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Cumulative System Evaluation Report of 10 Commercial Off-the-Shelf Angle-of-Attack Sensors and Display Systems

October 2018

Final Report

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16. Abstract

An evaluation of commercially available general aviation angle of attack indication systems. The commercially available systems were compared to a calibrated truth source that was mounted to a GA aircraft. Each system was installed on a test aircraft, along with an angle of attack truth source, and flown through various maneuvers designed to evaluate the ability of the system to accurately and repeatably measure angle of attack. Test data was analyzed, and any deficiencies observed were reported Flight test and evaluation also considered human factors aspects of the systems display and associated interface. This evaluation also included a review of each system's calibration procedure. Recommendations are provided for both the manufacturer and FAA/ASTM to consider for improving the performance of non-required/supplemental angle of attack systems. The results of those tests are documented herein. A comparison of a derived AOA algorithm to a truth source was also completed as part of this report.

17. Key Words

Angle of attack, AoA

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LIST OF ACRONYMS

α	Angle of Attack
α_{norm}	Normalized Angle of Attack
°	Degree
AAG	Adaptive Aerospace Group, Inc.
AIAA	American Institute of Aeronautics and Astronautics
AoA	Angle of attack
ASI	Airspeed indicator
ASTM	American Society for Testing and Materials
CFR	Code of Federal Regulations
CL	Coefficient of lift
COTS	Commercial off-the-shelf
g	Gravitational force multiple
GA	General aviation
Hz	Hertz
ICA	Instructions for Continued Airworthiness
L	Lift
LED	Light emitting diode
LSA	Low speed awareness
MGW	Maximum gross weight
NACA	National Advisory Committee on Aeronautics
n_y	Lateral acceleration (g)
n_z	Normal acceleration (g)
OAA	Optimum angle of attack
OEM	Original equipment manufacturer
V_{FE}	Maximum flaps extended speed
V_{MO}	Maximum operating limit speed
V_{NE}	Never-exceed speed
V_{REF}	Reference landing speed
V_S	Stalling speed
V_{S0}	Stalling speed in the landing configuration
V_{S1}	Stalling speed in the specified configuration
V_{SW}	Stall warning speed

EXECUTIVE SUMMARY

This research was conducted as the result of a concern within the FAA's Small Airplane Directorate regarding AIR Policy Memo AIR100-14-110-PM01, "Approval of Non-Required Angle of Attack (AoA) Indicator Systems." This policy memo provides relief from typical design approvals to manufacturers of non-required/supplemental angle-of-attack systems. The purpose of the research conducted was to evaluate all of the commercial off-the-shelf angle-of-attack systems available. Each system was installed on a test aircraft, along with an angle-of-attack truth source, and flown through various maneuvers designed to evaluate the ability of the system to accurately and repeatedly measure angle of attack. Test data were analyzed, and any observed deficiencies were reported. It was found that some commercially available angle-of-attack systems, manufactured and installed under AIR100-14-110-PM01, have characteristics that result in false indications of positive stall margin. However, the majority provided safe and appropriate indications throughout the conditions tested. Flight tests and evaluations also considered human factors, aspects of the system's display, and associated interface. This evaluation also included review of each system's calibration procedure. Recommendations are provided for manufacturers and FAA/American Society for Testing and Materials (ASTM) to consider for improving the performance of non-required/supplemental angle-of-attack systems.

1. INTRODUCTION

1.1 PURPOSE

This report summarizes the findings developed through a test program in which 10 angle of attack (AoA) display and measurement systems were subjected to a battery of tests to assess their accuracy, reliability, error susceptibility, and to evaluate the human factors of their installation, calibration procedures, and display effectiveness.

This report does not provide specific detail on the manufacturers or the model numbers of the hardware evaluated. Rather, it is a general summary describing the technologies and implementations available in the commercial off-the-shelf (COTS) market for installation onto certified and experimental aircraft.

Technical and specification recommendations based on research and observations of the test team will be provided with goals of standardizing display characteristics, identifying and minimizing error sources, providing safe and repeatable calibration techniques, and optimizing systems for low speed awareness (LSA).

2. PROGRAM DESCRIPTION

2.1 REGULATORY BACKGROUND

Prior to February 2014, AoA instrumentation required certification for installation onto a Title 14 Code of Federal Regulations (CFR) Part 23 certified aircraft. Although there is no 14 CFR 23 certification standard established for AoA systems, related requirements for this type of equipment include:

23.207	Stall warning
23.773	Pilot compartment view
23.1301	Function and installation
23.1308	High-Intensity Radiated Fields Protection
23.1309	Equipment, systems, and installations
23.1311	Electronic display instrument systems
23.1321	Arrangement and visibility
23.1322	Warning, caution, and advisory lights
23.1381	Instrument lights
23.1431	Electronic equipment
DO-160	Environmental Conditions and Test Procedures for Airborne Equipment
DO-178	Software Considerations in Airborne Systems and Equipment Certification

AoA has been commonplace in military aircraft for approach and LSA, and integrated into stall warning and stick push systems in commercial aircraft, for decades. Prior to 2014, AoA instrumentation had not had a large presence in General Aviation (GA)/14 CFR 23 light aircraft.

Targeting a reduction of low-speed loss-of-control accidents, the FAA instituted a policy on February 5, 2014 to provide a streamlined approval path for introducing AoA as a supplemental and non-required indicator into 14 CFR 23 certified aircraft (commuter categories excluded). Under the provisions of Policy Memo AIR100-14-110-PM01, COTS systems could be approved provided the following were met:

- System was designed to meet the requirements of ASTM F3011-13 Standard Specification for Performance of Angle of Attack System
- System operating instructions must include a test demonstrating that after calibration of the AoA system, it does not provide information conflicting with the stall warning from a certified stall warning system, if equipped.
- System must be a standalone unit and must not interface with a certificated system (e.g., pitot-static system and stall warning) with the exception of supplying electrical power.
- System must not provide misleading information to the pilot (i.e., audible or visual cues that may conflict or interfere with the aircraft stall warning, if equipped)
- System placarded: “Not for use as a primary instrument for flight.”
- The AoA display will not interfere with the pilot’s view of the primary flight instruments.
- Installation instructions must include: “This AoA system has not been determined to be suitable for installation in any specific aircraft by (the AOA system manufacturer). It may be installed in a type certificated aircraft, provided that it has been determined suitable for installation by an appropriately rated mechanic by means such as field approval or as a minor alteration.”
- The AoA display cannot be placed in the cockpit in such a manner as to obstruct the pilot’s view or cause distraction.
- The AoA system must not replace or modify an existing approved stall warning system.

Since the release of this policy, several systems have been approved for installation onto certified aircraft.

2.2 ASTM F3011-13 REQUIREMENTS

ASTM F3011-13 does not prescribe a minimum performance standard or accuracy requirement. Rather, it requires the manufacturer to specify the equipment’s resolution, accuracy, and the range of sideslip angles over which the accuracy is valid. These are required to be validated by test of a representative system.

The minimum environmental requirements of ASTM F3011-13 are that the system not be adversely affected by rain, not damaged by exposure to icing conditions, and tolerate any approved de-icing fluids for which the airframe is approved. Beyond this, the manufacturer is to specify its operating temperature range, storage temperature range, operating humidity range, operating altitude range, operating airspeed range, and precipitation conditions for which it is approved.

Additionally, the system may not be a source of radio frequency emissions (DO-160E, §21.0, Category M is considered as satisfying this requirement), shall function over the entire voltage range of the aircraft if aircraft power is used, and meet voltage surge requirements.

2.3 EVALUATION SCOPE

Under the FAA policy statement, manufacturers seeking approval are required to submit documentation of compliance with ASTM F3011-13 and with the installation requirements of Policy Memo AIR100-14-110-PM01.

The scope and intent of the research program documented in this report was to independently assess a wide range of COTS AoA products with intent to audit and validate compliance with FAA policy and ASTM requirements; to evaluate and make a human factors assessment on the user interface/display; and assess the calibration procedures in terms of safety, repeatability, and stability.

2.4 FLIGHT TEST PROCEDURES

During the selection and qualification of this test program, the evaluation team submitted a generalized test plan outlining the intended test scope and procedures. A summary of the test scope includes:

- Evaluation of the system’s calibration procedure
- Accuracy throughout the speed range of the aircraft in all configurations
- Determination of sensitivity to sideslip
- Determination of sensitivity to temperature and altitude
- Determination of sensitivity to turning flight and load factor
- Evaluation of performance during normal and accelerated stalls
- Identification and evaluation of any unique attributes identified on the Unit Under Test
- Analytical consideration of system accuracy related to technology limitations

2.5 FLIGHT TEST EQUIPMENT

2.5.1 Aircraft

Three test aircraft were used throughout this program, all currently maintained under the experimental airworthiness designation and certified. All aircraft types were representative of certified designs and were aerodynamically conforming prototypes used by their manufacturer in the certification of their type design. Two were low-wing single engine propeller tractor-driven aircraft of approximately 3000 lb and 300 horsepower. The third was a single engine light jet of approximately 6000 lb and 2000 lb thrust.

The subject aircraft were maintained in accordance with airworthiness standards for their type certified designs and systems by appropriately licensed airframe and power plant mechanics.

2.5.2 Test Instrumentation

Specialized test instrumentation including test booms with AoA and angle-of-sideslip probes were used. The probes were calibrated and maintained in accordance with the standards required for test equipment under 14 CFR 23 aircraft certification programs. Their accuracies, maintenance, and calibration programs were documented.

Measurement and recording systems included a laptop operated Microsoft® Windows® LabVIEW™ application for continuous recording up to 10 Hz of analog system output, and a LabVIEW or C+ Windows® application for continuous recording of Aeronautical Radio Incorporated or RS232 output from systems providing that format up to 62 Hz.

Additionally, during several of the test maneuvers, 30 frames-per-second video was recorded of the AoA indicator to correlate the illumination of each display item with sensor output, ship stall warning, and test boom data.

2.5.3 Air Data and Attitude and Heading Reference System Parameters

The type design avionics systems onboard the test aircraft had built-in data logging capabilities to record the following parameters at 1 Hz: indicated airspeed, indicated altitude, lateral acceleration (n_y), normal acceleration (n_z), static air temperature, pitch attitude, roll attitude, heading, ground track, and Global Positioning Satellite time. Post-flight analysis allowed calculation of a secondary AoA reference during level and steady maneuvers (pitch attitude and flight path angle) following the techniques described in section 12.2 of reference 1.

3. AOA APPLICATIONS

3.1 TRADITIONAL LSA INDICATIONS

GA aircraft are typically equipped with an airspeed indicator (ASI) and a stall warning system (see figure 1). The ASI is required to have two markings relevant to LSA as shown in figure 1: a white arc terminating at maximum gross weight (MGW) landing flap stall speed, and a green arc terminating at MGW clean flaps stall speed.

Figure 1. Conventional airspeed indicator LSA markings

Speed margin from these arcs is not directly correlated with stall margin. At a lighter weight, the speed margin is conservative (i.e., the actual stall speed is lower than MGW stall speed). During maneuvering flight, with an increase in load, the margin is not conservative (i.e., actual stall speed increases). There is no speed margin reference or arc termination with intermediate flaps. The Aircraft Flight Manual publishes tables showing stall speed in each flap configuration at varying weight and a separate table with bank angle (load factor) influence. These tables are not immediately available during flight and are not a valuable aide to LSA during flight.

Additionally, ASI errors may be as high as 5 knots, which is allowed by FAA Technical Standard Order. ASI calibration may be further corrupted by use of the alternate static system or pitot-static system contamination.

Modern certified aircraft are also required to have a stall warning system, which is generally a discrete Active/Inactive indicator and aural tone. Stall warning systems are typically based on something other than airspeed, activating only after some critical threshold is exceeded (typically AoA sensed). It does not provide any sense of margin prior to or after activation, and does not provide any trend information.

Based on GA safety statistics, ASI markings and stall warning systems, although required by regulation and intended by design to be conservative, are not completely effective in eliminating LSA accidents.

3.2 NORMALIZED AOA CONCEPT

This section introduces a non-dimensional convention whereby AoA can be considered as a normalized value ranging from 0 when $C_L=0$ (zero lift) to 1 when $C_L=C_{Lmax}$ (stall). This is not a necessary step in AoA processing, but this convention will better illustrate how specific AoA targets are equivalent to stall margin.

Details and derivations can be found in APPENDIX A—Normalized AoA Description. A summary of relevant conclusions are included below.

Consider a basic lift curve slope, as shown in figure 2:

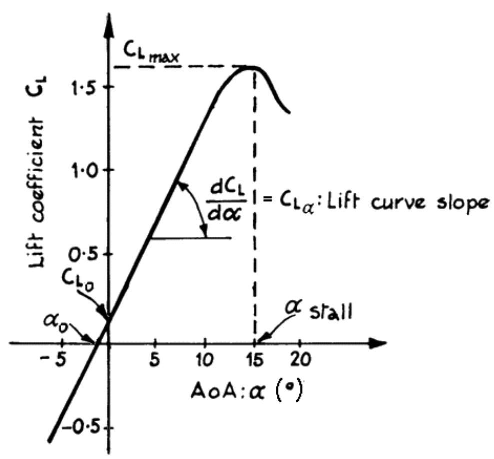

Figure 2. Lift curve slope

Knowing the zero lift AoA (α_o) and stall AoA (α_{stall}) in degrees, a non-dimensional scaling factor can be constructed for normalized AoA:

$$\alpha_{norm} = \frac{\alpha_{actual} - \alpha_o}{\alpha_{stall} - \alpha_o} \qquad (1)$$

Lift coefficient can be characterized as a simple linear function of that normalized parameter:

$$C_L = \alpha_{norm} \cdot C_{L\,max} \tag{2}$$

Lift coefficient will increase linearly from C_L=0 at zero lift AoA (α_{norm}=0) to C_{Lmax} at stall AoA (α_{norm}=1.0).

Using that convention and basic lift equation, some mathematical relationships can be established:

$$L = W = \frac{1}{2}\rho_o V^2 C_L = \frac{1}{2}\rho_o V^2 \alpha_{norm} C_{L\,max} \tag{3}$$

$$V^2 = \frac{2W}{\rho_o \alpha_{norm} C_{L\,max}} \tag{4}$$

At any desired speed multiple (i.e., *<u>Mult</u>*·V_S, where *Mult* is the desired multiple), a corresponding AoA target can be determined:

$$\alpha_{norm} = \frac{1}{Mult^2} \tag{5}$$

A reference approach speed of V_{REF}=1.3·V_S would be identical to α_{norm}= $(1/1.3)^2$ = 0.592.

With an appropriately calibrated system and indicator, maneuvering in pitch to maintain α_{norm}=0.592 would be precisely at V_{REF}.

Normalized AoA can also be mathematically shown to be:

$$\alpha_{norm} = \left(\frac{V_s}{V}\right)^2 \tag{6}$$

3.3 AOA APPLICATIONS

AoA is used in many commercial and military applications. When properly calibrated and integrated, it can provide better LSA by incorporating margin and trend information not available in traditional GA instrumentation.

Many key speeds are specific AoA targets (carrying over the normalized AoA concept), including:

Stall Speed (V_S)	As shown in APPENDIX A—Normalized AoA Description, stall is where α_{norm} = 1.0
Reference Approach (V_{REF})	As shown in APPENDIX A—Normalized AoA Description, V_{REF} is where α_{norm}= 0.592

Best Glide and Range

See APPENDIX A—Description for detail. As derived in that section, best lift-to-drag ratio AoA can be characterized as a distinct AoA and is purely a function of aerodynamic design parameters:

$$\alpha_{norm@best\ L/D} = \frac{\sqrt{C_{D_O}\pi eAR}}{C_{L_{Max}}} \tag{7}$$

Best Endurance

See APPENDIX A—Normalized AoA Description for detail. As derived in that section, best endurance AoA can be characterized as a distinct AoA and is purely a function of aerodynamic design parameters:

$$\alpha_{norm@best\ endurance} = \sqrt{3}\cdot\alpha_{norm@best\ L/D} \tag{8}$$

Cruise Efficiency

"Carson Cruise" is an efficient cruise point for a propeller aircraft. It is the point in which fuel flow per knot is at its minimum. A complete description and derivation for this can be found in [1]. It is summarized as:

$$\alpha_{norm@cc} = \frac{1}{\sqrt{3}}\cdot\alpha_{norm@best\ L/D} \tag{9}$$

Stall warn is not specifically an AoA-based target. It is defined by regulation as a minimum speed margin from stall. A suitable AoA target can be estimated assuming a stall speed of $V_s \approx 60$ knots (representative for light GA aircraft) and a 7 knot warn margin for desired $V_{SW} \approx 67$ knots. Following the relationship summarized in APPENDIX A—Normalized AoA Description, the following would satisfy this with appropriate but not excessive margin:

$$\alpha_{norm@sw} = \left(\frac{V_s}{V_{sw}}\right)^2 = \left(\frac{60}{67}\right)^2 \approx 0.80 \tag{10}$$

4. EQUIPMENT UNDER TEST

Under this research program, a total of 10 COTS AoA systems were evaluated. That included six FAA-approved systems for 14 CFR 23 aircraft under the 2014 policy, and four others not currently approved but serving as suitable reference points as to the availability and capability of technologies.

There are three basic sensor/probe types in use for AoA measurement: pressure, vane, and leading-edge tab. Each will be discussed in detail in this section. A summary of systems evaluated is shown in table 1.

Table 1. COTS AoA system types evaluated

System Number	AoA Probe Type
1	Pressure*
2	Pressure**
3	Pressure*
4	Vane
5	Pressure*

System Number	AoA Probe Type
6	Leading-Edge Tab
7	Vane
8	Vane
9	Vane
10	Vane

* Indicates q_c normalizing differential pressure system
** Indicates non-q_c normalizing differential pressure system

4.1 PRESSURE-SENSING PROBES

This section will address theory, observations, and recommendations unique to pressure-sensing-based AoA systems.

4.1.1 Aerodynamic Theory

Pressure-sensing AoA probes are based on the natural pressure distributions around a body in a flow stream. A simplified explanation is to consider the pressure distribution around a sphere or cylinder. Pressure at the stagnation point on the leading edge is high (q_c) and reaches a low at the points parallel to flow stream (see figure 3).

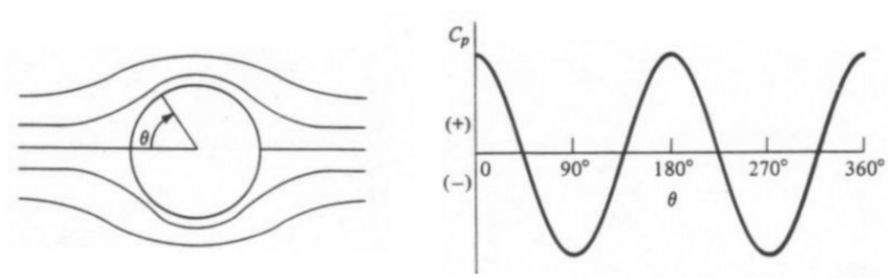

Figure 3. Pressure distribution around a cylinder

A pressure port on a fixed point on a probe body will sense a different pressure as the free stream direction of travel changes. Differential pressure measured between multiple ports on the probe surface will vary with flow angle. Reference 2 provides more detail on the aerodynamic theory.

The observed performance of one specific design is detailed in [3], and the theory is generally true for all ΔP systems. Testing demonstrated that over a reasonable range of flow orientations, ΔP varies linearly with AoA at any fixed flow speed (q_c), but that a different linear solution was provided at each different q_c. The study also demonstrated that the q_c influence was proportional and that when normalized by q_c, solutions converged on a single line [3] (see figure 4).

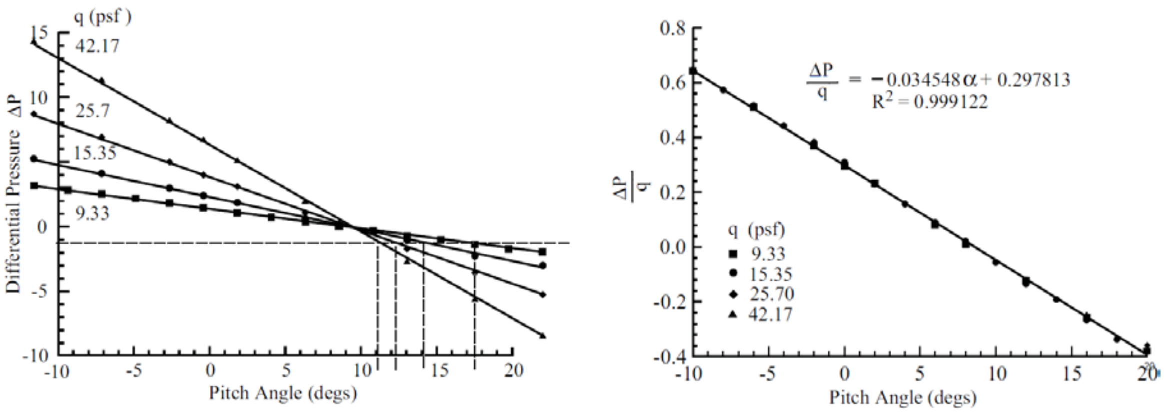

Figure 4. ΔP Variation with AoA and flow speed

Calibration shown in figure 4 is described by the equation below:

$$\frac{\Delta P_{AoA}}{q_c} = m_1\alpha + b_1 \tag{11}$$

For discussion purposes, m_1 and b_1 are considered probe parameters, characteristics of the probe design and its mounting angle only.

When installed on an aircraft, an added relationship is provided between AoA and q_c via the lift curve:

$$L = n_z W = q_c S C_L = q_c S\left(b_2 + m_2\alpha\right) \tag{12}$$

$$q_c = \frac{n_z W}{S} \cdot \frac{1}{m_2\alpha + b_2} \tag{13}$$

Where m_2 is the lift curve slope for that airfoil and b_2 is the lift coefficient at 0 degree AoA for that airfoil.

