DOT/FAA/TC-21/12

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Flight Test Data Driven Development of Means of Compliance for Low-Speed Flight Characteristics of Part 23 Aircraft

July 9, 2019

Final report

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

Technical Report Documentation Page

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

1. Report No. DOT/FAA/TC-21/12	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Flight Test Data Driven Development of Means of Compliance for Low-Speed Flight Characteristics of Part 23 Aircraft		5. Report Date July 2019 6. Performing Organization Code ANG-E27
7. Author(s) Brian Kish, Markus Wilde, Ralph Kimberlin		8. Performing Organization Report No. DOT/FAA/TC-21/12
9. Performing Organization Name and Address Florida Institute of Technology 150 W. University Blvd Melbourne, FL 32901		10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFACT-17-C-00001
12. Sponsoring Agency Name and Address AAQ-610 Facilities & Grants FAA William J. Hughes Technical Center Building 300, Fourth Floor Atlantic City, NJ 08405		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code AAQ-610-AFN

15. Supplementary Notes

The Federal Aviation Administration William J. Hughes Technical Center Aviation Research Division COR was Karen Mercer

16. Abstract

Loss of control in the traffic pattern is one of the primary causes for fatal accidents in general aviation. For a number of years, the FAA Small Airplane Directorate has been working with industry and academia to significantly enhance general aviation safety by introducing advances in technology, such as evolved in-cockpit warning systems and increased use of augmented flight controls, and by developing new means of compliance for the airworthiness certification standards. To give manufacturers more flexibility in how to demonstrate compliance with certification standards, and in order to stimulate the introduction of novel flight energy management and warning technologies, the envisioned means of compliance are based on certification point scores. The present project was focused on evaluating the effects of different sensory modes in angle-of-attack warning systems (visual, aural, and haptic) along with the stall characteristics of common single-engine, Part 23 aircraft, in order to develop a means of compliance. The period of performance for the project was 02/20/2017 – 09/09/2019. The proposed means of compliance combines fixed performance thresholds for coordinated stalls with a point system for uncoordinated, feet-on-the-floor stalls, longitudinal control force changes, free aircraft pitching response during configuration changes, and enhanced warning systems. The report presents the proposed means of compliance for flight characteristics of non-aerobatic level 1 to level 4 airplanes and documents the underlying flight test data. Flight tests for the characterization of angle-of-attack warning methods were executed on a fly-by-wire DA42 research aircraft developed by the Technical University of Munich and operated by Diamond Aircraft in Wiener Neustadt, Austria. Flight tests for the study of common stalling characteristics were executed at Florida Institute of Technology in Melbourne, FL, on six different aircraft (Diamond DA40, Piper PA28, Cessna 172N, Mooney M20C, Cirrus SR20, and Citabria). In total, 39 flights (59.7 hours) were conducted for this program.

17. Key Words Means of compliance, stall warning, AOA warning, stall protection, AOA protection, stall characteristics, flying qualities, flight characteristics, low-speed flight, Part 23 certification, general aviation, loss of control	18. Distribution Statement This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 94	22. Price

Acknowledgements

The team would like to thank the FAA for funding this effort and participating in the flight campaigns and analysis. David Sizoo and Ed Kolano flew as test pilots. David Webber and Ross Schaller flew as flight test engineers. Robert McGuire managed the program. Karen Mercer issued the contract. The team would like to thank David Mitchell and Eric Mitchell from Mitchell Aerospace Research for consultation and data analysis during the program. We also would like to thank Florian Holzapfel and the Technical University of Munich (TUM) for allowing access to their Diamond DA42 test bed. Lars Peter, Simon Schatz, and Patrick Lauffs from TUM were instrumental in integrating the technologies required to demonstrate audio, visual and haptic AOA warning. Thomas Wimmer, Niko Daroussis, and Ingmar Mayerbuch from Diamond Aircraft flew as safety pilots in the DA42. We would like to thank additional personnel from Florida Tech who supported the program. Jennifer Geehan assisted the TUM team in the preparation and execution of the DA42 flight campaign. Isaac Silver provided his Cessna 172 for the program as well as flight data recorders and video equipment. He also arranged for facilities at FIT Aviation and provided consultation based on an extensive career in flying and training pilots in Part 23 aircraft. David Calendar from FIT Aviation flew missions in the Citabria. We would like to thank Derek Fallon and C.J. Modine from Melbourne Flight Training for providing and flying a Cirrus SR20 and a Diamond DA40. We would like to thank the Matisons for leasing us their Mooney M20C. Finally, we would like to thank all the contract, admin, and aircraft support personnel who enabled the technical team to focus on the research.

Contents

Figures

Tables

Acronyms

Acronym	**Definition**
AOA	Angle-of-Attack
EASA	European Aviation Safety Agency
EFCS	Experimental Flight Control System
FAA	Federal Aviation Administration
FCC	Flight Control Computer
FOF	Feet on the Floor
FRSR	Free Return Speed Range
FSD	Flight System Dynamics
FTE	Flight Test Engineer
GA	General Aviation
LOC	Loss of Control
MOC	Means of Compliance
NORSEE	Non-Required Safety-Enhancing Equipment
NTSB	National Transportation Safety Board
TUM	Technical University of Munich

Executive summary

Loss of control in the traffic pattern is one of the primary causes of fatal accidents in general aviation. For a number of years, the FAA Small Airplane Directorate has been working with industry and academia to significantly enhance general aviation safety by introducing advances in technology, such as evolved in-cockpit warning systems and increased use of augmented flight controls, and by developing new means of compliance for the airworthiness certification standards. To give manufacturers more flexibility in how to demonstrate compliance with certification standards, and in order to stimulate the introduction of novel flight energy management and warning technologies, the envisioned means of compliance are based on certification point scores. The present project was focused on evaluating the effects of different sensory modes in angle-of-attack warning systems (visual, aural, and haptic) along with the stall characteristics of common single-engine, Part 23 aircraft, in order to develop a means of compliance. The period of performance for the project was 02/20/2017 – 09/09/2019. The proposed means of compliance combines fixed performance thresholds for coordinated stalls with a point system for uncoordinated, feet-on-the-floor stalls, longitudinal control force changes, free aircraft pitching response during configuration changes, and enhanced warning systems. The report presents the proposed means of compliance for flight characteristics of non-aerobatic level 1 to level 4 airplanes and documents the underlying flight test data. Flight tests for the characterization of angle-of-attack warning methods were executed on a fly-by-wire DA42 research aircraft developed by the Technical University of Munich and operated by Diamond Aircraft in Wiener Neustadt, Austria. Flight tests for the study of common stalling characteristics were executed at Florida Institute of Technology in Melbourne, FL, on seven different aircraft (Diamond DA40, Piper PA28, Cessna 172N, Mooney M20C, Cirrus SR20, and Citabria). In total, 39 flights (59.7 hours) were conducted for this program.

1 Introduction

1.1 Purpose

During 2012-2016, the National Transportation Safety Board (NTSB) recorded 6,397 accidents in general aviation (GA), of which 19% (1,193) resulted in fatalities (see Figure 1).

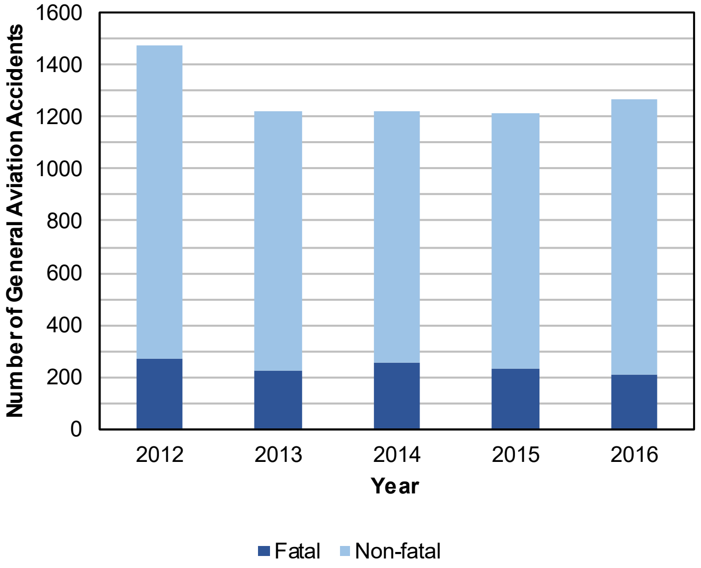


Figure 1. Annual number of GA accidents for 2012-2016

About 61% of GA accidents occurred with fixed-wing aircraft flown in personal use. As Figure 2 clearly shows, 46% of all fatal GA accidents can be attributed to inflight loss of control (LOC). This makes LOC the principal cause of fatal accidents in GA. Inflight LOC is defined by the NTSB as "loss of aircraft control while in flight, or extreme deviation from intended flightpath" [1]. In other words, a pilot is either distracted from the piloting tasks or is not paying sufficient attention to the aircraft, leading to a significant loss in airspeed and/or altitude, ultimately resulting in a crash. To counter the high incidence of LOC accidents, the focus of past and current GA safety research has been on improving the pilot's awareness for energy, airspeed and angle-of-attack through information and warning systems, designing aircraft for benign stall characteristics, and designing the aircraft for benign post-stall spin characteristics. However, a detailed look at the published NTSB accident data shows that 25% of all fatal accidents occur "en route", so at or around cruising altitude, whereas 35% occur during initial climb and approach, below 1000 ft in altitude (see Figure 3). If a stall or spin starts at such low altitude, the pilot does not have enough altitude/time to recover the aircraft and convert altitude into airspeed before hitting the ground. This is highlighted by research conducted by the European Aviation Safety Agency (EASA). In 2008, EASA analyzed 57 stall/spin accidents and determined their exact locations; 10 of the accidents occurred in the period 1999-2008 and involved aircraft designed to be “spin resistant”, namely the Cirrus SR-20 and SR-22; the rest were fatal fixed-wing GA accidents occurring in 2006. The analysis found that 45 of the 57 accidents happened at altitudes below 1000 ft, with 38 occurring within the traffic pattern (see Figure 4) [2]. The data clearly show that focusing on stall and spin characteristics of aircraft is too late in the mishap chain to prevent 35% of the total fatalities in fixed-wing, personal use GA. In the U.S. alone, this represents on average 73 fatalities per year or one every five days.

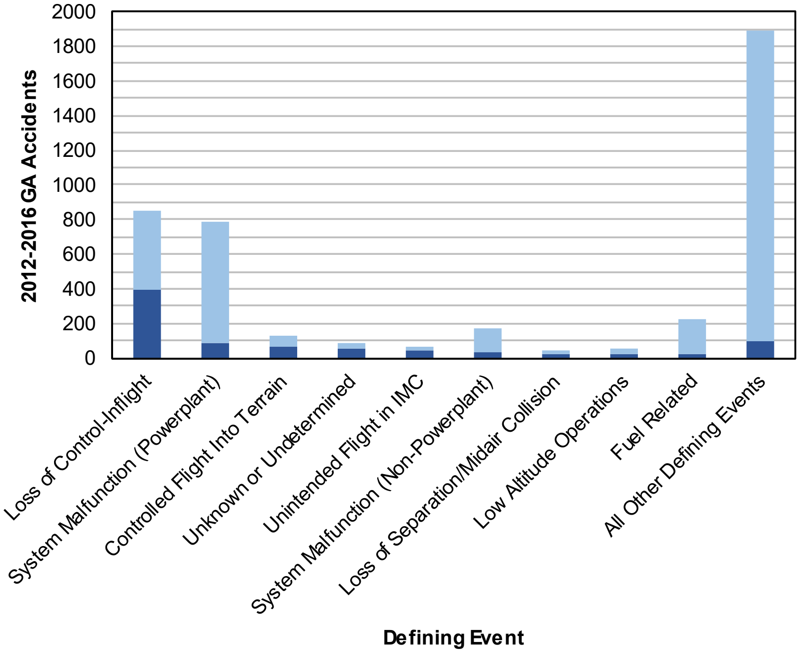


Figure 2. Defining events for GA accidents 2012-2016

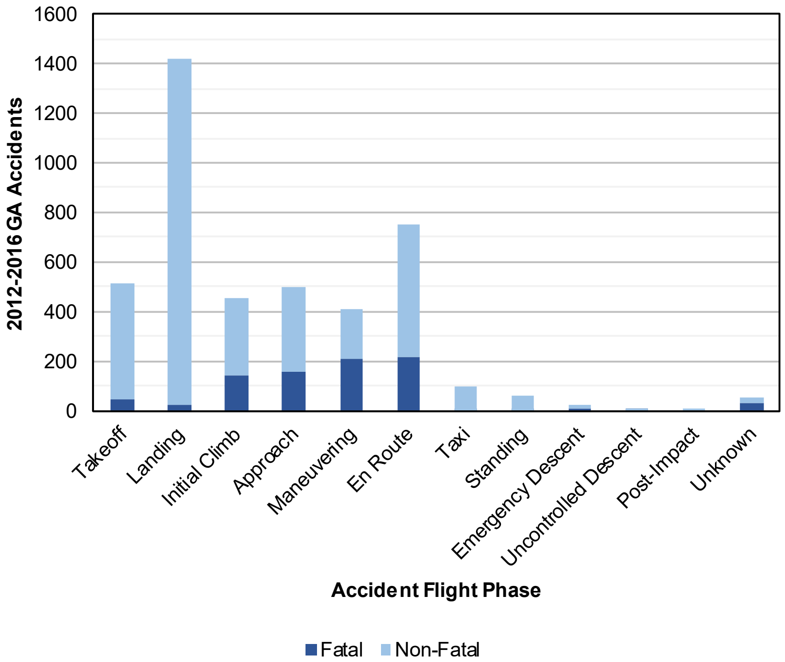


Figure 3. Flight phase during which accident occurred

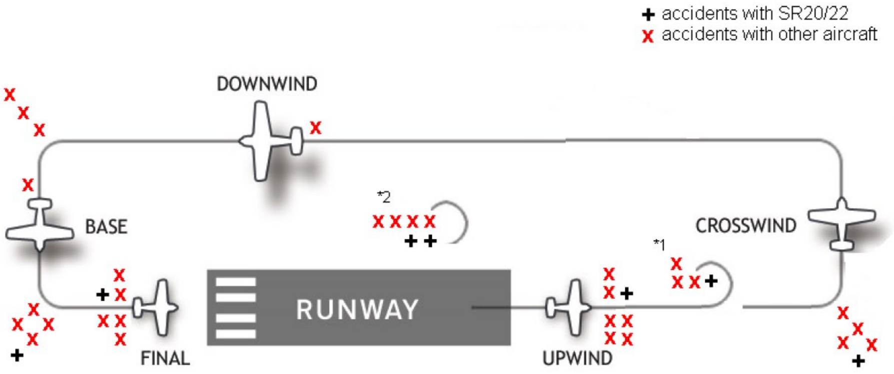


Figure 4. Positions of fatal stall/spin accidents within the traffic pattern [2, p. 31]

Aircraft manufacturers must be guided towards preventing LOC upstream of the stall or spin. This starts with the realization that a large number of LOC accidents involve an inexperienced and distracted pilot who is unaware of the low and decreasing energy state of the aircraft. Therefore, energy management and warning systems are an essential part of LOC prevention. In addition, the aircraft must be designed to change its energy state and flying characteristics in a steady manner while operating in the traffic pattern, in particular during configuration changes (i.e. flap extension and retraction). Unexpected and abrupt changes in aircraft pitching motion and longitudinal control forces can startle a pilot and cause a fatal LOC accident.

Therefore, airworthiness certification standards and the associated means of compliance must be amended to encourage good stalling characteristics, persistent flight energy awareness by the pilot, and flying characteristics that do not include any unexpected or abrupt changes in aircraft response or control forces. To ensure continued growth in the capabilities and safety of GA aircraft, the standards and means of compliance must be flexible enough to allow for the introduction of novel technologies, such as advanced auto-pilots, fly-by-wire systems, heads-up displays and augmented reality interfaces.

Recent changes to the certification rules for GA aircraft, 14 CFR Part 23 in the United States and Certification Specification Standard 23 (CS-23) in Europe, have targeted LOC through enhanced stall warning and improved post-stall characteristics. The revised certification rules now use performance-based standards [3, 4]. The Federal Aviation Administration (FAA) and the European Aviation Safety Agency (EASA) are both encouraging adoption of new technologies, and they both allow more flexible approaches for means of compliance. In the past, 14 CFR Part 23 and CS-23 were lengthy documents providing detailed prescriptive design requirements. Revising these documents involved a bureaucratic process that took a long time. Now, the FAA and EASA are relying on consensus organizations, such as the American Section of the International Association for Testing Materials (ASTM International) and the Society of Automotive Engineers (SAE) to develop standards and means of compliance that meet the performance-based intent of the high-level airworthiness requirements. These standards are updated through a consensus process involving representatives of manufacturers, users, and regulators.

ASTM International formed Committee F44 to develop LOC standards and means of compliance for GA. The committee proposed an approach called “departure aversion,” which uses a point-based scale allowing for multiple combinations of options to increase flight safety, while retaining the core goals of the regulators to increase requirements in the area of stall warning and handling characteristics in departure-prone situations. The departure aversion approach focuses on the key areas of stall warning and departure resistance by leveraging data from various research programs [5]. By placing upper and lower limits on the points awarded for individual contributing factors, departure aversion becomes a layered defense. The departure aversion approach also promotes recent technology developments in safety-enhancing features. Applicants will be able to increase their departure aversion scores using three categories of safety-enhancing features: Enhanced Indication Systems (EIS), Enhanced Envelope Awareness Systems, and Descent Arrest Systems [5]. One possible way this equipment may receive design and production approval for retrofit aircraft is via an FAA policy called Non-Required Safety-Enhancing Equipment (NORSEE) [6].

To be certified under the published ASTM standard F3180/F3180M-18 for low-speed flight characteristics of aircraft, an airplane must pass a comprehensive series of stall characteristics tests and spin tests and then achieve a minimum low-speed flight characteristics score, comprised of a stall warning score, a departure characteristics score, and a safety-enhancing features score. Each of the individual scores has a minimum pass/fail threshold. For Level 1 and Level 2 single-engine airplanes, this results in 90 or 114 flight test points to be executed. For Level 3 and Level 4 single-engine airplanes and all multi-engine airplanes, the number of test points is 110 or 190, depending on the alternative chosen for abused stalls [7].

There is apprehension within the small aircraft industry and the FAA that certification using the ASTM standard as published creates an excessive burden of cost and effort for applicants. There is also concern about some of the test points potentially causing unnecessarily dangerous testing conditions and that the test pilots' evaluation of the aircraft is not accounted for in the certification process.

The overarching goal of the project documented in the present report was to develop a means of compliance (MOC) that ensures achieving the minimum reasonable standards for acceptable low-speed handling qualities, acceptable stall characteristics, and tolerance to controls abuse by the pilot. The project was not tasked with developing standards or technologies to create a pilot-proof airplane (i.e. advanced autopilots or fly-by-wire systems), because such an effort was seen as futile and counterproductive given the average age of the GA fleet, the production levels of new GA aircraft, and the expected financial means of the average GA pilot. The desirable characteristics for the MOC were to be affordable with regards to the instrumentation, time, flight hours, resources and personnel required to conduct the certification tests, to be specific enough to ensure correct flight test procedures, and to be repeatable between flight test events, airplanes, and test pilots.

The MOC were to establish a balance between the un-augmented handling qualities of an airplane and any safety enhancements installed to improve pilot situational awareness and/or system autonomy. This notion is illustrated in Figure 5. The value on the y-axis of this conceptual certification chart expresses the un-augmented stall characteristics and configuration change response of the aircraft, as determined through flight test. The value on the x-axis captures the contribution to aircraft safety of passive warning systems and active stall prevention/recovery systems. Note that the warning and prevention systems shown in Figure 5 are notional and not all-inclusive. The combined score of stall characteristics and systems effects determines whether an aircraft could make it "over the line" (assuming that the systems functioned effectively), and would therefore be considered to have shown compliance to the regulatory requirements. Two examples are shown in Figure 5: Aircraft A (triangle) has good un-augmented stall characteristics and configuration change response, and would be certified with the standard audio stall warning currently required. Aircraft B (square) has deficient un-augmented stall characteristics and configuration change response and requires the installation of a stick shaker or more sophisticated stall warning/prevention systems to be certified.

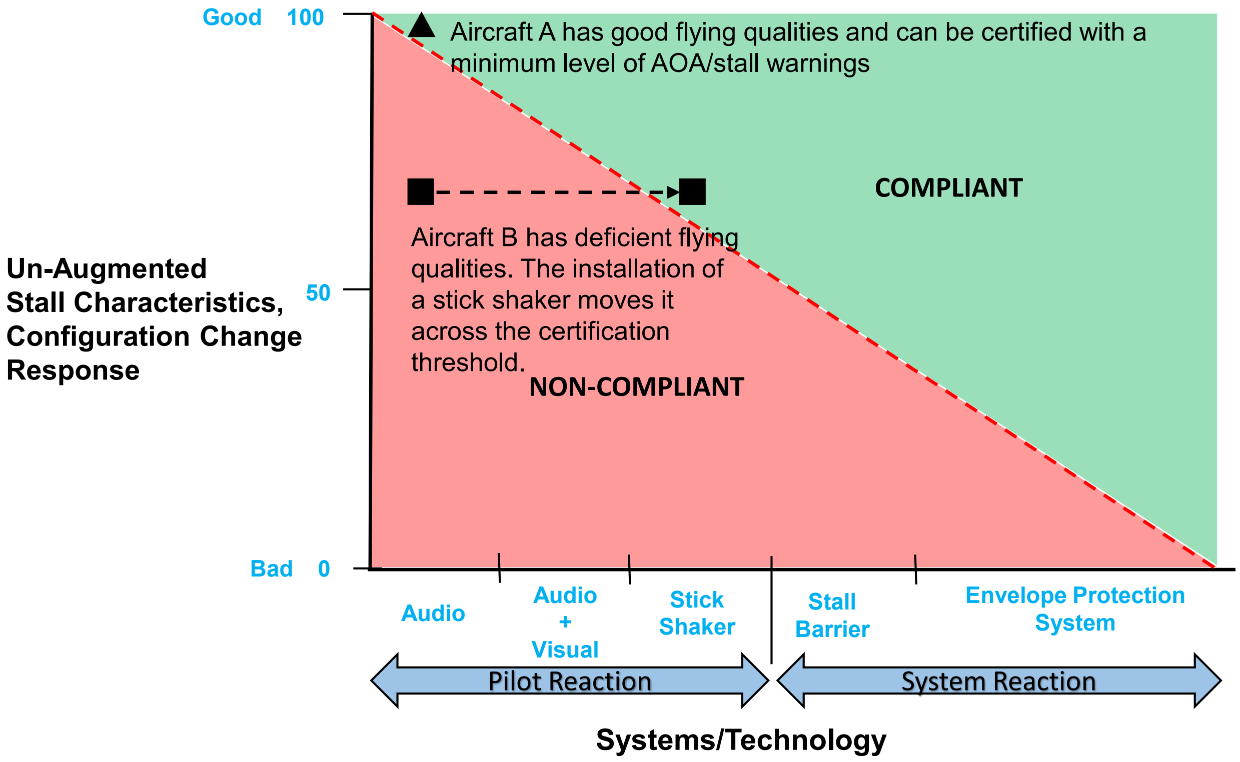


Figure 5. Conceptual pass/fail chart

The definition of acceptable pass/fail criteria for such a point-based certification method as well as the development of the associated MOC require flight test data to properly understand the stall behavior and configuration change response of typical GA aircraft, and to understand the advantages, disadvantages, and implementation challenges of passive and active stall warning/prevention systems. The research project DTFACT-17-C-00001 “Flight Demonstrations for AOA-limiting Systems on Part 23 Aircraft” was funded to provide data for both the x-axis and y-axis of the certification chart from flight tests using the combination of a unique GA fly-by-wire testbed and common GA aircraft.

The first phase of the program used a GA fly-by-wire testbed based on a Diamond DA42, owned and operated jointly by the Institute of Flight Systems Dynamics at the Technical University of Munich (Germany) and Diamond Aircraft (Wiener Neustadt, Austria), to evaluate the effectiveness and implementation challenges of various angle-of-attack (AOA) warning systems and to provide values for the x-axis of Figure 5. The flight test campaign executed in July 2017 evaluated various combinations of visual, aural, and haptic warning systems using a combination of established and experimental test methods. The warning systems could be activated individually or in various combinations, enabling the team to examine combined effects. The team also examined unintended consequences of installing these types of systems with respect to the "do no harm" policy of the FAA's NORSEE provisions.

The focus of second phase of the program was on the un-augmented stall characteristics and configuration change response of GA aircraft. The flight tests were designed to provide fundamental data on the stall characteristics of typical GA airplanes and on relevant, effective, and safe test metrics. The flight data collected during the flight test campaign executed in March 2018 and June 2018 serve to develop the scaling of the y-axis of the certification chart. The flight test campaign used six single-engine GA aircraft spanning the full range of contemporary designs. To simulate a certification flight test campaign, a 76-point stall matrix containing coordinated wings-level stalls, coordinated turning stalls, feet-on-the-floor wings-level stalls, feet-on-the-floor turning stalls, and abused-entry turning stalls was executed. Neither the stall matrix nor the flight test processes used were intended to directly replicate existing MOC accepted by the FAA.

Additional test points were executed to measure the changes in longitudinal control force and the free pitching response of the aircraft after a flap extension at representative pattern speeds and during simulated go-arounds. This part of the project was a follow-up to preceding research conducted and published by the FIT project team showing that abrupt or excessive free pitching response (up to 35° of nose-up pitch in less than 6 s) and/or excessive trim force changes (between 25 lb and 36 lb during flap extension) can occur after extending or retracting flaps [8]. To test for the effects of tail configuration and tail sizing, five of the six GA aircraft assembled for the stall characteristics tests were also used to expand the existing data set on configuration change behavior. The sixth aircraft was not equipped with flaps.

Based on the data gathered in the two phases of the project, a proposed MOC was developed and is presented to the FAA in this report.

1.2 Statement of work

The goal of the presented project was to contribute flight-test data to form a foundation for the proposed novel approach to the certification of GA airplanes. Following the "two-axes" approach illustrated in Figure 5, the project was executed in two phases.

Phase 1 focused on the “x axis”, i.e. the effectiveness of different AOA warning and limiting methods and the technical and operational challenges with regards to their implementation, certification and use. In Phase 1, the project was tasked to:

1. Identify and document existing & projected methods for AOA limiting systems appropriate for Part 23 aircraft.
2. Evaluate the DA42 testbed owned and operated by the Technical University of Munich as a test platform.
3. Select suitable AOA-limiting systems to emulate on the DA42 and demonstrate in-flight, using the existing set of AOA probes, onboard electronics, and an active stick for haptic feedback.
4. Define the minimum necessary and sufficient documentation, simulation, and flight test program a *developer would prefer* to certify an AOA-limiting system. The flight test program was to start with a standard stall maneuver matrix to assess stall characteristics and then develop additional maneuvers to challenge and possibly defeat the AOA-limiting system. The development of test methods was to involve input from the FAA.
5. Simulate and fly the “developer program” on the DA42, and gather additional data points as requested by the FAA.

