UNIVERSIDADE FEDERAL DE UBERLÂNDIA

DENISE DIAS DE OLIVEIRA

EVALUATION OF FLIGHT SIMULATORS QUALIFICATION REQUIREMENTS FOR FULL STALL TRAINING TASKS IMPACTS ON SAFETY AND INDUSTRY

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Undergraduate thesis submitted to the Course of Aeronautical Engineering of Universidade Federal de Uberlândia in partial fulfillment of the requirements for the Bachelor Degree in Aeronautical Engineering

Advisor: Prof. Dr. Leonardo Sanches

Co-Advisor: Eng. Marcelo Toledo Basile

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“Safety first is safety always”

HAYES, C.M.

ABSTRACT

This project, carried out in partnership with Embraer S.A., aims to address the issue of new training requirements for stall characteristics recognition in FSTD: Flight Simulation Training Device. Historically, pilot training in simulators was limited to the approach to stall and to recover from the stall warning first indication, which means the airplane was in the linear region of the lift coefficient curve. Following the occurrence of serious accidents around the world, where the crew was unable to properly identify and recover the aircraft from stall, the US Congress and Senate instituted the Public Law 111-216 - Aug. 1, 2010. This law was established as a proposal to amend the current requirement (14 CFR Part 60) and its means of compliance (Advisory Circulars), specifically AC 120-109, and to enforce full stall training in simulators, which goes beyond of the loss of lift, indirectly encouraging the challenge of modeling the non-linear behavior of the wing. The new requirement change proposal has raised a number of questions and doubts about the fidelity of the simulator and the possibility of "negative training", provoking huge debate among manufacturers, regulatory authorities, training providers and third parties. At the end of this paper, it is expected to provide an assessment of the pros and cons of this new training requirement impacts on flight safety and product development, and to account for the consequences for aircraft manufacturers.

Keywords: Full Stall Training, Stall Recovery, FSTD, High AOA, Simulator Fidelity

RESUMO

Este projeto, realizado em parceria com a Embraer S.A., tem como objetivo abordar a problemática dos novos requisitos para treinamento para reconhecimento de características de estol em simuladores. Historicamente, o treinamento dos pilotos em simuladores era limitado apenas à aproximação do estol, na região linear da curva de coeficiente de sustentação. Após a ocorrência de graves acidentes pelo mundo, em que a tripulação não soube identificar e recuperar a aeronave de um estol, o Congresso e Senado americano instituiu o *Airline Safety and Federal Aviation Administration Extension Act of 2010*, também conhecido como *Public Law 111-216*, em agosto de 2010. Tal ato se configurou como uma proposta para alteração do requisito vigente (14 CFR Part 60) e seus meios de cumprimento (*Advisory Circulars*), especificamente a AC 120-109 e impor o *full stall training* em simuladores, que vai além da perda de sustentação, indiretamente encorajando o desafio de modelagem da região não-linear da curva de sustentação da asa. A nova proposta de alteração de requisito provocou uma série de questionamentos e dúvidas quanto à capacidade e fidelidade dos simulares e quanto à possibilidade de “treinamento negativo”, provocando enorme debate entre os fabricantes, autoridades reguladoras, órgãos de treinamento e terceiros. O que se espera, ao final deste trabalho, é avaliar os impactos positivos e negativos deste novo requisito de treinamento na segurança de voo e no desenvolvimento do produto e explicitar quais serão as consequências para os fabricantes de aeronaves.

Palavras-chave: Treinamento de Estol, Recuperação de Estol, Estol, Simuladores, Alto Alfa.

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SYMBOLS AND ACRONYMS

α	Angle of Attack
α_{artf}	Maximum angle of attack allowed by the aircraft control law
$\alpha_{CL\,max}$	Angle of maximum lift coefficient
β	Angle of Sideslip
C_L	Lift Coefficient
C_{Lmax}	Maximum point of the Lift Coefficient curve
C_D	Drag Coefficient
C_l	Rolling moment coefficient
C_m	Pitching moment coefficient
$C_{m\alpha}$	Change in pitching moment coefficient with angle of attack $(dCm/d\alpha)$
C_n	Yawing moment coefficient
C_Y	Side force coefficient
D	Drag
Fr	Resultant Force
L_T	Total Lift of the aircraft
L_W	Wing Lift
L_{HT}	Horizontal Tail Lift
M	Mach Number
n	Load Factor
ρ	Air Density
q	Dynamic pressure
Re	Reynolds Number
S	Wing Area
V_S	Stall Speed
V_{s1g}	Stall speed for load factor equal to 1g
V_{SR}	Reference Stall Speed
V_{SW}	Stall Warning Onset Speed
W	Aircraft Weight
ϕ	Bank (roll) Angle
θ	Pitch Angle
ψ	Yaw Angle

δ	Control surface deflection
AC	FAA Advisory Circular
AIAA	American Institute of Aeronautics and Astronautics
ANAC	Agência Nacional de Aviação Civil
AOA	Angle of Attack
AP	Auto-Pilot
ARC	Aviation Rulemaking Committee
AURTA	Airplane Upset Recovery Training Aid
CA	Aerodynamic Center
CENIPA	Centro de Investigação e Prevenção de Acidentes Aeronáuticos
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CG	Center of Gravity
CL	Center of Lift
CVR	Cabin Voice Recorder
DAL	Design Assurance Level
DFBW	Digital Fly-By-Wire
ETPS	Empire Test Pilot School
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FCS	Flight Control System
FCU	Flight Control Unit
FDR	Flight Data Recorder
FFS	Full Flight Simulator
FSTD	Flight Simulation Training Device
FTD	Flight Training Device
FTE	Flight Test Envelope
FTI	Flight Test Instrumentation
FTT	Flight Test Technique
GMT	Greenwich Mean Time
HOA	High angle of Attack
HT	Horizontal Tail
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization

ICATEE	International Committee on Aviation Training in Extended Envelopes
IP	Issue Paper
LOC-I	Loss of Control In-flight
LOCART	Loss of Control Avoidance and Recovery Training Working Group
MBFT	Model Based Flight Test
NFE	Normal Flight Envelope
NPRM	Notice of Proposed Rulemaking
NSP GB	National Simulator Program Guidance Bulletin
NSPM	National Simulation Program Manager
NTSB	National Transportation Safety Board
OEM	Original Equipment Manufacturer
OFE	Operational Flight Envelope
PF	Pilot Flying
PNF	Pilot Not Flying
QPS	Qualification Performance Standards
QTG	Qualification Test Guide
RAeS	Royal Aeronautical Society
SME	Subject Matter Expert
SOC	Statement of Compliance
SPAW	Stick Pusher and Adverse Weather Event Training
SNPRM	Supplemental Notice of Proposed Rulemaking
ToT	Transfer of Training
UPRT	Upset Prevention and Recovery Training
USNTPS	United States Naval Test Pilot School
VTE	Validated Training Envelope

1 INTRODUCTION

Historically, stall training for air carriers has been limited to approach to stall training where recovery is initiated at the first indication of the stall (typically at the activation of the stall warning system or stick shaker). However, some recent accidents such as Air France flight 447 Rio de Janeiro – Paris, Colgan Air Flight 3407 Newark – Buffalo and Turkish airlines Flight 1951 Istanbul – Amsterdam have raised concern about flight crew ability to proper monitor the airplane angle of attack, identify the first indications of what would be an aerodynamic stall and to properly recover from stall. Motivated by public commotion and with the aim to prevent new catastrophes, the American Congress instituted the **Airline Safety and Federal Aviation Administration Extension Act of 2010**, also known as **Public Law 111-216 – Aug. 1, 2010**. This act was depicted as a proposal to amend the current requirement (14 CFR Part 60 and the operational flagship Part 121) and their respective Advisory Circulars, more specifically the AC 120-109, to amend the guidelines for full stall training in simulators.

Following Public Law 111-216 , the 14 CFR Part 121 Amendment nº 121-366 of November 12, 2013 requirement defined that all domestic, flag and supplemental air carriers must conduct instructor-guided, hands-on experience of recovery from full stall. In addition, the 14 CFR Part 60 Amendment n° 60-4 of May 31, 2016 requirement defined the FSTD (Flight Simulator Training Device) qualification standards for the full stall training maneuvers. The changes proposed has raised a number of questions and doubts about the ability and fidelity of the simulators in representing the real aircraft behavior and about the possibility of negative transfer of training, provoking enormous debate among the manufacturers, regulatory authorities, training providers and third parts. The difficulties involved to promote reliable FSTD models is due to the nature of non-linear, unsteady aerodynamics of the stall condition. Some experts doubt that this could be modeled with sufficient fidelity to guarantee a positive transfer of training, or without enforcing the Original Equipment Manufacturers (OEMs) to acquire additional data with specific flight test installation. Aerodynamic stall flight-testing may be hazardous or impractical due to safety and costs concerns and some experts also doubt that flight test data would be repeatable enough to build models with fidelity. Additionally, Public Law 111-126 marks an abrupt changing in airlines training philosophy. Before, pilots training were based on prevention and not to overcome the limits of a normal controlled operational flight. A new approach was required by FAA to train pilots how to recover from conditions that were never supposed to be reached in the flagship flight.

The technical background to support this debate is provided in Section 2, which explains the aerodynamic of stall and which shows the non-linearity aspects and covers the difficulties involved on a representation of a non-linear phenomenon in mathematical model. Moreover, The FSTD theory is detailed on Section 3: how the simulator models are done, how fidelity is defined and measured and the criteria for an FSTD evaluation. The three accidents prior mentioned are depicted in Section 4, focusing on flight crew actions during approach-to-stall and the stall event itself. The sequence of events that happened after Public Law 11-126 publication, involving the work of experts to provide the Part 121 and Part 60 Amendments, the concerns regarding the negative transfer of training and the public repercussion of the new FAA requirements. Section 6 is related to the human factors standpoint involving negative training concerns of the full-stall issue. Finally, in Section 7, results and comments of flight test pilots interviewed regarding the FTSD full stall training and recovery are presented.

At the end of this work, a clear understanding of the FAA 14 CFR Part 60 requirements for stall certification and training is expected. Moreover, an understanding of technical issues comprising the discussion, such as the aerodynamic and flight mechanics near stall definition, the procedures of validating a FSTD and the human factors behind flight crew stall training. At last, it is expected to come up with a proposed solution for the best way of providing air carriers with stall training, even if the proposed solution goes against FAA initially intended outcome.

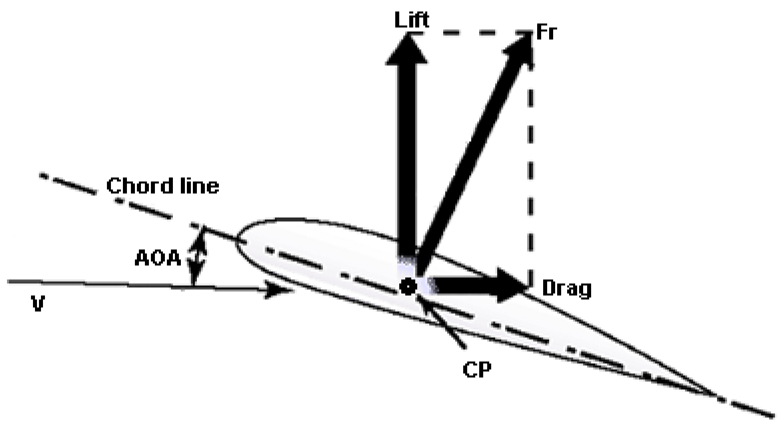
2 THEORY OF STALL

This section explains the aerodynamic background of stall covering non-linearity aspects and the difficulties involved on mathematical model representation. Moreover, it explains stall phases and the factors that affects stall margins, which sometimes may not be completely understood by pilots. The section ends with an explanation of 14 CFR Part 25 certification requirements for stall flight-testing.

2.1 Definition of Stall

Angle of Attack (AOA), also named as α, is the angle between the wing chord and relative wind, where the chord is a straight line from the leading edge to the trailing edge, as drawn in Figure 2-1 below. At low angles of attack, the airflow over the top of the wing flows smoothly and it is deflected down after the airfoil or wing passes. This change in momentum yields an aerodynamic resultant force (Fr) in opposite direction. See image below.

Figure 2-1 Aerodynamic forces.



Source: https://www.quora.com/What-do-pilots-do-if-they-are-on-the-final-approach-and-then-they-stall-Do-they-pull-up-or-put-the-nose-down. Access on: 20/12/2017.

The point in the chord that is at the intersection of the chord and the line of action of the resultant force is called Center of Pressure (CP), or Center of Lift (CL). Besides the force, air pressure distribution around the airfoil also imparts a pitching moment on it. As the AOA changes, the pressure distribution changes and therefore the aerodynamic force and the location of the center of pressure and the moment all change. So engineers consider the Aerodynamic Center (CA), which is the point where the aerodynamic moment remains constant, in aerodynamic analysis. The resultant aerodynamic force (Fr) is divided in two components, Lift (perpendicular to the relative wind) and Drag (parallel to the relative wind) which can be calculated as follows:

$$L = 0.5\, \rho\, V^2 S\, C_L \tag{1}$$

$$D = 0.5\, \rho\, V^2 S\, C_D \tag{2}$$

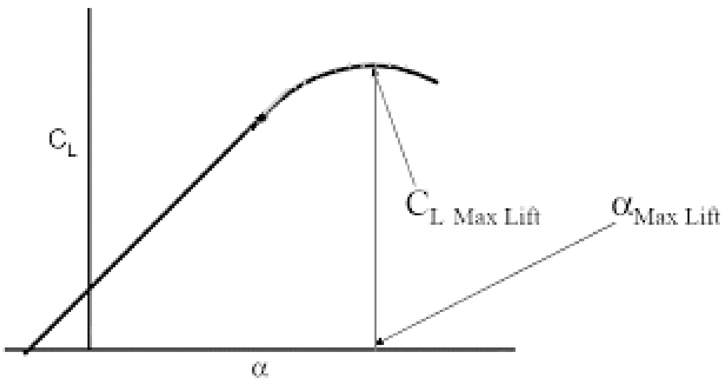
where ρ is the air density, V is the airspeed, S is the wing surface and C_L and C_D are, respectively, the dimensionless lift and drag coefficients, which depends on airfoil characteristics. The pitching moment is calculated as follows:

$$M = 0.5\, \rho\, V^2\, S\, c\, C_m \tag{3}$$

Where, c is the chord length and C_m is the moment coefficient of the airfoil.

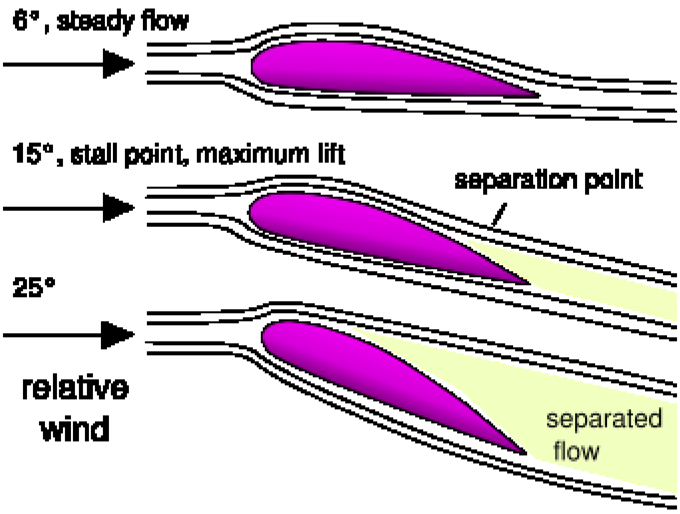
The stall may be defined as a condition in which the airplane wing is subjected to an (AOA) greater than the maximum lift AOA. In this condition a lift loss starts to occur due to boundary layer flow separation, as demonstrated in Figures 2-2 and 2-3. Since the C_L increases linearly with an increase in AOA until initiation of boundary layer flow separation, at some point the C_L gradient start to decrease until it maximum value from there it begins to drop off. This peak is called the maximum lift C_{Lmax} point and the angle in this point is called angle of attack for maximum lift coefficient, α_{CLmax}. The amount of lift the wing produces usually drops dramatically after exceeding the C_{Lmax}. At this condition, the linearity of the model has gone and the flow becomes vortical, turbulent and more unpredictable due to boundary layer detachments, which contribute to unsteady effects.

Figure 2-2 Cl x alpha curve.



Adapted from: USNTPS, Flight Test Manual – no.103.

Figure 2-3 Airflow representation.



Source: http://clipper440.blogspot.com.br/2015_05_01_archive.html. Access on: 03/30/2017.

An impending stall occurs when the airplane is approaching, but does not exceed the maximum lift coefficient. Full stall or developed stall occurs when the maximum lift coefficient is exceeded (FAA-H-8083-3B, 2016, p. 4-5), above the point of flow separation, where dynamic pressure is strongly reduced. Apart from loss of lift, more undesired aspects due to detached flow effects can be observed near C_{Lmax}, as described below:

1. Degradation in the effectiveness of the flight controls due to reduced dynamic pressure near the stall.

2. Large increases in induced drag may cause high sink rates, compromising flight path maintenance and control.

3. Uncommanded aircraft motions cannot be arrested by use of the piloting commands, sudden wing drop due to asymmetrical stall in the wings, and departures, which may involve pitch over followed by a deep stall or spin.

4. Undesirable flying qualities, which include intolerable buffet level, shaking of the controls, wing rock, aileron reversal, and degraded stability.

5. Reduction of elevator and horizontal stabilizer control effectiveness, which may lead to full nose up pitch control limits, may be reached before any of the above conditions occurs (USNTPS, 1992, p. 3.1).

According to equation (1) and Figure 2-2, as airspeed decreases AOA must increase to maintain the necessary lift to sustain the aircraft. The minimum speed that corresponds to AOA for maximum lift is defined as stall speed (V_S) and it is obtained from 2nd Newton's Law of forces balance for steady level flight:

$$L = W = \frac{1}{2} \rho V^2 S C_L \tag{4}$$

$$V_S = \sqrt{2W/\rho C_{L\,max} S} \tag{5}$$

In this equation, S is the aircraft referenced wing.

2.2 Factors Affecting Stall Speed

Factors affecting the stall speed can be found regarding eq. (5) variables (CAVCAR, Turkey). In summary: load factor, aircraft weight, air density and maximum lift coefficient. Other factors not directly explicit in eq. (5) are also included in subsections below.

2.2.1 Load Factor (n)

For non-steady, turning, ascending and descending flight, Lift is not equal to Weight, and we define load factor, for conventional transport aircrafts, as:

$$n = L/W \tag{6}$$

So, equations (4) and (5) can be written for general cases as:

$$L = n\,W = \frac{1}{2}\,\rho\,V^2\,S\,C_L \tag{7}$$

$$V_S = \sqrt{2nW/\rho\,C_{L\,max}\,S} \tag{8}$$

Therefore the stall speed is proportional to steady level flight stall speed, or 1-g stall (V_{S1g}) speed:

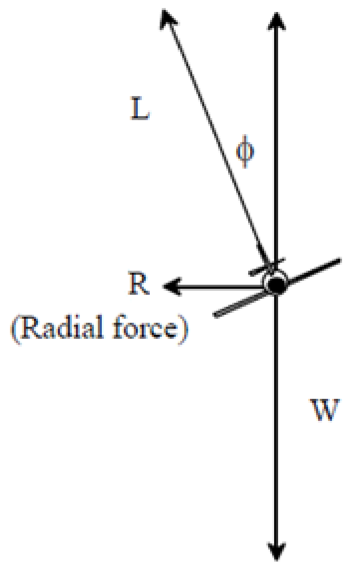
$$V_S = \sqrt{n}\,V_{S1g} \tag{9}$$

So, as the load factor is increased, the stall speed is also increased and stall margin becomes tighter. Giving an example of a turning flight: merely banking the aircraft into a turn reduces the amount of lift opposing gravity and supporting the aircraft's weight. Consequently, the aircraft loses altitude unless additional lift is created (FAA-H-8083-25B, 2016, p. 5-23). This is done by increasing the AOA until the vertical component of lift L.cosϕ is equal to the weight, as shown in Figure 2-4. Since the vertical component of lift decreases as the bank angle increases, the AOA must be progressively increased to produce sufficient vertical lift to support the aircraft weight. For this case, load factor is calculated as:

$$n = L/(L\,cos\phi) = 1/cos\phi \tag{10}$$

Following equation (7), when wing abruptly loses lift, the crew will feel a pronounced g-brake, which may be an abrupt decrease in load factor. The g-brake can be smooth or abrupt depending on the wing design characteristics

Figure 2-4 Forces during roll maneuver.



Adapted from: USNTPS, Flight Test Manual – no.108.

2.2.2 Aircraft Weight (W)

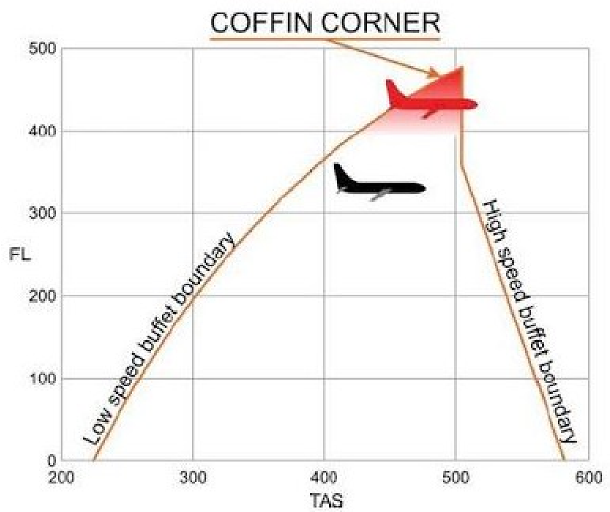
Following equation (8) as aircraft weight increases stall speed increases. Normally, Vs is calculated for aircraft takeoff weight and landing weight before each flight, as part of operational procedures. During flight, as weight varies the stall speed can vary as expressed below (HURT, 1965, p.35).

$$\frac{V_{S1}}{V_{S2}} = \sqrt{\frac{W_1}{W_2}} \quad (11)$$

2.2.3 Air Density (ρ)

Following equation (8) as air density decreases stall speed increases. It means that pilots should fly at higher speeds at higher altitudes to ensure safe margins from stall. However, depending on the altitude it may be not possible to ensure safe stall margins because the stall speed converges to critical Mach number as altitude is increased. The convergence point is named coffin corner, showed in image 2-6.

Figure 2-2-5. High altitude stall speeds: coffin corner.