These two equations can be combined into a single equation for ΔP_{AoA}:

$$\Delta P_{AoA} = \frac{n_z W}{S} \cdot \frac{m_1 \alpha + b_1}{m_2 \alpha + b_2} \quad (14)$$

There are two key points:

1. ΔP sense alone (ΔP_{AoA} equation above) is influenced proportionally by weight and load factor, and the calibration will be unique for each flap configuration (different m_2 and b_2).
2. When ΔP is normalized by q_c ($\Delta P_{AoA}/q_c$ equation above), a single calibration of $\frac{\Delta P}{q_c}$ is possible and remains unaffected by weight or load factor.

During this test program, one COTS probe without q_c normalizing was evaluated. Its sensitivity to n_z/maneuvering load factor was shown to be non-conservative (see figure 5). At 2.5 g, when the aircraft reached an actual AoA of 12.5 degrees (stall warn in the test aircraft), the COTS AoA system output was the same provided in 1 g flight at an AoA of 8 degrees. In this case, the system provided a false sense of positive AoA margin by more than 4 degrees in maneuvering flight.

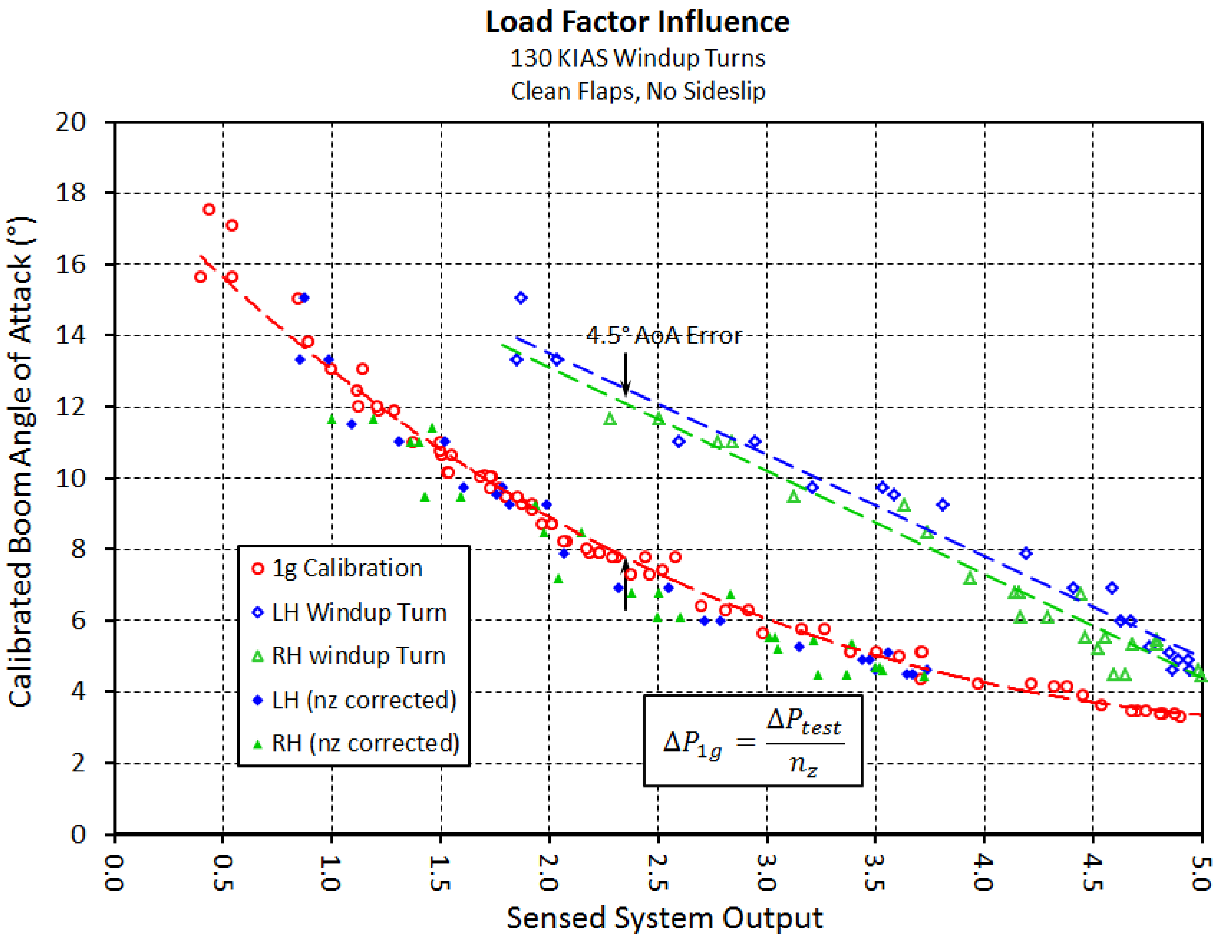

Figure 5. Load factor error without q_c normalizing (System 2)

As shown in figure 5, the load factor error was consistent with aerodynamic theory, and sensed data were capable of correction. An alternative to q_c normalizing, when considering load factor influence alone, would be incorporation of an accelerometer to measure actual n_z and correct the system output accordingly. Filtering would likely be required, and accelerometers tend to be "noisy," but the correction would be viable:

$$\Delta P_{corrected} = \frac{\Delta P_{sensed}}{n_z} = \frac{W}{S} \cdot \frac{m_1 \alpha + b_1}{m_2 \alpha + b_2} \tag{15}$$

Load factor influence is eliminated, but sensitivity to weight and flap configuration changes (changes m_2 and b_2) remain.

The same system was tested at light and heavy weights. A similar influence was observed, with heavy weights providing lower sensed AoA indications than light weight. Nearly a 1 degree AoA error was observed with a 600 lb weight change (see figure 6).

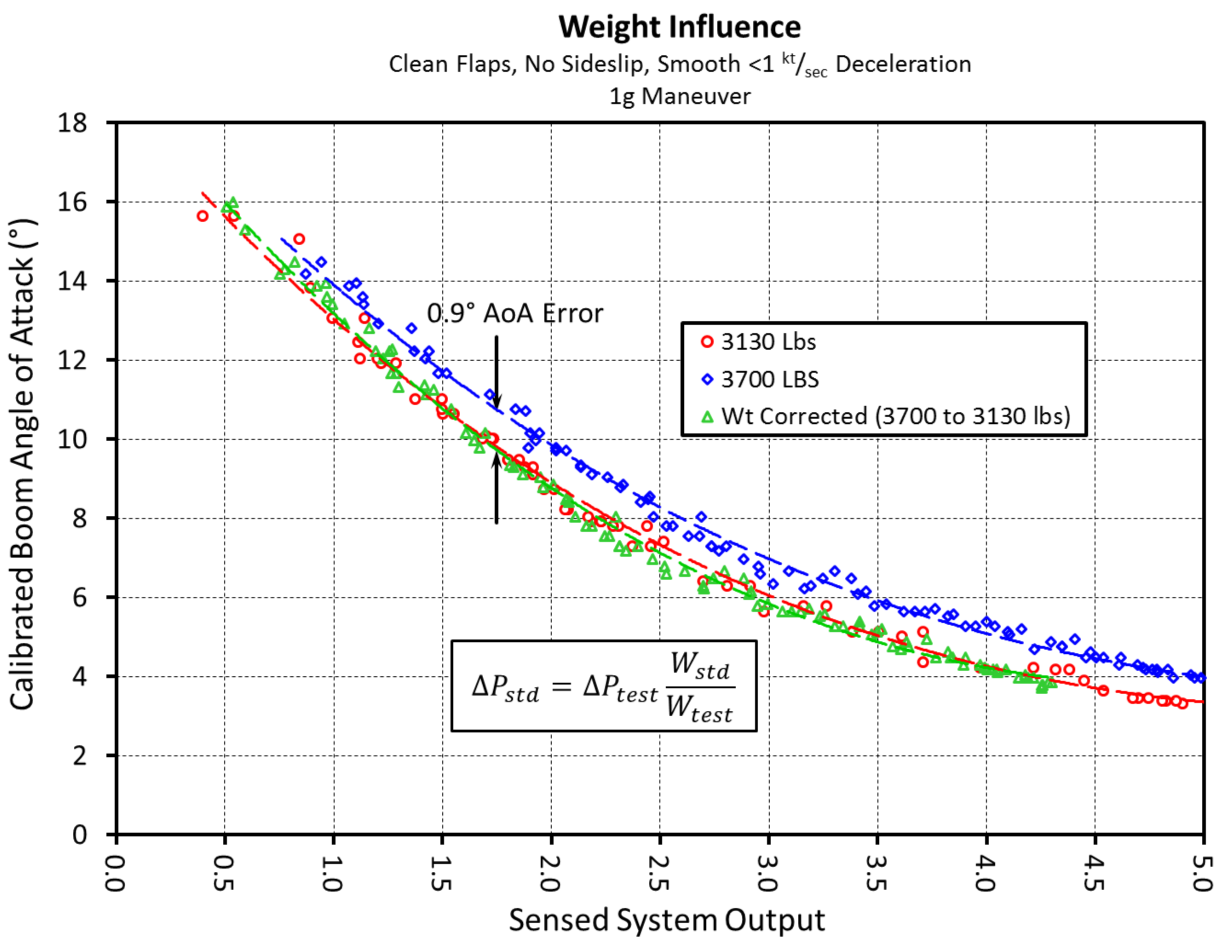

Figure 6. Weight induced error without q_c normalizing (System 2)

A non-q_c normalized system could be calibrated such that its display at maximum approved gross weight would provide suitable low-speed/AoA awareness. Flight at lighter weight would be conservative, indicating erroneously high AoA. That error would be conservative when considering LSA and that the magnitude of that error (less than 1 degree) is small enough that it would not tend toward excessive approach speeds or margins. It is important to note, however, that this calibration would remain susceptible to, and not compensate for, increased load factor errors as previously described.

4.1.2 Installation Considerations

4.1.2.1 Probe Location

The aerodynamic theory described above is based on free stream flow. In practice, the most suitable method of installation for a ΔP probe is under wing, similar to a pitot tube.

As shown in the wind tunnel flow field around an airfoil (see figure 7), the wing effectively behaves as a flow fence and aligns the local flow parallel to the wing skin. As the probe location is moved progressively aft or closer to the wing skin, the streamlines between two very different AoA become similar. This illustrates how an AoA probe becomes less sensitive to AoA as it moves closer to the wing skin or aft along the chord line.

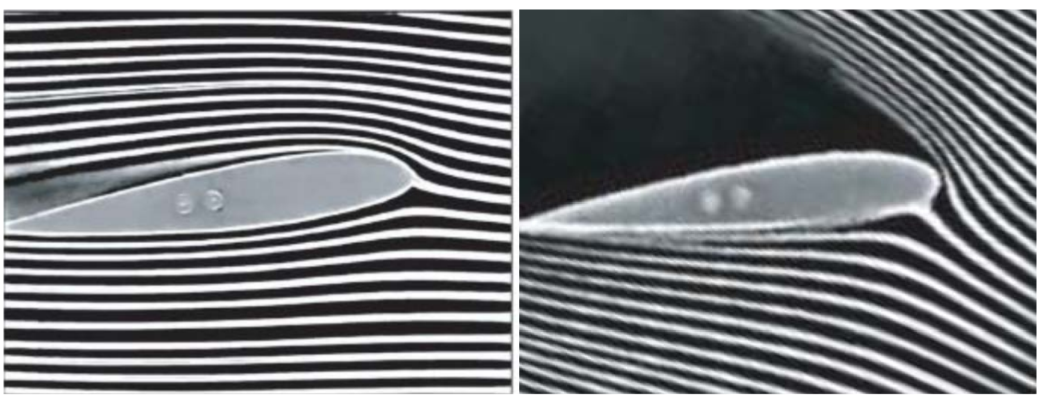

Figure 7. Streamline orientation along an airfoil and changes with AoA

Unlike a pitot tube, for which impact pressure alone is unaffected by the local flow alignment (through the typical range of AoA), a ΔP sensing AoA probe must be mounted in a location where the local flow does vary with AoA. The further forward or down away from the airfoil surface, the better. Size is limited by practical constraints of weight and cost and by flutter/vibration.

Underwing installations should also consider wingtip effects and sideslip for high dihedral wings.

4.1.2.2 Sensor Module Location

High-accuracy pressure sensors typically employ electronic temperature compensation. Their range of operation for maximum accuracy is generally limited. Cabin installation will afford a narrower range of typical operating temperatures than the wing cavity and will generally provide the best accuracy potential for temperature-compensated ranges of most low-cost COTS pressure sensors.

4.1.2.3 Line Sizing and Routing

Standard design and maintenance practices should be considered (to the extent possible) to ensure no low points, no long unsupported lengths, and to ensure lines are not exposed to any chafe hazards. By the nature of field installation, access can be limited in a way that prevents ideal application of those standard practices. When chafe concerns cannot be completely satisfied by installation procedures, chafe protections and sleeves can be added to manage those areas.

Lightweight/low-cost COTS pressure sensors for the ranges appropriate to this application may have small line diameters. The influence of moisture and freezing within pressure lines and natural line drainage are best facilitated by larger diameter pressure transmitting lines. Adapters installed at or near the sensor modules, oriented in a way to minimize any moisture and drainage concerns, will provide a more robust installation.

4.1.3 Sensor Accuracy Considerations

Varied levels of accuracy are available in the market with respect to sensors. Generally, as accuracy and stability improve, cost increases. The balance between suitable performance and keeping a COTS AoA system affordable and maintainable requires design consideration and trade-offs.

Each design should include an error analysis when establishing system accuracy. The most conservative analysis would consider the COTS pressure sensor manufacturers' published accuracy, stability, and drift. As discussed in section 4.1.2.2, if pressure sensors are not temperature compensated, or if temperature compensation is not within the range of expected operating temperatures, sensor accuracy is compromised

4.1.3.1 q_{ci} Sensor Accuracy Assessment Example

The following example considers a q_{ci} sensor as the sole source of error and is based on a specific installation of one COTS system and its installed performance in a market representative aircraft. For this assessment, potential sensor error will be referred to as "uncertainty" and equated to the best system accuracy supported by that sensor.

The installation was characterized in the test as follows:

$$AoA = 19.681 \cdot \frac{\Delta P_{AoA}}{q_{ci}} + 1.8595 \qquad (16)$$

Sensitivity to a q_{ci} uncertainty alone can be estimated as follows:

$$\frac{\partial AoA}{\partial q_{ci}} = -19.681 \cdot \frac{\Delta P_{AoA}}{q_{ci}^{\ 2}} \quad \rightarrow \quad \partial AoA = -19.681 \cdot \frac{\Delta P_{AoA}}{q_{ci}^{\ 2}} \cdot \partial q_{ci} \qquad (17)$$

At higher ΔP_{AoA}, the AoA uncertainty associated with any q_{ci} uncertainty is higher. Similarly, at low q_{ci}, the uncertainty associated with any ∂q_{ci} is higher.

For the analysis demonstration, it was assumed that the q_{ci} sensor was a 0–2 psi gauge sensor (suitable to 300 knot q_{ci}, rated speed range for this particular system). Low-cost/weight sensors such as Honeywell HSC line have accuracies in the range of 1–2% full scale. An assumed ∂q_{ci} of 0.02 psi (2.88 psf) was used for this analysis.

Two design points of concern in the test aircraft are listed in table 2 (based on 3,000 lb 1g stall speed in the test aircraft); the last row lists the associated AoA accuracy:

Table 2. q_{ci} error analysis for example COTS installation

	V_{REF}	V_{SW}
Indicated Airspeed	71.2 knots (2.1° AoA)	~ 60 knots (6.6° AoA)
Sensed q_{ci}	34.84 psf	12.21 psf
Sensed ΔP_{AoA}	0.3484 psf	2.93 psf
Sensor Accuracy ∂q_{ci}	0.02 psi (2.88 psf)	0.02 psi (2.88 psf)
Resulting AoA Uncertainty	0.02°	1.11°

As shown in table 2, the proposed sensor would afford an accuracy of 1.11 degrees based on q_{ci} sensor tolerance alone. The low-speed and high AoA cases are the most critical performance points for a LSA tool, which is unfortunately the point at which this system is most susceptible to error.

4.1.3.2 ΔPAoA Sensor Accuracy Assessment Example

This section considers ΔP_{AoA} as the sole source of error.

Using the same characteristic equation for ΔP_{AoA} uncertainty consideration:

$$AoA = 19.681 \cdot \frac{\Delta P_{AoA}}{q_{ci}} + 1.8595 \tag{18}$$

$$\frac{\partial AoA}{\partial \Delta P_{AoA}} = 19.681 \cdot \frac{1}{q_{ci}} \quad \rightarrow \quad \partial AoA = \frac{19.681}{q_{ci}} \cdot \partial \Delta P_{AoA} \tag{19}$$

ΔP_{AoA} values throughout the operating range of pressures are low. For this a smaller range sensor, such as ±0.362 psid, would be viable. For an analytic example, a Honeywell HSCxxxx025MD sensor was assumed with ±0.007 psi accuracy (stability and drift included). The error sensitivity assumed $\partial \Delta P_{AoA}$ of 0.007 psi (1 psf).

Considering the same cases as above, table 3 shows best system accuracy supported by that sensor error tolerance:

Table 3. ΔP_{AoA} error analysis for example COTS installation

	V_{REF}	V_{SW}
Indicated Airspeed	71.2 knots (2.1° AoA)	~ 60 knots (6.6° AoA)
Sensed q_{ci}	34.84 psf	12.21 psf
Sensed ΔP_{AoA}	0.3484 psf	2.93 psf
Sensor Accuracy $\partial \Delta P_{AoA}$	0.007 psi (1 psf)	0.007 psi (1 psf)
Resulting AoA Uncertainty	0.56°	1.61°

As with the previous discussion, low speeds result in the highest error.

4.1.3.3 Combined System Accuracy – Example

For statistical analysis purposes, the probability of all worst-case tolerances existing simultaneously is low. Considering these are advisory systems only, it is reasonable to apply a root sum square (RSS) analysis for combining error sources. For the example provided, that RSS would predict an accuracy of:

$$\sqrt{1.11^2 + 1.61^2} = \pm 1.96^\circ \text{ at stall warn point} \quad (20)$$

The error analysis does not take into account calibration. The published sensor accuracies and drift were assumed to be true throughout their full ranges. This was a conservative approach and, generally, sensors are well under their maximum specification error. The reason the analysis did not credit the installation calibration was because the system points of concern were not at discretely calibrated points for each sensor. Actual stall warn, for example, may be at a wide range of speeds (q_{ci}) and range of ΔP, depending on weight, load factor, and flap configuration. Although it is probable that any sensor intolerance errors would be compensated by calibration, additional research or rationale is required to establish this. Similarly, most COTS pressure sensors have drift with no guarantee of long-term stability beyond the specification.

4.1.4 Static System Error

Another source of error variation for a q_c normalized system is stability/error of the ambient pressure source (not considering sensor error, but actual pressure error). Policy Memo AIR100-14-110-PM01 does not permit a COTS AoA system to interface with the aircraft static system. All three q_c normalized systems tested under this program (systems 1, 3, and 5) sensed q_{ci} by differential pressure between the impact pressure on a pitot-like port on their probe and cabin pressure, not static pressure of the type design static system. Cabin pressure is analogous to alternate static selection on a typical aircraft pitot system.

Alternate static error would not be a significant problem were it stable or predictable. However, it tends to be affected by unpredictable variances like door-seal leak, window open/close state, and heating/ventilation state. A simplified method to quantify static effects by observations can be made by selecting the alternate static source on a typical GA aircraft and experimenting with windows and vents to whatever degree may be normal for that airplane type.

The test program for this system (i.e., system 1) used an aircraft without opening windows or hatches. While on the alternate static system, a configuration change from all environmental control system vents closed to all open showed an altitude decrease of 40 ft at 6000 ft MSL/-2°C (σ=0.8516). Cabin pressure change can be estimated as:

$$\Delta P_S' \approx \rho_o \sigma g \Delta H = 0.002377\ slug/\ ft^3 \cdot 0.8516 \cdot 32.2\ ft/sec^2 \cdot 40\ ft = 2.6\ psf \tag{21}$$

The influence of this will vary depending on the specific application, such as whether the system senses both ΔP_{AoA} and q_{ci} with reference to cabin or only qci referenced to cabin.

Figure 8 reports actual test data. The specific system tested in this example vented both ΔP_{AoA} and q_{ci} to the cabin. The influence of open and closed cabin vents induced a 1.4 degrees indication shift on the system's sense of AoA.

