Design of an innovative stall recovery device

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Abstract
Stall has been an inherent hazard since the beginning of flying. Despite a very successful stall mitigation strategy and a wide variety of solutions, stall as a phenomenon still exists. This contribution explores the nature and dynamics of stall as a loss of pitch control phenomenon and the remedies that have been developed over time.
This contribution proposes the introduction of a stall shield device. A multi-actor collaborative approach is suggested for the development of such a device, including the technological, control and simulation and operational aspects of the design by involving designers, pilots and investigators in its development. The introduction of the stall shield concept may serve as an example of how serendipity through accident investigation may disclose critical systemic and knowledge deficiencies in aircraft stability and control, leading to systems resilience by innovative solutions.

I. Introduction
From the early days of aviation, stall has been an inherent hazard. Otto Lilienthal crashed and perished in 1896 as a result of stall. Wilbur Wright encountered stall for the first time in 1901, flying his second glider. These experiences convinced the Wright brothers to design their aircraft in a ‘canard’ configuration, facilitating an easy and gentle recovery from stall. Over the following decades, stall has remained as a fundamental hazard in flying fixed wing aircraft. Stall is a condition in which the flow over the main wing separates at high angles of attack, hindering the aircraft to gain lift from the wings. Stall depends only on angle of attack, not on airspeed. Because a correlation exists between loss of lift and minimal airspeed, a "stall speed" is usually used in practice. This is the speed below which the airplane cannot create enough lift to sustain its weight in 1g flight. The angle of attack cannot be increased because at this point, the wing is at its maximum lift production and slowing below the stall speed will result in a descent. Airspeed is often used as an indirect indicator of approaching stall conditions. The stall speed will

vary depending on the airplane's weight, altitude, and configuration. Fixed-wing aircraft have been equipped with devices to prevent or postpone a stall, to make it less more severe or to make recovery easier.
Stall is an umbrella concept that covers various scenarios, aircraft configurations and has seen a wide variety of dedicated solutions.

2. Stall as a phenomenon

In practice, stall may occur under various conditions, configurations and can be caused by various failure modes. Consequently, various stall scenarios exist.

2.1 Stall scenarios

A fixed-wing aircraft during a stall may experience buffeting or a change in attitude. Most aircraft are designed to have a benign stall with characteristics that will warn the pilot. The critical angle of attack in steady straight and level flight can be attained only at low airspeed. Attempts to increase the angle of attack at higher airspeeds can cause a high-speed stall or may merely cause the aircraft to climb. Any yaw of the aircraft as it enters the stall regime can result in autorotation, which is also referred to as a 'spin'. Because air no longer flows smoothly over the wings during a stall, aileron control of roll becomes less effective and may incline the aircraft to enter into a spin. The dangerous aspect of a stall is a limited recovery capability due to a lack of altitude. Such stalls may cause accidents at a low altitude. At high altitude, upper and lower speed limitations become critical as the speed range reduces. The upper limit is defined by structural integrity demands, while the lower speed limits depend on air density and available engine power setting. As stall is reached, the aircraft will start to descend and the nose will pitch down. Recovery from this stalled state involves the pilot's decreasing the angle of attack and increasing the air speed, until smooth air-flow over the wing is restored. The maneuver is normally quite safe and if correctly handled leads to only a small loss in altitude. During training, a pilot is required to demonstrate competency to recognize, avoid, and recover from stalling the aircraft.

A special form of asymmetric stall in which the aircraft also rotates about its yaw axis is called a spin. The net effect is that one wing is stalled before the other and the aircraft descends rapidly while rotating, some aircraft cannot recover from this condition without correct pilot control inputs and loading. The most common stall-spin scenarios occur on takeoff (departure stall) and during landing (base to final turn) because of insufficient airspeed during these maneuvers. Stalls also occur during a go-around maneuver if the pilot does not properly respond to the out-of-trim situation resulting from the transition from low power setting to high power setting at low speed. Stall conditions are increased when the wing surfaces are contaminated with ice or frost creating a rougher surface, and heavier airframe due to ice accumulation.

