Stalling transport aircraft

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ABSTRACT

Airbus and Boeing are cooperatively presenting this topic dealing with transport aircraft stalls. The paper will begin by defining a stall, followed by a review of requirements, predictive validation and flight testing. There are various ways of designing modern jet transports for the stall regime such as aerodynamic approaches, flight deck indications, and augmentation control laws to deal with the high angle-of-attack (α) arena. The goal of augmented control laws for high α is common – no full aerodynamic stall or loss of climb performance should occur in the operational flight envelope, in Normal flight control modes. The validation techniques employed in preparation for a flight test campaign will follow. These include flight characteristic predictions based on wind-tunnel data as well as pilot-in-the-loop simulation rehearsals. The preparation for flight testing will be reviewed from both the engineer and pilot viewpoints. This will be followed by a review of various flight testing that has been conducted. The paper will close with a brief foray into what the future of transport stalls could be – perhaps protection features in degraded flight control modes? What are the benefits as well as drawbacks to increased augmentation for high α?

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> *"Every Boeing Commercial jet can be stalled, sometimes with a great deal of effort or in backup flight control modes, but they can be stalled. The manner in which they stall is not grossly different than most general aviation light aircraft. They are, in fact, certified to fairly similar Federal Air Regulations, thus the stall has many similar characteristics between the two types."*
>
> **Captain John E. Cashman**

> *"Do not confuse an approach to the stall and a full stall. An Approach to stall is controlled flight. An* aircraft *that is stalled is out of control and must be recovered. There is a world of difference between being just before, or even just at, the stall, and going dynamically well into it."*
>
> **Captain William Wainwright**

NOMENCLATURE

ATC	Air Traffic Communication
CFD	Computational Fluid Dynamics
CL_{BUFFET}	Lift coefficient recorded at initial buffet
CL_{MAX}	maximum lift coefficient
$CL(\alpha)$	lift coefficient curve as a function of angle-of-attack
HUD	Heads-Up Display
L/R delta	Fuel quantity difference between left and right wings
Nz	Normal load factor
THS	Trimmable Horizontal Stabiliser
T-tail	aircraft for which the horizontal tail is positioned on top of the vertical tail
$V2$	speed or velocity to be maintained after lift-off in order to ensure the minimum climb gradient in case of one engine inoperative
$VFTO$	speed or velocity to be maintained during final take-off in case of one engine inoperative (when leading and trailing-edge devices have been retracted)
VMC	Minimum Control Speed (one engine inoperative)
$VREF$	minimum approach speed or velocity in landing configuration
$Vs1g$	minimum speed or velocity at which a 1g flight condition can be maintained
VSR	stall reference speed or velocity
α	angle-of-attack
α_{BUFFET}	angle-of-attack value recorded at CL_{BUFFET}
α_{CLMAX}	angle-of-attack value recorded at CL_{MAX}
β	angle of sideslip

1.0 STALL DEFINITION AND REQUIREMENTS

In the frame of a new transport aircraft flight test campaign, extensive stall testing is performed very early in the development phase as the results will impact the rest of development and certification tests.

One of the first goals is to open very soon the lower side of the flight envelope (low altitude and low airspeed) in order to clear handling qualities and check that the aircraft is free of unexpected behaviour at high angle-of-attack (α)

Results of stall tests drive the parameters needed to freeze the different aerodynamic configurations of the aircraft. A complete aerodynamic identification is done by extracting from those tests

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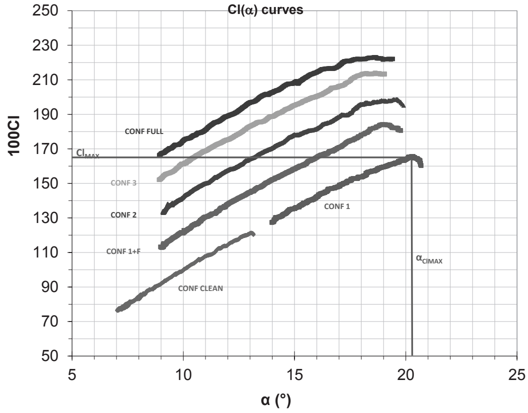

Figure 1. Recorded lift curve slopes.

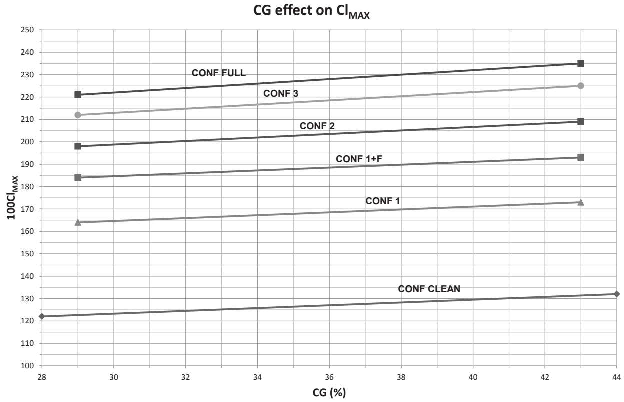

Figure 2. CG effect on lift.

the lift curves which will allow determining the CL_{MAX} and computing the Vs1g on which most performance speeds are based (V2, VFTO, VREF...).

In addition, stalling the aircraft provides the opportunity to identify and monitor induced loads as well as local α changes on the horizontal tail.

The stall is defined as the point when maximum aerodynamic lift is achieved. Further increases in α beyond the point of stall will cause a reduction in lift. Tracing the lift curves $CL(\alpha)$ allows identifying the CL_{MAX} and the corresponding α_{CLMAX} for each aerodynamic (slat/flap) configuration (see Fig. 1). During a stall test, reaching the CL_{MAX} can be recognised through a sudden decrease of vertical load factor called the 'g-break' or by the development of excessive airframe buffet.

1.1 Remark

It is to be noted that $CL(\alpha)$ curves identify the total aircraft lift which is not exclusive to the wing contribution but also to the horizontal tail and to a lesser extent the fuselage.

Slats and flaps effects can be easily identified in the lift curves. Extending slats mainly increases the αat which maximum lift can be reached. On the other hand, extending flaps increases significantly the amount of maximum lift which can be reached.

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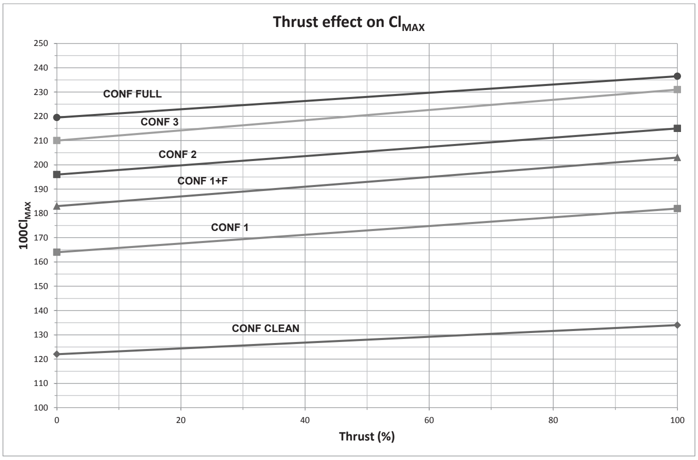

Figure 3. Thrust effect on lift.

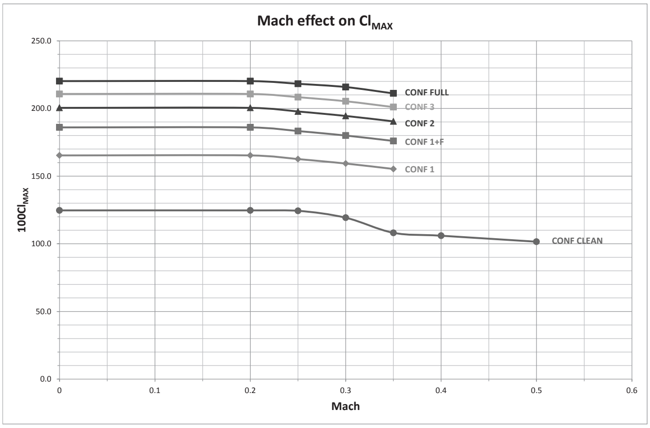

Figure 4. Mach effect on lift.

Based on CL_{MAX} determination and using the lift equation [nmg = 0·5ρSV2CL(α)], the Vs1g can be computed and is defined as the minimum speed at which the aircraft can generate enough lift to maintain a 1g flight condition. Most of the performance speeds are based on the Vs1g (by regulation V2 is limited by 1·13 Vs1g, VREF is limited by 1·23 Vs1g...).