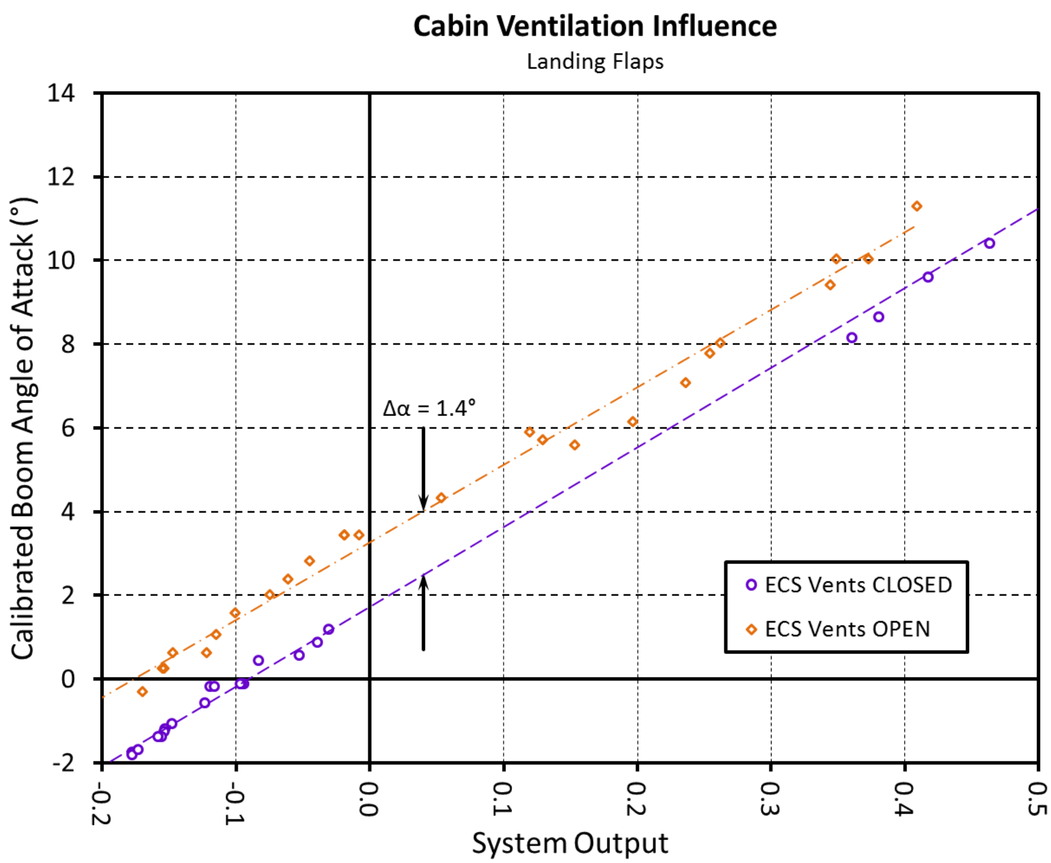

Figure 8. Ventilation/cabin pressure influence on q_c normalizing system (system 1)

4.1.5 Instructions for Continued Airworthiness

Pneumatic line runs for aftermarket COTS installations may not be properly constrained or supported throughout their runs and may be in contact with sharp edges. Best design and installation practices may be limited because of access and available routing. Small lightweight pressure sensors often have delicate connectors and are made from plastic that may crack in service if under some routing induced stress.

Of the systems tested under this program, none recommended periodic leak tests to identify leakage in any joints or degradation in any lines/connectors. Type design pitot-static systems are inspected at 24-month intervals for leaks.

4.1.6 Recommendations

4.1.6.1 Manufacturer Recommendations

The following are recommendations from the AoA system manufacturers:

- Employ q_c normalizing within system to eliminate the influence of weight and load factor.
- Employ n_z accelerometer to correct for the effects of maneuver-induced load factor (or else system provides misleading sense of greater AoA margin to stall) and perform calibration at MGW (lighter-weight flight will be conservative, indicating less margin than actual) if q_c normalizing not provided.
- Test and establish mounting recommendations based on chord line (i.e., no further aft than X% chord), and establish a minimum strut length suitable to avoid local flow fencing by wing skin.
- Consider line routing and installation to minimize chafing and pinching, and apply best practices to minimize susceptibility to moisture and freezing and promote natural external draining.
- Perform an error-sensitivity analysis, considering accuracy and drift of sensors when establishing system accuracy. Consider accuracy and drift of sensors when establishing the probe accuracy. An error-sensitivity analysis should be performed when establishing system accuracy.
- Consider potential static source error for q_c sensing accuracy when establishing system accuracy. At a minimum, the calibration procedure should require vents/windows configured to provide the most conservative calibration case (i.e., calibrate with window/hatch open if sensed AoA is low when window is open.)
- Consider use of temperature-compensated sensors (cost trade) to minimize environmentally induced errors.
- Consider repeat calibration or a calibration audit under FAA’s Instructions for Continued Airworthiness (ICA) if published drift/stability of the sensor is not consistent with the intended system accuracy.
- Establish a system leak test in ICA. This should consider equipment/tool limitations of typical pitot-static test sets (i.e., ability/inability to connect to AoA probe with test set plumbing fittings).

4.1.6.2 FAA/ASTM Recommendations

Consider permitting COTS AoA systems to interface with ship static system, provided potential compromises to the static system are addressed by the AoA system design. AC 43.13 and standard practices provide reasonable guidance on static pressure system interface. Sensors are robust in design, the system pressures are low (not burst critical), and static systems are subjected to repetitive leak tests under operating regulations. This will remove an error source inherent to systems that measure pressure relative to the cabin, which is susceptible to a wide range of pressure variation because of environmental control. A standard design practice/review is recommended to ensure interface will not introduce undue moisture ingression or leak hazards. Systems that can address those concerns would provide higher accuracy and safety benefits without detrimentally impacting the certified system.

4.2 VANE SENSING ELEMENTS

The vane-type installations were the most common, making up half of the systems evaluated under this program. It is believed that the vane-type probes evaluated used magnetic Hall effect sensors to measure the probe rotary angle, although a resistive potentiometer could be a suitable alternative.

4.2.1 Aerodynamic Theory

The vane-type AoA probe is perhaps the simplest of the COTS AoA probes evaluated. A flat or wedge-shaped, mast-mounted vane is free to align itself with the local airflow, and the sensing element measures the vane’s position. The vane itself may be mass balanced to minimize flutter and load-factor-induced error.

Vane-type AoA probes are influenced by local flow distortion due to nearby aerodynamic bodies—manufacturing imperfection in the vane resulting in asymmetry—and bending of the boom/mast under load.

Local flow field distortion occurs as the freestream passes around any aerodynamic body. The example shown in figure 9 illustrates flow field distortion around an airfoil. The flow field distortion around a typical airfoil results in an upward deflection around the leading edge (i.e., upwash). The result is an associated AoA increment, $\Delta\alpha_{uw}$, for a leading-edge boom-mounted AoA vane that is located within this region of distorted flow.

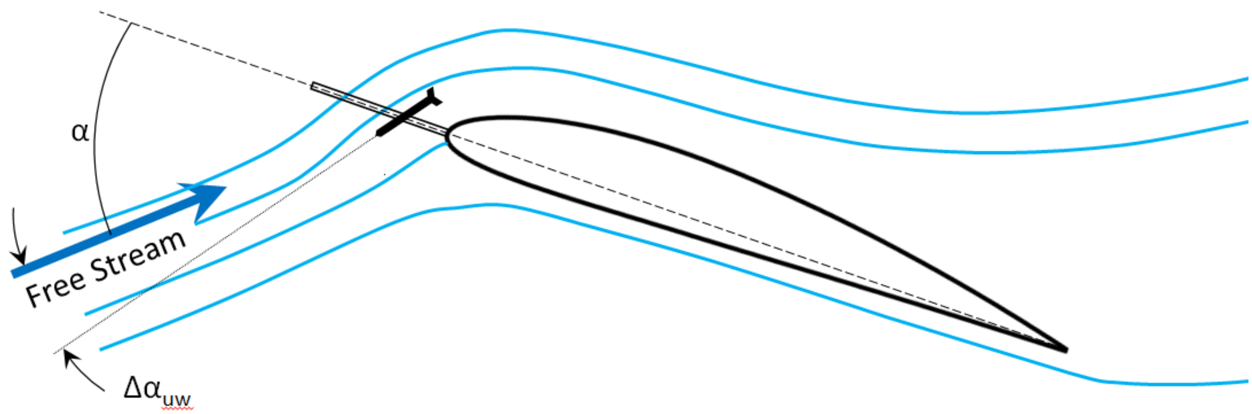

Figure 9. Upwash effect on local airflow

Similarly, an AoA vane mounted beneath the wing is susceptible to the same flow fence effect described in section 4.1.2.1.

Manufacturing imperfections in the AoA vane may also lead to erroneous alignment of the vane. Asymmetry of the vane results in a misaligned floating angle. Installed calibration of the AoA vane may account for such defects. An unbalanced vane (i.e., tail heavy) may result in flutter, causing erratic AoA indications.

Bending of the boom or mast to which the AoA vane is attached can also induce an AoA incremental error.

Some of these effects can be accounted for in the installed system calibration, but an understanding of these sources of error is required for proper probe placement.

4.2.1.1 Weight Influence

Weight was shown to have negligible influence on systems 4 and 10, which were vane-type AoA systems (see figures 10 and 11). Results for system 7 were inconclusive because of poor repeatability. The remaining system, system 9, did exhibit some influence due to weight (see figure 12).

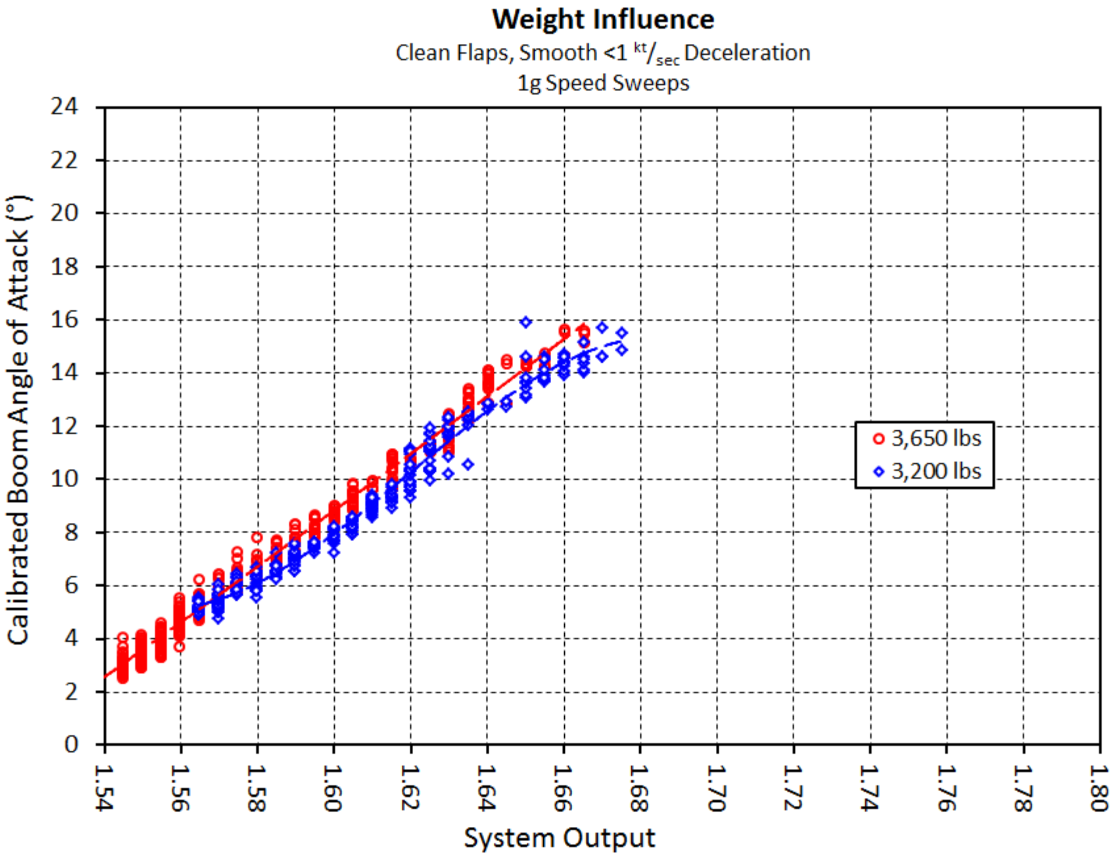

Figure 10. Weight influence, vane probe (system 4)

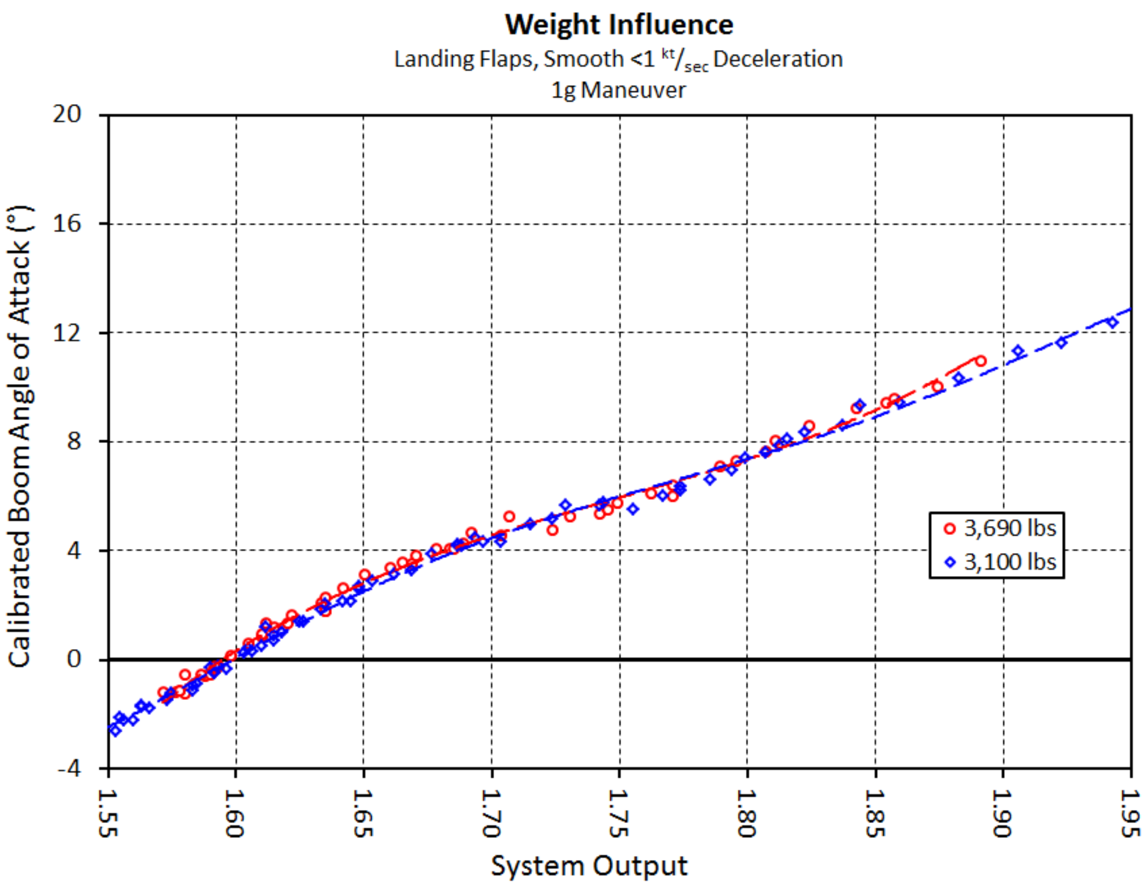

Figure 11. Weight influence, vane probe (system 10)

Although weight influence is not expected with a vane-type AoA probe, system 9 did exhibit some weight-induced influence on the system output (see figure 12). The most probable theory to explain this relationship is aerodynamic influence/tip effects. The pitot probe and AoA vane were installed at the outermost wing rib, and with higher wing, loading tip effects could be greater. The observed influence of higher weight was conservative with respect to system AoA indications, indicating a reading consistent with nominally higher AoA at the heavier weight. This raised a concern that the opposite may be true at lightweight flight, and the system would provide erroneously "safe" AoA indications. Based on these observations, it appears that the most conservative condition for calibration would be at light weight. Alternatively, moving the AoA vane away from the wing tip (inboard in the span-wise direction) may eliminate this weight-induced effect.

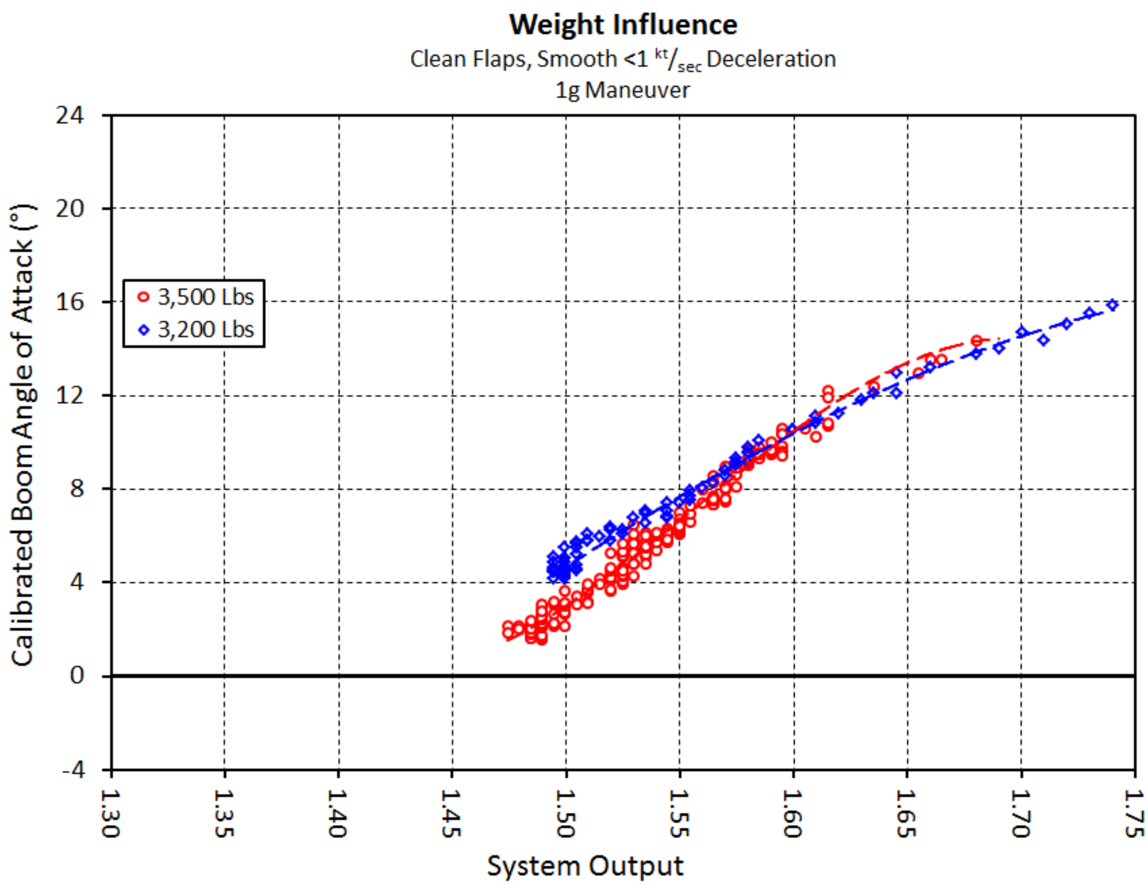

Figure 12. Weight influence, vane probe (system 9)

4.2.1.2 Load Factor Influence

Load factor was shown to have an influence on two of the vane-type AoA systems evaluated. Results for system 7 were inconclusive because of poor repeatability. The remaining two were unaffected by load factor.

For those systems exhibiting load-factor influence, the error observed during evaluation of system 8 was not conservative and provided a false sense of stall margin (see figure 13). Conversely, the error observed during evaluation of system 9 was conservative, and the stall warn was provided "early" (see figure 14). These errors are likely due to either an unbalanced vane or other local aerodynamic body influences.