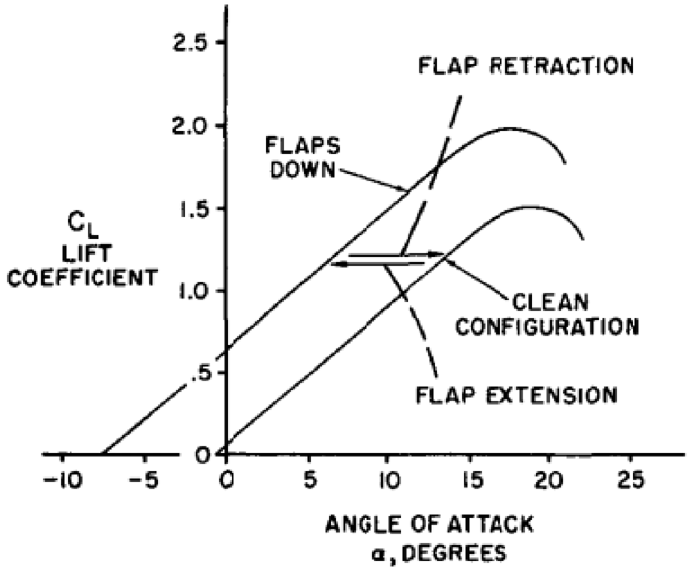


Source: https://en.paperblog.com/mountain-wave-and-the-coffin-corner-554785/. Access on: 06/19/1028.

2.2.4 Maximum Lift Coefficient ($CL\ max$)

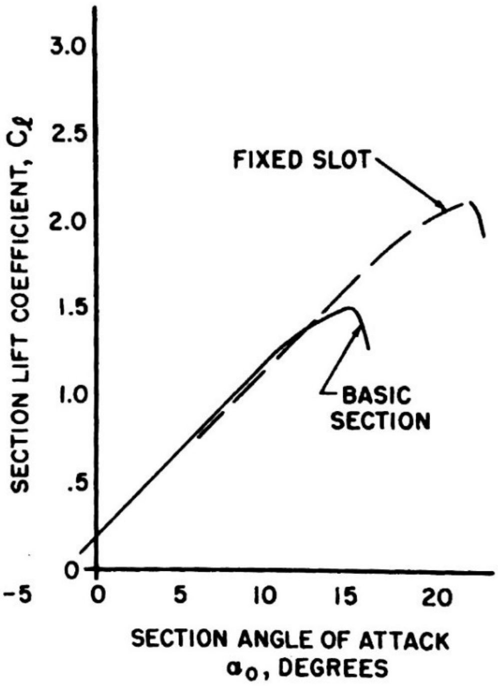
Higher maximum lift coefficient will result in lower stall speeds. Such an increase of maximum lift coefficient may be obtained in several ways. By deflecting high lift devices such as flaps and slats the $C_L\ \alpha$ curve may be changed as shown in Figures 2-6 and 2-7 below:

Figure 2-6 Effect of flaps in lift curve.



Source: KIMBERLY, Flight Testing of Fixed Wing Aircraft.

Figure 2-7 Effect of flaps in lift curve.



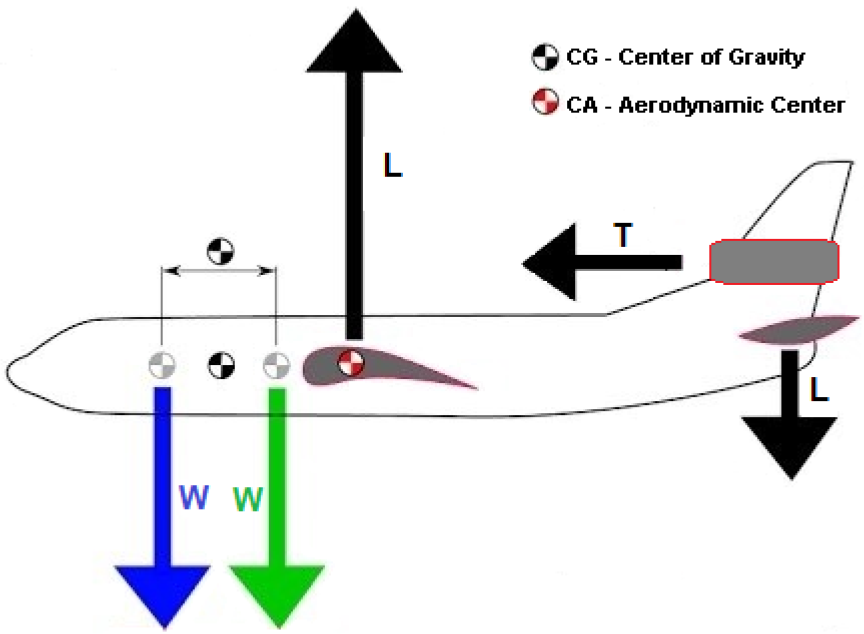
Source: KIMBERLY, Flight Testing of Fixed Wing Aircraft.

2.2.5 Thrust (T) and CG position

The four factors affecting stall speeds listed above are related to the wing. It is important to state that the wing is not the only lifting surface of conventional transport aircrafts. There is also the horizontal tail (HT), which produces the amount of lift to balance the airplanes pitching moment throughout the flight. If Center of Gravity (CG) is in front of the Aerodynamic Center (CA) the aircraft will have a pitch down tendency and horizontal tail must generate a lift down force to counter the pitching down moment. The most forward CG is, the higher lifting down force (-) the HT must produce (see Figure 2-8).

The opposite is also valid: if CG is behind CA, the aircraft will have a pitch up tendency and horizontal tail must generate a lift up force to counter the pitching up moment from the wing. The most aft CG is, the higher lifting up force (+) the HT must produce. It is an interesting design characteristic that improves performance (fuel consumption) during cruise flight. As the stability is reduced when CG goes aftwards CA, the pitch moment from the tail to counteract the wing pitch moment reduces, so the amount of trim, and so the trim drag.

Figure 2-8 Forces that produce pitch moments on aircraft.



Adapted from: https://commons.wikimedia.org/wiki/File:Longitudinal_aircraft_stability_00.svg. Access on 07/23/2017.

Whereas the total lift of the aircraft is $L_T = L_W + L_{HT}$ a forward CG results in a reduced total lift and a necessary increase in stall speed to sustain the aircraft weight. In other hand, aft CG results in increased lift and a decrease in stall speed. It explains why modern transport category aircraft, including some executive jets, may have their stability relaxed (low or neutral static margin) during cruise phase to reduce the trim drag, by demanding about low lift-down force in the HT (very small deflection) to keep the aircraft trimmed.

The thrust effect is quietly the same depending on the location of the engines. If they are placed below the CG, an increase in thrust will lead to an increasing pitch up moment, so the HT lift force must increase to counter this effect, increasing the total amount of lift and decreasing the stall speed. The opposite is when engines are placed above the CG, represented in Figure 2.8, where an increase in thrust will generate a pitch down moment and a decrease in HT lift force (or increase in HT lift down force) and the consequence will be less total lift and higher Vs to sustain the aircraft.

2.2.6 Mach Number (M)

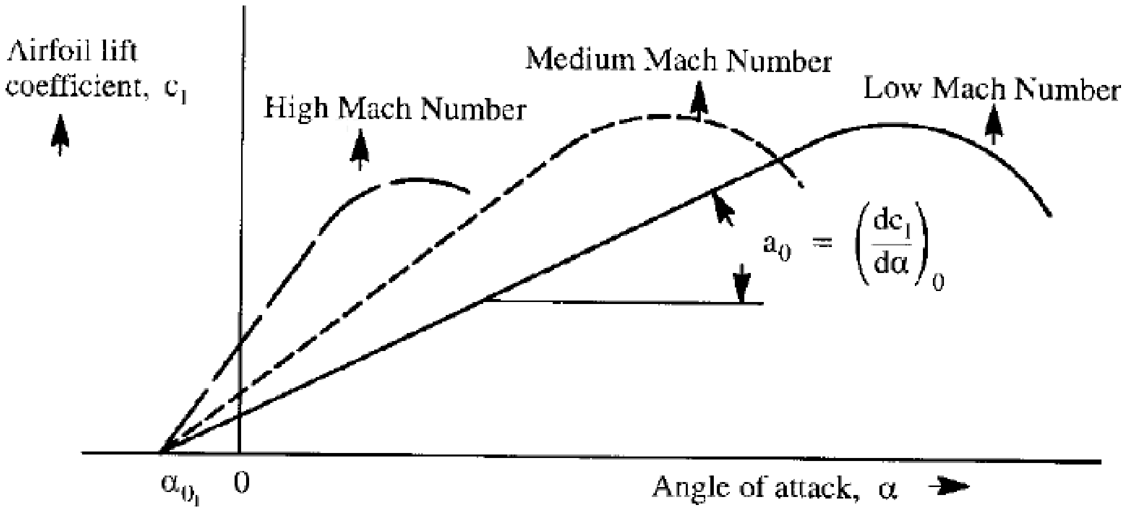
The aerodynamic characteristics of an airfoil, represented by the evolution of the $Cl = f(\alpha)$ curve, are different between the lower altitudes (low Mach, subsonic airflow, incompressible air) and the high altitudes (higher Mach, airflow close to transonic, influence of the compressibility of the air). At a high Mach, the compressibility of the air is notably manifested by the appearance of buffet at a high angle of attack, whose amplitude can then increase until it becomes dissuasive (deterrent buffet). In these cases, the flight tests are then interrupted before reaching C_{Lmax}.

Nevertheless there is a degradation of maximum usable C_L due to Mach effect as far the certification requirements 14 CFR 25.251(c) may limit it; it states:

> "There may be no buffeting condition, in normal flight, including configuration changes during cruise, severe enough to interfere with the control of the airplane, to cause excessive fatigue to the crew, or to cause structural damage. Stall warning buffeting within these limits is allowable" (FAA, 1992).

Therefore, the high Mach stall speed is considered as “buffet limit speed”, which is higher than low Mach stall speed. The Mach effect on $C_{L\alpha}$ curve is illustrated in Figure 2-9 below. The $\alpha_{CL\,max}$ achieved of high Mach number curve is the lowest and the C_{Lmax} is also the lowest, comparing to the other curves.

Figure 2-9 Compressibility effect on airfoil lift curve slope



Source: ROSKAN, Aerodynamics and Performance.

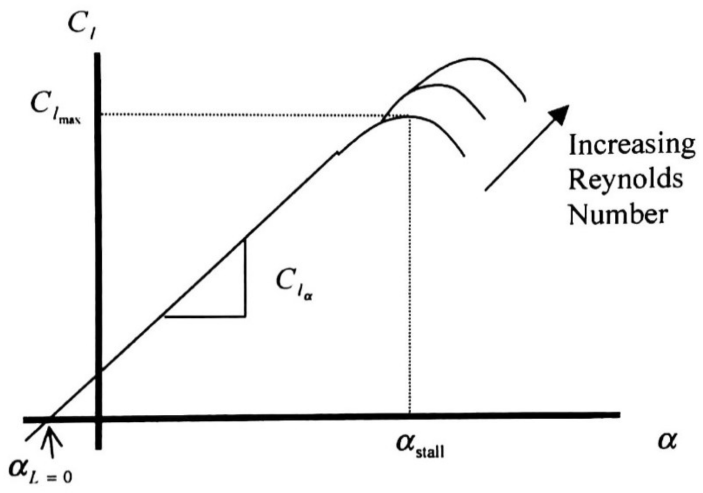
2.2.7 Reynolds Number (Re)

The dimensionless Reynolds number (Re) is a similarity parameter that correlates the inertia forces to viscous forces. For aircraft aerodynamics, it is defined as:

$$Re = \rho V c / \mu \tag{12}$$

where c is the wing chord representative length and μ is the air viscosity. An increase in Re tends to increase C_{Lmax} and delay the onset of stall as it is explained in Figure 2-10. An increase in Re means an increase in inertia forces relation to viscous forces, which means that the airflow has more kinetic energy resulting in delayed flow separation and delayed stall.

Figure 2-10 Effects of Reynolds Number on lift curve.

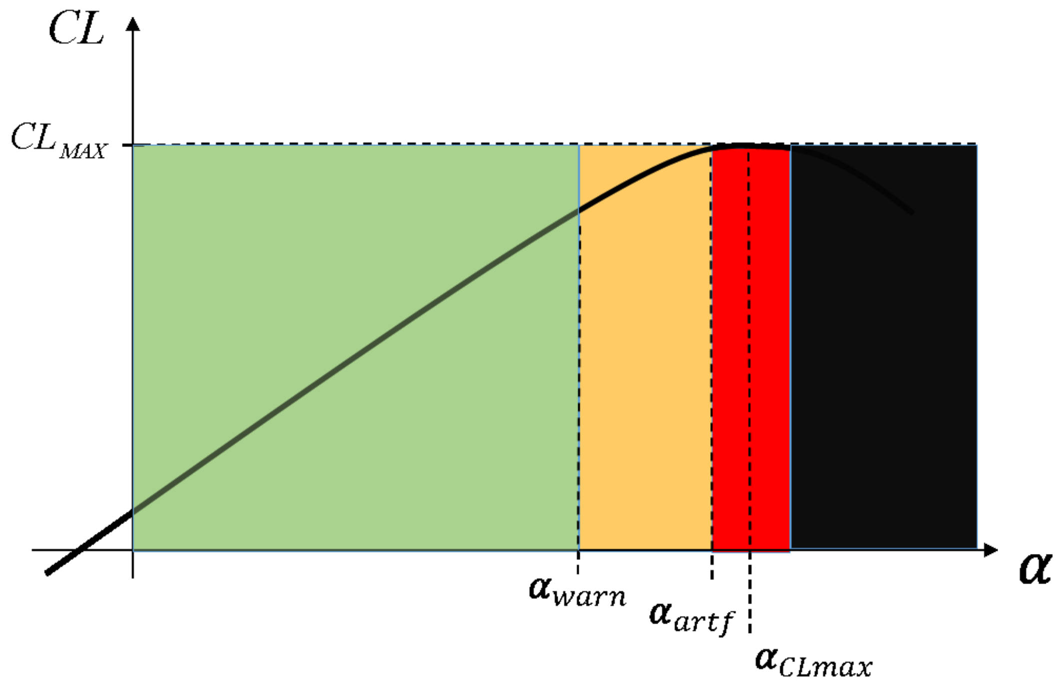


Source: YECHOUT, Introduction to Aircraft Flight Mechanics.

2.3 Stall Phases

The stall may be academically divided into phases as per ETPS (Empire Test Pilot School) Flight Manual: approach to stall, stall warning, stall definition and post-stall, they are exemplified respectively from left to right in figure 2-11 below.

Figure 2-11 Stall phases representation on Cl x alpha curve



2.3.1 Approach to Stall

In this phase, AOA is increasing, still on linear side of the Cl x alpha curve. In a conventional airplane, should not be followed by any undesirable characteristic as far as the speed range is mostly operational. Nevertheless is possible to note progressive increase in the stick force and displacement as alpha increases. In some airplanes, effect of the unbalanced or unsteady flows is possible to notice through “heavy” wing tendency for one of the sides.

2.3.2 Stall Warning

This phase is characterized by the entry of a stall warning. It is a natural or synthetic indication provided when approaching a stall that may include one or more of the following indications:

(1) Aerodynamic buffeting onset, defined by an oscillatory vertical acceleration whose amplitude reaches 0.2 g from peak to peak at the pilot’s seat (some airplanes will buffet more than others);

(2) Reduced roll stability and aileron effectiveness;

(3) Visual or aural cues and warnings;

(4) Reduced elevator (pitch) authority;

(5) Inability to maintain altitude or arrest rate of descent;

(6) Stick shaker activation.

(1), (2), (4) and (5) can be considered as a natural stall warning. Airplanes which do not exhibit adequate aerodynamic stall warning, such as airframe buffet, are frequently equipped with artificial stall warning devices which detect the approach of the stall and transmit a warning to the pilot. Stick shaker is a mechanical device to rapidly and noisily vibrate the control yoke (the "stick") of an aircraft to warn the pilot of an imminent stall. It is connected to the control column of most civil jet aircraft and large military aircraft. Any artificial stall warning system should satisfy the following requirements (USNTPS, 1997, p. 2.24):

I. The system should be capable of stall warning for any airplane configuration, airspeed, altitude, normal accelerations, sideslip, bank angle, and power setting. In addition, the system should not be susceptible to atmospheric influence, such as temperature and pressure variations, precipitation, and icing.
II. The warning provided the pilot should be unmistakable and sufficiently in advance of the stall to allow avoidance of the stall without undue pilot effort.
III. The stall warning should be reliable and repeatable.
IV. The system should be easy to maintain and easy to calibrate on the ground.

2.3.3 Stall Definition

The aerodynamic stall is when the maximum lift and critical AOA are reached. The stall definition is a more complex concept, because it has different characteristics from aircraft to aircraft and, even in the same aircraft may have different characteristics as function of slat/flap/gear speed brake. It may be defined naturally or artificially. The natural definition of stall may be desirable, acceptable or unacceptable under certification requirement standpoint. To be naturally desirable or acceptable it should have (FAA, AC 25-7C, p. 127):

- Deterrent Buffeting: high cockpit vibration, that pilots are no longer able to proceed with the speed reduction or increase in alpha, compelling them to recover the airplane
- Flight controls stop: occasionally it may occur in conventional airplanes where the pitch authority is limited to bring aircraft to the maximum wing lift capability
- Wing drop due to uncommanded roll and/or yaw which is still within the requirements limits (beyond limits may not be a safety issue but it turns out the aircraft to be not certifiable)
- Pitch down that cannot be arrested (the most desired).

Some of artificial stall definition existent to prevent the aircraft from aerodynamic stall are:

- **Stick pusher in the conventional flight control system (FCS) design**, which is a servo which pushes abruptly the yoke full forward away from seat position in a manner that cannot be counteracted by the pilot;
- **High AOA Protection function**, normally a feature found as part of a DFBW (Digital Fly-By-Wire) Envelope Protection System, which reduces the pitch authority by closing the control loop with alpha, alpha rate, pitch rate in order to achieve a commanded alpha. When the stick or yoke is at aft stops the commanded alpha is the one that guarantees acceptable aircraft handling qualities. This function does not allow the aircraft reach maximum AOA even with stick on the stop pulling up position. In this specific work we will call the maximum AOA allowed by the control law as α_{artf} (artificial alpha). Adverse situations, such as sensors failures, miscompares or loss of consistent signal processing, may lead to the so called Normal Mode control law to a Direct-To-Surface control law (or simply Direct Law), which owns a simple point gain schedule, but loses the closed loop features as the envelope protection. In this case, pilot should be aware of aircraft operational limitations, as far envelope protection features are not likely to be available. The artificial stall warning becomes active in this flight control law mode once the stall protection mode is no longer available.

2.3.4 Post Stall

This phase may involve angle of attacks greater than maximum lift coefficient (C_{Lmax}) AOA. In the post stall the airplane with benign and conventional stall characteristics pilot shall solely have to conduct the conventional recovery procedures. When the airplane exhibit unacceptable or non-certifiable stall characteristics, it may consist of several more or less distinct types of airplane motions as depicted below:

- Departure: characterized by divergent, large-amplitude, uncommanded aircraft motions, such as nose slice or pitch-up. Departure is equivalent to complete loss-of-control, it precipitates entry into a post-stall gyration, spin, or deep stall condition. (SELTZER, R. M., RHODESIDE, G. R., 1988, p.5).
- Post Stall Gyration: Random oscillations of the airplane about all axes following departure from controlled flight. (USNTPS, 1997, p. 2.42).

- Spin: maneuver during which the airplane descends rapidly toward the earth in a helical movement about a vertical axis (called the spin axis) at an angle of attack between the stall and 90 degrees. It is caused by a combination of two primary factors: exceeding stall AOA and sideslip. These two factors result in a phenomena known as autorotation, which occurs without lateral control input. (USNTPS, 1997, p.3.3).
- Deep stall: A flight condition in which the airplane has attained an AOA far higher than the $\alpha_{CL\,max}$ angle of maximum lift coefficient. (USNTPS, 1997, p.3.3). Loss of elevator effectiveness, when horizontal tail is in the turbulent wake of the wing, can occur. The moment coefficient with alpha, $C_{m\alpha}$, is both with positive gradient and in the positive side of the C_m versus C_L curve characterizing instability and divergence.
- Recovery is a post-stall phase maneuver characterized by lowering alpha and return to the controlled flight at the initial trim speed. Thrust must be applied accordingly in this phase, depending on the aircraft type design. For example, airplanes with high by-pass engine ratio: the vertical component of thrust produced in high AOA can lead to a pitch up moment, which may difficult the stall recovery and may result in secondary stalls. In this case, the best way of recovering is to move throttles to idle while pitching the nose down and add thrust only after alpha being below stall warning.

The stall recovery technique that must be applied follow below (FAA-H-8083-3B, 2016, p. 4-7):

1. Disengage auto-pilot and auto-throttle. In order to cover sensors failure like ADS and radio altimeter and avoid inadvertent changes.
2. Apply as much nose-down input as required to obtain nose-down pitch rate, in order to lower alpha as soon as possible. The focus should always be on lowering alpha to restore the sustaining airflow. Apply until stall warnings stop. Apply pitch trim needed.
3. Adjust bank angle, to regain aircraft control to wings level attitude.
4. Adjust thrust, once below stall protection entry or stall warning, in order to regain the trim speed.
5. Retract speed brakes, if not interlocked with speed or thrust lever angle.

6. When airspeed is sufficiently increased to regain the aircraft control, return to the desired flight path.

2.4 Stall Flight Test Techniques

Aircraft manufacturers currently execute stall flight tests to comply with civilian certification requirements: Part 25 for transport aircraft (see appendix A) and Part 23 for normal, utility and commuter category aircraft. This section will focus on Part 25 stall requirements. Most of information of stall flight test techniques are found in Advisory Circular 25-7C, which is the acceptance means of compliance for Part 25 aircraft.

Primarily, stall investigations are conducted for the following reasons:

1. Safety and operational considerations. Verify that no inadvertent stall could happen in all flight phases.
2. Determination of the stall speeds and identification of the stall characteristics (actual flight tests are the only means of determining stall characteristics).
3. Expansion and boundary determination of the operational flight envelope.
4. Determination of trim airspeeds for future tests.

Stall certification flight tests campaign are typically split into two phases: stall speeds and stall characteristics. It is important to highlight that the authorities require the manufacturers to determine stall speeds and demonstrate stall characteristics thoroughly, which includes the recovery procedure capability. It is desirable the recovery procedure technique being as conventional as possible and not demand exceptional piloting skills, strength or alertness. Otherwise, it shall be comprehensively substantiated.