Note: In some particular configurations it can happen that the “g-break” cannot be reached during flight test due to non-expected aircraft behavior such as sudden roll-off, strong pitch-up etc...

In that case and in accordance to the regulation the CL_{MAX} will be declared at the appearance of the phenomenon (if the phenomenon cannot be cancelled by any alternative aerodynamic modification).

Several effects have a direct impact on CL_{MAX} and Vs1g and have to be identified during flight tests.

1.2 Centre of Gravity (*CG*) effect

position has an effect on CL_{MAX} mainly due to the associated pitch trim position which makes the horizontal tail develop less down-lift at aft *CG* than at forward *CG* (see Fig. 2).

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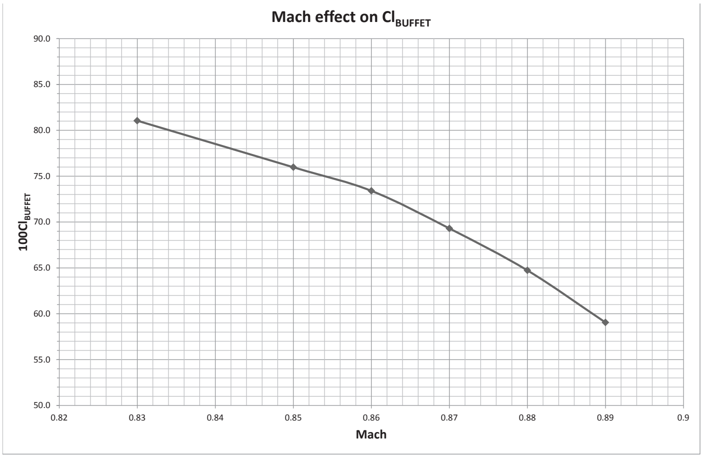

Figure 5. Initial buffet curve.

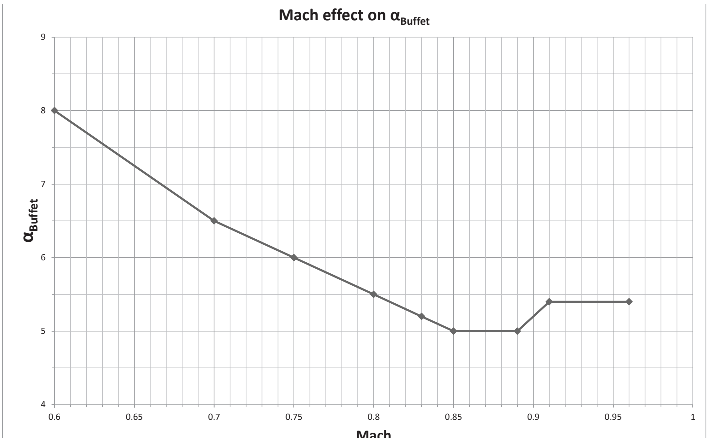

Figure 6. Mach effect on buffet α.

1.3 Thrust effect

On most transport aircraft engines are fitted under the wings. However, the effect of thrust has a direct impact on CL_{MAX}. For a given configuration, CL_{MAX} will be higher with maximum thrust than with idle thrust (see Fig. 3). This contribution to total aircraft lift is mainly due to the vertical component of the force induced by the thrust.

1.4 Mach effect

For a given configuration, the higher the Mach number, the lower will be CL_{MAX} (see Fig. 4).This phenomenon is mainly due to the appearance of flow separation due to stronger local shock waves which degrade the airflow along the wings and thus decrease the amount of available lift.

At high altitude/high Mach number, the Vs1g cannot be determined due to early triggering of buffeting. This buffeting is caused by flow separation behind strong local shock waves which excite the structural modes of the aircraft. Theoretically a CL_{MAX} may exist at high Mach number but the associated level of buffeting prevents efforts to identify it during flight tests for aircraft structural integrity and safety reasons.

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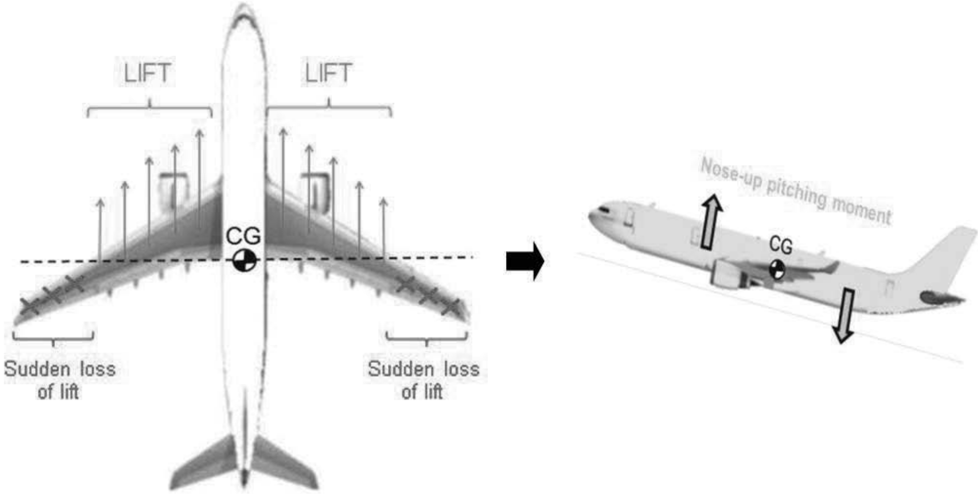

Figure 7. Pitch-up illustration.

Nevertheless, according to the regulation a minimum of 1·3g maneuverability up to ‘buffet onset’ must be demonstrated for each flyable Mach number. Therefore the CL_{MAX} for a given Mach number will generally be defined by the level of buffeting corresponding to ±0·1g vertical acceleration level measured at the pilot’s seat (so called ‘buffet onset’) and is named CL_{BUFFET} (see Fig. 5).

What is true for the CL_{BUFFET} is also true for the α at which the buffeting appears at high Mach number (α_{BUFFET}). The higher the Mach number, the lower will be α_{BUFFET} (see Fig. 6).

This induces reduced margins during a stall recovery.

1.5 Pitch-up

‘Pitch-up’ can be observed during stall mainly on aircraft fitted with swept wings. It is due to the sudden loss of lift on the outer part of the wings, which creates a nose-up moment (see Fig. 7). This phenomenon can also occur at high altitude/high Mach well before CL_{BUFFET} is reached and is again due to flow separation behind shock waves destroying the lift on the outer part of the wings.

1.6 Ground effects

Lift levels vary as the aircraft approaches the ground. The proximity to the ground causes a ‘cushion’ effect providing additional lift at the same α near the ground. There is, however, a reduction in maximum lift available in full ground effects (see Fig. 8).

Finally, stalls are performed with particular aerodynamic configurations corresponding to the most probable failure cases (abnormal slat/flap configurations, hydraulic failures leading to get several control surfaces floating, lateral CG offset, etc…).

1.7 Certification requirements for stalls

There are several FAA / EASA regulations governing stalled flight: 25·103 ‘Stall Speed’, 25.201 ‘Stall Demonstration’, 25·203 ‘Stall Characteristics’, and 25·207 ‘Stall Warning.’ These regulations describe the required behavior for transport category aircraft in the stalled flight regime. In particular,

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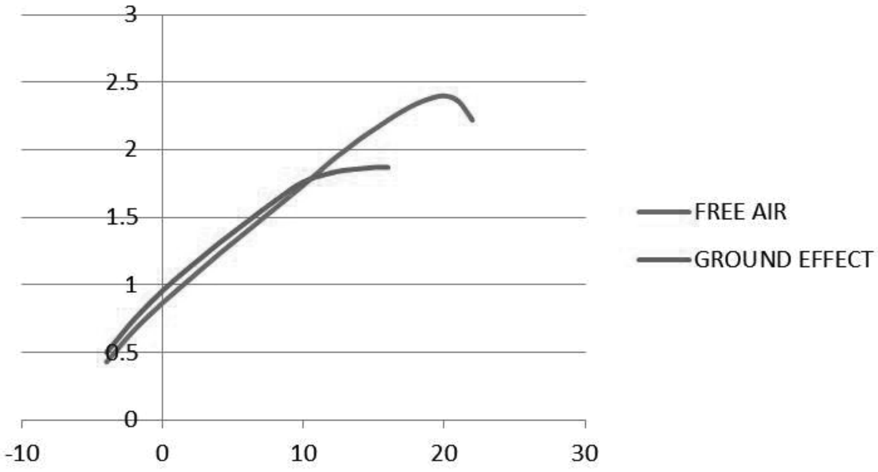

Figure 8. Ground effect on lift.

they describe how to calculate the stall reference speed, Vs – which is now Vs1g or Vsr. Vsr is a reference stall speed now adopted by the regulations. They also prescribe the particular conditions required to be demonstrated and how to identify a stalled condition. Most stalls require slow deceleration rates of approximately 1 knot/second, although ftaser decelerations (up to 3 knots/second) are also required. Requirements for the characteristics at stall are delineated as well as providing requirements for warning prior to stall. The set of regulations provides a comprehensive set of requirements for stalls and has been developed over the course of time by many different regulatory agencies.

