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USE OF FOQA DATA
TO ESTIMATE THE PROBABILITY OF VEHICLE UPSET OR LOSS OF CONTROL IN-FLIGHT

by

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Bachelor of Science, University of North Dakota, 2006

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Submitted to the Graduate Faculty
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This thesis, submitted by Shelby D. Balogh in partial fulfillment of the requirements for the degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

James Higgins - Committee Chair

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Brandon Wild – Committee Member

This thesis is being submitted by the appropriate advisory committee as having met all of the requirements of the School of Graduate Studies at the University of North Dakota and is hereby approved.

Dr. Grant McGimpsey
Dean of the School of Graduate Studies

Date

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Shelby David Balogh
21 April 2017

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ABSTRACT

The leading cause of fatal aviation accidents worldwide remains loss of control in-flight, whereby control of the aircraft is lost or the aircraft enters an extreme deviation from the intended flight path (LOC-I). The primary purpose of the research contained herein is to evaluate a purposed methodology of analyzing FOQA/FDM data recorded by a typical TAA general aviation aircraft in order to predict the probability that a vehicle upset or loss of control in-flight could occur. Probability values obtained from the purposed methodology could be used for root cause analysis of high risk occurrences and to assist in the development of and analysis of proactive mitigation strategies.

CHAPTER 1

INTRODUCTION

Background Information

After departing Teterboro, NJ airport, the commercial pilot of a general aviation aircraft registered as N13622 was advised by air traffic control (ATC) to expect an approach to runway 02 at KHVN airport in New Haven, Connecticut to be followed by a circle to land maneuver to runway 20, which happens to have no straight-in instrument approach procedure. At 11:15 am, N13622 was cleared for the approach and subsequently requested by ATC to report reaching a left downwind for runway 20. Four minutes later the pilot of N13622 reported the aircraft had reached the downwind for runway 20 and was cleared to land.

Investigators concluded that the accident aircraft was positioned much closer to the airport than normal, which required the pilot to enter a turn with a bank angle of at least 45 degrees, 15 degrees beyond the normal maximum for such a maneuver, in order to align the aircraft on final approach without overshooting the runway extended centerline. Radar data indicates that as the aircraft began its turn to align with the runway, airspeed decreased until it reached the wings level stall speed. At this point, the aircraft likely experienced an aerodynamic stall resulting in a near vertical descent with what witnesses described as a clockwise rotation until impact with the ground.

The NTSB's probable cause cited the pilot's failure to maintain airspeed while banking aggressively as a causal factor to the accident which tragically claimed the lives of two children on the ground, a passenger in the aircraft, and the pilot (National Transportation Safety Board, 2014b). The scenario described by eye witness accounts and examination of evidence by the NTSB indicates N13622 was heartbreakingly one of hundreds of accidents due to loss of control in-flight which occur each year in the United States.

Problem Statement

Commercial aviation operators in the United States operating under FAR part 121 have maintained an incredibly low accident rate of less than 1 accident per 100,000 flight hours, or just one fatal accident in all of 2010 and none in 2011 or 2012 (National Transportation Safety Board, 2012). In contrast, general aviation aircraft operating under FAR part 91 have experienced an accident rate which is nearly 6 times higher than small commuter and air taxi operators and more than 40 times higher than commercial flying, accounting for more than 1,200 accidents and 400 deaths annually (National Transportation Safety Board, 2014a).

General aviation is a large sector of aviation accounting for 96 percent of all registered aircraft in the United States with more than 200,000 aircraft engaged in aerial operations such as crop dusting, personal pleasure flights, corporate and business aviation, flight instruction, and air ambulance services (U.S. Government Accountability Office, 2012). Unfortunately, the general aviation accident rate has remained largely unchanged for the previous 10 years (Figure 1).

A worrisome statistic from the NTSB highlights specific types of flight, such as personal pleasure flying, has realized a 20 percent increase in accidents and a 25 percent increase in fatal accidents during the same 10-year period (U.S. Department of Transportation, 2012).

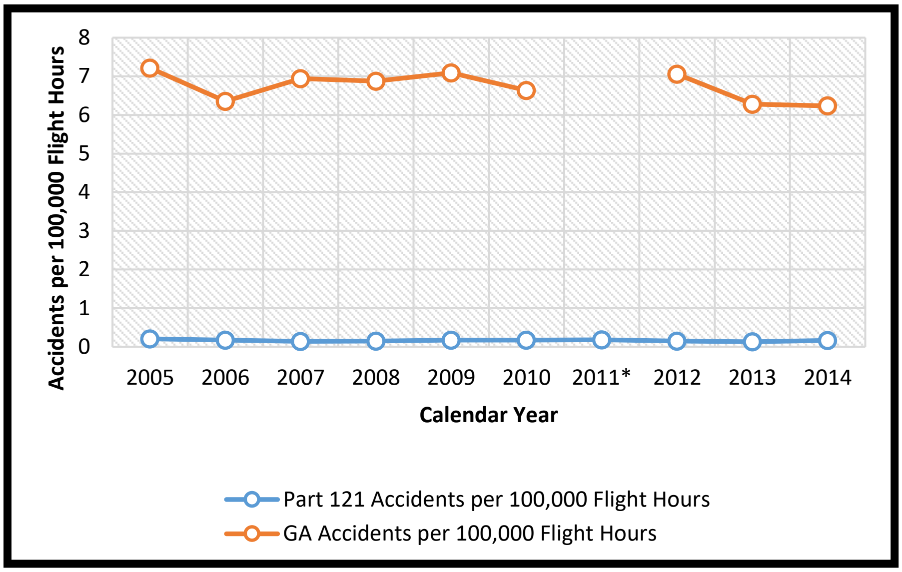

Figure 1. Aviation Accident Rates per 100,000 Flight Hours, 2005-2014.
(National Transportation Safety Board, 2014a)

Figure 2. GA Accidents by Location.
(National Transportation Safety Board, 2014a)

According to the NTSB, these accidents stem from pilots which have inadequate knowledge, skills, or lack of recurrent training necessary to maintain the skills required to ensure the safe and efficient operation of the aircraft (National Transportation Safety Board, 2016). In addition, newly designed technologically advanced aircraft (TAA) present a new layer of complication for general aviation pilots, leading to a greater need for aircraft specific and effective recurrent training (Kolly & Groff, 2010). A statistical analysis performed on accidents involving light general aviation aircraft equipped with glass cockpit displays experienced a lower total accident rate, but higher fatal accident rates (χ^2 (1, $N=266$) = 8.216, $p=0.004$) compared to the same type of aircraft equipped with conventional instrumentation, and a higher percentage of accidents attributed to loss of control in-flight (National Transportation Safety Board, 2010). The number one cause of fatal accidents in 2010 involved a loss of control while in-flight, or extreme deviation from the intended flight path (LOC-I) (Figure 5). The majority of these accidents occurred during daylight hours in visual meteorological conditions (VMC). Without minimizing the hazards of weather or controlled flight into terrain, loss of control in-flight is, and has been, the leading cause of fatal general aviation accidents in the United States for more than ten years. Despite improvements in technology, no significant decreases in accident rates have been observed (Federal Aviation Administration, 2016).

In addition to the NTSB's analysis, the Federal Aviation Administration recently convened the General Aviation Joint Steering Committee (GAJSC) after a seven year hiatus, to independently determine the root cause of fatal general aviation accidents. The GAJSC review and analysis determined the root cause of fatal general aviation accidents are in fact not the result of encounters with thunderstorms, mechanical malfunctions, or event midair collisions, but loss of control in-flight (General Aviation Joint Steering Committee, 2012).

The issue of loss of control in-flight was brought to the attention of general aviation pilots during the FAA's 2011 Safety Standdown (Parson, 2011). During this conference, it was announced that a five-year initiative on education and outreach would begin in an effort to reduce the fatal accident rate. The five-year strategy involved numerous initiative under four focus areas: risk management, outreach and engagement, training, and safety promotion (U.S. Government Accountability Office, 2012). In 2012, the FAA included the topic of "Maneuvering Flight-Attention to airspeed is critical" in an effort to better education pilots on the importance of the aerodynamic factors related to loss of control in-flight (U.S. Department of Transportation, 2012). Follow-up articles from the FAA highlighted pilot's awareness of angle of attack and stall speed as crucial factors in avoiding LOC-I.

Angle of Attack is the acute angle that forms between the relative wind, which acts parallel to but opposite the flight path of the aircraft and the wing's chordline (Figure 3).

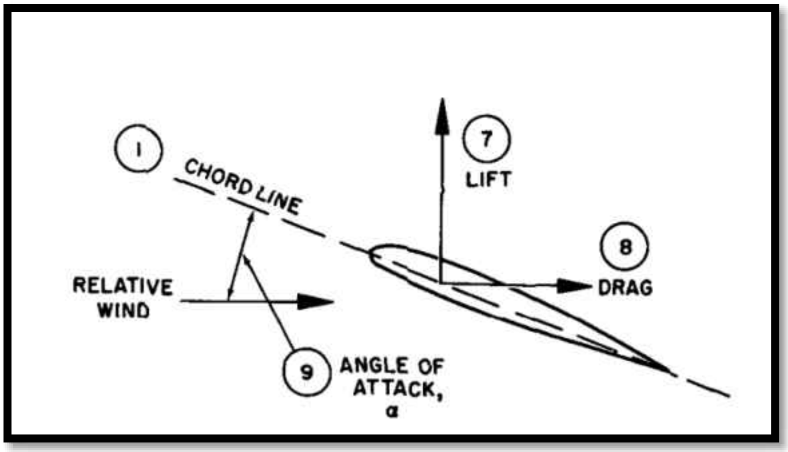

Figure 3. Relative Wind vs. Chordline with Lift and Drag Vectors.
(H. H. Hurt, Jr., 1965)

During initial training, pilots are taught that every wing in a specific configuration has a single critical angle of attack which, once exceeded, will always produce an aerodynamic stall. When an aerodynamic stall occurs, the ratio of dynamic pressure to lift pressure decreases substantially along with an increase in drag which causes the aircraft to lose lift and altitude (Dusenbury, Ullrich, & Balogh, Shelby D., 2016). Aerodynamic stalls are the leading cause of LOC-I accidents (ICATEE, n.d.).

Angle of attack information, however, is not generally available to pilots in most general aviation aircraft and is not a required flight instrument under CFR Title 14 USC §91.205 for aircraft being operated in visual flight conditions—nor the more challenging flights conducted in instrument meteorological conditions. CFR Title 14 USC §23 requires aircraft certified in the normal category, the certification standards used for many general aviation aircraft, to conduct flight testing for stalls and stall recoveries, and requires the airspeed from which an aircraft will stall under specific criteria to be determined and placarded on the airspeed indicator. Publishing a “stall speed” is problematic because an aircraft can stall at any airspeed, altitude, or pitch attitude (Federal Aviation Administration, 2016).

CFR Title 14 USC §23 prescribes additional stall safety through the installation of a stall warning system. This system typically consists of a small metal tab on the leading edge of the wing that has an on and off switch attached to an audio or visual alarm that activates at high angles of attack. While effective in most cases, this type of system does not display quantitative data or trends to the pilot. In cases where flight dynamics and angle of attack are changing quickly, this device may provide little to no warning to the pilot before a full aerodynamic stall occurs (Hirschman, 2011).

Other factors such as weight, center of gravity, load factor, power settings, and aircraft configuration all affect the actual speed at which the aircraft will stall; therefore, airspeed alone is simply not a reliable predictor of when an aircraft will stall (Federal Aviation Administration, 2013). Relying on airspeed exposes pilots to an unexpected or unanticipated stall while maneuvering. Stall recoveries require the pilot to reduce the angle of attack by lowering the pitch attitude which, even when conducted with precision, requires some reduction in the flight path angle and frequently a significant loss of altitude. If a stall is encountered at a critical phase of flight such as takeoff or landing, the height of the aircraft may be insufficient to allow the pilot to fully recover from the stall prior to impacting terrain (Federal Aviation Administration, 2016).

The importance of angle of attack is not a new concept. The “Wright Flyer” produced in 1903 used but one flight instrument, a protractor and a string, to estimate the angle of attack (Pope, 2011). Orville and Wilbur Wright relied upon to this simple instrument to anticipate and avoid stalls and what would today be known as loss of control in-flight. Now more than 100 years later, this basic instrument and the awareness of this acute angle is missing from the cockpit of most general aviation aircraft.

In 2010, the NTSB determined single engine aircraft equipped with glass cockpits had no better overall safety than aircraft equipped with conventional instrumentation. Not only was the increased level of technology installed not correlated with better overall safety, but in fact aircraft equipped with glass cockpits had a higher fatal accident rate than similar aircraft with conventional instrumentation (Kolly & Groff, 2010).

Reviewing narratives or statements of probable cause for accidents involving LOC-I often reveals phrases such as the “pilot failed to maintain” or “pilot error”, a cause which is attributed to a majority of accidents. However, as stated by Key Dismukes, a pilot and former chief scientist for human factors at NASA’s Ames Research Center, “pilot error isn’t a cause, it’s a clue. It suggests something is wrong with the larger picture” (Negroni, 2011). In part, pilot error is cited as a causal factor in many LOC-I related accidents due to the difficulties in identifying the causation for accidents involving pilot skill and experience as major factors coupled with the ambiguous process of identifying a LOC-I accident (Kwatny et al., 2013).

NASA’s Langley Research Center has undertaken a major review of LOC-I related accidents in an effort to better understand the nature of these occurrences. A report titled, “Aircraft Loss-of-Control Accident Analysis” reviewed 42 aircraft accidents which occurred over the course of a decade between 1997 and 2007 which resulted in 3,241 fatalities. Their analysis led to the well accepted definition of a LOC-I occurrence as “any uncommanded or inadvertent event with an abnormal aircraft attitude, rate of change of aircraft attitude, acceleration, airspeed, or flight trajectory” (Belcastro, 2010).

While the Commercial Aircraft Safety Team (CAST) defines in-flight loss of control as a “significant deviation of the aircraft from the intended flight path or operational envelope” (Russell & Pardee, 2000). Loss of control in-flight events can be initiated by a multitude of factors and additional research is required to better identify when the initial upset occurred and the most significant commonality in order to focus a proactive mitigation strategy that will be most effective (Kwatny, Dongmo, & Chang, 2009).

This recommendation led to a review of accident analyses conducted by the International Committee for Aviation Training in Extended Envelopes which indicated the majority of accidents analyzed were associated with or precipitated by an aerodynamic stall (Figure 4).

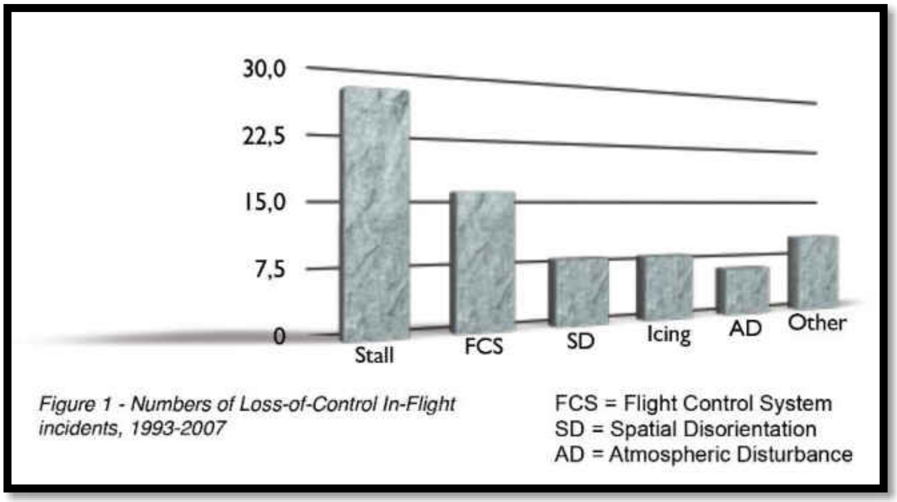

Figure 4. Number of LOC-I Accidents by Contributing Factor.
(ICATEE, n.d.)

The Commercial Aircraft Safety Team and Joint Safety Analysis Team (JSAT) reviewed flight trajectories from 24 CAST data sets based upon a proposal from Wilborn and Foster (Wilborn & Foster, n.d.). Using the Quantitative Loss-of-Control (QLC) metrics, they identified five envelopes: adverse aerodynamic envelope (normalized angle of attack and sideslip angle), unusual attitude envelope (bank angle vs. pitch angle), structural integrity envelope (normal load factor vs normalized airspeed), dynamic pitch control envelope (dynamic pitch attitude $\theta + \theta\Delta t$ vs percent pitch control command), and dynamic roll control envelope (dynamic roll attitude $\phi + \phi\Delta t$ vs percent lateral control command). According to their analysis, the two greatest variables which precipitated a loss of control were stalls (45.8 percent) and sideslip-induced rolls (25 percent). Wilborn and Foster also determined that the Adverse Aerodynamics Envelope is a useful indicator of LOC-I and noted that even small disturbances can cause dramatic changes in how the aircraft responds to control inputs when operating at speeds near stall speed (Kwatny et al., 2009).

Loss of control in-flight is also the greatest accident category for the world-wide commercial aircraft fleet. Additionally, it is the most complex accident category with the greatest number of contributing factors acting individually or in concert to produce off-nominal conditions (Belcastro, 2011).

Existing prevention strategies related to LOC-I events have focused on pilot training and awareness. In August of 2012, the FAA issued AC 120-109, which emphasizes best practices for training, testing, and checking for pilots. The advisory circular highlights a reduction in angle of attack at the first indication of a stall as paramount concern to avoid a loss of control in-flight, however this advisory circular primarily targets pilots who operate aircraft with angle of attack measuring equipment installed along with stall protection systems such as a stick shaker or pusher device (U.S. Department of Transportation, 2012).

The advisory circular does not address how the general aviation sector should alter its training syllabi or procedures to better equip pilots with the knowledge or skill required to mitigate LOC-I accidents. There is also a significant gap in research related to measuring the effectiveness of LOC-I mitigation strategies in general aviation.

In the 1960's a study was conducted by the Federal Aviation Administration to determine the effectiveness of using angle of attack indicators in primary pilot training. There were 30 students involved with the study evenly separated into control and experimental groups. The results of the study indicated students utilizing angle of attack indicators progressed more slowly in their training initially, but accelerated past their peers in the final 25 hours of training. At completion of the study, the FAA recommended additional studies be performed in this area (Forrest, 1969). Of key interest to researchers in this study was the effect that angle of attack presentation in the cockpit would have on pilot performance in areas related to loss of directional control events and the effectiveness of a training syllabus which included angle of attack training.

Nearly forty years later the General Aviation Joint Steering Committee's loss of control work group drafted a recommendation that the FAA should "develop policy that allows AOA indication as a secondary reference as non-essential information to be installed as a minor alteration in FAR Part 23 airplanes, thereby facilitating simplified low cost installations" (General Aviation Joint Steering Committee, 2012). The policy change was drafted to encourage general aviation operators to adopt a mitigation strategy that included the presentation of angle of attack in the cockpit. Furthermore, the GASJC recommended that the FAA and industry should investigate and implement financial incentives to encourage the installation of safety enhancing technologies. In 2014, the most recent year for which accident data is available for analysis from the NTSB, loss of control in-flight represents the defining event for the highest percentage of fatal accidents in general aviation.

