, the General Aviation Joint Steering Committee (GA-JSC) chartered the Safety Analysis Team (SAT) to conduct a review of fatal GA accidents from 2001 through 2010 in the United States.The GA-JSC is a joint Federal Aviation Administration (FAA) and aviation industry group established with the goal of improving the safety in general aviation (GA).The GA-JSC's technical arm, the Safety Analysis Team (SAT), identifies safety issues and develops mitigation solutions and strategies for the GAJSC to implement in GA.The SAT reviewed 2,472 fatal general aviation accidents based on Commercial Aviation Safety Team/International Civil Aviation Organization (CAST/ICAO) Common Taxonomy Team (CICTT) categories and identified Loss of Control – Inflight (LOC-I) accidents as the most prevalent accident type with 1,259 fatal.Industry and Government have agreed to propose a data-driven approach to identifying high priority safety initiatives for GA and jointly agree to work toward the mitigation of accident causes.The LOC Working Group (LOC-WG) was formed by the FAA and GA industry to review GA accidents related to LOC and to recommend safety enhancements.Some of the safety enhancements recommended by the LOC-WG are pertaining to the usage of Angle of Attack (AoA) systems in GA aircraft.

Nomenclature

α	angle of attack (deg)
Υ	flight path angle (deg)
θ	pitch angle (deg)
h	height above ground (ft)
d	distance along ground (ft)
ω_P	phugoid natural frequency (rad/s)
g	acceleration due to gravity (ft/s^2)
V	true airspeed (kts)
w	vertical speed (ft/ s)
u	groundspeed (kts)

1.2. Definition

The Angle of Attack is the angle formed by the chord of the airfoil and the flight path of an aircraft.The AoA can be increased to balance reductions in speed in order to maintain liftup to a point referred to as the critical angle of attack.Beyond this angle, there is a subsequent loss of lift and the airfoil is now considered to be stalled.As a mitigation strategy, it has been proposed that the use of an AoA indicator in an aircraft will keep the pilot informed of the AoA related to the aircraft performance and margin from the critical angle of attack thus, allowing the pilot to reduce the risk of an inadvertent stall resulting in a loss of control.It is important to note that although this technology is readily available, AoA systems are not required equipment and are not widely used in the GA community.There has been evaluative work concerning the awareness of angle of attack and potential stall conditions by groups such as the American Bonanza Society, Aircraft Owners and Pilots Association (AOPA), Boeing, and others when utilizing Angle of Attack Displays for angle of attack awareness.The FAA is currently in the process of analyzing the impact that the usage of an AoA display might have on the stability of an approach.This research is being conducted through the PEGASAS FAA Center of Excellence.

1.3. Industry usage

Pilots that have adopted AoA displays verbalize the benefit that is to be gained in the understanding of the complete picture that is presented when AoA displays are utilized as a crosschecking tool with airspeed indicators and attitude indicators.Aviation practitioners have expressed the ease with which pilots can intuitively understand the AoA of the aircraft during a given phase of flight and understand the proximity to the critical angle of attack during critical situations such as takeoff and landing and will also assist in the approach phase by compensating for factors that sole references to airspeed cannot.

1.4. Available options

While the objective of AoA displays is to provide input to the pilots as a crosscheck mechanism for standard instrumentation andlike any other flight deck instrument, its proximity to the primary instrument scan and primary field of viewaffectsthe ease of interpretation which could play a factor in the utilization of this information.Although there are currently numerous choices from manufactures as to the basic design and functionality of AoA indicators, significant variation is evident (Fig. 1.).

This type of instrumentation is available as add-on technologies with relatively little maintenance intervention.In a letter published by the FAA Small Aircraft Directorate, AoA systems such as the ones displayed would be no more than a minor alteration to the aircraft for installation.When aircraft owners are considering the purchase of supplemental additional flight deck instrumentation, because of the cost of adding equipment using a FAA Form 337 or a Supplemental Type Certificate (STC) this would be an important consideration for not only the decision to purchase but also from which manufacturer.It is important to recognize that the method of interpretation and analysis especially as a crosscheck mechanism for instrumentation displays may vary substantially depending on the aircraft avionics suite and the AoA display that is installed.