In addition, there exists advisory material that provides acceptable means of compliance for conducting stalls: *Airbus Flight Test Guide*, Ch 5, ‘Stalls’ and FAA AC 25-7C ‘Flight Test Guide.’

For many recent aircraft models, some of these regulations have been superseded by Special Conditions or Findings of Equivalent Safety. This is primarily due to the augmentation and envelope protection features that have arisen with the recent fly-by-wire control system designs.

2.0 PREPARING FOR FLIGHT TEST

Initial predictive data for a new aircraft model is normally obtained from wind-tunnel testing. CFD is being used to a greater extent, but the majority of the aerodynamic knowledge of the aircraft is still obtained through collection and analysis of both low-speed and high-speed wind-tunnel testing.

The raw wind-tunnel data is corrected and then refined into tables that support a full simulation database. The aerodynamic simulation modeling is comprised of a mathematical model which is a set of equations that sum up effects to reflect the total aerodynamic state of the aircraft in terms of forces and moments.

Next, design engineering creates extensive predictions using a pre-flight simulation database. These predictions are then reviewed looking for any areas that show unexpected or marginally acceptable characteristics.

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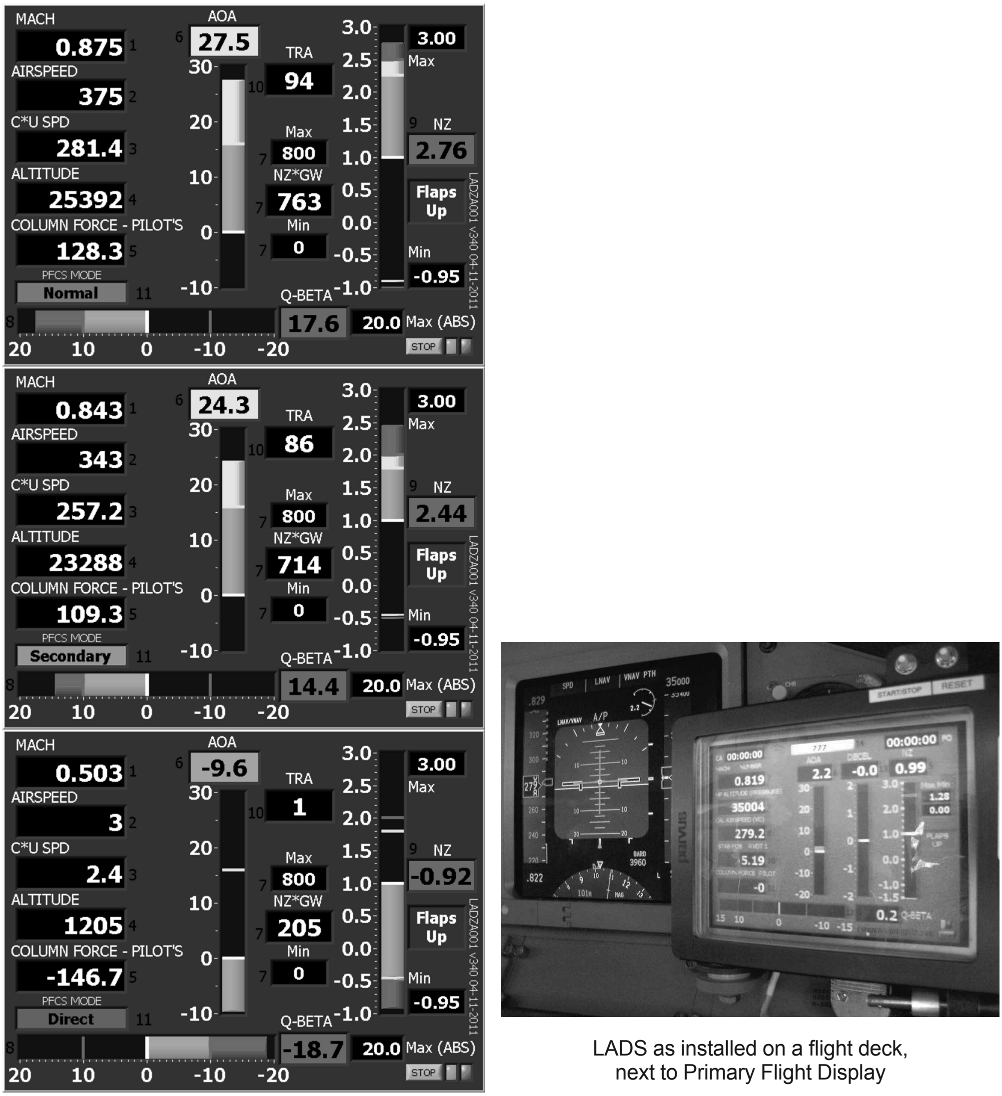

LADS as installed on a flight deck, next to Primary Flight Display

Figure 9. LADS pilot display.

Following all of this, pilot-in-the-loop simulation evaluations are conducted in a company simulation facility. The intent of these sessions is to obtain pilot feedback on characteristics and handling qualities.

All of the above work culminates in specific dry-runs or flight test rehearsals with both company and regulatory pilots/engineers. Feedback obtained from test pilots after having flown the subject aircraft is often that the simulation is an excellent replication of the aircraft in the normal flight envelope.

Following the completion of a flight test campaign, extensive work is undertaken to update the predicted simulation database with flight test extracted data. This then becomes the basis of most simulator training devices. For derivative aircrafts, the simulation database is often composed of increments from such flight-updated simulations of the parent aircraft.

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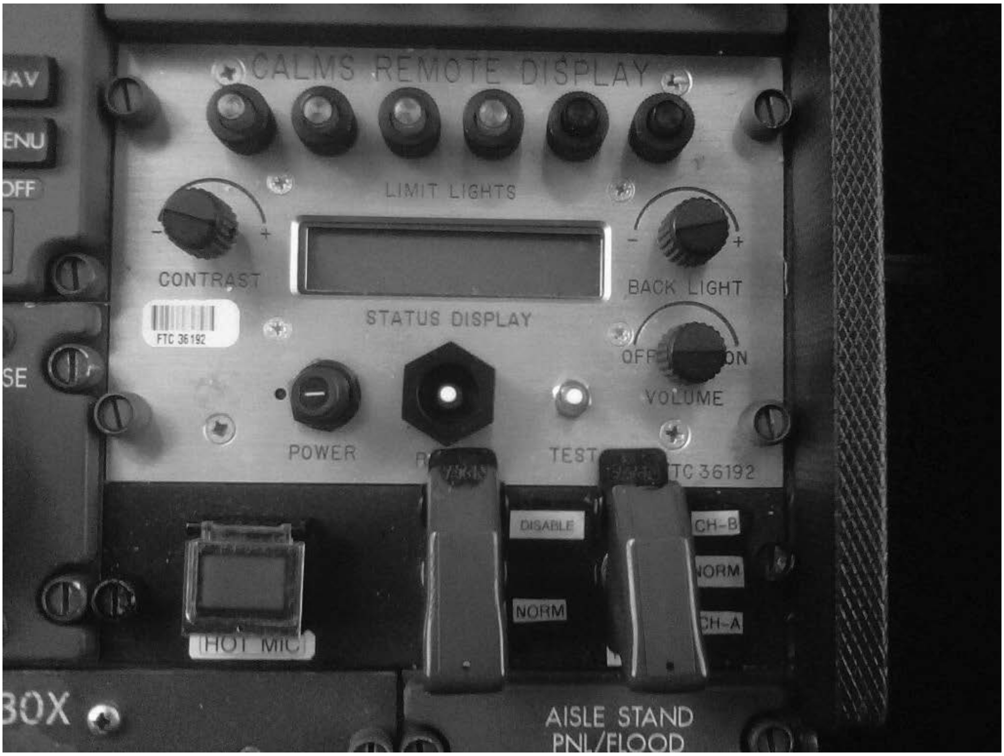

Figure 10. Tail loads monitoring interface.