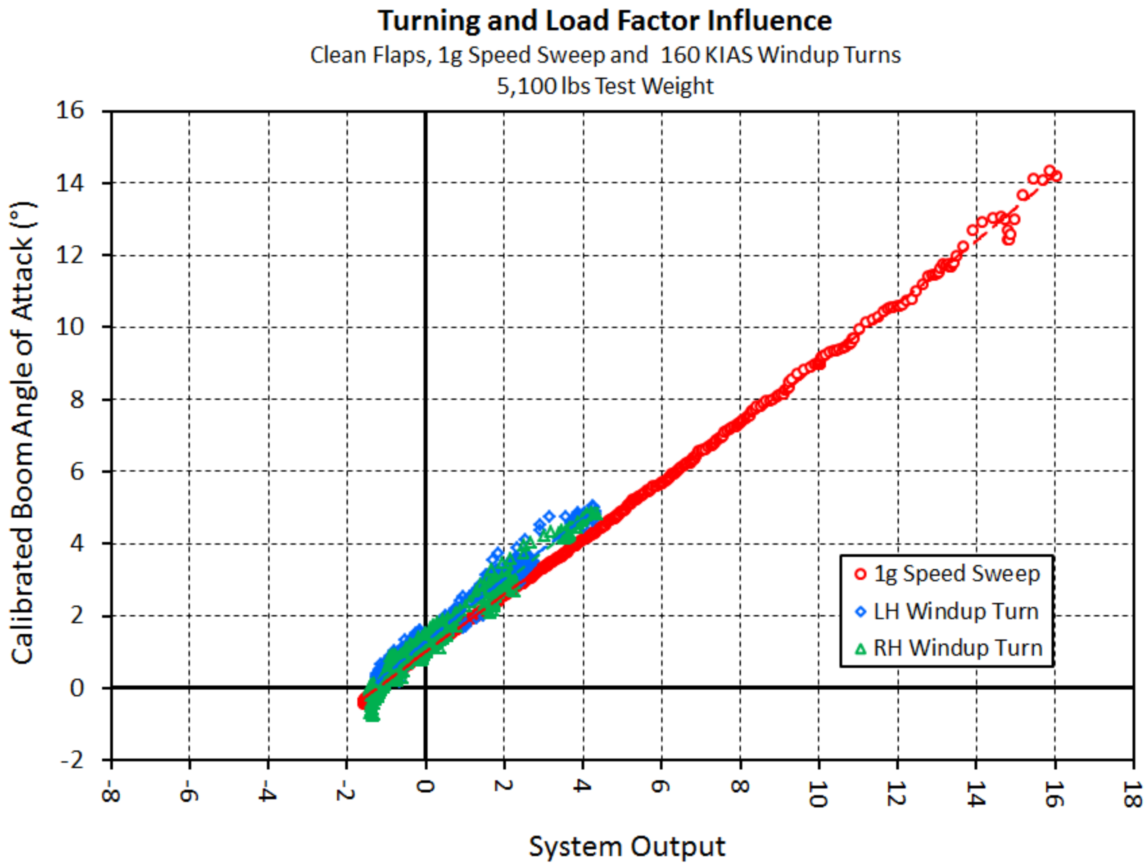

Figure 13. Load factor influence, vane probe (system 8)

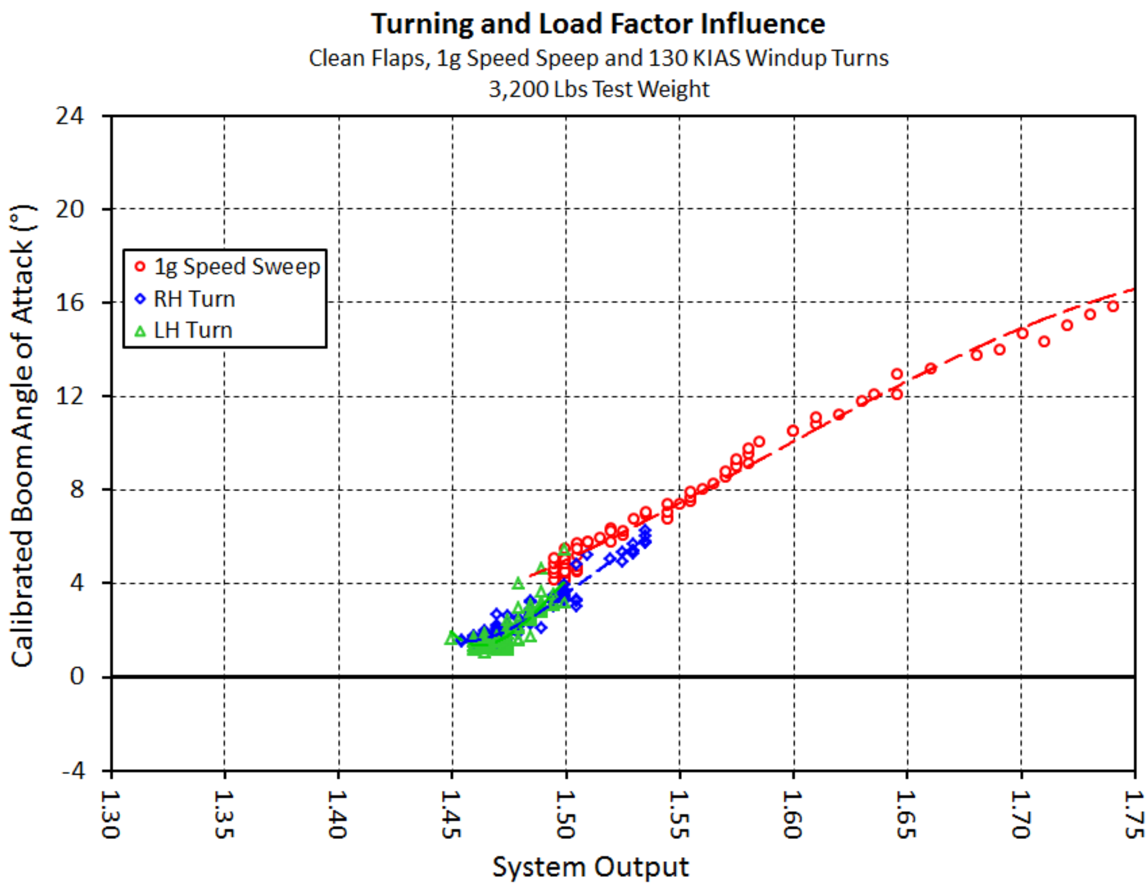

Figure 14. Load factor influence, vane probe (system 9)

Load factor did not appear to influence the output of systems 4 or 10 (see figures 15–16).

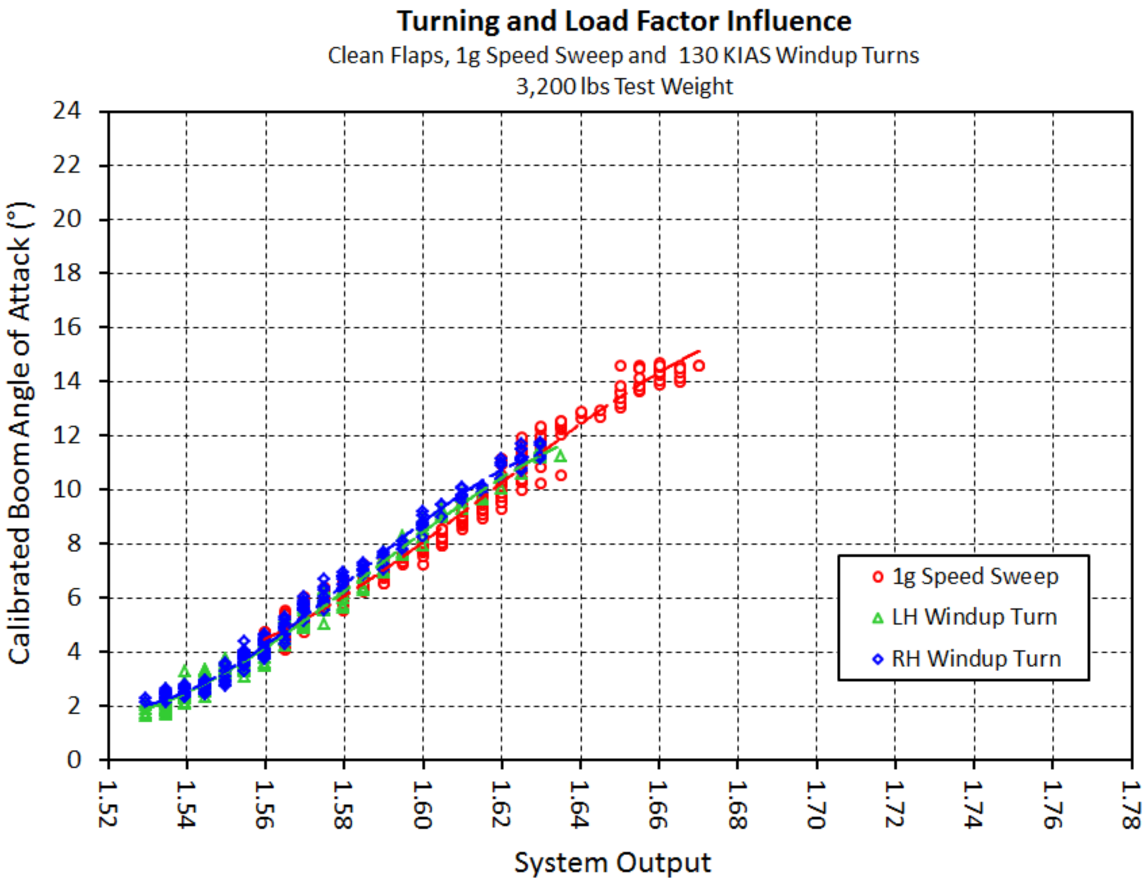

Figure 15. Load factor influence, vane probe (system 4)

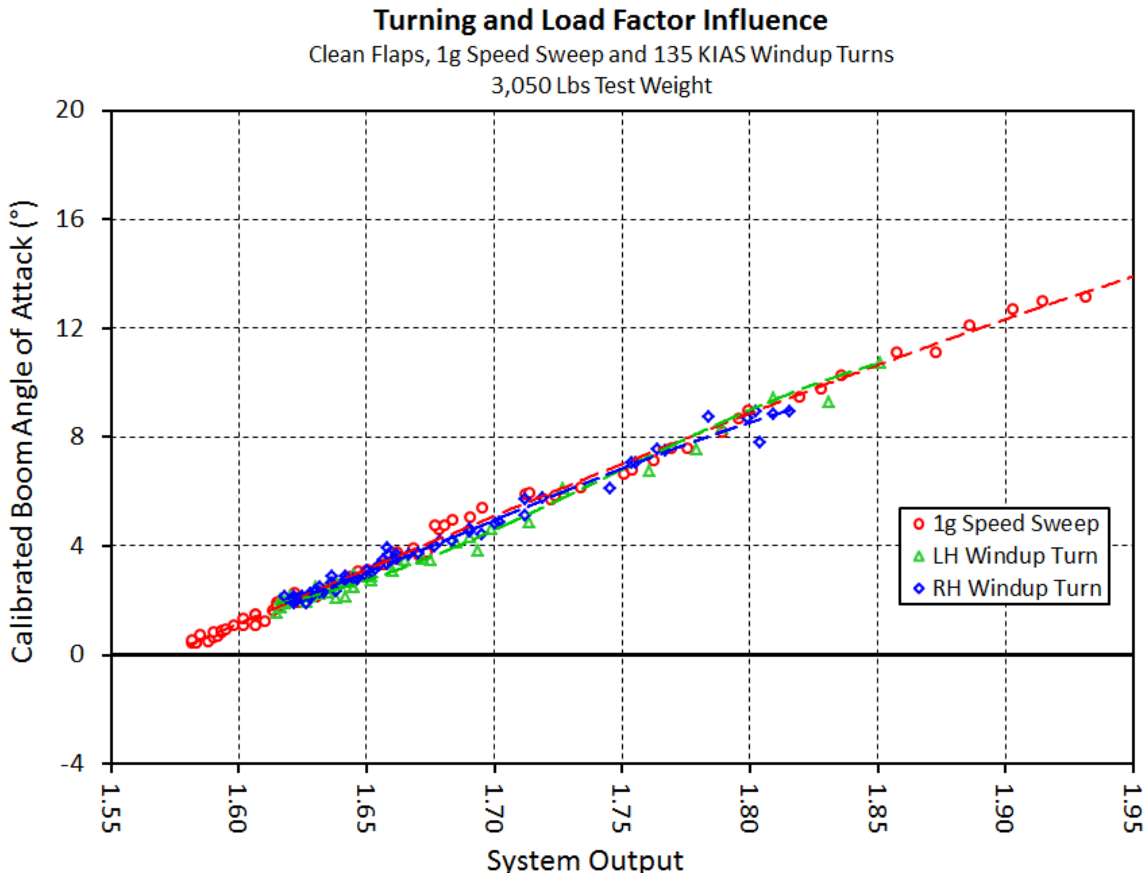

Figure 16. Load factor influence, vane probe (system 10)

4.2.2 Installation Considerations

4.2.2.1 Probe Location

As discussed under aerodynamic theory, AoA vanes not in the freestream are susceptible to aerodynamic body influences. Typical flight test installations of AoA vanes are boom mounted with the vane as removed from body influence as possible. However, they are still calibrated for such effects. Boom-mounted installation on a GA airplane is not practical.

For a single engine propeller airplane, fuselage-mounted AoA vanes are typically not practical because of the flow effects of propeller wash. Wing-mounted locations are typically suitable, considering the effects described in section 4.2.1. Similar to pressure sensing probes, the farther forward or down away from the airfoil surface the vane is located, the better.

4.2.3 Sensor Accuracy Considerations

The internal sensing element will have some angular accuracy and repeatability based on its design. That accuracy should be considered as an error source when specifying system accuracy.

4.2.4 Instructions for Continued Airworthiness

The sensing element for vane-type sensors installed on a single-engine GA aircraft is typically located external to the climate-controlled portion of the aircraft. The Hall effect or potentiometer-type sensors used in vane-type AoA probes are affected by temperature. Therefore, an external, non-environmentally controlled installation requires specific consideration for temperature effects. Integrated circuits associated with Hall effect sensors enable temperature compensation over a range of temperatures beyond the typical operating temperature range of most aircraft.

Disturbances such as vibration, moisture, dirt, or oil films are generally considered to not affect Hall effect sensors, making them an ideal choice for the environment outside of an aircraft.

These designs generally do not have any obvious service wear or reliability issues. Depending on sensor drift/accuracy, it may be suitable to recommend a calibration audit at some interval.

4.2.5 Recommendations

4.2.5.1 Manufacturer Recommendations

The following are recommendations from the AoA system manufacturers.

- Provide installation guidance for vane location. For underwing installations, a minimum mast height (i.e., minimum distance from lower wing skin) is recommended. For leading-edge installations, including a minimum distance forward of the wing's leading edge is recommended. For all installations, including a minimum span-wise distance (inboard) from wing tip is recommended.
- Consider use of temperature-compensated sensors (cost trade) to minimize environmentally induced errors.
- Consider repeating calibration or a calibration audit under ICA if published drift/stability of the sensor is not consistent with the intended system accuracy.

4.3 LEADING-EDGE-SENSING ELEMENTS

Only a single leading-edge tab probe was evaluated under this program (i.e., system 6). The relative positon of the leading-edge stagnation point imparts different aerodynamic forces on the leading-edge tab by which AoA can be characterized by calibration.

4.3.1 Aerodynamic Theory

A forward-facing tab mounted in a specific location on the wing's leading edge is balanced by internal springs and has a neutral position in absence of aerodynamic forces. The tab is located near the stagnation point location at stall warning. As AoA is increased, the stagnation point moves progressively down on the leading edge, and the aerodynamic forces on the tab change from downward forces at low AoA (stagnation above tab) to upward forces at high AoA (stagnation point below tab) (see figure 17).

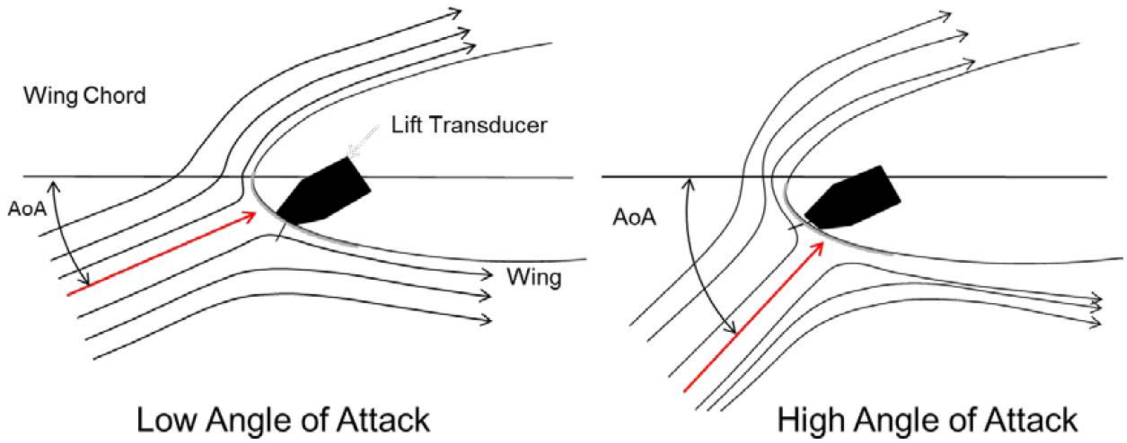

Figure 17. Leading-edge tab AoA probe

Simple discrete stall warning tab devices have been on certified aircraft for more than 30 years. Replacing discrete switch measurement with a proximity sensor (e.g., Hall effect or potentiometer) affords a measure that varies with AoA.

Calibration of these devices can be accomplished in two ways: 1) locating the probe in a position that provides good sensitivity about the stall warning AoA, and 2) making a refined calibration within the indicator or sensing electronics capable of making finer adjustments than possible with proximity changes.

In theory, the design may have several sources of influence:

- Weight – Aerodynamic forces at any given AoA will vary with weight (higher weight = higher q_c), thus the system may be weight influenced.
- Load Factor – Dependent on the tab center of gravity with respect to its pivot location, load factor may induce changes in deflection at the same AoA. Additionally, higher load factor will be similar to the weight influence—flight at any given AoA with a higher load factor will have higher q_c than that same AoA at 1g.

The influence of weight and load factor would be expected to be different at high AoA, when the tab deflects up with increased q_c (increased weight or load factor). At low AoA, the tab would tend to deflect further downward with increased q_c. It would be reasonable to expect that at high AoA, the system may indicate erroneously high with increased weight and load factor (conservative).

4.3.1.1 Weight Influence

Weight was found to have negligible influence (see figure 18).

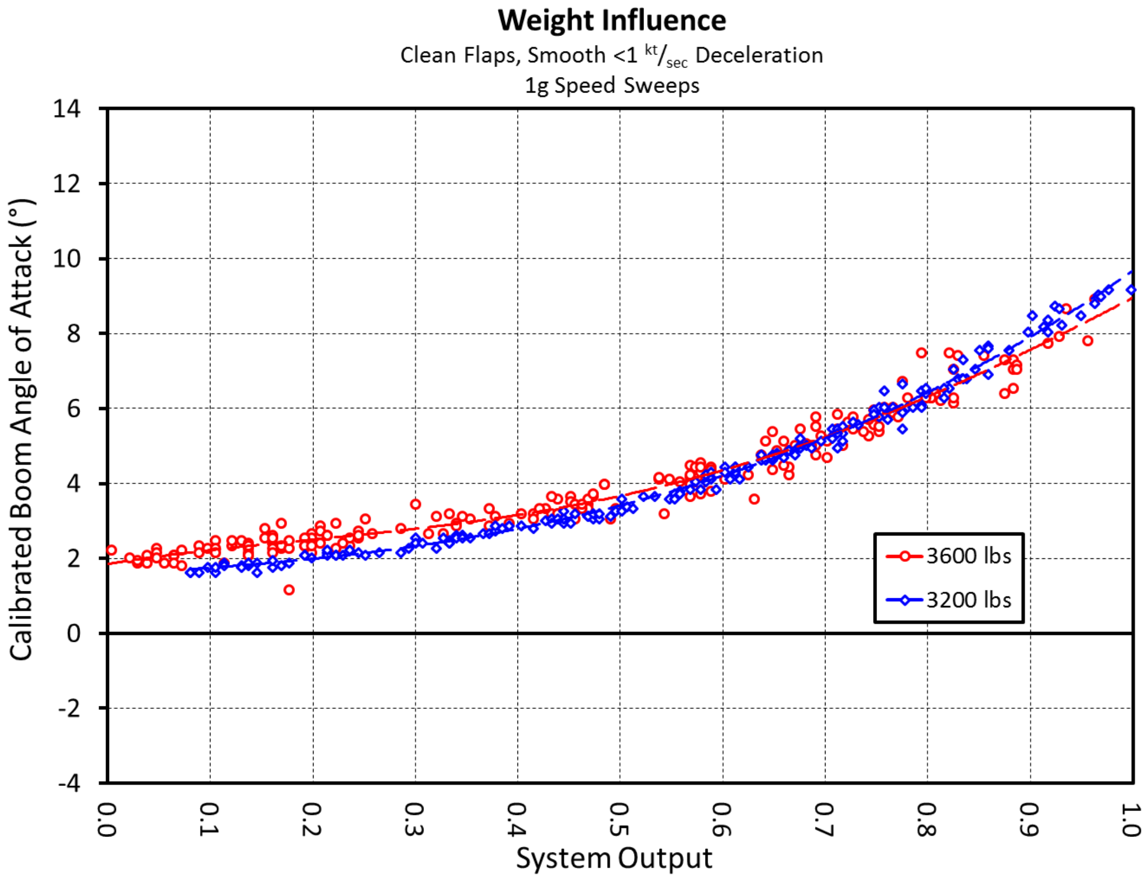

Figure 18. Weight influence, leading-edge tab probe (system 6)

At any given AoA, stable flight at that same AoA will be at higher airspeed and dynamic pressure for heavier weight flight. As discussed in section 4.3.1, the influence of increased weight is conservative (i.e., indication erroneously high) when at high AoA. At 8 degrees actual AoA (~ V_{REF}), the system provided an AoA indication 0.6 degrees higher at 3600 lb than it did at 3200 lb. The influence is opposite at low AoA (i.e., indication erroneously low). Considering the primary objective is enhanced LSA, a high AoA concern, the weight influence would be conservative provided the system was calibrated at light test weight.

4.3.1.2 Load Factor Influence

Load factor was shown to have an influence, but that influence was also found to be both minor and conservative (see figure 19).

At 3g, the system indication near V_{REF} was conservative and would provide stall warn approximately 2 degrees early.

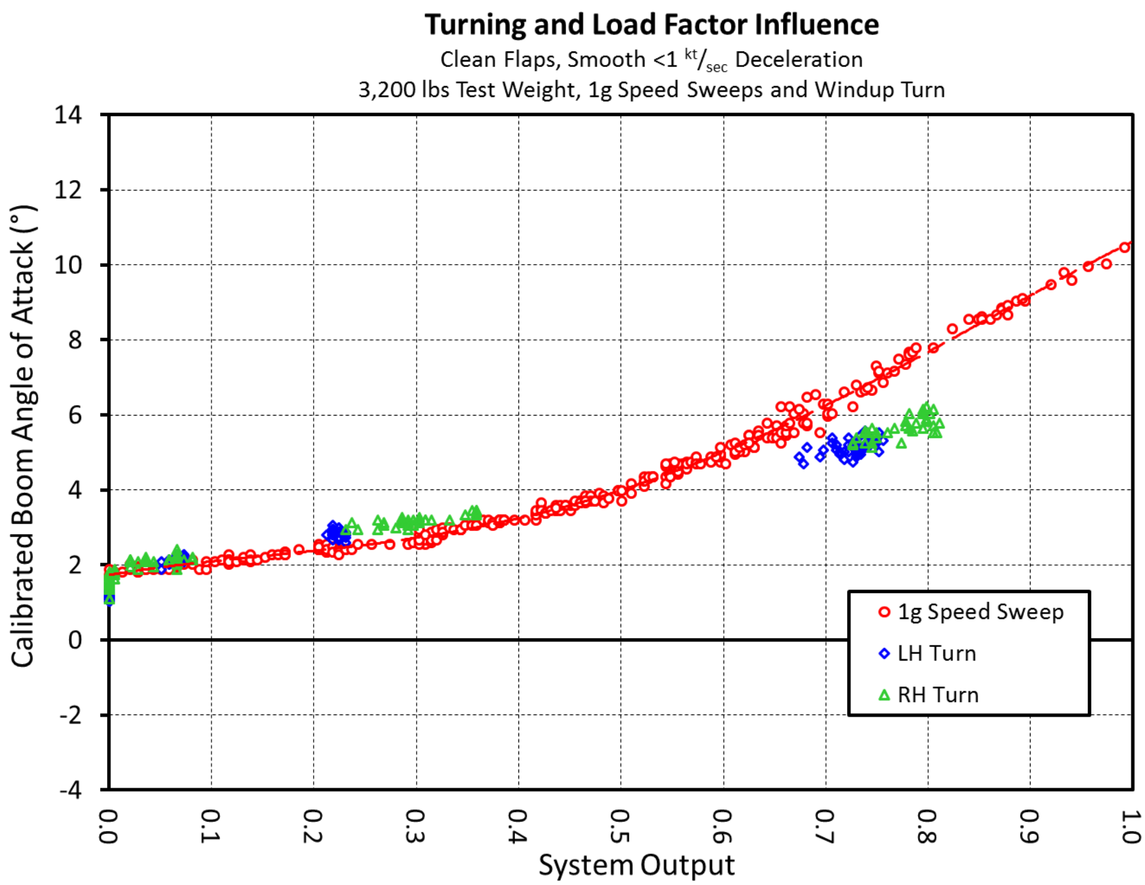

Figure 19. Load factor influence, leading-edge tab probe (system 6)

4.3.2 Installation Considerations

This design probe requires installation into the leading edge and modification to the aircraft structure is necessary. Unlike most other COTS probes, which can be installed from access panels, airframe-specific consideration was necessary. Adequate clearance for housing a sensor module and a narrow range of positions (stagnation-point-based) were required. The manufacturer of the specific device tested in this program coordinated with several airframe original equipment manufacturers (OEM) to provide suitable structural modification approval. The manufacturer also provided slotted mount screws on the sensor module to allow its positon to be nudged upward or downward if calibration showed it was not in a suitable location with respect to stagnation point.