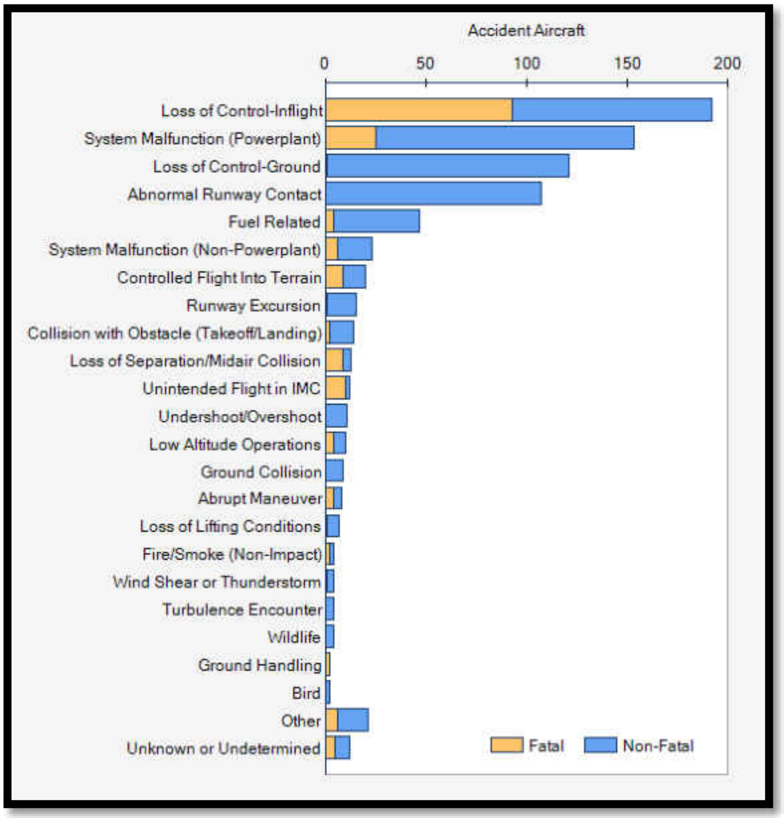

Figure 5. Personal Flying Accidents by Defining Event.
(National Transportation Safety Board, 2014a)

Research Question

What is currently known about loss of control in-flight for general aviation is largely based upon the analysis of accident data; few studies have been published using FOQA data to identify how atypical event sequences lead to undesired aircraft and crew performance. Gaps in knowledge related to exposure to risk factors and how aircraft and crews respond to flight beyond the normal flight envelope exists.

The objective of this research is to build on what is known from accident analyses by determining a reliable and valid quantitative method analyzing FOQA/FDM data using principles of aerodynamics, regression, and correlational statistics to identify off-nominal aircraft performance which have high probabilities of being correlated with vehicle upset or loss of control in-flight.

The results of this study will provide insight into the nature and root cause of loss of control or near loss of control in-flight occurrences, provide a foundation for identifying patterns and trends, and determine the effectiveness of mitigation strategies to advocate for changes to training or standard operating procedures that can prevent future accidents related to loss of control.

CHAPTER II

METHODOLOGY

Aerodynamics

Angle of Attack

Lift is the aerodynamic force which acts perpendicular to the flight path of an aircraft and acts as the primary force used to oppose gravity and maintain sustained flight. The shape of the main lifting airfoil for an aircraft is designed to generate a difference in static pressure force acting upon its upper and lower surfaces such that the lower surface generally maintains a higher static pressure than the area immediately surrounding the upper surface. The ratio between the dynamic pressure, which is the product of the velocity of the aircraft and the air density, and lift pressure is known as the coefficient of lift.

The quantity of lift being produced by an aircraft's wings can be expressed through the lift equation *(L)* = $\frac{1}{2}\rho v^2 S C_L$; where the amount of lift generated in pounds is dependent on air density (ρ), the surface area of the wing (S) and (C_L) the lift coefficient. The lift coefficient itself is affected by factors such as the shape of the wing, which can be augmented by the pilot through the position of both leading and trailing edge flaps, and variations in the acute angle that forms between the relative wind, which acts parallel to but opposite of the flight path and the chordline of the wing.

When slowing the aircraft for landing, the required reduction in speed will be offset by an increase in the coefficient of lift. Additional lift required for maneuvering must also be provided by an increased coefficient of lift if all other factors are constant.

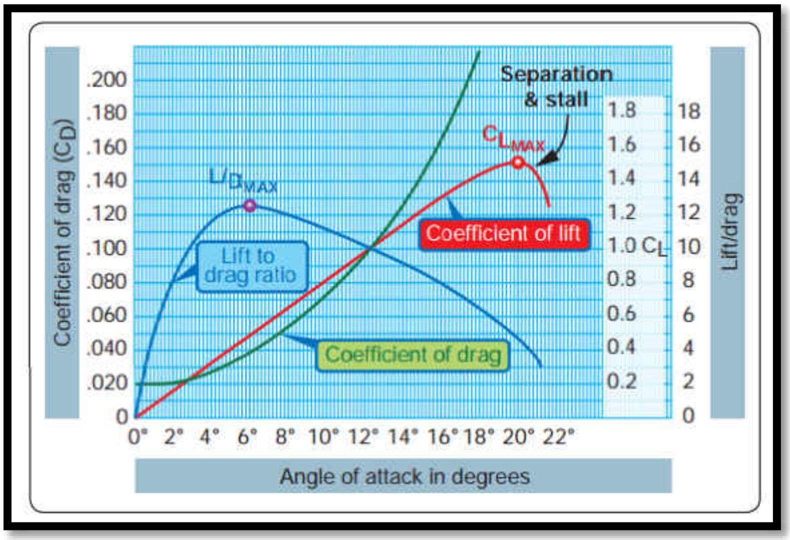

Figure 6. Relationship Between Coefficient of Lift and Angle of Attack.
(U.S. Department of Transportation, 2016)

For a constant wing configuration, the angle of attack is increased in order to increase the ratio of dynamic pressure and lift pressure. This positive correlation only exists until the maximum coefficient of lift (C_{Lmax}) is reached. After this point, any attempt to increase the angle of attack further will result in a negative correlation between the additional increases in angle of attack and lift coefficient. This phenomenon is known as a stall.

The formula in Figure 7 is used to estimate the angle of attack using FOQA data, as angle of attack is not a recorded parameter thus making it unavailable for direct analysis. Since the angle of attack is the acute angle formed between the flight path angle and the chordline, the flight path angle is first derived using the parameters of airspeed and vertical speed corrected for the effects of non-standard temperature and pressure.

Since the exact average angle of incidence is a constant, and as such does not affect the correlation between angle of attack and lift coefficient it is not a significant factor for this analysis. The parameter for pitch angle (degrees) is used to determine the value of acute angle between the chordline and the horizon. For airspeeds below the transonic flight range, the angle of attack is estimated through a formula (Figure 7).

$$AOA\ (\mathrm{deg}) = \frac{\varphi}{\cos\gamma} - \left(\sin^{-1} \frac{Vertical\ Speed\ (\frac{ft}{min}) * \left(\frac{1}{\sqrt{\left[\frac{1-(1-\left(\frac{\delta_1}{\delta_0}\right)) + (1-((-2.94\mathrm{E}^{-5} * z) + .986)}{\left(\frac{273+\mathrm{T}}{288}\right)}\right]}}\right)}{IAS\ (kts) * \left(\frac{1}{\sqrt{\left[\frac{1-(1-\left(\frac{\delta_1}{\delta_0}\right)) + (1-((-2.94\mathrm{E}^{-5} * z) + .986)}{\left(\frac{273+\mathrm{T}}{288}\right)}\right]}}\right) * 101.267}\right)$$

Figure 7. Formula for Estimating Angle of Attack.

Stall

As previously discussed, the vast majority of loss of control in-flight related accidents involved an aerodynamic stall which is defined in (FAA-H-8083-25B) as “a rapid decrease in lift caused by the separation of airflow from the wing’s surface, brought on by exceeding the critical angle of attack.” The velocity of air flowing over the upper surface of the wing is influenced by the present pressure gradient.

As the angle of attack increases, the magnitude of the pressure gradient on the upper surface of the wing increases such that the present gradient tends to slow the velocity of airflow close to the wing’s upper surface. When the velocity of airflow is insufficient to allow air to traverse the adverse pressure gradient, flow reverse occurs with air flowing from the trailing edge to the leading edge of the airfoil.

This effect is known as airflow “separation” and is the hallmark aerodynamic characteristic of a stall, which causes the suction pressure above the wing and lift coefficient to be substantially decreased. This aerodynamic principle can be illustrated by inserting the known weight of an aircraft into the lift equation and solving for the coefficient of lift. Results of plotting the derived angle of attack against the lift coefficient indicate a positive correlation as expected until reaching the critical angle of attack. The probability of the entering a stall and experiencing a loss of control in-flight increase as the angle of attack increases.

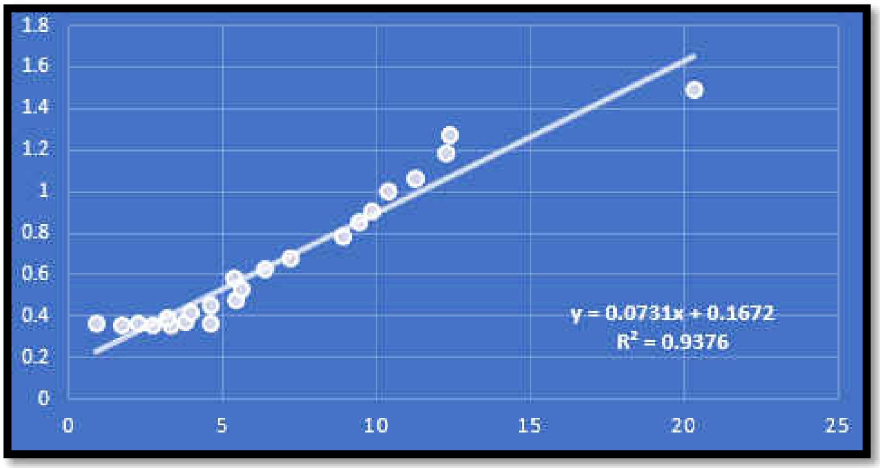

Figure 8. Observed Values Estimated Angle of Attack vs Lift Coefficient.

Coordination

As power is increased in an aircraft with a reciprocating engine and propeller as its primary source of thrust, there are many turning tendencies which tend to yaw the aircraft’s nose away from the flight path. In addition, if the aircraft enters a turn, such is the case when maneuvering the aircraft to align with the runway, the upward moving wing tends to yaw the aircraft opposite the direction of the turn due to the increased drag produced by the section of wing generating more lift due to the application of aileron. Use of the rudder by the pilot is required to counter balance the yawing tendencies of the aircraft with an aerodynamic force generated by rudder to keep the nose of the aircraft aligned with the flight path.

If the pilot fails to apply sufficient rudder, the longitudinal axis of the aircraft will no longer be aligned with the velocity vector which is tangent to the flightpath and the aircraft is said to have entered a slip where -β condition exists. If the pilot invokes a greater application of rudder than what is required to keep the aircraft's longitudinal axis aligned with the flight path, the aircraft is said to have entered a skid where +β condition exists. When the aircraft is in coordinated flight, the product of yaw rate and velocity will equal the product of the sine of the bank angle times the force of gravity.

It is a common expectation that aircraft coordination and aerodynamic symmetry will be maintained as the angle of attack is increased. Once airflow separation occurs in a stalled condition, asymmetric forces such as non-symmetrical wing stalls or torque moments induced by the power plant must be countered with the appropriate use of coordinated control input by the pilot (Foster et al., 2013).

Spin

A spin is an aggregated stall that results in an autorotation where the aircraft follows a spiral path vertically towards the earth's surface. The autorotation occurs when an aircraft enters a stall from uncoordinated flight. When this condition is present, one wing stalls first, producing an increase in drag and decrease in lift. The imbalance of forces tends to yaw the aircraft in the direction of the downward moving wing, while the reduction in lift produces a rolling moment in the same direction. If the angle of attack is increased further, both wings enter a stalled condition, however, one wing maintains a higher angle of attack, thus experiencing a disproportionately high amount of drag which perpetuates the yawing moment of the aircraft while the flight path angle decreases from level flight to near vertical (Federal Aviation Administration, 2016).

Accident Precursor Analysis

The Swiss Cheese Model of accident causation can be used to help understand how the aerodynamic elements described above can be used as an element in anomaly detection. Reason's 1990 model demonstrates the principle that accidents occur when inherent vulnerabilities in the safety system align allow a trajectory which ends in a catastrophic event (Reason, 1990).

The vast majority of the time however, failure mechanisms are deflected by a safety barrier and the threat is effectively deflected from continuing (National Aeronautics and Space Administration, 2011).

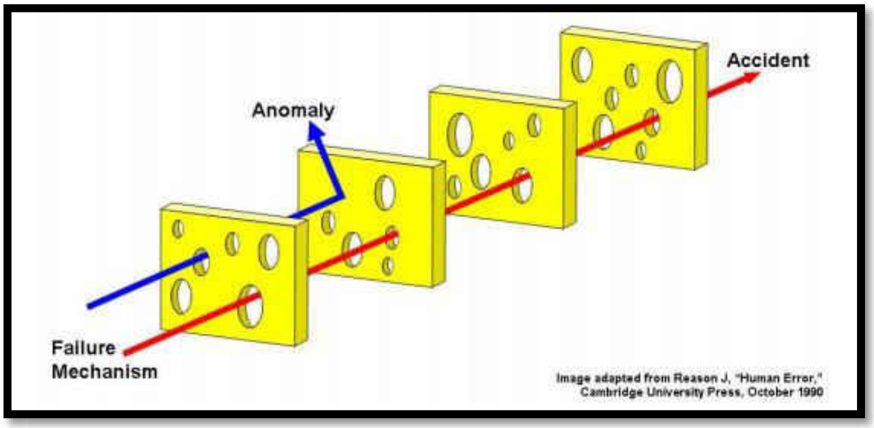

Figure 9. Swiss Cheese Model of Accident Causation.
(National Aeronautics and Space Administration, 2011)

As stated in NASA's Anomaly Detection Handbook, "A detected or reported anomaly can make an organization aware of failure mechanisms in the system that may, in combination with less favorable circumstances or left unattended for longer time periods, lead to a severe consequence. If there is indeed potential for the observed anomaly failure mechanism to recur and lead to an accident, then the anomaly may be called an accident precursor" (National Aeronautics and Space Administration, 2011).

One of the benefits of conducting an analysis of data known to contain accident precursors is that these data sets contain an abundance of occurrences which can be detected as compared to an analysis consisting of a database containing only a fraction of flights with actual accidents. Precursor data sets therefore are a much richer source for analysis (Accident Precursor Analysis and Management).

Since the primary elements of an event involving a loss of control in-flight are predicated on the conditional that the aircraft has both entered a stall and obtained uncoordinated flight, we can simply use the multiplication theorem to estimate the probability that a loss of control in-flight will occur where $P(X \cap Y) = P(X)*P(Y)$. Probability of stall and uncoordinated flight were estimated through data defined value where $P(X_1) = \alpha / \alpha_{\rightarrow > \mu + 4\sigma}$ and $P(Y) = \beta / \beta_{\rightarrow > 4\sigma}$.

$$P(A|B) = (\min(1, (abs((\frac{\varphi}{\cos\gamma}) - (\sin^{-1}\frac{Vertical\ Speed\ (\frac{ft}{min}) * (\frac{1}{\sqrt{\frac{1-(1-(\frac{\delta_1}{\delta_0}))+(1-((-2.94E^{-8} * z)+.986)}{(\frac{273+T}{288})}}})}{IAS\ (kts) * \left(\frac{1}{\sqrt{\frac{1-(1-(\frac{\delta_1}{\delta_g}))+(1-((-2.94E^{-8} * z)+.986)}{(\frac{273+T}{288})}}}\right) * 101.267}))/15)) * (\min(1, (\frac{abs(((\sin(\gamma * (\frac{\pi}{180})) * 32.2) - ((TAS * 101.267) * (\frac{d(heading)}{d(T)}) * (\frac{\pi}{180})))}{4}))$$

Figure 10. Formula for Determining the Probability of LOC-I.

Research Design

This is a quantitative study using de-identified flight data obtained from an existing FOQA/FDM database. For this analysis, all data obtained was generated from Cessna 172 aircraft equipped with Garmin G1000 integrated avionics that records flight related parameters as time series data, which is downloaded from an SD card at regular intervals from each aircraft. All data was analyzed using Microsoft Excel© and IBM© SPSS© Statistics 24.

Statistical Methodology

The primary goal of this study was to develop a tool that could effectively identify flight dynamics correlated with stalled flight and occurrences of loss of control in-flight. 30 flights were randomly selected and categorized into 3 groups, with each group containing 10 flights. Group 1 contains 10 flights with 70,075 samples of flight data containing only normal flight maneuvers; no stalls, spins, LOC-I, or upset maneuvers. Group 2 contains 10 flights with 40,343 samples of flight data including data during 70 observed occurrences of a stall maneuver, while Group 3 contained 10 flights with a total of 21,974 samples of flight data and 77 occurrences of loss of control in-flight (spin) maneuvers.

The first research question was, can the recorded altitude and altimeter setting set by the pilot be used to estimate the density ratio with enough precision for the derived values to accurate transform indicated velocities into true velocities? For this test, a linear regression was used to determine a line of best fit between recorded altitude and standard atmospheric pressure ratios, and derived values were then used to transform the recorded indicated airspeed into true airspeed. After transforming the indicated airspeed values, a bivariate correlation was used to determine the level of correlation between the recorded and predicted values of true airspeed. Tests for normality warranted the use of Spearman's rho to minimize the effects of extreme scores and violation of parametric test assumptions.

The second research question was to validate the hypothesis that calculated values of angle of attack during observed periods of LOC-I were greater than or equal to the values observed during stalls, and that calculated values of angle of attack during takeoff and landing and during normal flight are significantly less than observed during stalls. For this analysis, an ANOVA was conducted to evaluate the hypothesis that the mean values of angles of attack were not equal between groups.

The third research question was to validate the hypothesis that the values for coordination could be used as a predictor for the presence of pro-spin forces. For this test it was expected that the aircraft would be significantly uncoordinated during spins, perhaps marginally uncoordinated during stalls and during takeoff and landing (as might be required during crosswind landings), and generally coordinated during normal phases of flight. To answer this question an ANOVA was conducted to evaluate the hypothesis that the mean values of coordination are not equal between the populations of samples from observed spins when compared to the other events, including stalls.

The fourth research question was to validate a correlation observed between bank angle and yaw rate when controlling for true airspeed. A semi-partial correlation was used to evaluate the correlation between bank angles and yaw rates while controlling for the effects of true airspeed on bank angle.

The fifth research question was, after evaluating observed values of angle of attack, are the derived probability values for the presence of stall greatest during observed stalls and occurrences of loss of control in-flight? If it was more likely than not that a warning system designed to activate 5-10 knots prior to a stall would be active, then samples that met this requirement were reviewed as true for the observance of a stall. Values of pitch, vertical speed, power, bank angle, and load factor were manually reviewed. Due to non-normal distributions of stall warning values, Kruskal-Wallis non-parametric test was used to assess the hypothesis that samples of stall probabilities come from different populations. Follow-up analysis of the scores between groups was conducted using a pairwise comparison.