When operating beyond the normal flight envelope, including into the stall and especially the post-stall regimes, the simulation may provide adequate guidance. However, it is very difficult to rely on the simulation for 100% accuracy in these areas.

Flight test instrumentation has continued to evolve over the last century. Today's large transports record thousands or perhaps tens of thousands of channels of data – both from analog sources and digital bus traffic.

In addition to the standard displays available to the flight crew on the flight deck, flight test unique displays are also common. These devices can display data which is helpful for the conduct of the flight test as well as for situational awareness. Examples of these bits of information would be the real-time display of stall deceleration entry rate, and the digital or tape display of normal load factor.

Stalls also typically require special instrumentation to monitor horizontal tail loads which can become elevated approaching limit load during stalls and recoveries from stalls.

2.1 LADS (pilot data cueing)

Boeing uses a data visualisation tool, called LADS (Labview Airplane Display System) that can provide data to the flight crew to aid in their situational awareness during flight test as well as to provide data useful in the conduct of certain test points. This data is tailored on certain page formats that are maneuver-specific (see Fig. 9). For instance, normal load factor and airspeed or Mach number error are useful to aid in flying wind-up turns. Airspeed deceleration rate and angle-of-attack are useful during the conduct of stalls. Sideslip angle and rudder pedal angle are useful during steady sideslip test points.

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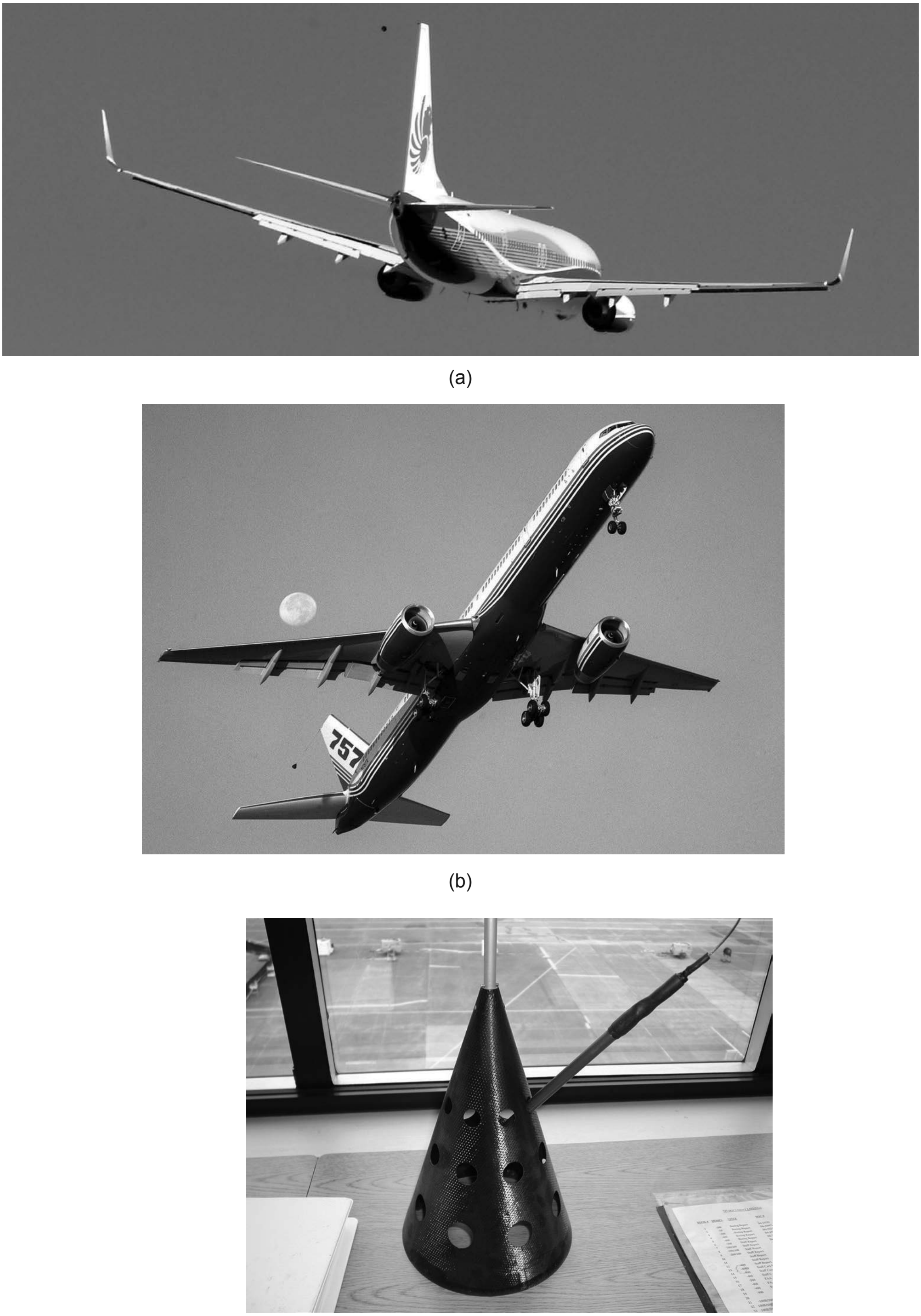

(a)

(b)

(c)

Figure 11. Trailing cone illustrations.

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2.2 CALMS (tail loads)

Boeing uses a horizontal tail loads monitoring system, referred to as CALMS (Complex Amplitude Load Monitoring System), during stall testing. This system utilises strain gauges as well as accelerometers to monitor for limit loads. The display visible to the test director and the flight crew has both a digital number as well as a set of six lights (see Fig. 10). The digital number reads the percentage of limit load from the various inputs. The six lights are comprised of two green lights, two amber lights, and two red lights. The first light illuminates at 70% of limit load and the last light indicates 100% limit load. An occurrence of all six lights necessitates a return-to-base.

2.3 Trailing fin cone static source

During development testing on any given model, there is a need to measure static pressure from an independent or ‘true’ source. One way of getting this static pressure measurement in use today is by deploying a trailing cone. The methodology is to use a retractable cone that protrudes from the upper tip of the vertical tail (see Fig. 11).

Figure 12. Flight test pitot installation.

Figure 13. Flow cone installation.

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2.4 Low speed pitot (Rosemount)

A low speed pitot (manufactured by Rosemount) is installed on aircraft in place of a standard Pitot during stall tests in order to gather precise total pressure information at very high α and thus better calibrate the aircraft anemometric system (see Fig. 12). It is bigger than nominal pitots, fitted with specific holes.

2.5 Flow cones

Flow cones are used as a means to visualise, in real time, the airflow separation on different parts of the wing during a stall. The cones will become unstable and reverse direction when the airflow over them is disturbed (see Fig. 13).

2.6 α probe installed on horizontal tail

A specific α vane is used to identify the local horizontal tail incidence during a recovery of a stall and check the margins towards horizontal tail CL_{MAX} (see Fig. 14).

2.7 Ice shapes

Ice Shapes are installed and fixed on leading edge from wings, horizontal and vertical tails in order to investigate stall characteristics in case of ice accretion (see Fig. 15). The shape and thickness of these devices are computed in accordance to the regulation (FAR/CS-25) corresponding to ice accretion during either the most unfavorable case (generally holding pattern) or take-off phase.

2.8 Tail booster

A tail booster can be installed particularly on aircraft fitted with a T-tail which are more prone to deep stall. It consists of a pyrotechnic device fitted on the tail allowing, in case of deep stall, to create an aircraft nose-down moment to recover horizontal tail and elevator efficiency (see Fig. 16).

Note: Deep stall corresponds to the blanking of the horizontal tail by wake off the wing at high α, resulting in total loss of elevator efficiency.

2.9 Flight test engineer real time visualisation

From the onboard Flight Test Engineer (FTE) station, stall execution can be monitored in real time through $CL(\alpha)$ curve visualisation, dedicated parameters traces (α, vertical load factor to call the 'g-break', spoilers extension…), control command activity and Primary Flight Display (PFD) (see Fig. 17).