Access for wiring of the sensor module was also a concern. Some viable path to run interface wiring from the cabin to the leading-edge mounted sensor is required.

4.3.3 Sensor Accuracy Considerations

The internal sensing element will have some accuracy and repeatability based on its design. That accuracy should be considered as an error source when specifying system accuracy.

4.3.4 Instructions for Continued Airworthiness

The design does not have any obvious service wear or reliability issues. Depending on sensor drift/accuracy, it may be suitable to recommend a calibration audit at some interval.

4.3.5 Recommendations

4.3.5.1 Manufacturer Recommendations

The following are recommendations from the AoA system manufacturers.

- Ensure calibration instructions provide recommendation to calibrate the stall warn at light test weight. The influence of increased weight relative to the calibration point is conservative with respect to LSA annunciations, but flight at lighter weights are the opposite.
- Ensure calibration for stall warn and V_{REF} is done at the most critical flap state for the selected aircraft. For the test aircraft, this was the landing flap case (flight with clean flaps provided conservative/early low-speed indications), but that relationship may be different for different installations.

5. AIRCRAFT CONFIGURATION

Discussions up to this point were focused on the sensor's capability and accuracy for reading AoA. On a more practical basis, an airfoil has different AoA targets and points of interest for each flap setting. Those typical references for the test aircraft are summarized in table 4.

Table 4. Test aircraft AoA references versus flap configuration

	Clean	Takeoff Flaps	Landing Flaps
Flap Deflection Angle	0°	16°	32°
Stall AoA	13.5°	12.1°	10.5°
Stall Warn AoA	10.6°	8.5°	6.8°
V_{REF} AoA	6.1°	4.5°	2.8°

Calibration data for each flap configuration of all probe types is shown in figures 20–23.

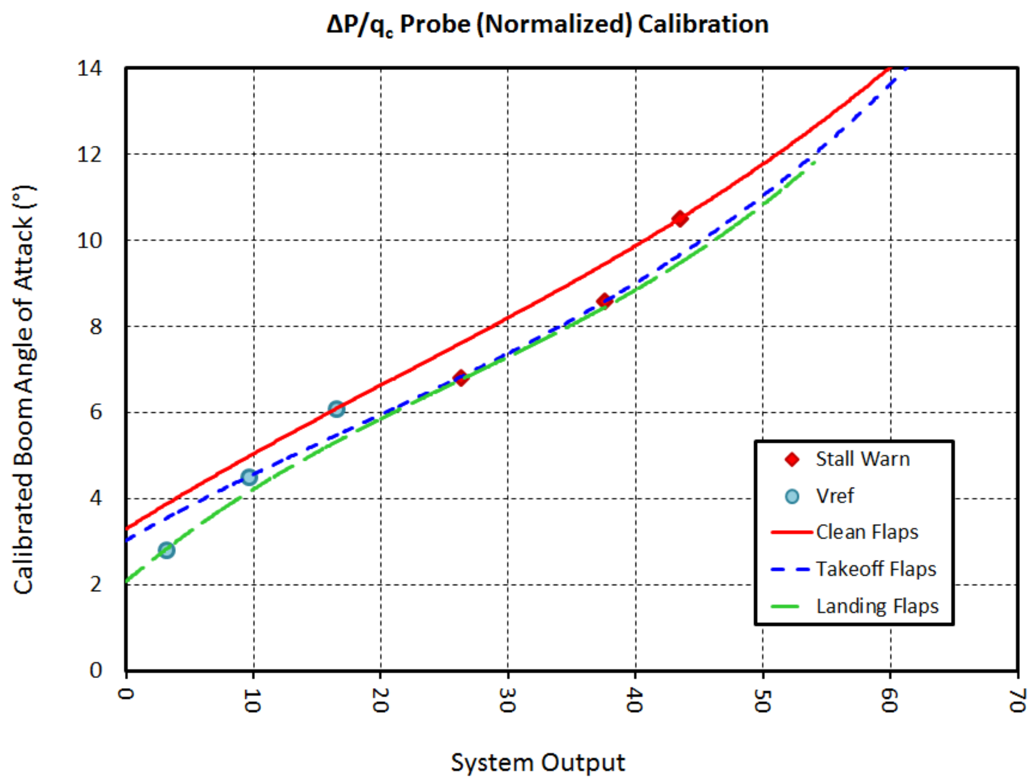

Figure 20. Flap influence, ΔP/q_c probe (system 3)

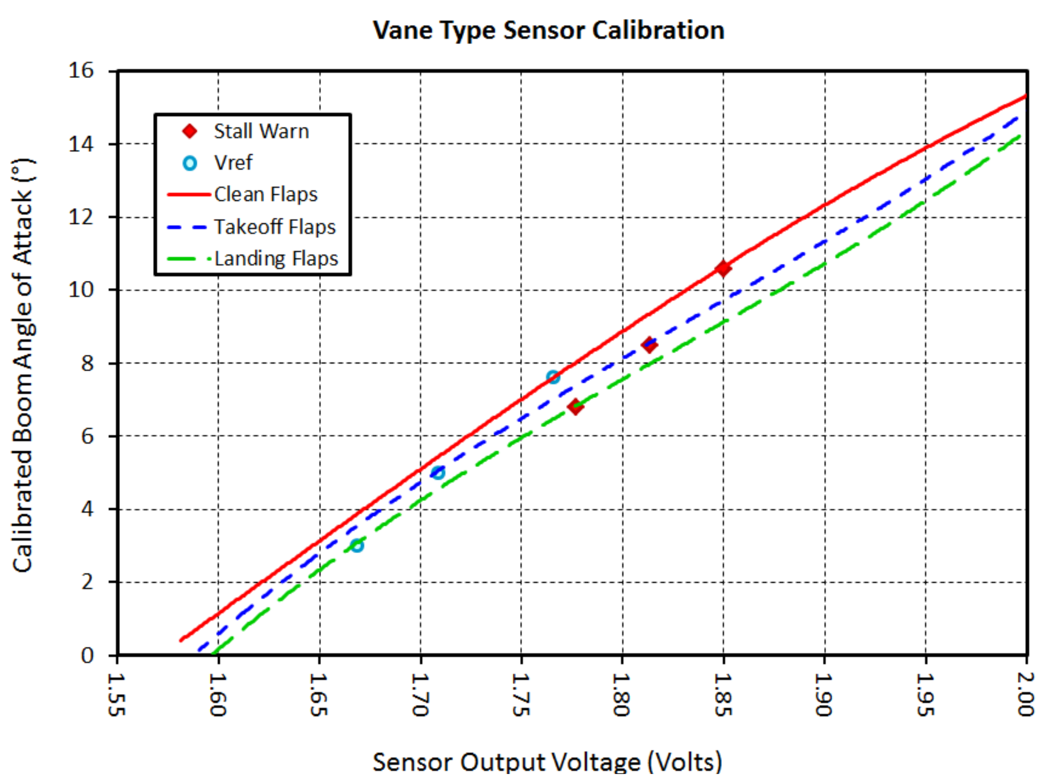

Figure 21. Flap influence, vane probe (system 10)

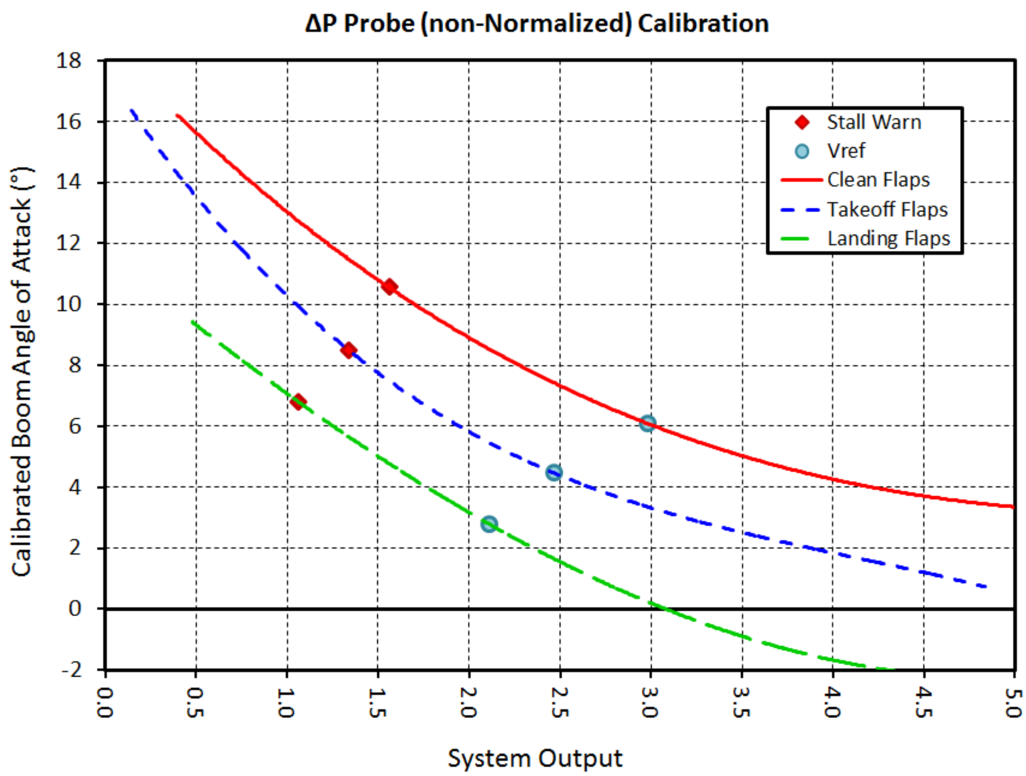

Figure 22. Flap influence, ΔP probe (system 2)

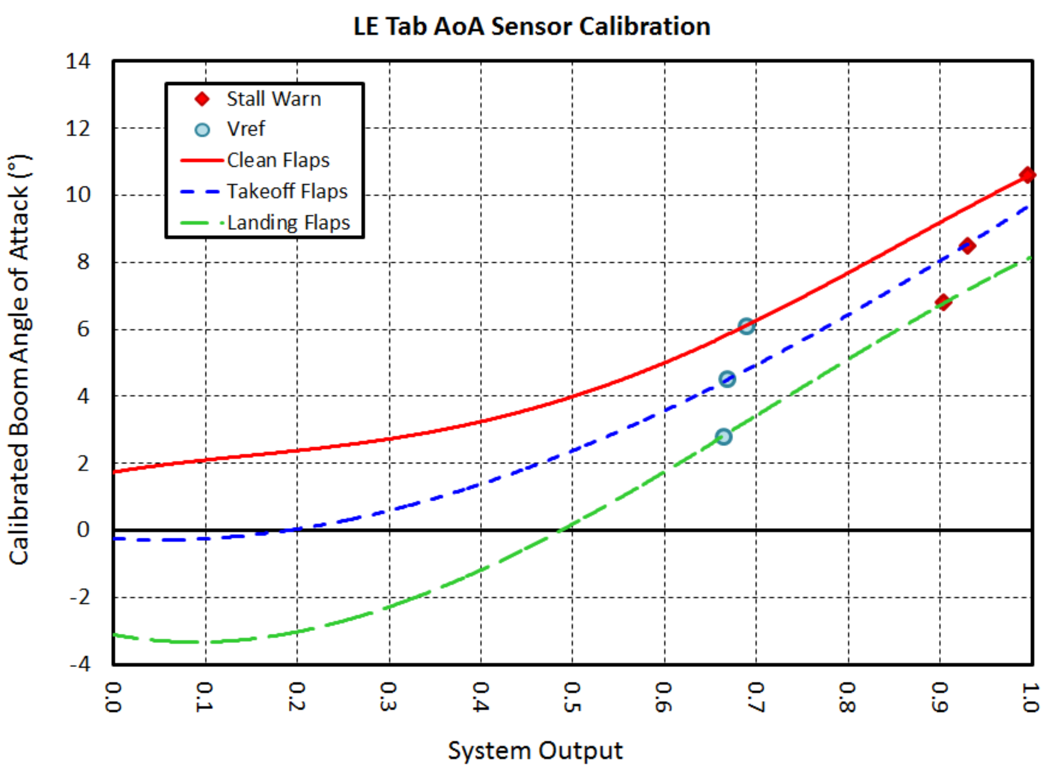

Figure 23. Flap influence, leading-edge tab probe (system 6)

The vane and the normalized $\Delta P/q_c$ probe calibrations are relatively insensitive to flap configuration, but each flap state will require a unique trigger for the display. For example, if the system shown in figure 20 was calibrated to provide on-speed indication at V_{REF} of 2.8 degrees in landing configuration, it would provide some form of on-speed symbology with a system output of 2.0. If flaps were clean, the system would provide the same on-speed indication at 2.0, and the aircraft would be considerably overspeed at 2 degrees AoA (clean V_{REF} should be 6.1 degrees). For the test aircraft, this would be 28 knots more than $1.3V_S$.

These probes were found capable of accurate and reliable output, but these systems required the addition of flap input to have unique indication thresholds for each flap state. Otherwise, guidance for reduced flap deflection approaches would be at excessive speeds.

The non-normalized ΔP probe (see figure 22) showed the opposite problem. For this probe, if the system were calibrated to provide on-speed guidance at V_{REF} of 2.8 degrees in landing configuration, it would associate on-speed symbology with a system output of 2.1. When flaps were clean, that same sensed output would equate to flying the clean approach at 8.3 degrees AoA (clean V_{REF} should be 6.1 degrees). For the test aircraft, this would be 9 knots below $1.3V_S$.

For the leading-edge tab sensor, although each flap calibration was unique, a single annunciator calibration provided suitable approach and stall warn guidance for all cases. For this system, it was calibrated to provide on-speed approach guidance at V_{REF} of 2.8 degrees in landing configuration (a system output of 0.664). That same sensed output in clean configuration provided approach guidance at 5.7 degrees AoA (clean V_{REF} should be 6.1 degrees). For the test aircraft, this was only 2 knots more than $1.3V_S$, a conservative speed/AoA margin but not excessive.

5.1 RECOMMENDATIONS

5.1.1 Manufacturer Recommendations

The following are recommendations from the AoA system manufacturers.

- Interface with the aircraft flap system in some way to determine the flap state, and include AoA calibration in each flap configuration such that appropriate approach advisory target and stall margin are provided in all flap states. (One of the COTS systems did provide a proximity sensor to install in the flap drive system, but that specific system was not approved under the FAA policy for installation onto certified aircraft. It is not clear from FAA policy whether a proximity sensor would be considered as not satisfying the "must not interface with a certificated system" requirement.)
- In absence of flap position sense, ensure that a calibration procedure is performed in the most conservative flap position such that other flap positions will provide conservative indications.

5.1.2 FAA/ASTM Recommendations

Consider formal language and restrictions as necessary to allow COTS systems to interface with flap indication so that more accurate approach and stall advisories are provided. As shown in figures 20–23, unacceptable margins are otherwise typical for many designs, including conventional vane-type probes used in 14 CFR 25.

6. DISPLAY DESIGN/HUMAN FACTORS

Each COTS AoA system evaluated had a unique presentation of AoA information. Numerous design and human factor aspects of the AoA presentation warrant discussion. These include indexer orientation, indexer coloration, indexer display elements, and indexer mounting location.

Of the nine indexers evaluated, each had a unique configuration. Some consisted of round light-emitting diode(s) (LEDs) only; others had bar graph style LED; and others consisted of various combinations of bar graphs, chevrons, arrows, and circles (e.g., donuts). Although many shared similar design concepts, there currently are no industry-standard indexer display requirements or guidance.

Consistent basic display standards or guidance are recommended to minimize system-specific training and reduce the potential for misinterpretation of system guidance due to variations in a manufacturer's display and display logic.

6.1 INDEXER ORIENTATION

Although all of the COTS AoA systems evaluated had vertically oriented indexers, there was at least one system commercially available with a horizontally oriented indexer. It is recommended that indexers associated with an AoA system be oriented vertically, as a vertical orientation is more intuitively associated with pitch control. A horizontal indexer orientation does not provide intuitive guidance relative to aircraft pitch attitude.

6.2 INDEXER COLORATION

Inconsistent indexer display coloration was observed during the evaluation of the nine COTS AoA system indexers evaluated throughout this program. All of the systems evaluated included green, yellow/amber, and red display elements, but one included blue as a fourth color on the indexer display.

With the primary reference condition for AoA indexer usage being approach speed guidance, the indexers evaluated each had unique on-speed, V_{REF}, and display coloration. Some indexers provided V_{REF} indication with green display element coloration, while others provided V_{REF} indication with yellow/amber coloration. Of the nine indexers evaluated, one provided V_{REF} indication with a blue display element.

In addition to approach speed guidance, stall awareness is also a typical element of AoA indexer display. As with approach speed guidance, stall warning indication was inconsistent between the indexers evaluated. Of those evaluated some provided yellow/amber indication at stall warning while others provided a red indication at stall warning.

Cockpit information display is regulated per 14 CFR 23.1322, Warning, caution, and advisory lights:

> If warning, caution, or advisory lights are installed in the cockpit, they must, unless otherwise approved by the Administrator, be—
> (a) Red, for warning lights (lights indicating a hazard which may require immediate corrective action);
> (b) Amber, for caution lights (lights indicating the possible need for future corrective action);
> (c) Green, for safe operation lights; and
> (d) Any other color, including white, for lights not described in paragraphs (a) through (c) of this section, provided the color differs sufficiently from the colors prescribed in paragraphs (a) through (c) of this section to avoid possible confusion.
> (e) Effective under all probable cockpit lighting conditions.

Maintaining similar logic for green, amber, and red for an indexer is recommended to keep similar design philosophy within the cockpit. The following recommendation for indexer color usage maintains the above philosophy:

- Green – Indexer indications from cruise to approach speed guidance (i.e., V_{REF}).
- Amber – Indexer indications slower than approach speed guidance to stall warning. Although flying between recommended approach speed and stall warning presents no immediate hazard, the pilot should correct this off-speed condition when workload permits.
- Red – Indexer indications from stall warning to stall. Flying between stall warning and stall requires immediate corrective action.

Discussion is also warranted regarding aircraft configuration (flap setting) and its effect on indexer guidance. Numerous evaluated AoA systems were susceptible to aircraft configuration influence on the AoA calibration. This resulted in the display coloration for a given condition to vary. For example, one system had a calibration that resulted in the first red display element being illuminated at stall warning in the clean configuration (0% flaps). The same system and calibration resulted in stall warning occurring at the last yellow/amber display element in the takeoff configuration (50% flaps), and stall warning occurring at the second red display element in the landing configuration (100 % flaps).

This indexer only had three red display elements, therefore minimal stall warning to stall margin awareness was available to the pilot in the landing configuration. See section 5 for further discussion.

6.3 INDEXER DISPLAY ELEMENTS

Of the COTS AoA systems evaluated, there were nine unique indexer configurations. The most basic indexer displays consisted solely of round LED. LED configuration ranged from a simple vertical stack of round LED one LED wide, to a stack of round LED one LED wide with approach AoA marked by three LED wide, to round LED arranged in the shape of multiple chevrons.

Other indexers included various forms of bar graph LED/lighted elements. The most basic of these indexers was a simple LED bar graph. Others incorporated chevrons into the display, along with the bar graph elements. Two of these types of indexers marked approach AoA with a circular/donut-shaped element.

As discussed, several indexers incorporated downward-pointing chevrons for AoA greater than the reference condition. This presentation of high AoA, when oriented vertically, provides an intuitive visual cue to the pilot that the nose of the aircraft should be lowered to resolve the high AoA condition.

This AoA indexer presentation (i.e., chevron usage) has been accepted by the United States military for use in various trainer/fighter aircraft (see figure 24). The Air Force Manual 11-248 discusses United States Air Force T-6 flight operations and provides the following explanation regarding AoA indexer chevron display elements:

> The symbols indicate distinct AOA conditions. The center donut illuminates when the aircraft is in the optimum AOA range. The upper and lower chevrons indicate, by the direction of the chevron angle, which direction to change pitch attitude to achieve optimum AOA [4].

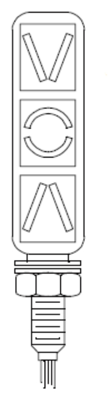

Figure 24. T-6A AoA indexer

The T-6A AoA indexer is provided as an example of accepted display element symbology but not intended to be the only acceptable configuration.