The sixth and final research question: are the observed values for probabilities of loss of control in-flight the greatest during observed occurrences of loss of control in-flight significantly different than values observed during stalls, takeoffs and landings, and normal phases of flight? Example values of the probability of LOC-I and flight path angle obtained from Group 3 are indicated in Figure 10. To test this hypothesis, the Kruskal-Wallis non-parametric test was used to assess the hypothesis that samples of LOC-I probabilities come from different populations. Follow-up analysis of the scores between groups was conducted using a pairwise comparison.

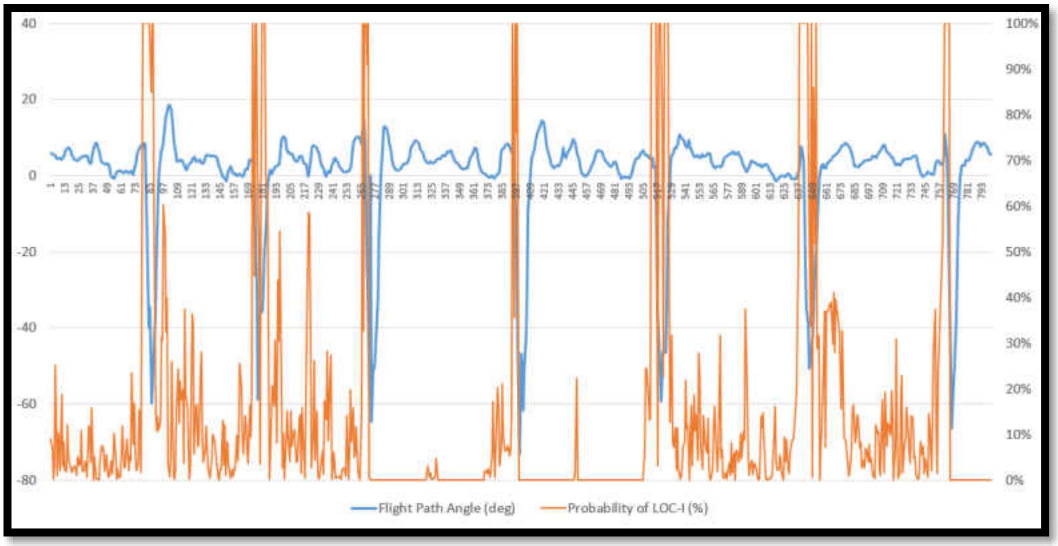

Figure 11. Probability of LOC-I (percent) vs Flight Path Angle (degrees): Group 3.

Population

Data for this study was obtained from an FDM program utilized by an accredited collegiate aviation training program conducting flight training under FAR part 141. The dataset does not contain any known occurrences of accidents as defined under Title 49 §830.2, and aircraft from which data was collected are approved for spin maneuvers when operated in accordance with the aircraft manufacturer's airplane flight manual, placards, and limitations.

Since all flight data was de-identified, to ensure the confidentiality of crewmembers, no data was collected or analyzed related to the demographics of the pilots, the certificates or ratings held, flight experience, or if the flight was conducted under the supervision of a qualified flight instructor.

Limitations

Since the flight data used for this study was de-identified, the researcher could not conduct crew contacts or interviews for further feedback or responses. There are many characteristics of the data recorded from the Garmin G1000 which limits the scope of the analysis. Limitations identified in this study include a 1 Hz sample rate of parameters limits the quality of analysis for maneuvers that involve highly dynamic movements of the aircraft. During extreme maneuvering of the aircraft it was noted that values for parameters obtained from the aircraft's Attitude Heading and Reference System (AHRS) were occasionally missing.

CHAPTER 3

RESULTS

Validation of Derived Parameter Values

Atmospheric Pressure Ratio

A simple linear regression was calculated to predict the atmospheric pressure ratio (δ) using input upon the altitude recorded by the aircraft and the altimeter setting set by the pilot such that $\delta = P / P_0$ where P is equal to the estimated ambient static pressure and P_0 equals the standard sea level static pressure (in.Hg). P is presumed to be the sum of the standard pressure ratio for a given altitude plus a correction factor for non-standard atmospheric pressure. The standard atmospheric pressure was estimated between sea level and 15,000 feet using a linear regression to evaluate the existence of a significant linear correlation between altitude and the standard pressure ratio. A significant correlation was found (F, (1, 10) = 1789.067, $p < .001$), adjusted R^2 of .994 where $\delta_1 =.986 + (-2.904E\text{-}5(\text{Altitude}))$ when altitude is measured in feet. An altitude of 15,000 feet MSL was selected as the maximum altitude required for pressure ratio estimations as this altitude was greater than the maximum altitude of any of the flights contained in the study.

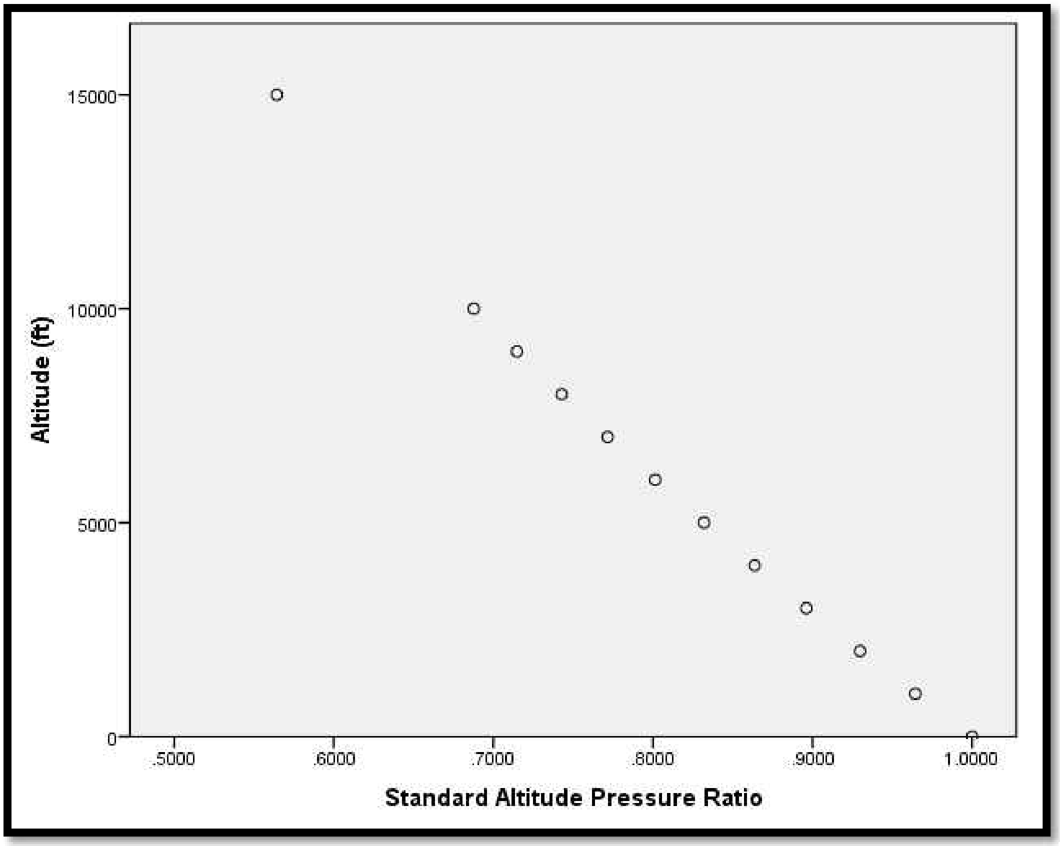

Figure 12. Standard Pressure Ratio vs Altitude (feet).

The predicted standard atmospheric pressure ratio is then corrected for non-standard seal level pressure by summing the predicted pressure ratio at a given altitude with the correction factor applied by the pilot (δ_2) such that the total estimated atmospheric pressure ratio is $\sum_{i=1}^{n} \delta = (1-(1-\delta_1))+(1-\delta_2)$. Results from the control group containing 70,341 samples from 10 flights produced the following values of δ (μ=.86, σ=.06302, σ^2=.004, n=70,341). Values of the predicted pressure ratio versus the recorded altitude of the aircraft above mean sea level in feet for a flight segment can be observed in Figure 13.

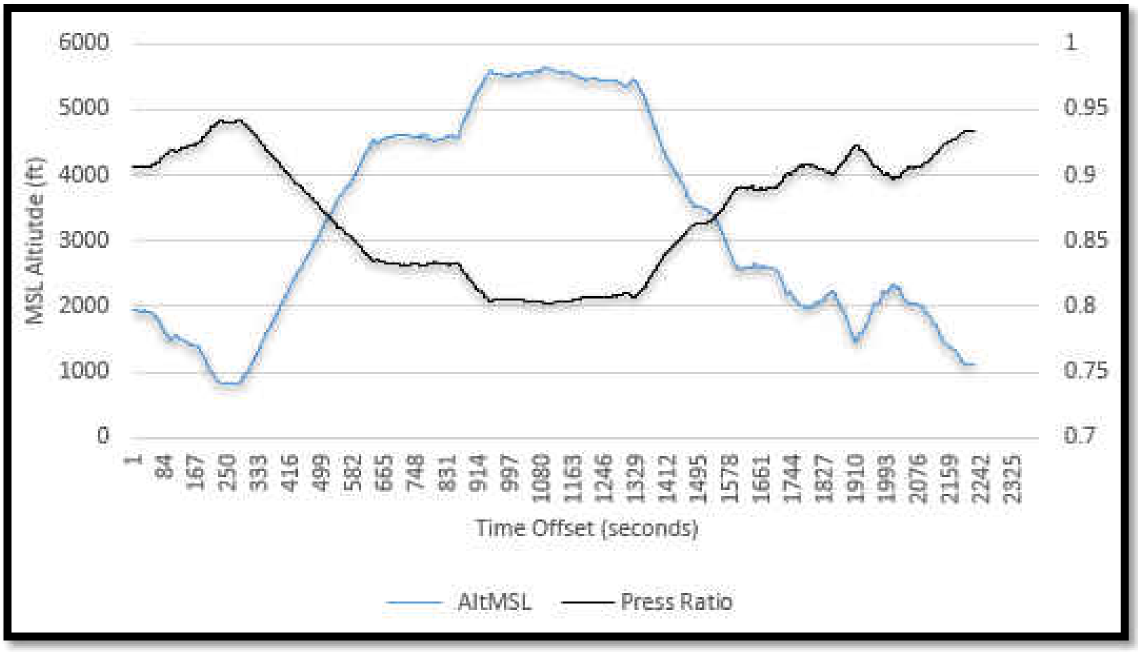

Figure 13. MSL Altitude (feet) vs Pressure Ratio.

Estimating True Airspeed

In order to compare the true velocity along the longitudinal axis to the true vertical velocity of the aircraft, it is necessary to correct the vertical speed recorded from the aircraft for changes in atmospheric pressure and temperature. Using the temperature ratio (ϴ) and pressure ratio (δ), the density ratio (σ) is obtained and used to convert indicated speeds to true speeds where $TAS = EAS \frac{1}{\sqrt{\sigma}}$ where EAS is assumed to equal IAS for airspeeds less than Mach 0.3.

Since the true horizontal speed is recorded by the aircraft, it is possible to determine the estimated horizontal speed error where $TAS_{recorded} = TAS_{estimated} + error_i$. Spearman's correlation coefficient was computed (two-tailed) to determine the correlation between estimated true airspeed and recorded true airspeed in order to validate the purposed methodology. Descriptive statistics for the recorded and estimated true airspeed are provided in Table 1. The results obtained from data in Group 1 indicate a strong correlation, r_s (70,103) = .999, *p<.001,* between the estimated and recorded true airspeed (Figure 14). Therefore the methodology purposed to determine a correction factor required to properly transform the horizontal and vertical indicated speeds into true airspeeds was accepted.

Table 1. Descriptive Statistics for Estimated and Recorded TAS.

Parameter	N	Mean	SD	SE	95% Confidence Interval	
					Lower Bound	Upper Bound
Recorded TAS (knots)	70105	102	22	.08	102	102
Estimated TAS (knots)	70105	102	22	.08	102	102

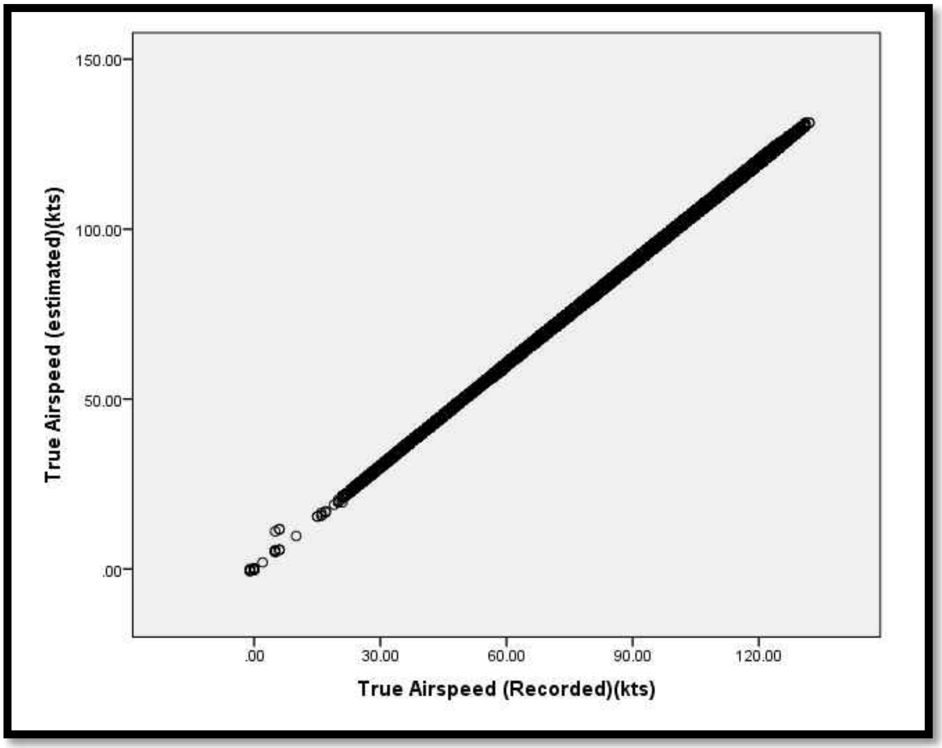

Figure 14. Recorded True Airspeed (knots) vs Estimated True Airspeed (knots).

Estimated Angle of Attack

Estimated AOA is higher during takeoff and landing. The next step in reviewing the accuracy of the purposed methodology for estimating the angle of attack during flight was to examine the control group to ensure the observed outputs during takeoff and landing (n=1,192) were significantly greater than those in all other phases of flight (n=68,843). This test is designed to confirm the sensitivity of observed values to small rate change, longer duration slow speed events that occur when the aircraft's speed is purposefully reduced for the purposes of takeoff and landing. Since flight data in the study is deidentified (exact aircraft identification removed), an independent samples t-test was used to confirm that a significant difference in the mean angle of attack observed between the two populations of samples existed.

Since aircraft generally spend a significant portion of the flight at a lower angle of attack, the data in this group presented with an abnormal distribution exhibiting characteristics of both skewness and kurtosis. Levene's test for equality of variances is significant, F(1935), $p<.001$, therefore equal variance cannot be assumed. Independent samples t-test, assuming non-equal variance, indicates the observed values of angle of attack during takeoff and landing ($M=5.77$, $SE=.103$) was 4.26 degrees higher than in all normal phase of flight ($M = 1.509$, $SE = .01$), $t(1200) = -41.089$, $p < .01$, and validates the hypothesis that observed values of the estimated angle of attack on average are higher during takeoff and landing when compared to all other phases of flight (climbout, cruise, descent, and approach). Since no stalls or loss of control in-flight occurrences were observed, the mean angle of attack between takeoff and landing is compared to all other normal phases of flight (Figure 15). The distribution of all values of angle of attack in Group 1 are provided in Figure 16.

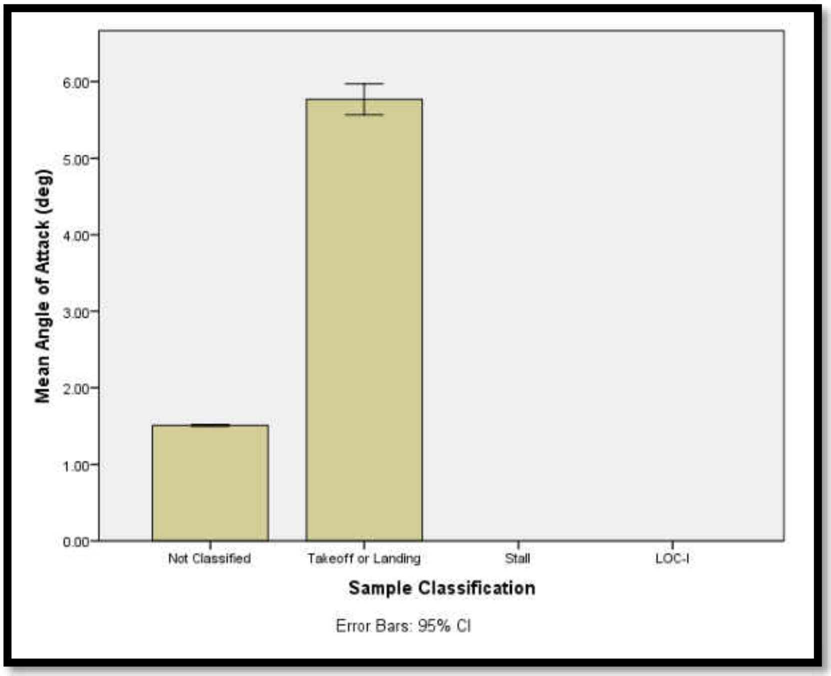

Figure 15. Mean Angle of Attack (degrees) by Sample Classification: Group 1.

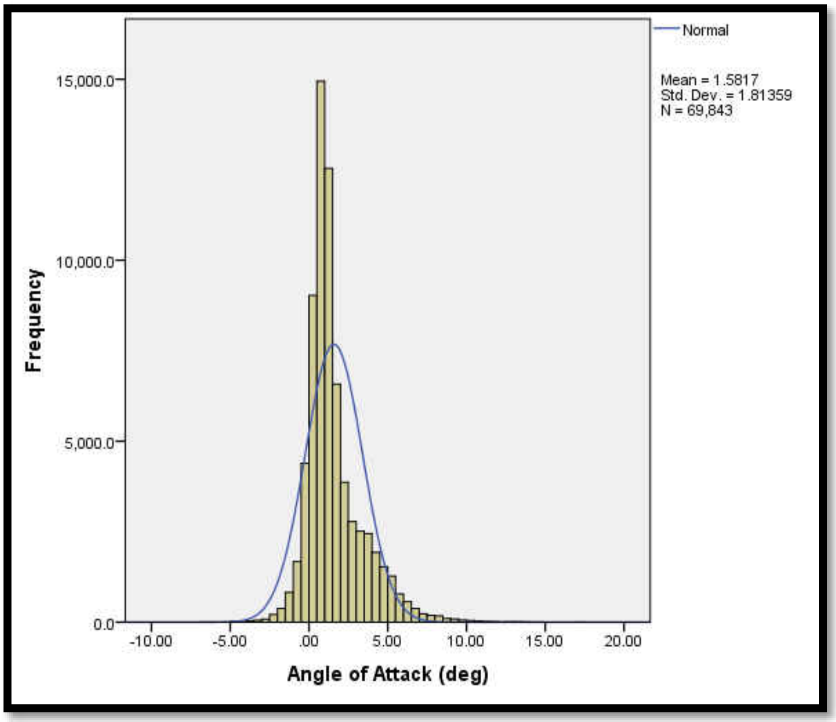

Figure 16. Distribution of Angle of Attack (degrees): Group 1.