Phase 2 then focused on the “y axis” by characterizing the un-augmented stall characteristics along with the free pitching response and longitudinal control forces due to flap configuration changes of six representative GA aircraft: American Champion Citabria, Piper Archer, Mooney M20C, Cirrus SR 22, Diamond DA40, and Cessna 172. The flight tests conducted for Phase 2 also served the development of minimum standard test methods for aircraft handling qualities in low-speed, low-altitude conditions.

1.3 Dissemination of results

The results of the project were disseminated regularly throughout the period of performance, to both the aeronautical engineering and aviation communities.

The results of Phase 1 were published in a paper at the 2018 IEEE Aerospace Conference and presented at the 2018 East Coast Symposium of the Society of Experimental Test Pilots [9, 10].

The results of Phase 2 were published in a paper at the 2018 AIAA Aviation Forum, in two papers at the 2019 IEEE Aerospace Conference, and presented at the 2018 annual meeting of the Partnership to Enhance General Aviation Safety, Accessibility and Sustainability (PEGASAS) [11, 12, 13, 14]. An article on the pitch response and longitudinal control force changes due to configuration changes is under preparation for submission to the Journal of Aircraft, with expected publication date in mid-2020.

The MOC developed for the present report was presented at the ASTM Annual Meeting in Brussels in 2019 [15]. A comprehensive overview of the MOC and the underlying flight test data will be published in a paper at the 2020 IEEE Aerospace Conference.

All data produced over the course of the project were reported to the FAA in biweekly conference calls and monthly progress reports.

1.4 Structure of the report

Section 2 presents the proposed MOC for low-speed flight characteristics of aircraft. They are considered the main result of the funded project. Section 3 documents the evaluation of AOA warning and limiting methods conducted with TUM on the DA42 fly-by-wire testbed. The flight tests conducted for the study of the stall characteristics of common GA airplanes are documented in Section 4, with the results of the tests for the configuration change response reported in Section 5. Section 6 provides initial results of a flight test campaign, determining the specific excess power characteristics of common GA aircraft. The data gathered in these flight tests will serve as a foundation for future development of flight energy management and warning algorithms and displays. Section 7 discusses the considerations underlying the development of MOC based on flight test data. Section 8 concludes this report and provides an outlook on future work.

2 Proposed means of compliance for low-speed flight characteristics of Part 23 aircraft

2.1 Overview

Certification of low speed flight characteristics uses a set of minimum standards to achieve reasonable assurance of acceptable low speed handling qualities, acceptable stall characteristics, and tolerance to control abuse. MOC specify a series of flight tests along with scoring systems or performance thresholds developed to ensure that the minimum standards are achieved. MOC must be specific enough to ensure correct flight test procedures and to ensure repeatability of the tests between individual events, airplanes, and test pilots. As the certification process represents a significant effort for both the certifying authority and the applicant, MOC must be designed to be reasonably affordable with regards to instrumentation requirements, time, number of flights, required resources, and personnel. MOC should comprise the minimum number of flight test events necessary to achieve a conclusion on the reasonable level of flight safety of the aircraft.

As a result of the flight test research documented in the present report, a stand-alone MOC is proposed to serve as an alternative for existing, published MOC. The proposed MOC presented in this report is based on experience gained through 39 flights (59.7 hours) on seven different aircraft (Diamond DA42, Diamond DA40, Piper PA28, Cessna 172, Mooney M20C, Citabria, and Cirrus SR20). Consideration was given to past CAR 3 and Part 23 guidance, as well as the MOC published by ASTM in October 2018 [7]. The flight tests showed that the MOC must evaluate (1) the stall characteristics of the aircraft, (2) the pre-stall handling qualities, in particular pertaining to longitudinal static stability and the effects of configuration changes, and (3) the effects of safety enhancements, such as AOA warning and limiting systems. The MOC then uses a point-based scoring system to balance strengths and weaknesses of aircraft designs in the three areas. Of the achievable 150 points, 40% are assigned to stall characteristics, 40% to pre-stall handling qualities, and 20% to safety enhancements. The applicant must achieve at least 100 points.

The MOC is based on data acquired with Level 2 aircraft, but is envisioned to be valid for Level 1 through Level 4. Future projects should test the suitability of the MOC for Level 3 and Level 4.

2.1.1 Stall characteristics

The experience gained during the flight tests showed that the stall characteristics must be tested in wings-level, turning, and accelerated flight. For each of the three flight modes, stalls must be tested power on and power off, gear/flaps up and down, in coordinated flight and with “feet on the floor” (FOF). FOF testing means that the pilot does not coordinate turns using rudder and ailerons and thus introduces minimum abuse scenarios representing the actions of inexperienced pilots in the traffic pattern. With inexperienced pilots, under-coordination is more likely than over-coordination. Therefore, FOF testing is proposed as a valid alternative to abused stalls with “full ball left/right” conditions, which may initiate spins of the aircraft during flight test. During the development of the MOC, the definition of the “stall” condition was a major point of discussion. Stall can be defined as the beginning of uncontrollable downward pitching motion. With this “pitch break” interpretation, it is unclear whether the first pitch break, the first break of a certain magnitude, or only aperiodic downward pitching motions constitutes a stall. An alternative definition is to interpret stall as the control stick/yoke held against the aft stop for a set time. This has the advantage that it closely resembles the likely response of a startled or panicked pilot, removes ambiguity, provides repeatability, and provides assurance of pitch control abuse. Secondary advantages of the “aft stick” interpretation are its suitability for the assessment of roll and yaw controllability and for the assessment of departure aversion. The consensus among the test pilots and flight test engineers involved in the project was to base the MOC on stall being defined as the control stick/yoke held against the aft stop for 2 seconds.

The historic criteria of no more than ±15° wing drop during a wings-level stall was loosened to ±20°, with a heading change of ±20°, except for FOF test points The criteria of allowing bank angles up to 90° during accelerated turning stalls was tightened to 60° (±30°). In addition, turning stalls should not progress through wings-level to a bank angle in the opposite direction of the entry.

Safe coordinated stalls are considered a minimum quality for an aircraft. No certification points are awarded for coordinated stalls and the aircraft must pass all 22 coordinated stall events. However, the MOC allows for some failures in FOF testing. With 20 FOF events and 3 points awarded for each pass, a maximum of 60 points are possible, of which 50 points must be achieved.

2.1.2 Pre-stall handling qualities

The proposed evaluation of pre-stall handling qualities focuses on longitudinal static stability and on the aircraft’s response to configuration changes.

For static stability, the MOC sets a minimum control force slope of 2 lb per 10 kts of airspeed, determined in a standard longitudinal static stability test. The minimum force slope is a hard acceptance limit. In addition, the free return speed range is measured and a maximum of 15 points each can be achieved for climb and approach conditions. A free return speed range of 10% of best rate-of-climb speed V_Y is a soft acceptance limit. A higher value will result in negative points.

To evaluate the effects of configuration changes, the MOC has the test pilot execute a rapid configuration change from cruise to power approach while maintaining altitude, and from power approach to go-around while maintaining airspeed. The peak control force within the first 5 seconds after the configuration change is recorded. A maximum of 15 points can be achieved for each of the two tests. A longitudinal control force of 25 lb is a soft acceptance limit. Any higher force will result in a negative point value.

2.1.3 Safety enhancements

The primary emphasis of the proposed MOC is placed on handling qualities. However, the benefits of warning devices are also acknowledged through available certification points. A maximum of 20 points are available, with the individual point value for the specific sensory mode of the warning system (visual, aural, haptic) scaling with its effectiveness determined in Section 3.

To reach the points necessary, the applicant must achieve at least 100 of the 150 points available. With the minimum point value achieved, the decision whether to recommend certification of the aircraft lies within the qualitative assessment by the certification authority test pilot.

In summary, the proposed MOC provides a minimum standard flight test methodology, crafted to address the low altitude and startled pilot LOC problem. The MOC allows a cost-effective flight test campaign, while achieving a higher standard than the previous 14 CFR Part 23 Amendment 62. It encourages good low-speed handling qualities, promotes flight characteristics over warning devices, redefines roll limits to appropriate values, and provides a clear definition of the stall event. The MOC also specifically asserts the certification authority test pilot's qualitative assessment for compliance determination.

2.2 Means of compliance

The flow chart in Figure 6 depicts the criteria path and requirements for low-speed flight characteristics. It is assumed the airplane has a clear and distinct, audible tone stall warning device. This device shall provide stall warning beginning at least 5 knots prior to the stall and continuing until the angle of attack is reduced to that at which stall warning began. The scoring approach for this means of compliance encourages airplaneairplane designs that reduce the possibility of loss-of-control through basic flying qualities versus focusing on stall characteristics and artificial safety enhancements. The points score is an aid to the certification authority test pilot for determining compliance with the regulations.

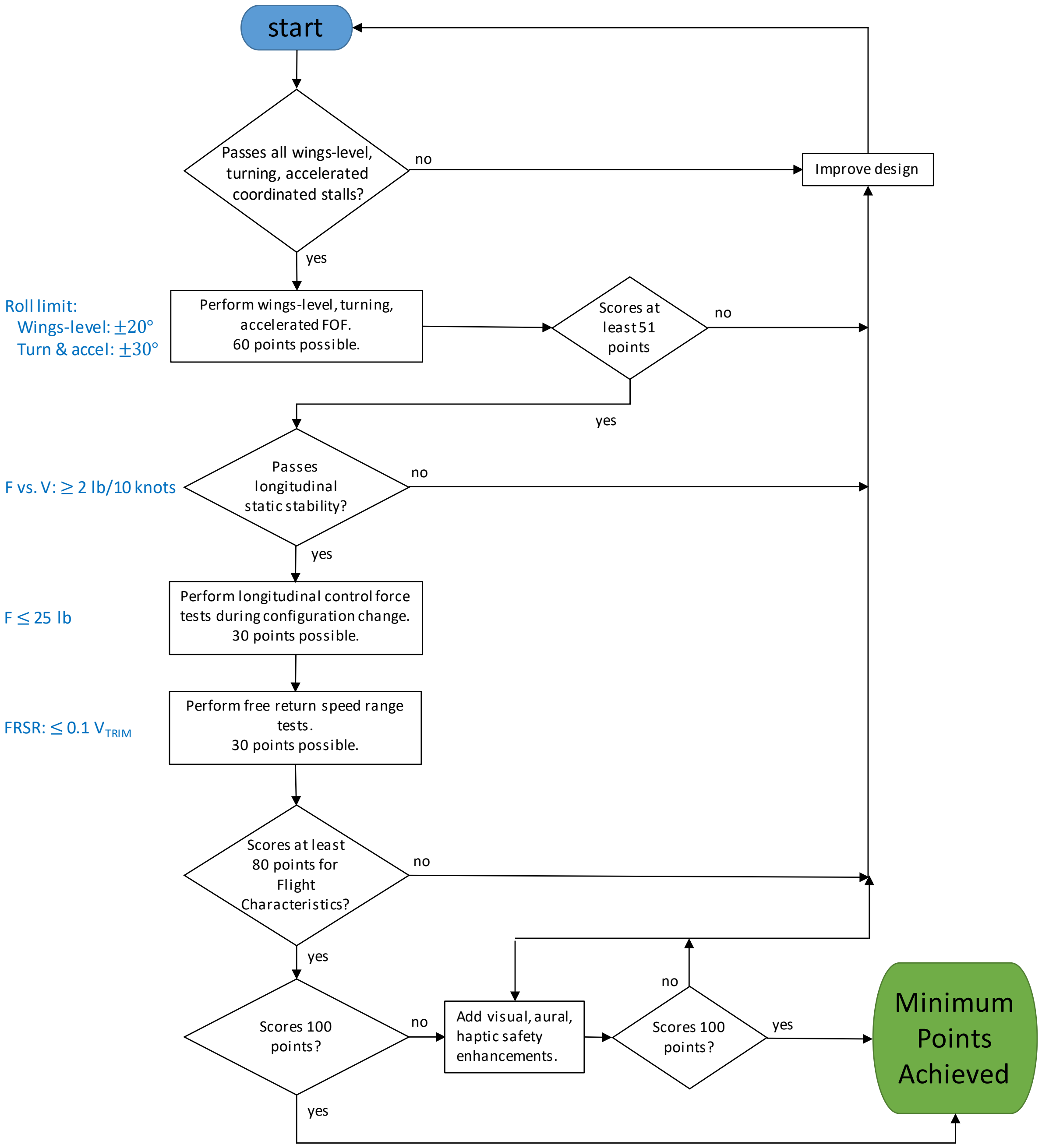


Figure 6. Certification flow chart

Flight Condition Definitions

1) Wing Flaps: retracted, fully extended, and each intermediate normal operating position as appropriate for the phase of flight.
2) Landing Gear: retracted for the configuration in which the wing flaps are retracted, and extended for all other wing flap extensions.

3) Cowl Flaps: open for the configuration in which the wing flaps are in the maximum approved extension for the takeoff configuration, otherwise closed.
4) Spoilers/Speed Brakes: retracted and extended unless they have no measurable effect at low speeds, or in their appropriate position if they are automatically actuated as part of normal operations.
5) Power/Thrust Off: idle.
6) Power/Thrust On:
   a) Reciprocating engines – at least 90 percent of maximum continuous power for wings-level stalls, or at least 75 percent of maximum continuous power for turning stalls. However, if the power settings result in a pitch attitude greater than 30° nose-high, the test may be carried out with the power required for level flight in the landing configuration at maximum landing weight and a speed of 1.4 V_{S0}, except that the power may not be less than 50% maximum continuous power; or
   b) Turbine engines – at maximum engine thrust, except that it need not exceed the thrust necessary to maintain level flight at 1.5 V_{S1} (where V_{S1} corresponds to the stalling speed with flaps in the approach position, the landing gear retracted, and most forward CG. at maximum landing weight).
7) Trim: the airplane trimmed at:
   a) 1.3 V_{S1} for any conditions with the flaps or landing gear extended,
   b) 1.5 V_{S1} or the minimum trim speed, whichever is higher for any conditions with the flaps and landing gear retracted.
8) Propeller: full increase revolutions per minute (rpm) position.
9) Weight: with the airplane at the most adverse operational weight(s) for the particular stall characteristics test being conducted, as determined by simple analysis from the applicant.
10) CG: with the airplane at the most adverse center of gravity location(s) (along the longitudinal, lateral, and directional axes) for the particular stall characteristics test being conducted, as determined by simple analysis from the applicant.

Coordinated Wings-Level Stall Characteristics

1) For Level 1, low-speed, single-engine airplanes with $V_{S0} \leq 45$ knots that have interconnected lateral and directional controls, it shall be possible to produce and correct roll by unreversed use of the lateral control without producing excessive yaw, up to the time the airplane stalls.
2) For all other Level 1 through Level 4 airplanes, it shall be possible to produce and correct roll by unreversed use of the lateral control and to produce and correct yaw by unreversed use of the directional control up to the time the airplane stalls.

3) The coordinated wings-level stall characteristics shall be demonstrated in flight as follows. Starting from a speed at least 10 knots above the stall speed, the longitudinal control shall be pulled back (with the slip-skid ball remaining centered) so that the rate of speed reduction will not exceed 1 knot/s until the longitudinal control reaches the aft stop. The longitudinal control must then be held against the aft stop for 2 seconds. Activation of a barrier system, such as a stick-pusher, does not require aft stop attainment of the longitudinal control.
4) From the initial trim condition through recovery, it shall be possible to prevent more than 20° of roll or heading change by the normal use of lateral and directional controls. Table 1 lists the coordinated wings-level stall conditions. No points are awarded for the events in Table 1. All events must be completed successfully.

Table 1. Coordinated wings-level stall conditions

No.	Wing Flaps	Landing Gear	Cowl Flaps	Power	Trim	Bleed Rate	Weight & C.G.
1	Up	Up	Closed	Off	1.5 V_{S1}	1 kt/s	Most Adverse
2	Up	Up	Closed	90%	1.5 V_{S1}	1 kt/s	Most Adverse
3	Max TO	Down	Closed	Off	1.3 V_{S1}	1 kt/s	Most Adverse
5	Max TO	Down	Open	90%	1.3 V_{S1}	1 kt/s	Most Adverse
6	Full	Down	Closed	Off	1.3 V_{S1}	1 kt/s	Most Adverse
7	Full	Down	Open	90%	1.3 V_{S1}	1 kt/s	Most Adverse

Coordinated Turning Stall Characteristics

1) Turning stalls and accelerated turning stalls shall be demonstrated by establishing and maintaining a turn in a 30° bank. While maintaining this bank angle, the speed shall be steadily reduced with the longitudinal control (with the slip-skid ball remaining centered) until the longitudinal control reaches the aft stop. The longitudinal control must then be held against the aft stop for 2 seconds. The rate of speed reduction shall be constant and:
   a) For a turning flight stall, shall not exceed 1 knot/s, and
   b) For an accelerated turning stall, be between 3 and 5 knots/s.
2) Throughout the stall approach, stall and recovery, it shall be possible to keep the bank angle within ±30° of the entry bank angle of 30°.
3) During the recovery, there shall be no excessive altitude loss, excessive pitch-up or exceedance of maximum permissible speed or allowable limit load factor. Table 2 lists the coordinated turning stall conditions. No points are awarded for the events in Table 2. All events must be completed successfully.

Table 2. Coordinated turning stall conditions

No.	Wing Flaps	Gear	Cowl Flaps	Power	Entry Trim	Entry Bank	Bleed Rate	Weight/CG
1	Up	Up	Closed	Off	1.5 V_{s1}	30° left	1 kt/s	Most adverse
2	Up	Up	Closed	75%	1.5 V_{s1}	30° left	1 kt/s	Most adverse
3	Max TO	Down	Open	75%	1.3 V_{s1}	30° left	1 kt/s	Most adverse
4	Full	Down	Closed	Off	1.3 V_{s1}	30° left	1 kt/s	Most adverse
5	Full	Down	Closed	75%	1.3 V_{s1}	30° left	1 kt/s	Most adverse
6	Up	Up	Closed	Off	1.5 V_{s1}	30° right	1 kt/s	Most adverse
7	Up	Up	Closed	75%	1.5 V_{s1}	30° right	1 kt/s	Most adverse
8	Max TO	Down	Open	75%	1.3 V_{s1}	30° right	1 kt/s	Most adverse
9	Full	Down	Closed	Off	1.3 V_{s1}	30° right	1 kt/s	Most adverse
10	Full	Down	Closed	75%	1.3 V_{s1}	30° right	1 kt/s	Most adverse
11	Up	Up	Closed	Off	1.5 V_{s1}	30° left	3-5 kt/s	Most adverse
12	Full	Down	Closed	Off	1.3 V_{s1}	30° left	3-5 kt/s	Most adverse
13	Up	Up	Closed	Off	1.5 V_{s1}	30° right	3-5 kt/s	Most adverse
14	Full	Down	Closed	Off	1.3 V_{s1}	30° right	3-5 kt/s	Most adverse

Feet-on-the-Floor Wings-Level Stall Characteristics

1) The feet-on-the-floor wings-level stall characteristics shall be demonstrated in flight as follows. With the airplane trimmed at the initial trim condition and starting from a speed at least 10 knots above the stall speed, the longitudinal control shall be pulled back (with feet remaining on the floor) so that the rate of speed reduction will not exceed 1 knot/s until the longitudinal control reaches the aft stop. The longitudinal control must then be held against the aft stop for 2 seconds with feet remaining on the floor. It shall be possible to prevent more than 20° of roll change by the normal use of lateral controls.
2) After the 2 seconds with longitudinal control at the aft stop, directional control may be used in the recovery.
3) Table 3 lists the feet-on-the-floor wings-level stall conditions. The airplane will receive 3 points for each successful event.

Table 3. Feet-on-the-floor wings-level stall conditions

No.	Wing Flaps	Gear	Cowl Flaps	Power	Entry Trim	Bleed Rate	Weight/CG
1	Up	Up	Closed	Off	1.5 V_{s1}	1 kt/s	Most adverse
2	Up	Up	Closed	90%	1.5 V_{s1}	1 kt/s	Most adverse
3	Max TO	Down	Open	Off	1.3 V_{s1}	1 kt/s	Most adverse
4	Max TO	Down	Open	90%	1.3 V_{s1}	1 kt/s	Most adverse

No.	Wing Flaps	Gear	Cowl Flaps	Power	Entry Trim	Bleed Rate	Weight/CG
5	Full	Down	Closed	Off	1.3 V_{s1}	1 kt/s	Most adverse
6	Full	Down	Closed	90%	1.3 V_{s1}	1 kt/s	Most adverse

Feet-on-the-Floor Turning Stall Characteristics:

1) Feet-on-the-floor turning stalls and accelerated turning stalls shall be demonstrated by establishing and maintaining a turn in a 30° bank with the airplane trimmed at the initial wings level condition and the trim remaining unchanged throughout the maneuver. While maintaining this bank angle, the speed shall be steadily reduced with the longitudinal control (with feet remaining on the floor) until the longitudinal control reaches the aft stop. The longitudinal control must then be held against the aft stop for 2 seconds with feet remaining on the floor. The rate of speed reduction shall be constant and:
    a) For a turning flight stall, shall not exceed 1 knot/s, and
    b) For an accelerated turning stall, be between 3 and 5 knots/s.
2) During this period, it shall be possible to keep the bank angle within ±30° of the entry bank angle of 30°.
3) After the 2 seconds with longitudinal control at the aft stop, directional control may be used in the recovery. To regain wings-level flight during the recovery, there shall be no excessive altitude loss, excessive pitch-up or exceedance of maximum permissible speed or allowable limit load factor. Table 4 lists the feet-on-the-floor turning stall conditions. The airplane will receive 3 points for each successful event.

Table 4. Feet-on-the-floor turning stall conditions

No.	Wing Flaps	Gear	Cowl Flaps	Power	Entry Trim	Entry Bank	Bleed Rate	Weight/CG
1	Up	Up	Closed	Off	1.5 V_{s1}	30° left	1 kt/s	Most adverse
2	Up	Up	Closed	75%	1.5 V_{s1}	30° left	1 kt/s	Most adverse
3	Max TO	Down	Open	75%	1.3 V_{s1}	30° left	1 kt/s	Most adverse
4	Full	Down	Closed	Off	1.3 V_{s1}	30° left	1 kt/s	Most adverse
5	Full	Down	Closed	75%	1.3 V_{s1}	30° left	1 kt/s	Most adverse
6	Up	Up	Closed	Off	1.5 V_{s1}	30° right	1 kt/s	Most adverse
7	Up	Up	Closed	75%	1.5 V_{s1}	30° right	1 kt/s	Most adverse
8	Max TO	Down	Open	75%	1.3 V_{s1}	30° right	1 kt/s	Most adverse
9	Full	Down	Closed	Off	1.3 V_{s1}	30° right	1 kt/s	Most adverse
10	Full	Down	Closed	75%	1.3 V_{s1}	30° right	1 kt/s	Most adverse
11	Up	Up	Closed	Off	1.5 V_{s1}	30° left	3-5 kt/s	Most adverse
12	Full	Down	Closed	Off	1.3 V_{s1}	30° left	3-5 kt/s	Most adverse

No.	**Wing Flaps**	**Gear**	**Cowl Flaps**	**Power**	**Entry Trim**	**Entry Bank**	**Bleed Rate**	**Weight/CG**
13	Up	Up	Closed	Off	1.5 V_{s1}	30° right	3-5 kt/s	Most adverse
14	Full	Down	Closed	Off	1.3 V_{s1}	30° right	3-5 kt/s	Most adverse

Longitudinal Static Stability – Stick Force vs. Airspeed (climb)

Starting from a trimmed condition at V_y with climb power and gear and flaps up, measure the longitudinal static stability (stick force versus airspeed) over the speed range of the greater of V_{TRIM} (plus FRSR) ± 40 knots or ± 15% of V_{TRIM} (plus FRSR).

The slope of stick force versus airspeed shall be no less than 2 pounds per 10 knots. No points are awarded for this event. It must be completed successfully.

Longitudinal Static Stability – Stick Force vs. Airspeed (approach)

Starting from a trimmed condition at 1.3 V_{s1}, gear and flaps down, power for 3° flight path, measure the longitudinal static stability (stick force versus airspeed) over the speed range of 1.1 V_{S1} to the lesser of 1.8 V_{S1} or V_{FE}.

The slope of stick force versus airspeed shall be no less than 2 pounds per 10 knots. No points are awarded for this event. It must be completed successfully.

Longitudinal Control Forces during Configuration Changes

1) Starting from a trimmed condition at V_{FE}, power for level flight, gear up and flaps up, abruptly lower the flaps to full. If the airplane has effective flap gates, the test should be performed to each gate, re-establishing a level flight trimmed condition at V_{FE} for each flap setting, and the points should be proportioned appropriately. Using longitudinal control (without re-trimming or changing power), maintain the initial altitude and record the peak stick force required within 5 seconds. The airplane will receive points using the following equation with F_S in pounds:

$$\text{Approach Trim Force Points} = 15 - 0.6 \cdot |F_S| \tag{1}$$

2) Starting from a trimmed condition at 1.3 V_{s1}, gear and flaps down, power for 3° flight path angle, initiate a go-around (go-around power, flaps up). Using longitudinal control (without re-trimming, changing the gear configuration or changing the throttle), maintain the initial airspeed and record the peak stick force required within 5 seconds. The airplane will receive points using the following equation with F_S in pounds:

$$\text{Go-Around Trim Force Points} = 15 - 0.6 \cdot |F_S| \tag{2}$$

Note that the equations for Longitudinal Trim Forces can result in negative points (i.e. points taken away) if the forces are more than 25 pounds[1]. Figure 7 shows a plot of the equation.

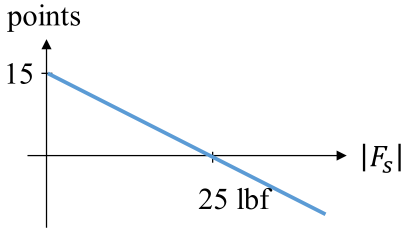


Figure 7. Longitudinal Trim Force Points

Longitudinal Static Stability - Free Return Speed Range (climb)

1) Starting from a trimmed condition at V_y with climb power and gear and flaps up, measure the free return speed range (FRSR).
2) The airplane will receive points using the following equation:

$$\text{Climb FRSR Points} = 15 - 150 \bullet (\text{FRSR}/V_Y) \tag{3}$$

Longitudinal Static Stability - Free Return Speed Range (approach)

1) Starting from a trimmed condition at 1.3 V_{s1}, gear and flaps down, power for 3° flight path, measure the free return speed range (FRSR).
2) The applicant will receive points using the following equation:

$$\text{Approach FRSR Points} = 15 - 150 \bullet (\text{FRSR}/1.3V_{S1}) \tag{4}$$

Note that the equations for free return airspeed range can result in negative points (i.e. points taken away) if FRSR exceeds 10% of the initial trimmed condition airspeed. Figure 8 shows a plot of the equation.

---

[1] The 25-pound longitudinal trim force limit is above MIL-F-8785D and MIL-STD-1797A, but half of the 50-pound limit in §23.143(c).

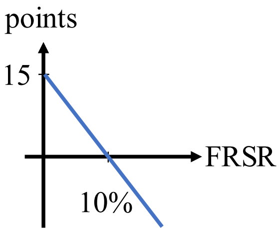


Figure 8. Free return speed points

Total Points toward Certification

Table 5 shows the total points possible in each evaluation category and the total points possible overall.