2.4.1 Performance: stall speeds

Determining stall speed in-flight is an important issue because it affects landing and takeoff performance, as the reference approach speed, landing, climb, landing-climb, approach-climb and takeoff speed are defined as multiples of V_{SR} (reference stall speed). The reference stall speed is the stall speed achieved in flight test regarding the decrease in recorded load factor, which apparently reduces stall speed without reflecting in real lift capability of the airplane. V_{SR} may not be less than the 1-g stall speed and is expressed as:

$$V_{SR} \geq \sqrt{\frac{1}{n}}\ V_s \tag{12}$$

According to FAR 25 § 25.103 requirements (Appendix A.1), stall maneuvers should be executed to demonstrate C_{Lmax} with (CG) at the extreme forward position of the airplane flight envelope (± 7% tolerance of CG travel during flight is accepted), because in such case it is the most degraded performance condition (see section 2.2.5). Afterwards, it must be a C_L correction for the most forward CG operational envelope (14 CFR 25.21, Proof of Compliance). Sufficient testing should be conducted to determine the effect of weight on stall speed.

The general procedures for executing stall speeds maneuvers are depicted in AC 25-7C 29.d.(3)(a):

> "The airplane should be trimmed for hands-off flight at a speed 13 percent to 30 percent above the anticipated Vsr, with the engines at idle and the airplane in the configuration for which the stall speed is being determined. Then, using only the primary longitudinal control for speed reduction, maintain a constant deceleration (entry rate) until the airplane is stalled (FAA, 20xx)."

The intention of this maneuver is focuses in obtain maximum C_L and V_{SR} data. Once stall definition is achieved, quick recovery is recommended. Then, the maximum lift coefficient C_L the data should be corrected for zero thrust, even though it is determined with idle thrust during flight test, and at last, a correction must be accomplished for the entry rate of -1 kt/s, which means a steady rate of speed reduction of 1 kt/s.

Stall speeds should be determined for all aerodynamic configuration (flaps / slats/ gear/ speed brake) to be certificated for use in the takeoff, enroute, approach, and landing configuration (FAA, AC 25-7C 29.d(2)(a)). For envelope protected airplanes, i.e. full DFBW, the operational normal mode control law shall be modified or failed to allow reaching α_{CLmax} . Depending on the airplane type, conventional or DFBW and envelope protection, the means of compliance may vary and the certification authority is likely to address the compliance finding through special conditions.

2.4.2 Flight qualities: stall characteristics

The definition of stall airspeed by Part 25 requirements is linked to the practical concept of minimum useable airspeed. Useable means controllable in the context of a mission task. The investigation of stall characteristics is one of the phases of flying qualities flight test certification program aiming to demonstrate compliance with 14 CFR 25 § 25.201 (Stall Demonstration), § 25.203 (Stall Characteristics) and § 25.207 (Stall Warning). To assure a safe and expeditious recovery from an unintentional stall, the behavior of the airplane during the stall and recovery must be easily controllable using normally expected pilot reactions. It should not require any unusual piloting technique nor should it require exceptional skill or repeated practice by the test pilot.

According to 14 CFR 25 § 25.201 and § 25.203 requirements, stall maneuvers should be executed to demonstrate C_{Lmax} with Center of Gravity (CG) at the most aft position, which is the most critical condition for longitudinal stability and the recovery maneuver, considering conventional aircraft type designs. Most of fly-by-wire type designs are required to conduct stall characteristics flight tests in the forward CG as well, as per special conditions. Stall characteristics should be investigated with wings level and in a 30-degree banked turn, with both entry rate up to -1 kt/s and up to -3 kt/s (accelerated stalls), with both power or thrust ON and power or thrust OFF (IDLE lever position) and in all configuration (slat/flap, gear up/down and speed brakes deployed) approved for normal operations. For thrust on stalls, power or thrust should be set to the value required to maintain level flight at a speed of 1.5 VSR at the maximum landing weight with flaps in the approach position, and the landing gear retracted. Also, stall characteristics should also be demonstrated with the maximum allowable asymmetric fuel loading.

The general procedures for executing stall characteristics maneuvers are depicted in AC 25-7C 29.e.(3)(a):

> "The airplane should be trimmed for hands-off flight at a speed 13 percent to 30 percent above the reference stall speed, with the appropriate

> power or thrust setting and configuration. Then, using only the primary longitudinal control, establish and maintain a deceleration (stall entry rate) as appropriate, until the airplane is stalled." (p.135).

The same trim reference (for example, 1.23 Vsr) should be used for both the stall speeds and characteristics testing.

For fly-by-wire aircraft, AC 25-7C 29.e.(2)(c) states that::

> "Stall characteristics should be investigated with any systems or devices that may alter the stalling behavior of the airplane in their normal functioning mode. Unless the design of the airplane's automatic flight control system precludes its ability to operate beyond the stall warning angle-of-attack, stall characteristics and the adequacy of stall warning should be evaluated when the airplane is stalled under the control of the automatic flight control system". (p. 134).

Depending on the aircraft flight control system, its certification may be addressed through special conditions. In exceptional cases and if properly substantiated by the applicant, the aircraft may be certificated with unacceptable stall characteristics, under certification standpoint, since it has demonstrated by system analysis, as per 14 CFR §25.1309, that the stall condition would be extremely improbable to be achieved, which means a 10^{-9} per flight hour failure rate and no single failure would result in the stall condition. Pilot error or mishap is not covered by such a requirement.

2.4.3 Stall warning tests

Stall warning tests are executed to demonstrate compliance with 14 CFR 25 § 25.207, whose aim is to provide an adequate spread between warning and stall to allow the pilot time to recover without inadvertently stalling the airplane. The spread is defined by 25.207 (c) requirement as an Vsw (speed when the stall warning begins) not less than five knots or five percent above Vsr for bleed rates up to - 1kt/s. For straight flight stalls up to -1 kt/s and engines in idle, Vsw should be not less than three knots or three percent (whichever is greater) above the reference stall speed. Stall warning margin tests are normally conducted in conjunction with the stall testing required by § 25.103 (stall speeds), § 25.201, and § 25.203, including consideration of the prescribed bank angles limits, power or thrust settings, and CG position. Again, for DFBW the administrator, requiring different conditions to be tested, may demand type design supplemental special conditions.

Moreover, § 25.207(f) requires the execution of accelerated stall maneuvers, slowdown turns with at least a 1.5g load factor normal to the flight path and an airspeed deceleration rate greater than 2 knots per second, to ensure that adequate stall warning exists to prevent an inadvertent stall under the most demanding conditions that are likely to occur in normal flight. The procedures for executing accelerated stall warning margin maneuvers are described in AC 25-7C 29.g.(2)(c):

> "Trim at 1.3 V_{SR}. Once trimmed, accelerate to a speed that will allow enough time to set up and complete the maneuver at the specified load factor and airspeed deceleration rate. Set power or thrust appropriate to the power or thrust for level flight at 1.3 V_{SR} and do not adjust it during the maneuver. In a level flight maneuver, 1.5g equates to a bank angle of 48 degrees. To prevent an excessive deceleration rate (e.g., greater than 3 knots per second), a descent may be used. Conversely, if the deceleration rate is too low, the maneuver should be conducted in a climbing turn. After the onset of stall warning, continue the maneuver without releasing stick force for one second before attempting recovery."

As recommended, maneuver is continued until one second after the stall warning onset. Normally, it does not reach stall definition.

2.4.4 Natural stall tests

One of the most challenging and waited phase in the flight test campaign is to check whether the first designed maximum lift coefficient C_{Lmax}, and initially assessed in the wind tunnel would be achievable or not in real flight. Differently from stall speeds and stall characteristics campaigns, which have the aim of showing compliance with Part 25 requirements, this one is done for aircraft development reasons, normally before the certification campaigns. When looking for the so desired mission maximum lift coefficient C_{Lmax} there are some facts which are inherent to the design process. In the wind tunnel, the lift and drag coefficient C_L and C_D, respectively, are corrected for Reynolds (Re) effect and scale factor, but it could have some wall effect that may not be correctly accounted. In the real design world the first wing manufactured may be associated with imperfections, aerodynamic seals not well fitted, the swirl thrust effect not accounted, and others related to the aircraft integration as whole, which may result in the aerodynamic figures not predicted when compared to designed values or even the wind tunnel figures, both which generated the first aerodynamic databank. It may occur towards good side, i.e., more C_L or less drag (C_D) which is not common, towards the bad side, i.e., well below the designed C_{Lmax} values and above expected drag figures, or the most common: just in the threshold, missing some lift counts or exceeding by some drag counts.

Either way, the only method to determine the real wing capability is to execute the straight flight stall without any interference of artificial protection (conventional airplane) or maximum alpha envelope protection feature disabled to check during the approach to stall whether the predicted values are being achieved or not. It is normally conducted with mid CG, and afterwards, forward CG (or corrected to the forward CG position) to obtain as close as to the certification conditions values.

2.4.5 Stall FTT Risks

The risks involved with flight test are quite different from those experienced in airliners flight, which are not supposed to operate exploring the limits of the aircraft and beyond the operational limits. Here, it is listed some hazards that can happen while executing stall maneuvers proceeding:

- Loss of control In-Flight (LOC-I), due to unpredicted aerodynamic response or unpredicted High AOA protection behavior.
- Dual engine failure, due to high AOA at the engine’s inlet, causing inlet flow distortion. It is more likely to happen in high altitudes, because of combination of low density and high AOA at the inlet.
- Flight Control System failure. An unpredicted aerodynamic response can also cause air data probes misleading, which can lead to a failure of FCS.

The risk of stall maneuvers, specially of accelerated stall maneuvers, is considered from medium to high due to the difficulty of execution, with tight tolerances in the alpha control and the probability of getting into an unsafe situation due to overshoot or when recovering the airplane. This type of test flight is always undertaken during the day, in VMC conditions and in a calm atmosphere. Natural stalls are normally categorized as high risk test and it is conducted with crew fitted with helmets and parachute, the aircraft with tailchute installed and all the flight is supported by a pacer and telemetry with the engineering design office support.

2.5 Section Summary

This section presented the elements of stall theory, which were important ideas for the discussion in this work:

- ✓ Stall is a lift loss due to flow detachment of wing surface.
- ✓ Detached flow characteristics: vortical, turbulent, unstable, unpredictable. Linear model can no longer be representative.
- ✓ Stall phases are: approach to stall, stall warning, stall definition and post-stall.
- ✓ Current FTTs are defined and executed up to stall definition and does not cover post-stall region
- ✓ Stall maneuvers are risky and can lead to a LOC hazardous.
- ✓ Stall flight tests data is limited to the maneuvers envelope covered by current FTTs.

Summary of FTTs executed for Part 25 requirements:

Figure 2-11 Summary of Part 25 Stall Flight Test Techniques.

Flight Test	Objective	Maneuver Description	Limits	Risk
Stall Speeds	Determine Clmax and Vsr	CG most FWD, all config, aircraft trimmed 1.3 Vsr, -1kt/s until stall	α_{CLmax}	H
Stall charac	Prove acceptable characteristics inside envelope	CG most AFT, all config, wings level/ 30º bank, thrust ON/ OFF, aircraft trimmed 1.3 Vsr, entry rates -1/ >-3 kt/s	α_{artf}	M / H
Star Warning	Prove stall warning safe margins	Accelerated stall, aircraft trimmed 1.3 Vsr, -2kt/s, 1.5 g ~ 48° bank	$\alpha_{warn} + 1s$	M / H
Natural Stall	Development	Direct mode, as required for development	α_{CLmax}	H

3 FLIGHT SIMULATION TRAINING DEVICE (FSTD)

Flight simulators are nearly always used for training pilots in the commercial aviation industry, making the learning process cheaper, safer and more productive when compared to real flight training. Flight Simulation Training Device (FSTD) is defined by FAA in 14 CFR Part 1, section 1.1 - Definitions and Abbreviations, as “a full flight simulator or a flight training device” whose definitions are:

> “A Flight Training Device (FTD) is a replica of aircraft instruments, equipment, panels, and controls in an open flight deck area or an enclosed aircraft cockpit replica. It includes the equipment and computer programs necessary to represent aircraft (or set of aircraft) operations in ground and flight conditions having the full range of capabilities of the systems installed in the device.
>
> Full Flight Simulator (FFS) means a replica of a specific type; or make, model, and series aircraft cockpit. It includes the assemblage of equipment and computer programs necessary to represent aircraft operations in ground and flight conditions, a visual system providing an out-of-the-cockpit view, a system that provides cues at least equivalent to those of a three-degree-of-freedom motion system, and has the full range of capabilities of the systems installed in the device […]” (FAA,1962).

Despite simulation training facilities, the FSTD as any other device has its limitations and fidelity to real aircraft environment is one of them. The objective of this chapter it to describe the main concepts of FSTD fidelity, its dependence on modeling and how transport aircraft aerodynamic models for simulators are obtained and matched with flight test data. Finally, explain current regulations to validate an FSTD.

3.1 FSTD Fidelity

Fidelity is a term that is very commonly used term and it recalls the ideas of similarity, resemblance. Flight Simulator Training Device fidelity can be defined as a measure of the degree to which a simulation system represents a real-world system. (MEYER et al., 2012, p.1). The real-world system applied in the scope of stall training is the aircraft dynamics and flight environmental condition (altitude, turbulence, etc). According to Young and Lenné (2017, p.6), three aspects of simulator fidelity features:

- Physical fidelity: the degree to which the simulated environment looks and sounds like the real environment. For example, the simulator cockpit has the same design as the real aircraft cockpit, with buttons, knobs and panels equally spaced and placed just as the real aircraft cockpit.

- Functional fidelity: the degree to which the simulated environment behaves like the real environment. It is related to the aircraft dynamics behavior, the simulator must respond the same way to the same pilot inputs just as in the real aircraft.
- Psychological fidelity: the degree to which the simulated environment evokes the same psychological processes, such as perceptions, emotions and self-awareness of the real world.

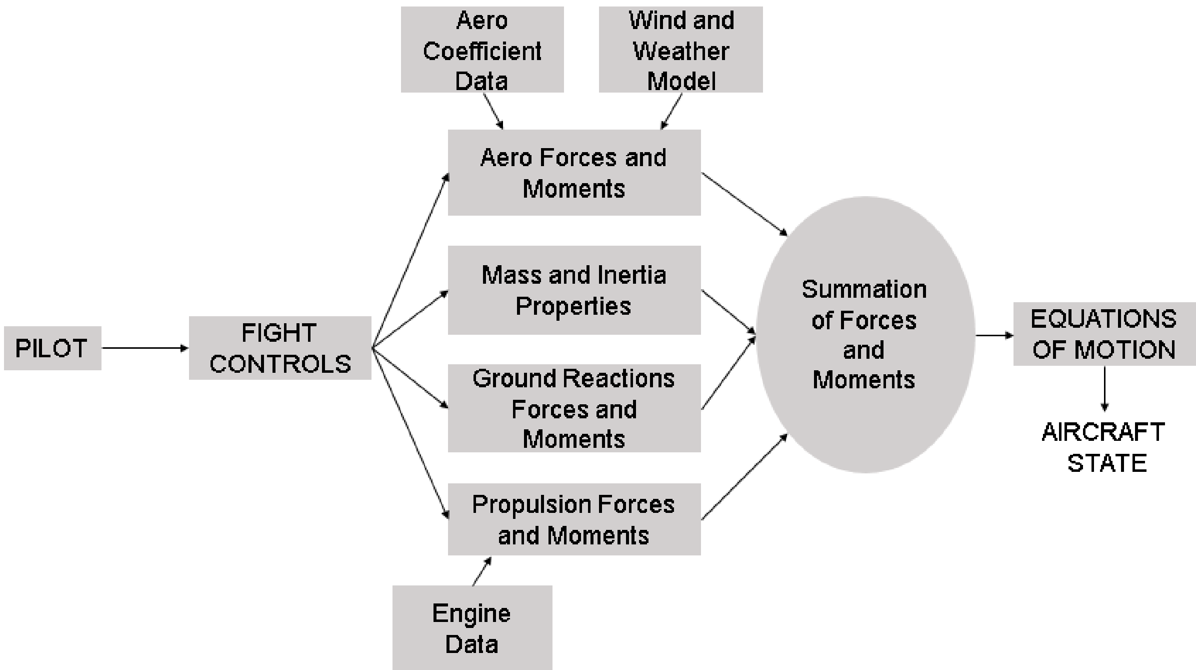
Fidelity is a factor of prime importance of simulation design. Lack of FSTD accuracy and realism could expose crew to unnecessary safety risk when facing a situation that is different from what they have been previously experienced in training. As it is explained by FAA in 79 FR 39461 document (2014, p. 39464), “the lack of ability for an FSTD to adequately conduct certain training tasks could contribute to misunderstanding of recognition cues, learning of inappropriate recovery techniques, or a lack of understanding of dangerous flight conditions […]”. In addition, in this document the FAA states that FSTD lack of fidelity may have been a contributing factor in some accidents. One example is the Airborne Express DC–8 aircraft accident in Narrows, Virginia, 1996. According to the NTSB’s accident investigation report (1997), the ABX DC-8 simulator developed a stable, nose-high, wings-level descent, with no tendency to pitch down in a stall break (abrupt nose-down pitch or roll) whereas the actual DC-8 airplane’s stall characteristics include a pronounced stall break. “Further, after slowing well below stall speed, the simulator entered a mode in which the aerodynamic buffet stopped and the airspeed did not continue to decrease”. (NTSB, 1997, p.40). It is clearly a contributing factor to misunderstanding of recognition cues.

The FSTD ability to reproduce real-world tasks highly depends on the mathematical model built to represent the aircraft dynamics. Poor modeling affects functional fidelity, once the simulator’s behavior can differ from aircraft behavior for the same inputs, and affects also psychological fidelity because a different behavior cause different sensorial perceptions on trainees. Model fidelity is necessarily function of the quality and amount of data sources, ranging from flight test and wind tunnel data sources through established extrapolation methods.

3.2 Preliminary Modeling

Typical flight simulation model, represented in Figure 3-1, includes the equations of motion (EOMs), which are the foundation of all flight simulators. Starting from the inputs, which includes pilot commands, flight controls and wind inputs, basing on aerodynamic and engine terms, the EOMs represents the state of the simulated aircraft, particularly forces, moments, attitude, altitude, heading and velocities (ALLERTON, D., 2009, p.16). During the first stages of the aircraft design process, it is difficult to obtain reliable aerodynamic information, assessing performance, stability and flight handling qualities throughout the flight envelope of the aircraft (AKRAM, U.; CRISTOFARO, M.; DA RONCH, 2016, p.4). Traditional preliminary design methods are based on low–fidelity, linear, small-perturbations assumptions.

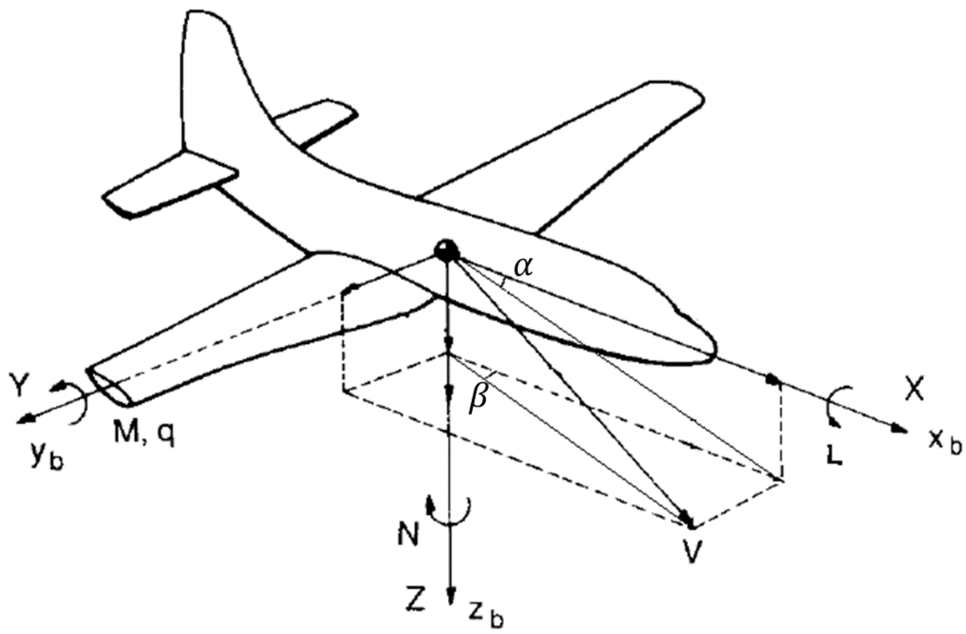
Figure 3-1 Typical flight simulation model.



Adapted from: THOMAS GALLOWAY, 31st Flight and Ground Vehicle Simulation Course.

Aerodynamic preliminary modeling usually combine computational fluid dynamics (CFD) with semi-empirical data of aerodynamics originally developed for conventional aircraft configurations and built into a computer program such as Datcom (STEVENS; LEWIS, 2003, p.79). Input data to Datcom must include a geometrical description of the aircraft. The aim is to obtain a database of estimated force coefficients (C_L ,C_D, C_Y), moments coefficients (C_m , C_l , C_n) and their derivatives as function of (α, β, δ, M, h, T); where α is the angle of attack (AOA), β is the angle of sideslip (AOS), δ is the control surface deflection, M is Mach number, h is altitude and T is Thrust (STEVENS and LEWIS, p.75). The aerodynamic coefficients will feed the 6 equations of motion, which are specified in table 3-1.

Figure 3-2 Aircraft body axis and moments



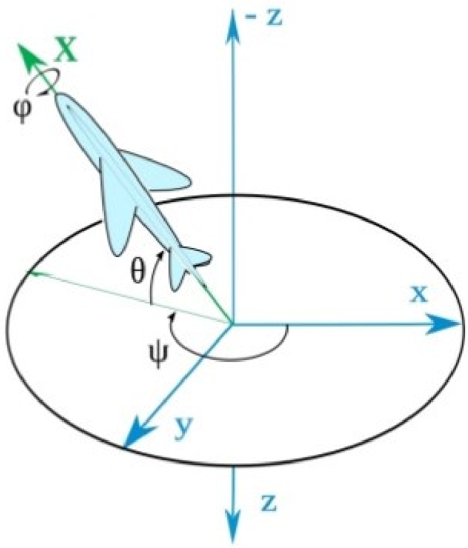
Adapted from: NELSON, Flight stability and automatic control.