Since the distribution of scores is influenced by the manual observation of takeoff and landing, Figures 17 (Observed Takeoff and Landings vs MSL altitude (feet): Group 1) and 18 (MSL Altitude (feet) vs Indicated Airspeed (knots): Group 1) are provided to indicate the locations of the flights where a takeoff and landing was recorded as true.

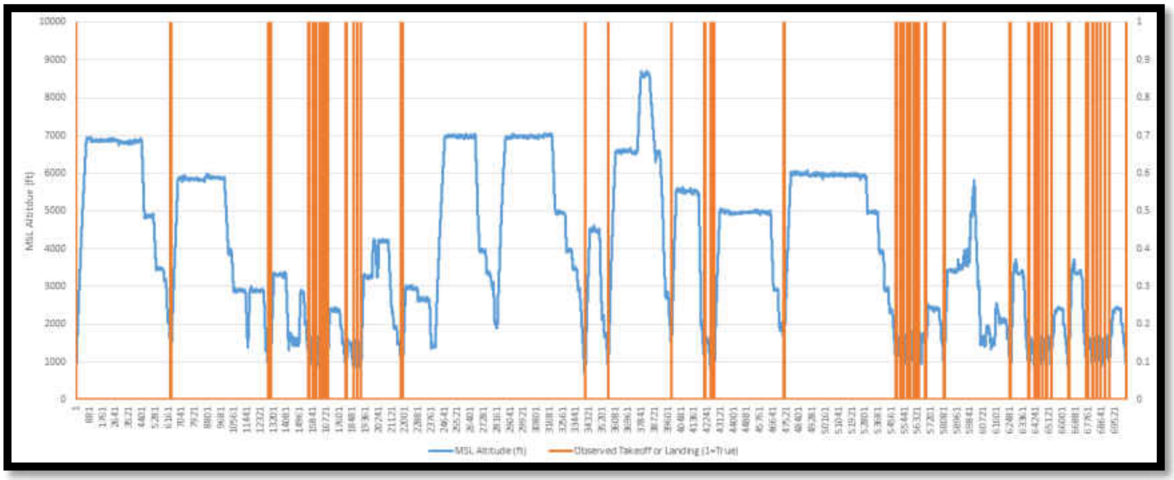

Figure 17. Observed Takeoff and Landings vs MSL altitude (feet): Group 1.

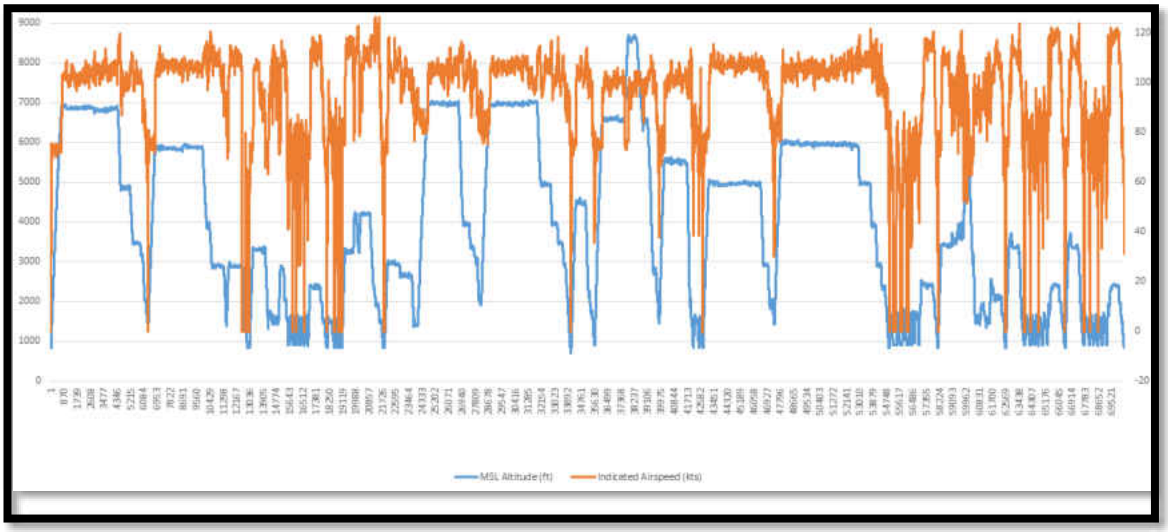

Figure 18. MSL Altitude (feet) vs Indicated Airspeed (knots): Group 1.

Angle of attack is greater when stalls are observed. The next portion to validate was that the observed values of the estimated angle of attack are sensitive to shorter duration, higher rate change events such as stalls. During the execution of demonstrating and practicing stalls in flight training, changes of airspeed, pitch, vertical speed, and angle of attack have higher rate changes and demonstrate more variance than compared to normal flight or takeoffs and landings. Additionally, when intentionally conducting stalls the angle of attack is typically held at a much higher value for a longer period of time than what might be observed during a normal takeoff or landing, therefore it is expected that the angle of attack on average should be higher during stalls.

To test the hypothesis that the observed angles of attack are in fact higher during stalls than all other phases of flight, a one way-ANOVA was used to compare the mean angle of attacks between samples observed during the occurrence of a stall, takeoff and landing, and all other phases of flight. The distribution of angle of attack values from the group of flights containing stalls ($n=40,343$, $M=2.5449$, $SE=.015$) is provided in Figure 19. As was observed in the distribution of angle of attacks from the normal flight group, the distribution of angles of attack in the group of flights containing stalls indicates some skewness and kurtosis likely caused by the high number of samples where the aircraft is not taking off or landing, or stalling and thus have a higher speed and lower angle of attack for the majority of the flight. Test for normality and homogeneity of variances (Levene's test) are significant (F=353.42, p<.001). Since these tests can be significant for large samples even in small unimportant effects, a visual inspection of normality was also conducted (Figure 20).

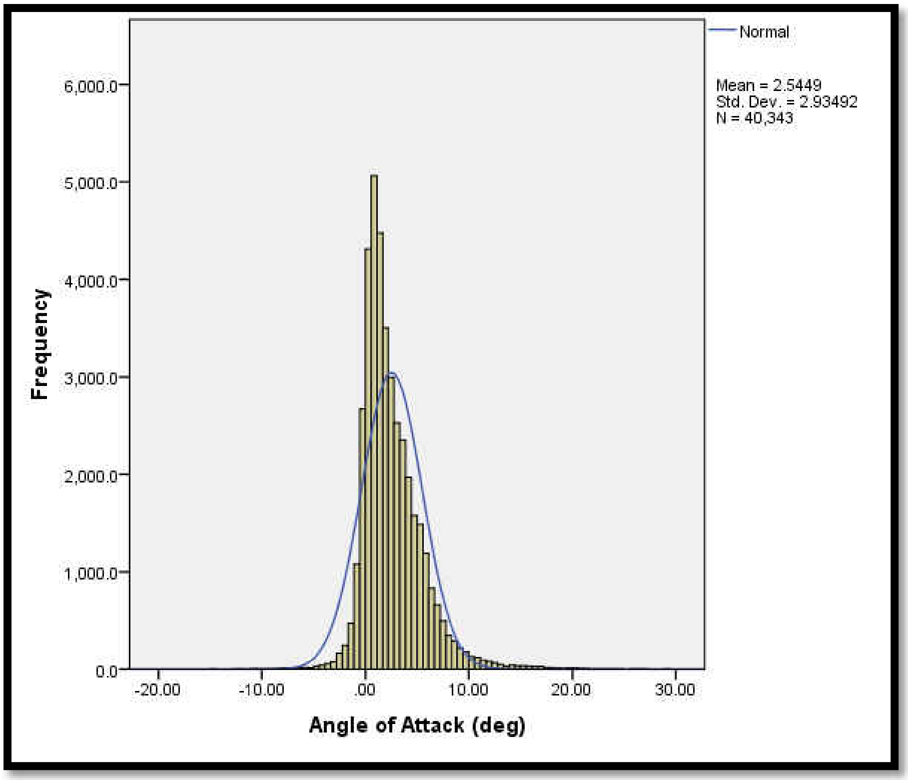

Figure 19. Distribution of Values for Angle of Attack (degrees): Group 2.

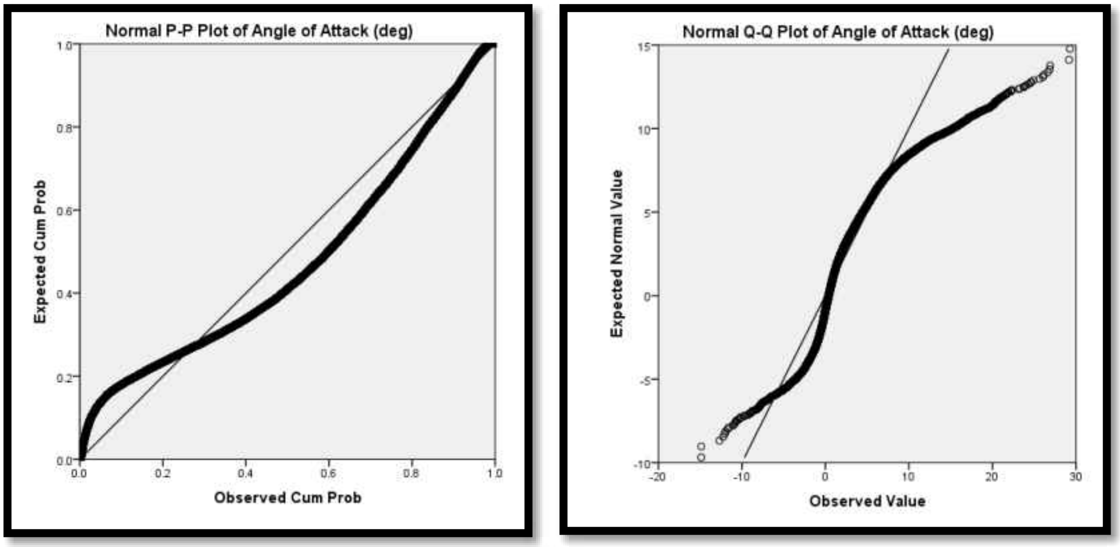

Figure 20. P-P and Q-Q Plots for Angle of Attack (degrees): Group 2.

Analysis of variance indicates a significant difference in the angle of attack output from the normal flight samples (Figure 21. Mean Angle of Attack by Review Classification) compared to the takeoff and landing or stall events, $F(2, 40340) =$

7526.36, *p*<.001. Post hoc analysis using Tukey's HSD indicates that the mean angle of attack when aircraft in the group containing stalls were taking off or landing was 3.8 degrees greater than the mean angle of attack in all other normal phases of flight (*p<.001*), 95 percent CIs (3.55, 4.04) and samples where stalls were occuring had a mean angle of attack that was 10.9 degrees higher than in all other normal phases of flight (*p*<.001), 95 percent CI (10.68, 11.12).

Table 2. Tukey HSD Comparison of Angle of Attack (degrees): Group 2.

Sample Classification	Mean Diff (I-J)	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Takeoff or Landing	3.8***	.11	3.6	4.0
Stall	10.9***	.10	10.7	11.1

**p < .05. **p<.01. ***p<.001*

Since homogeneity of variance cannot be assumed, Dunnett's T3 and Games-Howell tests were conducted to generate more conservative values. Dunnett's T3 indicates the samples of angle of attack when the aircraft was taking off or landing were 3.79 degrees higher than in all other normal phases (*p*<.001), 95 percent CI (3.49, 4.10) and samples during stalls indicated an average angle of attack that was 10.90 degrees higher, 95 percent CI(10.48, 11.33). Similar results were obtained from Games-Howell, samples during takeoff and landing indicated an average increase in angle of attack of 3.80 degrees, (*p<.001*), 95 percent CI (3.50,4.10) and an average increase during stalls of 10.9 degrees (*p*<.001), 95 percent CI (10.49, 11.32).

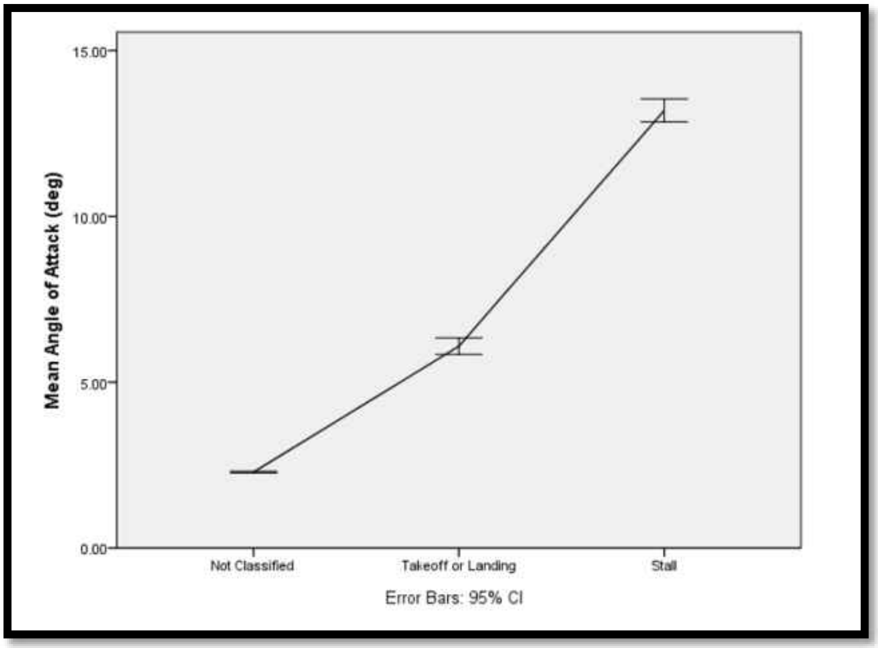

Figure 21. Mean Angle of Attack by Review Classification: Group 2.

Transformation of observed AOA values. To reduce the affect of test assumption violations, the one way-ANOVA was repeated after completing a square root transformation of the data (Figure 22). Using transformed values, a significant difference in angle of attack existed between samples recorded during takeoff and landing, stalls, and all other phases of flight, *F*(2, 40340) = 4149, *p*<.001. Post hoc analysis using Tukey's HSD indicated that the mean transformed angle of attack when aircraft in the test group containing stalls were taking off or landing was .96 degrees greater than the mean angle of attack in all other normal phases of flight (*p<.001*), 95 percent CIs (.88, 1.02). Samples where stalls were occuring had a mean transformed angle of attack that was 2.18 degrees higher than in all other normal phases of flight (*p*<.001), 95 percent CI (2.12, 2.24). Since homogeneity of variance could still not be assumed despite transformation, Dunnett's T3 and Games-Howell tests were conducted to generate more conservative values.

Dunnett's T3 indicated the observed values of the transformed angle of attack when the aircraft was taking off or landing were .96 degrees higher than in all other phases (*p*<.001), 95 percent CI (.89, 1.02) and samples during stalls indicated an average transformed angle of attack that was 2.18 degrees higher, 95 percent CI(2.12, 2.23). Similar results were obtained from Games-Howell, samples during takeoff and landing indicated an average increase in transformed angle of attack of .96 degrees, (*p<.001*), 95 percent CI (.89, 1.02), and an average increase during stalls of 2.18 degrees, (*p*<.001), 95 percent CI (2.13, 2.23).

Table 3. Tukey HSD Comparison of Transformed Angle of Attack (degrees): Group 2.

Sample Classification	Mean Diff (I-J)	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Takeoff or Landing	1.0***	.03	.9	1.0
Stall	2.2***	.03	2.1	2.2

**p < .05. **p<.01. ***p<.001*

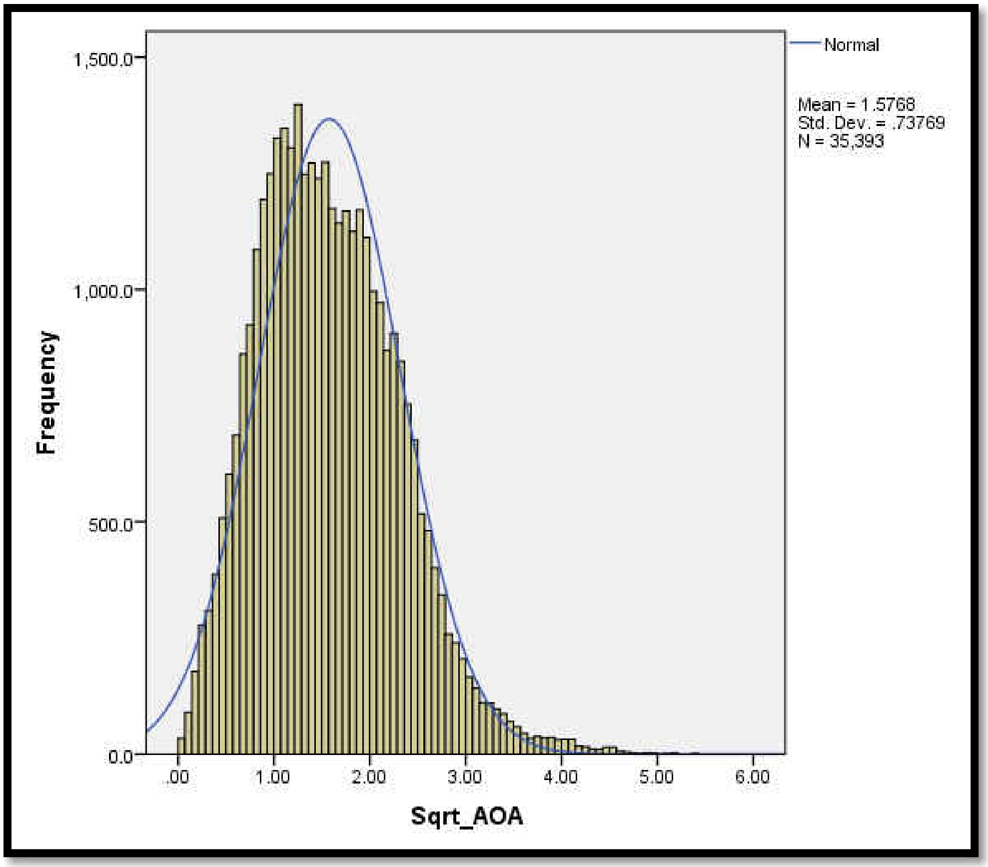

Figure 22. Distribution of AOA Values After sqrt Transformation: Group 2.

Observed values of angle of attack during LOC-I (spins) are equal to or greater than values observed during stalls. The last test conducted to validate that observed values of angle of attack during takeoff and landing, stalls, and spins (loss of control in-flight) were significantly different from each other or, at minimum, that the values of angle of attack during spins are equal to or greater than those observed during stalls. To evaluate this hypothesis, a one-way ANOVA was done using values of angle of attack obtained from the third test group containing 10 flights with stalls and 77 spins. The number of samples in each category are as follows: normal phases of flight (*n*=20771), stalls (*n*=598), and LOC-I (*n*=841).