Table 5. Flight characteristics point totals

Category	Points Possible	Points Achieved
Wings-level FOF stalls	18	
Turning FOF stalls	42	
Approach Config Change Control Forces	15	
Go-Around Config Change Control Forces	15	
Climb FRSR	15	
Approach FRSR	15	
Total	120	

Points Achievement Summary

The airplane must achieve a minimum of 50 points from the wings-level, turning and accelerated FOF stalls. The airplane must achieve a minimum of 80 points from the combined scores of the FOF stalls, configuration control force tests and free return speed range tests. If the airplane achieves more than 80 points but less than 100 points, safety enhancements (Table 6) will be required. A minimum score of 100 total points is required.

The certification authority test pilot will determine the acceptability of the airplane’s stall, control forces and stability characteristics, using the point system for guidance. Table 6 shows the maximum points for various safety enhancement devices. The certification test pilot will determine the actual points achieved based on the effectiveness of each device. Although the point total in Table 6 is 30, the maximum points the airplane can earn for safety enhancement devices is 20.

Table 6. Safety enhancement point totals

Area	Points Possible	Points Achieved
Visual (AOA, Pitch Limit, etc.)	5	
Aural (synthetic voice, etc.)	10	
Haptic (stick shaker, pusher, etc.)	15	
Total	30	

Example 1: Airplane A passes all feet-on-the-floor stalls (60 points), has 10 pound peak configuration change control forces for both approach and go-around (18 points), and 2% FRSR/V in both approach and go-around free-return airspeed (24 points), for a total of 102 points. Assuming the test pilot assesses the airplane's low-speed handling qualities as acceptable, the airplane can be certified with only the basic audible constant tone stall-warning device (i.e. no additional safety enhancements).

Example 2: Airplane B passes all feet-on-the-floor stalls (60 points) has 20 pound peak configuration change control forces for both approach and go-around (6 points), and 5% FRSR/V in both approach and go-around free-return airspeed (15 points), for a total of 81 points. It still needs 19 more points for certification. The applicant has the option of improving the design (e.g. lowering configuration change control forces, and/or decreasing free return airspeed range), or the applicant could add a synthetic voice stall warning (10 points possible) along with stick vibration stall warning (15 points possible), assuming the subjective test pilot assessment results in 19 of the 25 possible points.

Example 3: Airplane C fails 3 feet-on-the-floor stalls (51 points), but has 10 pound configuration change control forces for both approach and go-around (18 points), and 2% errors FRSR/V in both approach and go-around free-return airspeed (24 points) for a total of 93 points. It still needs seven more points for certification. The applicant could improve the design (e.g. lowering configuration change control forces, and/or decreasing free return airspeed), but getting 7 of the 18 remaining points available may not be realistic. Instead, the applicant could add a stick vibration stall warning (15 points possible), assuming the subjective test pilot assessment results in 7 of the 15 possible points.

Example 4: Airplane D fails 4 feet-on-the-floor stalls (48 points). This airplane does not meet the minimum feet-on-the-floor point requirement of 50.

Example 5: Airplane E passes all feet-on-the-floor stalls (60 points), and it has 2 pound configuration change control forces in both approach and go-around. (28 points), and 2% FRSR/V in both approach and go-around free-return airspeed (24 points) for a total score of 112, but its static stability slope is 1 pound per 10 knots. This airplane does not meet the MOC criteria.

3 Evaluation of AOA warning methods

3.1 Objective

The objective was to test the effectiveness of various AOA warning systems and to provide values for the x-axis of Figure 5.

3.2 Background

Stall warning systems are designed to give the pilot critical information about the proximity to the stall-threshold with sufficient time to react and return the aircraft to a safe flight regime. Aerodynamic stall occurs when the angle-of-attack (AOA) of an airfoil reaches a critical threshold. AOA is defined as the angle between the oncoming airflow (relative wind) and the chord line of the airfoil. The critical AOA is where the lift begins to collapse as the flow detaches from the airfoil. Figure 9 illustrates a typical lift curve charting the coefficient of lift versus AOA.

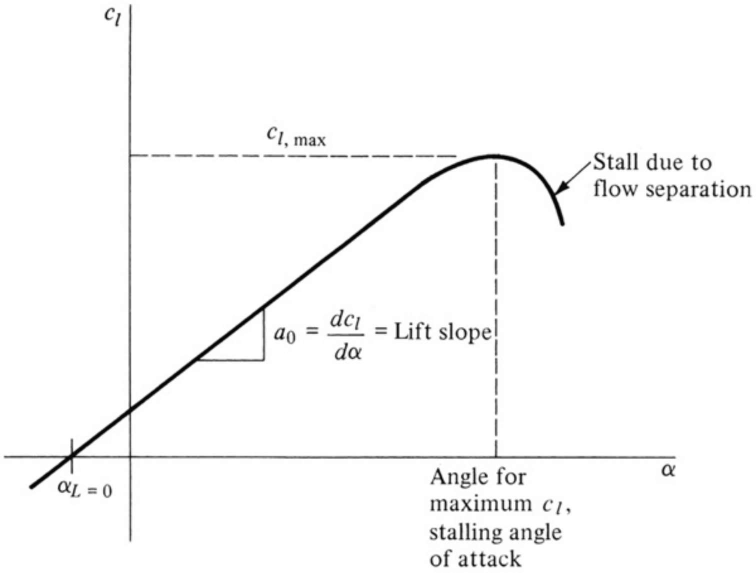


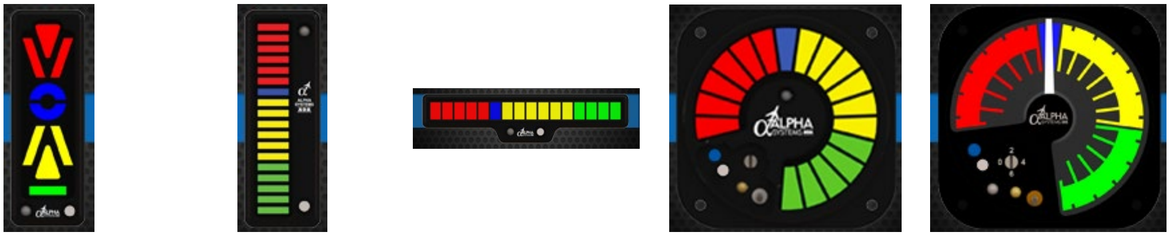
Figure 9. Typical lift curve [16]

Once the flow has become separated, it is no longer flowing smoothly over the control surfaces of the aircraft. Therefore, the aircraft will not only lose lift during stall, but there is also the potential for losing controllability. Beyond the aerodynamic definition of stall, there are numerous other definitions used in aviation, ranging from reaching the full aft stop of the control stick or yoke, to uncontrollable downward pitching motion.

Ideally, a pilot should recover an aircraft from a stall by reducing backpressure on the stick or yoke and/or adding power. However, this requires the pilot to be aware of the situation. Since most GA airplanes do not have the capability of displaying AOA to the pilot, there are published stall speeds in the pilot operating handbooks. While this is a good estimate of when the aircraft will stall, an airplane can stall at any airspeed if the AOA exceeds the safe limit. Therefore, it is important to investigate methods of informing the pilots about the current AOA to increase their knowledge of the energy state of the aircraft and to warn them of impending stall.

An effective warning message usually consists of two elements: (1) a signal making the pilot aware of the existence of an off-nominal or dangerous system state and (2) a directive on what to do in order to return to a nominal or non-critical system state. Warning messages can use three independent sensory channels: visual, aural, and haptic. Visual warnings could take the form of warning lights, numeric displays, or graphical representations of the system state. Aural warnings can consist of constant or intermittent warning tones or verbal messages. Haptic warnings could add vibrations to the control stick, pedals or seats, or actively move the control interfaces in the direction required to alleviate the situation.

Humans derive over 90% of sensory information from visual stimuli [17]. This is referred to as *visual dominance* [18]. Visual perception can distinguish multi-layered signals in frequency, shape, color, and brightness. Visual displays can thus convey a large amount of information that is readily accessible to the pilot. Furthermore, visual displays are easy to implement and easy to integrate into existing cockpit environments. There are currently several AOA indicators on the market with varying cost points and display options. Based on their preferences, pilots can choose amongst a wide variety of display styles. Figure 10 shows a typical sample of AOA indicator styles available from the manufacturer Alpha Systems. The colors green, yellow, and red are typically used to indicate whether the AOA is within a safe, intermediate, or critical range.



Chevron and diamond | Vertical light bar | Horizontal light bar | Segmented round display | Needle display

Figure 10. Alpha Systems AOA indicators [19]

The indicators typically get the AOA from a simple two-hole probe that can be mounted on a modified inspection plate under the aircraft's wing. The hoses are then run from the wing to the instrument in the cockpit. The FAA classifies the installation of such AOA indicators as minor modification and not the installation of a primary flight instrument. Therefore, the installation does not require a supplemental type certificate, and it must only be noted in the aircraft's logbook by a private pilot performing preventative maintenance or by an airframe & powerplant mechanic.

While visual AOA indicators are easy to install and intuitive to use, they may actually not address the root cause of LOC. One theory for the cause of LOC in the approach pattern is that the pilots are so preoccupied with navigation, radio, and traffic, that they do not pay sufficient attention to the cockpit instruments, in particular the air speed indicator. Adding another visual indicator to the scan of cockpit instruments in all likelihood will not significantly reduce the number of LOC incidents.

The typical alternative to visual AOA indicators are aural stall or AOA warnings. Aural warnings could be either verbal callouts, interrupted sounds, or constant sounds. The common version of aural warning is the stall horn, in which an AOA close to stall, either mechanically or electronically, sets of an annoying buzzing sound in the cockpit, thus alerting the pilot. The urgency of a particular message can be indicated by the volume, the frequency, and also the "pleasantness" of the signal used. A 1969 study compared the effectiveness of a continuous horn and an interrupted horn in generating a pilot's response in a high-workload environment. The results showed that the continuous tone horn was effective 64% of the time, whereas the interrupted tone was effective 84% of the time [20]. However, the sound of the stall horn is only one of numerous sounds surrounding the pilot in a modern cockpit. The pilot must cope with radio traffic, aural messages about landing gear status, traffic, etc. Additional aural warning addressing AOA or energy state could thus be drowned out in the background noise and inadvertently be ignored by the pilot. The most "talkative airplanes" are the so-called

Technologically Advanced Aircraft (TAA). A TAA is an aircraft that is at a minimum equipped with an integrated autopilot and an IFR-certified GPS navigation system with moving map or a multi-function display (MFD) with weather, traffic or terrain graphics [21]. These support systems frequently issue callouts or warnings that compete with AOA or stall warnings for the pilots' attention.

Another modality that can be used to increase pilot situation awareness is haptic feedback. Haptic cues vary one or more dimensions of vibratory stimulation in order to convey information. Such dimensions of stimulation are locus, amplitude, frequency, duration and spatial/temporal separation. Based on these stimuli, haptic interfaces have a number of beneficial characteristics. Firstly, haptic cues are silent and non-intrusive, and can therefore be received simultaneously with visual and aural information [18]. Secondly, haptic cues are omnidirectional, i.e. the pilot does not need to look at any particular location in order to receive the information [18]. Thirdly, the reaction to haptic stimuli is quicker than to a visual stimulus [22]. In addition to purely aural warnings, Ontiveros also studied a stick shaker and the combination of a stick shaker with a "clacker" aural tone. The stick shaker was effective 99% of the time, and the stick shaker with "clacker" was effective 100% of the time [20].

In addition to pilot situation awareness, pilot workload is a driving factor for aviation safety. Therefore, an AOA warning system must not only be designed to inform or warn the pilot about the current AOA, but also to minimize the mental workload associated with registering, processing, and understanding the information presented. During high-workload task, the phenomenon of selective or focused attention can ensue [23]. The phenomenon can be compared to tunnel vision, but involving all senses. The focusing of auditory attention can be described as the "cocktail party effect," in which the pilots focus completely on one aural message and tune out all other messages and sounds in their environment. This can become critical if the pilots focus on a message for low fuel, gear status or traffic, but tune out a call out for low speed or high AOA. In this case, the pure presence of warning signals for every potentially dangerous aircraft state can actually drown out the message indicating an acute danger. In aviation emergencies, with time being a critical factor, this can decrease the probability of timely detection of a change in critical flight systems, lead to rushed judgements, and potentially to overreaction. A similar situation regarding visual stimuli is described as "attentional capture" or "inattentional blindness." These terms describe the effect that humans miss a large number of important objects or cues when they appear unexpectedly while attention is focused on other information [24]. With a combination of such effects, excessive attentional load can cause otherwise capable pilots to perform in a way that they would, under normal circumstances, deem irresponsible or dangerous.

To fully evaluate the effectiveness of AOA warning systems, the test methods must account for workload and the focusing of pilot attention. A common way of achieving a repeatable task with raised pilot attention load is to use a tracking task. As an example, Bailey [25] developed a tracking task for the testing of a side-stick controller. In order to measure pilot performance qualitatively, a flight-tracking task was devised, in which the pilots has to hold a constant 60° roll while following cockpit prompts, in addition to compensating to wind gusts simulated by random noise. The pitch axis was varied during the tests to measure the different pilot responses. In order to see whether the changes to the side-stick pitch axis had any real effects on the operability of the aircraft, the attentional load of the pilot was designed to be high. The score for stick effectiveness was the absolute value of attitude error during the turn. Thus, the pilots were so focused on the task at hand that they had no spare capacity to compensate directly for any changes in the stick behavior.

For the testing of AOA warnings in the GA context, the intention of increasing pilot workload is to distract the pilot from paying constant attention to the AOA indicators, as would be the case in real-life situations leading into LOC. However, proper care must be taken to ensure that the high workload does not test the pilot skills and capabilities more than the interaction between warning system and pilot.

3.3 TUM DA-42 testbed

The flight tests were executed on Technical University of Munich's (TUM) Flying Testbed (see Figure 11) with tail number OE-FSD. Based upon a Diamond Aircraft DA42 Next Generation Multi-Purpose Platform (MPP) aircraft, the OE-FSD is a flexible, highly modular and cost-effective research aircraft. Owned by the TUM Institute of Flight System Dynamics (FSD) in Munich, Germany, and operated jointly with the aircraft manufacturer Diamond Aircraft Industries (DAI) out of Wiener Neustadt, Austria, the OE-FSD provides a unique platform for research and flight testing in various fields of application. The aircraft was funded by the Bavarian Ministry of Economics and serves as a research testbed for universities, research institutes, and industry partners.

Figure 11. TUM's DA42 Flying Testbed

Development and systems engineering of the research aircraft were performed by FSD in collaboration with industry partners and the aircraft manufacturer. Major additions to the off-the-shelf aircraft include:

- An Experimental Flight Control System (EFCS), providing Fly-by-Wire access to primary and secondary flight controls, featuring variable authority actuators and online system monitoring.
- A set of high precision reference sensors, conventional aviation sensors, and provisions to install experimental sensors for units under test.
- An independent generator supplying electrical power for all experimental installations without interference with the aircraft's basic avionics.
- A flexible and variable flight test instrumentation and data recording system, including options for bidirectional data exchange via telemetry data link.
- A data link for remote control of the aircraft from a ground control station.
- Modular equipment compartments for mission specific devices, including a standard 19" rack.

The EFCS provides in-flight access to all flight controls, including trim systems and engine power via back-driven auto throttle levers. The system is designed to provide a safe development and test environment for experimental flight control software. Aircraft control can always be safely reverted to mechanical operation by the safety pilot. The EFCS utilizes the conventional, mechanically actuated primary and secondary control surfaces. Each primary control surface is actuated by an actuator drivetrain via the existing mechanical linkage, thus moving both the control surface and the mechanical pilot inceptor of the safety pilot. A safe disconnect of the experimental actuators can be executed via two clutches (see Figure 12).

The actuators are internally redundant and can be operated with variable torque and speed via variable DC supply voltage. The control authority ranges from conventional autopilot speeds and torques up to high bandwidth scenarios. The actuator travel is mechanically limited to further safeguard operations with high authority settings.

The flight control software is hosted on the Flight Control Computer (FCC). Experimental flight control software can be installed on the FCC within the existing operating system and data-handling framework. The FCC’s application software (i.e. the flight controller) is designed in Matlab/Simulink® and Stateflow®. Existing controller functions include a DA42-specific inner-loop controller (based on load-factor and bank-angle), as well as multiple outer-loop functionalities such as classical autopilot modes, trajectory, and waypoint flight.

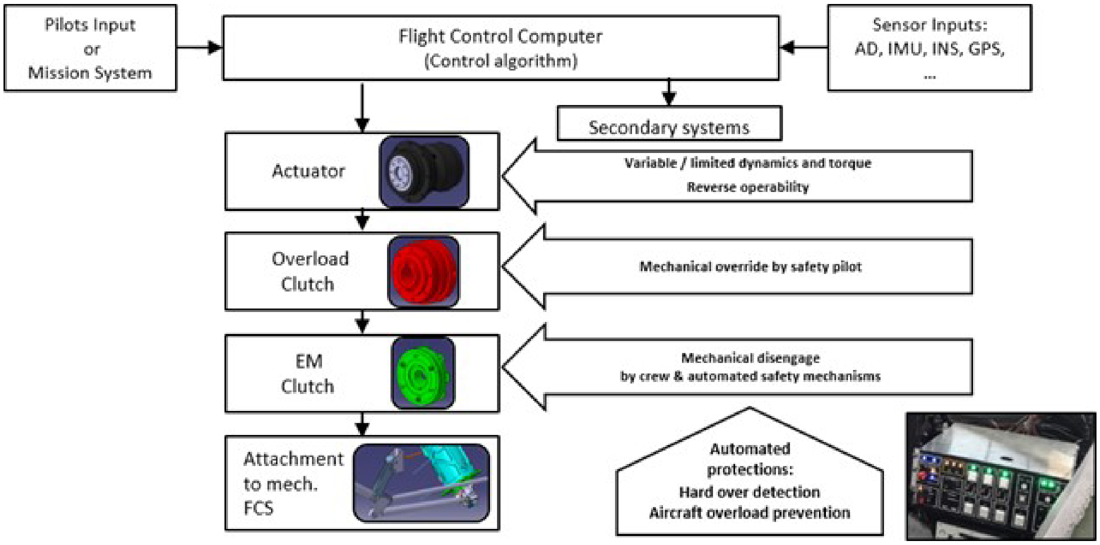
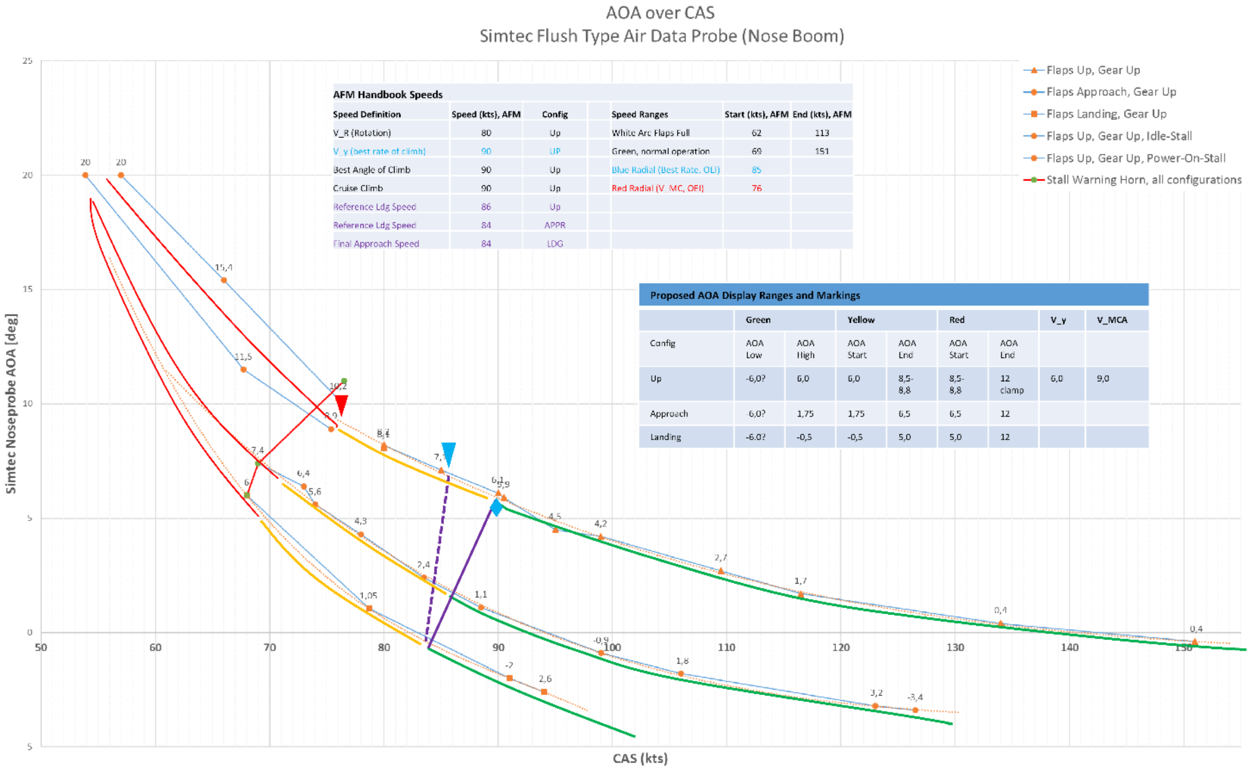


Figure 12. Flight control system overview

3.4 Experimental AOA warning systems

Before AOA warning systems could be evaluated, logic needed to be determined based on a normalized AOA. Then, the logic could be used on multiple aircraft. In addition, normalized AOA needed to work for all flap configurations. Figure 13 and Table 7 show the normalized definitions for the Diamond DA42.



AFM Handbook Speeds

Speed Definition	Speed (kts), AFM	Config		Speed Ranges	Start (kts), AFM	End (kts), AFM
V_R (Rotation)	80	Up		White Arc Flaps Full	62	113
V_y (best rate of climb)	90	UP		Green, normal operation	69	151
Best Angle of Climb	90	Up		Blue Radial (Best Rate, OEI)	85	
Cruise Climb	90	Up		Red Radial (V_MC, OEI)	76	
Reference Ldg Speed	86	Up				
Reference Ldg Speed	84	APPR				
Final Approach Speed	84	LDG				

Proposed AOA Display Ranges and Markings

	Green		Yellow		Red		V_y	V_MCA
Config	AOA Low	AOA High	AOA Start	AOA End	AOA Start	AOA End		
Up	-6,0?	6,0	6,0	8,5-8,8	8,5-8,8	12 clamp	6,0	9,0
Approach	-6,0?	1,75	1,75	6,5	6,5	12		
Landing	-6.0?	-0,5	-0,5	5,0	5,0	12		

Figure 13. Normalized AOA values for the DA42

Table 7. Normalized AOA values for the DA42

Normalized AOA	Flaps UP [°]	Flaps APP [°]	Flaps LDG [°]
1.0	14	10	9.2
0.9	12	8.7	7.1
0.8	10	7.4	6
0.7	8.2	4.3	2.9
0.6	6.9	2.3	-0.1
0.5	6.0	0.8	-1.6

3.4.1 Visual indicator

For visual warning, AOA was displayed to the pilot on the experimental Primary Flight Display (PFD) mounted above the glare shield using the display shown in Figure 14, modified from a design used on Icon aircraft. The modifications made were starting the AOA dial on the horizontal axis, depicting the flap position on the airfoil, and changing the airfoil color to match the AOA region.

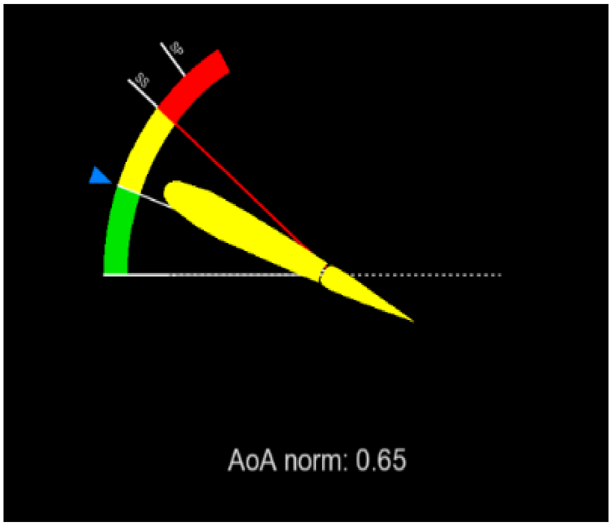


Figure 14. AOA visual display

3.4.2 Aural warning system

For aural warning, a male synthetic voice called out “AOA Yellow” when $\alpha_{norm} \geq 0.7$ followed by “Push” 1.65 seconds after the α_{norm} trigger. If $\alpha_{norm} \geq 0.8$, a synthetic voice called out “AOA Red” followed by “Push” 1.65 seconds after the α_{norm} trigger and a second “Push” 2.2 seconds after the α_{norm} trigger. Red callouts overrode yellow callouts. If the aircraft remained in a callout region, the callout message was repeated every 6 seconds. When the aircraft left the red region but remained in the yellow region, the yellow callout started 6 seconds after the transition.

After the first flight, the evaluation pilot asked to change the male synthetic “AOA Red, Push, Push” callout to a human female callout of “Stall! Stall!” The evaluation pilot felt the tone and duration of the synthetic voice was not sufficient to elicit a timely pilot response. More on this will be discussed later.

3.4.3 Haptic stall warning and prevention

The present project used a prototype Active Control Stick developed by Wittenstein Aerospace & Simulation shown in Figure 15. To make the Active Control Stick emulate a mechanical system (where forces change with dynamic pressure $\bar{q}$), Wittenstein implemented a multiplying factor, f, to shape the force gradient. The equation below shows the function for the calculation of f. Table 8 shows the values of the parameters selected for this project.

$$f = \left(c_0 + k_q \cdot \frac{\bar{q}}{1000\,N/m^2}\right)(1 + k_{nz} \cdot |n_z|) \tag{5}$$

Table 8. Active Control Stick force shaping values

Pitch axis	**Roll axis**
$c_0=7$	$c_0=1$
$k_a = 2$	$k_a = 2$
$k_{nz} = 0$	$k_{nz} = 0$

Figure 15. Active Stick at co-pilot seat

For this program, the team needed to apply step changes to the stick force as well as shake the stick and push the stick depending on the value of AOA. In an attempt to evaluate these techniques independent of a specific aircraft, the team developed a trigger logic based on normalized AOA (where 1.0 is just below stall AOA). Table 9 lists the logic for the various Active Control Stick effects.