Fig. 1.Examples of Angle of Attack Displays.

2. Literature review

2.1. Early usage

Angle attack systems have been used as an aid to flying since the first flight of the Wright brothers.The Wright brothers angle of incidence indicator consisted of a small vane and angle pointer attached to the outboard strut connecting the upper and lower wings [1].With the advent of high-speed heavy piston engine aircraft and jets in World War II and shortly afterwards the U.S. Navy was an early adopter of angle of attack technologies. The key driver for this was the need for controlled carrier deck landings from 1957 onwards with the majority of U.S. Navy aircraft being fitted with a variety of angle of attack measuring instruments [2]. Use of angle of attack and glide path indication became standard procedure for the U.S. Navy [3] since AoA is not affected by gross weight, bank angle, load factor, velocity, density altitude or position errors of the airspeed indicator and high angles of attack. To complement this, the U.S. Navy adopted the attitude flying technique [4], 'attitude plus power equals performance'.They noted that flying the correct AoA meant flying the correct airspeed is an essential requirement for a stable carrier approach and therefore used elevator as the primary means to control for airspeed and power setting as the primary means to control rate of descent. With regards to presentation of angle of attack, studies were conducted to assess whether or not the presentation of angle of attack information in pilot training would enhance pilot learning[5].The report concluded that there was no significant difference between pilot groups trained with or without angle of attack instrumentation fitted in combination with airspeed instrumentation.This indifference was attributed to the benefits of using AoA being negated by the additional learning required to use AoA and airspeed in combination.In addition, it was felt that contact (flying training) time was of more importance than ground school education time in the use of AoA.Notwithstanding these points, the study recommended further research should be conducted into the use of AoA in lieu of airspeed and for the use of AoA in instrument flight.

2.2. Early research

In 1969 NASA conducted an in-flight evaluation of the use of an angle of attack system fitted to a modified Piper PA-30 Twin Comanche [6]. The assessment was conducted to investigate safety improvements in performance and flight safety with the use of angle of attack systems using a wing-mounted vane and electronic computer unit.The first test programme focused on flying in the low speed region of flight where accident rates are notably their highest [7].Limited benefits were realized and the report concluded that the use of angle of attack did not represent significant improvement in performance or safety. It should be noted that the test aircraft used was a relatively low powered twin engine aircraft, atypical of the general aviation fleet.It is likely that the undesirable longitudinal phugoid and lateral/directional stability and substantial time lag in the display of AoA (up to 2 seconds), contributed negatively to this overall assessment [8]. A study in the 1980s considered pilot workload during the carrier landing whilst using AoA systems[9], however this study used subjective pilot evaluation only and this challenging flying environment demanded compensatory, pursuit and pre-cognitive pilot behavior.Heffley's study did suggest that pilot workload increased during the approach as a result of the phugoid mode being triggered during the turn to finals.Previous studies have therefore lacked general aviation context, and quantitative and qualitative assessment of pilot workload and performance.

2.3. Current trends

Despite these apparent limitations, AoA systems have grown in popularity in the general aviation sector since the 1980's. With the recent FAA relaxation of certification requirements [10] there has been a proliferation of AoA systems on the market. Different methods of sensing and presenting AoA highlight the lack of standardization in the market which might prove problematic to widespread adoption. In addition, there is a lack of education and training material concerning the use of AoA either from the FAA as overarching guidance or from manufacturers on the application of specific usage of the display.Display interpretation is covered thoroughly by manufacturers for their specific systems, but best practice applications as well as educational guidance is not as robust.The effects of the use of AoA on pilot workload are yet to be determined.

3. Theory

3.1. Flying an approach

In general aviation flying,a pilot of average ability is performing a compensatory tracking task [11].After selecting the aiming point and establishing the fligthpath and considering the longitudinal pitch axis only, the pilot makes small continuous adjustments to airspeed and rate of descent to maintain the desired fligthpath.Airspeed and rate of descent may not be managed directly but rather by use of pitch attitude ('pitch controls airspeed') and power ('power controls rate of descent') as surrogates [4].Managing the fligthpath requires adjustment of two cross-coupled parameters using primary (pitch stick) and secondary (engine power) control inputs.As a side note, the mantra of "pitch controls airspeed and power controls rate of descent" is not accepted as a standard for approach and landing by all pilots.For the purposes of this paper, the former technique is highlighted.