An analysis of variance is used to identify significant increases in the mean angle of attack during takeoff and landing, stalls, and LOC-I. It is important to note that the observed values of angle of attack are absolute values as the flight dynamics involved with LOC-I may involve inverted flight or flight with highly negative pitch attitudes and extreme bank angles (Figure 23). For the purposes of this study, it was not necessary to differentiate the observed values of angle of attack between the stall group and the LOC-I group as both are stalled conditions, only between the stall or LOC-I groups and the normal flight or takeoff and landing groups as the end goal was to enable anomaly detection in the takeoff and landing phase of flight where the vast majority of LOC-I accidents occur. Figure 24 indicates values of the median angle of attack (degrees) and median absolute value of angle of attack (degrees).

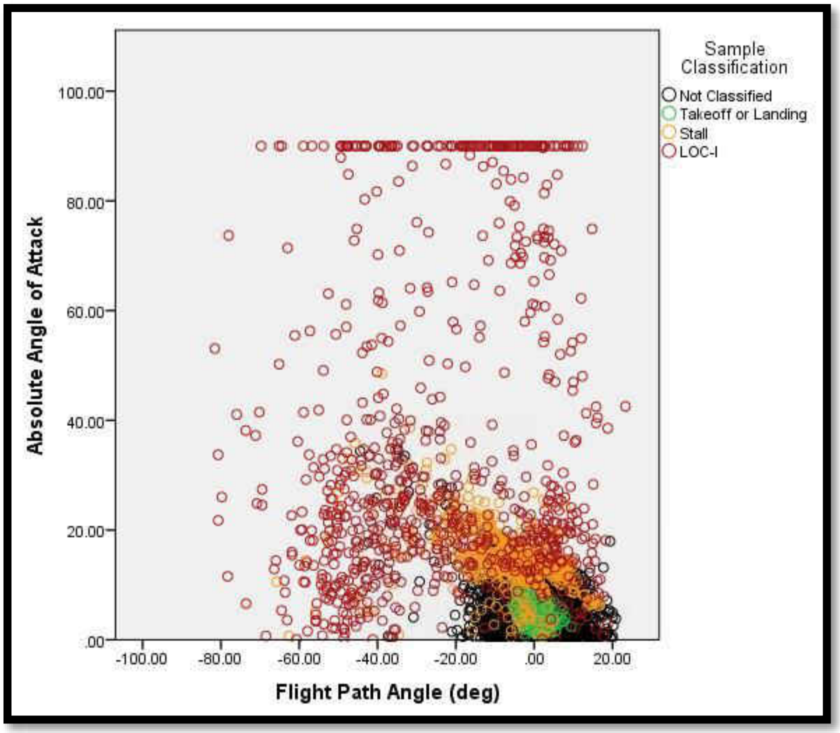

Figure 23. Absolute Angle of Attack (degrees) vs Flight Path Angle (degrees): Group 3.

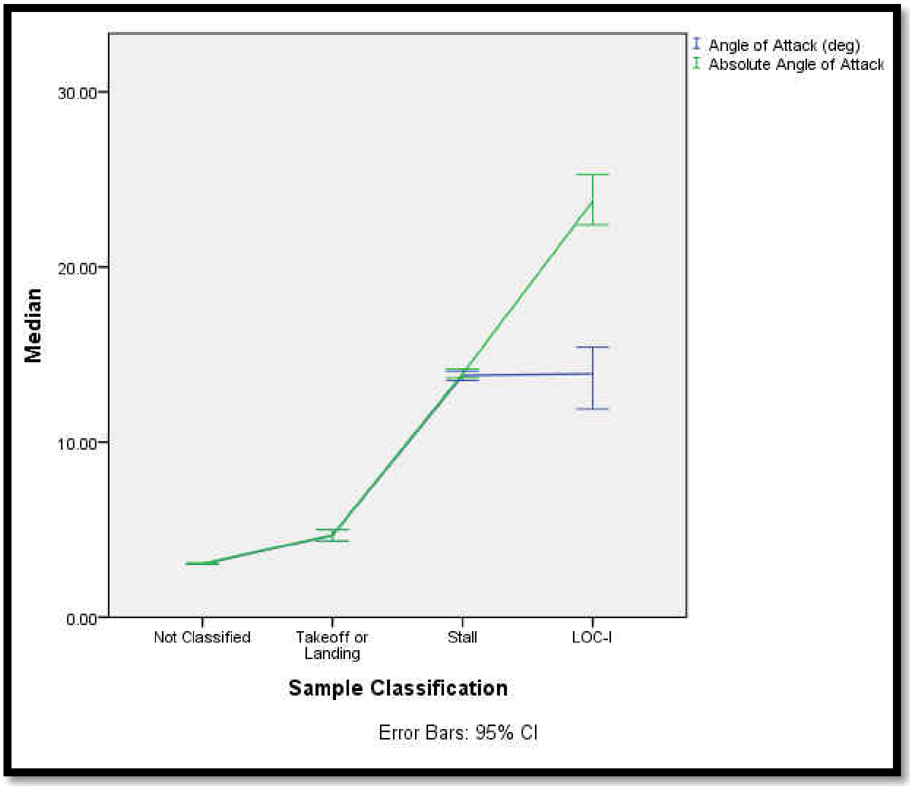

Figure 24. Median AOA and Absolute AOA Binned by Classification: Group 3.

Analysis of variance indicates a significant difference in the absolute value of angle of attack output from the normal flight samples compared to the takeoff and landing, stall, or loss of control in-flight events, *F*(3, 21969) = 7844.17, *p*<.001. Post hoc analysis using Tukey’s HSD indicates that the mean angle of attack when aircraft in the test group containing stalls were taking off or landing was 1.8 degrees greater than the mean absolute value of angle of attack in all other normal phases of flight (*p<.001*), 95 percent CIs (1.01, 2.71). Samples where stalls were observed had a mean absolute value of angle of attack that was 11.47 degrees higher than in all other normal phases of flight (*p*<.001), 95 percent CI (10.81, 12.12). Finally, samples where LOC-I was observed had a mean absolute value of angle of attack that was 30.69 degrees higher than in all other normal phases of flight (*p*<.001), 95 percent CI (29.66, 31.68).

Since homogeneity of variance cannot be assumed, Dunnett's T3 and Games-Howell test were conducted to generate more conservative values. Dunnett's T3 indicates the samples of the absolute value of angle of attack when the aircraft was taking off or landing were 1.86 degrees higher than the angle of attack during the normal phases of flight (p<.001), 95 percent CI (1.43, 2.29). Samples during stalls indicated an average absolute value in angle of attack that was 11.47 degrees higher, 95 percent CI(10.85, 12.10). Samples during LOC-I indicated an average absolute value in angle of attack that was 32.53 degrees higher, 95 percent CI(29.88, 35.18).

Similar results were obtained from Games-Howell. Samples during takeoff and landing indicated an average increase in the absolute value of angle of attack was 1.86 degrees higher than in all other normal phases (p<.001), 95 percent CI (1.44, 2.28). Samples during stalls indicated an average absolute value in angle of attack that was 11.47 degrees higher, 95 percent CI(10.86, 12.08). Samples during LOC-I indicated an average absolute value in angle of attack that was 32.53 degrees higher, 95 percent CI(29.94, 35.12).

Table 4. Tukey HSD Comparison of Absolute Angle of Attack (degrees): Group 3.

Sample Classification	Mean Diff (I-J)	Std. Error	95% Confidence Interval Lower Bound	Upper Bound
Takeoff or Landing	1.9***	.33	1.0	2.7
Stall	11.5***	.26	10.8	12.1
LOC-I	32.5***	.22	32.0	33.0

**p* < .05. ***p*<.01. ****p*<.001

Aircraft Coordination as a Valid Predictor of Pro-Spin Forces

To estimate the coordination of the aircraft, values of β were observed where + values of β indicated a skidding condition, which occurs when the yaw rate (degrees/second) of the aircraft is too large when compared to the bank angle, and where –β condition represents a slip where the magnitude of yaw rate is too low when compared to the bank angle. Since rate of turn is not a recorded parameter, the derivative of magnetic heading is used to express the rate of turn in degrees per second and is then multiplied by the true velocity of the aircraft to estimate the horizontal vector component required for coordination that comes from yaw rate. In this case, when the aircraft is coordinated there should exist a positive correlation between bank angle and rate of turn for a given value of *TAS* (knots). The hypothesis of a positive correlation between bank angle and rate of turn is tested using a linear regression.

Since there exists no recorded air/ground position for the aircraft or a methodology of accurately determining when the aircraft is airborne and being airborne is a factor which would greatly affect the relationship between yaw rate and bank angle, all samples below 2,000 feet MSL were excluded. In addition, only data from Group 1 was analyzed as data from Group 2 (stall) and Group 3 (spin) would likely contain a multitude of samples where uncoordinated flight conditions exist. Figure 25 (Bank Angle vs Yaw Rate) contains all values of the yaw rate (degrees/second) and bank angle (degrees) during the normal phases of flight (n=53590). When we control true airspeed on the relationship between bank angle (degrees) and yaw rate (degrees/second), we find the following partial correlation, $r = .92$, $p < .001$.

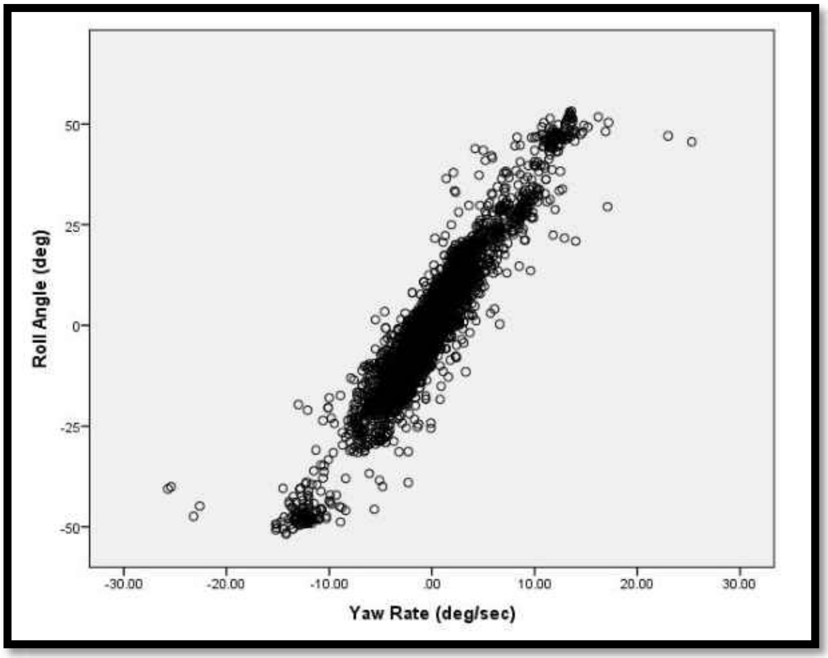

Figure 25. Bank Angle vs Yaw Rate (degrees/second): Group 1.

When all samples of flight data are included, the uncoordinated yaw rate vs bank angle samples from ground operations such as taxi and the rollouts of takeoff and landing appear on the horizontal axis as seen in Figure 26.

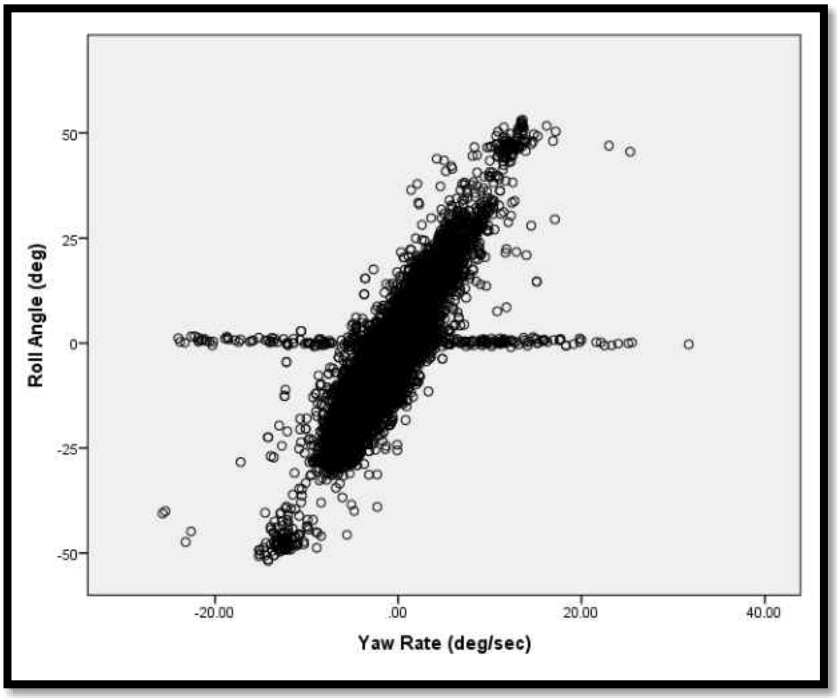

Figure 26. Roll Angle (degrees) vs Yaw Rate (degrees/second) (all samples): Group 1.

After analyzing results obtained from the the derived parameters, the next step was to take the insights gained and apply them to values used to determine probabilities of the existence of a stall and the existence of uncoordinated flight, which are two of the leading contributions to a loss of control in-flight. Although the presence of a stall may be operationally significant in certain phases of flight, including low altitude maneuvering flight, the most deadly encounters occur when a stall and uncoordinated (slipping or skidding) flight occur simultaneously. A benchmark score of 15 for absolute values of angle of attack to determine the presence of a stall condition was obtained from the result of analyzing observed values of angle of attack from samples of data in the group containing spins (*M*=14.81, 95 percent CI (14.34, 15.27)), due to the aerodynamic limitation that an aircraft must be stalled to spin. The value of 15 is greater than six standard deviations above the mean angle of attack in the normal flight group during all phases of flight except takeoff and landing (*M*=1.51, *SD*=1.68), and very near the value of three standard deviations above the mean angle of attack during takeoff and landing (*M*=5.76, *SD*=3.57).

The same methodology for anomaly detection regarding coordination and the probability of uncoordinated flight or the existence of pro-spin forces was conducted and a value of 4 was selected as a benchmark. Values of 4 or greater may indicate a high probability that pro-spin forces exist. The value of 4 was again obtained from an analysis of flight data in the group of flights with spins as seen in Figure 26, where samples during normal flight *N=20170*, (*M*=1.27, 95 percent CI [1.25, 1.30]) had significantly better coordination than samples where LOC-I was true *N*=841 (*M*=34.89, 95 percent CI [31.30, 38.49]), *F* (3, 21957)=2738.78, *p*<.001. Since Levene's test for homogeneity of variance was significant, *p*<.001, homogeneity of variance cannot be assumed. Analysis of variance using Tukey HSD indicates a non-significant decrease in coordination during takeoff and landing (*M*=.06, *p*=1.0), 95 percent CI (-1.40, 1.51), an additional significant decrease in coordination during stalls was observed (*M*=1.23, *p*=.026), 95 percent CI (.10, 2.35), and a significant decrease in coordination during LOC-I (*M*=33.62, *p*<.001), 95 percent CI (32.67, 34.57).

Similar results are observed using Dunnett's T3 which indicated a non-significant decrease in aircraft coordination during taking off or landing were (*M*=.056, *p*=.969), 95 percent CI (-.14, .25). Samples during stalls indicated a significant decrease in coordination (*M*=1.23, *p*<.001), 95 percent CI (.72, 1.73). Samples during LOC-I reveal a further decrease in coordination (*M*=33.62, *p*<.001), 95 percent CI (28.79, 38.46).

Again values using Games-Howell test produced similar results indicating a non-significant decrease in coordination during takeoff and landing *(M*=.06, *p*=.868), 95 percent CI (-.13, .24). Samples during stalls indicated a significant decrease in coordination (*M*=1.23, *p*<.001), 95 percent CI (.74, 1.71). Samples during LOC-I indicated further decrease in coordination (*M*=33.62, *p*<.001), 95 percent CI (28.90, 38.34).

Table 5. Tukey HSD Comparison of Absolute Coordination Estimate: Group 3.

Sample Classification	Mean Diff (I-J)	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Takeoff or Landing	.06	.57	-1.4	1.5
Stall	1.2*	.44	.1	2.4
LOC-I	33.6***	.37	32.7	34.6

**p* < .05. ***p*<.01. ****p*<.001

Follow-up nonparametric significance testing using the independent-samples Krukal Wallis Test indicates a non-significant difference (asymptotic significance (2-sided test)), with significance values adjusted with Bonferroni correction for multiple tests, in the absolute value of coordination between observed samples in the normal phase of flight and takeoff and landing, H= -173.77, p > .99. However a significant difference between the coordination during normal flight and loss of control in-flight was observed, H= -9,941.51, p <.001, r= .31, as well as a significant difference in coordination between stalls and loss of control in-flight, H= -8,335.96, p < .001, r= .65. The pairwise comparisons of sample classifications are shown in Figure 28.

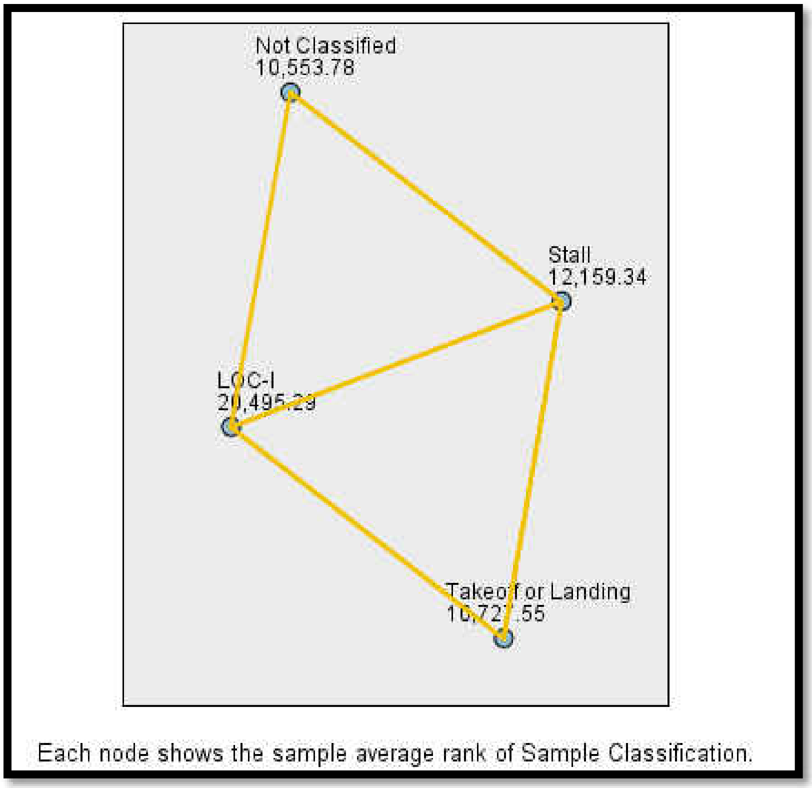

Figure 27. Pairwise Comparisons of Sample Classification.