Table 9. Active Control Stick trigger logic

Warning Level	**Stick Action**	**Start Condition**	**End Condition**
Yellow	1st 5 lbf. force step	$\alpha_{norm} \geq 0.7$	$\alpha_{norm} < 0.65$
Red	2nd 5 lbf. force step	$\alpha_{norm} \geq 0.8$	$\alpha_{norm} < 0.75$
	Stick Shaker	$\alpha_{norm} \geq 0.8$	$\alpha_{norm} \geq 0.80$ $\alpha_{norm} < 0.90$
	Stick Pusher	$\alpha_{norm} \geq 0.9$	$\alpha_{norm} < 0.65$

The Active Control Stick logic represents a layered approach to a stall/AOA warning. The first layer started at $\alpha_{norm} > 0.6$, defined as the start of the "yellow" region. A 5 lbf. stick force step occurred as shown in Figure 10, for $\alpha_{norm} \geq 0.7$, along with an audio warning (described below). Ideally, a pilot would react to these warnings and never get into the "red" region. Since the project specifically tested the effects in the red region, the evaluation pilots were routinely instructed to ignore all yellow warnings. The red region began at $\alpha_{norm} \geq 0.8$, and the system added another 5 lbf. step change in stick force, another audio warning, and a stick shaker. If $\alpha_{norm} \geq 0.9$ for 0.2 seconds, active AOA reduction was triggered in the form of a stick pusher. Figure 16 shows how this logic worked.

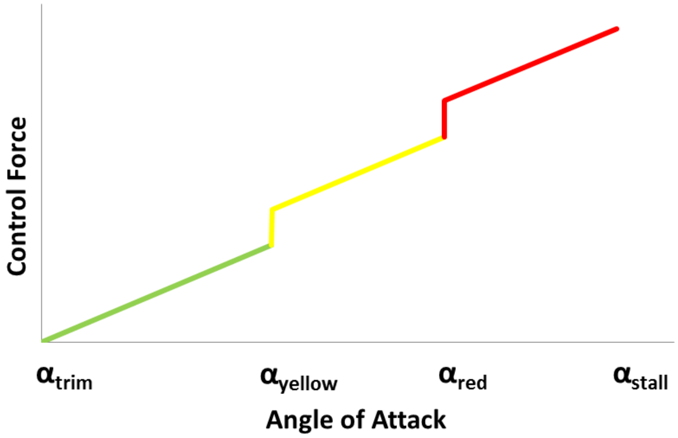


Figure 16. Stick force step changes

Two sources for AOA were available in the experiments: a Space Age Control two-vane probe mounted on the wing tip as shown in Figure 17 and a five-hole Smart Air Data probe mounted on the nose as shown in Figure 18.

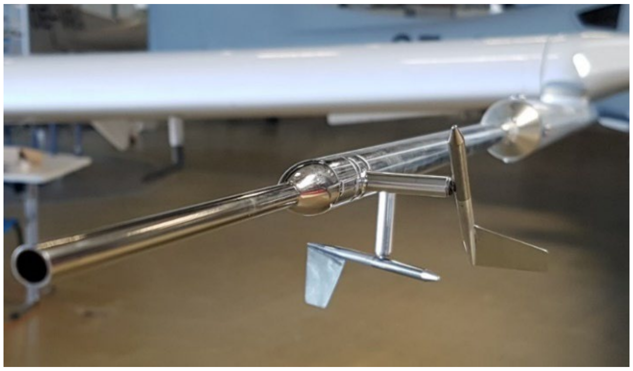


Figure 17. Wing tip Space Age Control AOA source

Figure 18. Five-hole Smart Air Data AOA source

While data were recorded from both AOA sources, the Active Control Stick logic was based on the 5-hole Smart Air Data probe mounted on the nose. As AOA data are typically "noisy", the logic was based on filtered AOA values. Thus, a momentary spike in raw AOA did not activate a trigger. In the case of the stick pusher, the filtered, normalized AOA needed to be at or above 0.9 ($\alpha_{norm} \geq 0.9$) for 0.2 seconds to trigger.

3.5 AOA warning methods evaluation flight test campaign

3.5.1 Test objectives and procedures

The program had three overall test objectives, as follows:

- Establish a means of compliance for Part 23 aircraft with AOA-limiting systems.
- Propose a method to certify a low cost enhanced AOA-limiting system with haptic feedback.
- Document the technical hurdles encountered in system integration.

From these overall test objectives, the team defined the following four means of compliance:

- Traditional stall matrix
- Legacy tracking task
- AOA tracking task
- Operational evaluation

3.5.1.1 Traditional stall matrix

The common method of evaluating stall warnings or stall characteristics is to fly a matrix of stalls using varying entry conditions, configurations, and power settings as shown in Table 10. For the present project, 32 individual stalls were defined, but these stall matrices can grow to hundreds of test points for actual certification programs. In addition, the evaluation pilot knows the stall is imminent and is “spring-loaded” for recovery. Moreover, results can vary significantly among pilots with only minor differences in entry conditions.

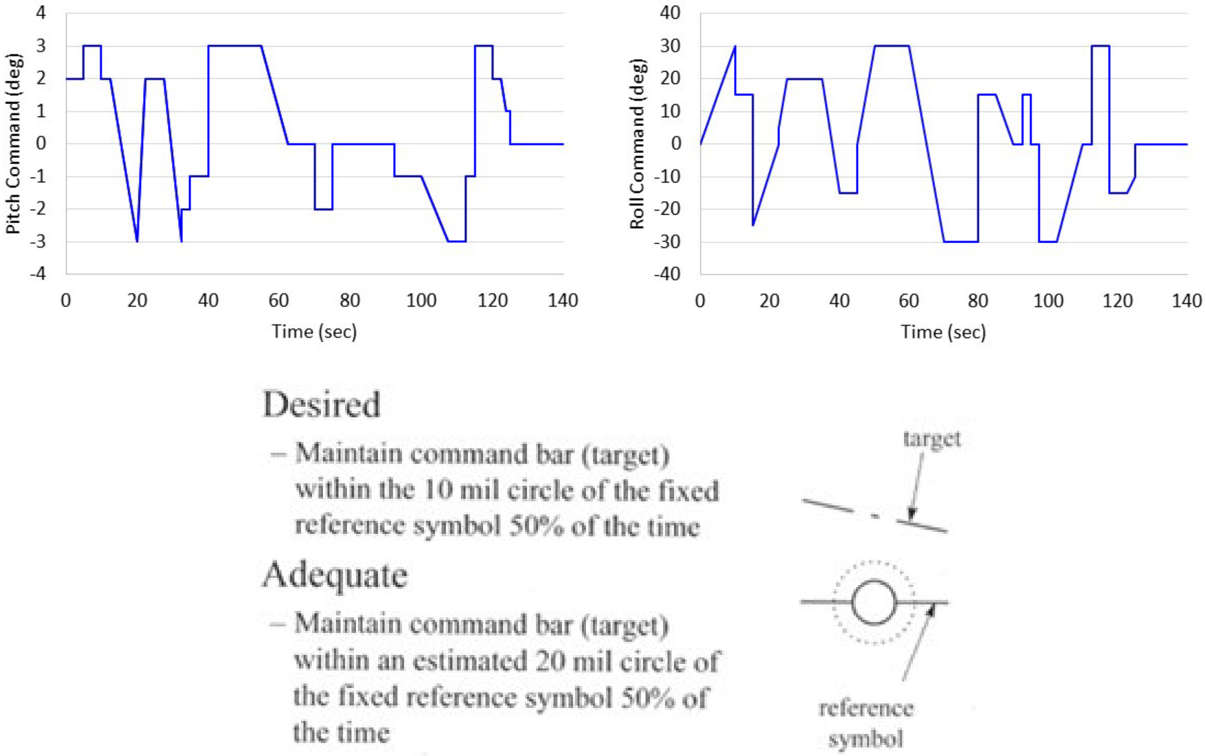
Table 10. Stall test matrix

#	Bank	Bleed Rate	Power	Gear and Flaps
1	0°	1 kt/s	off	up
2	0°	3-5 kts/s	off	up
3	0°	1 kt/s	off	down
4	0°	3-5 kts/s	off	down
5	0°	1 kt/s	on	up
6	0°	3-5 kts/s	on	up
7	0°	1 kt/s	on	down
8	0°	3-5 kts/s	on	down
9	15°	1 kt/s	off	up
10	15°	3-5 kts/s	off	up
11	15°	1 kt/s	off	down
12	15°	3-5 kts/s	off	down
13	15°	1 kt/s	on	up
14	15°	3-5 kts/s	on	up
15	15°	1 kt/s	on	down
16	15°	3-5 kts/s	on	down
17	30°	1 kt/s	off	up
18	30°	3-5 kts/s	off	up
19	30°	1 kt/s	off	down
20	30°	3-5 kts/s	off	down
21	30°	1 kt/s	on	up
22	30°	3-5 kts/s	on	up
23	30°	1 kt/s	on	down
24	30°	3-5 kts/s	on	down
25	45°	1 kt/s	off	up
26	45°	3-5 kts/s	off	up
27	45°	1 kt/s	off	down
28	45°	3-5 kts/s	off	down
29	45°	1 kt/s	on	up
30	45°	3-5 kts/s	on	up
31	45°	1 kt/s	on	down
32	45°	3-5 kts/s	on	down

3.5.1.2 Legacy tracking task

Traditional stall matrices focus on airspeed and not AOA. However, many current and future stall warning techniques use AOA (α) and even AOA-rate ($\dot{\alpha}$) in their logic. The Active Control Stick for this project used AOA to trigger the stick force effects. To address the variability inherent to flying traditional stall matrices, and to ensure the evaluation of an aircraft at specific AOAs, the project examined the use of tracking tasks as a means of compliance.

Tracking tasks have been used for decades to evaluate handling qualities. Calspan Corporation developed a tracking task for heads-up and heads-down displays that has the pilot tracking a target moving in both pitch and roll [26]. Although this "legacy" tracking task uses pitch attitude and not AOA, the team tried it in this project to see what AOAs would be achieved for a given entry airspeed. Figure 19 shows the targeted pitch attitude and roll angle commands in the legacy tracking task. The figure also shows the desired and adequate criteria used for handling qualities evaluations. Since most GA aircraft are limited to 60° of bank angle, the team scaled the roll command to a maximum of 30°, instead of 70° in the original Calspan tracking task.



Desired

- Maintain command bar (target) within the 10 mil circle of the fixed reference symbol 50% of the time

Adequate

- Maintain command bar (target) within an estimated 20 mil circle of the fixed reference symbol 50% of the time

Figure 19. Calspan's legacy tracking task [26]

3.5.1.3 AOA tracking task

Rather than fly a pitch attitude tracking task and "hope" the aircraft achieves a desired AOA or AOA-rate, why not fly an AOA tracking task? In theory, an AOA tracking task could guarantee certain AOA values are achieved. In addition, certain AOA-rates could also be achieved. Bounds could be placed on the pilot performing the AOA tracking task to determine if the test was valid (and therefore repeatable).

Thus, the team developed the AOA tracking task shown in Figure 20. Using this task resulted in flying the desired AOA and AOA-rate values, whereas the pitch attitude (θ) was not controlled. Most GA aircraft, unless designed for aerobatic flight, need to stay within $-30° \leq \theta \leq 30°$. Furthermore, the task included bank-angle changes to examine the effects of AOA source location (nose mounted versus wing-tip mounted).

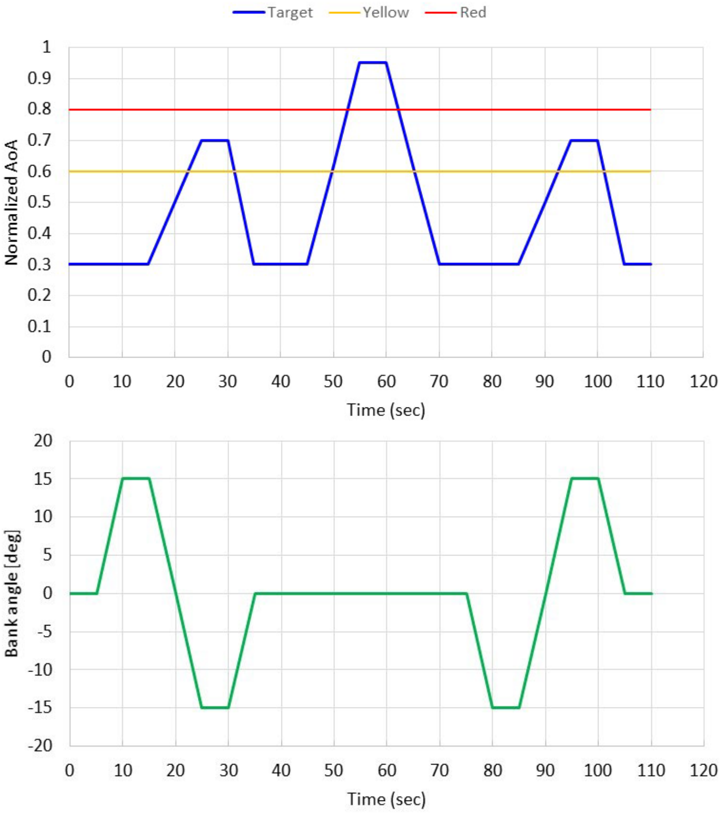


Figure 20. AOA tracking task

3.5.1.4 Operational evaluation

The ASTM committee identified the need for operationally-representative data. When discussing the challenge of determining point values for assessing stall-warning effectiveness, values need to be derived from experience, and eventually, data [4]. Therefore, the evaluation pilots flew simulated patterns at safe altitude. Some of the patterns were “normal”, and some were “abused” (e.g. overshoot at final or applying rudder to turn the aircraft). These patterns served the gathering of representative data for values of AOA and AOA-rate a typical pilot might see in the pattern. This would tell the team if the AOA tracking task was operationally representative.

Throughout the project, it was critical to keep in mind that the task was to evaluate the *means of compliance* and *not* the implementation of the various techniques or trigger points. A means of compliance can be valid even though a given stall warning technique failed. Nonetheless, the team constantly tweaked the implementations of the AOA warning system and ultimately also evaluated the various techniques. The DA42 testbed proved to be an extremely valuable tool, with system changes being implemented quickly.

All data collection flights were launched from the Wiener Neustadt East Airport (identifier: LOAN) south of Vienna, Austria. The approximate flight test area is depicted in Figure 21. All tests were performed during the day under Visual Flight Rules (VFR). The safety pilot (pilot in command) flew in the left seat. The evaluation pilot flew in the right seat using the Active Control Stick. A Flight Test Engineer (FTE) flew in the backseat and ran the flight test control and data systems.

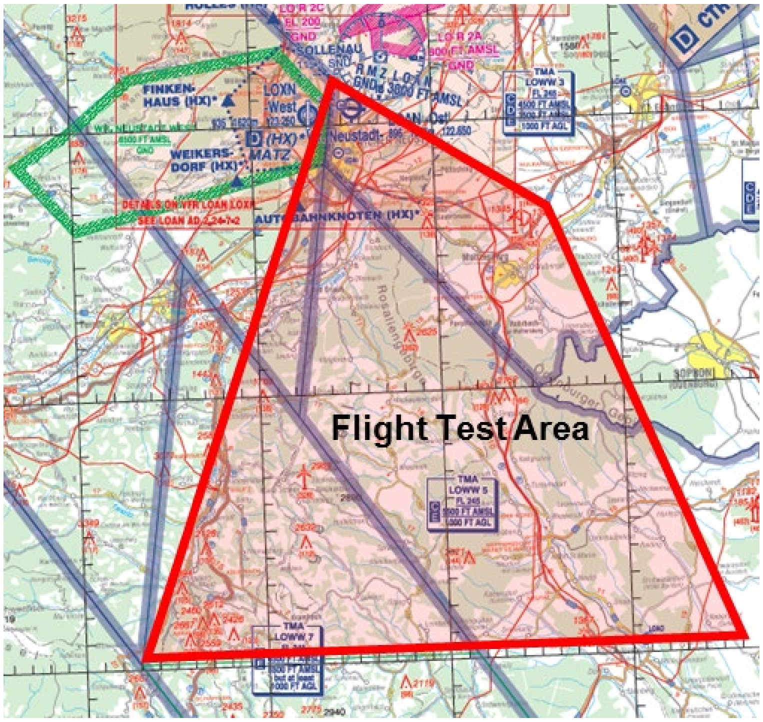


Figure 21. Test location

3.5.2 Results

A total of eleven flights were flown in seven days for total of 12.5 hours. Weather cooperated, and the DA42 test bed was working nearly flawlessly. The only minor issue with the DA42 was that the recording of intercom voice on the video files failed; however, ambient cockpit audio was recorded. Thus, the video files were of use to qualitatively assess each flight.

Two evaluation methods for AOA warning/limitation systems were tested:

- Common stall matrix (Table 10)
- Pilot-in-the-loop tracking tasks (Figure 19 and Figure 20)

The common stall matrix proved superior in evaluating the effectiveness and performance of the following five AOA warning/indication features:

- A visual AOA indicator
- A two-level, verbal audio warning
- A two-level haptic stick-feedback force bias feature
- A stick shaker
- A stick pusher.

Table 11 shows the flight log. Table 12 shows the tasks used during the eleven flights.

Table 11. Flight log

No.	Day	Dur.	Eval. Pilot	Safety Pilot	FTE	Objectives
1	1	1:12	EP 1 (FIT)	SP 1 (DA)	FTE 1 (TUM)	Straight stalls
2	2	1:10	EP 1 (FIT)	SP 2 (DA)	FTE 1 (TUM)	Banked stalls
3	2	1:00	EP 1 (FIT)	SP 2 (DA)	FTE 2 (TUM)	Legacy Task, free patterns
4	3	1:01	EP 1 (FIT)	SP 1 (DA)	FTE 3 (TUM)	AOA Task 1
5	4	0:38	EP 1 (FIT)	SP 3 (DA)	FTE 2 (TUM)	AOA Task 2
6	5	0:32	EP 2 (FIT)	SP 2 (DA)	FTE 1 (TUM)	Straight stalls, AOA Task 1
7	5	0:32	EP 3 (FIT)	SP 2 (DA)	FTE 1 (TUM)	Straight stalls
8	6	1:54	EP 4 (FAA)	SP 3 (DA)	FTE 1 (TUM)	Stall matrix, AOA Task 1
9	6	1:25	EP 5 (FAA)	SP 2 (DA)	FTE 1 (TUM)	Stall matrix, AOA Task 1
10	7	1:58	EP 4 (FAA)	SP 2 (DA)	FTE 1 (TUM)	Stall matrix, free patterns
11	7	1:09	EP 5 (FAA)	SP 2 (DA)	FTE 1 (TUM)	Stall matrix, free patterns

Table 12. Task list

Flight	Task	Matrix	Active Warning Systems
1	01-01	1	v
	01-02	1	v + a
	01-03	1	v + a + f
	01-04	1	v + a + f + s
	01-05	1	v + a + f + s + p
	01-06	3	v
	01-07	3	v + a
	01-08	3	v + a + f
	01-09	3	v + a + f + s

Flight	Task	Matrix	Active Warning Systems
	01-10	3	v + a + f + s + p
	01-11	5	v
	01-12	5	v + a + f + s + p
	01-13	7	v + a + f + s
	01-14	7	v + a + f + s + p
	01-15	2	v
	01-16	2	v + a
	01-17	2	v + a + f
	01-18	2	v + a + f + s
	01-19	2	v + a + f + s + p
2	02-01	3	v + a + f + s + p
	02-02	7	v + a + f + s + p
	02-03	9	v + a + f + s + p
	02-04	11	v + a + f + s + p
	02-05	13	v + a + f + s + p
	02-06	15	v + a + f + s + p
	02-07	17	v + a + f + s + p
	02-08	19	v + a + f + s + p
	02-09	25	v + a + f + s + p
	02-10	20	v + a + f + s + p
	02-11	24	v + a + f + s + p
3	03-01	Simulated traffic pattern	v + a + f + s + p
	03-02	Legacy tracking task	v + a + f + s + p
4	04-01	AOA tracking task 1, 15° bank, 100 kts	warnings off
	04-02	AOA tracking task 1, 15° bank, 100 kts	v + a + f + s + p, ignore all warnings
	04-03	AOA tracking task 1, 15° bank, 100 kts	v + a + f + s + p, respond to all warnings
	04-04	AOA tracking task 2, 15° bank, 110 kts	warnings off
	04-05	AOA tracking task 2, 15° bank, 108 kts	v + a + f + s + p, ignore all warnings
	04-06	AOA tracking task 2, 15° bank, 100 kts	v + a + f + s + p, respond to all warnings
	04-07	AOA tracking task 1, 15° bank, 100 kts	v + a + f + s + p, respond to warnings on first AOA
	04-08	AOA tracking task 2, 15° bank, 100 kts	v + a + f + s + p, respond to warnings on first AOA
5	05-01	AOA tracking task 3, 15° bank, 110 kts	warnings off
	05-02	AOA tracking task 3, 15° bank, 110 kts	a
	05-03	AOA tracking task 3, 15° bank, 110 kts	p
	05-04	AOA tracking task 3, 15° bank, 110 kts	s
	05-05	AOA tracking task 3, 15° bank, 110 kts,	a
	05-06	AOA tracking task 3, 15° bank, 110 kts,	p
	05-07	AOA tracking task 3, 15° bank, 110 kts,	s
6	06-01	1	v
	06-02	1	v + a
	06-03	1	v + a + f + s + p
	06-04	AOA tracking task 2, 15° bank, 110 kts	v + a + f + s + p
	07-01	1	v

Flight	Task	Matrix	Active Warning Systems
7	07-02	1	v + a
	07-03	1	v + a + f + s + p
	07-04	AOA tracking task 2, 15° bank, 110 kts	v + a + f + s + p
8	08-01	1	v
	08-02	1	v + a
	08-03	1	v + a + f
	08-04	1	v + a + f + s
	08-05	1	v + a + f + s + p
	08-06	3	v + a + f + s
	08-07	3	v + a + f + s + p
	08-08	5	v + a + f + s
	08-09	5	v + a + f + s + p
	08-10	7	v + a + f + s
	08-11	7	v + a + f + s + p
	08-12	2	v + a + f + s + p
	08-13	4	v + a + f + s + p
	08-14	6	v + a + f + s + p
	08-15	8	v + a + f + s + p
	08-16	1	v + a + f
	08-17	9	v + a + f + s + p
	08-18	13	v + a + f + s + p
	08-19	19	v + a + f + s + p
	08-20	AOA tracking task 2, 15° bank, 105 kts	v + a + f + s + p
	08-21	AOA tracking task 2, 15° bank, 105 kts,	v + a + f + s + p
	08-22	Simulated traffic pattern	v + a + f + s + p
	08-23	Legacy tracking task, 105 kts	v + a + f + s + p
9	09-01	1	v
	09-02	1	v + a + f
	09-03	1	v + a + f + s
	09-04	1	v + a + f + s + p
	09-05	3	v + a + f + s
	09-06	3	v + a + f + s + p
	09-07	5	v + a + f + s + p
	09-08	7	v + a + f + s
	09-09	2	v + a + f + s + p
	09-10	4	v + a + f + s + p
	09-11	6	v + a + f + s + p
	09-12	8	v + a + f + s + p
	09-13	17	v + a + f + s + p
	09-14	19	v + a + f + s + p
	09-15	25	v + a + f + s + p
	09-16	AOA tracking task 2, 15° bank, 110 kts	v + a + f + s + p
	09-17	AOA tracking task 2, 15° bank, 110 kts,	v + a + f + s + p

Flight	Task	Matrix	Active Warning Systems
	09-18	Simulated traffic pattern	v + a + f + s + p
10	10-01	Simulated traffic patterns	various combinations
11	10-01	Simulated traffic patterns	various combinations

Three iterations of the tracking task were flown, as follows:

- A pitch-roll Legacy Task based on the Calspan method (Figure 19).
- An AOA Tracking Task combining AOA slopes and roll maneuvers in clean configuration (Figure 20).
- An AOA Tracking Task combining three configuration changes with simultaneous roll and AOA maneuvers (discarded after first attempt).

At the 120-kt entry speed flown, the legacy tracking task proved ineffective in producing the desired AOA values. The AOA tracking tasks were effective in producing high AOA values during the first AOA buildup. However, for the subsequent AOA peaks, achieving the targeted AOA depended primarily on the tracking performance of the pilot. The AOA tracking task also resulted in large pitch attitude and velocity changes, and would need to be run in different aircraft configurations to provide complete information. In general, the pilots and FTEs remarked that these tasks were difficult to track and did not lead to repeatable conditions. At this point, the usefulness of tracking tasks for a means of compliance is doubtful. More research regarding the tuning of the maneuvers and the tailoring towards different airplanes would be needed. However, if a test required verifying a given $\dot{\alpha}$, then a wings-level tracking task could be valuable.

Throughout the campaign, the implemented AOA warning/limitation features were adjusted based on pilot and FTE feedback. For the AOA display, the scaling was adjusted in order to not give the impression of negative AOAs being flown. The wing representation was adjusted to change color with the AOA region. Figure 22 shows the original AOA display compared to the final AOA display. The resulting visual AOA warning received good pilot reviews.

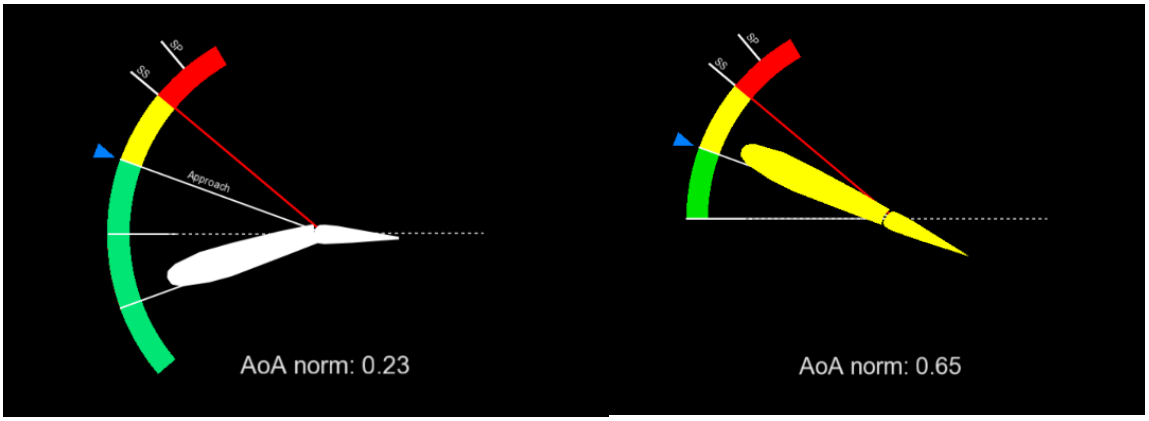


Figure 22. AOA display changes (original left, final right)

According to one of the evaluation pilots, "The visual angle-of-attack display on the DA42 was one of the best I have seen. Not only did it let you know what your relative angle-of-attack was, it also provided flap configuration. I felt that it made much more sense than any of the after-market angle-of-attack indicators that I have seen so far. However, I believe all visual systems suffer from the same problem. Pilots who lose control are not looking at them, which includes the airspeed indicator."

Various adjustments to the audio warning were tested. In general, it was found that the verbal warnings help in getting the pilots' attention against the background of warning tones. However, nuances in intonation, volume, and acoustic contrast are essential to consider in means of compliance. According to one of the evaluation pilots, "With exception of the 'Stall! Stall!' warning, the aural warnings were lost in the background plethora of warnings in today's modern cockpit. The warnings for landing gear and other warnings soon caused one to ignore the aural channel."

Results were mixed on the effectiveness of the steps in force gradient. According to one of the evaluation pilots, "Experienced pilots may consider this feature a nuisance; however, for inexperienced pilots it may be valuable." The first force step in the AOA yellow region was sometimes missed when the pilots were performing an operational task. More research is needed regarding the strength, number, and positioning of the force steps.