The fligthpath angle,ϒis given by:

$$\gamma = \tan^{-1}\frac{h}{d} \quad (1)$$

h and d may be obtained by integrating rate of descent, w and groundspeed u, with respect to time.The rate of descent w, is presented to the pilot in the cockpit via the vertical speed indicator, however the ground speed is not.

When angle of attack is presented to the pilot in the cockpit environment then this may be used to directly manage the fligthpathangle ϒ and may be approximated by [12] :

$$\Upsilon = \theta - \alpha \quad (2)$$

3.2. External variables

Normally in flight, however an aircraft is rarely completely undisturbed in the trimmed flight condition.The aircraft may encounter disturbance from a number of external and internal sources:

External (environmental) factors:

- wind gusts;
- turbulence;
- windshear.

Pilot (control input) factors:

- intentional manoeuvring (e.g. base to finals turn);
- intentional (& abrupt) pitch control;
- significant configuration change (e.g. flap deployment);
- significant change in power setting;
- significant& abrupt change in elevator trim.

These factors in isolation or combination inevitably trigger the aircraft's phugoid or long period oscillation mode [13]. This is usually a lightly damped, low frequency oscillation in speed u, which is coupled with pitch attitude θ and height h.One noticeable characteristic of this mode is that the angle of attack α, remains predominantly constant throughout.The frequency of the phugoid mode is inversely proportional to the steady trimmed airspeed about which the mode oscillates and damping is almost zero [14].The frequency of the phugoid mode may be approximated to:

$$\omega_p = \frac{g}{V}\sqrt{2} \quad (3)$$

The phugoid mode sometimes referred to as the 'nuisance mode' usually appears to the pilot as a trimming problem. During the approach, the typical light airplane exhibits reduced longitudinal static stability [15] and in combination with an excited phugoid mode at increased frequency (due to reduction in airspeed) as airspeed may result in significantly higher workload for the pilot when compared to management of angle of attack,α since this remains largely constant during the mode.

4. Pilot utilization of angle of attack equipment for aircraft control

4.1. Pilot objective

Despite all the aerodynamic, internal, and external variables highlighted earlier, the ultimate objective of any display, sensor, or instrument inside an aircraft is to provide information to the pilot that can be utilized for aircraft control in an intuitive manner.The type of sensors, displays, and understanding of the system plays a vital role in the workload necessary for the pilot to incorporate the information in a beneficial manner.The resulting pilot performance can be attributed to the synergy of these factors with an understanding of the information that is being presented.Being able to discern the angle of attack of an aircraft is a skill that comes over time.A new student pilot may understand the concept of angle of attack, be able to draw the components that are used to determine the angle of attack, and even measure the angle of attack from representative aircraft being flown along pre-determined flight paths.But to "see" the angle of attack of the wing in the dynamic flight environment as it's happening real-time can be difficult at first.Over years of experience the pilot starts to pick up on subtle cues that help to discern the angle of attack and the pilot will start to be able to see the developing flight path and in conjunction with the wing orientation be able to determine the approximate angle of attack.The pilot can also start to pick up on cues that shift the angle of attack either subtlety or in an aggressive fashion.Not to say that this change happens without expending effort and there are occasions where the pilot doesn't perceive these changes due to fixation or omission.High pressure situations such as when dealing with emergencies or encountering unfamiliar environments such as with non-standard airport layouts or environments can cause the pilot's ability to perceive the angle of attack to degrade.It is in these situations where an angle of attack device can level the playing field and minimize the workload necessary to either obtain a skillset or to supplement the mental capacity so that the level of performance does not diminish.