A specific form of stall occurs while the aircraft is exposed to load factors higher than 1g. This stall is referred to as accelerated or turning flight stall and is typical for military aircraft which conduct their missions under extreme conditions. Modern civil commercial aircraft do not enter these flight regions by the protection of the flight envelope restrictions. Different aircraft configurations have different stalling characteristics. A benign stall is one where the nose drops gently and the wings remain level throughout. Slightly more demanding is a stall in which one wing stalls slightly before the other, causing that wing to drop sharply, with the possibility of entering a spin. A dangerous stall is one in which the nose rises, pushing the wing deeper into the stalled state and potentially leading to an unrecoverable *deep stall*. This can occur in some specific aircraft configurations wherein the turbulent airflow from the stalled wing can blanket the control surfaces at the tail.

Finally, a loss of pitch control may occur due to other causes than aerodynamic stall, but may result in a stall. Such stall modes origin from technical failure of rudders, exceeding the allowable c.g. range due to shifting cargo or fuel imbalances, damage to pitch control rudders by external damage such as space debris or bird strikes, loss of critical air data due to pitot port blockage by frost, foreign objects or insect intrusions.

2.2 Air accidents related to stall

Despite all efforts to reduce stall and deep stall to acceptable levels of occurrence, such events still happen occasionally in the commercial aviation community. They raise concern about their emerging complexity, dynamics and impact on public perception on safety of aviation. Such events have been subjected to major accident investigations and serve as triggers for change throughout the aviation industry.

These events have clarified specific failure modes and conditions. Most recent cases that have fuelled discussion on potential stall causes are Turkish Airlines TK 1951, Colgan Air 3407 and Air France AF 447.

3. Aircraft configuration

3.1 Swept wings

In particular swept wings are sensitive to flow disturbances by a phenomenon known as spanwise flow. This flow results from the sweepback of the wing where the thickening of the boundary layer near the tip of the wing causes a reduction of the maximum lift capability, compared with a two dimensional flow. At reaching the point of maximum lift coefficient, for straight wings with a constant airfoil section and without twist, initial stall would be expected to occur near the tip of the wing. For swept wings with the tip of the wing swept to the rear, the net lift distribution moves forward. Further increase of the angle of attack would create inward progression of the stall, causing the plane to pitch up, leading to more stalling of the wing. Pitch up at stall is a highly undesirable flight characteristic, which is paid much attention to during the design and configuration arrangement in the development of a new aircraft. Such behavior is in contrast with straight wing aircraft that have inherent stability at stall and pitches down to a lower angle of attack back into an unstalled and fully controllable flight condition.

The solution to this stall problem took many forms, dealing with the aerodynamic design of the wings and stall avoiding or reducing devices, such as wing fences or notches to the leading edge. Modern solutions, driven by the need for shorter take off and landing than early large jets, have largely resolved the problem by the introduction of leading edge slats and compound trailing edge flaps.

Stall however, not only depends on the wing-alone stalling characteristics. Stalling and subsequent pitching characteristics depend on the aircraft configuration. The longitudinal and vertical position of the horizontal tail with respect tot the wing is particularly important.

3.2 T-tails

In general aviation with a T-tail configuration, the elevator is above most of the effect of downwash from the propeller, as well as the airflow around the fuselage and wings during normal flight conditions. Operating the elevators in this undisturbed airflow allows control movements that are consistent throughout most fly regimes. T-tails have become popular with light aircraft, because it removes the tail from the propeller wake or exhaust blast of the engines. Especially with sea planes and amphibians the horizontal surfaces are as far from the water as possible.

The configuration of small business aircraft favors an aft positioning of the engines mounted on either sides of the fuselage close to the tail. The size of this category of aircraft does not permit a mounting of the engines underneath the wing due to the restricted ground clearance and access comfort. In addition, during flight, passenger comfort is increased when the noise of the engine is at the aft, behind the passenger compartment. This positioning of the engines favors a T-tail configuration.

In the development of large commercial jet engine aircraft the T-tail has become a popular configuration. Its advantages included clean wing airflow without disruption by nacelles or pylons and decreased cabin noise. At the same time, placing heavy engines that far back created challenges with the location of the center of gravity in relation to the center of lift, which was at the wings. To make room for the engines, the tail planes had to be relocated to the tail fin, which had to be stronger and therefore heavier, further compounding the tail-heavy arrangement. T-tails also require additional design considerations to encounter the problem of flutter.

The high load on the vertical stabilizer, caused by the positioning of the horizontal control surfaces at the top of the tail, creates additional momentum arms on the vertical tail. This must be compensated by an increased stiffness of the vertical tail fin and consequently, a weight increase.