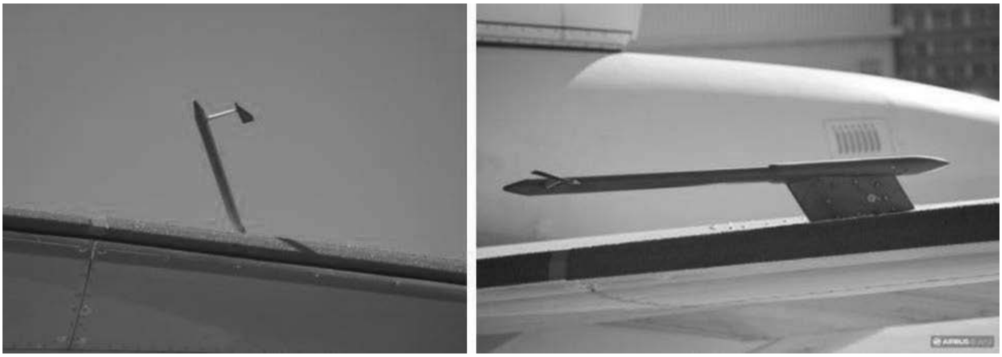

Figure 14. Horizontal tail α probe installation.

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Figure 15. Ice shape installation.

Figure 16. Tail booster installation.

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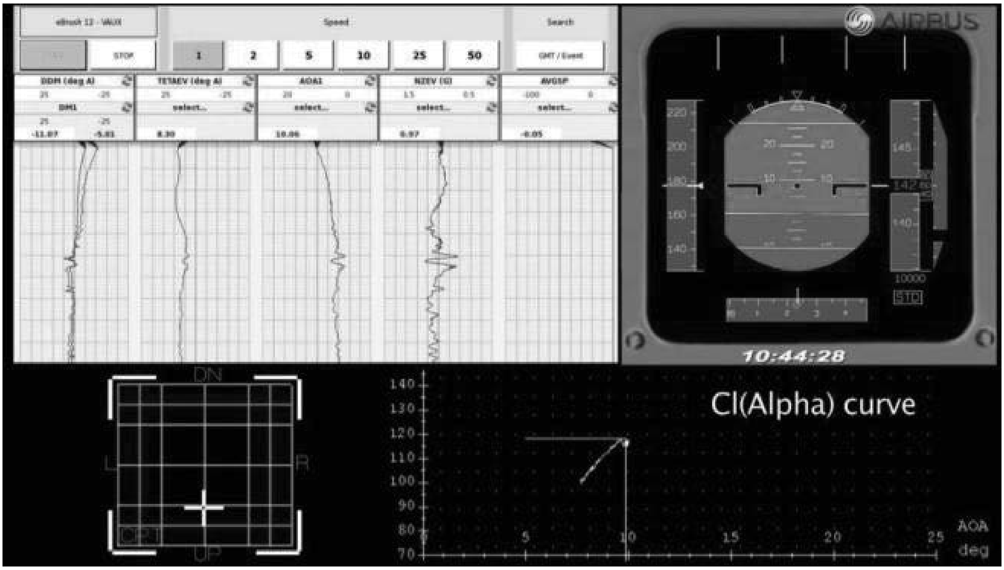

Figure 17. Flight test engineer display.

3.0 FLIGHT CREW TECHNIQUES FOR STALL TESTING AND RECOVERY

3.1 Stall protection overview

All large aircraft will stall. To help prevent this, many features have been added to the aircraft that provide both passive and non-passive detection, warning and in some cases stall prevention. There are too many model specific features to discuss in this short paper but the following description is adequate when speaking in generic terms.

The minimum maneuver speed is represented by an amber band on the pilot's primary flight display, PFD. The top of the amber band at high altitude typically provides a 0·3g margin to low speed buffet and options available for an alternative approved maneuver capability depending on customer requirements. At low altitude the amber band represents a 0·3g margin to stick shaker with the flaps down or VREF + 80 with the flaps up, whichever is less. When the autothrottle is armed but not active it will 'wake up' and automatically advance thrust to protect the top of the amber band. If the autothrottle switches are turned off an 'AIRSPEED LOW' caution message is displayed (halfway into the amber band) and a pitch limit indication (PLI) will appear on the PFD (see Fig. 18) to indicate the pitch limit for stick shaker. The nose up trimming function is inhibited. If the aircraft continues to slow down then the stick shaker will activate at approximately five knots prior to stall (ref FAR Part 23.207) and the autopilot (if engaged) will begin a descent to control a speed which corresponds to the stick shaker alpha –1° (note: this logic is dependent on the phase of flight). Finally, if the pilot disconnects the autopilot and attempts to return to level flight the feel force on the control column will increase dramatically in an attempt to 'discourage' the pilot from continuing to pull (see Fig. 19). From the pilot's point of view this looks like a stick pusher. Airbus aircraft and the 787 have added features which limit the angle-of-attack to approximately CL_{max} making these aircraft remarkably stall resistant in the NORMAL flight control mode. These features must be temporarily disabled prior to testing.

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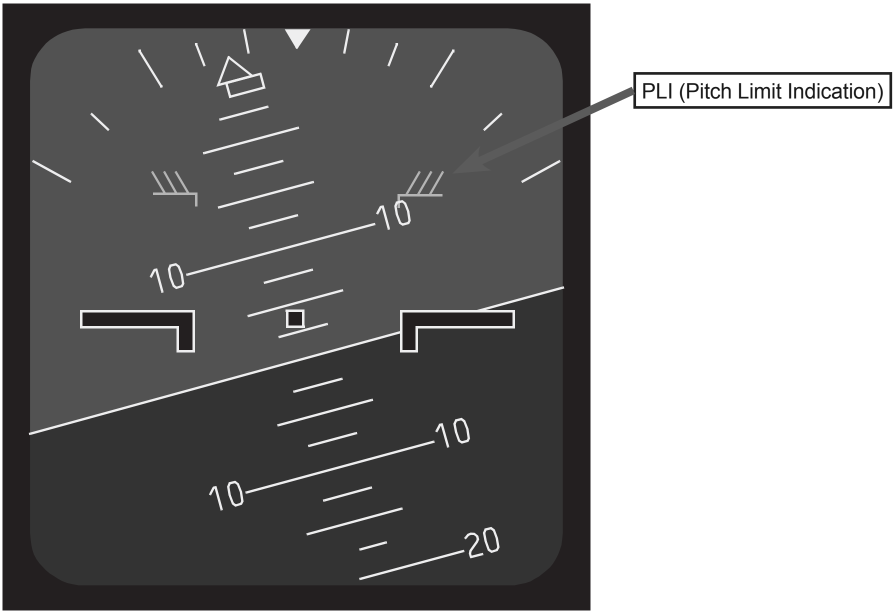

Figure 18. Pitch Limit Indicator.

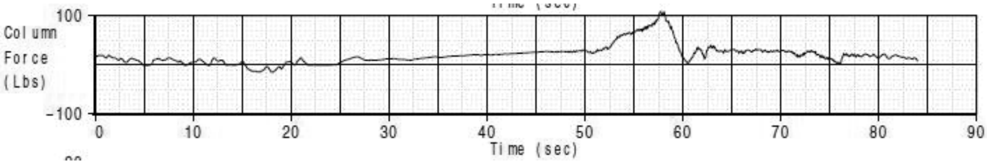

Figure 19. Column force time history.

3.2 Expected 1g stall characteristics of large aircraft

Typical stall characteristics of transport aircraft in 1g non-accelerated flight (ref FAR Part 23.201) begin with the onset of initial buffet. This is best described as light airframe buffet which begins a few knots prior to stick shaker. As the aircraft approaches CL_{max} the level of buffet generally increases and can become severe to deterrent in nature. It is not uncommon to see buffet with a repetitive load factor of ±1g in the vertical direction and ±·5g in the lateral direction (see Fig. 20). It feels similar to driving an automobile across railroad ties. Buffet on large aircrafts tends to be much greater than experienced in smaller aircraft. This is due to wing airflow separation and turbulent airflow vortices which produce a strong excitation forcing function on the wing. This excites the fundamental frequency of the fuselage leading to large vertical and horizontal deflections. It can be very evident on the flight deck, where anything not securely tied down, such as an errant water bottle, can get hurtled into the air.

Stall identification is deterrent buffet for most recent models in the clean wing configuration. With flaps down, however, stall identification is either full column deflection to the control stop for two seconds, with no further pitch increase, or a nose down pitching moment that cannot be readily arrested.