4.2. Learning to "see" AoA

Pilots are supposed to understand that pitch and angle of attack are different.Pitch is the angle between the longitudinal axis of the airplane and a line tangent to the earth below the aircraft.The most common reference that the pilot can use to approximate the longitudinal axis is the nose of the airplane.While this isn't always directly in line with the longitudinal axis, it is a good approximation of the forward tip of the longitudinal axis for most airplanes.The earth is readily visible in most situations so it's pretty easy to determine an approximate pitch since the references are physically visible to compare against each other.Angle of attack is the angle between the chord line of the wing and the relative wind.The relative wind is equal and opposite to the flight path of the airplane.There is no physical representation of the flight path and therefore it must be derived by interpretation of the movement of the aircraft and a determination of the trend of flight.Much like the longitudinal axis of the airplane, the chord line is also not technically visible, but the nose is a good approximation.So to determine the angle of attack the pilot must compare the nose of the airplane to the flight path.To increase the complexity of the situationthe pilot uses a common reference point of the nose to determine pitch and angle of attack which makes it easy to confuse.Furthermore, the angle of attack and the pitch attitude are very close to each other in most instances.In these instances, angle of attack devices could be used as an educational tool to help new pilots see how pitch and angle of attack are different.A simple maneuver can be conducted as follows:-

1. Achieve a stable altitude with power to maintain target airspeeds for an approach
    a. Ideally the aircraft will be trimmed for level flight
2. Place power at idle and maintain a constant pitch
    a. In most aircraft this will require back elevator movement unless the aircraft has a "T-tail"

3. The flight path will shift downward and the resulting angle of attack will increase
   a. This increase in AoA can be seen by the movement in the AoA display

A comparison of the constant pitch attitude with shifting AoA should allow the student pilot to help solidify the different between AoA and pitch and be a powerful toolin the educational technique of primary flight instructors.

4.3. Understanding the limitations and interpreting the display

As demonstrated earlier, there are multiple types of displays that are available and it is largely a decision based upon personal preference.It is important to understand that each type of display has capabilities and limitations and should be understood fully before being utilized in high risk environments.A substantial aspect to the successful utilization of the device is the seamless interpretation of the display and the corresponding ability of the pilot to translate that into aircraft control.If the pilot has to process too much information to interpret the display and then correlate that with a corrective input then the amount of workload that is placed on the pilot could have a detrimental effect to the safety of the flight.This is especially true during high pressure situations where timely interpretation and response are necessary.Just as there are visual, auditory, and tactile learners, there are differences in each pilot’s ability to interpret displays.While some pilots may find it easier to interpret a dial with numbers other pilots may find it easier to interpret a display with striations and differences of color.And if the striations are bent into a curved shape or an angular representation it is important to determine if the direction of perceived “pointing” matches with the pilot’s interpretation and therefore correlates correctly with the necessary flight control input.If this assessment isn’t done correctly, the amount of workload for the pilot will increase and may result in a corresponding decrease in performance or ability.

4.4. Workload

There are two common statements by experienced pilots when first being exposed to an angle of attack device; “This makes it so easy to fly an approach” and/or “This instrument doesn’t add anything to my ability to fly the airplane”.While both of these statements may be true in a normal approach, it is the deviation from the norm that can highlight an angle of attack device’s true value.The effect of an angle of attack device on the workload necessary to perform a given task is a complex dynamic that isn’t fully understood at this point in time.As mentioned earlier, there are many types of displays that can affect the interpretation by the pilot and if the display isn’t selected carefully it could increase the workload necessary to conduct a stable approach.These types of situations would result in a response by the pilot similarly to the latter statement.If paired correctly, and the situation under which the display is being utilized is different enough than the type of approach than the pilot normally conducts then the display is seen as a valuable asset.These types of situations would result in a response by the pilot similarly to the first statement.Further work will need to be conducted to fully understand the affect that an angle of attack device has on the workload necessary for safe operations.