In applying T-tails, during the majority of regular flight conditions, the horizontal tail planes are not influenced by the wake of the propellers. This exposure of the tail planes to the actual airspeed instead of the accelerated air flow of the wake causes a higher deflection of the rudder in order to achieve a similar pitch control force. Since the force on the elevators is proportional with the air speed, at high speeds a higher force has to be executed. Consequently, a T-tail configuration requires a higher control force on the rudders than another configuration. Alternatively, with an equal deflection of the rudder as in other configurations, a larger tail surface is required to achieve a similar pitch angle. In addition, in achieving an equal pitch momentum, the pitch forces required in a T-tail configuration are higher because the momentum arm is shorter. In addition, the positioning of heavy engines at the back of the aircraft creates an aft positioning of the center of gravity, reducing the momentum arm of the tail surfaces to the cg. Fluctuations in the cg must be compensated by a careful trim of the elevator, creating an induced drag penalty. While a T-tail configuration has considerable advantages regarding clean wing

aerodynamics, passenger comfort and noise footprint, the configuration comes with a penalty of a heavier construction, additional weight and stall sensitivity as an inherent hazard.
In applying a swept wing configuration, at higher angles of attack closing in on the stall angle, the aerodynamic center of the main wing will travel forward, creating an additional negative momentum that has to be compensated by the elevator (Obert 2009).

3.3 Cm-alpha diagram

The dynamic longitudinal behavior of an aircraft depends on the ability to recover from a stall and is expressed by the relation between the pitching moment and angle of attack.
In order to correct immanent stall at high angles of attack, a strong nose-down pitching moment is required. If such a moment is not produced, the angle of attack will increase until the tail plane becomes immersed in the wake of the separated flow of the wing (1). At such high angles of attack, the airplane will rotate further due to positive values of the moment coefficient (2). It will remain unstable and continue to pitch up until a new equilibrium is achieved at a very high angle of attack (b). Such equilibrium will be achieved at very high angles of attack because the pitching moment will become negative again. Due to the decreasing lift on the wings on these very high angles of attack, this maneuver may result in a 'flat spin' from which it is very hard to recover. The stability and controllability particularly of aircraft with T-tail configurations require very careful design to prevent the aircraft from entering such a 'deep stall' or 'locked-in stall' situation.

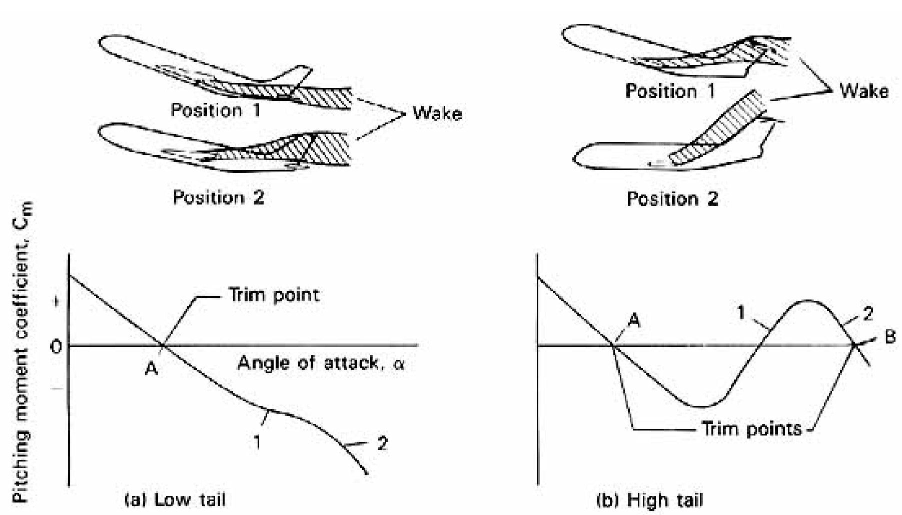

Fig 1. Cm alpha for large angles of attack

4. Stall devices.

4.1 Stall mitigation devices

Over the years, a wide range of devices has been developed to prevent, postpone or recover from a stall. Although a distinction is required between the various configurations, several generic aerodynamic, mechanical, warning and recovery devices have been applied.