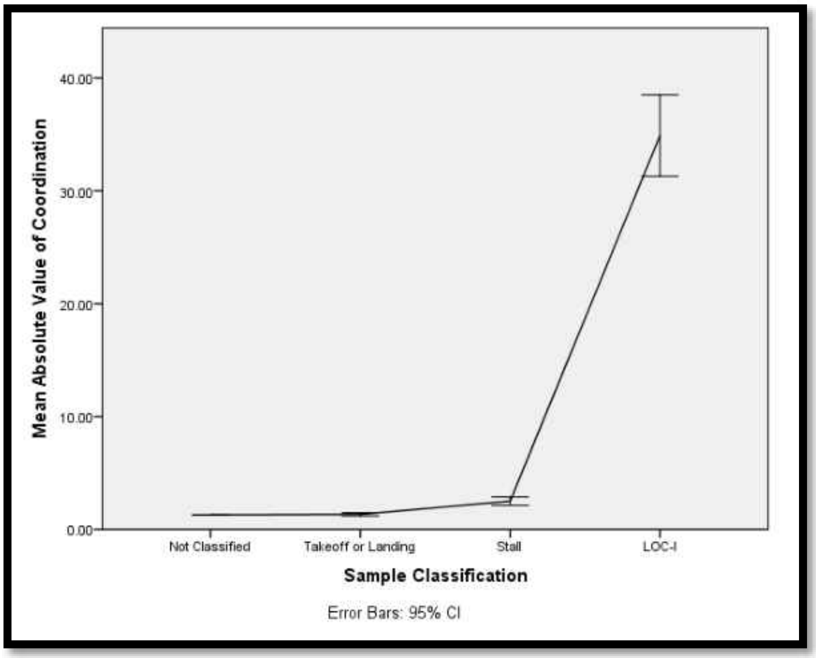

Figure 28. Mean Absolute Value of Coordination by Sample Classification: Group 3.

Table 6. Independent-Samples Kruskal Wallis Test Average Rank Samples Classification: Group 3.

Sample 1 – Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.	Effect Size
Normal Phase – Takeoff or Landing	-173.8	340.9	-.51	.61	1.0	---
Normal Phase – Stall	-1,605.6	263.1	-6.1	<.001	<.001	.04
Normal Phase – LOC-I	-9,941.51	223.1	-44.6	<.001	<.001	.31
Takeoff or Landing – Stall	-1,431.78	425.9	-3.4	<.001	.005	.11
Takeoff or Landing – LOC-I	-9,767.75	402.5	-24.3	<.001	<.001	.71
Stall – LOC-I	-8,3356.0	339.1	-24.6	<.001	<.001	.65

Asymptotic significances (2-sided test) displayed

Validation of Probability Estimates as Valid Predictors of Stall or LOC-I Occurrences

Probability P|A| of Stall

Analysis of stall probabilities during normal phases of flight. Observed values of angle of attack were transformed into probability values, such that the probability of stall increases linearly with each incremental increase in angle of attack until the angle of attack reaches a value of 15 degrees, at which point the probability will remain at a maximum of 100 percent. The next research question to answer was, are the stall probabilities reasonably low in the group containing no stalls?

In the first group, there were a total of 10 flights which contained zero observed stalls or spins. The distribution of the stall warning probabilities are indicated in Table 7 and displayed in Figures 29 and 30, where the mean probability for stall and loss of control are binned by the classification for each sample. The no classification binning represents all normal phases of flight. Within the group of flights containing no stalls (*N*=70,075), the stall probabilities were in fact relatively low (*M* =.12, *SD*=.11), as were the probabilities of loss of control in-flight (*M* =.03, *SD* = .06).

Table 7. Descriptive Statistics for Stall Warning and LOC-I Probabilities (percent): Group 1.

					95% Confidence Interval	
Parameter	N	Mean	SD	SE	Lower Bound	Upper Bound
Stall Probability	70075	11.5%	11%	.0	11.4%	11.6%
LOC-I Probability	69847	3.4%	6.4%	.0	3.3%	3.4%

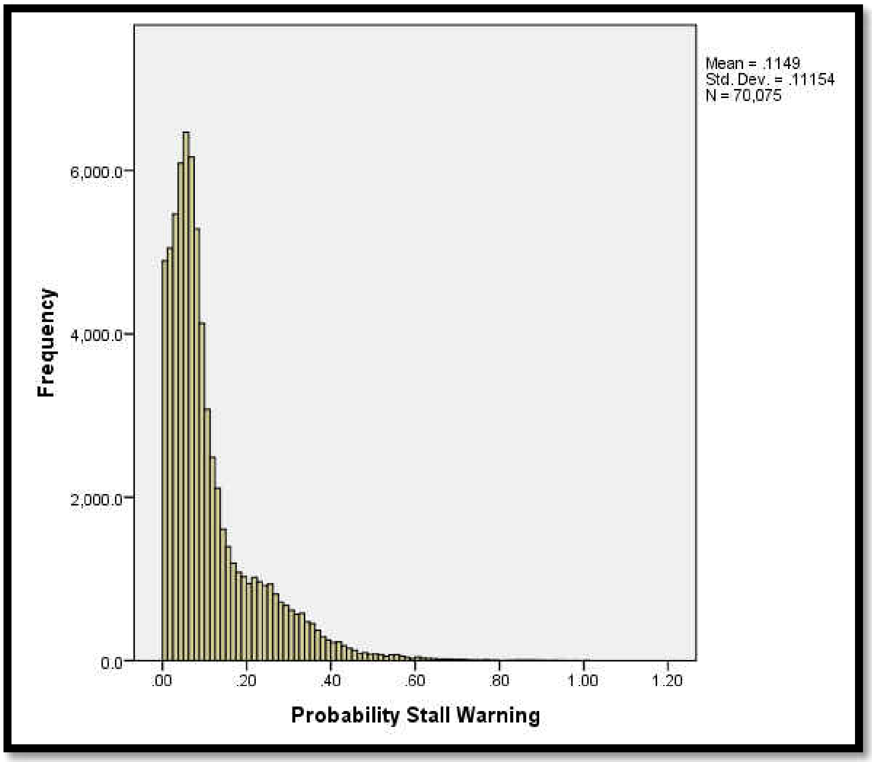

Figure 29. Distribution of Stall Probabilities: Group 1.

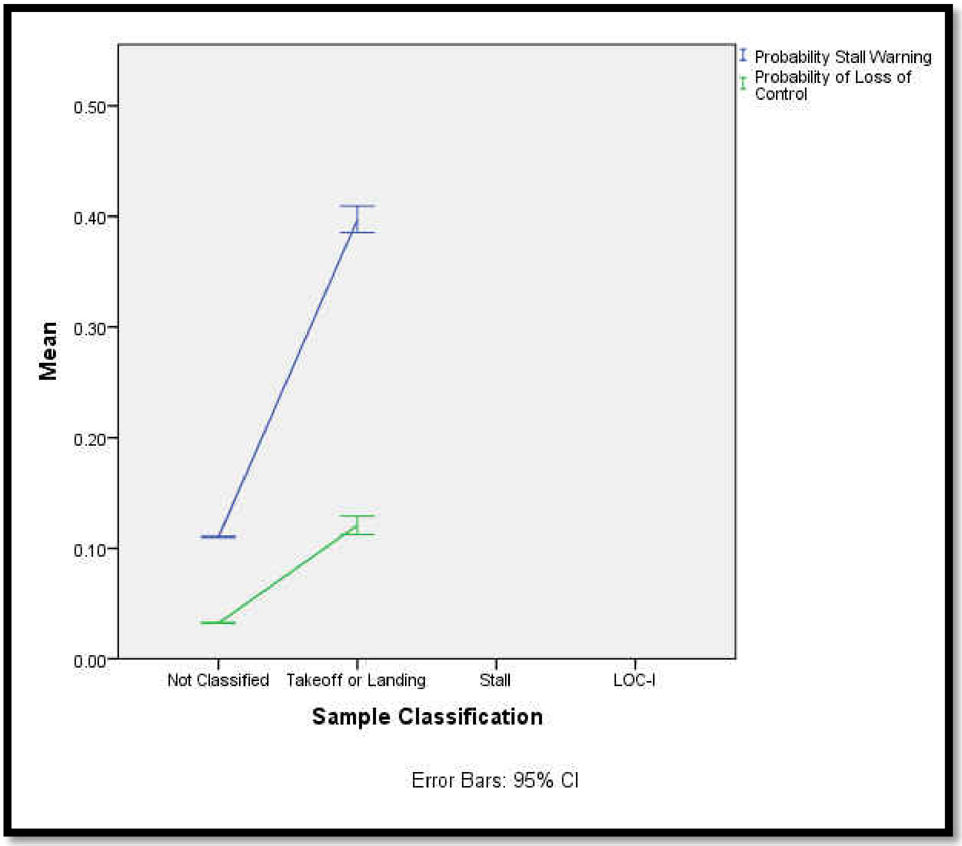

Figure 30. Mean Stall and LOC-I Probability by Sample Classification: Group 1.

Filtering for stall probabilities when the takeoff or landing is false reveals an outlier for stall probability in the normal phase of flight category at point 14238 (Figure 31).

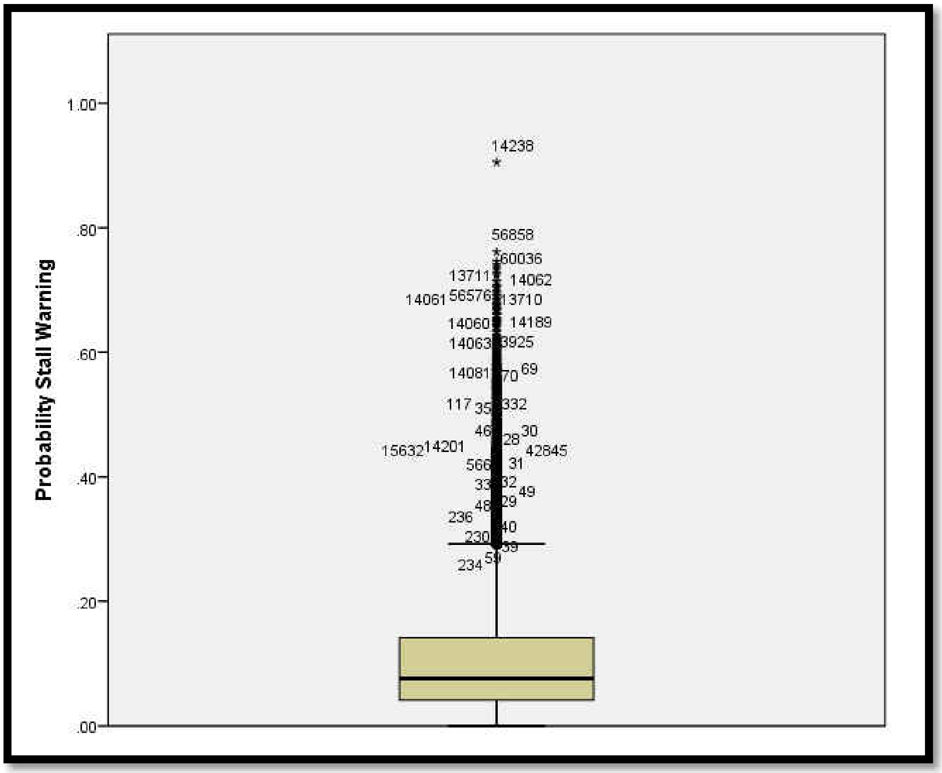

Figure 31. Stall Probabilities When Takeoff or Landing is False: Group 1.

Investigation of this outlier indicates a go-around maneuver was performed from an approach where the angle of descent increased to a -9.28 degree flight path angle and negative 1,142 fpm vertical speed, followed by a transition to a climbing pitch attitude with an increase to +1.3g of normal acceleration. The maneuver occurred at 68 knots of indicated airspeed and resulted in a 10 degree increase of the calculated angle of attack from 3 degrees to 13.58 degrees. Two seconds before and after the maximum AOA was observed, the calculated angle of attack was 2.62 degrees and 6.81 degrees respectively, indicating only a momentary increase in the probability of stall as the aircraft abruptly transitioned to a missed approach.

Analysis of stall probabilities in group containing stalls. In the group of flights containing stalls, there were a total of 40,343 samples of data obtained from 10 flights which contained a total of 747 samples of data encompassing 70 observed stalls with no loss of control in-flight events. Table 8 contains descriptive statistics of the stall and LOC-I probability values binned by sample classifications. Distributions for stall warning and loss of control in-flight probability scores are provided in Figures 32 and 33 while Figure 34 indicates the mean probabilities for stall and loss of control in-flight controlling for the 4 review classifications.

Table 8. Descriptive Statistics for Stall Warning and LOC-I Probabilities (percent): Group 2.

					95% Confidence Interval	
Parameter	N	Mean	SD	SE	Lower Bound	Upper Bound
Normal Phases						
Stall Probability	38602	16.8%	14.6%	.0	16.7%	16.9%
LOC-I Probability	38602	6.4%	9.5%	.0	6.3%	6.5%
Takeoff or Landing						
Stall Probability	573	40.9%	19.5%	.0	39.2%	42.5%
LOC-I Probability	573	14.7%	15.9%	.0	13.3%	16.0%
Stalls						
Stall Probability	738	82.7%	19.2%	.0	81.3%	84.1%
LOC-I Probability	738	38.4%	31.9%	.0	36.1%	40.7%

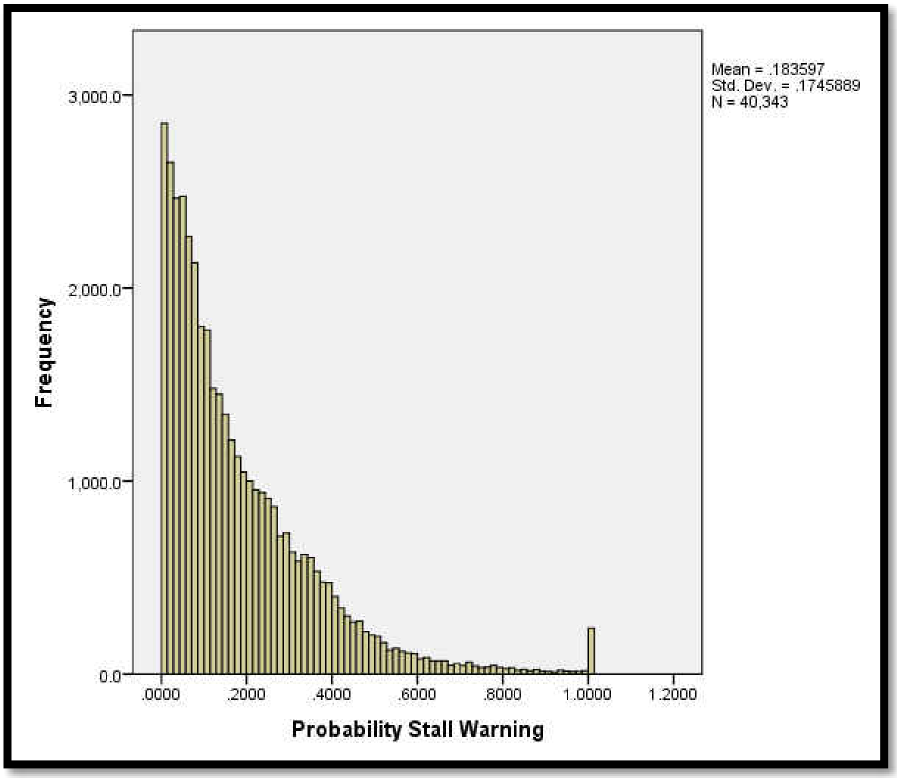

Figure 32. Distribution of Stall Probability: Group 2.

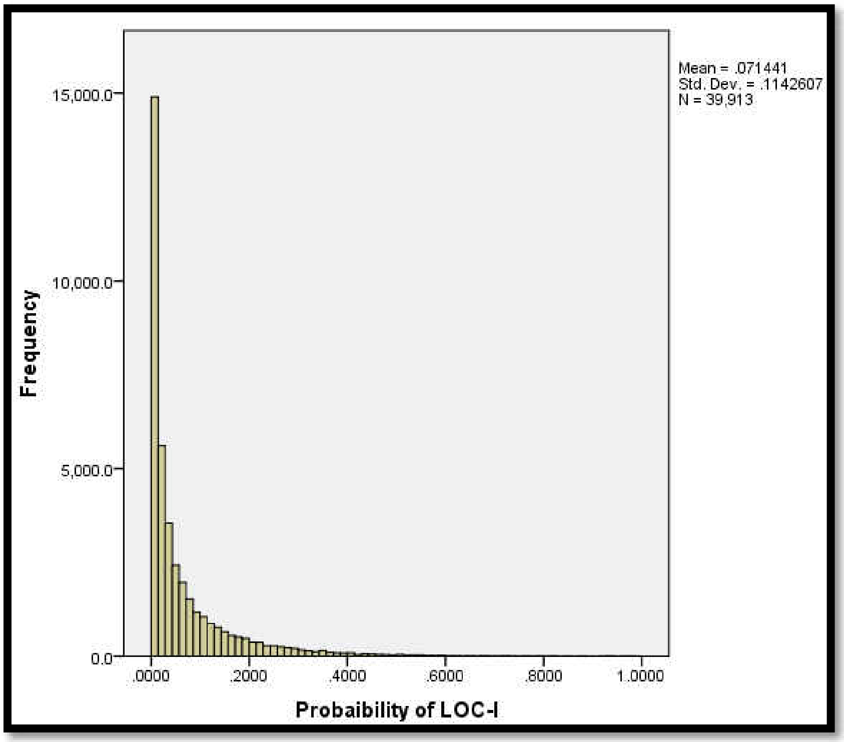

Figure 33. LOC-I Probability Distribution: Group 2.

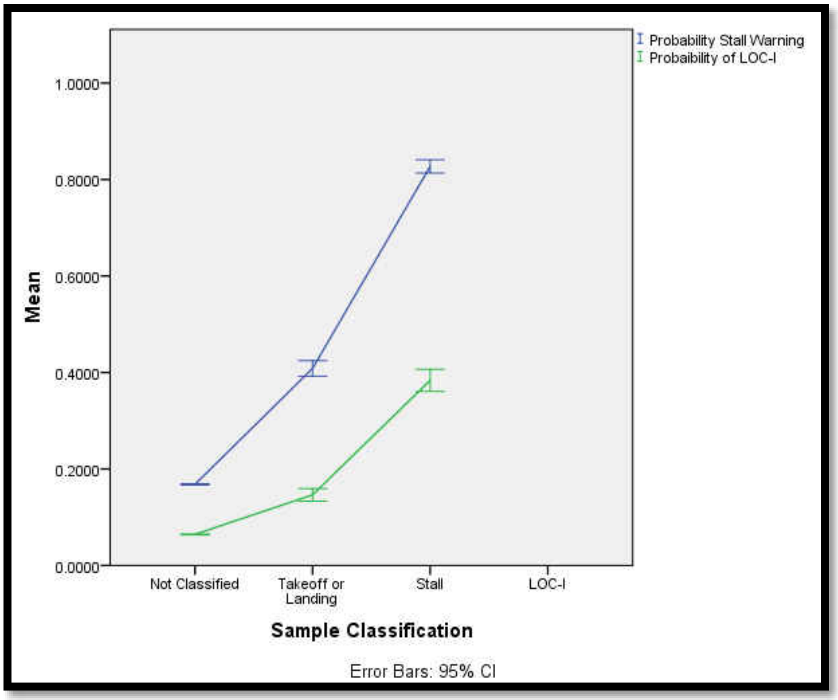

Figure 34. Mean Probability of Stall Warning and LOC-I by Sample Classification: Group 2.