Table 3-1. Aircraft forces, moments, and respective axis.

Forces	**Equation**	**Direction**
Drag, D	$D = q\ S\ C_D$	X_W axis
Lift, L	$L = q\ S\ C_L$	Z_W axis
Side force, Y	$Y = q\ S\ C_Y$	Y_b axis
Moments	Equation	Direction
Roll, L	$L = q\ S\ b\ C_l$	X_b axis
Pitch, M	$M = q\ S\ c\ C_m$	Y_b axis
Yaw, N	$N = q\ S\ b\ C_n$	Z_b axis

As it is demonstrated in tables, the EOM come from Newton's 2nd law, sum of forces and moments in 3 translational and 3 rotational axes, where $q = \rho V^2/2$ is the dynamic pressure. They may be referred to the aircraft-fixed coordinate system, called body reference frame, with its origin on aircraft's center of mass. To transform Lift and Drag forces from wind axes to body axes, α and β angles must be accounted. Gravity force is always with respect to an inertial reference frame (earth-fixed) and transformed to body axis by accounting Euler angles: ϕ (roll angle), θ (pitch angle) and ψ (heading angle), represented in Figure 3-3.

Figure 3-3 Euler Angles



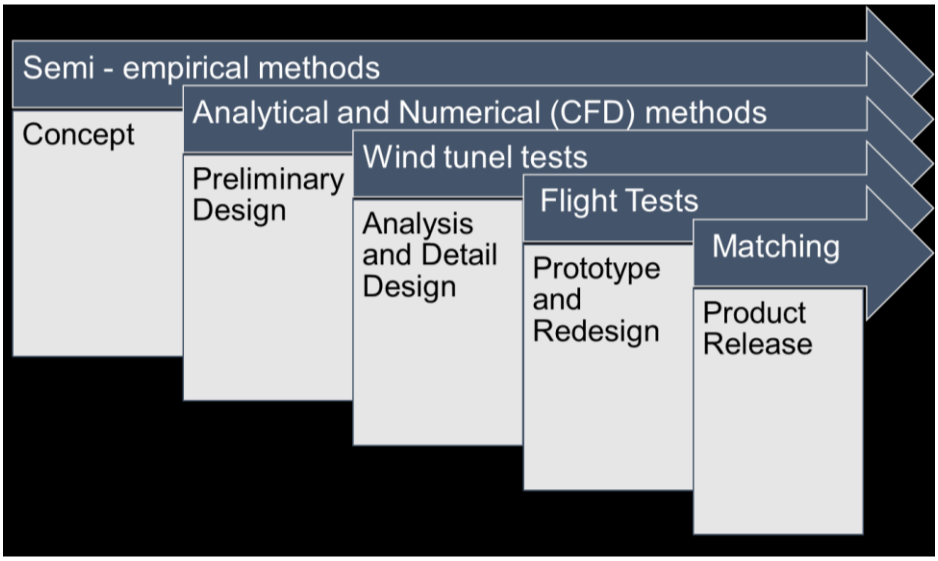
Source: Wikipedia.

3.3 Refined Modeling

Preliminary studies derives the first figures for derivatives, moment coefficients and other parameters to estimate aircraft flying qualities and performance. Wind tunnel testing in sub-scaled aircraft model provides realistic data to validate the first simulations and refine the mathematical model by and combining all semi-empirical, analytical, numerical and wind tunnel results. In this phase of aircraft design, conceptual design was finished and aircraft geometry was fixed to build the sub-scaled model. It is applied the Reynolds corrections for real flow and generated an updated aerodynamic databank.

However, wind tunnel testing is limited by physical constraints, such as blockage, scaling, mount interferences and by Mach and Reynolds effects. So, after detailed design phase, a prototype is built and flight test data will be provided continue refining model. Flight test assessment improves accuracy of aerodynamic predictions, and it is certainly the most expensive method to obtain the needed parameters (AKRAM, U.; CRISTOFARO, M.; DA RONCH, 2016, p.19). Figure 3-4 timeline briefs the modeling refinement process whilst aircraft development process occurs. The aerodynamic package generated by the aircraft manufacturer has high commercial value and may not be available for public domain. It is generally provided to the simulator manufactures as part of a confidential agreement (ALLERTON, D., 2009, p.17).

Figure 3-4 Aircraft model development process.



3.4 High AOA modeling

Sections 3.2 and 3.3 described the traditional aerodynamic modeling practices for transport aircraft, which are inadequate for modeling post-stall motions (MURCH, 2007, p.4). The unsteady and random behavior of high AOA airflow cannot be represented by the ODE of motions. CFD nonlinear results could be achieved with expensive computational cost through the Navier-Stokes equations, which predicts flow detachment by incorporating viscosity and compressibility terms. However, data is necessary for all numerical or analytical model first validation and minimal wind tunnel data are taken for the purpose of predicting post-stall departure (FOSTER et al., 2005, p.2). Common wind tunnel testing in commercial aviation is limited to static effects measurements only. Research on dynamic and rate damping effects modeling have been conducted under the NASA LaRC wind tunnels (shown in Figures 3-5 and

3-6), with motions hinges allowing to obtain the rotary steady-state and oscillatory components (FOSTER et al., 2005, p.3). Validating new research methods is also an issue, due to limited post stall flight test data.

Figure 3-5 Roll forced oscilation rig, NASA LaRC 14x22 ft Tunnel

Source: MURCH & FOSTER, Recent NASA Research on Aerodynamic Modeling of Post- Stall and Spin Dynamics of Large Transport Airplanes.

Figure 3-6 Rotary balance rig, NASA LaRC 20 Ft Vertical Spin Tunnel

Source: MURCH & FOSTER, Recent NASA Research on Aerodynamic Modeling of Post- Stall and Spin Dynamics of Large Transport Airplanes

3.5 Flight Test Data Matching

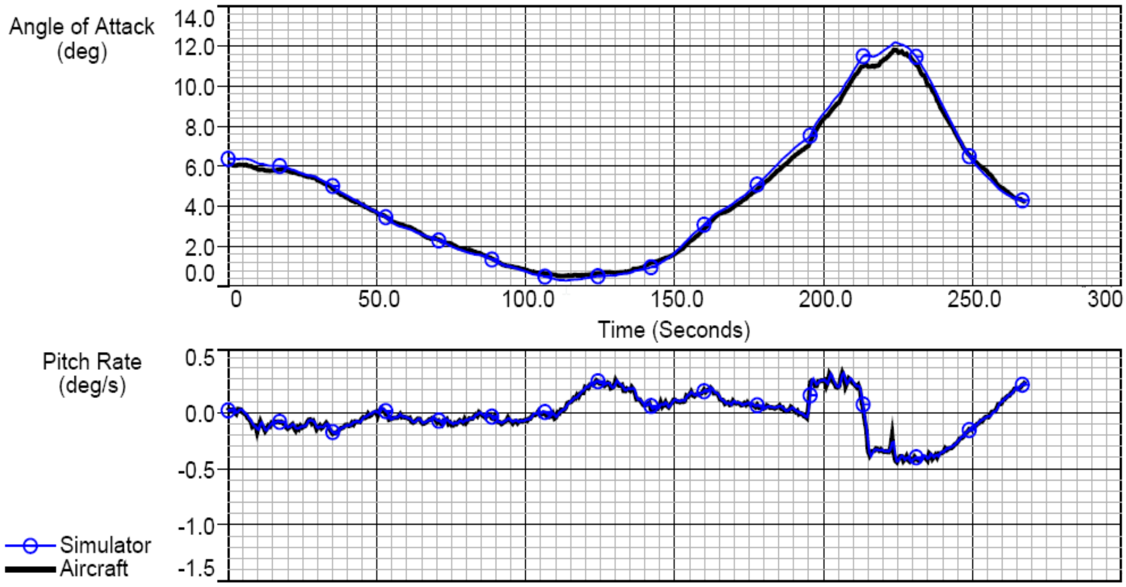
Once the FSTD model was defined by preliminary studies refined by wind tunnel or flight test data then it must be compared with flight test model, which is obtained by interpolating the data points collected from specific maneuvers in-flight. For advanced simulators, the aerodynamic data accuracy requirements are greater than almost any other application in the aerospace industry, including aircraft certification. While flight test data for aircraft certification should only demonstrate that the aircraft meets some particular characteristics, a simulator model must duplicate exactly the same characteristics (RAeS, 2005, p. A-2).

Therefore, data for simulators should be of the highest quality. Tests should be conducted by qualified personnel in the most stable atmospheric conditions obtainable. Each test run must be started from a fully trimmed, steady state condition with all parameters which can affect the test being known and recorded. Flight test instrumentation should be properly calibrated and all pertinent parameters should be measured. This data is usually provided by the airframe manufacturer because it has the greatest familiarity with its own products and can better identify representative data, which accurately defines the airplane. Although, FAA requirements allows data from third party as described in 14 CFR § 60.13 (b):

> "The validation data package may contain flight test data from a source in addition to or independent of the aircraft manufacturer's data in support of an FSTD qualification, but only if this data is gathered and developed by that source in accordance with flight test methods, including a flight test plan, as described in the applicable QPS." (FAA, 20xx).

Afterwards, the same maneuvers executed in-flight are repeated in simulator, so both models can be fairly compared, from the same inputs. Time-history plots such as those exemplified in Figure 3-7 are made for comparison: in this example case, AOA and pitch rate measured in a longitudinal stability maneuver were plotted and the difference between aircraft and simulator data are minimal. This difference should be within the tolerances specified in Part 60 requirements (see Appendix B), required only for linear modeling.

Figure 3-7 Aircraft and simulator time-history plots

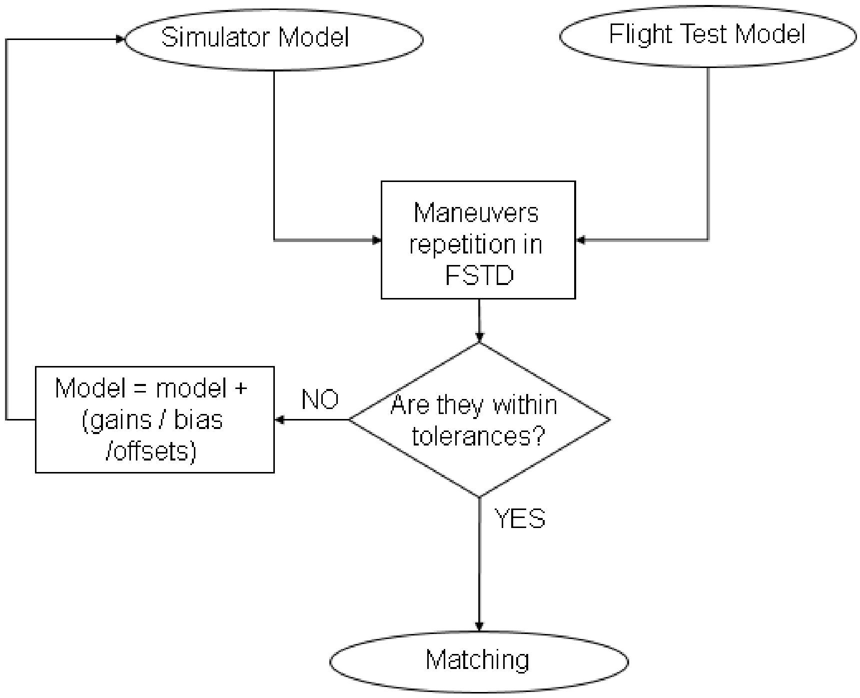


Source: EMBRAER (For confidential reasons the scale values have been modified).

The matching process, shown in figure 3-8, aims to establish preliminary analytical/numerical/empirical simulator model refined by wind tunnel data into specified tolerances by comparing to flight test data and applying some gains, offsets or bias to adjust the model. It can be done manually or using optimization algorithms, as least squares, linear quadratic regulator (LQR), differential evolution and others.

Once repeatability is a determining factor of flight test data quality, the quality of data obtained beyond AOA max may be doubtful and strict time-history based matching against flight test data may not adequately represent the aerodynamic model in an unstable flight regime, such as stalled flight. It explains why the tolerances specified in Part 60 requirements (see appendix B) are required only for linear modeling.

Figure 3-8 Matching with flight data process.



3.6 FSTD Validation

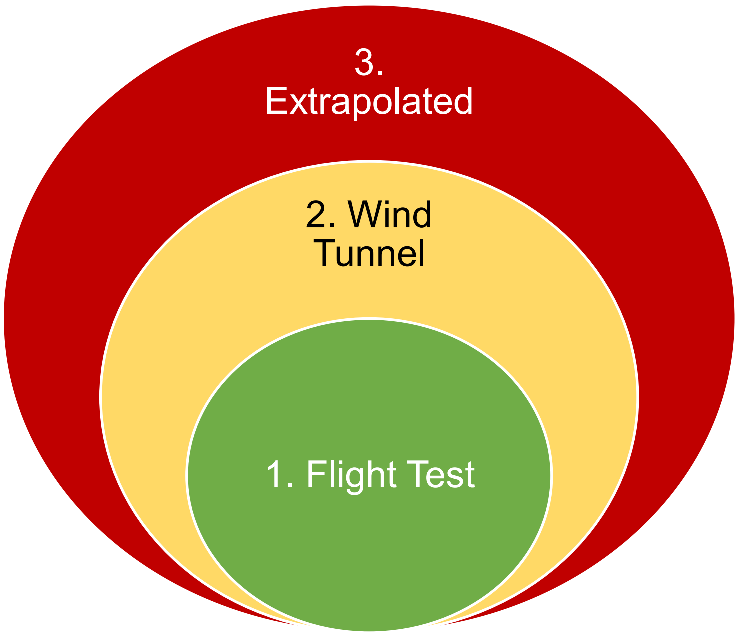
FSTDs can only be approved for training after the execution validation tests in order to show compliance with 14 CFR Part 60 QPS (Qualification Performance Standards). This test compare simulator performance against the standard, i.e., the airplane flight test or other acceptable data, to check if matching is acceptable. Acceptable means within the tolerances specified by 14 CFR Part 60 requirements for the test to pass or substantiated by rational engineering judgment. When executing validation tests, two different approaches can be considered: objective tests and subjective tests.

Objective evaluation tests require quantitative measures and plots, and compare the FSTD's performance and handling qualities against flight-test-collected validation data within tolerances prescribed in 14 CRF Part 60 Table A2A (Full Flight Simulator Objective Tests). Besides the tolerances for each parameter, Table A2A also describes the minimal required tests for each FSTD level, the initial conditions and test procedures. Objective tests are usually executed by automatic algorithms that provides the proper inputs (i.g, step, pulse, doublet, etc.) for each test and records the model response to be compared to flight-test baseline. It might be also possible to conduct each test manually while recording all appropriate parameters.

Subjective evaluation tests are qualitative tests that tries to identify the degree of realism felt by the users' point of view through a Subject Matter Expert (SME) assessment. A SME is normally a pilot with enough knowledge of the cues necessary to accomplish the required training objectives and experience in piloting the real aircraft which is being tested. Part 60 Table A3A (Functions and Subjective Tests) address pilot functions, including maneuvers and procedures, called flight tasks. While objective tests provide a basis for measuring and evaluating FFS performance, subjective tests provide a basis for determining that the FFS satisfactorily simulates each required task and for verifying correct operation of the FFS controls, instruments, and systems.

The FAA explains the regions and expected confidence levels of the FSTD validation envelope in Attachment 7, section B of Part 60 Appendix A. These regions, shown in Figure 3-9, are defined by the amount and type of validation and analysis used to develop the aerodynamic model. They can be represented as follows:

Figure 3-9 Level of FSTD fidelity regions.



"1. **Flight test validated region:** This is the region of the flight envelope which has been validated with flight test data, typically by comparing the performance of the FSTD against the flight test data through tests incorporated in the QTG and other flight test data utilized to further extend the model beyond the minimum requirements. Within this region, there is **high confidence** that the simulator responds similarly to the aircraft. Note that this region is not strictly limited to what has been tested in the QTG; as long as the aerodynamics mathematical model has been conformed to the flight test results, that portion of the mathematical model can be considered to be within the flight test validated region.

2. **Wind tunnel and/or analytical region:** This is the region of the flight envelope for which the FSTD has not been compared to flight test data, but for which there has been wind tunnel testing or the use of other reliable predictive methods (typically by the aircraft manufacturer) to define the aerodynamic model. Within this region, there is **moderate confidence** that the simulator will respond similarly to the aircraft.

3. **Extrapolated:** This is the region extrapolated beyond the flight test validated and wind tunnel/analytical regions. The extrapolation may be a linear extrapolation, a holding of the last value before the extrapolation began, or some other set of values. Whether this extrapolated data is provided by the aircraft or simulator manufacturer, it is a “best guess” only. Within this region, there is **low confidence** that the simulator will respond similarly to the aircraft”. (FAA-Part 60, 2016, p.232).

New FSTD evaluation requirements for stall recognition and aircraft handling qualities are necessary if training is to be conducted to a full stall. Most aerodynamic modeling on modern FSTDs assumes a certain amount of linearity from objectively validated test points to extrapolate aircraft performance and handling qualities between test points. As an aircraft approaches a stalled flight condition, this linearity can no longer be assumed, and more test points are required to validate the fidelity of the model.

Besides FAA regulations, the International Standards for the Qualification of Airplane Flight Simulators stablishes the requirements for an International Qualification Test Guide. It was agreed following working group meetings and international conferences which provide guidelines for objective and subjective tests.

3.7 Section Summary

- ✓ Fidelity is the degree to which a simulation system represents a real-world system. It depends on the model and the amount of data available for matching and validation.

- ✓ Aerodynamic modeling of conventional aircraft combines semi empirical, analytical, CFD, wind tunnel and flight test methods.
- ✓ Traditional aerodynamic modeling practices for transport aircraft are inadequate for modeling post-stall motions.
- ✓ High fidelity confidence requires flight test enough data for validation, which may not be feasible for high AOA and post stall cases.
- ✓ A FSTD model based only in wind tunnel data and engineering analysis will be classified as moderate fidelity confidence.

4 ACCIDENTS THAT MOTIVATED PUBLIC LAW 111-126

United States of America Public Law 111-126 (August, 2010) sec. 208 states that:

> "The FAA (Federal Aviation Administration) shall conduct a rulemaking proceeding to require domestic, flag and supplemental air carriers to provide flight crewmembers with flight training or flight simulator training to recognize and avoid a stall of an aircraft or, if not avoided, to recover from the stall" (U.S. Congress, 2010).

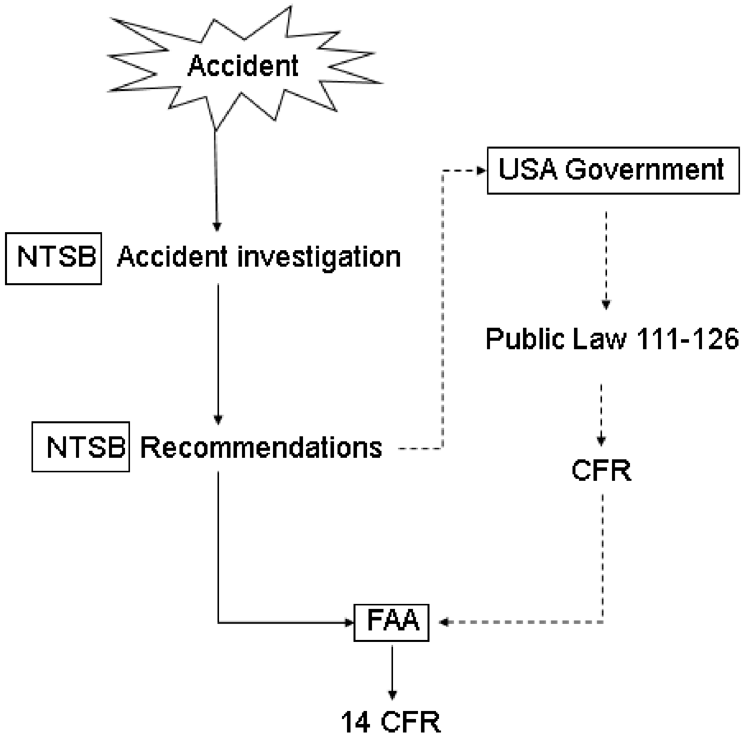
When an airplane accident happens, NTSB (National Transportation Safety Board) is the US organization in charge of the investigation (see Figure 4-1), it in some way resembles to CENIPA (*Centro de Investigação e Prevenção de Acidentes Aeronáuticos*) in Brazil, but with much more broad actuation rather than CENIPA. NTSB, also, exerts a lot of influence in both operational and certification requirements, in the most of cases, issuing recommendations for modifications to sort the probable accident causes out. The other main difference between CENIPA´s role and NTSB´s is the conclusion. CENIPA come with contributing factor for the accident whilst NTSB come with probable cause or the cause itself.

When the investigation is finished, the NTSB addresses some Safety Recommendations to FAA (Federal Aviation Administration). FAA is responsible for number 14 Code of Federal Regulations (CFR), also named FAR (Federal Aviation Regulations), which includes all aspects of civil aviation regulations, such as: construction and operation of airports, the management of air traffic, the certification of personnel and aircraft, and the protection of US assets during the launch or reentry of commercial space vehicles. In Europe, the equivalent to FAA is an agency that join all the countries, which are signed to the EU, the EASA (European Aviation Safety Agency).In Brazil, the organization in charge of these tasks is ANAC (*Agência Nacional de Aviação Civil* (see table 4-1).

Table 4-1. Aviation organizations and responsibilities.

Responsibility	USA	Europe	Brazil
Regulate all aspects of civil aviation	FAA	EASA	ANAC
Investigate and prevent airplane accidents	NTSB	ENCASIA	CENIPA

Figure 4-1 Lessons learned with accident: common x flight 3407 process.



This is what normally happens, explained in the solid line at the left hand side Figure 4-1 scheme above. However, in the case of the airliners pilots stall training issue, the American Congress was under public opinion pressure after some catastrophic accidents happen. The consequence was Public Law 111-126 determining that FAA shall proceed with new rulemaking to implement stall prevention and recovery training as represented by the dashed line right hand side scheme above. As FAA and ANAC have both signed a bilateral agreement these rules impact Brazilian companies like Embraer, which must demonstrate compliance with FAA requirements.

This section analyzes three accidents that had major impact in the public opinion, both because of the number of deaths involved and due to the way they happened. They are: Colgan air flight 3407, Turkish Airlines flight 1951, and Air France flight 447. Although it is known that airplanes accidents are caused by a chain of events, the objective of the following analysis is to focus on the stall aspect, and the pilot's reaction to stall cues.