Wing design, aerodynamic devices:

- aerodynamic twist will enable recovery because the downward twist at the tip will delay stall at the position of the ailerons, maintaining roll control when the stall begins
- stall strips, to trigger stall on certain positions of the wing to facilitate a controlled and gentle stall initiation and progressive stall development
- stall fences in the direction of the cord to stop progression of separated flow along the wing and dog tooth notches at the leading edge of the wing
- vortex generators to energize the flow, increasing the inertia of the boundary layer and delaying the separation of the boundary layer from the wing
- vortilons consist of flat plates near the wing leading edge. These vortex generators have a similar effect as the pylons of wing mounted jet engines and produce less drag than stall fences

Pilot controlled mechanical devices:

- stick pushers prevent a pilot to from entering stall because it pushes the elevator control forward, reducing the angle of attack while overriding the pilots input
- stick shakers are devices that warn the pilot for an oncoming stall by introducing artificial vibrations.

Pilot controlled warning devices:

- stall warning signals are applied to alert the crew audibly as the stall speed is approached
- angle of attack limiter is a flight computer that automatically prevents a pilot from a control input that rises the aircraft over its stall angle.
- angle of attack indicators are pressure differential instruments that integrate air speed and angle of attack in a continuous visual readout to the pilot as an indicator of available lift in the slow speed envelope.

4.2 Canard wings

A specific class of aerodynamic stall devices is created by the application of the canard configuration. The canard is a control surface that functions as a horizontal stabilizer, located in front of the main wing. A canard actually creates lift to hold the nose up in contrast with a aft-tail design which creates a downward force to balance the aircraft preventing a nose down rotation. Canards can be designed either as the equivalent to an aft-tail control surface with similar size or as a tandem wing with the main wing. Canards advantages are in the area of stall characteristics because due to its design, the canard will stall before the main wing stalls, preventing a progressive nose-up rotation. Canards have several limitations. It is important that the canard stall before the main wing in order to prevent uncontrollable pitch up because the canard is positioned well before the centre of gravity. Because the canard stalls first, some loss of maximum lift is incorporated

because the main wing will never achieve its maximum angle of attack. Application of lift increasing devices on the main wing such as flaps, also require lift increase on the canard, putting strength and size demands to accommodate flap use. Finally, the downwash of the canard may interfere negatively with the flow on the main wing.
Canards have been applied on supersonic aircraft to improve the flight characteristics at low speed, such as with the Concorde and military fighters. A series of innovative designs has successfully applied canards to improve the overall aircraft flight characteristics, such as with the Piaggio P180, Beechcraft Starship and Rutan Long-EZ. However, in these cases canards are applied in combination with other unconventional configurations such as aft cg range, pusher power supply and specific tail designs.

4.3 Stall recovery

In order to recover from a stall, pilots have to be knowledgeable about the attitude and state of the aircraft and its dynamic behavior. Stall contributing factors should be familiar to pilots, such as the angle of attack, the air speed and the positioning of the center of gravity. A T-tail configuration as such is not principally different, but sensitizes the aircraft to a stall and deep stall behavior. In particular in landing configurations, the pilot must understand and follow proper landing procedures, in particular regarding the center of gravity position. Such information involves also aircraft loading, weight and balances, trim, flap and power setting and meteorological issues, such as icing conditions. During the flight, pilots depend on reliable air data information in order to interpret and monitor their flight performance. In modern fly by wire cockpits with flight envelope protection, impaired air data information may degrade normal protection systems. In many modern aircraft, an air data computer is applied to calculate airspeed, rate of climb, altitude, Mach number and rudder travel limits. Such a computer derives its information from the pitot static system, measuring the forces acting on the aircraft as a function of temperature, density, pressure and viscosity of the air. Errors in the pitot static system can be very dangerous because the information is critical to a successful flight performance. The pitot tube is sensitive to disturbances, such as clogging by water or ice, insects or other obstructions. Blocking the static port is a serious problem, because it affects all pitot static instruments. Such blocking will influence the horizontal and vertical airspeed indicator as the static tube is blocked at the altitude at which freezing occurred, misinforming the pilot about the actual horizontal and vertical airspeed. Erroneous data information will have its effect on the aircraft computer system by impairing the air data functions such as flight director, autopilot, auto throttle, rudder travel protection, speed calculations, wins shear protection and switches control authorities between Control Modes.
While recovery from a stall requires pilot skills that are considered basic to the aviator profession and are an integral part of flying skills, several dedicated mechanical devices for stall recovery have been developed:

- spoilers on either side of the wings can be deployed as asymmetric lift reducers to recover from an uncommanded roll towards the stalling wing by initiating a reversed roll due to lift loss on the non-stalling wing
- parachutes and rocket deployment underneath the tail end are developed as deep stall and spin recovery systems by providing a force pitching over the nose of the aircraft after entering a stall. Such systems are applicable on smaller aircraft only

- a specific design was developed with Piaggio P180 and Learjet where a small forward wing combined with a main wing configuration. Although the front wings resemble a canard, a conventional tail provides stability. Aerodynamic stall recovery forces are provided by two ‘delta fins’ mounted under the tail.