The stick shaker was generally found to be the most effective feature. According to one of the evaluation pilots, "After about 5 hours of doing approaches to stalls, I found the stick shaker to be so effective that I would assign it a very high point value. First, it cannot be ignored. Secondly, it should be relatively easy to install in the GA fleet, including older airplanes." This result matches the result found by Ontiveros [20].

The stick pusher was found to be very effective by not permitting a stall. However, it could potentially also cause safety problems by engaging at low altitudes in the traffic pattern. A pusher would also be difficult to retrofit in the current GA fleet. More research is required regarding the proper tuning of a pusher. There could be unintended consequences of installing this type of system with respect to the “do no harm” policy of the FAA’s NORSEE provisions.

In addition to the qualitative comments, the team recorded time histories of all the maneuvers. Figure 23 shows a sample of an AOA time history of a wings-level, 1 kt/s bleed-rate stall. For this example, the pilot ignored all warnings. However, it gives quantitative data on how much time it takes to transition through the various warning trigger points. A future study could be performed to measure pilot reaction times while flying operationally-representative maneuvers. This could give developers an idea of where to place warning triggers. Obviously a warning trigger that is too conservative and fires often can become a nuisance (and possibly be ignored), thereby reducing the effectiveness.

During the flight campaign, the evaluation pilots ran test points up-and-away from the ground. The safety pilots performed all takeoffs and landings. Data were recorded throughout the entire flight, so the team captured operationally-representative data in the pattern. As such, the team could analyze if and where the AOA warning triggers would have fired to help determine any safety benefits or concerns during critical phases of flight. In Figure 23, one can see that the pilot got into the yellow region shortly after rotation. In Figure 24, one can see that the pilot transitioned in and out of the yellow region and briefly got into the red region. This is not surprising, since a common landing technique involves flaring to near stall just prior to touchdown.

The time histories, along with the cockpit environment at the time, are both needed to properly assess effectiveness or dangers of the various triggers. Constant “AOA, Yellow” callouts, frequent stick vibrations, or an ill-timed firing of a stick pusher could actually decrease safety. On the other hand, pilots could achieve maximum performance during maneuvers knowing exactly where they are on the AOA curve.

Figure 24 and Figure 25 also show the range of AOAs achieved in the pattern. AOA rates can be determined from the slopes of the AOA time histories. Future flight test campaigns should compile data from a large number of pilots flying many takeoffs and landings to determine parameter ranges, averages, minimums, and maximums. The data would be valuable to ASTM committees and developers to understand the trade space of the various warning systems.

During the flight campaign, it became clear how valuable TUM's DA42 test bed is for assessing the effectiveness of AOA warnings. According to one of the evaluation pilots, "the fly-by-wire DA42 is the first and only aircraft where in 54 years of flying airplanes, I have had the opportunity to compare visual, aural, tactile, and pusher stall warning systems at the same time which I found to be enlightening." The team was able to bring up any warning system one or two-at-a-time, all together, or in any other combination. In addition, the Garmin-configured DA42 cockpit environment was never silenced during the flights. Thus, the team got insight into how systems perform in a modern cockpit environment, involving many tones, call outs, lights, etc. While a synthetic voice warning may be effective in the relatively sterile cockpit environment of a Piper Cherokee 180, the effectiveness may diminish in a modern cockpit environment like the DA42.

The team also witnessed how seemingly minor system details matter. It was already mentioned how important intonation, volume, and acoustic contrast are with aural warnings. Stick pusher details also count. The initial implementation resulted in normal accelerations (n_z) near 0 g. Figure 26 and Figure 27 show the response to pusher activations. While control laws could easily be modified to limit $n_z \geq 0.5$ g, it highlighted the fact that one-size-fits-all concepts may not work. Implementations for all systems will need to be optimized to the given platforms.

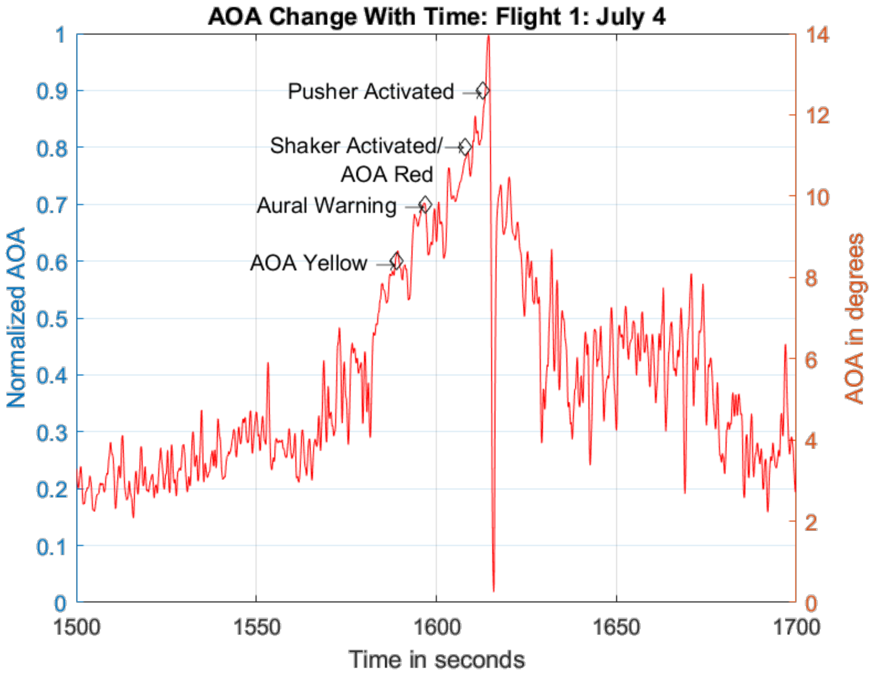


Figure 23. Sample AOA time history with triggers

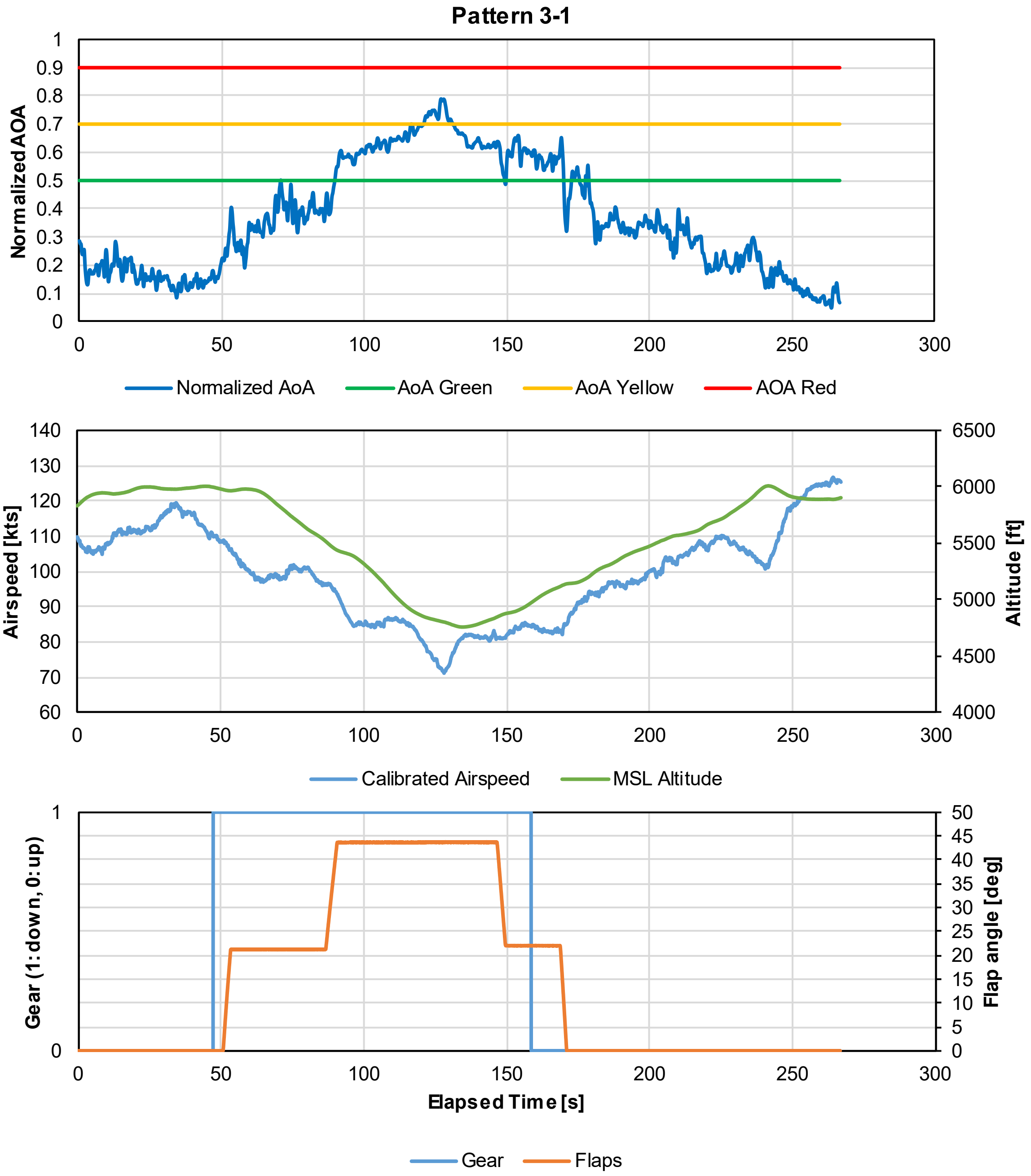


Figure 24. Simulated approach pattern 1 on flight 3

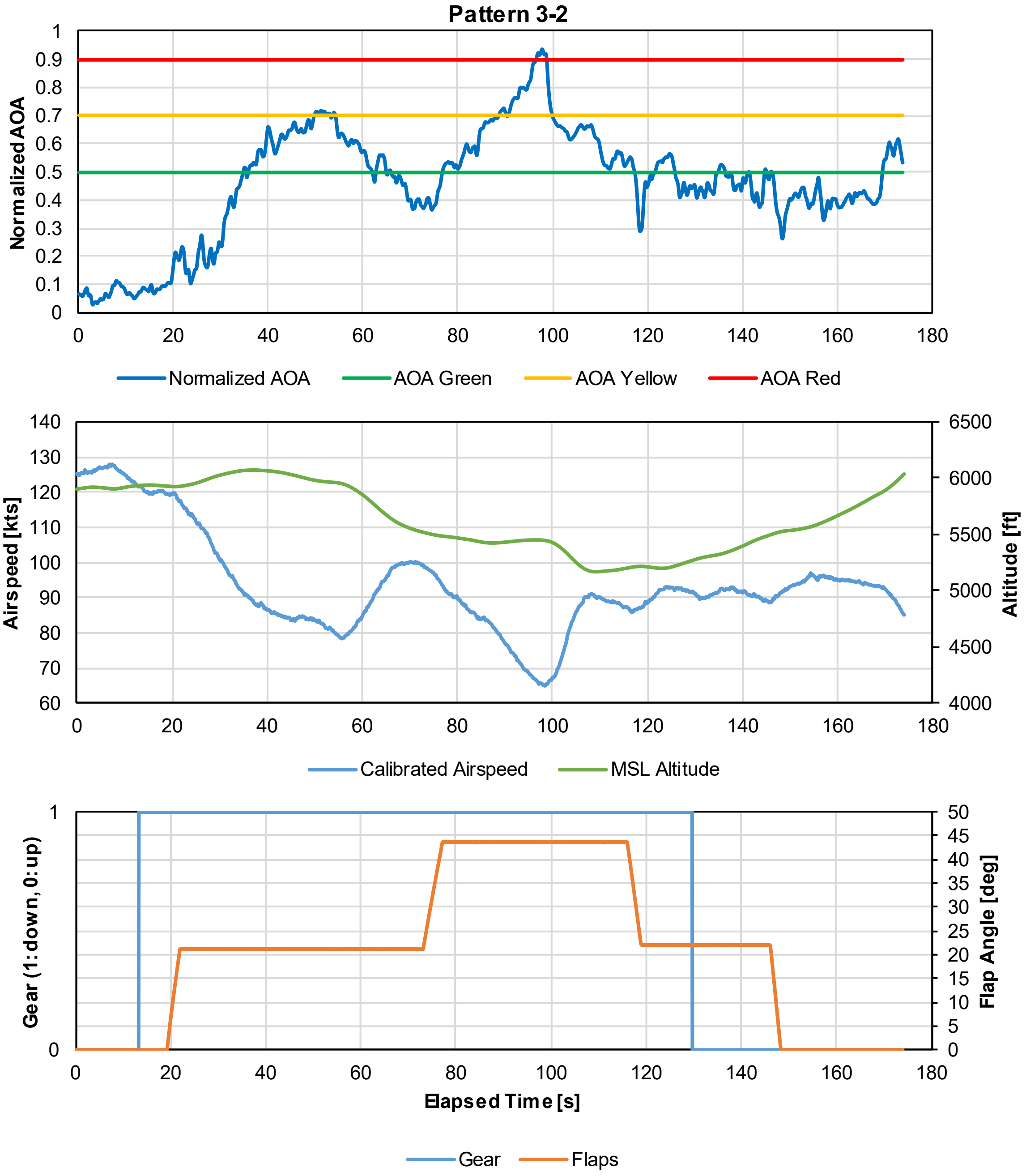


Figure 25. Simulated approach pattern 2 on flight 3

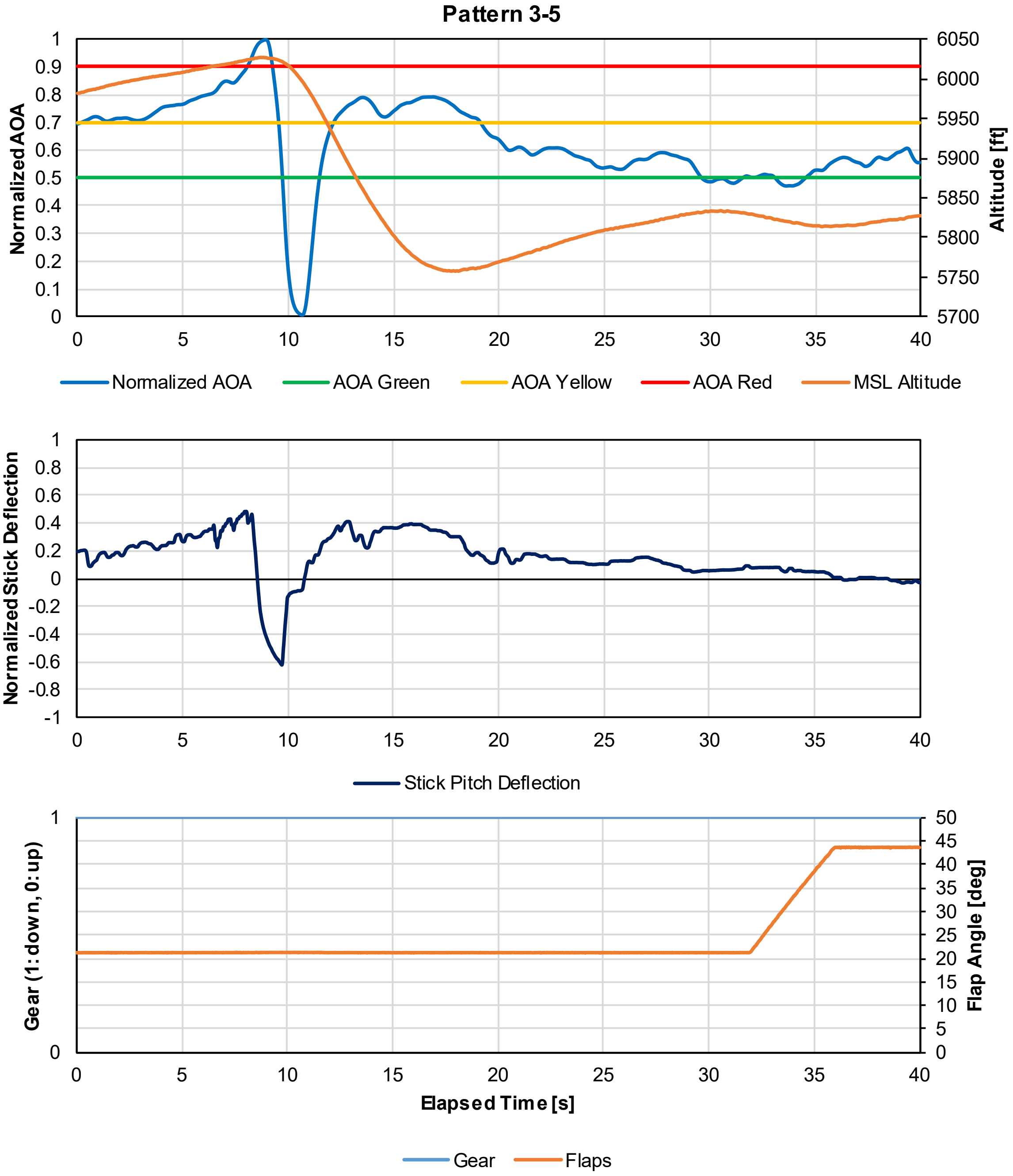


Figure 26. Altitude loss due to pusher activation on pattern 5 of flight 3

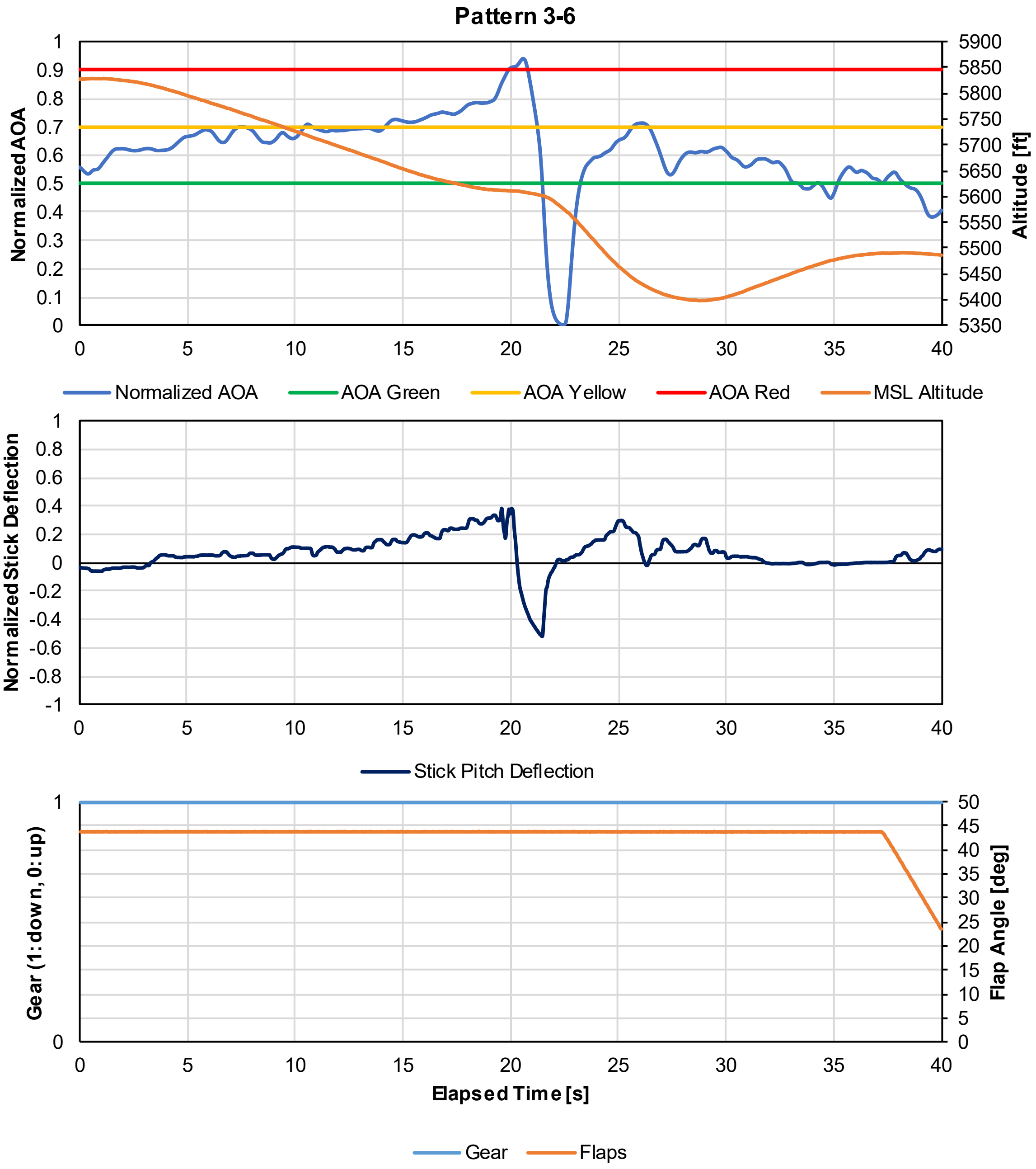


Figure 27. Altitude loss due to pusher activation on pattern 6 of flight 3

A comparative evaluation of the different methods is needed to inform the points awarded in the reworked certification process. To this end, a survey was distributed to all project pilots. In the survey, the pilots were asked to suggest certification point values for stall warning and enhanced indication system options taken from a draft of the 23.2150 ASTM committee means of compliance. In addition to the survey, the team challenged all project members to assess the overall value of a certification points matrix compared to a more integrated systems evaluation performed by multiple pilots flying operationally relevant flight profiles. Figure 28 shows the range and mean of the surveys.

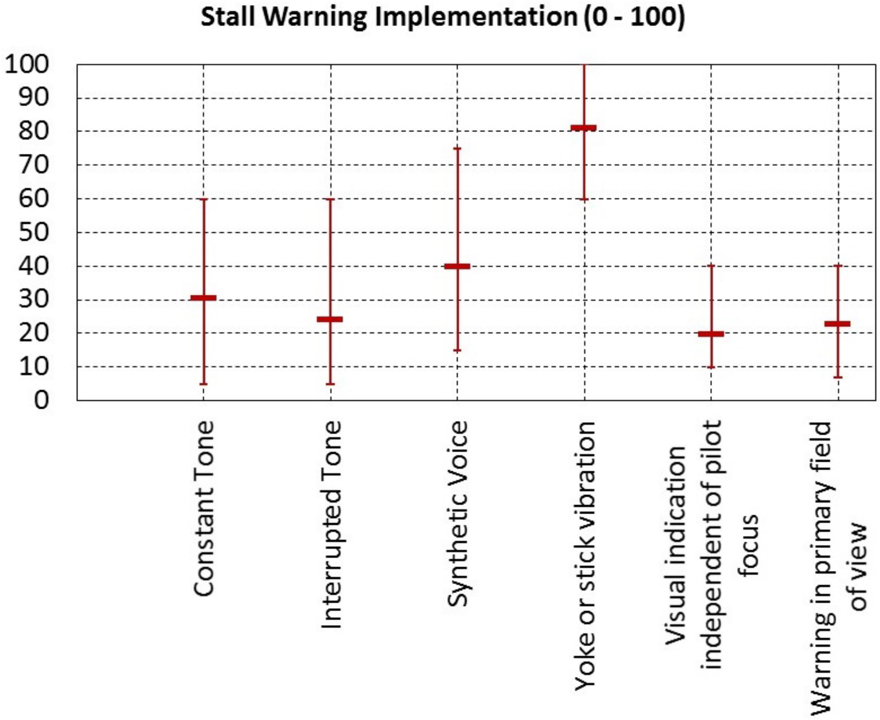


Figure 28. Relative effectiveness of warning systems

Based on the limited, but valuable exposure the team had flying TUM's DA42, the team finds that assigning a single point value for a given warning system is *not* sufficient. Combining different AOA warning/limitation features to accumulate a set number of points for certification may actually be detrimental to flight safety. Therefore, any certification system would have to account for the fact that the effects of such combined warning/limitation systems could both be more or less than the sum of their individual elements. Instead of "one-size-fits-all" point values, a range of points should be considered. This is reflected in the MOC presented in Section 2. The ranges of point values available for Safety Enhancement systems listed in Table 6 were set based on Figure 28. The test pilots can award points within these ranges to reflect their individual assessment of the effectiveness of the system implementation.

The team concurs with the ASTM committee's guidance that more effort will be needed to help craft the standards. Any weaknesses or loopholes discovered along the way will need to be addressed using relevant flight data. In addition, the committee should address the effectiveness of multiple systems involving multiple sensory paths installed in a specific cockpit environment.

The overall effectiveness could be more or less than the sum of its parts. Clearly, more flight research is needed.

4 Stall characteristics of common general aviation aircraft

4.1 Aircraft and instrumentation

Six common single-engine GA aircraft were selected for the flight test campaign: Diamond DA40, Citabria, Mooney M20C, Cirrus SR 20, Cessna 172, and Piper Archer. The aircraft are shown in Figure 29. These six aircraft were selected to span various designs (low vs. high wing, tail dragger vs. tricycle gear, T-tail vs. conventional tail, metal vs. composite, traditional thicker wings vs. modern wings with leading-edge cuffs).

Table 13lists the critical airspeeds from the various pilot operating handbooks.

Diamond DA40 Citabria

Mooney M20C Cirrus SR 20

Cessna 172 Piper Archer

Figure 29. Aircraft used in the flight test campaign

Table 13. Critical airspeeds defined in pilot operating handbooks

Speed	**Diamond DA40**	**Citabria**	**Mooney M20C**	**Cirrus SR 20**	**Cessna 172N**	**Piper Archer**
V_{S0}	42 – 49 kts	50 mph	63 mph	56 kts	36 – 41 kts	45 kts
V_S	47 – 52 kts	50 mph	70 mph	65 kts	42 – 47 kts	50 kts
1.3 V_{S0} (FD)	64 kts	65 mph[1]	82 mph	73 kts	53 kts	59 kts
1.5 V_S (FU)	78 kts	75 mph[1]	105 mph	98 kts	71 kts	75 kts
V_{FE}	91 kts	n/a	120 mph	100 kts	85 kts	102 kts
V_A (V_0)	108 kts	113 mph	132 mph	122 kts	96-101 kts	113 kts
V_{NE}	178 kts	162 mph	200 mph	200 kts	160 kts	154 kts
V_{glide}	60 – 73 kts	65 mph	100 mph	87 kts	65 kts	79 kts

[1] Since the Citabria does not have flaps, the different speeds are due only to the different multipliers of V_{S0} (V_S)

All aircraft were instrumented with GoPro® cameras and Stratus 2S AHRS data recorders (by Appareo) in the cockpits. One camera was oriented to capture the cockpit instruments; one camera was pointed over one wingtip (see Figure 30). The intercom audio was fed into the cockpit camera and recorded with the video.

Figure 30. Sample GoPro frames. Left: cockpit view. Right: wing view

Data from the Cessna 172's Garmin G5 and data from the Diamond DA40's Garmin G1000 were also acquired. The G5 logged attitude and speed data at 10 Hz, the G1000 at 1 Hz. The hand-held force gauge in Figure 31 was used to measure longitudinal control forces. The force measurement was read-off during flight and noted on the flight cards.