In addition to differences in the shape/arrangements of indexer display elements, differences in element illumination and presentation sequence were observed. Some indexers illuminated a single element at a time, others blended illumination of two elements (i.e., one element on, then adjacent element would fade in while previous element would fade out), and the remaining would fill or remove remaining elements within the stack.

Those indexers that filled or removed elements from the entire stack exhibited significant display logic difference. For example, at low AoA, one indexer would initially illuminate a single element at the bottom of the indexer. As AoA increased, additional elements would illuminate. At or near stall AoA, all of the indexer display elements were illuminated. Conversely, one of the indexers evaluated would have all of the display elements illuminated at low AoA. As AoA increased, elements would extinguish. At or near stall AoA, a single element would be illuminated. The former indexer's display logic is recommended because the additional illumination of elements emphasizes the importance of the current AoA situation (i.e., more illumination at high AoA to reinforce the need for corrective action) and supports the "dark cockpit" philosophy.

System calibration may also result in inconsistent AoA guidance. For example, pilot A may perform the calibration procedure with a specific calibration result, and pilot B may also perform the calibration procedure with a different calibration result. These calibration differences may lead to the indexer approach speed/stall warn/stall guidance occurring with different display elements illuminated. See section 7 for further discussion.

6.4 INDEXER MOUNTING LOCATION

It is recommended to locate the AoA indexer so that it remains within the pilot's peripheral vision while looking outside the aircraft during a visual approach. Military aircraft, such as the T-6A and F-14, position the AoA indexer on the glareshield to remain within the pilot's peripheral vision while flying a visual approach. Placing the indexer on the instrument panel results in it getting lost among the other aircraft instruments, and it is no longer readily visible to perform its job as a visual cue to approach condition.

Airspeed is one of the main causes of loss of control inflight

> Many loss of control incidents or accidents can be attributed to improper management of airspeed, especially those leading to aerodynamic stall or departure from controlled flight. Some examples include inattention to airspeed during approach and landing…from which recovery becomes increasingly difficult as altitude decreases. This can be due to a wide range of factors including improper monitoring, distraction…[5]

Providing a visual cue within the pilot's peripheral vision while flying a visual approach offers feedback to the pilot regarding the aircraft's current energy state. A pilot who is not being attentive to airspeed, as displayed on the instrument panel, would not benefit from an AoA display also mounted on the instrument panel. Conspicuous and intuitive AoA indexer colors and display elements offer near-immediate feedback to a pilot while flying a visual approach:

> The AOA indexers were unanimously accepted. In general, it was felt that the indexers allow the pilot to fly "heads up" in the traffic pattern. This allowed better clearing and more precise patterns with smoother aircraft control. The red chevron provided a much more effective cue "to do something" than a corresponding 5–6 knot low airspeed deviation [6].

Note that recent industry discussion emphasizes the need for AoA display research:

> Current research into the display of AoA is needed. Research (should) be conducted into how to best display AoA and when it should be used…The effectiveness of AoA, or any parameter for that matter, is significantly influenced by where and how the information is presented and how it can be integrated and used in the intended operation [7].

7. CALIBRATION PROCEDURES

The majority of calibration procedures would be best described as indicator calibration, not sensor calibration. This is perfectly suitable for the application, in which the procedures effectively "train" the display to provide a suitable indication based on the sensor's output when flown at the target calibration points. This method does effectively compensate for sensor or installation variation, but warrants some consideration of the software and storage media to ensure it is suitable for stable retention of that calibration. Most systems would require repeated calibration if any components were changed. Only a few of the ICA reflected that.

Several were also dependent on technologies that tend to have in-service drift, (specifically true for the pressure-sensing solutions). When sensor drift/stability does not support the published sensor accuracy, found true in some cases, their ICA should include repeated calibration or audited at a suitable interval to accommodate drift. The q_{ci} compensated sensors are, in a sense, doubly exposed to drift. As discussed in section 4.1.3, when a given AoA is flown at one test weight, its individual sensors are at a very specific point with respect to q_{ci} and ΔP, and the initial calibration compensates for those errors. If the same AoA is flown at a different weight or configuration, each respective sensor is off its calibration point, and the validity of that calibration becomes less accurate in proportion to the deviation from its calibration.

7.1 POINT SUITABILITY

A wide variation in calibration procedures were recommended by the OEM of the different systems evaluated under this program. Several involved stable points that were very subjective and not likely repeatable.

One such example is a unit that defined an optimum AoA (OAA) in the clean configuration and at a slow but safe speed with "lower power setting (such as a downwind or landing pattern power setting)." The pilot is instructed to identify OAA by increasing pitch (AoA) until the aircraft is no longer able to climb but holding altitude.

"Optimum" is a bit of a misnomer, as the point is not optimum with respect to LSA or performance. This point is subjective, dependent on the power setting selected by the calibrator. Its identification is imprecise, and specific recognition of a point at which climb rate is zero is prone to interpretation error.

If performed with no interpretation error, OAA will identify the point at which power required for level flight is equal to power available (P_{req}=P_{avail}). Another important consideration is that a controlled and deliberate reduction in speed to identify this point would be valid only for that power setting. Figure 25 illustrates the sensitivity to power. A small change in power will cause the speed/AoA of intersection between P_{req} and P_{avail} to vary on the order of 5–10 knots with 2–3% power changes.

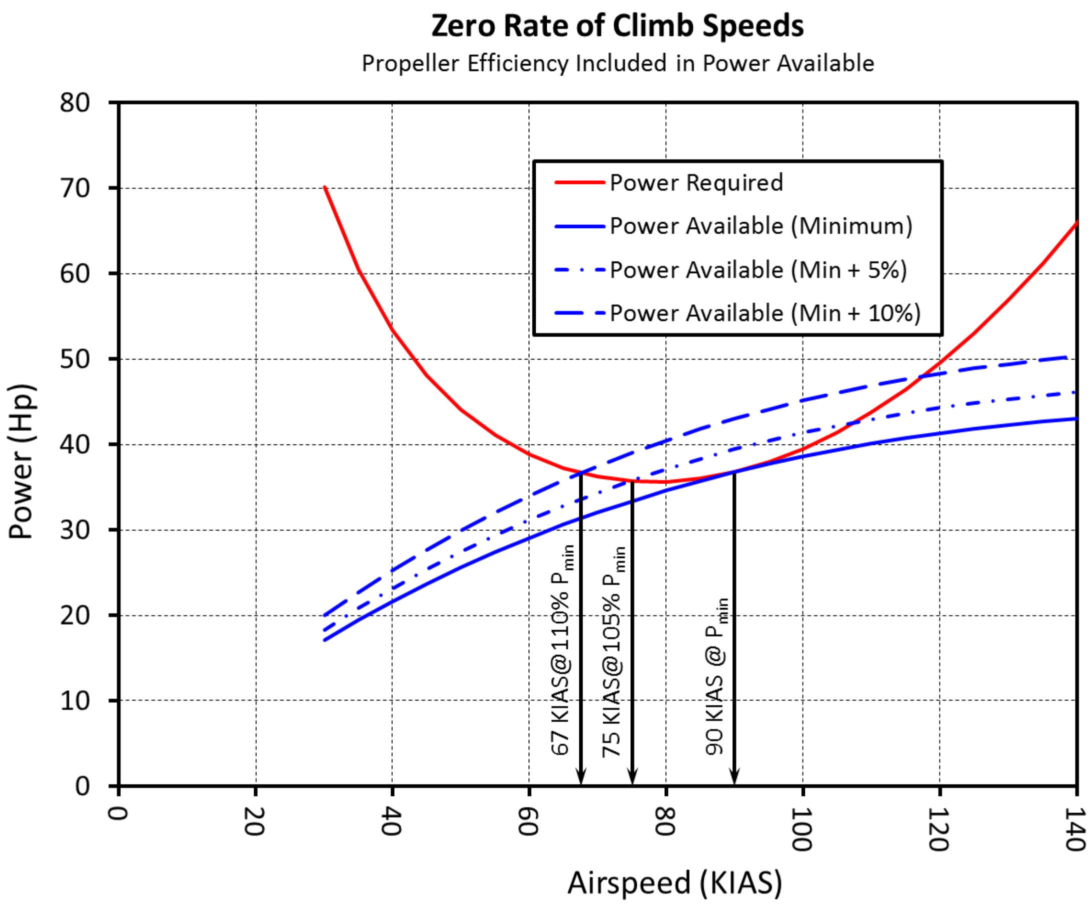

Figure 25. OAA sensitivity to power setting (variation)

Considering potential variation in technique via power selection and in identifying the point at which excess power reaches zero (no climb or sink rate), this is not a reliable, repeatable point and will not support standardization across installations, even in aircraft of the same type.

Several systems instructed pilots to fly "just above the stall speed" for their aircraft (below stall warning). This would be a difficult point to fly with stability, considering proximity to stall, and introduces a potential safety hazard, considering that the target audience for the procedure is a GA pilot.

The concern regarding operation near stall was recently addressed by the FAA in a change to the Airmen Certification Standards, "Maneuvering During Slow Flight" task [8]. Previously, the Practical Test Standards [9] defined slow flight as "an airspeed at which any further increase in angle of attack, increase in load factor, or reduction in power, would result in an immediate stall." The Airmen Certification Standards, which superseded the Practical Test Standards, now defines slow flight as "an airspeed, approximately 5–10 knots above the 1g stall speed, at which the airplane is capable of maintaining controlled flight without activating a stall warning."

Several systems were designed with distinct on-speed indications for reference approach speed. Of those, some did not calibrate the indicator for that speed reference. All of the systems tested under this program included some form of red indicator state intended to coincide with stall warning. Only a few of the systems performed a discrete calibration at that point.

7.2 DESIGN SENSITIVITY TO WEIGHT AND IDENTIFICATION OF CRITICAL WEIGHT/CG

Many of the systems tested showed sensitivity to weight. Their calibration recommendations were not always synchronized with the critical cases for their design. If, for example, lower test weights provide lower AoA indication or margin, a light-test weight would be the most conservative calibration point. Flight at heavier-than-calibration weights would provide greater margin. There is no generalization with respect to this, and it was dependent on each design. Some had higher margins at heavy weight, some at light.

7.3 DESIGN SENSITIVITY TO FLAP CONFIGURATION AND IDENTIFICATION OF CRITICAL CONFIGURATION

As described in section 5, many of the tested systems provided differing margins at each flap configuration. Ideally, a design would be insensitive or have the capability to detect flap configuration and provide a different threshold for indication. However, the constraints of Policy Memo AIR100-14-110-PM01 and ASTM F3011-13 limit the options in many cases to include the capability to detect this. For those systems which were sensitive, a few did not identify the most critical configuration in which to establish the calibration.

7.4 DESIGN SENSITIVITY TO CABIN VENTILATION AND IDENTIFICATION OF CRITICAL CONFIGURATION

As described in section 4.1.4, most q_{ci} compensated ΔP systems vented their q_{ci} sensor to cabin pressure. With respect to airspeed indication, this is generally an insignificant source of error when, for example, the aircraft is using the alternate static system. When applied to the $\Delta P/ q_{ci}$ calibration, those errors, which are trivial with respect to airspeed, can induce AoA errors of 2 degrees or more (equivalent to five or more knots of margin change). None of those systems had any recommendations that identified and set the most critical cabin pressure errors (e.g., vents open, windows open, etc.).

7.5 RECOMMENDATIONS

7.5.1 Manufacturer Recommendations

The following are recommendations from the AoA system manufacturers.

- Ensure that system calibration points are well defined such that they would be clear and repeatable by multiple calibrators.
- Ensure calibration points adequately consider the sources of margin variation (e.g., weight, flap configuration and ventilation configuration) and select the configuration that will ensure conservative errors when those variations are experienced.

- Ensure calibration points are safe and stable. Calibration points below stall warn speed should be avoided because they may introduce hazards with inexperienced pilots and are otherwise susceptible to variation due to buffet.

8. AOA IMPLEMENTATION

8.1 SITUATIONAL AWARENESS

AoA display in the cockpit is a valuable tool for aiding pilot/crew situational awareness. When properly presented, an AoA indexer/display provides near-immediate visual feedback to the flight crew regarding LSA (i.e., stall margin). However, the current status of COTS AoA systems and associated installation policy/guidance has led to dissimilar indications and display logic.

As discussed in section 6, the lack of consistent display indications and logic has resulted in unique AoA displays by each manufacturer. The result is system-specific training required to correctly interpret the AoA presentation, not considering the effects of calibration differences potentially encountered during system setup.

Appropriate and consistent presentation of AoA information provides intuitive and consistent feedback to the pilot for inadequate stall margin resolution. The consistent use of intuitive indexer orientation, coloration, and display elements offers a convenient means to inform the pilot in an expedient manner when it is most critical (i.e., on approach at low speed and low altitude).

8.2 FLIGHT ENVELOPE MONITORING SYSTEM AND FLY-BY-WIRE INPUTS

Modern GA integrated avionics systems, such as Garmin's Electronic Stability & Protection™ or Avidyne's Envelope Protection® and Envelope Alerting®, are incorporating flight envelope monitoring systems into their automatic flight control systems. The purpose of these systems is to aid in preventing unusual attitudes, high-speed exceedances (i.e., flight beyond V_{NE}, V_{MO}, and V_{FE}), and low-speed exceedances. AoA information would be a useful flight envelope, monitoring system input to be used for monitoring AoA during unusual attitude recovery, high-speed exceedance recovery, or LSA.

More advanced GA aircraft are now incorporating digital fly-by-wire control systems. Currently produced fly-by-wire GA aircraft such as Dassault 7X, Gulfstream G650, or Embraer Legacy 500 are equipped with AoA systems of sufficient accuracy and reliability required to support the fly-by-wire system. These types of flight control systems are not typical of a modern general aviation aircraft that would seek to install a COTS AoA system.

For either a flight envelope monitoring system or fly-by-wire flight control system, the AoA system must be capable of providing repeatable AoA information of suitable accuracy for its control influence. It may be possible to sacrifice design accuracy if the system incorporating the AoA input is calibrated with the system installed on the aircraft. If the flight envelope monitoring system or fly-by-wire system requires a specific/known AoA value (i.e., calibration not performed with installed system), accuracy cannot be sacrificed.

As shown in table 4 in section 5, the AoA margin between stall warn and stall varies from 2.9 degrees (clean flaps) to 3.7 degrees (landing flaps) for the test aircraft. Of the COTS AoA systems evaluated, two systems had a published AoA accuracy of ±1.0 degree or better, while the remaining eight systems had published accuracies greater than ±1.0 degree, or did not have a published accuracy. One AoA system (system 4) had published accuracy of ±2.0 degrees. An error of 2 degrees is greater than 50% of the stall warning to stall margin. For the purposes of the COTS AoA systems installations, errors in accuracy may be reduced by in-flight calibration of the system. With the in-flight calibration completed, the ability of the AoA system to perform its intended function becomes more dependent on the repeatability of the AoA measurement. None of the systems evaluated had published repeatability information, however, and test results showed that all but one (system 7) of the systems produced repeatable AoA measurements. If the flight envelope monitoring or fly-by-wire flight control systems incorporating the COTS AoA system are capable of "as-installed" calibration, the accuracy of the system becomes less important and the repeatability of the system becomes limiting.

Another limiting factor in any of the evaluated COTS AoA systems as an input to a flight envelope monitoring or fly-by-wire system was the lack of aircraft-configuration-dependent AoA calibration. As discussed in section 5, flap configuration changes the AoA thresholds for a particular airfoil. Additionally, for many of the systems evaluated, the AoA measurement and associated system output varied from one configuration to the next. For example, the flap configuration dependence of the system depicted in figure 23 is a 4-degree range between clean flaps and landing flaps, whereas the AoA system output remains constant at 0.5.

9. DERIVED AOA

During the evaluations of COTS AoA systems conducted under grant DTFACT-15-C-00002, parallel research was being conducted by Adaptive Aerospace Group, Inc. (AAG) to explore an AoA estimation derived from unconventional means under grant DTFACT-15-C-00005. AAG requested flight test data for specific test points of interest as a means to evaluate a proprietary AoA estimation algorithm. Those maneuvers were flown during the conduct of these COTS AoA system evaluations and subsequently analyzed by AAG. Results of the AAG analysis are included in APPENDIX B—Adaptive Aerospace Report on Derived AoA. Test results showed good correlation between the "truth" source AoA and derived AoA, up to an AoA of ~13 degrees.

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APPENDIX A—NORMALIZED AOA DESCRIPTION

Consider a basic lift curve slope as shown in figure A-1:

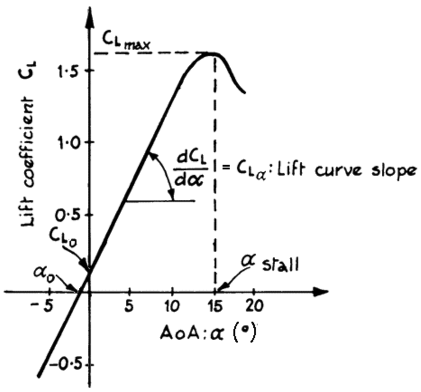

Figure A-1. Lift curve slope

Knowing the zero-lift angle of attack (AoA) (α_o) and stall AoA (α_{stall}) in degrees, a non-dimensional scaling factor can be constructed for normalized AoA:

$$\alpha_{norm} = \frac{\alpha_{actual} - \alpha_o}{\alpha_{stall} - \alpha_o} \quad \text{(A-1)}$$

This normalized parameter will vary linearly with Actual AoA (α_{actual}), from $\alpha_{norm} = 0$ when AoA = zero-lift AoA to 1.0 when AoA = stall AoA. Lift Coefficient can be characterized as a simple linear function of that normalized parameter:

$$C_L = \alpha_{norm} \cdot C_{L_{max}} \quad \text{(A-2)}$$

Lift coefficient will increase linearly from $C_L = 0$ at zero-lift AoA (α_{norm}=0) to C_{Lmax} at stall AoA (α_{norm} = 1.0).

Using that convention and basic lift equation, some mathematical relationships can be established:

$$L = W = \frac{1}{2}\rho_o V^2 S C_L = \frac{1}{2}\rho_o V^2 S \alpha_{norm} C_{L_{max}} \quad \text{(A-3)}$$

$$V^2 = \frac{2W}{\rho_o S \alpha_{norm} C_{L_{max}}} \quad \text{(A-4)}$$

At stall, by definition: $V=V_S$ @ $\alpha_{norm} = 1.0$:

$$V_s^2 = \frac{2W}{\rho_o S C_{L_{max}}} \tag{A-5}$$

Conversely, equation can be reorganized to characterize normalized AoA:

$$\alpha_{norm} = \frac{2W}{\rho_o V^2 S C_{L_{max}}} \tag{A-6}$$

At any desired speed multiple (i.e., $\underline{M}\cdot V_s$, where M is the desired multiple), a corresponding AoA target can be determined:

$$\alpha_{norm} = \frac{2W}{\rho_o \left(M \cdot V_s\right)^2 S C_{L_{max}}} = \frac{1}{M^2}\frac{2W}{\rho_o V_s^2 S C_{L_{max}}} = \frac{1}{M^2}\cdot\frac{2W}{\left(\frac{2W}{\rho_o S C_{L_{max}}}\right)\rho_o C_{L_{max}}} = \frac{1}{M^2} \tag{A-7}$$

A reference approach speed of $V_{REF} = 1.3\cdot V_S$ would be identical to $\alpha_{norm} = (1/1.3)^2 = 0.592$.\

With an appropriately calibrated system and indicator, maneuvering in pitch to maintain $\alpha_{norm} = 0.592$ would be precisely at V_{REF}.

Lift and Drag can be characterized as from normalized AoA:

$$C_L = \alpha_{norm} C_{L_{max}} \tag{A-8}$$

$$C_D = C_{D_o} + \frac{{C_L}^2}{\pi e AR} = C_{D_o} + \frac{{\alpha_{norm}}^2 {C_{L_{max}}}^2}{\pi e AR}$$

Incorporating into best lift over drag $(L/D)_{max}$ discussion:

$$\left(\frac{L}{D}\right)_{max} = \left(\frac{C_L}{C_D}\right)_{max} \tag{A-9}$$

To find maximum:

$$\left.\frac{L}{D}\right|_{Max} when \frac{d\,\frac{C_L}{C_D}}{d\alpha_{norm}} = 0 \tag{A-10}$$

Differential Calculus: Quotient Rule

$$\frac{d\frac{C_L}{C_D}}{d\alpha_{norm}} = \frac{C_D \cdot \frac{dC_L}{d\alpha_{norm}} - C_L \frac{dC_D}{d\alpha_{norm}}}{{C_D}^2} = 0 \qquad \text{(A-11)}$$

Simplifying equation shows that the following is true at best L/D point:

$$C_D \cdot \frac{dC_L}{d\alpha_{norm}} = C_L \frac{dC_D}{d\alpha_{norm}}$$

$$\left(C_{Do} + \frac{{\alpha_{norm}}^2 {C_{L\max}}^2}{\pi eAR}\right) \cdot C_{L\max} = \left(\alpha_{norm} C_{L\max}\right) \cdot 2\frac{\alpha_{norm} {C_{L\max}}^2}{\pi eAR} \qquad \text{(A-12)}$$

$$\alpha_{norm} = \frac{\sqrt{{C_D}_O \pi eAR}}{C_{L_{Max}}}$$

As shown, the best L/D can be characterized as a distinct AoA and is purely a function of aerodynamic design parameters.