4.4 Stall survival

Landing the aircraft safely despite a deep stall or unrecoverable spin is optional due to the design and development of a ballistic recovery system. Such a device brings down the entire aircraft to the ground by deploying a parachute in case of emergency. Such solutions however are restricted to smaller and light aircraft such as the Cirrus 20 series.

4.5 Beyond stall flight

Most military combat aircraft have angle of attack indicators indicating the pilot how close he is to the stall point. Modern commercial airlines collect information on the angle of attack, but do not directly display this information to the pilot. Instead, this information may drive a stall warning indicator system or provides performance information to the flight computer. In commercial aircraft, an immanent stall is indirectly communicated to the pilot through the Indicated Air Speed, depending on accurate and reliable air speed indicator equipment.

While the solutions to stall recovery took many and dedicated forms, modern commercial aircraft design takes stall into account in an integral design. The need for shorter takeoff and landing requirements have lead to the introduction of leading edge slats and large compound flaps, largely resolving the issue. In military aircraft, high maneuverability capability demands and beyond stall flight requirements have introduced the concept of vectored thrust. This engine thrust replaces the lift while maintaining alternative control over the aircraft replacing the loss of the ailerons and tail surfaces. Such post stall flights at very high angles of attack provides tactical advantages for military fighters and repeatedly have been demonstrated during air shows. Although such aircraft may be inherent unstable, their performance is kept under control by the ‘fly by wire’ system. Current fighters may perform in the deep stall region routinely using thrust vectoring, while at rare occasions, commercial aircraft have been able to recover from an emergency by thrust vectoring their engines.

5 Towards stall prevention?

In an article on High-Altitude Upset Recovery, captain Sullenberger described the AF447 accident as a seminal accident. "We need to look at it from a systems approach, a human/technology system that has to work together. This involves aircraft design and certification, training and human factors. If you look at the human factors alone, then you're missing half or two-thirds of the total system failure...".

He also believes that accurate airspeed indications alone aren't the best data the crew needs to recover from an upset. That requires knowing the wing's angle of attack (AoA). "We have to infer angle of attack indirectly by referencing speed. That makes stall recognition and recovery that much more difficult. For more than half a century, we've had the capability to display AoA (in the cockpits of most jet transports), one of the most critical parameters, yet we choose not to do it."

This practical approach complies with emerging scientific notions on safety control and systems engineering as discussed in the academic safety community, where user participation, practical observations and systems theory applications cover both technical and organizational dimensions. Increasing analytical and diagnostic capabilities requires feedback from design and operational decisions, creating partnerships between academia and investigation agencies (Saleh et.al. 2010). Safety boards may serve as problem providers for knowledge development (Stoop and Van der Burg 2012).

5.1 Intermediate observations

Some intermediate observations on stall as an aerodynamic phenomenon can be drawn:

- Since the beginning of flying with fixed wing aircraft, stall has been an inherent hazard to flight safety.
- Various stall scenarios exist, discriminating between various flight conditions, aircraft configurations and flight envelope restrictions
- Stall does not derive from airspeed and can occur at any speed. Stall only occurs at too high an angle of attack, separating the air flow from the wings.
- Stall is recognized as an inherent risk to aircraft with specific configurations, in particular aircraft with swept wings and T-tails
- A variety of dedicated solutions has been developed for stall recognition and recovery, covering aerodynamic, mechanical and behavioral issues.
- During the development of modern aircraft, a more generic approach has been developed, dealing with high lift wing design, flight envelope protection and pilot warning systems. This avoidance strategy of getting close to a stall region has reduced the occurrence of stall to an acceptable level of occurrence
- In the military, a different approach has been favored, with dedicated designs for thrust vectoring, taking over the loss of lift and controls by engine power vectoring the aircraft performance through the deep stall region.