Figure 31. Hand-held force gauge

4.2 Flight test campaign

4.2.1 Test points, procedures, pass-fail criteria

All test points began with trimming the airplane (in all axes) at either 1.3 V_{S0} (with flaps down) or 1.4 V_S (with flaps up) at an altitude of 5000 ft or above. “Power-Off” was defined as idle; “Power-On” was defined as 75% of maximum continuous power.

Table 14 through Table 19 list 76 test points used to determine the stall characteristics. Test points were flown in order 1 through 76, as safety risk was assumed to grow with test point number. In general, “Power-Off” points were flown prior to “Power-On”. Coordinated entries were flown prior to feet-on-the-floor (FOF) entries. Wings-level entries were flown prior to turning entries. Abused entries were flown last. If an airplane failed a test point, testing beyond that point was at the judgment of the pilot. A stall was defined as either pitch-break or the control column reaching the aft limit.

Table 14 lists the test points for coordinated, wings-level stall characteristics. The pilots were instructed to center the ball during the entire entry. When stall was achieved, the pilot could use all means necessary to keep the bank angle within ±15° for 2 s. If the bank angle ϕ exceeded 15° in either direction, the test point was scored as a fail.

Table 14. Test points for coordinated, wings-level stall characteristics

No.	Flaps	Power	Entry	Gear	Altitude [ft]	Bleed rate
1	Up	Off	coord	Down	5000	1 kt/s
2	Down	Off	coord	Down	5000	1 kt/s
3	Up	On	coord	Down	5000	1 kt/s
4	Down	On	coord	Down	5000	1 kt/s

Table 15 lists the test points for coordinated, turning stall characteristics. The pilots were instructed to center the ball during the entire entry. When stall was achieved, the pilot could use all means necessary to keep the bank angle within the following limits:

- For 1 kt/s entry with $\phi = 30°$: $-30° \leq \phi_{max} \leq 60°$.
- For 1 kt/s entry with $\phi = -30°$: $-60° \leq \phi_{max} \leq 30°$.
- For 3-5 kts/s entry with $\phi = 30°$: $-60° \leq \phi_{max} \leq 90°$.
- For 3-5 kts/s entry with $\phi = -30°$: $-90° \leq \phi_{max} \leq 60°$.

If the bank angle exceeded these limits, the test point was scored as a fail.

Table 15. Test points for coordinated, turning stall characteristics (30° bank)

No.	Flaps	Power	Entry	Direction	Gear	Altitude [ft]	Bleed rate
5	Up	Off	Coord.	Left	Down	5000	1 kt/s
6	Up	Off	Coord.	Right	Down	5000	1 kt/s
7	Down	Off	Coord.	Left	Down	5000	1 kt/s
8	Down	Off	Coord.	Right	Down	5000	1 kt/s
9	Up	Off	Coord.	Left	Down	5000	3-5 kts/s
10	Up	Off	Coord.	Right	Down	5000	3-5 kts/s
11	Down	Off	Coord.	Left	Down	5000	3-5 kts/s
12	Down	Off	Coord.	Right	Down	5000	3-5 kts/s
13	Up	On	Coord.	Left	Down	5000	1 kt/s
14	Up	On	Coord.	Right	Down	5000	1 kt/s
15	Down	On	Coord.	Left	Down	5000	1 kt/s
16	Down	On	Coord.	Right	Down	5000	1 kt/s
17	Up	On	Coord.	Left	Down	5000	3-5 kts/s
18	Up	On	Coord.	Right	Down	5000	3-5 kts/s
19	Down	On	Coord.	Left	Down	5000	3-5 kts/s
20	Down	On	Coord.	Right	Down	5000	3-5 kts/s

Table 16 lists the test points for feet-on-the-floor, wings-level stall characteristics. The pilots were instructed to keep their feet on the floor during the entire entry. When stall was achieved, the pilot could use all means necessary to keep the bank angle with ±15° for 2 s. If the bank angle exceeded 15° in either direction, the test point was scored as a fail.

Table 16. Test points for feet-on-the-floor, wings-level stall characteristics

No.	Flaps	Power	Entry	Gear	Altitude [ft]	Bleed rate
21	Up	Off	FOF	Down	5000	1 kt/s
22	Down	Off	FOF	Down	5000	1 kt/s
23	Up	On	FOF	Down	5000	1 kt/s
24	Down	On	FOF	Down	5000	1 kt/s

If the bank angle exceeded these limits (or the pilot “knocked-it-off” prior to a limit for safety concerns), the test point was scored as a fail.

Table 17 lists the test points for feet-on-the-floor, turning stall characteristics. The pilots were instructed to keep their feet on the floor during the entire entry. When stall was achieved, the pilot could use all means necessary to keep the bank angle within the following limits. If the bank angle exceeded these limits, the test point was scored as a fail.

- For 1 kt/s entry with $\phi = 30°$: $-30° \leq \phi_{max} \leq 60°$.
- For 1 kt/s entry with $\phi = -30°$: $-60° \leq \phi_{max} \leq 30°$.
- For 3-5 kts/s entry with $\phi = 30°$: $-60° \leq \phi_{max} \leq 90°$.
- For 3-5 kts/s entry with $\phi = -30°$: $-90° \leq \phi_{max} \leq 60°$.

If the bank angle exceeded these limits (or the pilot "knocked-it-off" prior to a limit for safety concerns), the test point was scored as a fail.

Table 17. Test points for feet-on-floor, turning stall characteristics (30° bank)

No.	Flaps	Power	Entry	Direction	Gear	Altitude [ft]	Bleed rate
25	Up	Off	FOF	Left	Down	5000	1 kt/s
26	Up	Off	FOF	Right	Down	5000	1 kt/s
27	Down	Off	FOF	Left	Down	5000	1 kt/s
28	Down	Off	FOF	Right	Down	5000	1 kt/s
29	Up	Off	FOF	Left	Down	5000	3-5 kts/s
30	Up	Off	FOF	Right	Down	5000	3-5 kts/s
31	Down	Off	FOF	Left	Down	5000	3-5 kts/s
32	Down	Off	FOF	Right	Down	5000	3-5 kts/s
33	Up	On	FOF	Left	Down	5000	1 kt/s
34	Up	On	FOF	Right	Down	5000	1 kt/s
35	Down	On	FOF	Left	Down	5000	1 kt/s
36	Down	On	FOF	Right	Down	5000	1 kt/s
37	Up	On	FOF	Left	Down	5000	3-5 kts/s
38	Up	On	FOF	Right	Down	5000	3-5 kts/s
39	Down	On	FOF	Left	Down	5000	3-5 kts/s
40	Down	On	FOF	Right	Down	5000	3-5 kts/s

Table 18 lists the test points for post-stall controllability. The pilots were instructed to center the ball during the entire entry. When stall was achieved, the pilots were instructed to initially achieve 15° of bank in either direction while the control column remained at the aft limit. Then the pilots were instructed to achieve 30° of bank in both directions with the control remaining at the aft limit. Achieving and maintaining ±30° of bank angle accomplished the task and passed the test point.

Table 18. Test points for post-stall controllability (bank-to-bank)

No.	Flaps	Power	Direction	Gear	Altitude [ft]	Bleed rate
41	Up	Off	Straight	Down	5000	1 kt/s
42	Down	Off	Straight	Down	5000	1 kt/s
43	Up	On	Straight	Down	5000	1 kt/s
44	Down	On	Straight	Down	5000	1 kt/s

Table 19 lists the test points for abused-entry, turning stall characteristics. Once the airplane was trimmed, the pilots were instructed to enter a turn with 30° of bank. Once established in the turn, the pilots were instructed to achieve either a 1-ball displacement or ½ rudder pedal displacement (whichever occurred first), then freeze that rudder pedal displacement for the remainder of the stall entry. When stall was achieved, the pilot could use all means necessary to keep the bank angle within the following limits:

- For 1 kt/s entry with $\phi = 30°$: $-30° \leq \phi_{max} \leq 60°$.
- For 1 kt/s entry with $\phi = -30°$: $-60° \leq \phi_{max} \leq 30°$.
- For 3-5 kts/s entry with $\phi = 30°$: $-60° \leq \phi_{max} \leq 90°$.
- For 3-5 kts/s entry with $\phi = -30°$: $-90° \leq \phi_{max} \leq 60°$.

If the bank angle exceeded these limits (or the pilot "knocked-it-off" prior to a limit for safety concerns), the test point was scored as a fail.

Table 19. Test points for abused-entry, turning stall characteristics (30° bank)

No.	Flaps	Power	Direction	Rudder or Ball	Gear	Altitude [ft]	Bleed rate
45	Up	Off	Left	½ rudder or 1-ball left	Down	5000	1 kt/s
46	Up	Off	Right	½ rudder or 1-ball left	Down	5000	1 kt/s
47	Up	Off	Left	½ rudder or 1-ball right	Down	5000	1 kt/s
48	Up	Off	Right	½ rudder or 1-ball right	Down	5000	1 kt/s
49	Down	Off	Left	½ rudder or 1-ball left	Down	5000	1 kt/s
50	Down	Off	Right	½ rudder or 1-ball left	Down	5000	1 kt/s
51	Down	Off	Left	½ rudder or 1-ball right	Down	5000	1 kt/s
52	Down	Off	Right	½ rudder or 1-ball right	Down	5000	1 kt/s
53	Up	Off	Left	½ rudder or 1-ball left	Down	5000	3-5 kt/s
54	Up	Off	Right	½ rudder or 1-ball left	Down	5000	3-5 kt/s
55	Up	Off	Left	½ rudder or 1-ball right	Down	5000	3-5 kt/s
56	Up	Off	Right	½ rudder or 1-ball right	Down	5000	3-5 kt/s
57	Down	Off	Left	½ rudder or 1-ball left	Down	5000	3-5 kt/s
58	Down	Off	Right	½ rudder or 1-ball left	Down	5000	3-5 kt/s
59	Down	Off	Left	½ rudder or 1-ball right	Down	5000	3-5 kt/s
60	Down	Off	Right	½ rudder or 1-ball right	Down	5000	3-5 kt/s
61	Up	On	Left	½ rudder or 1-ball left	Down	5000	1 kt/s
62	Up	On	Right	½ rudder or 1-ball left	Down	5000	1 kt/s

No.	Flaps	Power	Direction	Rudder or Ball	Gear	Altitude [ft]	Bleed rate
63	Up	On	Left	½ rudder or 1-ball right	Down	5000	1 kt/s
64	Up	On	Right	½ rudder or 1-ball right	Down	5000	1 kt/s
65	Down	On	Left	½ rudder or 1-ball left	Down	5000	1 kt/s
66	Down	On	Right	½ rudder or 1-ball left	Down	5000	1 kt/s
67	Down	On	Left	½ rudder or 1-ball right	Down	5000	1 kt/s
68	Down	On	Right	½ rudder or 1-ball right	Down	5000	1 kt/s
69	Up	On	Left	½ rudder or 1-ball left	Down	5000	3-5 kt/s
70	Up	On	Right	½ rudder or 1-ball left	Down	5000	3-5 kt/s
71	Up	On	Left	½ rudder or 1-ball right	Down	5000	3-5 kt/s
72	Up	On	Right	½ rudder or 1-ball right	Down	5000	3-5 kt/s
73	Down	On	Left	½ rudder or 1-ball left	Down	5000	3-5 kt/s
74	Down	On	Right	½ rudder or 1-ball left	Down	5000	3-5 kt/s
75	Down	On	Left	½ rudder or 1-ball right	Down	5000	3-5 kt/s
76	Down	On	Right	½ rudder or 1-ball right	Down	5000	3-5 kt/s

Table 20 lists the test points for longitudinal control force after flap extension. The pilots were instructed to stabilize the aircraft in level flight at maximum flaps-extended airspeed (V_{FE}), and then extend the flaps to the first flap setting listed while maintaining altitude. After re-trimming for level flight, the pilots were instructed to move the flaps to the second setting listed, hold altitude, and measure the control force.

Table 20. Test points for longitudinal control force after flap extension

No.	Flaps	Gear	Min Altitude [ft]
1	0 to 1	Down	2000
2	1 to 2	Down	2000
3	2 to 3	Down	2000
4	0 to 3	Down	2000

Table 21 lists the test points for longitudinal control force after simulated go-around. The pilots were instructed to achieve approach airspeed (V_{APP}) at the first flap setting listed. Then, pilots were instructed to increase power to takeoff power setting, move the flaps to the second setting listed, hold altitude, accelerate in level flight to V_Y, then maintain V_Y and measure the control force.

Table 21. Test points for longitudinal control force after go-around

No.	Flaps	Gear	Min Altitude [ft]
5	3 to 2	Down	2000
6	2 to 1	Down	2000
7	1 to 0	Down	2000
8	3 to 0	Down	2000

Table 22 lists the test points for free response after flap extension. The pilots were instructed to trim for level flight at the maximum flaps-extended airspeed (V_{FE}) at the first flap setting listed. Then, the pilots had to move the flaps to the second setting listed, and observe the free response.

Table 22. Test points for free response after flap extension

No.	Flaps	Gear	Min Altitude [ft]
9	0 to 1	Down	2000
10	1 to 2	Down	2000
11	2 to 3	Down	2000
12	0 to 3	Down	2000

Table 23 lists the test points for free response after go-around. The pilots were instructed to achieve approach airspeed (V_{APP}) and 3° flight path angle at the first flap setting listed. Then, the pilots had to increase power to takeoff power setting, move the flaps to the second setting listed, and observe the free response.

Table 23. Test points for free response after go-around

No.	Flaps	Gear	Min Altitude [ft]
13	3 to 2	Down	2000
14	2 to 1	Down	2000
15	1 to 0	Down	2000
16	3 to 0	Down	2000

4.2.2 Schedule and flight log

The test flights were executed in the periods 2-9 March 2018 and 21-28 June 2018 at the facilities of FIT Aviation at Orlando-Melbourne International Airport (KMLB). The flights involved one test pilot and two flight test engineers (FTE) from FIT and two test pilots and two FTEs from the FAA. The six aircraft and their experienced pilots-in-command (PIC) were drawn from FIT Aviation and other local flight-training providers. The original test plan called for all three test pilots flying each aircraft at least once, but that was not possible due to the compressed schedule, pilot availability, and aircraft availability. In total, 28 test flights for 47.2 hours were flown.

Table 24 and Table 25 show the flight log for the program. In order not to directly connect the results of this study with specific aircraft manufacturers and types, the six aircraft are labelled A – F in random order. The different test pilots are indicated with the letters P1, P2, and P3.

Table 24. Flight log, 2-9 March 2018

Aircraft	03/02/2018	03/05/2018	03/06/2018	03/07/2018	03/08/2018	03/09/2018
Aircraft A (5.9 hr)	1: 1.5 hr (P1) 2: 1.5 hr (P1)		3: 1.5 hr (P1) 4: 1.4 hr (P1)			
Aircraft B (2.4 hr)					1: 1.2 hr (P3) 2: 1.2 hr (P3)	
Aircraft C (10.7 hr)			1: 1.7 hr (P2) 2: 1.7 hr (P2)	3: 1.7 hr (P2) 4: 1.7 hr (P2)	4: 1.7 hr (P2) 5: 1.1 hr (P2)	6: 1.1 hr (P3)
Aircraft D (7.1 hr)				1: 2.0 hr (P1)	2: 2.0 hr (P1)	3: 2.0 hr (P1) 4: 1.1 hr (P3)
Aircraft E (3.3 hr)		1: 1.7 hr (P3) 2: 1.6 hr (P3)				
Aircraft F (3.1 hr)		1: 1.6 hr (P1) 2: 1.5 hr (P1)				

Table 25. Flight log, 21-28 June 2018

Aircraft	06/21/2018	06/22/2018	06/23/2018	06/25/2018	06/26/2018	06/27/2018	06/28/2018
Aircraft A	Not flown						
Aircraft B (7.1 hr)				1: 2.3 hr (P1)	2: 2.5 hr (P1)	3: 2.3 hr (P1)	
Aircraft C	Not flown						
Aircraft D (1.7 hr)							1: 1.7 hr (P1)
Aircraft E (4.2 hr)	1: 1.2 hr (P1)	2: 1.5 hr (P1)	3: 1.5 hr (P1)				
Aircraft F	Not flown						

4.3 Stall characteristics

The stall characteristics test score for the aircraft was calculated from the number of test points passed, normalized over the total number of test points, 76. The perfect test score would be 100%, indicated as a score of 100. If an aircraft is not equipped with flaps, such as aircraft F, the total score was normalized over the modified total of 38, also resulting in a maximum score of 100.

Table 26 shows the number of passed test points for each general entry condition, not differentiating between wings-level and turning flight. Of note is the low number of flight hours for aircraft B and aircraft E, which did not permit all test points to be completed, thus resulting in low stall characteristics scores. It is expected that the scores for these two aircraft will improve after more flights are accomplished at a later date.

Table 26. Summary of stall characteristics results

Airplane	Flights	Hours	Coordinated 20 pts	Feet-on-floor		Post-Stall 4 pts	Abused 32 pts	Total Points	Test Score
				Pwr off	Pwr on				
F	2	3.1	10	5	5	0	16	36	95[1]
A	4	5.9	20	10	7	1	32	70	92
D	5	8.8	18	10	8	2	9[2]	47	62
C	7	12.4	20	10	10	0	7	47	62
B	5	9.5	20	10	9	0	4	43	57
E	5	7.5	17	10	10	0	1	38	50

[1] Since aircraft F has no flaps, only half the test points have to be flown.

[2] Only unaccelerated abused stalls were flown

The stall characteristics test score is based on two types of failure. In a Type-I failure, the aircraft pitch and roll attitude exceeded the acceptable limits for the particular stall case, based on the current airworthiness certification standards spelled out in FAR Part 23 Amendment 62 [11]. In a Type-II failure, the test pilot, PIC, or FTE aborted the test due to safety reasons, but without the aircraft violating the certification standards. Therefore, a Type-I failure would actually represent a test point failure in a certification campaign. Type-II failures are particular to the experiment procedures and do not permit any conclusions about the stall characteristics of an aircraft. Each airplane had test point failures, sometimes Type-I and Type-II in combination.

Two examples are provided. The first is an attempt to pass test point 23 with aircraft D, shown in Figure 32. The test point was a wings-level, power-on stall with feet-on-the-floor and a 1 kt/s bleed rate. The pilot was unable to keep the airplane from rolling more than 15°, which is a Type-I failure. In addition, the pilot also aborted the test due to an excessive roll rate of 40°/s, which elicited a Type-II failure.

The second example is an attempt to pass test point 57 with aircraft C, shown in Figure 33. This was an abused-entry, flaps-down, power-off, left turn, left rudder stall with a bleed rate of 3-5 kts/s. The pilot aborted the maneuver prior to the 90° limit, because the roll-rate would have caused the airplane to become inverted. This is a pure Type-II failure.

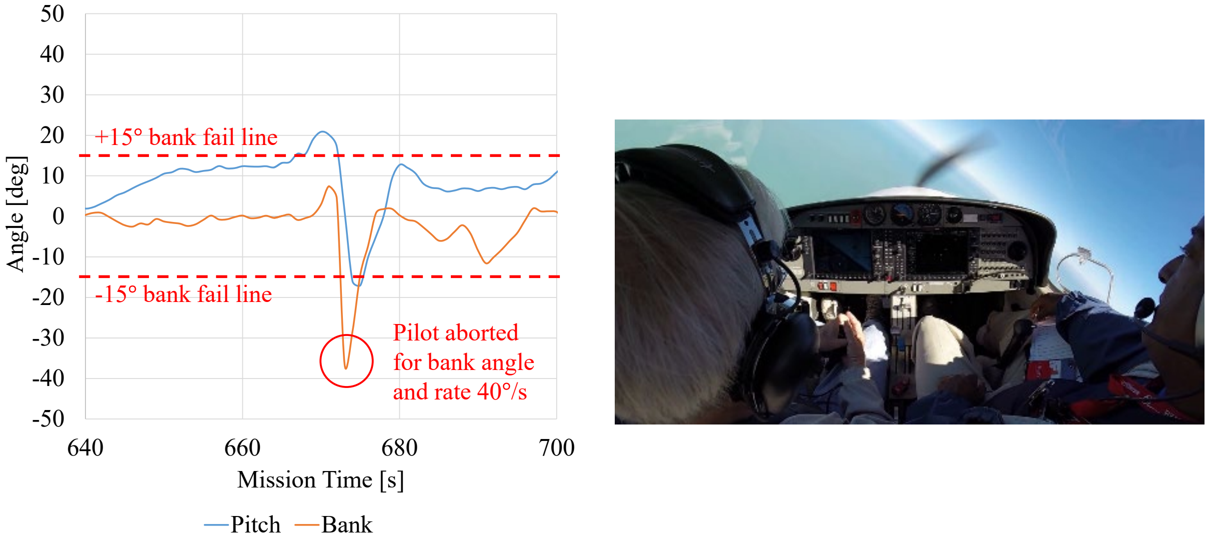


Figure 32. Example test point scored as a fail for aircraft D

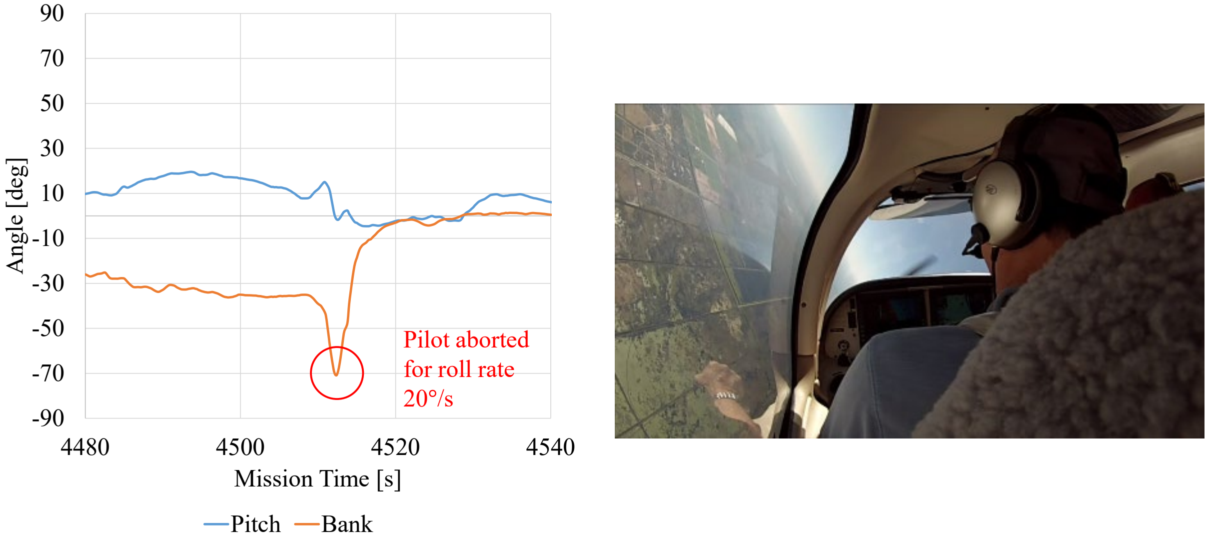


Figure 33. Example test point scored as a fail for aircraft C

5 Airplane response to configuration changes

5.1 Configuration change effects as possible contributor to loss of control

Whereas stall characteristics are only relevant once the stall happens, changes to the configuration change response can act upstream of the stall and actually prevent stalls and LOC accidents. Configuration changes (i.e. extending and retracting flaps) during approach and go-arounds cause significant changes in longitudinal trim forces and abrupt pitching motion with large magnitude. The magnitude of the control force changes and the direction and magnitude of the free response motion are driven by the wing and tail design of the aircraft.

Downwash from the main wing alters the effective angle of attack on the horizontal tail. As shown in Figure 34, airspeed dictates how much downward tail load is necessary for balanced flight (zero pitch rate). To achieve the required downward tail load, the horizontal tail must adjust its angle of attack (stabilator) or camber (elevator) based on the airflow it experiences from the downwash of the main wing. If the horizontal tail is not in the downwash (e.g. T-tail), then the angle of attack it sees is based on the freestream air.

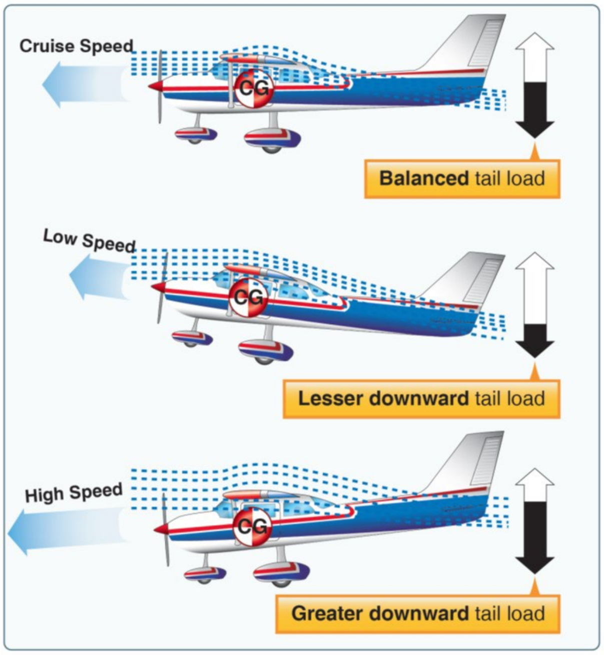


Figure 34. The effects of downwash from the main wing on the horizontal tail [27]

When flaps are extended, the main wing camber (along the length of the flaps) is increased. Aerodynamically, this increase in camber should result in a nose-down pitching moment. This would increase the required downward tail load for balanced flight. The increased camber of the main wing could also alter the effective angle of attack experienced by the horizontal tail. That is, the downwash angle could increase, thereby increasing the effective negative angle of attack on the horizontal tail. This situation would assist the horizontal tail in providing some additional downward tail load without having to change its position. However, it would likely not be the exact amount required, and the horizontal tail would have to change its position.

Vortices are another aerodynamic effect that can alter the airflow experienced at the horizontal tail. Typically, vortices are thought of as a wingtip phenomenon as shown in Figure 35.

However, when flaps are extended, vortices are shed at the “flap tips” just like a wingtip. The location of a flap tip dictates how much the vortices impact the horizontal tail.

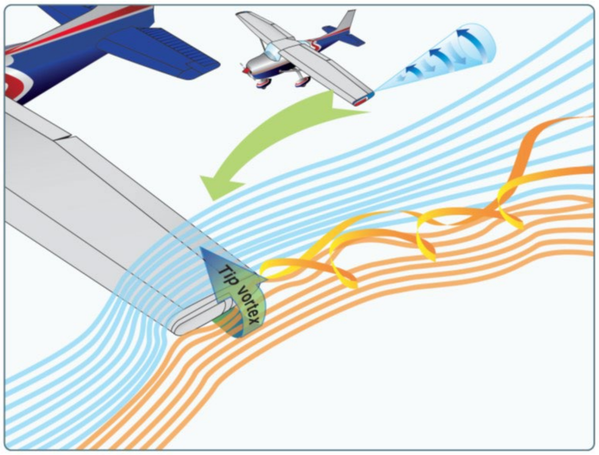


Figure 35. Tip vortices [27]

To visualize the possible impact flap-tip vortices can have on the horizontal tail, consider some typical geometries used in general aviation. Figure 36 shows two low-wing airplanes with conventional tails. Airplane I has the inboard flap tip flush with the fuselage. It is assumed the fuselage will nullify any vortices caused by the inboard flap tip. The outboard flap tip, however, has nothing to impede the vortex. If large enough, the vortex could impact the horizontal tail as shown. This would result in an even larger negative angle of attack seen by the horizontal tail (in addition to downwash), possibly resulting in a substantial downward tail load. The overall effect could be a nose-up pitching moment. Airplane II in Figure 36 has the inboard flap tip displaced from the fuselage. The vortex generated by the inboard flap tip would circulate in the opposite direction as the outboard flap tip. Since the fuselage is nearby, the strength of the vortex for the inboard flap tip should be lower than outboard flap tip. The side views in Figure 36 show how downwash may impact the horizontal tail. Figure 37 shows how flap-tip vortices and downwash impact the horizontal tail for a high-wing airplane with a conventional tail (Airplane III). For Airplane IV in Figure 37, the flap tip is far enough outboard that the vortex does not impact the horizontal tail. Airplane IV’s horizontal tail is also mounted higher on the fuselage (just on the upper edge of the downwash). This would change at higher main-wing angle of attack.