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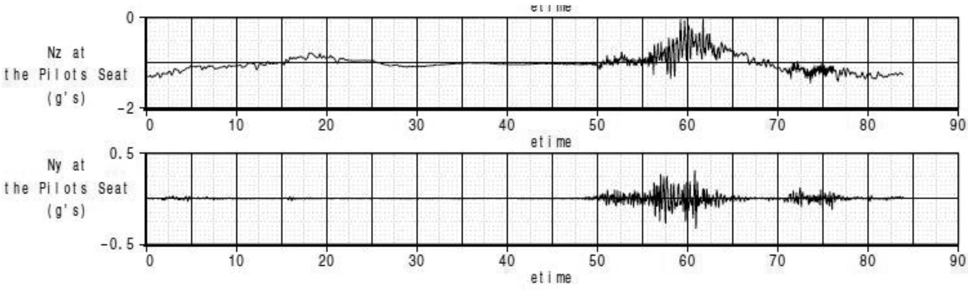

Figure 20. Deterrent buffet time histories.

3.3 Recognition and recovery techniques for low altitude stalls

Low altitude stall behavior and recovery is fairly straight forward, ‘assuming the pilot understands aerodynamic fundamentals applied to large aircrafts’ (Ref. 1) and the critical nature of correct and timely pitch control. For example, at some flap, weight and CG configurations, the control column or stick can be pulled and held at aft stop thereby limiting the pitch up authority. In this condition the aircraft may appear to be somewhat stable and in control but other indications such as buffet (heavy at times), a high sink rate and a lack of roll control may indicate that it is actually stalled (Ref. 2). This was pointed out a few years ago by the industry airplane upset recovery training aid team. They stated that ‘Even if the aircraft is in descent with what appears like ample airspeed, the wing surface can be stalled’ (Ref. 3). In other configurations the nose down pitching moment may increase until it can no longer be opposed by the pilot with up elevator. In fact, if the pilot holds the elevator, the aircraft may stall, recover, and stall again in porpoise like motion losing altitude at a tremendous rate.

Recovering from a stall is straight forward and is in fact nearly identical to that used in general aviation aircraft. First and foremost the angle-of-attack must be lowered using elevator. During recovery the buffet level can momentarily increase, however, this tends to be transitory in nature. Engine thrust can also aid in stall recovery but, the timing of its use is absolutely critical. If thrust is added too soon, the upward pitching moment of under wing-mounted engines may cause an increase in the angle-of-attack. Under certain conditions it may even be necessary to reduce thrust to prevent the angle-of-attack from increasing (Ref. 3). Regardless of when or if thrust is used, the altitude cannot be maintained and should be of secondary importance to reducing the angle-of-attack with the elevator (Ref. 2). Also, of secondary importance, is the restoration of normal pitch and roll attitudes. Flight testing has shown that a properly conducted stall recovery at low altitude using the elevator as the primary control typically results in minimal altitude loss.

3.3 Recovery techniques for turning stalls

Most transport aircraft will remain fully controllable in the roll axis right up to the stalling speed. In turning or accelerated stalls there is a characteristic in some aircraft, such as the 777-200, to roll out of the turn near CL_{max}. If desired, however, there is enough roll power to maintain the bank angle up to CL_{max} and beyond.

A sequential two axis recovery works best for turning stalls. For example, the stall is broken first by lowering the angle-of-attack with the elevator. If difficultly is encountered lowering the nose it may be necessary to apply full column and pitch trim (Ref. 4). As the airspeed begins to build the aircraft is smoothly rolled back to the horizon to complete the maneuver.

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A dual axis stall recovery, the simultaneous use of pitch and roll, is not recommended because (1) the ailerons and spoilers may not be effective at very low speeds (above CL_{max}) and (2) doing so increases torque stresses on the tail.

Rudder is not normally required for stall recovery on aircraft with a conventional tail. In fact, it can worsen loss of control due to sideslip. Rudder also adds high asymmetric rolling and yawing moments on the vertical and horizontal tail when uncoordinated or used excessively. Never say never though because there have been many documented cases of deep stall (primarily a problem of T-tail designs) where rudder was absolutely critical in the safe recovery. One example is a near fatal 727 flight test that occurred in 1963 where Captain Lew Wallick used aileron and rudder to rock the aircraft out of a deep stall (Ref. 5).

3.4 Anticipated differences between low altitude and high altitude stalls

High altitude stalls are discussed in Supplement #1 to the *Airplane Upset Recovery Training Aid* which says ‘Altitude has no relationship to the aerodynamic stall’ (Ref. 3). This is true but flight testing has shown there are additional challenges brought about when doing stall testing above FL250. First, there is a significant loss of engine performance. This negates the use of thrust for recovery (Ref. 3). Second, Mach effects will reduce the stall angle-of-attack and the pitch attitude (Ref. 3). Because of this, test pilots should be very wary of approaching pitch attitudes that were used during low altitude stalls. Third, the time constant for recovery is much longer at high altitude, meaning much more altitude will be lost.

3.5 Recovery techniques for high altitude stalls

There are three key skills test pilots must master when engaging in stall testing at high altitude: (1) stall identification and recognition; (2) knowing how to break the stall; and (3) being willing to trade altitude for airspeed. Stall identification can come in the form of buffet, a high sink rate, and a reduction of pitch authority or a lack of roll control (Refs 1,2,3,4). The elevator remains the primary flight control for recovery but extreme care must be used to prevent secondary stalls from occurring. For example, once the nose is lowered and airspeed begins to build a gentle continuous pull on the elevator works best. Since the airflow over the wing is marginally attached it can separate if too much load factor is applied. One useful flight test technique is to put the nose on the Pitch limit Indicator then smoothly follow it back to the horizon as the speed increases. This yields repeatable results while minimising the altitude loss. Patience is a virtue because several thousand feet of altitude may need to be traded for airspeed at high altitude.

3.6 Instrument failure discussion

The amplitude of buffet near CL_{max} can be less than that seen at low altitude (see time history plot of buffet at stall). In fact, low speed buffet has been misinterpreted by flight crews as high speed buffet. This tendency is exacerbated in aircraft with unreliable flight instruments. Flight testing has shown that the pitch indicator or an angle-of-attack meter can be used, in an emergency, to safely maneuver an aircraft back to controlled flight. Knowing typical pitch and power settings appropriate to the phase of flight cannot be over stated. Once the aircraft is back in control all the flight instruments can be methodically cross checked to determine which are reliable and which have failed.

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4.0 FINAL PREPARATION AND TEST CONDUCT

4.1 Transport aircraft stall investigation

4.1.1 Safety considerations

The aircraft should be properly prepared for stall testing. Flight Test Instrumentation (FTI) should include precise calibration of indicated airspeed, angle-of-attack (α), and angle of sideslip (β). Because outside references are frequently used by the pilot to insure a smooth increase in angle-of-attack from level flight, the instruments used by the flight crew to observe α and β must be near the pilot's line of sight. A special probe to measure angle-of-attack should be fitted to the Trimmable Horizontal Stabiliser (THS) and properly calibrated. The aircraft cabin must be prepared in the same manner as the aircraft is prepared for negative g testing – it must be swept for debris and foreign objects, and all personal items used by the crew must be either stowed or secured while not in use. If the crew needs to unload quickly, or if the aircraft unloads unexpectedly , there is high probability that personal items (such as water bottles), could become airborne in the cockpit or cabin and cause injury.

The pre-flight briefing must include an appropriate review of predicted aircraft stall characteristics and limitations (α, β, Nz, engine, etc). Limits specific to the test, such as maximum roll, maximum yaw, and yaw damper operation at the stall should be discussed. The role of the person monitoring a specific parameter, and the communications to be used if that parameter exits specific limits must be defined. Discussing these details in the briefing and using them in flight will lead to fewer surprises in testing. For example, the Flight Test Engineer (FTE) will normally call 'Break!', when the Nz trace begins to drop. However, if something abnormal occurs, the word 'Recover!' is used, and can be called by any member of the crew. Each crewmember must have a fully operational headset with 'hot mic' capability. Since initial stall testing is considered experimental, it is rated at the highest level of risk and is normally flown with minimum crew. An additional member of the crew is the telemetry chief on the ground, who is monitoring on 'hot mic', and listening to ATC communications.