4.1 Continental Connection Flight 3407

Continental Connection flight 3407 Newark- Buffalo (see Figure 4-2 map) accident in February 12, 2009, was the biggest motivator for the discussion. The NTSB investigation technical report (2010) evidences crew's unpreparedness in the face of a stall situation and lets several recommendations for the safety of future flights, among them the specific and regular training of pilots in stall approach and recovery.

Figure 4-2 Flight path of light 3407 DHC-8-400 aircraft.

Source: https://www.baumhedlundlaw.com/commuter-plane-crash-near-buffalo-ny-kills-50-people/. Access on: 05/21/2018.

Figure 4-3 Continental Connection Bombardier DHC-8-400 aircraft.

Source: https://en.wikipedia.org/wiki/Colgan_Air_Flight_3407. Access on: 05/21/2018.

4.1.1 History of the flight

On February 12, 2009, a Colgan Air, Inc., Bombardier DHC-8-400 (see Figure 4-3), N200WQ, operating as Continental Connection flight 3407, was on final approach to Buffalo-Niagara International Airport, Buffalo, New York, with the following configuration: landing gear down, flaps at 15º position and both engines' torque values at minimum thrust. CVR recorded captain and first officer comments recognizing ice conditions. The airspeed was about 145 knots and it was decreasing very quickly. Then the stick shaker warning activated and the autopilot disengaged. At this time the airspeed was about 131 knots. The captain pulled the column aft and, one second later, advanced thrust levers to 70º, increasing engines power to about 75 percent torque. FDR data showed that, while engine power was increasing, the airplane pitched up; rolled to the left, reaching a roll angle of 45° left wing down; and then rolled to the right.

As the airplane rolled to the right through wings level, the stick pusher activated. The first officer told the captain that she had put the flaps up. FDR data confirmed that the flaps had begun to retract while the airplane's airspeed was about 100 knots. FDR data also showed that the airplane rolled until 105° right wing down position and then the airplane began to roll back to the left and the stick pusher activated a second time.

At this moment, the airplane's pitch angle was -1°, the roll angle had reached about 35° left wing down before the airplane began to roll again to the right. Then the airplane's pitch and roll angles had reached about 25° airplane nose down and 100° right wing down, respectively, when the airplane entered a steep descent. The stick pusher activated a third time. At this moment the flaps were fully retracted and CVR recorded the captain stating, "we're down," and a sound of a thump.

The airplane crashed into a residence in Clarence Center, New York, about 5 nautical miles northeast of the airport. The 2 pilots, 2 flight attendants, and 45 passengers aboard the airplane were killed, one person on the ground was killed, and the airplane was destroyed by impact forces and a post-crash fire. (NTSB, 2010, p.1-5).

4.1.2 Crew's Reaction to Stall

Accident report evidences that crew failed in monitoring airspeed via their primary flight display (PFD), letting it decrease until the alarm started. The first reaction (captain) to stall warning was moving the column aft and applying thrust. As is it explained in sec. 2.3.4., she was supposed to push the column in order to apply nose-down input, so that AOA could be decreased. Crew failed to recognizing the stick shaker onset as airspeed fell and pitch increased warning. The second reaction (first officer attaining to captain's order) was to retract flaps. As it is explained in section 2.2.4 if the airplane is stalled in low speed flight (approach to landing), retracting flaps increases lift loss and puts the airplane into more severe stall conditions. The NTSB attributed crew failures to their approach-to-stall training.

> "During post-accident interviews, the NTSB learned that, during the approach-to-stall recovery exercises for initial simulator training, pilots were instructed to maintain the assigned altitude and complete the recovery without deviating more than 100 feet above or below the assigned altitude, which had been previously required by the practical test standards for the check ride." (NTSB, 2010, p.36).

4.1.3 Investigation Conclusion

The National Transportation Safety Board conclusion was:

> “The probable cause of this accident was the captain’s inappropriate response to the activation of the stick shaker, which led to an aerodynamic stall from which the airplane did not recover. Contributing to the accident were (1) the flight crew’s failure to monitor airspeed in relation to the rising position of the low speed cue, (2) the flight crew’s failure to adhere to sterile cockpit procedures, (3) the captain’s failure to effectively manage the flight, and (4) Colgan Air’s inadequate procedures for airspeed selection and management during approaches in icing conditions.” (NTSB, 2010, p.78).

The NTSB addressed safety recommendations to FAA concerning crew stall training. These are fallows:

- (A-10-22) “Require 14 Code of Federal Regulations Part 121, 135, and 91K operators and 14 Code of Federal Regulations Part 142 training centers to develop and conduct training that incorporates stalls that are fully developed; are unexpected; involve autopilot disengagement; and include airplane-specific features, such as a reference speeds switch.”
- (A-10-23) “Require all 14 Code of Federal Regulations Part 121, 135, and 91K operators of stick pusher-equipped aircraft to provide their pilots with pusher familiarization simulator training.” (NTSB, 2010, p. 157).
- (A-10-24) “Define and codify minimum simulator model fidelity requirements to support an expanded set of stall recovery training requirements, including recovery from stalls that are fully developed. These simulator fidelity requirements should address areas such as required angle-of-attack and sideslip angle ranges, motion cueing, proof-of-match with post-stall flight test data, and warnings to indicate when the simulator flight envelope has been exceeded.” (NTSB, 2010, p.158).

4.2 Turkish Airlines Flight 1951

4.2.1 History of the Flight

The Boeing 737-800 (flight TK1951) operated by Turkish Airlines was flying from Istanbul Atatürk Airport in Turkey to Amsterdam Schiphol Airport, on 25 February 2009, with 128 passengers on board and three crew members in the cockpit: the captain, who was also acting as instructor, the first officer who had to gain experience and was accordingly flying under supervision, and a safety pilot who was observing the flight. During the approach, the left radio altimeter system displayed an incorrect height of -8 feet, which could be seen on the captain’s (left-hand) primary flight display, while the first officer's (right-hand) primary flight display indicated the correct height, as provided by the right-hand system. The left-hand radio altimeter system, however, categorized the erroneous altitude reading as a correct one, and did not record any error.

The auto-throttle was receiving the incorrect information from the left-hand radio altimeter system. When the aircraft started to follow the glide path (the ideal path to the runway), the auto-throttle moved into the 'retard flare' mode. This mode is normally only activated in the final phase of the landing, below 27 feet. The 'RETARD' flag was displayed on PFD and the thrust from both engines was accordingly reduced to a minimum value (approach idle). However, the right-hand autopilot, which was receiving the correct altitude from the right-hand radio altimeter system, attempted to keep the aircraft flying on the glide path by rising the aircraft's nose, creating an increasing angle of attack of the wings to maintain the same lift as the airspeed reduced.

At 126 knots, the frame of the airspeed indicator changed color and started to flash. The artificial horizon was showing that the nose attitude of the aircraft was becoming far too high, but the cockpit crew did not respond to these indications and warnings. The situation was not recognized until the stick shaker went off at an altitude of 460 feet. The first officer responded immediately to the stick shaker by pushing the control column forward and also pushing the throttle levers forward, while the captain commenced to take over control. Although, the first officer's selection of thrust was interrupted by the auto-throttle, which was not yet switched off, and throttles were immediately commanded by the system back again to the IDLE position.

Once the captain had taken over control, the auto-throttle was disconnected, but throttles were pushed forward only nine seconds after. At this point, the aircraft had stalled and height remaining about 350 ft was insufficient for recovery. The aircraft crashed into a field at a distance of about 1.5 kilometers from the threshold of the runway. Figure 4-4 is a photo of the aircraft after crash. This accident cost the lives of four crew members, including the three pilots, and five passengers, with a further three crew members and 117 passengers sustaining injuries. (DSB, 2010, p. 5-6).

Figure 4-4 TA flight 1951 Boeing 737-800 aircraft after crashed.

Source: DSB, TA flight 1951 Boeing 737-800 Accident Report.

4.2.2 Crew's Reaction to Stall

The crew failed in preventing stall by not monitoring the decreasing airspeed. The recovery procedure was correct except by the non-disengagement of auto-throttle, which moved throttles back to idle position in a critical moment of the recovery when the aircraft was supposed to gain speed.

4.2.3 Investigation Conclusion

The DSB concludes that the causes of the accident are: (1) improper functioning of the left-hand radio altimeter system that led to the thrust from both engines being reduced by the auto-throttle to a minimal value too soon, ultimately causing reduction in speed, (2) crew failure of monitoring the airspeed and pitch attitude of the aircraft; (3) and a failure to implement the approach to stall recovery procedure correctly. "This resulted in a situation where the wings were no longer providing sufficient lift, and the aircraft crashed." (DSB, 2010, p. 7).

Recommendations addressing the stall issue:

> 4. "Boeing should review its 'Approach to stall' procedures with regard to the use of autopilot and auto throttle and the need for trimming".

5. “Turkish Directorate General of Civil Aviation (DGCA), International Civil Aviation Organization (ICAO), FAA and EASA should change their regulations in such a way that airlines and flying training organizations see to it that their recurrent training programs include practicing recovery from stall situations on approach”. (DSB, 2010, p. 12).

4.3 Air France 447 Rio-Paris

4.3.1 History of the flight

On 31 May 2009, the Airbus A330-200 flight AF 447 took off at 22h29 (GMT) from Rio de Janeiro Galeão airport bound for Paris Charles de Gaulle with 3 flight crew members, 9 cabin crew members, and 216 passengers on board. The aircraft was flying above Atlantic Ocean, when the autopilot (AP) disconnected, and the flight control law reconfigured from normal to alternate, likely following the incorrect airspeed indications, caused by the obstruction of the Pitot probes by ice crystals.

The copilot Bonin was in control of the aircraft (Pilot Flying - PF), while the copilot Robert was handling radio conversing (Pilot Not Flying - PNF). Captain Dubois was not in the cabin at this moment. The PF recognized the loss of AP and incorrect airspeed indications and made a nose-up input that increased the airplane pitch attitude up to 11° in ten seconds. Consequently, the aircraft began to climb and to slow down until the stall warning was triggered at AOA around 6 degrees.

After stall warning triggered, the thrust levers were put in the TO/GA detent and the PF made nose-up inputs. The recorded angle of attack continued to increase and the PF continued to make nose-up inputs. The airplane’s altitude reached its maximum of about 38,000 ft, its pitch attitude and angle of attack were 16 degrees. The aircraft at this moment was clearly stalled, and began to drop.

Then the Captain re-entered the cockpit, but he was unable to understand the situation. The two copilots informed him that they has lost control of the airplane. During the following seconds, all of the recorded speeds became invalid and the stall warning sounded continuously for more 54 seconds. Crew dialogues evidences that they did not recognize what was happening. The altitude was then about 35,000 ft, the angle of attack exceeded 40 degrees and the vertical speed was about -10,000 ft/min. However, CVR records shows that crew were doubtful if the airplane was climbing or going down The airplane was subject to roll oscillations to the right that sometimes reached 40 degrees. The PF made an input on the side-stick to the left stop as an attempt to level the aircraft with the horizon and also nose-up inputs.

The aircraft was not flying, but falling and the crew were confused, they did not understand what was happening to the airplane. Records show that PF voice said “[we’re going to arrive] at level one hundred”, which means that they recognized that the airplane was going down. The angle of attack, when it was valid, always remained above 35 degrees. The Ground Proximity Warning System (GPWS) “sink rate” and then “pull up” warnings sounded until the crash into the ocean. (BEA, 2012, p.21-24).

4.3.2 Crew’s Reaction to Stall

The analysis of AF 447 flight crew reactions and decisions has raised the concern about pilot’s inability to manually fly the airplane when computers are failed, such as under unreliable airspeed. The first reaction of copilot Bonin, after loss of airspeed indication, was pulling the stick back, which is an incomprehensible attitude that can lead to a stall. The second reaction, to the stall warning, was exactly the opposite of what the PF was supposed to do. He should have pulled the stick forward, lowering AOA. The crew probably did not believe that the aircraft was into a stall situation as they had many unreliable information and had to make sense of what was reliable and how the airplane was actually behaving. Even though they could not believe in artificial stall warning, the aerodynamic noise due to buffet and turbulence was recorded. The third reaction, when the aircraft was already stalled, were many confusing inputs: putting thrust to maximum and 2 minutes later reducing to minimum, roll inputs, nose down and then nose up inputs. All this reaction shows that crew did not know what to do.

The crew’s reaction to stall might be explained by the training received. Its introduction indicated that “a stall is a dangerous phenomenon which is expressed mainly by loss of altitude”. (BEA, 2012, p.152). Crew were trained to simultaneously reduce the AOA and apply TOGA thrust from the first signs of the stall (stall warning / buffet onset) and a minimal loss of altitude is expected.

4.3.3 Investigation conclusion

The 447 accident investigation was finished only in 2012, due to the difficulty in localizing the airplane wreckage in the ocean. It was localized on 2 April 2011 during the fourth phase of the sea searches. The technical report conclusion was:

> "The accident resulted from the following succession of events:
>
> - Temporary inconsistency between the measured airspeeds, likely following the obstruction of the Pitot probes by ice crystals that led in particular to autopilot disconnection and a reconfiguration to alternate control law,
> - Inappropriate control inputs that destabilized the flight path,
> - The crew not making the connection between the loss of indicated airspeeds and the appropriate procedure,
> - The PNF's late identification of the deviation in the flight path and insufficient correction by the PF,
> - The crew not identifying the approach to stall, the lack of an immediate reaction on its part and exit from the flight envelope,
> - The crew's failure to diagnose the stall situation and, consequently, the lack of any actions that would have made recovery possible." (BEA, 2012, p.200).

BEA recommended, " EASA review the content of check and training programs and make mandatory, in particular, the setting up of specific and regular exercises dedicated to manual aircraft handling of approach to stall and stall recovery, including at high altitude" (BEA, 2012, p.204). It is important to state that the investigation was finished only in 2012, the airplane wreckage was localized on 2 April 2011 during the fourth phase of the sea searches.

4.4 Section Summary

Important ideas:

- ✓ Public Law 111-126, section 208, mandates FAA to require air transport pilots to receive stall prevention and recovery training.

- ✓ The greatest motivation of Public Law was CC flight 3407 accident, which could have been prevented if crew's had received properly stall recognition and prevention training.
- ✓ The three accidents reports addressed the recommendation of incorporating stall recovery to aircrew training. However, the AF 447 final report and recommendations were published in 2012, after the enactment of Public Law 111-126.
- ✓ While flight computer and automation advance, pilots have been losing the ability to actual fly the airplane.
- ✓ Pilots were instructed to execute inappropriate stall recovery techniques, which were focused in avoiding altitude loss, applying maximum power and allowing the aircraft to accelerate.

5 NEW FAA RULEMAKING FOR STALL TRAINING

As it was explained before, FAA is responsible for the 14 Code of Federal Regulations, which comprises all Federal Aviation Regulations (FAR). This 14 CFR is divided in parts, depending on their applicability and their specific subject. For instance, Part 25 establishes airworthiness requirements for Category Transport aircraft, Part 121 regulates all domestic, flag and supplemental operations, including crewmember training program and qualification, and finally, Part 60 prescribes the rules governing the initial and continuing qualification and use of all aircraft Flight Simulation Training Devices (FSTD). The FAA's Advisory Circulars (ACs) specifies the guidelines to demonstrate compliance with each related requirement. Per example, AC 25-7C provides means of flight test compliance demonstration of requirements for transport category airplanes and AC 120-109A provides guidance for Stall Prevention and Recovery Training.

The Loss of Control In-flight (LOC-I) issue, including stall, was studied by some working groups with the aim to address FAA recommendations which were helpful to the new rulemaking and AC guidelines construction. The working groups were: Industry Stall and Stick Pusher Working Group, International Committee on Aviation Training in Extended Envelopes (ICATEE), Stick Pusher and Adverse Weather Event Training Aviation Rulemaking Committee (SPAW ARC) and Loss of Control Avoidance and Recovery Training (LOCART), their work and main recommendations are explained below.

5.1 Working Groups

The working groups detailed below were composed of SMEs (Subject Matter Experts) in pilot training as well as SMEs in FSTD design, engineering, and validation. Through these working groups, the FAA was provided with numerous recommendations to improve the FSTD evaluation standards that support training in full stall maneuvers. These recommendations were taken under consideration as part of the final rulemaking work to modify the Part 60 FSTD qualification standards and Part 121 crewmember training program and qualification. Their main recommendations were concerned with FSTD fidelity. A potential lack of simulator fidelity could contribute to inaccurate or incomplete training on new training tasks, which could lead to an associated and unnecessary safety risk.

5.1.1 Industry Stall and Stick Pusher Working Group

The Stall and Stick Pusher Working Group was initiated in March 2010 and lasted until December 2010. During this 9 month period the FAA worked with industry leaders (Airbus, ATR, Boeing, Bombardier and Embraer, simulator manufacturers, training companies, pilot associations and also airlines) to address concerns arising from the increase in stall and loss of control accidents and produced many training recommendations to prevent stall events included members from aircraft manufacturers and the FAA. The working group advised that the old stall recovery techniques, focused on applying thrust and minimizing altitude loss, were inappropriate. It collaborated in creating a generic **stall recovery template**, which is basically as recovery procedures described in Section 2.3.4, valid for all types of airplanes by agreeing on basic recovery principles and the order of steps that pilots must accomplish (ROSENKRANS, W., 2010, p.2).

In addition, in order to provide best training practices using current simulation, the working group also warned FAA of FSTD fidelity concerns of latero-directional and stall buffet characteristics in post-stall training, which might not be representative of the aircraft. Also, it recommended simulators in use today should not be used for training to or surpass the aerodynamic stall unless further testing and validation in that flight regime are performed for the specific simulator and approved by the FAA. (FAA, 79 FR 39461, p.39645).

5.1.2 ICATEE (International Committee on Aviation Training in Extended Envelopes)

The ICATEE was initiated by the Royal Aeronautical Society (RAeS) Flight Simulation Group in June 2009 with the task to deliver a long-term strategy to reduce the rate of LOC-I accidents and incidents through enhanced Upset Prevention and Recovery Training (UPRT) (EASA, 2017, p.4). It recommend improvements to simulation devices used to conduct training. This working group included subject matter experts in many facets of industry and government including airlines, flight training providers, research entities, FSTD manufacturers, airframe manufacturers, regulatory authorities, and airline pilots associations.

The ICATEE working methodology was to first conduct a training needs analysis using subject matter experts in the area of pilot training and then determine the training device requirements as a function of the identified training needs. Through the work of ICATEE, it was concluded that stall recovery training does not require, nor it is practical due to unsteady aerodynamics, that the post stall behaviour of the aircraft be exactly replicated in the FSTD, with tight tolerances. The working group concluded that a ‘‘type representative’’ qualitative post stall model should suffice in properly training the recovery maneuver. (FAA, 79 FR 39461, 2014, p.39470).

5.1.3 SPAW ARC (Stick Pusher and Adverse Weather Event Training Aviation Rulemaking Committee)

An ARC (Aviation Rulemaking Committee) is a rulemaking committee, headed by industry and FAA, which provides information, advice and recommendations to the FAA. The formation of the SPAW ARC was mandated by Public Law 111–216, Section 208, with the intent to provide the FAA with recommendations to address the LOC-I issue. It held its first meeting on November 30, 2010, and held its last full group meeting on May 12, 2011. The group included members from aircraft manufacturers, simulator manufacturers, training companies, pilot associations, airlines and also FAA authorities. The group positioned against any simulator training being conducted beyond the first indication of the stall unless the simulator modeling and fidelity are such that the simulation of the specific airplane is representative in this flight regime. As ICATEE, SPAW ARC also recommended that the use of analytical methods, engineering simulation, and wind tunnel methods in combination with subject matter expert pilot assessment should be authorized to develop and validate a ‘‘type representative’’ post stall models, instead of objective evaluation.

The SPAW ARC also made recommendations concerning the evaluation of FSTD stall characteristics in flight conditions such as high altitude cruise stall, turning flight (accelerated) stall, and the objective validation of stick pusher forces, where equipped in the aircraft). Moreover, the group addressed some particular concerns to FAA regarding FSTD fidelity for full stall maneuvers, such as the modeling of aircraft stability and response to control inputs, and improved modeling of the stall buffet to cover a broader range of flight conditions (FAA, 79 FR 39461, 2014, p.39466).

5.1.4 LOCART (Loss of Control Avoidance and Recovery Training) Working Group

The Federal Aviation Administration (FAA), supported by ICAO, launched the LOCART initiative, with EASA's participation, in March 2012. The working group consisted of technical experts, including experts of the SPAW ARC, and provided recommendations to ICAO and the FAA. (EASA, 2017, p.4). LOCART has defined the objectives of UPRT in a simulator as "pilots should demonstrate applied knowledge and skills to prevent an upset, or if not prevented, to recover from one" and "the device must support each specific training exercise". According to LOCART, instructors should be able to teach, assess and debrief some important aspects such as the limitations of the device, disorientation, recognition and recovery strategies and type specific characteristics. The focus of the training must be on awareness and prevention, rather than current focus on recovery only. The final report from this working group included technical recommendations to revise the Part 60 FSTD standards to include minimum FSTD evaluation requirements for upset prevention and recovery training maneuvers. (FAA, 79 FR 39461, 2014, p.39466).

5.2 AC 120-109

In August 2012, the FAA issued AC 120–109, named **Stall and Stick Pusher Training** (FAA, 2012). The content of this AC was developed using the recommendations of the previous working groups and was intended to provide best practices on training, testing, and checking of stall warnings, aerodynamic stalls, and stick pusher activations and recommended recovery procedures. (FAA, 79 FR 39461, 2014, p.39465). The base philosophy is that an effective stall training curriculum should provide pilots with the knowledge and skills to avoid undesired aircraft states that increase the risk of encountering a stall event or, if not avoided, to respond correctly and promptly to this event.

This AC states that instructors/evaluators must have a clear understanding of the FSTD limitations to avoid negative training. Instead of what was instructed before (recovery focused on minimizing altitude loss), AC 120-109 guidelines for stall recovery procedures emphasizes:

- The immediate reduction of the airplane AOA,
- Management of thrust, and
- Returning the airplane to a safe flying condition.

These procedures matched with stall recovery template, the evaluation criteria of the recovery from an approach-to-stall should no longer be based on altitude loss, but on their timely response and effective use of available energy (i.e., altitude and speed) during stall recovery. Evaluation criteria suggested by AC 120-109 were:

1) Prompt recognition of stall event;
2) Correct application of the approach-to-stall recovery procedure; and
3) Recovery of the airplane without exceeding the airplane's limitations.