Results of K-Means cluster analysis using data from Group 2 was used to assess the hypothesis that 3 clusters would exist (normal phases, takeoff and landing, and stall), representing each of the sample classification groups whereby the cluster centers are evaluated based upon stall warning probabilities. Results are indicated in Tables 9 and 10. Examining the means and distances between each of the 3 cluster centers supports the hypothesis. The next research question answered was, do values of stall probability increase significantly when a stall is observed?

Table 9. K-Means Final Cluster Centers: Group 3 (stall probabilities).

Cluster	1	2	3
Stall Probability	.31	.09	.68
Number of Cases in Each Cluster	12316	25756	2271

Table 10. K-Means Final Distance Between Cluster Centers: Group 3.

Cluster	1	2	3
1		.228	.368
2	.228		.596
3	.368	.596	

Stall probability values for samples during which a stall was observed (*Mdn* = .863) were significantly higher than values of stall probability during which stalls were not observed (*Mdn* = .128), $U = 29{,}096{,}243$, $z = 45.37$, $p < .001$, $r = .23$. To account for the large number of samples where no observed stall was occurring, the test for a significant difference between the population of samples was repeated by randomly selecting 1000 samples of stall probabilities when a stall was observed ($n = 984$, missing = 16) and 1000 samples of stall probabilities when no stall was observed ($n = 976$, missing = 24) in order to test for a significant difference in stall probability values between the observed and not observed stalls. Occasionally, samples are missing as can occur if the airspeed drops to 0 knots during the landing rollout or, less frequency, if data was missing from the recording.

As samples were randomly selected from each group, the corresponding samples of randomly missing data is reported. Figure 35 indicates the frequency distribution of the stall probability scores of the randomly selected samples observed in each group. Stall probabilities values when stalls were observed (*Mdn* = 1.0) were significantly greater than the stall probabilities when no stalls were observed (*Mdn* = .21), *U* = 937,088, *z* = 37.0, *p* <.001, *r* = .84.

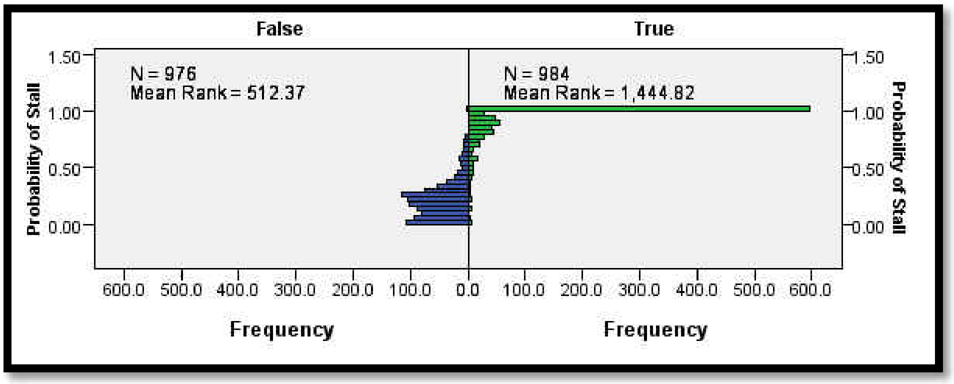

Figure 35. Frequency Distribution of Random Selection Groups for Stall Probability Ranking vs Observed Stalls.

Probability P|B| of Loss of Control In-Flight

Analysis of loss of control in-flight scores within the group of flights containing stalls. As no observed occurrences of loss of control in-flight existed within Group 2, an analysis of the loss of control in-flight probability scores was conducted to ensure the values of loss of control in-flight were reasonably low, even when the aircraft was stalled. This analysis confirms that the coordination estimates for pro-spin forces and the benchmarked angle of attack values are working in combination to provide adequate discrimination between a stall and a true loss of control in-flight. Figure 36 includes boxplots of the probability values for loss of control in-flight for each of the classification groups.

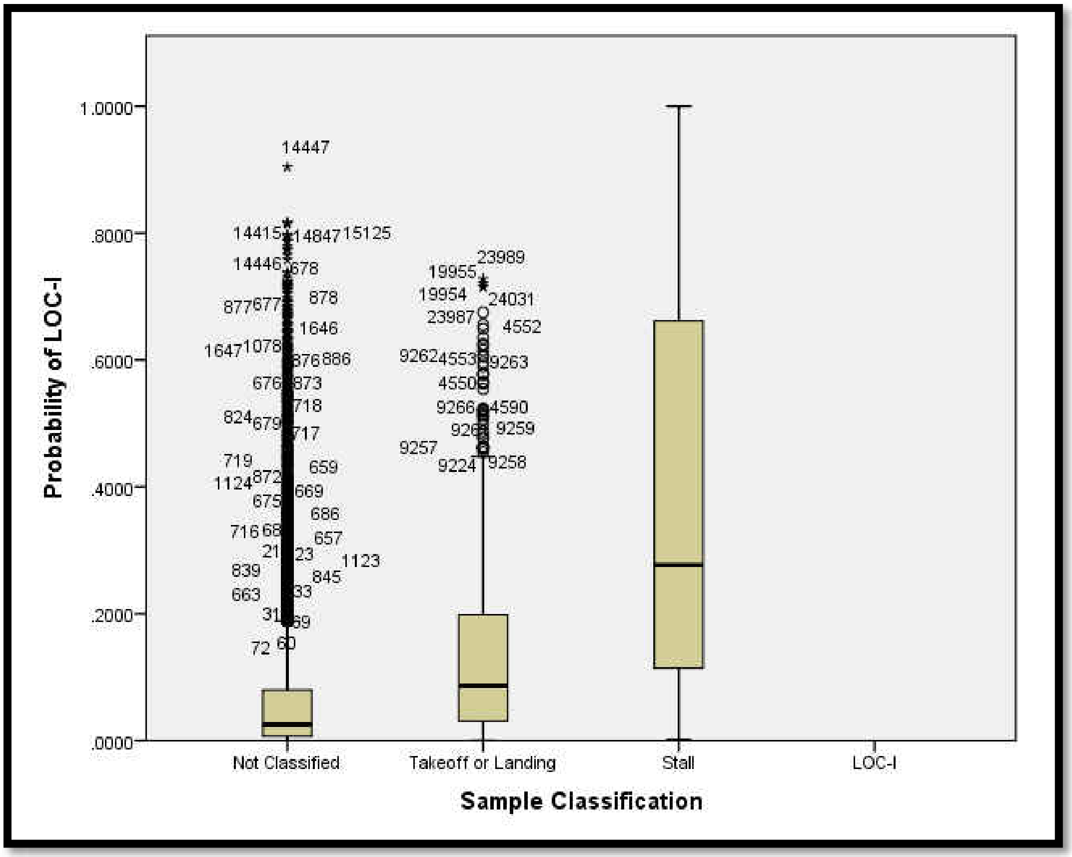

Figure 36. Boxplot of LOC-I Probabilities: Group 2.

The mean probability for loss of control in-flight in Group 2 (flights containing stalls) was *.07, (SD* = .11). As expected, there was a significant increase in the median value for loss of control in-flight when the aircraft was taking off or landing (*Mdn* = .09), *U* = 7,879, *z* = 16.25, *r* = *.68*, and a further significant increase in values when the aircraft was stalling (*Mdn* = .28), *U* = 14,840.78, *z* = 34.66, *r* = .78.

Analysis of outlier point 14447 indicates a go-around maneuver which was performed at an altitude of 1607 feet MSL. After initiating the go-around maneuvering, the pitch become stable around 7-8 degrees nose high, however, the airspeed began to decay. When the airspeed reached 57 knots indicated airspeed, the pitch had increased to 17.14 degrees and the angle of attack increased to 13.56 degrees. At the peak recorded pitch value, the aircraft's yaw rate increased to 3.4 degrees/second at a bank angle of 2.09 degrees, indicating a high pitch, low speed, uncoordinated flight condition. After the peak LOC-I probability value of 90.42 percent was obtained, the aircraft reached an apparent desired level off altitude of 1,900 feet MSL, at which time the aircraft pitch was reduced to level flight and the angle of attack was reduced to less than 6 degrees.

Analysis of Loss of Control In-flight Probabilities in Group Containing Spins

Loss of control in-flight for training purposes. Since the data analyzed in this study was an analysis of flight data from a pre-existing dataset, it is important to note that all data has been de-identified and no attempt to measure or evaluate compliance of the aircraft operations according to the limitations set forth by the FAA or aircraft manufacturers was made. During the conduct of normal flight training, pilots occasionally receive training on recovery techniques from occurrences of aircraft upsets and loss of control in-flight conditions including spins. The research question to be answered is, can the probability distributions observed from these populations be used to properly identify the LOC-I events being conducted and do the values observed during these events vary significantly from the population of samples obtained during all other normal phases of flight?

In the group of flights containing stalls, there were a total of 21,974 samples of data obtained from 10 flights which contained a total of 823 samples of data encompassing 77 observed spins. Figure 37, 38, and 39 indicate the distribution of stall warning and loss of control in-flight probability scores, followed by the mean probabilities for stall and loss of control in-flight controlling for the 4 review classifications. Visual inspection of stall probabilities in Figure 37 indicates the presence of a multimodal distribution with a high count of scores equaling 100% probability of stall.

Table 11. Descriptive Statistics for Stall Warning and LOC-I Probabilities (percent): Group 3.

Parameter	N	Mean	SD	SE	95 % Confidence Interval Lower Bound	95 % Confidence Interval Upper Bound
Normal Phases						
Stall Probability	20150	22.2%	16.4%	.0	22%	22.4%
LOC-I Probability	20150	6.7%	9.4%	.0	6.6%	6.9%
Takeoff or Landing						
Stall Probability	354	34.7%	20.1%	.0	32.6%	36.8%
LOC-I Probability	354	12.1%	15.3%	.0	10.5%	13.7%
Stalls						
Stall Probability	596	84.0%	20.2%	.0	84.0%	87.2%
LOC-I Probability	596	32.0%	27.7%	.0	29.7%	34.2%
LOC-I						
Stall Probability	823	90.3%	22.4%	.0	88.7%	92.8%
LOC-I Probability	823	83.9%	28.5%	.0	82%	85.8%

Results of K-Means cluster analysis using data from Group 3 was used to assess the hypothesis that 4 clusters would exist (normal phase, takeoff and landing, stall, and LOC-I) representing each of the sample classification groups whereby the cluster centers are evaluated based upon loss of control inflight probabilities. Results are indicated in Tables 10 and 11 below. Examining the means and distances between each of the 4 cluster centers supports the hypothesis.

Table 12. K-Means Final Cluster Centers: Group 3.

Cluster	1	2	3	4
LOC-I Probability	.97	.03	.48	.18
Number of Cases in Each Cluster	737	16824	759	3603

Table 13. K-Means Final Distance Between Cluster Centers: Group 3.

Cluster	1	2	3	4
1		.933	.484	.786
2	.933		.449	.147
3	.484	.449		.302
4	.786	.147	.302	

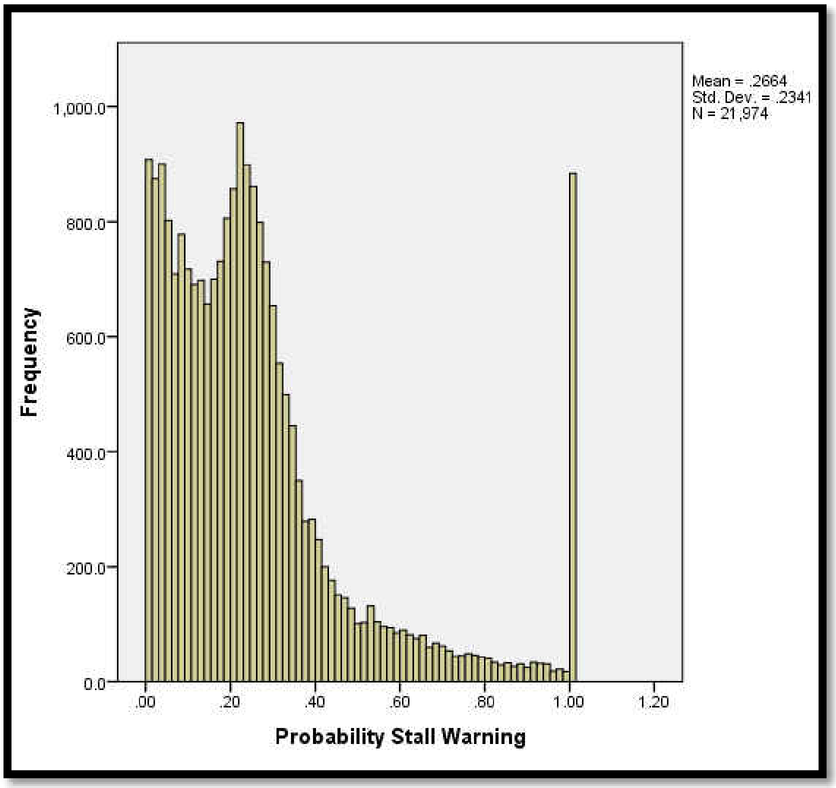

Figure 37. Distribution of Stall Warning Probabilities: Group 3.

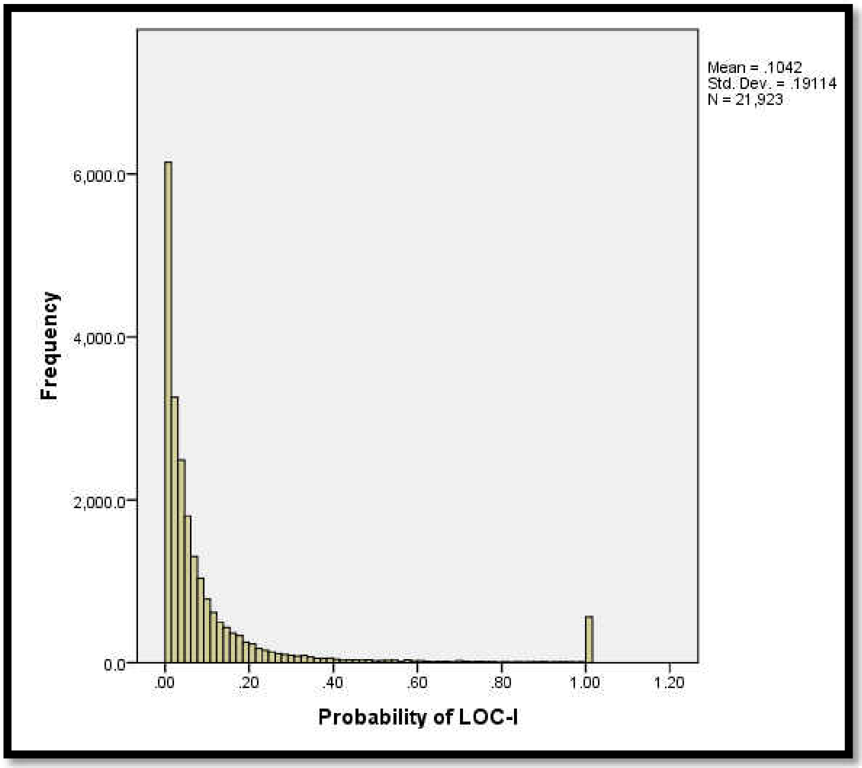

Figure 38. Distribution of LOC-I Probabilities: Group 3.

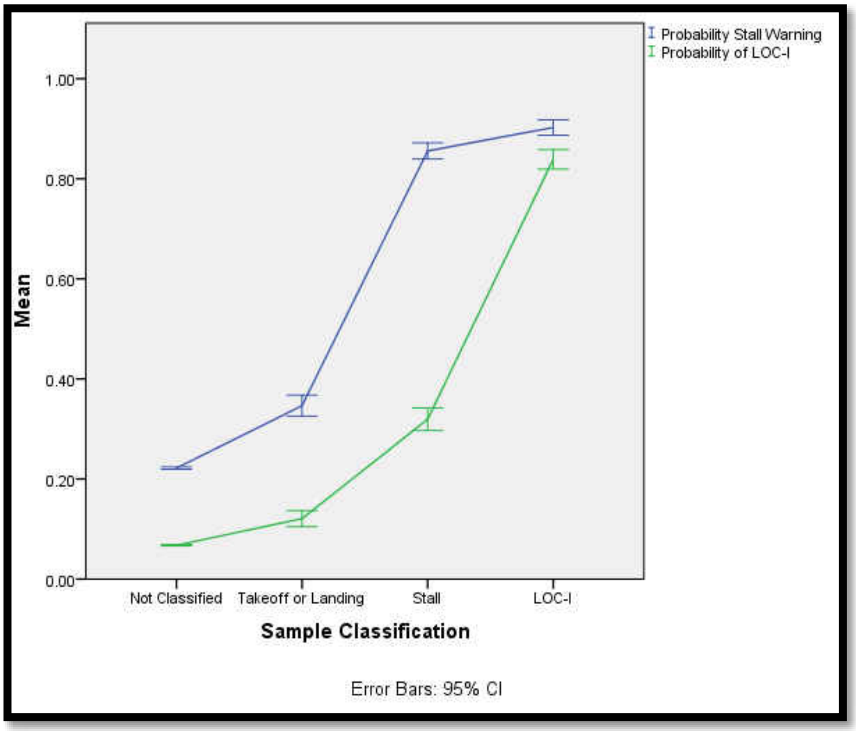

Figure 39. Mean Probability of Stall Warning and LOC-I: Group 3.

Additional testing was conducted to answer the research question: are the probabilities of stall and loss of control in-flight significantly higher than values observed during takeoff and landing or normal phases of flight within the group of flights where spins were observed? Loss of control in-flight probability values for samples during which a spin was observed (*Mdn* = 1.0) were significantly higher than values of stall probability during which stalls were not observed (*Mdn* = .04), *U* = 16,856,782, *z* = 45.89, *p* <.001, *r* = .31.

To account for the large number of samples where no observed stall was occurring, the test was repeated by randomly selecting 500 LOC-I samples (*n = 490*, missing = 10) and 500 non LOC-I samples (*n* = 488, missing = 12) to test for a significant difference in stall probability values between the observed and not observed stalls. Figure 40 indicates the frequency distribution of the ranked loss of control in-flight probability scores of the randomly selected samples observed in each group. Loss of control in-flight probabilities values when spins were observed (*Mdn* = 1.0) were significantly greater than the LOC-I probabilities when no spins were observed (*Mdn* = .04), *U* = 16,856,782, *z* = 45.89, *p* < .001, *r* = .82.