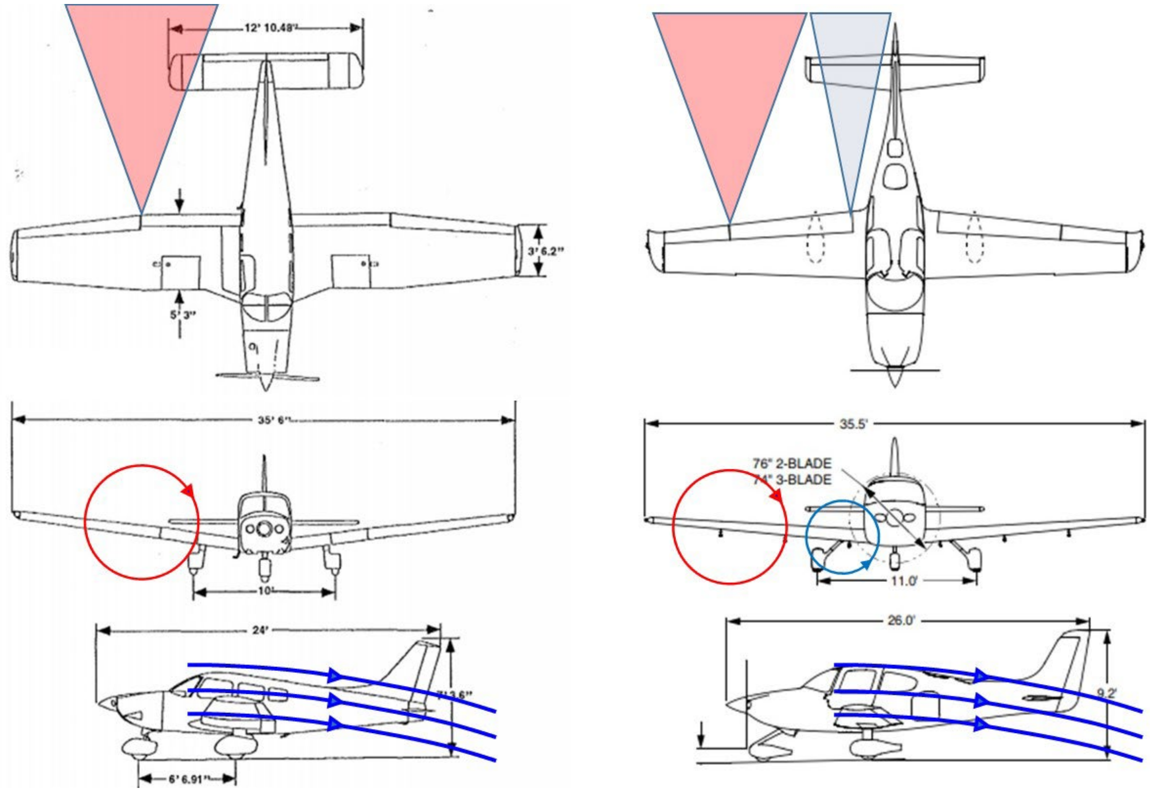


Figure 36. Airplane I (left) and Airplane II (right)

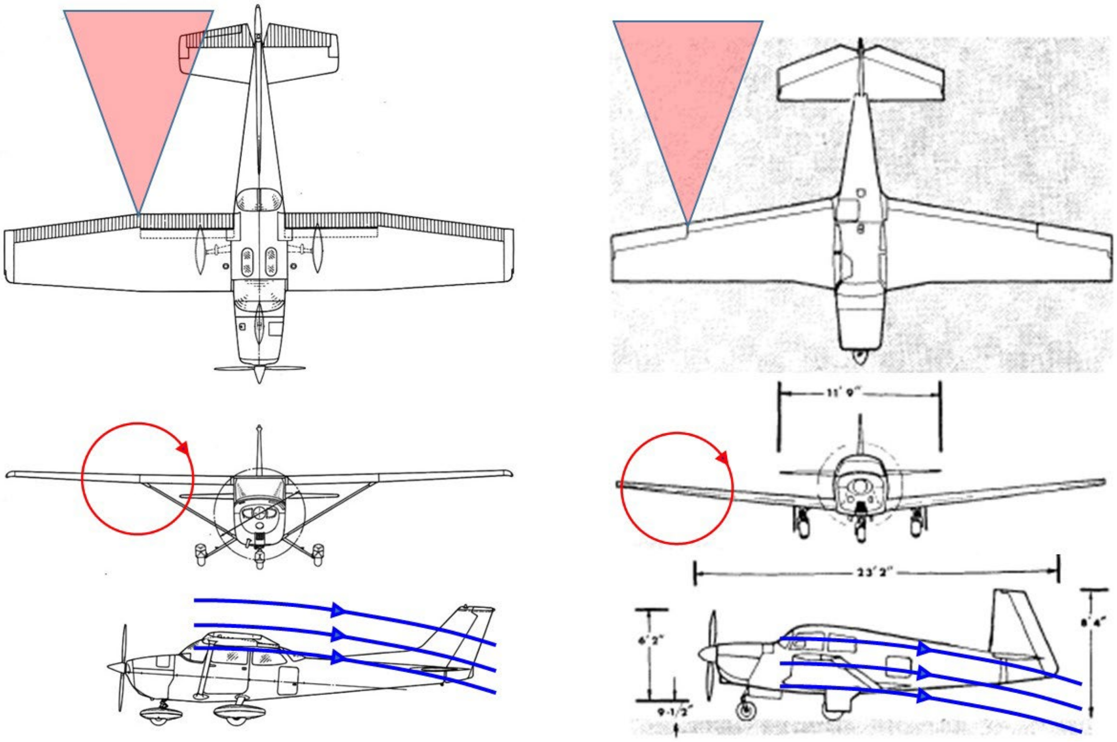


Figure 37. Airplane III (left) and Airplane IV (right)

Figure 38 shows a low-wing airplane with a T-tail (Airplane V). Like Airplane IV, the vortex from the outboard flap tip doesn't impact the horizontal tail. Neither does the vortex from the inboard flap tip, since the horizontal tail is higher up in the air flow. In fact, the main wing downwash does not really impact the horizontal tail (at least at low main-wing angle of attack).

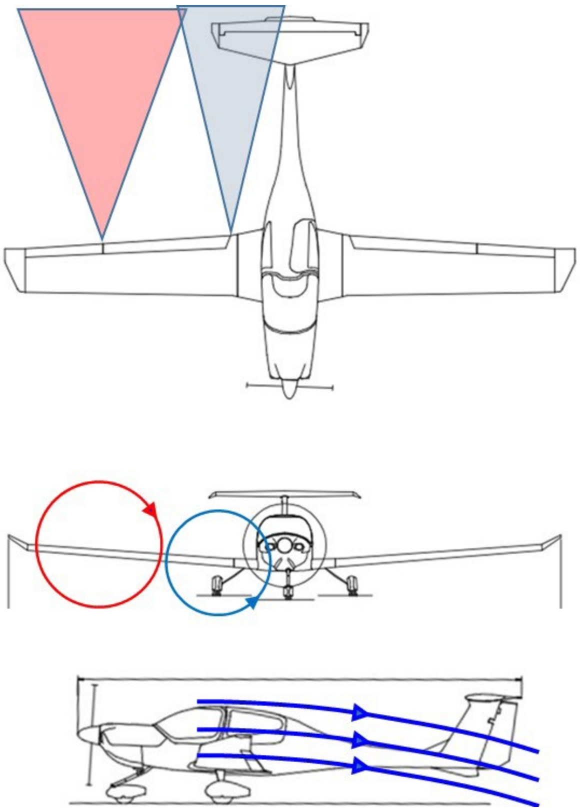


Figure 38. Airplane V

These illustrations are designed to provide qualitative explanations for why an airplane either pitches noseup or nosedown after extending the flaps. Obviously, airspeed, power setting, and main-wing angle of attack are factors that could either enhance or diminish these effects.

Ideally, a pilot should be able to extend the flaps and have the airplane remain in balance (zero pitch rate). If the effects of downwash and flap-tip vortices is quantified and repeatable for a given airplane geometry (e.g. Airplane I), then a flap-elevator interconnect or flap-trim tab interconnect could be added to nullify the effects.

The effects of downwash and flap-tip vortices discussed above have been for flap extension. The opposite effects should occur if retracting flaps from a balanced flight condition. In both cases (extension and retraction), consideration for power effects must also be done. The go-around scenario (typically within feet of the ground) involves adding full power *and* retracting flaps.

5.2 Trim force changes

The longitudinal control forces during configuration changes, i.e. flap extension, were measured with the hand-held force gauge shown in Figure 31. The gauge was placed between the hand of the pilot and the yoke or control stick. Reading off the dial, the test pilot called out the highest force measurement and the FTE noted it in the flight cards. Variability due to pilot technique was not accounted for. Note that no data is available for aircraft F, as the aircraft is not equipped with flaps. Figure 39 shows the maximum observed stick forces during simulated approaches and go-arounds.

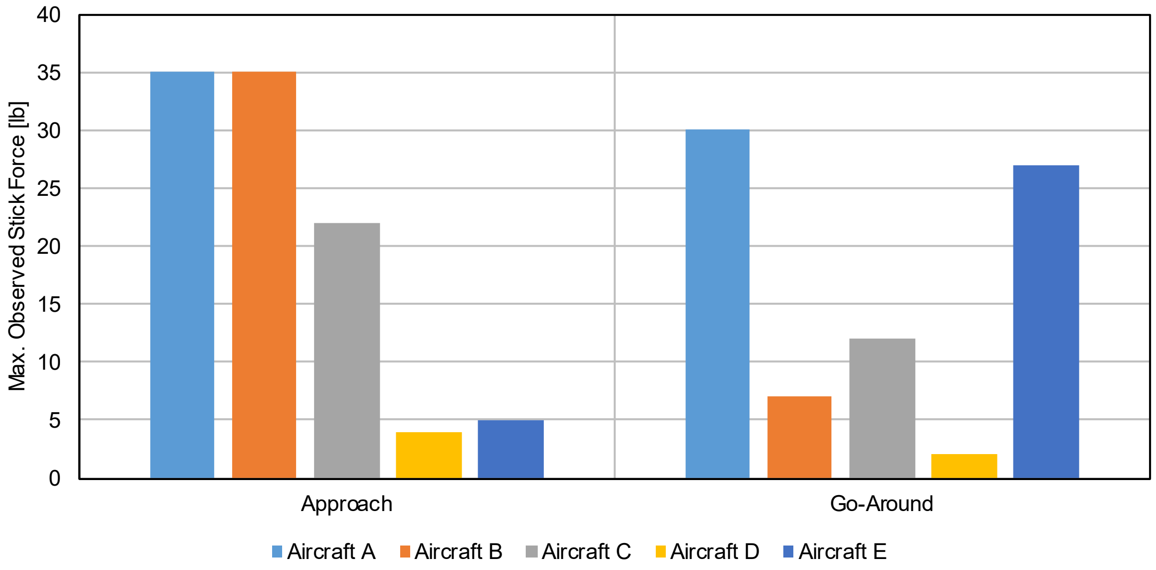


Figure 39. Longitudinal force data for simulated approaches and go-arounds

5.3 Free aircraft response

The magnitude of the free pitch response of the aircraft during and directly after configuration change was also recorded by the FTE. The time it took the aircraft to reach maximum response were recorded in-flight by the FTE and later compared against the flight data acquired from the Stratus 2S AHRS, G5, or G1000. The magnitude of the free response depends on the flap setting. Figure 40 shows this for the example of aircraft B. As can be seen, the larger the change in flap setting, the higher the free response pitch. To be able to compare the free response of different aircraft, the response to a quick change in flap setting from zero to full was tested for both extending the flaps during approach and retracting the flaps during go-arounds. The results are summarized in Table 27.

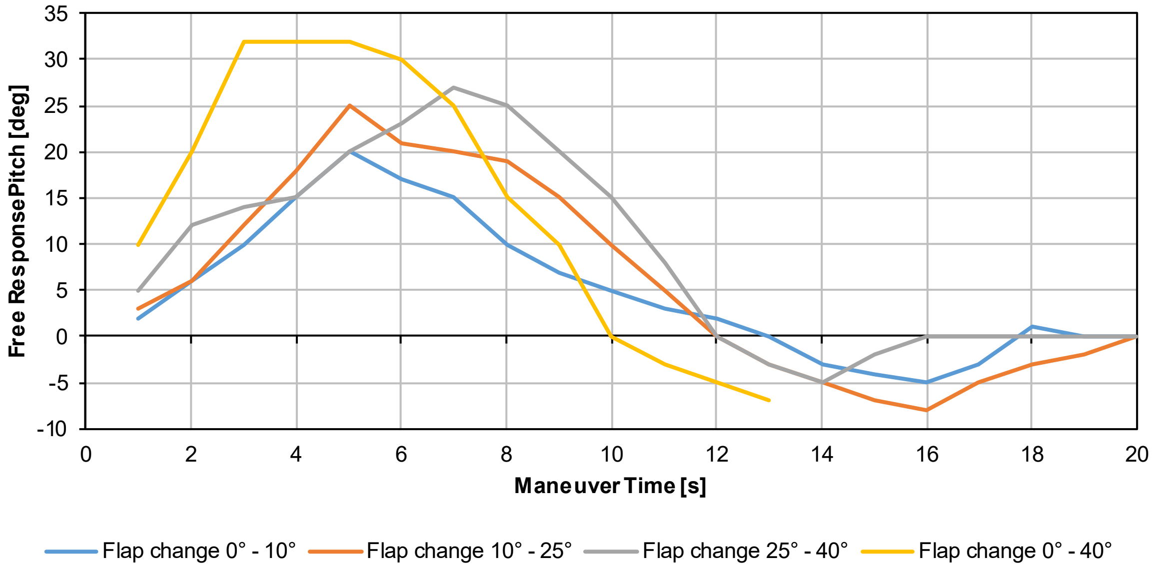


Figure 40. Aircraft B free response pitch for different flap configurations

Table 27. Control forces and pitching motion for simulated approaches and go-arounds

Aircraft	Approach			Go Around		
	Max. stick force [lb]	Free response		Max. stick force [lbs]	Free response	
		Max. pitch [°]	Time to max. [s]		Max. pitch [°]	Time to max. [s]
A	35	+25	2	30	-10	2
B	35	+32	5	7	-15	5
C	22	+35	2	12	+10	10
D	4	+12	5	2	+15	15
E	5	-3	2	27	+25	3
F	n/a	n/a	n/a	n/a	n/a	n/a

The next two figures show the impact of required trim force on free response. Figure 41 shows free-response pitch attitude versus time. Forces above 30 pounds result in pitch attitudes above 30° in less than 5 seconds. Figure 42 shows free-response airspeed versus time. As one would surmise, the high pitch attitudes from Figure 41 result in low airspeeds in Figure 42. Pilots intervened to prevent stalls. However, had they not intervened, those airplanes would have stalled. The scenario involving a pilot flying in the traffic pattern who becomes distracted, abruptly extends flaps while looking outside the airplane, and fails to notice airspeed and pitch-attitude is likely to occur. The airplane free response should not add to the problem.

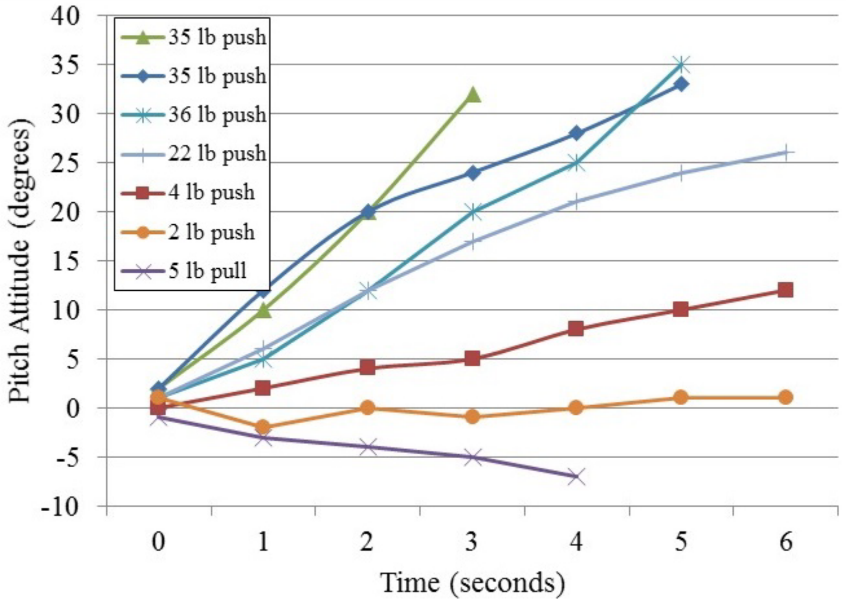


Figure 41. Free response pitch for different required trim forces

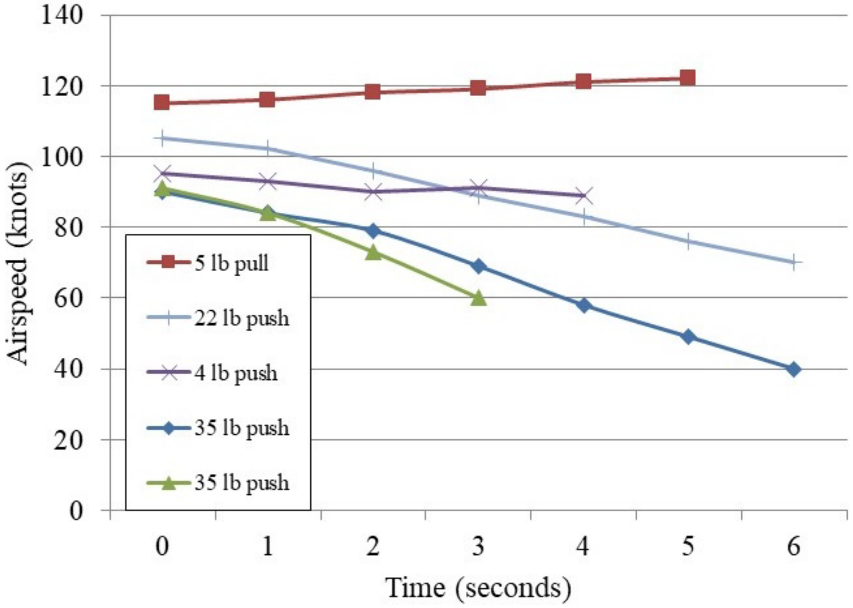


Figure 42. Free response airspeed for different required trim forces

6 Initial quantification of specific excess power P_S

The concept of “Enhanced Envelope Awareness,” which starts informing the pilot about the aircraft’s energy state well in advance of an impending stall of controlled flight into terrain, is important to consider. Making the pilot aware of an aircraft’s current energy state, the amount of excess power available, and the control inputs needed to transition to a "healthy" energy state prior to stalling or flying into the ground has the potential to prevent fatalities.

As Detwiler stated, "Energy management was a lesson learned the hard way for we young fighter pilots during the Vietnam War." [28] This growing awareness to the importance of aircraft energy management led to the creation of the Navy's "Top Gun" program and Air Force energy management training. Detwiler stated, "How were we to get to that higher energy state if we were slow? We were taught to roll off, go to zero G, light the afterburners and basically head for the ground. By going to zero G, there was no lift being produced. Without lift, there is zero induced drag. The only drag on the aircraft at the initiation of this maneuver was the relatively low parasite drag. If you did that with 34,000 pounds of thrust and gravity aiming you at terra firma, airspeed came back fast, real fast. If you ran out of kinetic energy (airspeed), or couldn't get it back fast enough, you had better have lots of potential energy (altitude above your adversary) or you might not be drinking at the bar that night." [28]

While this fighter pilot story may not directly apply to GA aircraft, the basic idea to unload, roll wings-level, and add power helps any aircraft get to a "healthier" energy state. Studying the specific excess power (P_s) data of one's own aircraft as well as an adversary aircraft is a fundamental part of Top Gun and the Air Force Weapons School. The question motivating the study presented in this paper was: Could a similar study of P_s data help the GA pilot? To answer that question, a complete set of flight data was needed.

Data were recorded from the production instruments. The aircraft were flown with three people on board and full fuel. No measures were taken to achieve a specific weight or center-of-gravity location by adding ballast. All aircraft were flown from the Orlando-Melbourne International Airport (KMLB). Sea level temperatures for all flights were above standard, between 85° F and 90°F. The P_s curves shown in Figure 43 through Figure 47 were generated using the level acceleration curve. The left anchor of the curve is power-on stall speed (V_{s1}). Level accelerations were accomplished at a pressure altitude of 3000 ft. For this experiment, altitude remained within ±50 ft throughout all of the level accelerations. The level accelerations were flown to maximum level flight speed (V_h), forming the right anchor of the curves. A cell phone camera was used to record the cockpit gauges. During data analysis, the video was paused at one-second increments to record airspeed and altitude. The data were then tabulated in a spreadsheet for each aircraft. Polynomial curve fits were applied to the indicated airspeed versus time data. Derivatives of each curve fit equation were taken to get $\dot{V}$ at each time step, which corresponded to a given airspeed. The standard equation for calculating P_s is listed below.

$$P_s = \frac{dh}{dt} + \frac{V}{g} \cdot \frac{dV}{dt} \tag{6}$$

As the flight altitude was held within tight bounds, dh⁄dt can be assumed to be zero during a level acceleration. The ranking of aircraft according to P_s is not important for the scope of this study. Therefore, the results are presented in terms of generic aircraft designation (i.e. Aircraft A, B, C, D, and E).

From the tabulated P_s data collected for each aircraft, plots of P_s versus calibrated airspeed were generated. Power-on stall speeds and maximum level flight speeds were used to shape the final curve fits. With a P_s plot, one can determine the maximum P_s available along with the associated speed, which can be interpreted as the maximum rate-of-climb speed (V_y). Figure 43 through Figure 47 show the P_s plots for each of the five aircraft individually. Figure 48 shows the P_s plots for all five aircraft on the same plot.

When viewing Figure 43 through Figure 47, the reader should compare and contrast power-on stall speeds, maximum P_s, maximum rate-of-climb speed, the range of speed where $P_s \geq 200\ \text{ft/min}$, and maximum level flight speed. The same x and y scales are used in Figure 43 through Figure 47 to aid with the comparisons. Discrete data points are shown with symbols, and curve fits are shown with continuous lines. The same color assigned to each aircraft plot is used in the composite plot in Figure 48. Finally, the aircraft have differences in weight, wing span, and engine power. One of the aircraft flew with the gear retracted. Nonetheless, interesting features do emerge.

Figure 43 shows P_s versus calibrated airspeed for Aircraft A. Power-on stall speed was V_{s_1}= 57 kts. The maximum P_s was 740 ft/min at V_y= 90 kts. The maximum level flight speed was V_h= 128 kts.

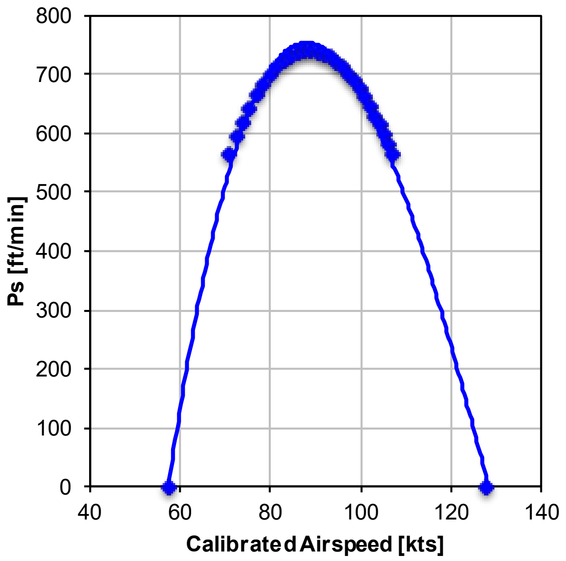


Figure 43. Specific excess power plot for Aircraft A

Figure 44 shows P_s versus calibrated airspeed for Aircraft B. Power-on stall speed was V_{s_1}= 50 kts. The maximum P_s was 420 ft/min at V_y= 90 kts. The maximum level flight speed was V_h= 119 kts.

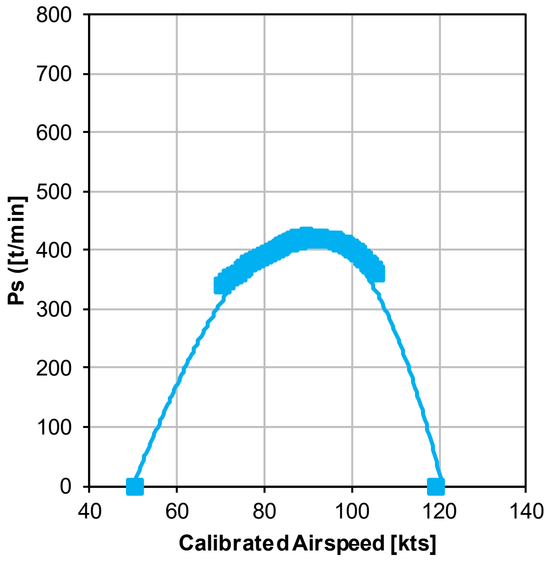


Figure 44. Specific excess power plot for Aircraft B

Figure 45 shows P_s versus calibrated airspeed for Aircraft C. Power-on stall speed was V_{s_1}= 49 kts. The maximum P_s was 745 ft/min at V_y = 97 kts. The maximum level flight speed was V_h= 139 kts.