5.3 Crewmember and Aircraft Dispatcher Training Final Rule

On November 12, 2013, the FAA published the Crewmember and Aircraft Dispatcher Training Final Rule (78 FR 67799), adding the full stall and upset recovery training tasks required by Public Law 111–216. As a result, all Part 121 air carriers are required to conduct stall prevention training, and beginning March 12, 2019 (5-year compliance period), all Part 121 air carriers must conduct instructor-guided, hands-on experience of recovery from full stall and, if equipped, stick pusher activation (see Appendix C.1: § 121.423(c)). Revisions to Part 60 were also required to ensure FSTDs are properly evaluated in order to fully implement the required training. The requirement for Part 121 pilots to receive stall recovery training stablished in the Crewmember and Aircraft Dispatcher Training Final Rule was statutorily mandated in Public Law 111-216, Section 208. The FAA did not have the authority to exempt any Part 121 air carrier from this requirement.

5.4 NPRM Part 60 for Stall Training

On July 10, 2014, the FAA published a Notice of Proposed Rulemaking (NPRM) Part 60 (79 FR 39461) proposing changes to the Part 60 FSTD technical evaluation standards to address new training tasks required by the Crewmember and Dispatcher Training final rule, including the full stall training tasks. The proposed requirement of High Angle of Attack Modeling for FSTD states that:

> "After March 12, 2019, any FSTD being used to obtain credit for full stall training maneuvers in an FAA approved training program must include aerodynamic modeling for high angle of attack maneuvers to at least ten degrees beyond the stall angle of attack or as required to execute a recovery from a fully stalled flight condition. The following stall maneuvers must be evaluated for qualification:
>
> - Stall entry at wings level (1g)
> - Stall entry in turning flight of at least 25° bank angle (accelerated stall)
> - Stall entry in a power-on condition (required only for propeller driven aircraft)
> - Aircraft configuration of second segment climb, high altitude cruise (near performance limited condition), and approach or landing." (81 FR 18177, table A1A, 2.1.7.S).

The proposed testing requirements emphasized the objective validation of simulator performance and handling qualities and was limited to only validating stall warning speeds, stall buffet onset speeds, and the stall speeds in flight conditions typically used for aircraft certification testing in a very controlled environment (such as wings level stalls in approach and climb configurations). As it is explained in sections 2 and 3, objective data based evaluation against flight test data may not adequately validate the aerodynamic model in an unstable flight regime, such as stalled flight, particularly in cases where significant deviations are seen in the aircraft stability and control. Also, the safety risk associated with the flight data collection might limit available data. As a result, the objective testing requirements defined in Table A2A of this document (FAA, 79 FR 39461) did not prescribe strict tolerances on any parameter at angles of attack beyond the stall angle of attack.

In lieu of mandating objective tolerances to flight test data at angles of attack at and beyond the stall, a Statement of Compliance (SOC) was proposed to define the source data and methods used to develop the stall aerodynamic model which defined stall characteristics as applicable for the simulated aircraft type. The requirements for high angle of attack modeling are intended to provide aircraft specific recognition cues, performance and handling qualities of a developing stall, through the stall break and recovery. The SOC includes first the identification of the sources of data, which may be flight test, wind tunnel data, analytical or numerical methods or a reasonable blending of these sources. For the flight test data, a list of the types of maneuvers used to define the aerodynamic model for angle of attack ranges greater than the first indication of stall must be provided per flap setting. Second, the SOC also must include the validity range declared by the FSTD sponsor. For full aerodynamic stall training tasks, model validation and/or analysis should be conducted through at least 10 degrees beyond the critical angle of attack. In cases where training is limited to the activation of a stall identification system (stick pusher), model validation may be conducted at a lower angle of attack range, but the FSTD Sponsor must specify and restrict the use of the FSTD to those maneuvers that have been appropriately validated. Within the declared range of model validity, the SOC must address and the aerodynamic model must incorporate the following typical stall characteristics where applicable by aircraft type:

i. Degradation in static/dynamic lateral directional stability
ii. Degradation in control response (pitch, roll, yaw)
iii. Uncommanded roll response
iv. Apparent randomness or non-repeatability
v. Changes in pitch stability
vi. Stall hysteresis
vii. Mach effects

Finally, the SOC must include a SME pilot evaluation of the stall model. The pilot must have enough knowledge of the cues necessary to accomplish the required training objectives and with experience in conducting stalls in the type of aircraft being simulated and be acceptable to the NSPM (National Simulation Program Manager). Final evaluation and approval of the Sponsor's FSTD must be accomplished by an SME pilot with knowledge of the training requirements to conduct the stall training tasks.

5.5 Public Comments

The FAA received approximately 675 individual comments in response to the NPRM. The comment period closed on January 6, 2015, and commenters included air carriers, simulator training providers, FSTD data providers, FSTD manufacturers, the NTSB, labor organizations, trade associations, aircraft manufacturers, and individuals. The comments are published and can all be found in FAA document 81 FR 18177 (2016). As expected, none of them resulted in any substantive changes to the proposed requirements. The main ones for the discussion of this work are depicted in subsections below:

5.5.1 Ten degrees beyond the AOA Model

The modeling range was a controversial point of discussion, since the 10 degrees post-stall aerodynamics is non-linear, unsteady, random and difficult to be represented with reliability. CAE, Inc. commented that the 10 degrees beyond the stall AOA requirement should be further reviewed, since pilot's application of the recovery should immediately lead to a reduction in AOA, and therefore would be inappropriate to relate the requirement to an AOA that are not supposed to be reached in training tasks. CAE recommended that the 10 degrees requirement be replaced by the upper limit of AOA modeling in the required SOC, provided and properly justified by rationale.

On the other hand, the NTSB supported the modeling requirements, citing that a peak AOA growth of about 10 degrees beyond the stall is typical for most incidents and accidents it has investigated. For example, Colgan flight 3407 accident resulted in an AOA that extended to 13 degrees beyond the stall AOA. FAA further have disagreed with CAE and have agreed with NTSB, maintaining the 10° above critical angle of attack requirement. (81 FR 18177, p.18184).

5.5.2 Conventional and DFBW Aircraft Differences on this Subject

Embraer, Airbus, and an individual commenter questioned why computer controlled aircraft with stall envelope protection systems are treated differently from aircraft equipped with stick pusher systems with respect to model validity ranges and associated objective testing. Since the system reliability and DAL (Design Assurance Level) for DFBW high level functions are Class A, why DFBW type airplanes shall comply with the 10 degrees beyond critical AOA requirement and stick pusher holders not? Delta Airlines, Inc. (Delta) further questioned whether such non-normal mode modeling and testing would be required for an Airbus A350 aircraft that has Part 25 special conditions on stall testing for airplane certification. (81 FR 18177, p.18185). The special conditions allows an aircraft with DFBW systems to be certified even if it has poor flying qualities just after stall definition. The manufacturer only would need to prove that FBW envelope protection feature failure rate is extremely improbable ($<10^{-9}$), as for catastrophic event. This is the case of RSS (Relaxed Static Stability) aircraft, whose safe and controlled flight depends on flight control computers. Therefore, what would be the point of modelling the existent uncontrollable stall characteristics into degraded mode and training pilots to recover from it? The philosophy of modern aircraft is to focus on prevention and advanced systems technology that are designed for a high availability of its envelope protection features and for a fairly reduced failure rate to prevent from degraded flight control conditions.

FAA have disagreed with those questionings and have argued the stick pusher would be “clear and distinctive” indication of a stall definition which would accomplish the training objectives, providing the stall recognition cues that a pilot needs to learn to prevent and recover from a stall, while simply reaching the AOA limits of an envelope protected aircraft would not (81 FR 18177, p.18185). This would be the rationale behind the requirement of the aerodynamic stall models going beyond the stall definition for DFBW envelope protected aircraft, in order to represent a distinctive characteristic of the aircraft stall, which might be buffeting, g-brake, rolling motions, or others.

5.5.3 Safety Considerations of Full Stall Flight Test

Embraer commented that during the development flight test campaign, full aerodynamic stalls that are considered hazardous or impractical could only be done if the aircraft is equipped with additional safety and mitigation features, such as a tail parachute or other equivalent device, and those features obviously change the aircraft behavior during stall recovery if they are employed. Additionally, Embraer emphasized that for safety reasons in the certification flight test campaign, depending upon the aircraft aerodynamic characteristics during full developed stalls, a full aerodynamic stall flight tests would not be done nor recommended to be done in control states in which the stall protection system would not be available. FAA agreed with the commenter and strengthened that this rulemaking has not specifically required additional flight test validation data to be collected at an AOA beyond where it is reasonably safe to do so. In fact, allowances for aerodynamic stall models to be developed and validated using engineering and analytical methods were included. (81 FR 18177, p.18186).

5.5.4 Third party source of data

American Airlines, Flight Safety International, A4A, JetBlue Airways and Delta manifested concerns whether the “non-OEM” provided source of data would be acceptable to meet the representative stall model requirements. FAA justified by stating that the stall models only based on airplane manufacturers data could impose high cost on the FSTD sponsors and may not be possible in some instances where the airplane manufacturer does not support a simulator data package or is no longer in existence. Moreover, FAA stated that third party models investigations by SME pilot have been executed and found that they may be acceptable. (81 FR 18177, p.18186).

5.6 AC 120-109 A

AC 120-109 A was published in November 24, 2015, and cancelled AC120-109. It incorporated the full stall training requirement of Public Law 111-216 and presented comprehensive modifications from the original version, including the title change, which flipped from Stall and Stick Pusher Training to Stall Prevention and Recovery Training. The Chapter 5 of this AC provides specific information for training stall recovery, which would be an instructor-guided, hands-on experience of applying the stall recovery procedure for a full stall. The objective of this training is to provide pilots the experience of the airplane handling characteristics near and at full stall, the related cues, and full stall recovery (Appendix 4 of the AC includes an example of Full Stall Experience Training). The AC 120-109A guidelines specify the checking criteria for trainee’s evaluation and the full stall demonstration is not included. Instead, the focus is on the prompt recognition of impending stall, the correct application of the stall recovery procedure, and recovering without exceeding the airplane’s limitations.

For airplanes equipped with a stick pusher, stall recovery training includes pilots to experience the sudden forward movement of the control yoke/stick during a stick pusher activation in order to develop the proper response (allowing the pusher to reduce AOA instead of pulling it back) when confronted with a stick pusher activation. Stick pusher training should be completed as a demonstration/practice exercise, including repetitions, until the pilot’s reaction is to permit the reduction in AOA even at low altitudes and is not a checked maneuver. For envelope-protected aircraft, stall recovery training must be carefully developed so that: (1) the failure paths to reach the degraded modes are understood, (2) pilots learn to identify the rarely occurring impending or full stalls, and (3) pilots demonstrate they have the skill to return the aircraft to safe flight with the degraded flight control laws.

5.7 14 CFR Part 60 Final Rule

On May 31, 2016, FAA publishes the 14 CFR Part 60 Final Rule, 81 FR 18177 document (see Appendix B.2). The most significant changes from previous NPRM of FSTD requirements for full stall training were:

- Maintained the 10 degrees range beyond the stall identification AOA, which has been also applied to aircraft equipped with stick pusher devices.
- Improved the definition of the stall AOA for the purposes of defining the required aerodynamic modeling range:

> "The point where the behavior of the airplane gives the pilot a clear and distinctive indication through the inherent flight characteristics or the characteristics resulting from the operation of a stall identification device (e.g., a stick pusher) that the available to the instructor airplane has stalled." (p. 18226).

- Clarified stall and post-stall "type representative" modeling.

> "Aerodynamic stall modeling that includes degradation in static/dynamic lateral-directional stability, degradation in control response (pitch, roll, and yaw), uncommanded roll response or roll-off requiring significant control deflection to counter, apparent randomness or non-repeatability, changes pitch stability, Mach effects, and stall buffet, as appropriate to the aircraft type." (81 FR 18177, p. 18226).

- Clarified that third party data may be acceptable if they meet the modeling and SME pilot evaluation requirements, just as it has been accepted in the past (see 14 CFR § 60.13 (b)).
- Improved the qualification requirements for subject matter expert (SME) pilots that subjectively evaluate the stall model. Adds deviation authority if an acceptable SME pilot cannot be located. Allows for SME evaluation to be conducted on an engineering or development simulator where objective proof-of-match test cases are provided that verifies the model implementation on the FSTD. (p.18182).

5.8 AC120-109 CHG 1

In January 4, 2017, the first change of AC 120-109 A – Stall Prevention and Recovery Training was issued (FAA, 2017). The modifications were minors and previous AC 120-109 A remains valid. They consisted of some additional topics; such as recognition of full stall indication of most swept-wing transport category aircraft, which may be usually different from those typically experienced in General Aviation (GA), which was added to academic training guidelines.

5.9 EASA Opinion

In Opinion No 06/2017 document (2017, p.14), EASA does not propose post-stall training to be required in an FFS and reiterates that existing FSTDs may be used to facilitate UPRT. The FSTD post-stall qualification and further training should be optional. Training providers may decide, in addition to the mandatory approach to stall exercise, to deliver stall exercises on the basis of a careful evaluation in consultation with the competent authority to ensure that negative transfer of training is avoided.

5.10 Section Summary

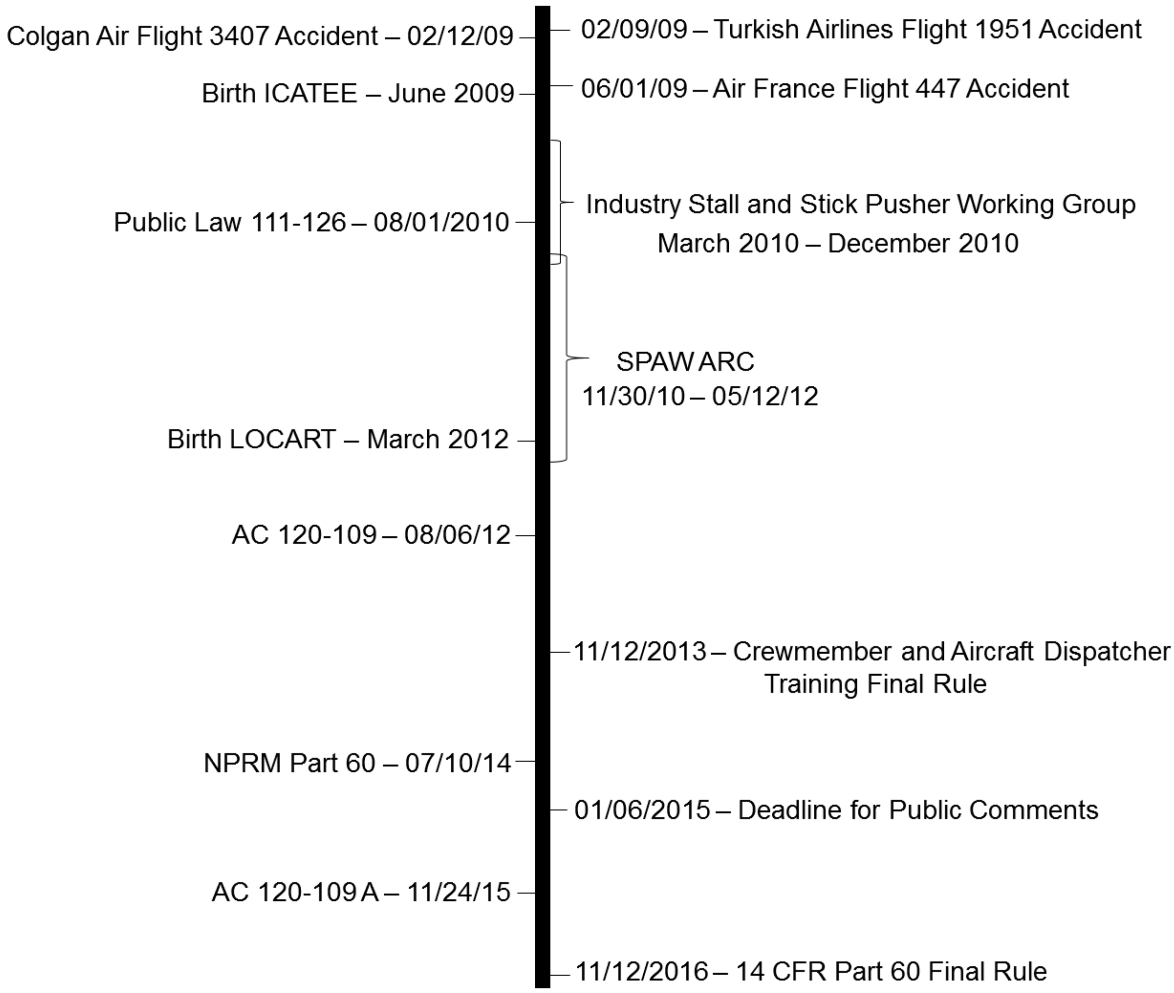
Important ideas:

- ✓ Working groups helped FAA with stall recovery training rulemaking. There primarily concern was about FSTD lack of fidelity that can lead to negative training and unsafe situations.
- ✓ FAA requires 10 degrees beyond de maximum AOA modeling for FSTD and justifies based on NTSB accidents reports where such condition have been reached.
- ✓ Manufacturers concern about the hazards of flight test maneuvers for FSTD matching. FAA highlights the allowance for other sources data modeling when flight test data is not available.
- ✓ Industry comments about part 25 special conditions for modern aircraft and part 60 different philosophies.

✓ Part 60 Final Rule strengthens the "clear and distinctive" stall characteristics modeling for training pilot's proper recognition.

Figure 5-1 timeline resumes the sequence of events mentioned in this section

Figure 5-1 Timeline of events involving stall issue.



6 HUMAN FACTORS OF FSTD STALL TRAINING

As seen in section 5, an existing concern about FSTD fidelity challenges FAA to put the new rulemaking into action. The intention was to avoid a possible negative training, which would lead to unsafe situations. This section explains what is negative training and negative transfer and low FSTD fidelity under the human factors standpoint, and also mention other current factors that can lead to negative training.

6.1 Negative Training and Transfer Concepts

Negative training is defined by IATA (International Air Transport Association) as a training which unintentionally introduces incorrect information or invalid concepts, which could actually decrease rather than increase safety. (IATA, 2015, p. xi). The ultimate goal of training is for the trainee to transfer what was learned in training to the actual real-world setting. Transfer of training (ToT) refers to the application of knowledge, skills and abilities learned on training programs to real-world situations and to the maintenance of these knowledge, skills and abilities over time on the job. (VINCENZI et al, 2018, p. 50).

A negative transfer occurs when existing knowledge and skills from previous experiences impedes proper performance in a different task or environment. In other words, it occurs when the trainee reacts to the transfer stimulus correctly as he or she was trained, but incorrectly in relation to the real world. (VINCENZI et al, 2018, p. 50). For example, consider a pilot who is trained to recover from stall by pushing forward the yoke and applying full thrust. In the real aircraft, applying thrust actually pitches up the aircraft nose, whenever engines are mounted below wing and below aircraft longitudinal axis (negative side of z axis). The pilot is likely to do the same as usual in a real-flight situation and may not succeed in recovering control of the airplane. This is a case of negative transfer of stall training that can endanger flight crew and passengers.

Negative transfer can develop for the following reasons:

1) System design changes;
2) Mismatch between training system and the actual task;
3) Inappropriate learned techniques;

System design changes is when pilots are trained in a simulator of a specific type design, but in a different model. **Mismatch between training system and the actual task** is the case of low fidelity of FSTD. Fidelity is a primary issue in simulator transfer of training effectiveness – the higher the fidelity, the better the transfer. For example the case of Airborne Express DC–8 aircraft accident, mentioned in section 3.1., demonstrates the hazards that may happen when stall training are performed in a FSTD whose fidelity is low. Because flight experience with stalls in the DC-8 was obtained in a simulator without a stall break, the crew could not practice the nose-down control inputs required to recover a stalled airplane that is pitching down or at a nose-low attitude. Moreover, because the PF and PNF were exposed during extensive simulator experience to what they presumed was the stall behavior of the DC-8, the stall break that occurred in the airplane most likely surprised them (NTSB, 1997, p.40). **Inappropriate learned techniques** can be exemplified by the case mentioned in sections 4.2.2., 4.3.2. and 5.2.1 of trainees who were taught without no mention of any requirement to reduce AOA and encouraged to maintain altitude during recovery from an approach to a stall.

6.2 Inappropriate Stall Recovery Techniques

The technique that has been recommended was to apply maximum power and allow the aircraft to accelerate out of this high alpha stall-warning regime. This technique could be successful in some cases but it may fail, per example, when applying thrust produces a pitching up moment or increase the stall speed. It also may mislead pilots to think that stall is always correlated to low speed, which is not true, since the wing can be brought into an excessive AOA at any speed as explained in section 2.2.6. It is impossible to recover from a stalled condition without reducing the angle of attack and that will certainly result in a loss of altitude, regardless of how close the airplane is to the ground. Although the thrust vector may supplement the recovery it is not the primary control. At stall angles of attack, the drag is very high and thrust available may be marginal for that given drag. At high altitudes, where the available thrust is reduced, it is even less of a benefit to the pilot. The elevator is the primary control to recover from a stalled condition. (AURTA. 2008, #1, p.6).

6.3 Training outside the Operational Flight Envelope (OFE)

The Operational Flight Envelope, which is also named as Normal Flight Envelope (NFE) for the DFBW aircraft type design is the flight envelope allowed during normal operations. Loss of control accident data goes well beyond the OFE and include the accidents caused by stall when exceeding the critical alpha. If pilots are trained to recover from such a critical situation, then the issues of training outside the aircraft envelope should be considered and mitigated. First issue is the negative training due to lack of fidelity. If exceeding the OFE is so hazardous that lead to the cited accidents, then it could be also hazardous to conduct flight test in these conditions, which means limited available flight test data to validate the simulators. In fact, the Flight Test Envelope (FTE) is wider when compared to the OFE because test are executed until the cleared structural limits of the aircraft (by design office and for specific conditions) and, in the stall case are conducted until the stall definition, but those tests do not reach the extreme conditions of these accidents. As explained in section 3.4, the region of simulator FE outside the FTE would be classified as moderate or low confidence, depending on wind tunnel or analytical model, thus there is an increased risk that the simulator will no longer accurately replicate the aircraft, possibly resulting in negative training.