Best Endurance Derivation

Best Endurance occurs at the point where minimum power is required.
Power required can be summarized as:

$$P_{req} = V_T \cdot D = \frac{V}{\sqrt{\sigma}} \cdot \frac{1}{2}\rho_o V^2 S \left(C_{D_O} + \frac{{C_{L_{max}}}^2 {\alpha_{norm}}^2}{\pi e AR}\right) = \frac{\rho_o S}{2\sqrt{\sigma}} \cdot V^3 \left(C_{D_O} + \frac{{C_{L_{max}}}^2 {\alpha_{norm}}^2}{\pi e AR}\right) \quad \text{(A-13)}$$

Simplified from previous, Velocity can be characterized as:

$$V = \sqrt{\frac{2W}{\rho_o S \alpha_{norm} C_{L_{max}}}} = \sqrt{\frac{2W}{\rho_o S C_{L_{max}}}} \cdot {\alpha_{norm}}^{-\frac{1}{2}} \quad \text{(A-14)}$$

$$P_{req} = \frac{\rho_o S}{2\sqrt{\sigma}} \cdot \left(\frac{2W}{\rho_o S C_{L_{max}}}\right)^{\frac{3}{2}} \cdot \left(C_{D_O} {\alpha_{norm}}^{-\frac{3}{2}} + \frac{{C_{L_{max}}}^2 {\alpha_{norm}}^{\frac{1}{2}}}{\pi e AR}\right) \quad \text{(A-15)}$$

Differentiate to find minimum:

$$P_{req}\Big|_{\min} \; when \; \frac{dP_{req}}{d\alpha_{norm}} = 0$$

$$\frac{dP_{req}}{d\alpha_{norm}} = \frac{\rho_o S}{2\sqrt{\sigma}} \cdot \left(\frac{2W}{\rho_o S C_{L_{max}}}\right)^{\frac{3}{2}} \cdot \left(-\frac{3}{2} \cdot C_{D_O} {\alpha_{norm}}^{-\frac{5}{2}} + \frac{1}{2} \cdot \frac{{C_{L_{max}}}^2 {\alpha_{norm}}^{-\frac{1}{2}}}{\pi e AR}\right) = 0$$

$$\frac{3}{2} \cdot C_{D_O} {\alpha_{norm}}^{-\frac{5}{2}} = \frac{1}{2} \cdot \frac{{C_{L_{max}}}^2 {\alpha_{norm}}^{-\frac{3}{2}}}{\pi e AR}$$

$$\alpha_{norm,best\ endurance} = \frac{\sqrt{3}\sqrt{C_{D_O} \pi e AR}}{C_{L_{max}}} = \sqrt{3} \cdot \alpha_{norm,Best\ L/D}$$

APPENDIX B—ADAPTIVE AEROSPACE REPORT ON DERIVED AOA

Use of a Derived Angle-of-Attack Algorithm using Flight Data from a Single-Engine Jet

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Based on research efforts funded by grant by the Federal Aviation Administration

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4 November 2016

Table of Contents

Abstract

This informal report outlines calibration and testing of a novel derived Angle of Attack (AoA) estimation algorithm using flight test data provided by Skyward Bound, Inc. from a prototype single-engine general aviation jet aircraft. The algorithm was developed by Adaptive Aerospace Group, Inc. (AAG). The purpose of this report is to provide Skyward Bound with information to include in their formal report to the FAA.

Keywords: Angle-of-attack estimation, Derived AoA, Flight Test, Sensed AoA, Stall Margin, Stall Protection, Simulation, Flight Test, General Aviation

Use of a Derived Angle-of-Attack Algorithm using Flight Data from a Single-Engine Jet

A novel derived angle-of-attack estimation algorithm relying on data available from a typical Air Data, Attitude, and Heading Reference System (ADAHRS) was developed using a single-engine piston-powered general aviation aircraft previously described[1]. Under this current effort, the same algorithm was applied to data collected during flight of a single-engine jet-powered general aviation aircraft post-flight. The estimated angle-of-attack generated by the algorithm was compared with measurements of in-flight angle-of-attack taken by an air data boom, corrected for static (position error, upwash) and dynamic (moment-arm) effects, for a series of maneuvers including moderate turns, steep turns, accelerated stalls, and straight-ahead stalls.

Test Aircraft

The aircraft under test was an advanced single-engine jet-powered general aviation jet aircraft under development. A telemetry and data recording system was used to generate time-history based data in engineering units. A series of calibration (trim) points in level flight and with a steady atmosphere were recorded as well as a set of dynamic maneuvers (moderate turns, steep turns, and a stall series) for two separate flights. However, due to insufficient quality of slow-flight calibration points on the first flight, only data from the second flight was used in this report.

The only vehicle configuration tested was with the landing gear and high-lift devices retracted.

Calibration Maneuvers

The calibration maneuvers consisted of straight-and-level flight at a steady airspeed, holding steady conditions for at least 25 seconds. Nine such trim points were flown, starting with 150 knots indicated airspeed (KIAS) and concluding with 80 KIAS.

Dynamic Maneuvers

The aircraft was flown through both 45°- and 60°-banked turns, both left and right. The 45° turns were through 180° of heading change; the 60° turns were through 360° heading change. An accelerated stall to the left with a 45° bank was flown, as well as straight-ahead gradual (incipient) stalls and rapid (full) stalls.

Results

The attached plots depict the results of this test of the AAG derived AoA algorithm.

Trim Points

Figure 1 shows the angle-of-attack time history for the trim point maneuvers plotted versus time. Three measures of AoA are shown: the black triangles denote the "best estimated" angle of attack for each 25 second steady-state trim point based on pitch attitude and geometric flight path angle; the blue curve denotes the calibrated AoA value from the flight test boom, and the brown curve shows the results of the calibrated AoA value derived from AAG's algorithm. A small bias is shown between the two colored lines, gradually increasing in bias with increasing angle of attack, on the order of one degree of error.

Calibration Curves

Figures 2 through 4 show the pitch attitude, flight path angle, and best-estimated angle of attack for the same points shown in figure 1. Pitch attitude was the average of ADAHRS measured pitch angle over the 25 second steady trim point. Flight path angle was estimated from finding the arctangent of the ratio between GPS altitude change vs. horizontal distance traveled through the atmosphere (obtained by true airspeed and wind component) during the same time. Best-estimated angle of attack was the difference between these two angles; it is plotted against the measured angle of attack from the air data boom (corrected for static and dynamic effects by the flight test operator).

Figure 5 shows a straight line of normal force coefficient (obtained by normalizing recorded vehicle weight by estimated dynamic pressure, and multiplied by the cosine of pitch attitude) versus best-estimated angle of attack. This calibration curve was subsequently used for AoA estimation in the opposite sense: using normal acceleration (N_z) and estimated weight, with estimated dynamic pressure based on indicated airspeed, to derive the estimated angle-of attack.

Estimation Results

The results of applying the AoA estimation algorithm against time histories of test maneuvers flown on the same flight as the calibration are shown next. It should be noted that, while flight test data included a channel for vehicle weight, this was only used during calibration; for estimation, the vehicle weight was assumed to be constant at 4,900 lbs. Reference wing area was assumed to be 195 ft^2.

Level turns. Figures 6 and 7 show estimated and measured angle of attack for the 180° left and right turns at 45° bank angle. Note the same approximate 1° AoA bias.

Figures 8 and 9 show estimated and measured angle of attack for the 180° left and right turns at 60° bank angle, with a similar bias.

Accelerated stall. Figure 10 shows estimated and measured angle of attack for an accelerated stall occurring during of a left turn with 45° bank. The conservative bias between estimate and measured grows slightly in this more dynamic event, but the linearity of the estimator fails to follow the non-linearity of the lift-slope curve occurring above 13° AoA, about where the aircraft stalls.

One-g stalls. Figures 11 and 12 show wings-level stalls; figure 11 is for an "incipient" maneuver which approaches the stall more slowly than the more dynamic stall shown in figure 12. Again, a conservative one-degree bias appears as the stalls is approached, but the estimator does not track well in the post-stall region above 13° AoA.

Concluding Remarks

A novel angle-of-attack estimation algorithm was tested using flight data from a prototype single-engine jet-powered general aviation aircraft. The data included maneuvers necessary for calibration and subsequent operation of the estimation algorithm, as well as air data boom "truth" angle-of-attack data. Comparisons between the estimated AoA and measured AoA showed good correlation, with some conservativeness in the estimation (AoA higher than actual by about one degree) even for somewhat dynamic maneuvers, up to stall AoA of approximately 13°.

References

1. Jackson, E. Bruce and Hoffler, Keith D.: "Flight Test Results of Direct-Measure and Derived Angle-of-Attack Systems for General Aviation Airplanes." Report prepared for, and pending publication by, the FAA: Submitted June 2016.

Figures

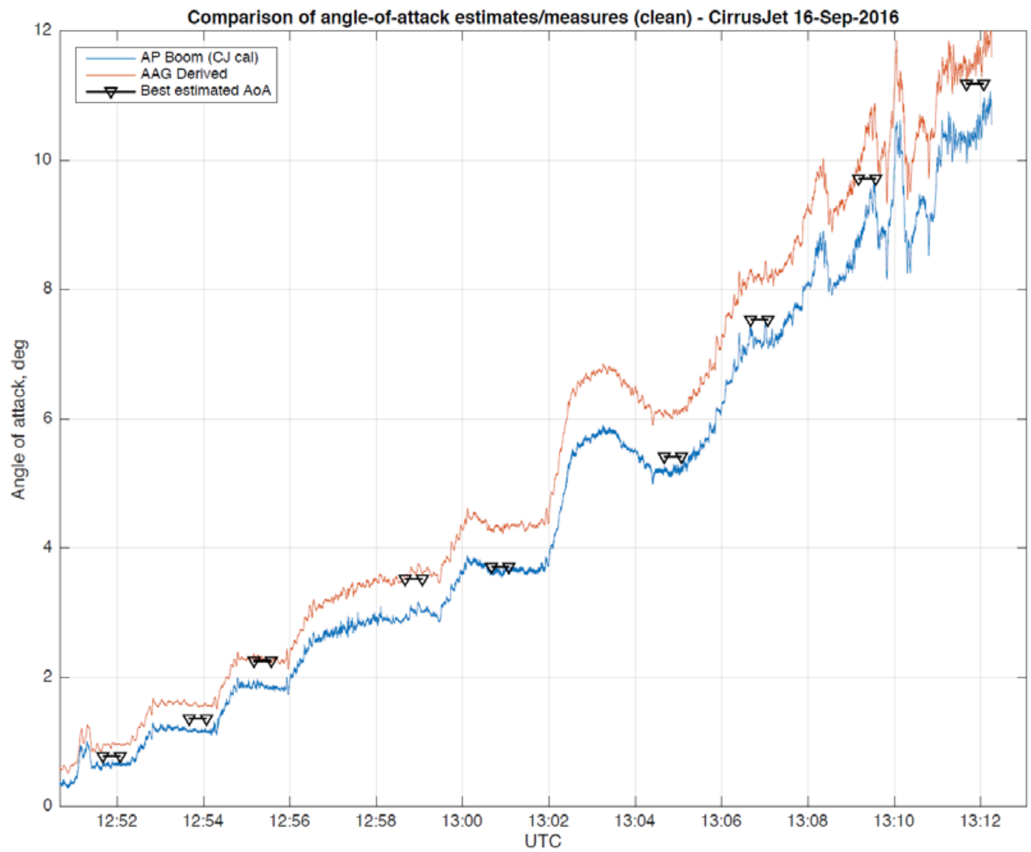

Figure 1. Comparison of best-estimated, measured and derived angle of attack for the calibration trim test points for the data flight.

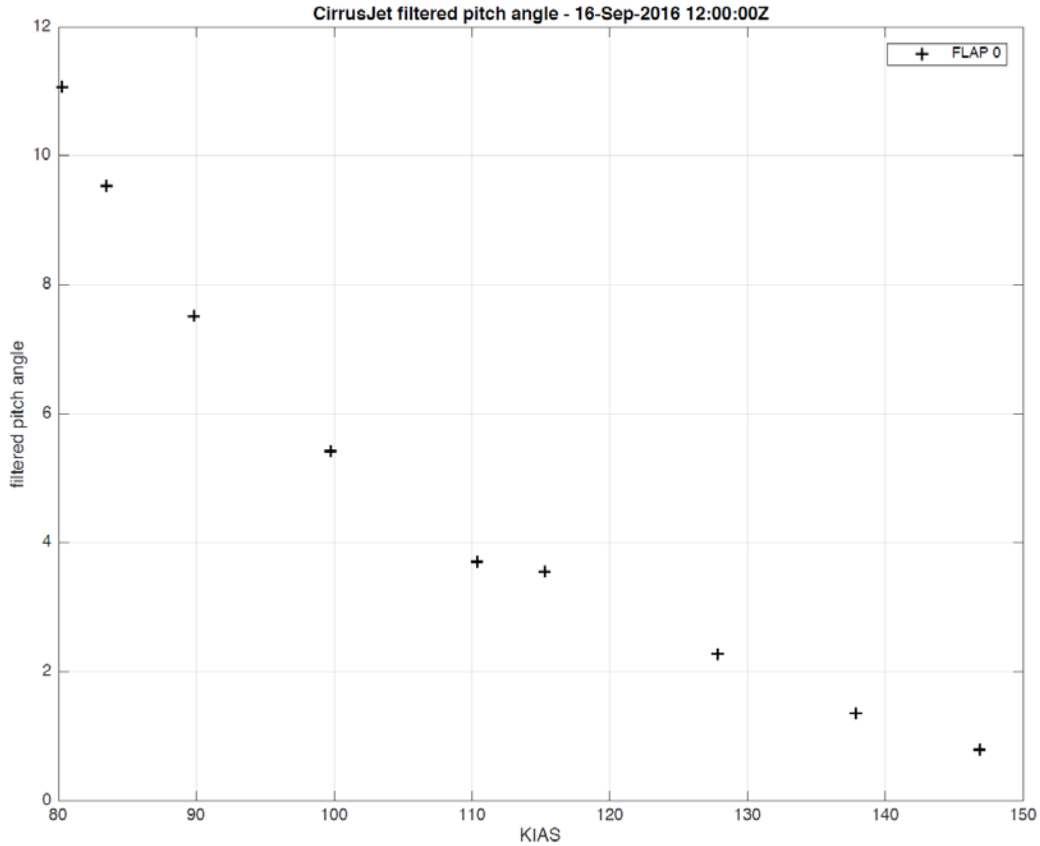

Figure 2. Average pitch attitude during each calibration trim test point.

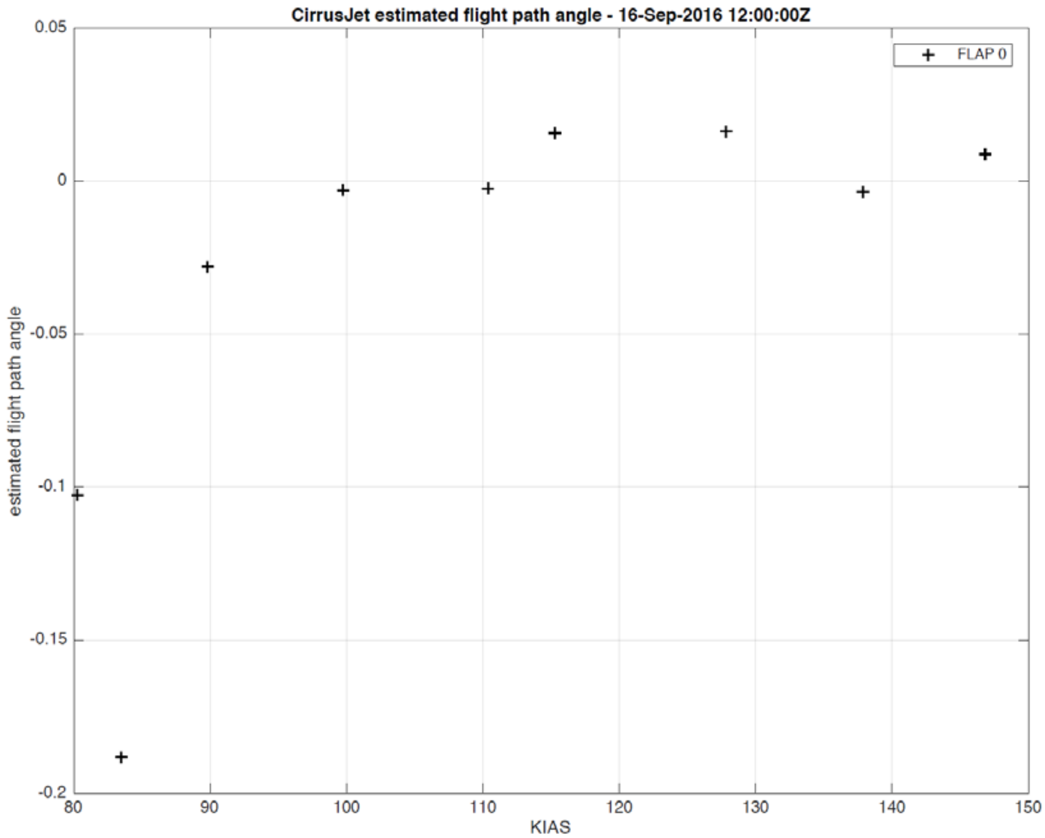

Figure 3. Average atmosphere-relative flight path angle during each calibration trim test point.

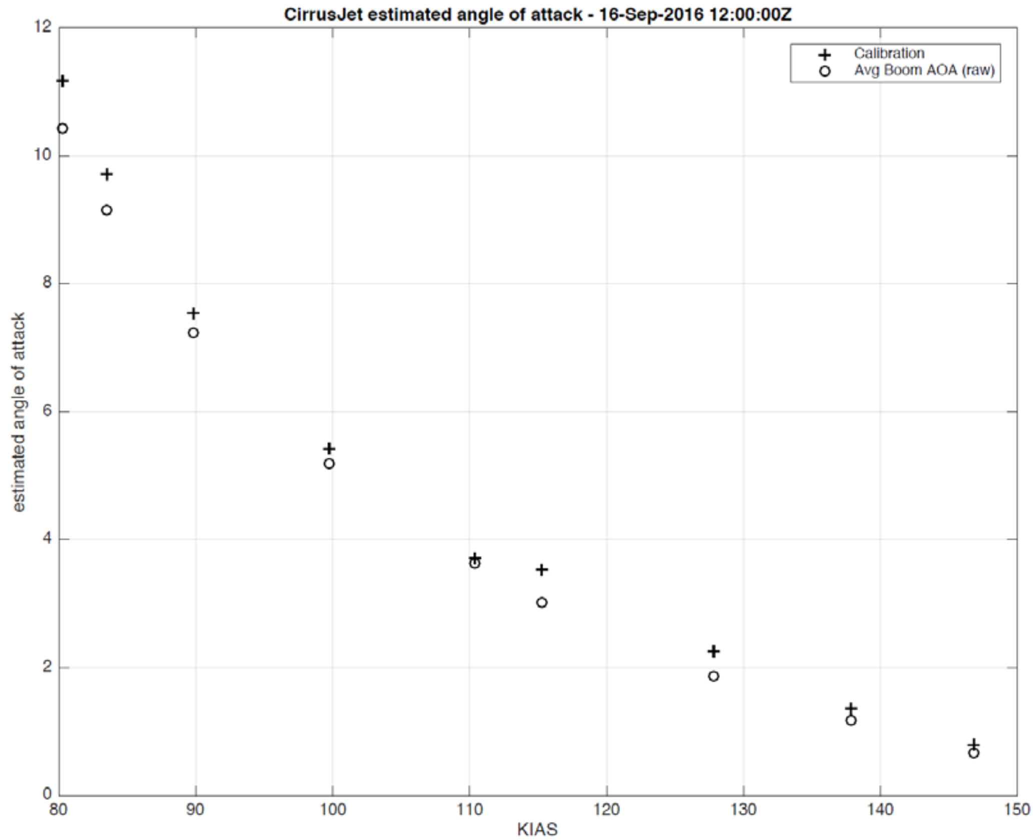

Figure 4. Best-estimated and air-boom measured angle of attack vs. indicated airspeed for each calibration trim test point.

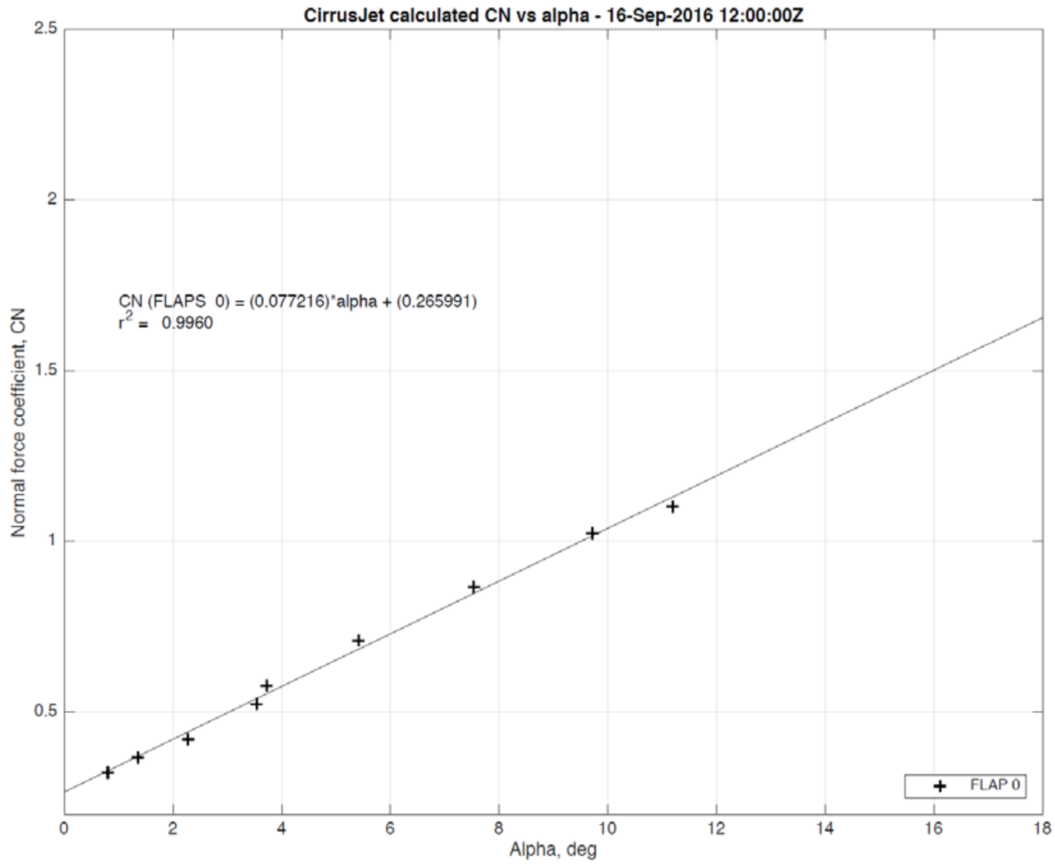

Figure 5. Normal force coefficient estimated from each calibration trim test point.