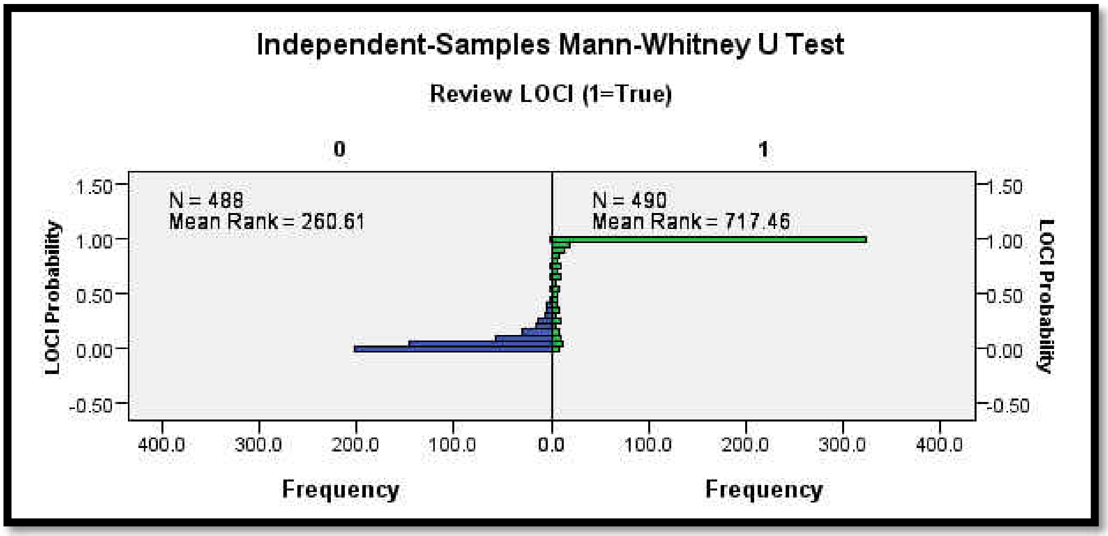

Figure 40. Frequency Distribution from Randomly Selected Samples: Stall Probability Ranking vs Observed Stalls: Group 3.

Since the data analyzed in this study was an analysis of an existing dataset, it was presumed that all loss of control in-flight events would occur at an altitude that would permit a safe recovery from such maneuvers without impacting the safety of flight. Therefore, the tested hypothesis is that high probabilities of loss of control in-flight should be contained above a safe maneuvering altitude. Figure 41 indicates the probabilities of loss of control in-flight against the altitude above mean sea level (feet). A sharp decline in LOC-I probabilities is observed below 3,000 feet and Figure 42 indicates the corresponding distribution of LOC-I scores against the altitude at which the score was recorded and whether or not a LOC-I event was observed.

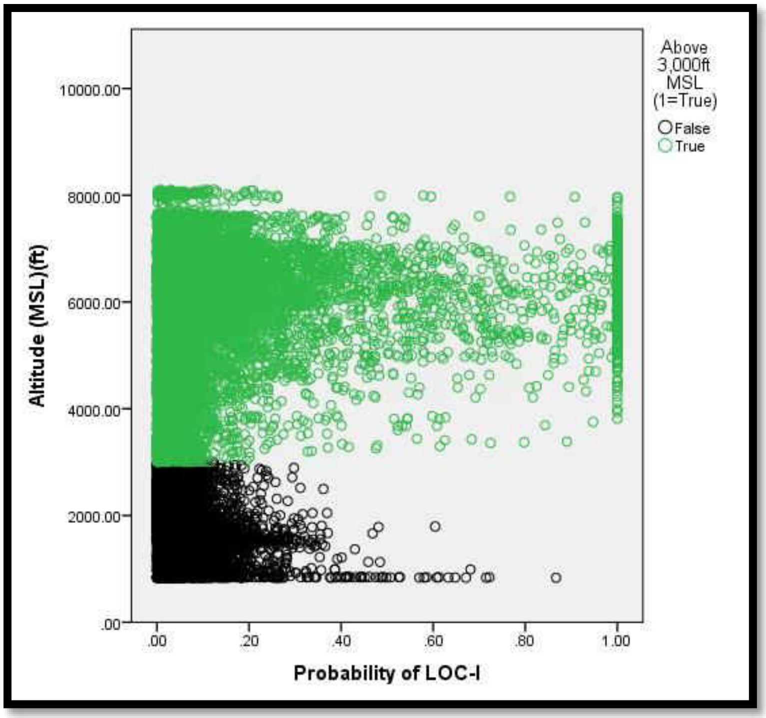

Figure 41. Probability of LOC-I vs MSL Altitude (feet).

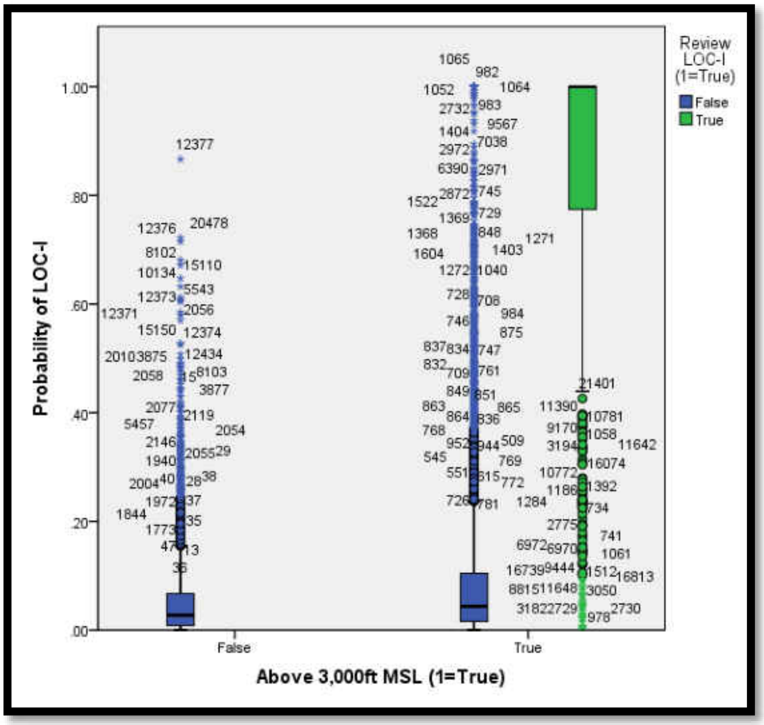

Figure 42. LOC-I Probability vs. Altitude and Review Classification.

Outlier point 12377 occurred at an altitude of 834 feet MSL, which is 2 feet higher than the MSL altitude when airspeed equaled zero. At the peak value of LOC-I, the airspeed was 31.42 (kias), pitch was 9.81 (degrees), roll was -1.44 (degrees), lateral acceleration was .74 (g), normal acceleration was 1.76 (g), the yaw rate was 2.9 (degrees/second) and the angle of attack was 14.93 (degrees). All values are likely synonymous with a kick out technique during a crosswind landing. Examination of wind recorded at 1000 feet MSL shows the wind was from 127 degrees at 17 knots and the mean heading during roll out was 179 degrees. From this it is possible that a 13.39 knot crosswind component existed during the round out and flare, which is a relatively high component when compared to the maximum demonstrated crosswind of 15 knots. 10 seconds prior to this point, the 3 sample average probability of loss of control in-flight was .16. Figure 43 is provided to indicate the loss of control in-flight probability values and altitude MSL in time series format for additional visualization of probability values occurring over all flights in Group 3.

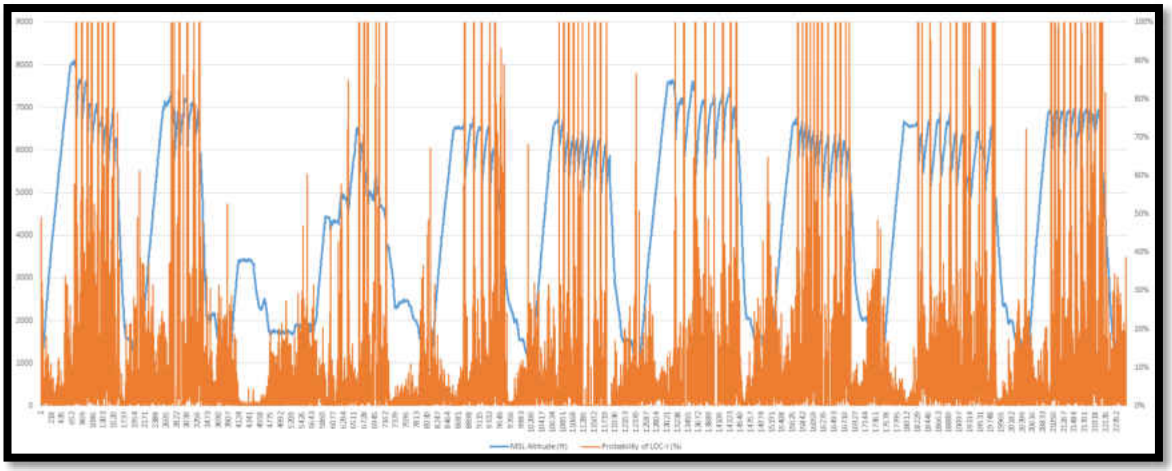

Figure 43. Probability of LOC-I and MSL Altitude (feet) vs Time (seconds).

Follow-up nonparametric significance testing using the independent-samples Krukal Wallis Test indicates a significant difference (asymptotic significance (2-sided test)), with significance values adjusted with Bonferroni correction for multiple tests, in the probability of loss of control in-flight between all sample classifications within group 3, $H(3) = 2{,}857$, $p<.001$. The probability for loss of control in-flight was significantly higher during takeoff or landing than in all other normal phases of flight, $H= -2{,}446$, $p <.001$, $r= .05$. The probability for LOC-I was significantly higher during stalls than values observed during takeoff or landing, $H= -4{,}549$, $p <.001$, $r= .35$ and the probability of LOC-I during observed periods of LOC-I was significantly greater than during stalls, $H= -3{,}562$, $p <.001$, $r= .28$.

Table 14. Independent-Samples Kruskal Wallis Test Average Rank Samples Classification: Group 3.

Sample 1 – Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.	Effect Size
Normal Phase – Takeoff or Landing	-2,446	339.3	-7.2	<.001	<.001	.05
Normal Phase – Stall	-6,996	263.0	-26.6	<.001	<.001	.18
Normal Phase – LOC-I	-10,558	225.1	-46.9	<.001	<.001	.32
Takeoff or Landing – Stall	-4,549.3	424.7	-10.7	<.001	<.001	.35
Takeoff or Landing – LOC-I	-8,111.98	402.3	-20.2	<.001	<.001	.58
Stall – LOC-I	-3,562.64	340.4	-10.5	<.001	<.001	.28

Asymptotic significances (2-sided test) displayed

CHAPTER 4

DISCUSSION

Key Findings

An analysis of flight data from a preexisting dataset was conducted to determine the ability of FOQA data to be monitored for the presence of risk factors related to loss of control in-flight, the leading cause of fatal accidents in aviation. In general aviation, the majority of fatal accidents involve a condition where the angle of attack has exceeded the critical angle above which a stalled condition occurs. If the presence of pro-spin forces exists at a high enough magnitude, the aircraft may enter a stalled condition whereby an autorotation develops which requires a significant amount of altitude to recover. If such a condition is encountered during the final stages of the approach and landing, it may become unrecoverable prior to impact with the surface.

Since many general aviation aircraft do not record the angle of attack, the first goal of the research project was to determine a method to estimate the angle of attack with enough accuracy that it could be used as a valid predictor of the presence of a stall. To make this determination, flights were analyzed for the presence of stall and loss of control in-flight occurrences.

Prior to this analysis, flights were randomly selected from a pre-existing dataset of FOQA/FDM data and each flight was binned into one of three groups (normal flights, flights containing stalls, and flight containing spins), and 10 flight were then randomly selected. After the random selection of flights was complete, each flight was reviewed and every sample of flight data was classified as either being associated with a takeoff and landing, stall, loss of control in-flight, or a normal phase of flight.

The first step was to derive the necessary atmospheric correction factor for non-standard air density (slugs/ft^3). The correction factor required an input from the aircraft's altimeter as well as the applied sea level pressure correction. A linear regression was used to evaluate the goodness of fit between the estimated pressure ratio against standard values of pressure ratios for a given altitude (p<.001), then using the recorded outside air temperature, the atmospheric density ratio (σ) was calculated. Values of density ratio were then used to obtain indicated speeds to true airspeeds since speed indicators are calibrated to indicate the true speeds only when standard atmospheric conditions exist (H. H. Hurt, Jr., 1965). The correction from indicated to true airspeed was then compared to the recorded true airspeed of the aircraft to ensure a strong correlation, r_s (70,103) = .999, p <.001, to verify the correction being applied to both airspeed and vertical speed was accurate.

After validating the true airspeed and vertical speed parameters, the next step was to compute the flight path angle of the aircraft, and assuming the relative wind is acting parallel to but opposite the direction of the flight path angle, sum the values of the flight angle and pitch to estimate the angle of attack with a correction for bank angle. The derived value was then tested in each of the review classifications to make sure that the observed values of the estimated angle of attack indicated higher values in the normal flight group when the aircraft was taking off or landing. Analysis indicated that in the data set obtained from the population of flights where only normal maneuvers were conducted, the samples classified as being associated with takeoff and landing were 4.26 degrees higher than all other phases of flight, $p < .001$, assuming non-equal variances.

After verifying that the angles of attack were sensitive to the longer duration, slow speed events, the next step was to assess the values of angle of attack during the period of time in which stalls were being conducted. Generally stalls involve higher derivative values of the parameters used to estimate the angle of attack. This test was used to validate the performance of the derived parameters during shorter duration, higher angle of attack events. Using samples of data from the 10 flights in the stall group, it was found that the angle of attack during stalls was 10.9 degrees higher than in all other normal phases of flight, $p < .001$, assuming non-equal variance. Since equal variance could not be assumed, samples of angle of attack were transformed using a square root transformation in an attempt to normalize the distribution. After transformation, equal variance could still not be assumed. However, the analysis was duplicated and found a significant increase in the values of angle of attack during takeoff and landing as well as during stalls when compared to the normal phases of flight, $p < .001$.

The last analysis of derived parameters was conducted using flight data from the population of samples obtained from the 10 flights randomly selected that included loss of control in-flight events. Since the purpose of the study is to conduct anomaly detection rather than examine exact values of AOA, the absolute value of angle of attack was used in this test group, as samples of data in this group contained flights at more extreme angles of pitch and bank, and aircraft can stall at both high and low values of AOA. In this group, it was found that angle of attack was higher during takeoffs and landings when compared to the normal flight samples, $p <.001$, and values of angle of attack were 11.47 degrees higher during stalls than when compared to normal flight samples, $p <.001$. The next step was to then ensure that the angles of attack during LOC-I events was equal to or greater than the angles of attack during stalls as the LOC-I events are stalled conditions. Analysis indicates that the mean angle of attack was 30.69 degrees higher during a spin when compared to the normal flight samples, $p <.001$. After validating the observed values of angle of attack correlated with generally expected values, analysis of the coordination parameter was conducted. It was found that takeoffs and landings involved a non-significant decrease in coordination when compared to normal cruise flight, $p=1.0$. Coordination during stalled flight, however, was significantly worse than in normal flight, $p <.001$, and coordination in spins was significantly worse than observed during stalls, $p < .001$.

After validation of the observed values of derived parameters, an analysis was performed to determine what values of angle of attack and aircraft coordination would be used to benchmark a current sample of flight data's probability of being involved with either a stall or uncoordinated flight (existence of pro-spin forces); the necessary elements for the occurrence of a loss of control in-flight event such that P | LOC-I | = P|Stall| * P|Pro-Spin Forces|. Analysis of the data indicated that the probability of stall increased until reaching an observed value of 15 degrees, at which point there was a high probability that a stalled condition or stall warning activation was likely to be present.

Then an analysis of the probabilities of stalls and spins was conducted to determine the existence of a significant difference in the distribution of probability scores between samples of data observed during normal flight, takeoffs and landings, stalls and LOC-I events. The mean probability of stall in the group of 10 flights where no stalls exist was .11, (n= 70,075, SD=.11). In the group of 10 flights containing stalls, the probability of stall was significantly different (Mdn = .13) than the probability of stall when stalls were observed (Mdn= .86), $p < .001$, $r = .23$. Follow-up analysis with 2,000 randomly selected samples from within the group of flight data (1,000 normal phases, 1,000 stall occurrences) was completed, a significant difference in stall probabilities was present where the median probability of stall from the normal phases of flight was .21 and the median value of stall probability when a stall was observed was 1.0, $p< .001$, $r= .84$. Given the higher level of observed stall probabilities, the null hypothesis was rejected and the alternative hypothesis that the stall probability values are significantly different when a stall is observed was accepted.

After observing the higher levels of stall probabilities during observed stalls, the probability of loss of control values were then analyzed within the group of 10 flights containing spin (LOC-I) events. It was found that the probabilities of LOC-I when a spin was observed were significantly different than values observed during stalls and samples observed during normal phases of flight, $p <.001$, $r = .31$. Additional analysis of 1000 randomly selected samples from the group of 10 flights with spins found that a significant difference in LOC-I probabilities values existed, $p <.001$, $r = .82$.

Future Research

Investigation of the outlier observed at point 14238 for stall probabilities in the group of 10 flights without a stall observed indicates that operators analyzing their FOQA data for anomaly detection could benefit from a focused study on flights where observed values of stall probability are greater than 80 percent in regions where stalled flight is *not* expected to occur. Such analyses could lead to a greater understanding of the root cause for these values and permit a mitigation strategy to be implemented and its effectiveness evaluated.

Follow up analysis of the outlier observed at point 14447 in the group of flights containing only stalls indicated high observed values in the probability of loss of control during a go-around. Additional research into loss of control in-flight probabilities during takeoff and climb out, turns from upwind to downwind, and turns from base to final approach could provide operators with additional information to support the integration of this data into their FOQA or FDM program in order to complete risk assessment and root cause analysis. Identifying predictors for high LOC-I probabilities with the stated purposes of reducing the operator’s risk through the implementation of a targeted mitigation strategy with results that can be quantifiably measured is an essential step in reducing the number of fatal accidents annually in general aviation.

Further study could also focus on gathering quantitative (what happened) and qualitative data (why or how it happened) to support initial or recurrent training initiatives. Specifically studying the ways this data can drive outcomes for more effective training techniques related to stall and spin awareness and recovery from vehicle upsets or loss of control in-flight. Analysis of FOQA/FDM data for trends and anomaly detection related to altitude loss observed during stalls, coordination during specific maneuvers, or during power applications, and the effects of flight dynamics during stall entry on the altitude required to recover, could lead to insights ultimately increasing pilots' awareness of critical factors leading to a loss of control in-flight and the effectiveness of recovery techniques.

Recommendations

Every operator of an aircraft that is capable of collecting flight data should participate in a FOQA/FDM program. The collection and analysis of quantitative data related to stall and loss of control in-flight is necessary to identify root causes and measure the effectiveness of mitigation strategies. An integral part to that assessment requires measuring two critical components: proximity to stall and the detection of pro-spin forces. In particular, the general aviation community would benefit tremendously from the ability to benchmark and evaluate both their known and unknown risk exposure to one of aviation's most deadly encounters, loss of control in-flight. Based upon the findings from this research, it has been demonstrated that FOQA data can be used to detect anomalous flights and the rate of detection of high risk flights could be monitored as one of the operator's safety performance indicators, especially if high values are observed in critical phases of flight where aircraft may be at an increased risk for a low altitude stall or loss of control in-flight encounter from which recovery may not be possible.

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