Moreover, even if flight test engineers and pilots decide to execute flight test in these conditions and include post-stall, the generated data could not be reliable because of the unsteadiness, randomness and non-linearity of airflow. It is a big issue and the proposed solutions relies on instructor knowledge and abilities to recognize the simulator validated envelope and alert their trainees of how representative of the aircraft is the training they will be executing. For example, the SPAW ARC working group recommended improved instructor feedback tools, which can display to help instructor to identify and inform the trainee when he or she has exceeded either the accepted simulator model envelope or the known aircraft load factor envelope. (FAA, 79 FR 39461, p. 39466).

IATA (2015, p.13) recommends to avoid exposing crews to non-validated flight regimes, and perform the training program within the VTE (Validated Test Envelope) of each specific FSTD as much as possible. The VTE includes data representing the actual aircraft behavior that are typically available from the OEMs (Original Equipment Manufacturers), which were recorded during the aircraft certification flight test process to prove compliance with the certification specifications and additional data from wind tunnel testing and/or analytical methods and extrapolated data beyond flight test and wind tunnel/analytical regions. In instances when flight data is not readily available, engineering data may be used as a supplement, as long as the model is checked by a subject matter expert pilot. These data are represented by both a validated aerodynamic envelope and the aircraft design limits. As most models of today‘s FSTDs are deficient in adequately representing the aerodynamic stall regime, they are not validated beyond the critical angle of attack and aerodynamic stall characteristics are not fully reflecting reality. Thus, some recovery training tasks may exceed the VTE and stall training should presently be limited to approach-to-stall training, if possible with enhanced modeling of airplane-specific cues including stick pusher activation (if installed), and recovery should be initiated at the first indication of stall.

Additionally, another issue of training outside the Operational Flight Envelope (OFE) is influencing decision-making process by giving excess of confidence to the pilot, or the perception that an upset or stall situation is always normal and recoverable, and that the situation is under control. For example, negative training could arise from allowing trainees to ignore stall warnings, omitting callouts, deviating from procedures or from intentionally leaving the boundaries of the OFE without proper briefing by the instructor. When choosing this methodology, the training program should take into account that trainees normally will not be able to precisely fly the desired entry attitudes and energy states of the intended recovery exercise. (IATA, 2015, p.46). AC 120-109A guidelines establishes that during training, the pilot may be asked, for demonstration purposes, to ignore some aural and visual indications of impending stall in order to practice the more difficult control movements needed to recover from the stick shaker. During his evaluation, the pilot should be evaluated on recovering at the first indication of a stall, even if it is based on an aural or visual indication that occurs before the stick shaker or stick pusher (if installed).

6.4 Section Summary

- ✓ Negative training in FSTD occurs when existing knowledge and skills from previous FSTD training impedes proper performance in real aircraft.
- ✓ Training outside the OFE addresses two negative training issues: limited FSTD fidelity and the psychological effect of intentionally leave the OFE

- ✓ FSTD fidelity has also two barriers to overcome: limited flight test data, due to risks, and reliability of flight test data;

The human factors aspects briefed in this section are considered for debate in the interview with test pilots, subject of the next section.

7 INTERVIEW WITH FLIGHT TEST PILOTS

The interview process was conducted with 20 Embraer test pilots. First of all, a brief resume of sections 4, 5 and 6 was told to the pilot, with the aim to explain Public Law 11-126 and the new Part 60 and affected Part 121 requirements. This comprehensive explanation was proceeded as impartially as possible since the interviewed group had several aeronautical backgrounds. There were pilots who participated of some meetings of the Industry Stall and Stick Pusher Working Group, SPAW ARC and LOCART, some pilots who did not participated but were updated on the discussion, but also pilots who did not know about the new full stall training requirements. Then, they were asked to answer the five questions listed in subsections below. There were no objective prompt answers, so pilots were free to comment and express their opinion as they want to. Finally, in order to filter subjectivism, the answers were classified into five level of response according to the idea and built in the bar graph, displayed in subsections below.

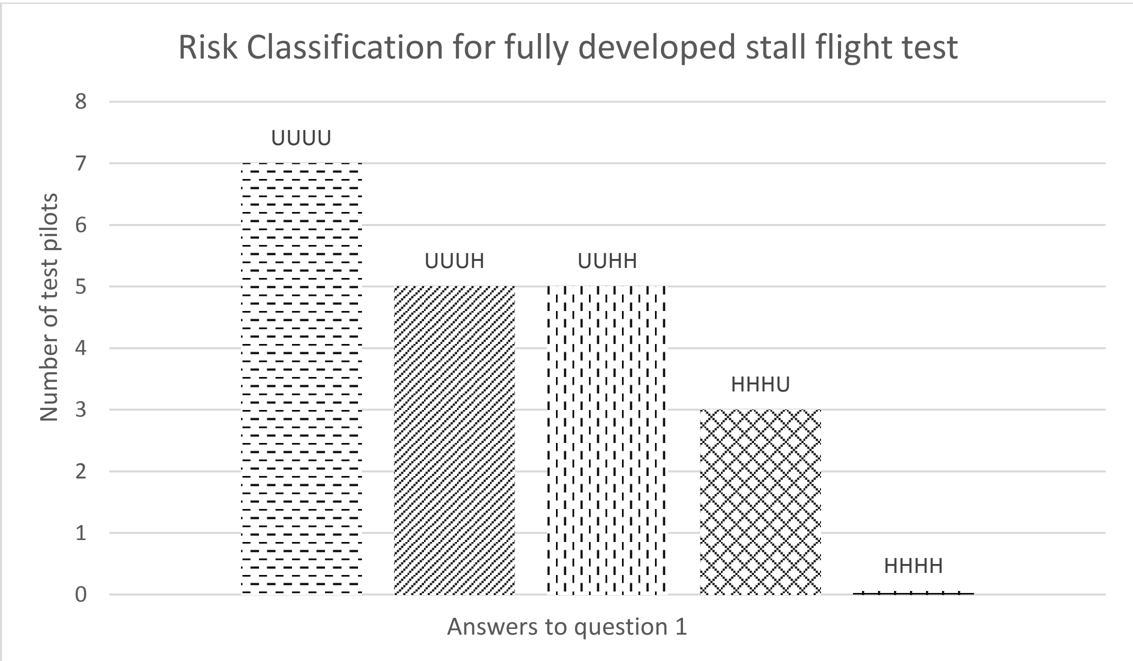
7.1 Risks of Generating Flight Test Data

For the first question, test pilots were asked for what would be the risks of executing fully developed stall flight test techniques to gather simulator data. Then they were asked to grade the level of risk and justify the answer. The risk classification had only two types of answers: High (H) or Unacceptable risk (U). As expected, nobody answered for Medium or Low risk. The 20 subjective answers were divided into five categories:

- (UUUU) Unacceptable risk, involving crew and prototype loss.
- (UUUH) Risk could only be acceptable if devices such as tail chute or ejection seats are used.
- (UUHH) Unacceptable risk, deeper analysis is needed to see if it can be mitigated to high.
- (HHHU) High risk. It could be acceptable depending on engineering's model confidence.
- (HHHH) High risk. It would be acceptable.

Results are illustrated in Figure 7-1, the major group (seven) of test pilots considered unacceptable risks, which matches with Embraer safety concerns sent to FAA mentioned in subsection 5.5.3. Five test pilots considered that risk could be acceptable only if some devices such as tail chute, parachute, ejection seats (which are common in the military world) are introduced in commercial aircraft flight tests. Another group of five considered that risk is primarily unacceptable, however, after a deep analysis and mitigation techniques considered it could become reduced to high. A minor group of three test pilots answered for high risk, depending on engineering's model confidence. Nobody answered for high risk without any consideration.

Figure 7-1 Pilots opinions on full stall flight test risk.



7.2 Practicability of full-stall FTTs

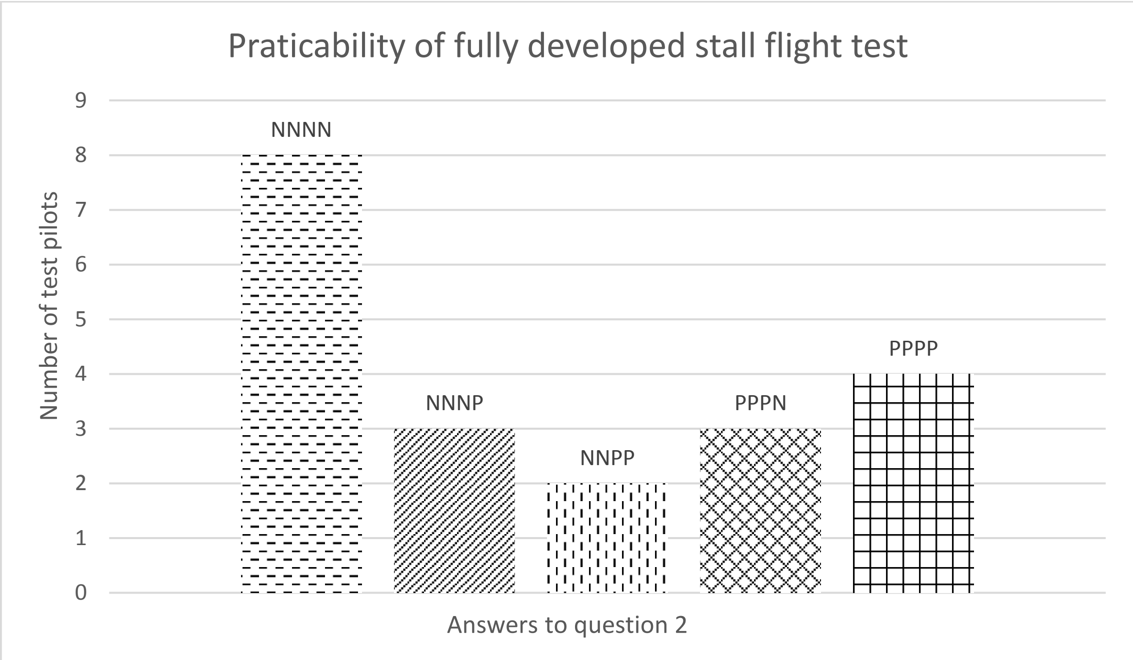
Then, test pilots were questioned whether they would consider the FTTs for investigating post- stall conditions practicable or not and they were required to justify. All 20 collected answers were divided into 5 categories as described below:

- (NNNN) No way. Not practicable due to the unacceptable risks.
- (NNNP) Not practicable due to financial constraint, costs and risks that are not suitable only for training purposes.

- (NNPP) Practicable for conventional, but not for modern DFBW aircraft.
- (PPPN) Practicable, but with severe financial costs and risks that limit ate the amount of data collected.
- (PPPP) Yes, it is practicable.

Results are shown in figure 7-2 below, the majority pilots considered not practicable at all due to safety concerns.

Figure 7-2 Pilots opinions on full stall flight test practicability.



When asked about the practicability of flight tests, eight pilot voted for complete impracticability justified by safety limitations; six pilots commented about the financial burden, which divided opinions. Half of them considered that investments and costs of ejection seats, parachutes, tail chutes and other devices used to conduct extreme dangerous tests were only applicable to military market. Three others consider that the cost would be severe, but it would be practicable. Their comments points also to the financial issue that may limit safety. One point that has not been commented is the possible influence of some design features on aerodynamic behavior that may provide doubtful data, as cited in Embraer's public comment sent to FAA, Section 5.5.3. Quality of flight test data is an important point, which is asked for pilot opinions in next subsection.

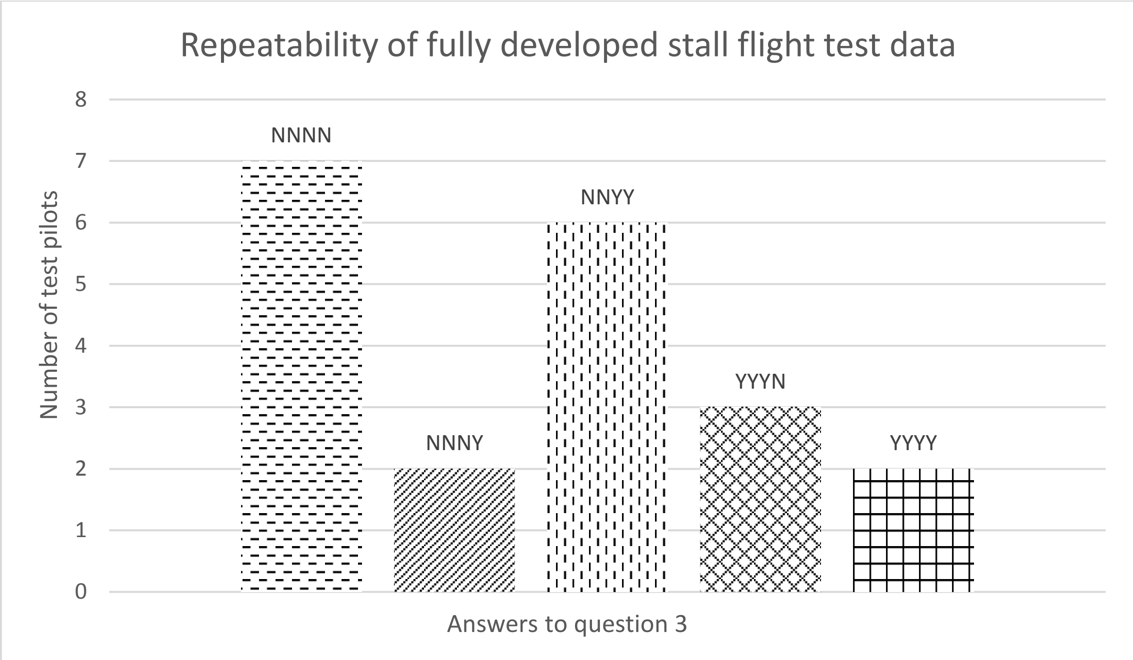
7.3 Quality of Flight Test Data

For the third question test pilots were required to consider whether data collected from fully developed stall tests would be repeatable or not. By repeatability means that the data would be qualified for building a representative model. The less repeatable and more random data the most difficult is to come up with a mathematical model which would better represent the nature. The answers were classified into:

- (NNNN) No. Stalled region is unpredictable, it would be inconclusive random data.
- (NNNY) Not for modern DFBW aircraft. For conventional aircraft the stall is quite predictable.
- (NNYY) Yes. Data would be random, but some trend/patterns could be repeatable. For example, the percentage of pitch ups, roll left, roll right, and other characteristics could be calculated and putted into a simulator model.
- (YYYN) Yes, for same Mach, altitude, weight, CG, configuration and pilots inputs.
- (YYYY) Yes.

Results are shown in figure 7-3, the majority of the test pilots considered that the randomness of aerodynamic stall behavior would lead to inconclusive results, which could not be properly modeled for simulator training purposes. A relevant part of them (six test pilots) recognized the randomness of data but have believed that would be possible to represent it in a mathematical model. That is exactly what the Part 60 Final Rule (see Appendix B.2) requires to be done. Two pilots mentioned the differences between conventional and computer controlled aircraft and considered the stall of a conventional aircraft could be predictable to be represented in a FSTD. Three pilots highlighted that data could be repeatable if same conditions for the next test point were maintained.

Figure 7-3 Pilots opinions on repeatability of full stall flight test data.



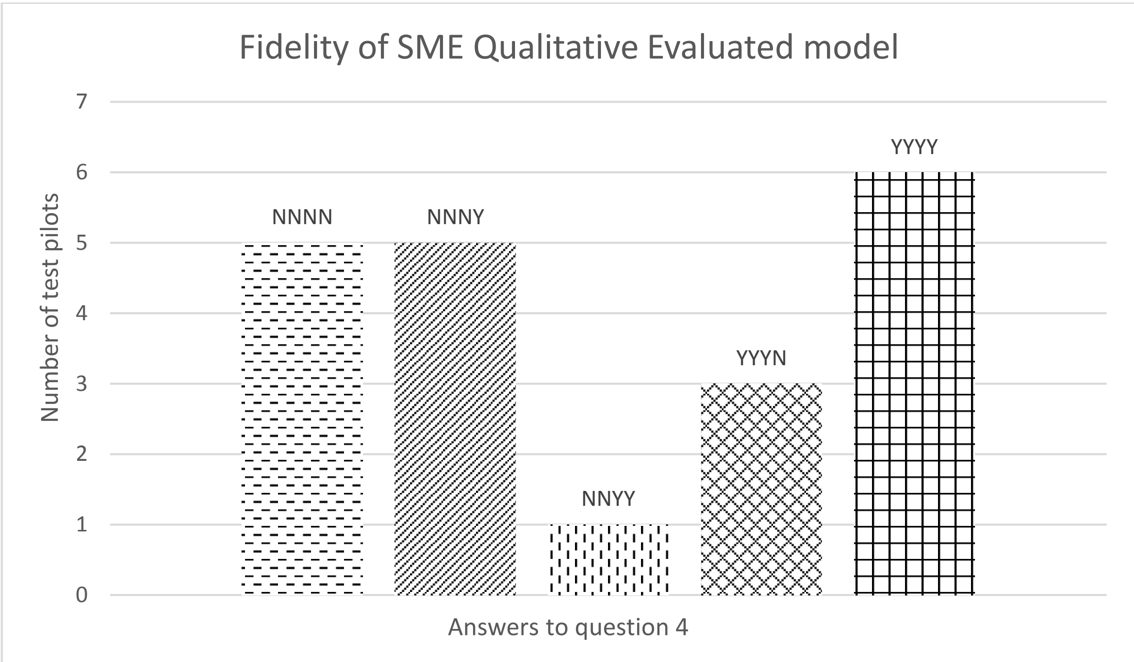
7.4 Fidelity of Qualitative Evaluation

Regarding the fourth question, the group was asked if they believed that a SME qualitative evaluation of a type-specific model based in other sources (CFD, analytical and wind tunnel data) would be enough to ensure FSTD fidelity and proper FSTD training. The answers were classified into:

- (NNNN) No. Aerodynamic modeling methods are limited tools for determining full stall conditions; only flight test can determine aircraft behavior.
- (NNNY) No. SME would not have post-stall knowledge; they only can evaluate stall definition properly.
- (NNYY) Yes, but SME should declare the envelope he or she knows, which may not attend the FAA AOA critical + 10° requirement.
- (YYYN) Yes, enough fidelity to ensure proper training but not complete fidelity. Instructors should be aware and make trainees aware of it.
- (YYYY) Yes. It is enough for the training objectives; it can give an idea of stall event identification to trainees.

Figure 7-4 below shows that for the fourth question opinions have resulted divided. Half of test pilots believed that the post-stall modeling defined by FAA would not be sufficient to ensure FSTD fidelity and airliners proper training. Five of them thought that only real flight test might determine aircraft behavior and, the other five, stated the model would not be proper evaluated because even the SME would not know the post-stall characteristics once flight tests were conducted solely to stall definition. Six pilots believed that the qualitative aerodynamic modeling and evaluation proposed by FAA would be enough to accomplish the training objectives of stall and post-stall event demonstration.

Figure 7-4 Pilots opinions on qualitative evaluated model fidelity.



The fact of questioning SME knowledge of post stall characteristics of the aircraft is important. FAA allows non flight-tested and non OEM data. However, to evaluate the sponsor model an SME will be required, who should be clearly the flight test pilot of the aircraft. This turns back to the aircraft manufacturer that may have to execute sufficient stall flight maneuvers at least to ensure SME`s proper knowledge and qualitative perceptions of the stall behavior.

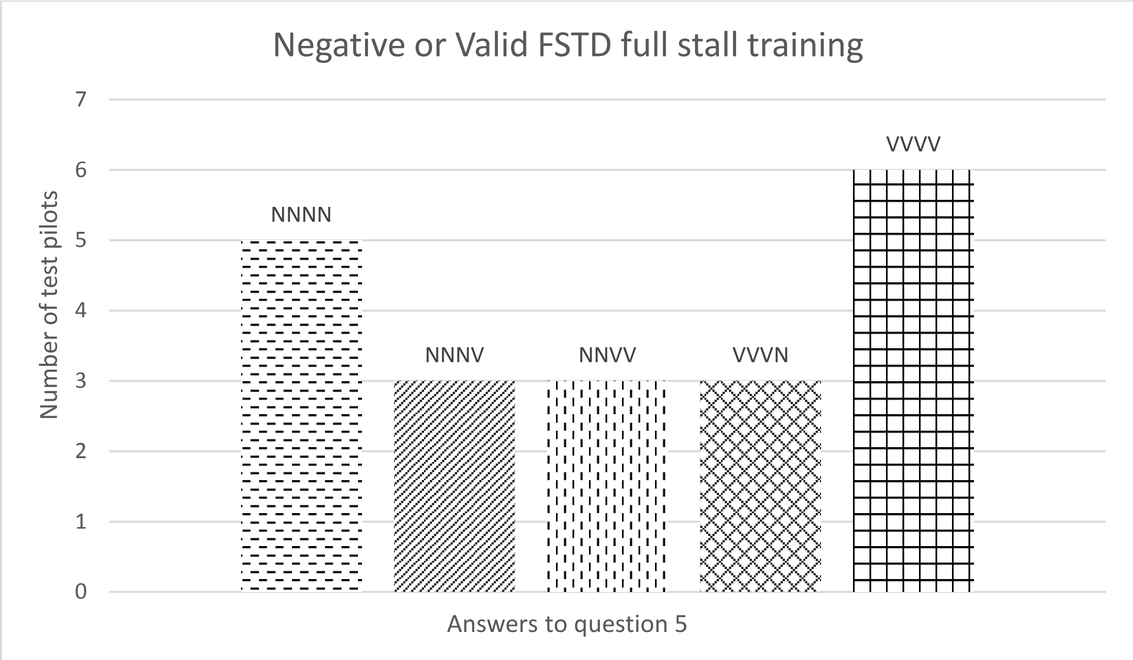
7.5 Negative or Valid Training

Finally, the fifth and probably one of the most important question concerning this discussion, the group was required to provide their opinion about the full stall training in FSTD. The questioning was whether they believed that this kind of training would be valid or negative. Newly, the answers were classified into five categories:

- (NNNN) Training would be negative for pilots.
- (NNNV) Training as the way it is proposed by FAA would be negative. I would recommend only generic training in simulators, following the stall recovery template.
- (NNVV) Post-stall training would be negative. I would recommend approach to stall and recovery training limited to the stall definition of each aircraft.
- (VVVN) Training would be valid, but only if reliable flight test data and other sources models are guaranteed.
- (VVVV) It would be a valid training.