4.2 Weather conditions and altitude block

Depending on time of year and time of day, conditions for stall testing are seldom ideal. Most important is a nicely discernible horizon, allowing the pilots to maintain attitude awareness with peripheral vision cues. Cloud conditions should be such that a sufficient cloud clearance is available to maintain VMC during stall entry and recovery, and during repositioning turns. Depending on the purpose of the stall, aircraft configuration, and stall entry technique, an altitude loss of 1,500 to 2,500ft can be expected. Some scattered high clouds are actually desired, so the pilot can see very small motions in α and β as angle-of-attack is increased. While heading into the sun is not desired, poor sun conditions will occur at some time during the flight. Every effort should be made to acceptably shade the pilot's eyes, specifically during recovery, and to be sure that deep shadows in the cockpit do not degrade the ability to read key instrumentation.

The desired altitude block for stall testing to measure Vs1g is the range from 14,000ft down to 8,000ft (over flat terrain with 7-8,000ft of ground clearance). To obtain altitude and mach effects on stall angle-of-attack, some tests will be performed at lower and higher altitudes.

4.3 FBW flight control laws to be tested

Stalls are normally performed in a specially developed version of direct law, called stall law, which is where stick commands are proportional to control surface movement. In cases where

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control is expected to be difficult during recovery, a super direct law is available, where control deflections are not limited, and will allow control deflections which could impose ultimate loads on the structure. Direct law, in contrast, restricts control deflections so that limit loads are not exceeded, and is designed as a ‘safe flight control’ mode to return and land from a degraded control situation. Stall law is established through the FTI and inserted into the digital data bus of the aircraft. In production aircraft, there are gain changes appropriate to direct law (low gain close to neutral stick, with increasing gain close to full back stick), which must be considered. Stall law with constant gain, makes the response a bit sensitive about the neutral stick position but makes any aerodynamic anomaly detectable by the pilot. In the roll axis, stall law inhibits spoiler deflection with small lateral stick deflection so as to not jeopardise maximum lift measurement at the stall.

4.4 Pre-stall checklist

Before beginning stall testing, whether it is the initial stalls of a new design, or stall testing for experimental and developmental work, a specific checklist has been developed and incorporated in the Flight Test Guide (FTG):

1.	Pitch Trim	Set For 1·23Vs1g (at idle thrust)
2.	Flight Controls	Stall Law
3.	Ignition	On (if relevant)
4.	Fuel Balance	Minimum Possible L/R Delta
5.	Configuration	Established
6.	Altitude	Sufficient
7.	Thrust	Idle (or as required by the test order)
8.	Rudder Trim	Set for hands off, beta checked near zero
9.	Predicted α at stall	Briefed for each configuration

4.5 Roles and responsibilities – flight crew and telemetry

Each member of the flight crew is assigned a dedicated area of responsibility. Some of the subjects are defined by crew position, and others are specifically assigned. The FTE has the overall responsibility for conduct of the mission, which includes detailed pre-flight planning to establish stall boundaries for the weight, cg, and Mach number to be flown. The FTE will utilise the appropriate FTI configuration, and in the case of parameter loss, make the final decision if the instrumentation is acceptable or not. The FTE will conduct the briefing and assign the key parameters for each crewmember to monitor. The FTE is responsible for loading the software configuration that puts the aircraft into Stall Law without shutting off essential flight control computers. At the FTE station, the primary parameters to be monitored over the intercom during stall testing are CL and Nz. With those two parameters, the FTE can determine the stall by a well-defined g-break and loss of lift coefficient. Because the top of the $CL(\alpha)$ curve is relatively flat in large transport aircraft, the loss of lift and g-break may not be sensed by the pilots. In all cases, it is the FTE’s responsibility to call ‘Break!’ at the stall, as the signal for the pilots to initiate stall recovery.

The Test Flight Engineer (TFE in the cockpit jump seat) is responsible for the overall mechanical status of the aircraft, and will advise the crew if the status of the aircraft and systems is acceptable for the stall test. In addition, the TFE closely monitors both α and β, and is responsible for calling

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out α in 0·5-degree increments to keep the pilots audibly informed of α and α rate. Since the TFE is focused on α, he has the responsibility to say 'Recover!' when α reaches the pre-briefed limit (a small margin above where the stall is predicted to occur).

The Test Pilots will insure that the aircraft is properly in trim. A very small amount of rudder trim is acceptable to keep wings level without aileron input. On top of specific roll kinematics, this helps to avoid any spoiler extension, which invalidates the test point. Beginning at the top of the altitude block, thrust is brought to idle and in stall law, the aircraft is trimmed hands off at a speed equal to 1·23 Vs1g. Although manual trim is very precise, it takes patience and some altitude loss with thrust at idle to put the aircraft perfectly in trim at the proper speed. When the trim point is achieved, the stall series can be flown without touching the manual trim control. Obviously, before any 'Break' or 'Recover' call, if the pilot is uncomfortable with anything felt or observed, recovery should be initiated immediately to share those impressions with the team, before any progress toward the stall is resumed.

4.6 First stalls in a new aircraft

For a new aircraft, the initial stalls series is normally performed with a mid-cg (a good compromise between stability and maneuverability), since the main purpose is to verify the aerodynamic predictions. After properly trimming and climbing to the top of the planned altitude block, a 1-knot/sec deceleration is performed to a pre-planned α, followed by recovery. This provides the build-up in α toward the stall, and consistent data to verify that at each step, positive control is available for recovery. Stall Law does not allow full elevator deflection, and the initial setting for maximum deflection in Stall Law may not provide enough pitch authority to reach the stall α. In this case, a small amount of nose-up trim (not more than what is needed to fly at 1·13 Vs1g, which is the maximum allowed for certification) can be applied to provide the necessary pitch authority.

When trimmed for 1·23 Vs1g , and engines at idle in a stable descent, it is possible to use a very small amount of rudder to maintain wings level during the approach to the stall. The small amount of sideslip induced will not affect the results. In all cases, sideslip must be carefully monitored. If it begins to drift, or reaches an unacceptable limit (4-5°), recovery should be initiated. The non-flying pilot should have the ECAM (Electronic Centralised Aircraft Monitoring) Flight Control systems page in view to check for spoiler deflection. If there is any spoiler deflection prior to the stall, the test should be stopped and repeated.

A deceleration rate of 1 knot/sec is best visualised by a 10-knot speed trend vector on the PFD or HUD. To maintain a constant rate of deceleration, the pilot should concentrate on constantly increasing backpressure. While it is desired to achieve a true 1g-stall condition, the stall is performed with a small rate of descent to allow a constant deceleration rate. A small amount of pitch up may be encountered during the approach to the stall α. It is generally best not to quickly counter the pitch-up, but to continue to seek a constant deceleration rate. In the case where pitch-up exists over a large range of α, less back stick can be used.

As α increases, an increasing level of buffet will be felt, particularly in the clean configuration. At the stall, buffeting will be at the deterrent level, and can be quite substantial at the pilot station. Stall recovery should be accomplished with smooth but positive nose down elevator input to reduce angle-of-attack. If a wing drops just before or at the stall, it can be recovered with aileron as α is being reduced. The use of rudder should be avoided unless necessary to reduce sideslip. Pitch attitude will be 5 to 10° nose down when recovered, and typical altitude loss is 1,500-2,500 feet.

With some aircraft, if the stick is aggressively moved forward, the horizontal tail will pass through the stalled wake of the wing, which has not yet reacted to the change in angle-of-attack demanded by the pilot. This can put unacceptably high loads on the horizontal tail. Smoothly

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applying forward stick will fly the aircraft out of the stall, and keep horizontal tail loads to an acceptable level.

During recovery, after quickly checking engine status, either the TFE or non-flying pilot should monitor α. Even with idle thrust, airspeed will increase above trim speed and forward stick will be required to control pitch attitude without changing trim. To return to level flight and subsequently to climb, some back stick will be required. This will unbalance the trim condition and allow angle-of-attack to increase. Increasing thrust during the recovery will also unbalance the trim condition. With engines mounted under the wings, a nose up moment is applied with increasing thrust. Both aft stick input and thrust application during recovery will tend to increase α, and could trigger the stall warning if α is not carefully monitored.

4.7 Initial stalls at forward CG

The major concern with forward CG is the risk of tail plane (THS) stall. The risk is highest during stalls with the flaps fully extended, because the flow is deflected downward, increasing the α seen by the THS (which is negative with respect to the wing). During recovery, the local angle-of-attack of the THS will increase rapidly. Even though the THS lift curve slope is relatively flat at high THS angle-of-attack, the reduction of THS down-lift during stall recovery can cause a diverging nose down situation with catastrophic results.