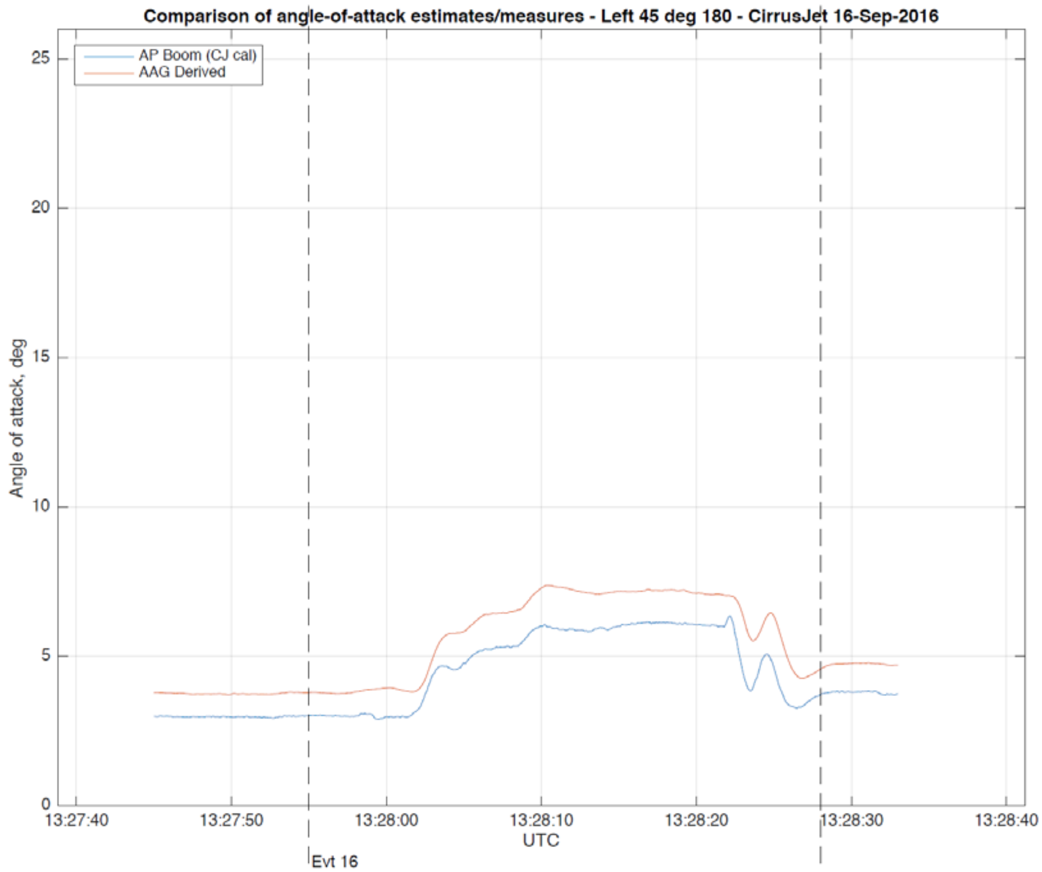

Figure 6. Comparison of estimated vs. measured angle of attack for a 180° turn to the left with 45° bank.

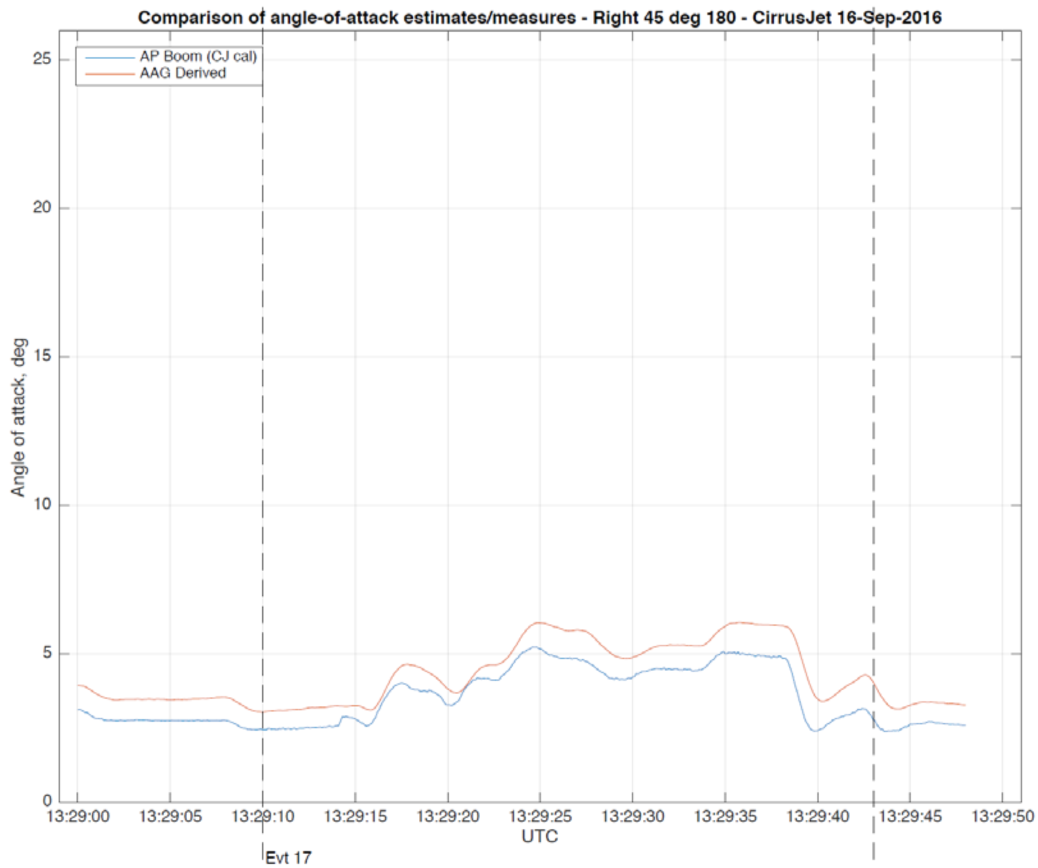

Figure 7. Comparison of estimated vs. measured angle of attack for a 180° turn to the right with 45° bank.

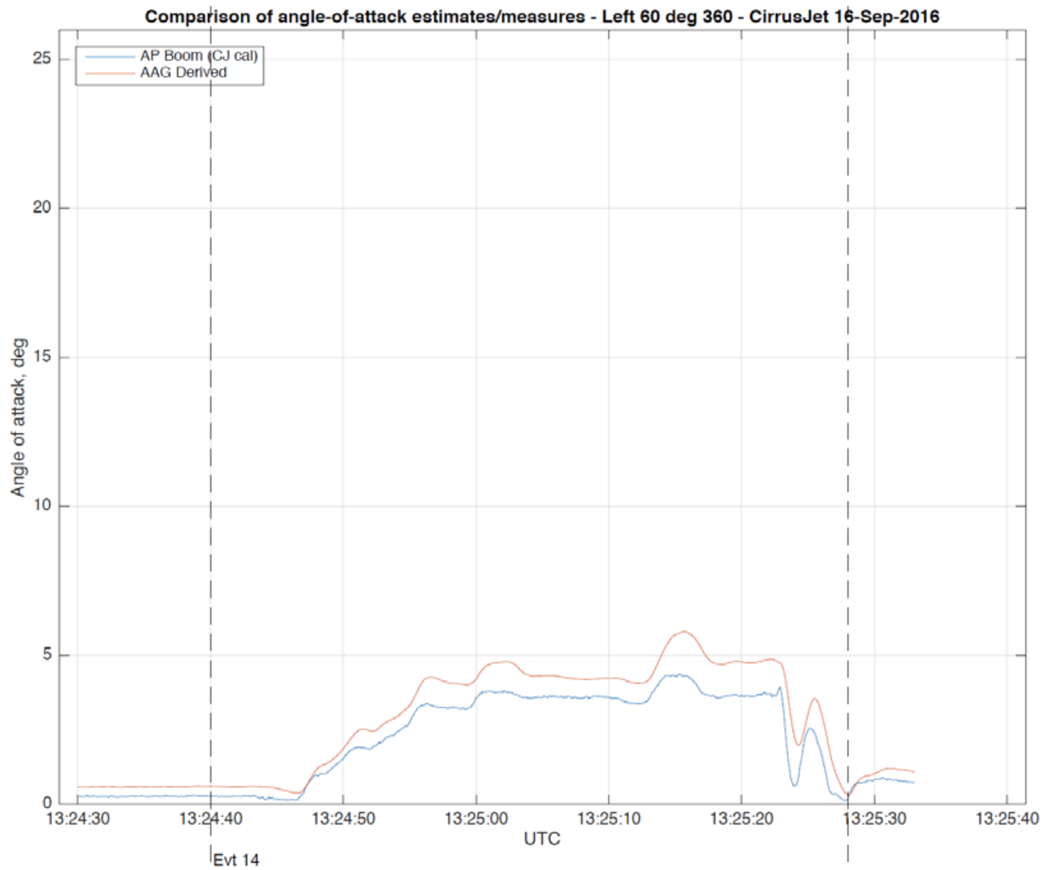

Figure 8. Comparison of estimated vs. measured angle of attack for a 360° turn to the left with 60° bank.

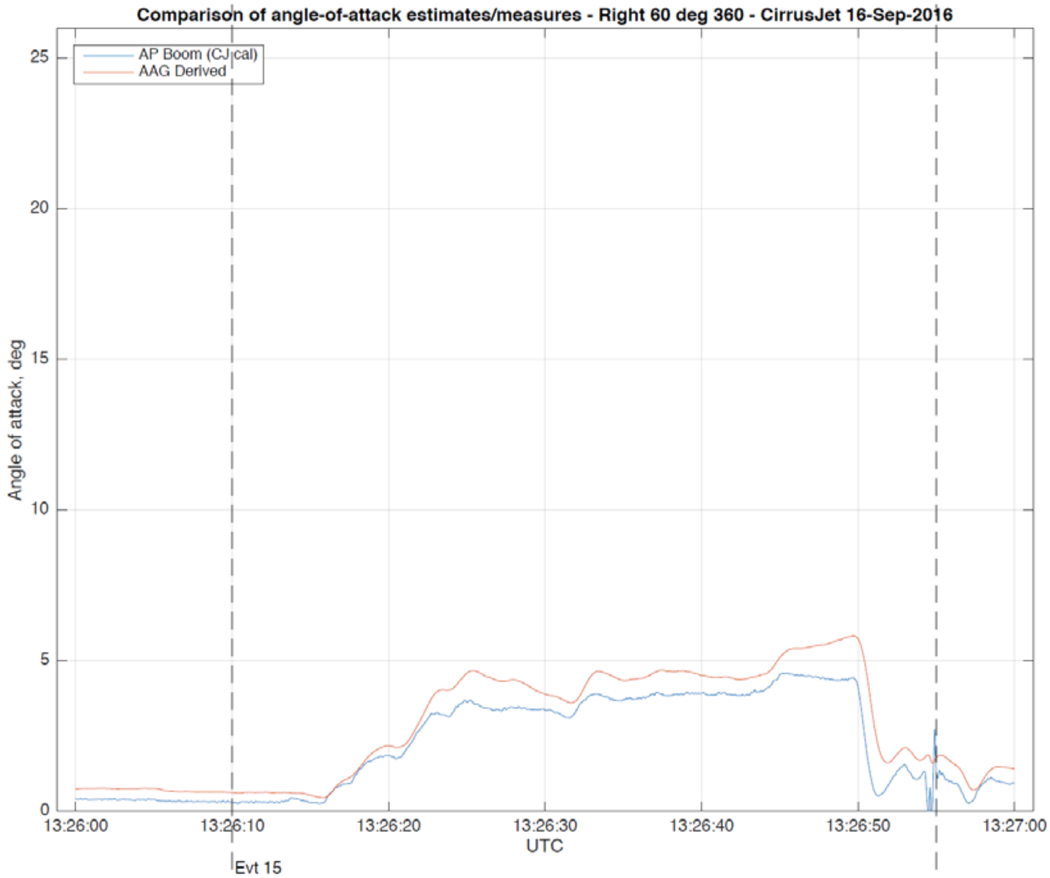

Figure 9. Comparison of estimated vs. measured angle of attack for a 360° turn to the right with 60° bank.

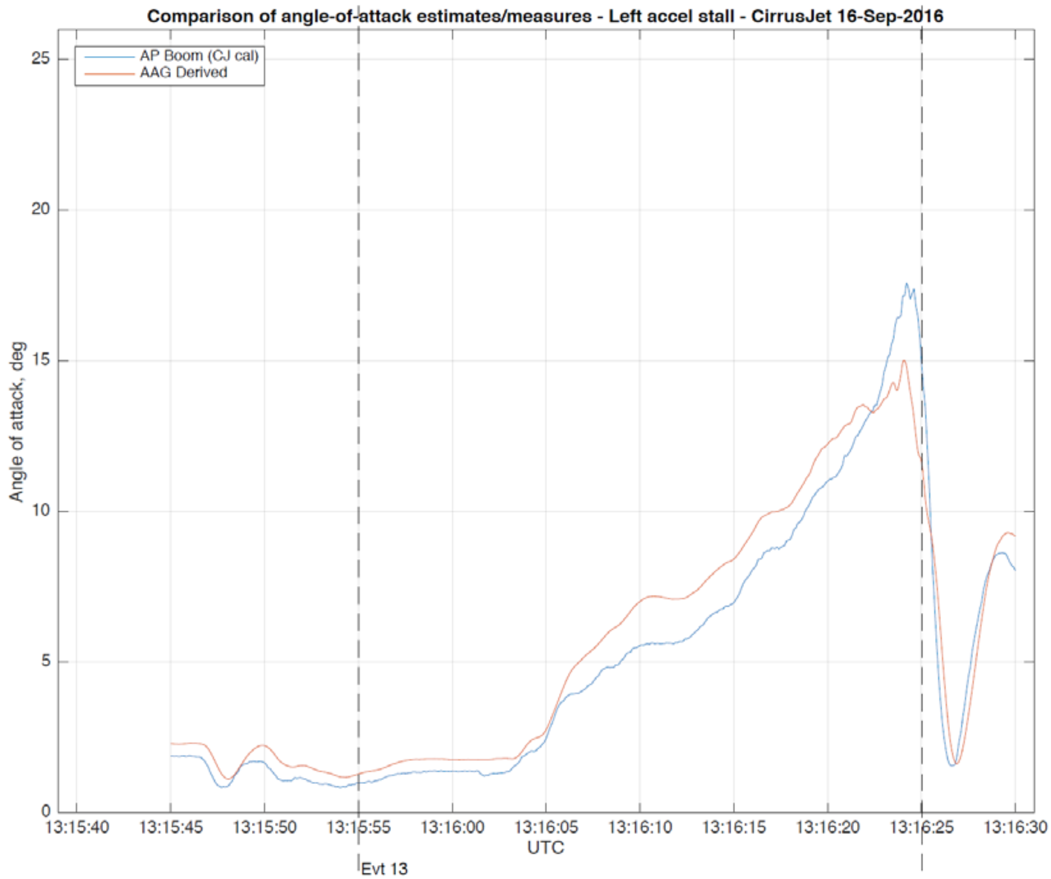

Figure 10. *Comparison of estimated vs. measured angle of attack for an accelerated stall to the left with 45° bank.*

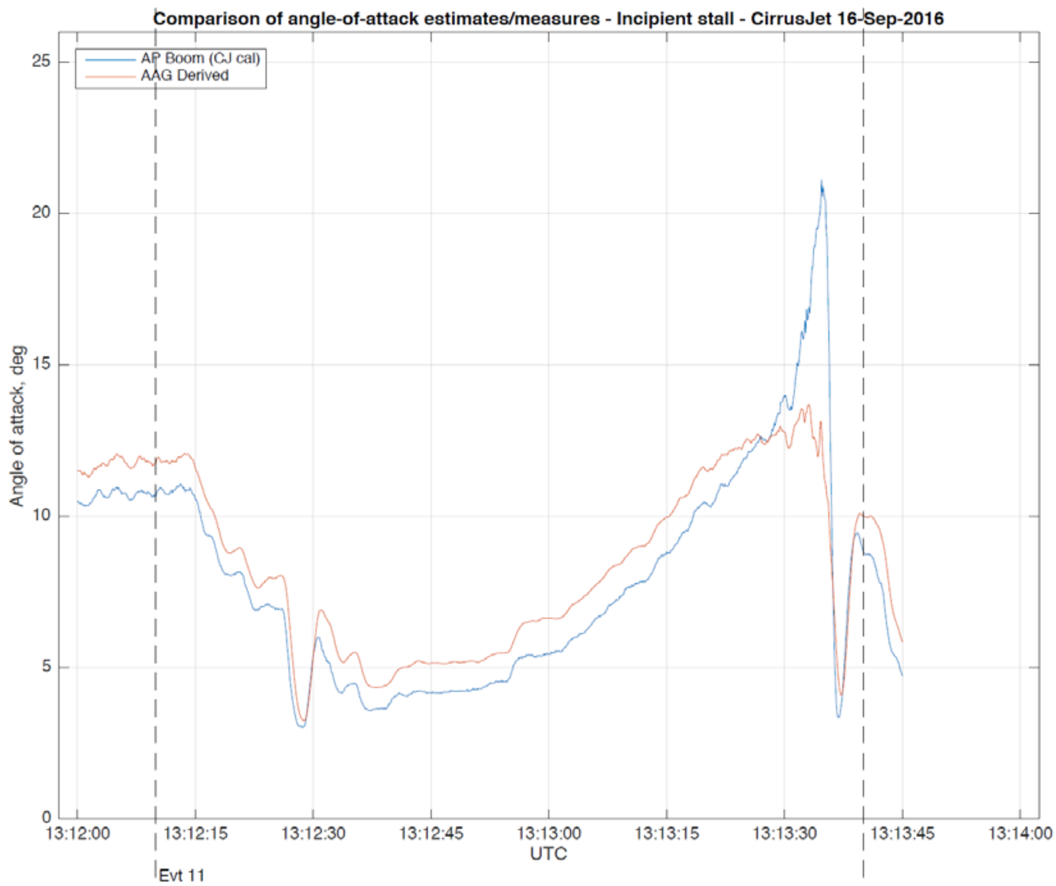

Figure 11. Comparison of estimated vs. measured angle of attack for 1-G stall with gradual deceleration.

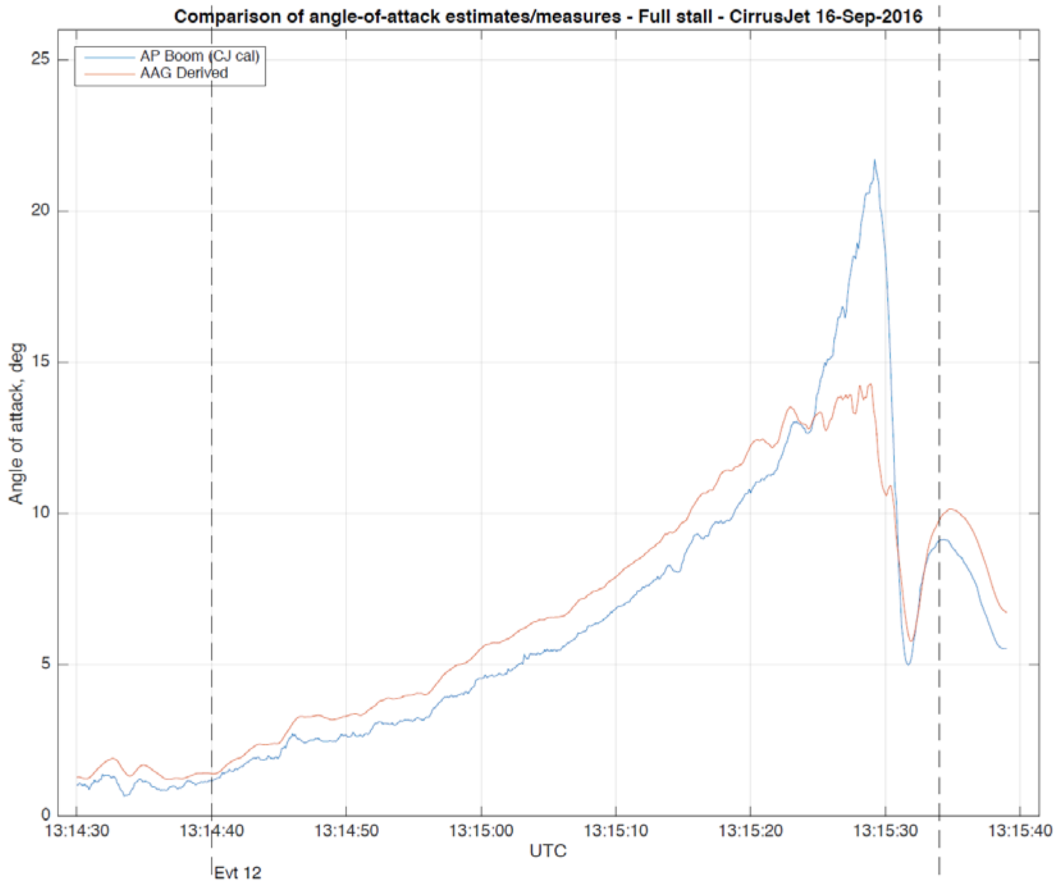

Figure 12. Comparison of estimated vs. measured angle of attack for 1-G stall with more rapid deceleration.