Results of the last question are depicted in figure 7-5. The greatest part of the pilots (six) were of opinion that the full stall training in FSTD would be valid followed by five pilots that have disagreed with the majority group of six pilots previously mentioned, and they have considered the extreme opposite would happen: it would cause transfer of negative training. The remaining opinions were tied: three have recommended the training to be executed under the condition of being generic and non-type representative, because of the difficulty of representing the reality of a specific aircraft stall. Other three have recommended the training to be done solely to stall definition, which is likely to be well known, as far it would be representative region and possible to be assessed in their opinion. Moreover, the final three pilots have believed the training must be accomplished only if reliable models are assured and possible of being compared with some flight test data, which is a big issue

Figure 7-5 Pilots opinions whether valid or negative FSTD full stall training.



7.6 Comments

It was noticed that the interviewed group had different points of views and some interesting comments that are listed below:

7.6.1 Agreeing with FAA

- "Children of magenta[a] should be trained in degraded modes to learn how to actual fly an aircraft."
- "Demanding pilots to ignore alarms and go until post stall demonstrates hell to trainees. It would not give an excessive confidence to them. It would be a positive when showing the hazards of stall and would encourage them to give more importance to the alarm."
- "Deprive pilots from outside the operational envelope knowledge does not improve safety. It only gets situational awareness worse."

[a] "Children of magenta" is an expression used to criticize automatism industry that has turned pilots into dependents on the guiding magenta-colored lines on their screens.

7.6.2 Disagreeing with FAA

Some pilots commented about the discrepancies between FAR Part 25 and Part 60 requirements for computer controlled aircraft.

- "The philosophy of modern aircraft are exactly to have degraded static stability in order to increase performance. It is not expected to have good stall characteristics nor to be recoverable after the certified envelope. We do this…. We develop this kind of aircraft because we thrust in our modern systems and flight controls computers".
- "At post-stall condition the aircraft falls like stone… What is the point of modeling a falling stone?"
- "It is insane to require that industry develops a representative model of the unknown."
- "Investigating post-stall characteristics of modern aircraft could be suicide."
- "There is a conflict between Part 25 and Part 60 regulations. Even the OEM may not know its own aircraft post stall characteristics and it cannot guarantee that it is recoverable. So why training in this condition? The requirement only makes sense if FAA imposes that only aircraft with recoverable post-stall characteristics will be certified, which is not the actual Part 25 and Special Conditions police".
- "Modern RSS aircraft have probably deep stall characteristics which are probably unrecoverable. And Part 25 does not require it to be recoverable. So what is the point of training pilots over there?"
- "There is no world after stall definition. There is not what to train. That is all worthless investment."
- "I see these new rulemaking as an overreaction of US government to meet public opinion. Only set right the stall recovery procedures and start teaching the appropriate techniques, suggested by stall recovery template would be sufficient."

7.7 Section Summary

The interview confirmed that this debate is very controversial and does divide opinions. When the subject of questions was about flight tests risks, practicability and quality of flight test data the Embraer pilots were more conservative. The majority of the interviewed group have considered following FAA new police of unacceptable risks, non-practicable and others have considered too dangerous and expensive for collecting non-repeatable data. However, when the subject was the FSTD training itself, excluding flight test and considering other sources of data modeling, the overall opinion became half-to-half divided, which demonstrates the controversial and polemic aspect of the debate.

FAA has tasked working groups, has made efforts to develop valued stall recovery training guidelines for instructors and for FSTD sponsors, but one specific issue was not well covered by studies, and arguments were not convincing: the aerodynamic stall or post-stall modeling for computer controlled aircraft. This topic was largely commented by many pilots during the interview because FAA have contradicted itself by addressing special conditions allowing an aircraft to be certified even if it has poor flying qualities just after C_{Lmax} demonstration or stall definition, in case of compliance found for FBW envelope protection failure rate to be extremely remote; and then, for training purposes, have required industry to model the aircraft stall behavior with envelope protection disabled.

On the other hand, some pilots have commented the excess of automatism limiting airlines knowledge of flying, which is a real and consolidated issue in the aviation and pointed as one of the causes of accidents such as AF 447. The degraded modes training required by FAA is an attempt of providing pilots with the situational awareness and recognition cues necessaries to fly an aircraft in case of computers failure.

8 CONCLUSION

The objectives of this work were achieved and the importance of promoting safety debates has been reinforced. Section 2 provided an understanding of stall theory and the flight test maneuvers that industry currently execute for Part 25 certification requirements. The maneuvers are usually classified as high risk and are executed up to stall definition, which does not cover post-stall region. Section 3 presented the FSTD theory and Part 60 requirements; explained the importance of mathematical models on fidelity and how they are developed, updated and validated. Moreover, presented the importance of flight test data to ensure high fidelity level and the challenges of developing post-stall models. Section 4 resumed three accidents reports that motivated the introduction of full stall training. Failures in stall training recovery procedures and crew's inability to prevent and recognize stall and fly in degraded mode were detected.

In addition, section 5 related the sequence of events following Public Law 111-126. The way that FAA implements Part 60 changes (10 degrees beyond de maximum AOA modeling, not necessarily based on flight test data and qualitative SME evaluation) was highly questioned by industry experts. The main concern was about FSTD fidelity levels and the possibility of negative training. Section 6 depicted the human factors covering the transfer of training; reviewing not only fidelity aspects but also the psychological effects of deliberately leave the OFE and the consequences of teaching inappropriate techniques. Finally, Section 7 added test pilots opinions about the possibility of executing post-stall flight test, which were, in majority, conservative and shows that high fidelity FSTD remains a big issue. Also, when other modeling and validation methods (as proposed by FAA) were considered, Section 7 demonstrated that the validity of FSTD full stall training really divides opinions.

Following the industry and some experts comments, the way of avoiding negative training would be to introduce the stall recovery training in FSTD up to stall definition where the level of model confidence is high. Moreover, this is the known region and well tested by the OEMs and the range where the SME proper knowledge is trustable; therefore he/she could properly and qualitatively evaluate the stall characteristics. In addition, the amount of linearity until the maximum AOA aerodynamic could provide an objective evaluation, then, from this perspective, trainees should be oriented to recover immediately after stall definition characteristics are manifested. For envelope protected aircraft, the full-stall training in type-specific FSTD should only be conducted in normal flight controls mode. It is also important to address the recognition cues of degraded modes of this kind of aircraft and it could be done by generic FSTD training reproducing accidents situation and the most common DFBW aircraft stall characteristics. It should be made clear that in all stall cases lowering alpha is always the main recovery action. Some of the ideas presented in this work to ensure positive transfer of training disagrees with FAA's rulemaking and probably will find a lot of resistance from the Administrator. Even though, the amount of stall accidents are more likely to be reduced. Not necessarily due to the post-stall experience, but due to improved situation awareness, recognition, stall recovery techniques and mainly the prevention of getting to a stall, always focused on AOA reduction instead of minimizing altitude loss that are also part of new Part 121 aircrew training package.

9 FUTURE PERSPECTIVES

In the future, post-stall models will be probably developed without available flight test data. Of course, due to existing risk and safety issue but primarily due to financial issues. If the SOC allows complying with Part 60 requirements using other sources of data, then the industry will probably not invest in post-stall flight-testing without gaining in performance, making the product more competitive in the market and improving profits. Airframe manufacturers and FSTD sponsor will find a way of developing post-stall aeromodelling by improving wind tunnel, CFD, engineering analysis methods. However, to ensure safety, model cannot be completely blind: at least some qualitative knowledge of immediately after stall definition characteristics should be provided. Fortunately, recent flight test techniques such as parameter identification and Model Based Flight Test (MBFT) permits to obtain aerodynamic coefficients precisely, minimizing risk exposure and better take benefit of stall development flight test campaign.

For those OEM, which produces computer controlled aircraft, a bigger challenge to comply with new Part 60 requirements is imposed. Research investments to look for the best solution to provide a “clear and distinctive” stall model must be accounted. One possible idea is introducing an artificial stall characteristic on the aircraft itself, which should be compelling enough, such as an artificial roll tendency to each flap configuration or a nose down that could not be arrested together with a buffeting characteristic deterrent to any increase in the alpha. This could be achieved by adding asymmetrical input wave form in the primary surfaces summed with pilot control through a FBW feature in order to force a controlled rolling tendency. Thus, the characteristic could be artificially introduced in FSTD model, by adding this roll derivative.

Aircraft are still to fly for a long time, with technology increasing its complexity much faster than engineers’ ability to assess it, thus the FAA training requirements changes may not be sufficient to prevent future accidents. Stall characteristics is no longer defined by aerodynamics alone, but also by the systems behavior and new types of human errors, commonly related to inadequate human-machine interaction, are identified. Therefore, lessons learned with the past may not be sufficient once new types of hazards are expected and consequently, new safety assessment methods may be needed. For the future, the scenery imposed challenges engineers not to learn safety by accident, but to improve safety to prevent the next accident.

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APPENDIX A: 14 CFR Part 25

A.1. § 25.103 Stall speed.

(a) The reference stall speed, VSR, is a calibrated airspeed defined by the applicant. VSR may not be less than a 1-g stall speed. VSR is expressed as:

$$V_{SR} \geq \frac{V_{CLmax}}{\sqrt{n_{zw}}}$$

where:

V_{CLmax} = Calibrated airspeed obtained when the load factor-corrected lift coefficient:

$$\left(\frac{n_{zw}W}{qS}\right)$$

is first a maximum during the maneuver prescribed in paragraph (c) of this section. In addition, when the maneuver is limited by a device that abruptly pushes the nose down at a selected angle of attack (e.g., a stick pusher), V_{CLmax} may not be less than the speed existing at the instant the device operates;

n_{zw} = Load factor normal to the flight path at V_{CLmax}

W = Airplane gross weight;

S = Aerodynamic reference wing area; and

q = Dynamic pressure.

(b) V_{CLmax} is determined with:

(1) Engines idling, or, if that resultant thrust causes an appreciable decrease in stall speed, not more than zero thrust at the stall speed;

(2) Propeller pitch controls (if applicable) in the takeoff position;

(3) The airplane in other respects (such as flaps, landing gear, and ice accretions) in the condition existing in the test or performance standard in which VSR is being used;

(4) The weight used when VSR is being used as a factor to determine compliance with a required performance standard;

(5) The center of gravity position that results in the highest value of reference stall speed; and

(6) The airplane trimmed for straight flight at a speed selected by the applicant, but not less than 1.13 VSR and not greater than 1.3 VSR.

(c) Starting from the stabilized trim condition, apply the longitudinal control to decelerate the airplane so that the speed reduction does not exceed one knot per second.

(d) In addition to the requirements of paragraph (a) of this section, when a device that abruptly pushes the nose down at a selected angle of attack (e.g., a stick pusher) is installed, the reference stall speed, VSR, may not be less than 2 knots or 2 percent, whichever is greater, above the speed at which the device operates.

[Doc. No. 28404, 67 FR 70825, Nov. 26, 2002, as amended by Amdt. 25–121, 72 FR 44665, Aug. 8, 2007]

A.2 § 25.201 Stall demonstration.

(a) Stalls must be shown in straight flight and in 30 degree banked turns with—

(1) Power off;

(2) The power necessary to maintain level flight at 1.5 VSR1 (where VSR1corresponds to the reference stall speed at maximum landing weight with flaps in the approach position and the landing gear retracted).

(b) In each condition required by paragraph (a) of this section, it must be possible to meet the applicable requirements of §25.203 with—

(1) Flaps, landing gear, and deceleration devices in any likely combination of positions approved for operation;

(2) Representative weights within the range for which certification is requested;

(3) The most adverse center of gravity for recovery; and

(4) The airplane trimmed for straight flight at the speed prescribed in §25.103(b)(6).

(c) The following procedures must be used to show compliance with §25.203;

(1) Starting at a speed sufficiently above the stalling speed to ensure that a steady rate of speed reduction can be established, apply the longitudinal control so that the speed reduction does not exceed one knot per second until the airplane is stalled.

(2) In addition, for turning flight stalls, apply the longitudinal control to achieve airspeed deceleration rates up to 3 knots per second.

(3) As soon as the airplane is stalled, recover by normal recovery techniques.

(d) The airplane is considered stalled when the behavior of the airplane gives the pilot a clear and distinctive indication of an acceptable nature that the airplane is stalled. Acceptable indications of a stall, occurring either individually or in combination, are—

(1) A nose-down pitch that cannot be readily arrested;

(2) Buffeting, of a magnitude and severity that is a strong and effective deterrent to further speed reduction; or

(3) The pitch control reaches the aft stop and no further increase in pitch attitude occurs when the control is held full aft for a short time before recovery is initiated.

[Doc. No. 5066, 29 FR 18291, Dec. 24, 1964, as amended by Amdt. 25–84, 60 FR 30750, June 9, 1995; Amdt. 25–108, 67 FR 70827, Nov. 26, 2002]

A.3. § 25.203 Stall characteristics.

(a) It must be possible to produce and to correct roll and yaw by unreversed use of the aileron and rudder controls, up to the time the airplane is stalled. No abnormal nose-up pitching may occur. The longitudinal control force must be positive up to and throughout the stall. In addition, it must be possible to promptly prevent stalling and to recover from a stall by normal use of the controls.

(b) For level wing stalls, the roll occurring between the stall and the completion of the recovery may not exceed approximately 20 degrees.

(c) For turning flight stalls, the action of the airplane after the stall may not be so violent or extreme as to make it difficult, with normal piloting skill, to effect a prompt recovery and to regain control of the airplane. The maximum bank angle that occurs during the recovery may not exceed—

(1) Approximately 60 degrees in the original direction of the turn, or 30 degrees in the opposite direction, for deceleration rates up to 1 knot per second; and

(2) Approximately 90 degrees in the original direction of the turn, or 60 degrees in the opposite direction, for deceleration rates in excess of 1 knot per second.

[Doc. No. 5066, 29 FR 18291, Dec. 24, 1964, as amended by Amdt. 25–84, 60 FR 30750, June 9, 1995]

A.4. § 25.207 Stall warning.

(a) Stall warning with sufficient margin to prevent inadvertent stalling with the flaps and landing gear in any normal position must be clear and distinctive to the pilot in straight and turning flight.

(b) The warning must be furnished either through the inherent aerodynamic qualities of the airplane or by a device that will give clearly distinguishable indications under expected conditions of flight. However, a visual stall warning device that requires the attention of the crew within the cockpit is not acceptable by itself. If a warning device is used, it must provide a warning in each of the airplane configurations prescribed in paragraph (a) of this section at the speed prescribed in paragraphs (c) and (d) of this section. Except for showing compliance with the stall warning margin prescribed in paragraph (h)(3)(ii) of this section, stall warning for flight in icing conditions must be provided by the same means as stall warning for flight in non-icing conditions.

(c) When the speed is reduced at rates not exceeding one knot per second, stall warning must begin, in each normal configuration, at a speed, VSW, exceeding the speed at which the stall is identified in accordance with §25.201(d) by not less than five knots or five percent CAS, whichever is greater. Once initiated, stall warning must continue until the angle of attack is reduced to approximately that at which stall warning began.

(d) In addition to the requirement of paragraph (c) of this section, when the speed is reduced at rates not exceeding one knot per second, in straight flight with engines idling and at the center-of-gravity position specified in §25.103(b)(5), VSW, in each normal configuration, must exceed VSR by not less than three knots or three percent CAS, whichever is greater.

APPENDIX B: 14 CFR Part 60

B.1. NPRM High AOA Modeling

Table A1A

Minimum Simulator Requirements

	QPS REQUIREMENTS	Simulator Levels				INFORMATION
Entry Number	**General Simulator Requirements**	**A**	**B**	**C**	**D**	**Notes**
	• An SOC is required that defines the source data used to construct the flight test and wind tunnel/analytical envelope. • The SOC must verify that each upset prevention and recovery feature programmed at the instructor station and the associated training maneuver has been evaluated by a suitably qualified pilot using methods described in this section. The statement must confirm that the recovery maneuver can be performed such that the FSTD does not exceed the flight test and wind tunnel envelope described above, or when exceeded, that it is within the realm of confidence in the simulation accuracy. • The SOC must confirm the source of data used for the aircraft operating limits which are used to provide the instructor indications or warnings on approaching or exceeding these limits.					
2.1.7.S	High Angle of Attack Modeling The simulator must include aerodynamic modeling for high angle of attack maneuvers to at least ten degrees beyond the stall angle of attack or as required to execute a recovery from a fully stalled flight condition. The following stall maneuvers must be evaluated for qualification: ▪ Stall entry at wings level (1g) ▪ Stall entry in turning flight of at least 25° bank angle (accelerated stall) ▪ Stall entry in a power-on condition (required only for propeller driven aircraft) ▪ Aircraft configurations of second segment climb, high altitude cruise (near performance limited condition), and approach or landing. Tests required For stick pusher equipped aircraft, a Statement of Compliance (SOC) is required verifying that the stick pusher system has been modeled, programmed, and validated using the aircraft manufacturer's design data or other acceptable data source. The SOC must address, at a minimum, stick pusher activation and cancellation logic as well as system dynamics, control displacement and forces as a result of the stick pusher activation. A Statement of Compliance (SOC) is required which describes the aerodynamic modeling methods, validation, and checkout of the stall characteristics of the FSTD. The SOC must also include verification that the FSTD has been evaluated by a subject matter expert pilot with acceptable supporting documentation and/or direct experience of the stall characteristics of the aircraft being simulated. See Attachment 7 of this Appendix for detailed requirements. For aircraft equipped with a stall identification system (e.g. stick pusher) that is required for aircraft dispatch, objective testing will only be required through activation of the stall identification system to recovery to a normal flight attitude. The aerodynamic model must be programmed and evaluated using the best available data to demonstrate the expected aircraft behavior should the stall identification system be overridden or disabled as required for training. Specific FSTD limitations due to data availability must be identified to the NSPM and indicated on the Statement of Qualification. See objective testing requirements for details.			X	X	See Attachment 7 of this Appendix for further guidance material. Specific guidance should be available to the instructor which clearly communicates the flight configurations and stall maneuvers that have been evaluated in the FSTD for use in training. The use of an "alpha/beta" validation envelope that defines the range of stall model validation is encouraged (see section 2.1.6.S.on upset recognition and recovery).
2.1.R	Reserved					

B.2. Final Rule High AOA Modeling

2.m.	High Angle of Attack Modeling Aerodynamic stall modeling that includes degradation in static/dynamic lateral-directional stability, degradation in control response (pitch, roll, and yaw), uncommanded roll response or roll-off requiring significant control deflection to counter, apparent randomness or non-repeatability, changes in pitch stability, Mach effects, and stall buffet, as appropriate to the aircraft type. The aerodynamic model must incorporate an angle of attack and sideslip range to support the training tasks. At a minimum, the model must support an angle of attack range to ten degrees beyond the stall identification angle of attack. The stall identification angle of attack is defined as the point where the behavior of the airplane gives the pilot a clear and distinctive indication through the inherent flight characteristics or the characteristics resulting from the operation of a stall identification device (e.g., a stick pusher) that the airplane has stalled. The model must be capable of capturing the variations seen in the stall characteristics of the airplane (e.g., the presence or absence of a pitch break, deterrent buffet, or other indications of a stall where present on the aircraft). The aerodynamic modeling must support stall training maneuvers in the following flight conditions: (1) Stall entry at wings level (1g); (2) Stall entry in turning flight of at least 25° bank angle (accelerated stall); (3) Stall entry in a power-on condition (required only for propeller driven aircraft); and (4) Aircraft configurations of second segment climb, high altitude cruise (near performance limited condition), and approach or landing. A Statement of Compliance (SOC) is required which describes the aerodynamic modeling methods, validation, and checkout of the stall characteristics of the FSTD. The SOC must also include verification that the FSTD has been evaluated by a subject matter expert pilot acceptable to the FAA. See Attachment 7 of this Appendix for detailed requirements. Where known limitations exist in the aerodynamic model for particular stall maneuvers (such as aircraft configurations and stall entry methods), these limitations must be declared in the required SOC. FSTDs qualified for full stall training tasks must also meet the instructor operating station (IOS) requirements for upset prevention and recovery training (UPRT) tasks as described in section 2.n. of this table. See Attachment 7 of this Appendix for additional requirements.			**X**	**X**	The requirements in this section only apply to those FSTDs that are qualified for full stall training tasks. Sponsors may elect to not qualify an FSTD for full stall training tasks; however, the FSTD's qualification will be restricted to approach to stall training tasks that terminate at the activation of the stall warning system. Specific guidance should be available to the instructor which clearly communicates the flight configurations and stall maneuvers that have been evaluated in the FSTD for use in training. See Attachment 7 of this Appendix for additional guidance material.

APPENDIX C: 14 CFR Part 121

C.1 § 121.423 Pilot: Extended Envelope Training

(a) Each certificate holder must include in its approved training program, the extended envelope training set forth in this section with respect to each airplane type for each pilot. The extended envelope training required by this section must be performed in a Level C or higher full flight simulator, approved by the Administrator in accordance with § 121.407 of this part.

(b) Extended envelope training must include the following maneuvers and procedures:

(1) Manually controlled slow flight;

(2) Manually controlled loss of reliable airspeed;

(3) Manually controlled instrument departure and arrival;

(4) Upset recovery maneuvers; and

(5) Recovery from bounced landing.

(c) Extended envelope training must include instructor-guided hands on experience of recovery from full stall and stick pusher activation, if equipped.

(d) Recurrent training: Within 24 calendar months preceding service as a pilot, each person must satisfactorily complete the extended envelope training described in paragraphs (b)(1) through (4) and (c) of this section. Within 36 calendar months preceding service as a pilot, each person must satisfactorily complete the extended envelope training described in paragraph (b)(5) of this section.

(e) Deviation from use of Level C or higher full flight simulator:

(1) A certificate holder may submit a request to the Administrator for approval of a deviation from the requirements of paragraph (a) of this section to conduct the extended envelope training using an alternative method to meet the learning objectives of this section.

(2) A request for deviation from paragraph (a) of this section must include the following information:

(i) A simulator availability assessment, including hours by specific simulator and location of the simulator, and a simulator shortfall analysis that includes the training that cannot be completed in a Level C or higher full flight simulator; and

(ii) Alternative methods for achieving the learning objectives of this section.

(3) A certificate holder may request an extension of a deviation issued under this section.

(4) Deviations or extensions to deviations will be issued for a period not to exceed 12 months.

(f) Compliance with this section is required no later than March 12, 2019. For the recurrent training required in paragraph (d) of this section, each pilot qualified to serve as second in command or pilot in command in operations under this part on March 12, 2019 must complete the recurrent extended envelope training within 12 calendar months after March 12, 2019.

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