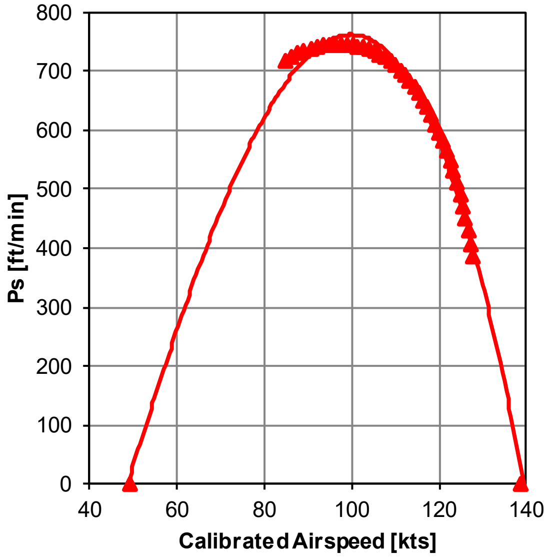


Figure 45. Specific excess power plot for Aircraft C

Figure 46 shows P_s versus calibrated airspeed for Aircraft D. Power-on stall speed was V_{s_1}= 66 kts. The maximum P_s was 431 ft/min at V_y= 87 kts. The maximum level flight speed was V_h= 138 kts

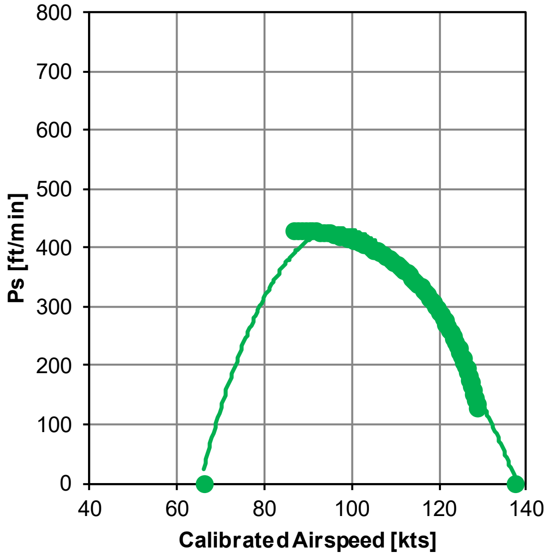


Figure 46. Specific excess power plot for Aircraft D

Figure 47 shows P_s versus calibrated airspeed for Aircraft E. Power-on stall speed was V_{s_1}= 46 kts. The maximum P_s was 389 ft/min at V_y= 87 kts. The maximum level flight speed was V_h= 113 kts.

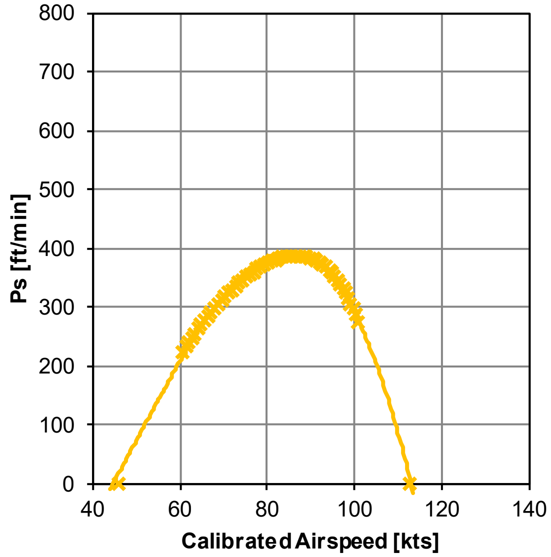


Figure 47. Specific excess power plot for Aircraft E

Figure 48 shows P_s versus calibrated airspeed for all five aircraft. The same color schemes used in Figure 43 through Figure 47 are applied in Figure 48. Two of the aircraft (A and C) stand out from the group. One of those flew with retracted gear.

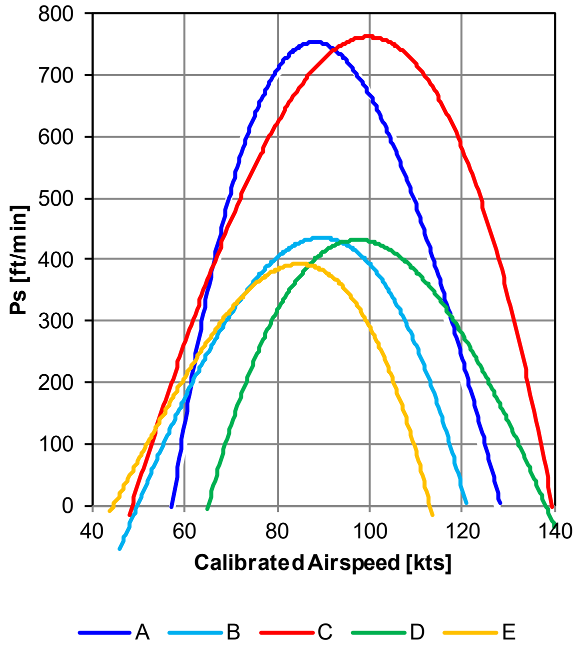


Figure 48. Specific excess power plot for all five aircraft

Four of the aircraft have power-on stall speeds below 58 kts. Aircraft D has a power-on stall speed nearly 10 kts greater. If an algorithm was developed using 55 or 60 kts as a tripping point, it would work pretty well for all but Aircraft D.

All of the aircraft can achieve a P_s of at least 400 ft/min. An algorithm could use 400 ft/min in the logic for maximum P_s. The maximum rate-of-climb speeds are actually in a fairly tight range of 87 to 97 kts. Considering the flatness of the curve for Aircraft C, 97 kts could be replaced by 90 kts with only a 10 ft/min penalty. Therefore, a "global" speed of 90 kts seems to work for maximum rate-of-climb speed for any of the five aircraft.

Table 28 shows the range of speed where $P_s \geq 200$ ft⁄min for each aircraft, along with the $\pm$ delta speed (ΔV) from 90 kts. Once again, Airplane D stands out on the low speed limit with V = 72 kts. Airplane E stands out on the high speed limit. One could envision an algorithm that uses a speed range of 70 to 110 kts as a "healthy" region for P_s. This is ± 20 kts from 90 kts chosen above for a "global" speed for maximum rate-of-climb. If Airplane D is omitted, the range could be expanded to 60 to 120 kts (±30 kts from 90 kts) as a "healthy" region for P_s.

Table 28. Range of speed where specific excess power is over 200 ft⁄min

Aircraft	Speed Range [kts]	90 kts $\pm\Delta v$ [kts]
A	60 to 122	30
B	60 to 115	25
C	55 to 135	35
D	72 to 125	18
E	57 to 105	15

With respect to maximum level flight speeds, there is less of a common trend. Aircraft C and Aircraft D have nearly the same V_h. Using the "speed is life" saying, all five aircraft have plenty of kinetic energy at their respective V_h speeds. The differences among the aircraft come down to the nuances in the designs (horsepower, wing span, aerodynamics, weight, metal vs composite, etc.). If Aircraft E is omitted, assuming V_h= 130 kts works to within ±10 kts of the other four aircraft. Overall, the data gathered in this section is valuable for the development of GA energy state warning systems and energy state management systems that could potentially contribute to an increase in GA safety.

7 Discussion of test results and means of compliance

Empirical data derived from actual flight test data of GA aircraft is essential for the formulation of new Part 23 airworthiness standards and the associated means of compliance. To reduce the cost and effort of the certification process, the number of test points to be flown should be minimized. More analysis is needed to eliminate non-critical conditions and to focus certification flight testing on test points most conducive to LOC. Another focus of means of compliance development should be on reducing pilot variability and thus increasing the repeatability of test cases. The feet-on-the-floor entry condition introduced in this paper shows promise to accomplish that.

Aircraft certification should also include more than the un-augmented stall characteristics. At a minimum, the longitudinal control forces and free pitching response caused by configuration changes should be accounted for in an aircraft's airworthiness certification score. In addition, cockpit design, control location and dynamics, as well as trim speeds can have major impact on aircraft handling qualities. An airplane can meet all the numbers, achieve a high certification score, and still be difficult to deal with from a pilot's perspective. Future research should produce quantitative data on the effects of these design characteristics and recommend scoring methods and scoring weights to contribute to the overall airworthiness score. Some flight testers also commented on the "startle factor" of different stall characteristics, with a hypothesis that high velocity-vector roll rates (combined roll and yaw rate) at the stall might induce a panic reaction in an unsuspecting pilot; further research is warranted as to whether such parameters could be useful for future standards and means of compliance.

The research presented in this report was limited to single-engine aircraft. The FIT researchers suggest that a future program involving light twin-engine aircraft be accomplished to produce the required data for the certification knowledge-base.

Assuming a score-based certification method were to be applied, the six aircraft tested in this flight test campaign would perform as illustrated in Figure 49. Aircraft A and F could be certified with a simple audio AOA warning system, aircraft D would require the addition of a visual warning indicator, aircraft B and C a stick shaker, and the aircraft E a stall barrier, typically a stick pusher. There can be other devices that are just as effective along the x-axis of the plot that are not being considered in this paper. The examples listed here serve to illustrate the process as a notional starting point. Care must be taken not to ignore the opinion of the test pilots when assigning the overall certification score based on this method. Namely, the test pilot's opinion of the plane's handling qualities (based on no unusual skill, strength or alertness) during slow-speed flight, stalls and configuration changes. An airplane can meet all the numbers, achieve a high score, and still be difficult to deal with from a pilot's perspective. Potentially, test pilots could scale the final certification score based on their handling qualities assessment. However, this may conflict with the concept of a deterministic path towards aircraft certification.

Note that there are two major caveats to the airworthiness certification score chart presented in Figure 49: (1) the current ranking of the effectiveness of stall warning and prevention systems is purely qualitative, as no quantitative data yet exists; (2) the stall characteristics scores presented here also include Type-II test failures that do not actually fail any airworthiness certification criteria.

The overall picture changes substantially when the configuration change score is taken into consideration, as shown in Table 29. A combined weighted average score based 75% on the stall characteristics score and 25% on the configuration change score is proposed. These weights can be reassessed based on future flight data and/or pilot opinion. Applying the score-based safety evaluation would lead to the aircraft performance illustrated in Figure 50.

Table 29. Combined aircraft airworthiness score

Aircraft	**Stall Characteristics Score (75%)**	**Configuration Change Score (25%)**	**Total Safety Score**
F	97	n/a	97
D	80	83	81
A	93	17	74
E	49	88	59
B	62	33	55
C	54	29	48

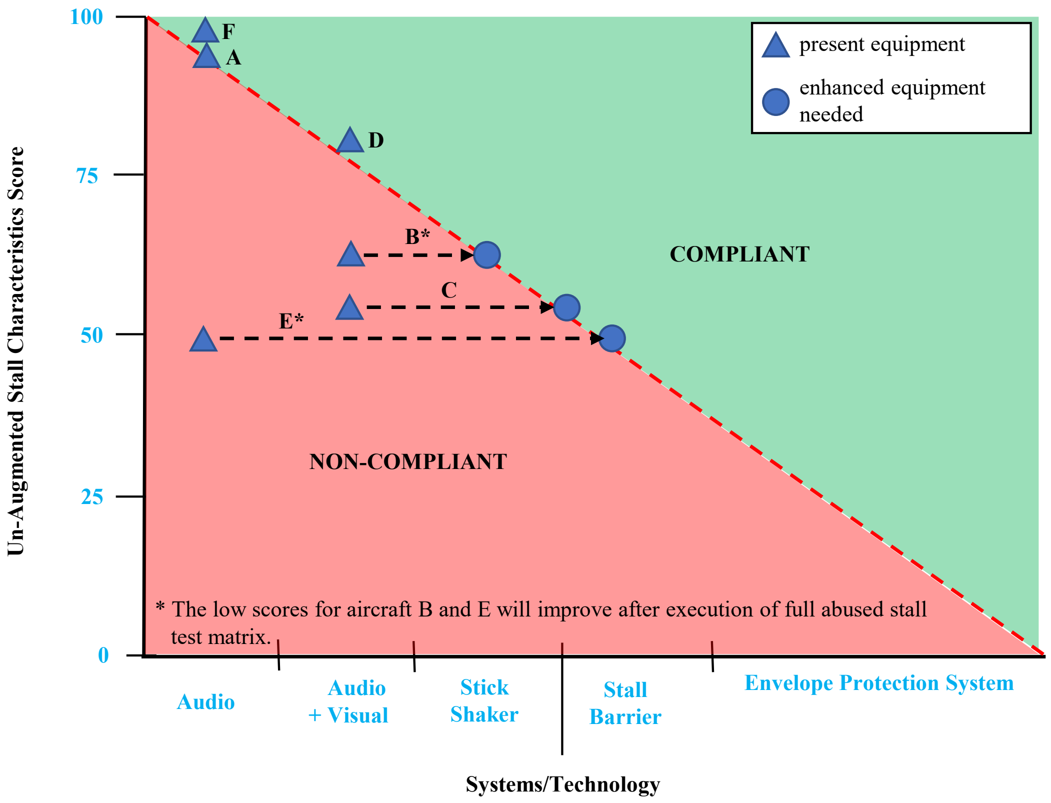


Figure 49. Effects of AOA warning/prevention systems on the proposed certification score

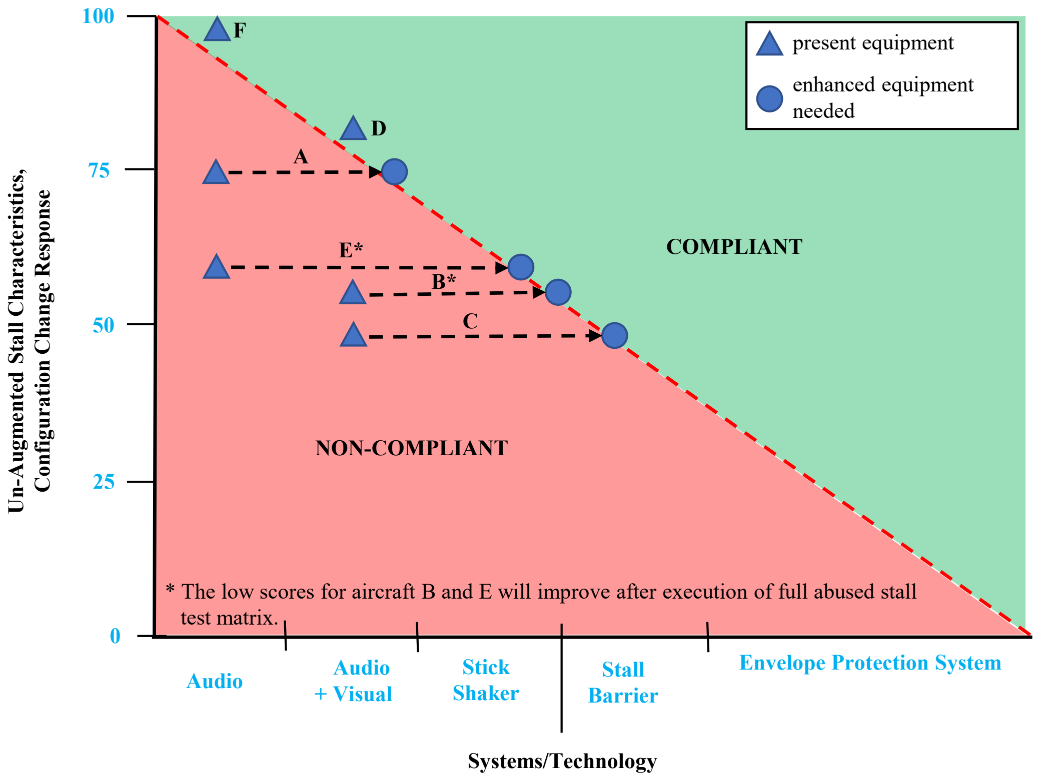


Figure 50. Effects of the combined stall characteristics/configuration change score

Figure 50 brings in a configuration score. However, more "upstream" items to loss-of-control events could be added. One unexpected result in the flight campaign came when a test aircraft had substantial friction in longitudinal control. The test pilot was forced to apply push forces to break the stall rather than simply releasing back pressure. The fix was having a maintenance technician wipe a little bit of lubricant on the control shaft. The flight was repeated, and the test pilot recovered from all stalls by releasing back pressure. The contrast in the two flights was remarkable. Another unexpected result was the inability for the test pilot to properly trim one of the test aircraft. The electric trim motor was simply too fast, and the test pilot "fought" the trim the entire time. These items caused the team to add "flying qualities" assessments to the means of compliance in terms of static stability (control force slopes) and control system friction (in terms of free-return airspeeds) to recommended means of compliance in Section 1 of this report. Figure 51 shows the suggested bounds on control force slopes recorded during static longitudinal stability tests. The lower bound was included in the proposed MOC as a certification threshold. The upper bound is a recommendation based on pilot experience, but could be relaxed or removed.

The value of having three test pilots fly the seven different aircraft cannot be overstated. Many outcomes occurred, some expected and others unexpected. Despite having different safety records, all of the aircraft had decent stall characteristics and normal recovery behavior (i.e. simply releasing the back pressure recovered the aircraft). This caused the team to consider items "upstream" of the stall. Trim forces required after configuration changes was a known issue for Part 23 aircraft based on previous research. However, experiencing the differences among the aircraft tested was enlightening. In the case of the Mooney, the forces and free response were in the opposite direction of the other aircraft. Thus, a universal training technique cannot be used to counter design deficiencies with respect to required trim forces.

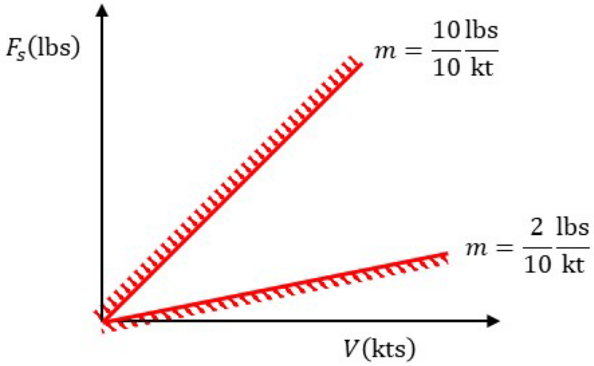


Figure 51. Suggested bounds on stick force gradients during static longitudinal stability

Performing stalls with feet-on-the-floor was expected to generate substantial sideslip. The ball did wander from side to side often reaching one or more ball widths. However, the stall characteristics were not as "scary" as one might expect. The feet-on-the-floor technique was operationally representative, proved to generate sufficient sideslip and yaw rates, and was repeatable. In contrast, having a pilot perform stall entries (especially with power on) holding the ball one ball-width out potentially sets the pilot up for a spin. Thus, feet-on-the-floor became the recommended technique.

Implementation details of any stall or AOA warning system impact the effectiveness. Haptic systems were more effective than audio systems, which were more effective than visual systems. A subjective assessment in the applicable cockpit environment must be accomplished. The ability to see and interpret a display in various cockpit lighting conditions and sun angles must be evaluated. The audio environment of a cockpit (typical tones, voice warnings, ambient noise, etc.) effects the ability to perceive and interpret an audio stall or AOA warning. The strength and frequency of a stick shaker effects the ability of the pilot to perceive the warning. The logic of when to engage a stall or AOA warning system determines whether the system becomes a nuisance or a useful device. Therefore, the x-axis of the concept shown in Figure 50 is less deterministic than the y-axis. The stall barrier and envelope protection side on the x-axis should be considered in a future research program.

Based on these findings, the team chose to weight stall characteristics (using feet-on-the-floor) 40%, flying qualities 40%, and enhanced stall warning 20% of the possible certification points.

8 Conclusions and recommendations for future work

Loss of control is a real issue in general aviation. Lowering the chance for loss of control is possible, but only if items “upstream” of a loss-of-control event are addressed. Those items include general flying qualities, pilot training, pilot proficiency, and effectiveness of warning systems. If a loss-of-control event occurs in the traffic pattern, it is most likely too late to recover safely. That being said, good stall characteristics are still important. This research did not address any of the pilot training or pilot proficiency items. The focus was on warning system effectiveness, stall characteristics, and flying qualities. The final deliverable is a suggested means of compliance.

The test team members enjoy flying general aviation aircraft and want to see the industry survive (and hopefully thrive). The test team also recognizes that one fatality every three to four days is unacceptable. Thus, the team carefully considered realistic ways to increase safety while not killing the industry with overly burdensome rules and regulations. Applicants should be able to get a new aircraft certified in a reasonable amount of time for a reasonable cost. While there are always inherent risks in flight test, the applicants should not have to subject their test pilots to extreme test conditions with no operational basis. The means of compliance should be clear, easily measurable, and repeatable. Finally, the certification test pilot should reserve the right to deny certification to an aircraft that meets a numerical threshold, but has safety concerns not revealed through the scoring.

A suggested means of compliance for “Flight Characteristics of Non-Aerobatic Level 1 to Level 4 Airplanes” is provided in Section 2 for consideration by the FAA and ASTM F44 Committee. This suggested means of compliance was based on the experience gained during the program flying 39 flights (59.7 hours) on seven different aircraft (Diamond DA42, Diamond DA40, Piper PA28, Cessna 172, Mooney M20C, Citabria, and Cirrus SR20). The overall certification passing score is set 100 points out of 150 available. Stall characteristics make up 40% of the points available. Flying qualities make up 40% of the points available. Safety enhancements make up the final 20% of the points available.

The value of having multiple test pilots fly many different aircraft in a short time window cannot be overstated. Test assets such as the Technical University of Munich's Diamond DA42 offered the ability to access warning systems in ala carte fashion. The combined experience of the test pilots on this program spanned 100 years and over 10,000 flight hours in hundreds of different aircraft. Yet, each test pilot walked away with new knowledge and new experiences. The general aviation industry is not known for using high-fidelity simulators. Fortunately, the flying costs are sufficiently low (compared to jet aircraft) making flight test campaigns like this program cost effective research. Therefore, the team has the following recommendations for future programs:

1. Run the recommended means of compliance with 6 to 10 single-engine aircraft, some in the Level 3 category.
2. Run the recommended means of compliance with 3 to 6 twin-engine aircraft.
3. Explore flap-elevator trim interconnect systems.
4. Explore augmented flight path concepts such as EZ-fly.
5. Explore active sticks with stick pusher capabilities to define logic and strength.
6. Evaluate advanced inceptors and display concepts for future cockpits.

9 References

[1] National Transportation Safety Board, "Review of U.S. Civil Aviation Accidents 2007-2009," NTSB, Washington, DC, 2011.

[2] R. Hankers, F. Pätzold, T. Rausch, R. Kickert, M. Cremer and J. Troelsen, "Safety Aspects of Light Aircraft Spin Resistance Concept," European Aviation Safety Agency, Cologne, 2009.

[3] FAA, "Revision of Airworthiness Standards for Normal, Utility, Acrobatic, and Commuter Category Airplanes," *Federal Aviation Administration Final Rule, Federal Register, 81:251,* pp. 96572-96701, 30 December 2016.

[4] European Aviation Safety Agency, "Certification Specifications for Normal-Category Airplanes," *CS-23, Amendment 5,* 29 March 2017.

[5] N. K. Borer, "Development of a New Departure Aversion Standard for Light Aircraft," in *17th AIAA Aviation Technology, Integration, and Operations Conference (AIAA AVIATION)*, 2017.

[6] FAA, "Approval of Non-Required Safety Enhancing Equipment (NORSEE)," *Policy No. PS-AIR-31.8-1602, U.S. Department of Transportation, Federal Aviation Administration,* 31 March 2016.

[7] ASTM International, "F3180/F3180M-18: Standard Specification for Low-Speed Flight Characteristics of Aircraft," American Society for Testing and Materials, West Conshohocken, PA, 2018.

[8] B. A. Kish, T. Bernard and R. Kimberlin, "A Limited Investigation of Airplane Response to Flap Extension," in *IEEE Aerospace Conference*, Big Sky, MT, 2016.

[9] B. A. Kish, M. Wilde, R. D. Kimberlin, D. G. Sizoo, D. G. Mitchell, L. Peter, P. J. Lauufs, S. Schatz and J. Geehan, "FAA Part 23 Methods of Compliance for AOA Warning/Limiting Systems," in *IEEE Aerospace Conference*, Big Sky, MT, 2018.

[10] R. Kimberlin and B. Kish, Writers, *Lessons Learned Evaluating AOA Warning Systems on General Aviation Aircraft.* [Performance]. Society of Experimental Test Pilots East Coast Symposium, February 2018.

[11] B. Kish, M. Wilde, R. Kimberlin, I. Silver, E. Kolano, R. Schaller, D. Sizoo and D. Webber, "Stall Characteristics and Trim Changes of Six General Aviation Aircraft," in *AIAA Aviation Forum and Exposition*, Atlanta, GA, 2018.

[12] B. Kish, M. Wilde, R. Kimberlin, I. Silver, D. Sizoo, D. Webber, E. Kolano, R. Schaller and M. Toepfer, "Trim Forces and Free Response to Configuration Changes on General Aviation Aircraft," in *IEEE Aerospace Conference*, Big Sky, MT, 2019.

[13] B. Kish, M. Wilde, R. Kimberlin, I. Silver, D. Sizoo, D. Webber, E. Kolano, R. Schaller and Y. Auguste, "Comparing Specifi Excess Power of Five General Aviation Aircraft," in *IEEE Aerospace Conference*, Big Sky, MT, 2019.

[14] B. Kish, Writer, *Flight Testing to Determine Stall Characteristics and Trim Force Changes on GA Aircraft.* [Performance]. PEGASAS Annual Meeting, May 2018.

[15] R. Kolano and R. Kimberlin, Writers, *FAA-FIT Low Speed MOC Alternative.* [Performance]. ASTM Annual Meeting, Brussels, April 2019.

[16] J. D. Anderson, Introduction to Flight, 7th Ed., New York, NY: McGraw-Hill, 2005, p. 301.

[17] S. Lichiardopol, "A Survey on Teleoperation," Technische Universiteit Eindhoven, DCT Report DCT 2007.155, Eindhoven, The Netherlands, 2007.

[18] N. J. Cooke, H. L. Pringle, H. K. Pedersen and O. Connor, Human Factors of Remotely Operated Vehicles, Amsterdam, The Netherlands: Elsevier JAI, 2006.

[19] Alpha Systems, "AOA Kits," 2018. [Online]. Available: http://www.alphasystemsaoa.com/index.php?id=8. [Accessed 19 January 2018].

[20] R. J. Ontiveros, "Experimentation and Evaluation of Improved Stall Warning Equipment," U.S. Department of Transportation, Federal Aviation Administration, Report NA-69-35 (DS-69-15), 1969.

[21] AOPA Air Safety Foundation, "Technologically Advanced Aircraft - Safety and Training," AOPA Air Safety Foundation, Frederick, MD, 2007.

[22] J. L. Rochlis, "Human Factors and Telerobotics: Tools and Approaches for Designing Remote Robotic Workstation Displays," Ph.D. Dissertation, Massachussetts Institute of Technology, Cambridge, MA, 2002.

[23] C. D. Wickens and J. G. Hollands, Engineering Psychology and Human Performance, 3rd Ed., Prentice-Hall, 2000.

[24] D. J. Simons, "Attentional capture and inattentional blindness," *Trends in Cognitive Sciences,* vol. 4, no. 4, pp. 147-155, 1 April 2000.

[25] A. J. Bailey, "Development of a Side-Stick Controller for Aerospace Vehicles," in *Testing of Manned Flight Systems Conference*, Edwards AFB, CA, 1963.

[26] R. E. Bailey and L. H. Knotts, "Interaction of Feel System and Flight Control System Dynamics on Lateral Flying Qualities," NASA CR-179445, 1990.

[27] FAA, "Pilot's Handbook of Aeronautical Knowledge," FAA-H-8083-25B, Federal Aviation Administration, Washington, DC, 2016.

[28] R. Detwiler, "Energy Is Life: Keepeth thou thy smash," *Business and Commercial Aviation,* March 2018.