During stall testing, an α probe is installed on the top surface of the THS to measure angle-of-attack. The angle-of-attack characteristics of the THS are carefully recorded during stalls at mid CG. THS angle-of-attack is carefully monitored with increasing flap deflection and compared with predicted results.

The progression of stall testing at forward CG begins in the clean configuration, then continues with increasing flap deflection. Although it is not a part of the normal stall campaign, at increasing values of α a pushover maneuver is performed to measure the change in angle-of-attack at the THS. The pushover inputs begin small then increase in deflection. With flaps fully extended, the pushover will be performed progressively toward 2/3-stick deflection to determine the margin to THS stall. It is desired to have nominally 2° of margin to THS stall.

4.8 Stalls at aft CG

The major considerations for stalls at aft CG are lateral departure, pitch-up, and nose down elevator authority with full thrust applied. At aft CG, there is less resistance to lateral departure, and as previously mentioned, angle of sideslip must be monitored carefully and recovery started immediately if pre-briefed limits are exceeded.

If the tendency to pitch up is present when approaching the stall, it will appear worse with aft CG. The approach to the stall must be performed very slowly in each configuration to determine the effects of pitch up. In the same manner as performing stalls for the first time, tests are repeated with recoveries at increasing α, and pitch authority at recovery should be carefully monitored. In the case of a strong pitch up tendency, the stall warning α must be set such that enough margin to stall exists to consider reaction time so that recovery is initiated before α becomes unacceptably high.

Finally, the amount of pitch authority at the stall can limit the operational CG. The worst case is nose down authority at low speed to counter the nose up pitching moment produced with TOGA thrust applied. In all configurations, there must be enough pitch authority to positively reduce α, even with TOGA thrust

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4.9 Certification stall requirements for FBW aircraft

Stalls for certification are performed initially at forward CG to determine the stall speeds that will be used for speed computations. For FBW aircraft, stalls must be performed in normal law to demonstrate the ability to control the aircraft throughout the stall and recovery, should an inadvertent stall occur despite the protections (for example, in the case of severe windshear). Because the angle-of-attack limits in Normal Law prevent the aircraft from stalling, a specific version of the Normal Law is created which shifts the limiting α to a higher value (usually by 10°). Additional stalls are then performed in degraded control laws, in all configurations, and at aft CG. For stalls in augmented control laws, it is essential to place the stick forward of neutral during recovery, since the C* law is g-demand law, and neutral stick is a 1·0g command. If the stick is not placed forward of neutral, more nose up elevator than desired will be applied at the stall break.

Stalls at high altitude are not required in the classic sense. Instead, a series of wind-up turns are performed at constant Mach number to determine buffet boundaries. This determines how much g the aircraft can sustain before the aircraft begins to buffet, which is useful to the operational pilot when flying at maximum altitude for a given weight. If the aircraft is flown too slowly, there will be an increase in buffet to the point that altitude will have to be sacrificed to regain speed. The same holds true if the aircraft enters turbulence which applies g loads higher than the buffet boundary for a given Mach/altitude/weight combination.

4.10 Stalls at high Mach number

Stalls at Mach numbers normally associated with cruise flight (0·78-0·89 Mach) are not possible in level flight because Mach number decreases as the aircraft decelerates. This increases CL_{max} and effectively increases the margin to the stall. It is difficult to tell when the test point will end, because the end point is shifting. Angle of attack limits for safety are equally difficult to predict. As the aircraft decelerates, the level of buffet increases significantly and rapidly becomes deterrent buffet. The g-break may be difficult to recognise, either from the g trace, or the CL trace, therefore a rapid change in vertical velocity may be the first good cue of the stall. Pitch-up may be present during deceleration, complicating the pilot's ability to smoothly control pitch with increasing levels of buffet.

Recovery from stalls at high Mach begin with a smooth but positive nose-down input to a modest nose down pitch attitude (–5 to –10°). Since flight path angle is becoming more negative, a reduction in α should be confirmed before the nose down input is reduced. A reduction in buffet to low or no buffet is a good sign. The pilot should expect the nose to move further down when the pitch-up characteristic disappears, and the pilot will have to relax a little nose down pressure accordingly. The nose down attitude should be maintained until a positive speed increase is achieved. Acceleration will be slow due to the strong effects of induced drag until α is reduced. Thrust can be used during the recovery, and will moderate the nose-down pitch attitude during acceleration and recovery. However, application of thrust produces a nose-up pitching moment in most cases, and must be countered with forward stick to keep α from increasing again.

When accelerating, Mach will increase and this actually decreases α margin to the stall because as Mach increases, α for CL_{max} decreases (see Fig. 21). If effort is made to pull-up prematurely, the onset of buffet will occur very quickly. The capability to apply any g load during the recovery will be low, and the nose up motion will be quite slow. An altitude loss of 5-7,000 feet can be expected during recovery.

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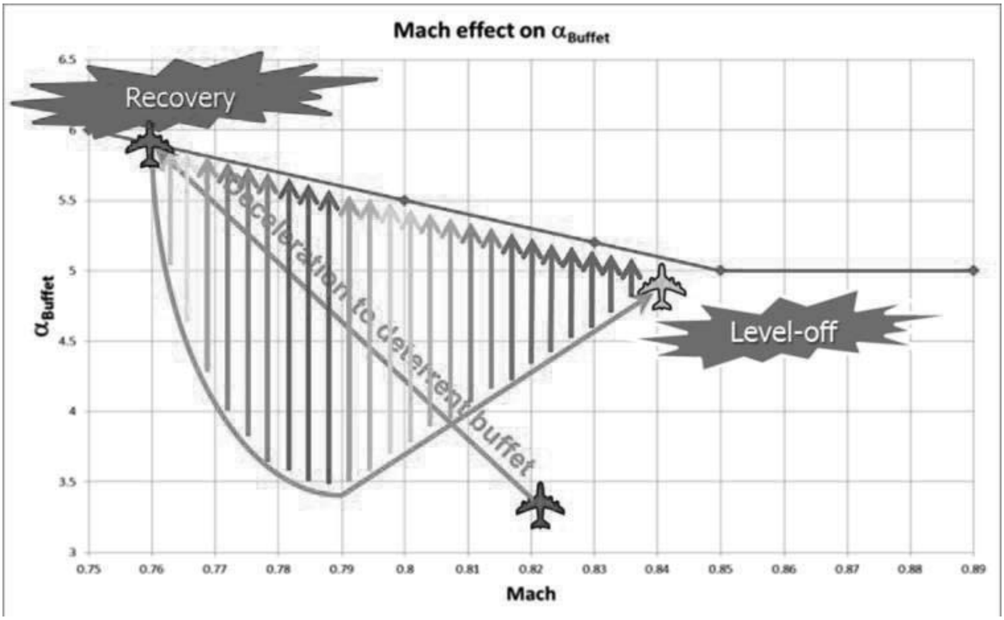

Figure 21. High Mach number stall depiction.

5.0 STALLS IN THE FUTURE

5.1 The future – what's next for stall flight testing

As large transports continue to evolve and become ever-more automated, a few questions often arise about the future.

What about augmenting degraded flight control modes? Currently envelope protection/limiting exist only in normal fight control laws. Could this be expanded to include degraded modes? There are inherent difficulties with this approach as the primary reason for degrading modes is the lack of information that could be necessary for α protection.

Another question could be posed as this, if stall or α limiting becomes 'standard' and is proven to be highly reliable, will stalls cease being demonstrated? Is it possible that aircrafts simply won't be able to be stalled? Are we skilled enough to imagine all possible reasons for aircrafts to achieve high α environments? Most likely there will always be reasons to conduct and certify stalls. We, as pilots and engineers, cannot possibly know or imagine every situation that could excursions into the high α regime.

6.0 SUMMARY AND CONCLUSIONS

In summary, we have discussed how both of our organisations discuss, plan for, and conduct stall flight testing. We've shared insights from both the engineering point of view as well as the test pilot point of view. We've tried to show what stall testing is like from the standpoint of both inside the plane as well as describing flow visualisation of the wing in stall. We've even left you with some questions about the future of this topic.

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The collaboration of our two companies on this paper resulted in a realisation that, while there are some differences in the way each approaches stall testing, the vast majority of things discussed are common. While we may be fierce competitors in the sales arenas around the world, when it comes to flight test safety, there is no competition.

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