5. Discussion

5.1. Possible benefits

The primary benefits highlighted in this paper include an ability to use AoA displays as an educational tool, a potential tool for workload reduction, and an informational tool for pilot performance.To this point, however, the incorporation of an AoA display is still largely a personal determination.The pilot population within the United States, the United Kingdom, and around the World is quite diverse in their certification requirements, degree of activity, and the complexity of the operating environment.The process by which a pilot becomes certified to fly an aircraft and the expectation for maintaining proficiency also vary.The ultimate objective, however, remains a reduction in the accident rate of LOC-I occurrences and the mitigation of disturbances that can create dynamic situations that could lead to flight path departure.The phugoid mode was discussed earlier and while pilots may not experience the culmination of this phenomenon, the introduction of AoA displays could facilitate earlier detection and adjustments to impact variables such as power and configuration changes that tend to displace aircraft from a steady state.Additionally, AoA displays could reduce the workload necessary for a pilot to maintain a consistent level of flight path departure prevention with exacerbating factors.It is clear that the full understanding of the potential benefits of AoA displays hasn't been recognized and it's important to continue further investigation to fully understand the potential benefits of these systems to aviation safety.

6. Conclusion and recommendations

6.1. Future research

There is a lot that the aviation industry doesn't fully understand concerning AoA systems, displays, and their usage by pilots within the industry.Additional research still needs to be conducted to have a robust understanding of the true benefits of AoA systems.LOC-I is a dynamic issue that will require a multitude of strategies for successful mitigation.Human interaction with the displays and the potential for shortening the response time to displacements needs to have a more in-depth investigation as to which factors are consistent across all situations and which factors are important to consider for selective environments.This area of investigation is not a "one size fits all" resolution where all operations will be addressed with a singular system.

References

[1]Tuomela, C., Angle of Attack as an Aid to Flying, SAE Technical Paper 650250, 1965.
[2]Gracey, W., Summary of Methods of Measuring Angle of Attack on Aircraft, NACA Technical Note 4351, National Advisory Committee for Aeronautics, Washington DC, August 1958.
[3] Hurt, H.H., Aerodynamics for Naval Aviators, Navair 00–80T–80, Naval Air Systems Command, US Government, Washington, USA, 1960, pp 358 – 359.
[4]Hurt, H.H., Aerodynamics for Naval Aviators, Navair 00–80T–80, Naval Air Systems Command, US Government, Washington, USA, 1960, pp 327.
[5] Forest F.G., Angle of Attack Presentation in Pilot Training, Report Number DS – 69 – 6, Department of Transportation, Federal Aviation Administration, Aircraft Development Service, Washington DC, March 1969.
[6]Gee, S.W., Gaidsick, H.G. & Enevoldson, E.K., Flight Evaluation of Angle of Attack as a Control Parameter in General Aviation Aircraft,NASA Technical Note, NASA TN D – 6210, National Aeronautics and Space Administration, Washington DC, March 1971.
[7]NTSB, "General Aviation Stall/Spin Accidents 1967-1969," Report Number NTSB-AAS-72-8, NTSB, Washington, USA, September 13, 1972.
[8] Fink, M.P. & Freeman, D.C.Jr, Full-scale Wind Tunnel Investigation of Static Longitudinal and Lateral Characteristics of a Light Twin-engine Airplane, NASA Technical Note, TN D–4983, National Aeronautics and Space Administration, Washington DC, January 1969.
[9]Heffley, R.K., Workload Oriented Model of the Carrier Landing, Paper Number 83-1, Proceedings of the 19th Annual Conference on Manual Control, MIT, Cambridge, Massachusetts, 23rd – 25 May 1983.
[10] FAA, AoA notice, February 2014.
[11] McRuer, D.T., Progress and Pitfalls in Advanced Flight Control Systems, AGARD Report no. CP-321, 1982.
[12] Cook, M.V., Systems of Axes and Notations, Chapter 2, Flight Dynamics Principles, 3rd Edition, Elsevier Aerospace Engineering Series, Oxford, UK, 2013, pp 20-21.
[13] Lanchester, F.W., Aerodonetics, Constable and Company Ltd, London, UK, 1908.
[14] Cook, M.V., Longitudinal Dynamics, Chapter 6, Flight Dynamics Principles, 3rd Edition, Elsevier Aerospace Engineering Series, Oxford, UK, 2013, pp 159-160.
[15] Bromfield, M.A., and Gratton, G.B. 'Factors Affecting the Apparent Longitudinal Stick-free Static Stability of a Typical High-wing Light Aeroplane'. Aeronautical Journal 116 (1179), 2012.