Despite these solutions, stall and incidentally deep stall, still occur. Flow separation on the wing may induce stall, while also the elevator will lose its effectiveness. A separated flow over the complete wing span will also eliminate most of the aileron effectiveness. A roll-off may result in a spin, which will most likely at these high angles of attack be a flat spin from which recovery is very difficult. Recent major accidents indicate the potential for stall, at a high altitude as well as low altitude. A timely recognition of stall is critical, but may be hampered by the ability of the crew to recognize and diagnose a stall in a timely manner and respond accordingly. The transparency of the automated flight management system for the crew is a safety critical factor in the ability to diagnose and recover from a stall. Under all flight circumstances a stable and controllable flight performance should be maintained. Several recent air crashes indicate that due to operational circumstances beyond the aircraft design characteristics and performance envelope, such performance is jeopardized.

However, some more fundamental flight performance issues also emerge from this survey of the stall phenomenon:

- all stall recognizing and mitigating strategies have not eliminated the stall as a phenomenon. Major stall related accidents still occur, possibly in a new form.

- airspeed indications are not redundant and only rely on the use of pitot tube technology. Applications of a new technology -such as GPS- might provide necessary redundancy in air data information supply
- in contrast with roll and yaw control, pitch control of aircraft is not redundant. There are no substitute strategies for controlling the pitch of commercial aircraft, in contrast with the military where thrust vectoring is an option
- the angle of attack is only indicated as a secondary parameter, derived from the Indicated Air Speed. Commercial aviation has no direct alpha indicator, in contrast with military aircraft
- civil aviation aircraft lack the ability to create a negative pitch moment throughout the flight performance envelope by having direct access to speed and attitude as safety critical flight parameters.

5.2 Exploring solutions

In exploring new solutions, stall recovery has been a topical issue in several research and development programs in the European Union:

- a simulator training program in a dedicated simulator has been developed in the SUPRA program (Simulation UPset Recovery in Aviation). In developing a combined motion simulator, disorientation trainer and advanced research laboratory, a dynamic modeling and training of pilots for recovery of high altitude upset becomes feasible
- the High Level Group on Aviation Research of the European Union has developed a research and development program in which stakeholder participation, technical innovation and societal demands are combined into a EU research agenda for the aviation industry.

Such generic developments however, leave room for a dedicated diagnosis of critical phenomenon such as stall recovery, generating additional suggestions for innovations on specific topics.

6 Towards innovative designs

6.1 Stall shield device

While pragmatic and dedicated solutions have achieved a high level of sophistication in stall mitigation and recovery, a more fundamental approach to stall avoidance could be developed in order to deal with systemic deficiencies in stall avoidance.

An innovative solution to this more fundamental issue should comply with principles of dynamic flight control over the fundamental forces that are exercised on general aviation and commercial aircraft:

- introducing new aerodynamic forces instead of manipulating existing forces
- introduction of such aerodynamic forces in uncorrupted air flow
- generating high pitching moments by small forces combined with long arms
- introducing correcting forces only in case of emergency.

In dealing with stall, an innovative design is suggested, based on these principles of dynamic vehicle control (De Kroes 2012). Such a design is called a ‘stall shield device’ and consists of the following features:

- on the fuselage of the aircraft, several adjustable control surfaces are present, discriminating a neutral position in which the surfaces are incorporated in the fuselage structure and an operating position, extended into the free air flow around the fuselage

- these control surfaces are located at the nose and tail section of the aircraft in order to minimize the size of the aerofoil surfaces, providing the largest momentum arm to the center of gravity
- these stall shields are only deployed in case of near stall and emergent unstable flight to eliminate parasite aerodynamic drag in normal flight conditions
- to control the dynamic behavior of the aircraft in a near stall or stall these surfaces can adjust the required aerodynamic forces by manual or automated control over the surfaces by changing their size and/or angle of attack
- these surfaces can be operated by either select nose or tail shields or combine a nose and tail mode of operation to provide a stable flight performance, depending on the stall scenario, flight phase, aircraft configuration and operating conditions
- a stall shield control system is integrated in the flight management system, supported by dedicated computer software, depending on the level of sophistication of the aircraft control systems
- the stall shield device also incorporates a flight simulator program. Such a simulation program can be applied to train pilots in a flight simulator, or to assess stall characteristics in the early phases of a design by combining such a simulator with CFD applications. This may speed up the aircraft certification process, facilitating rapid safety critical design interventions before the phase of wind tunnel tests and flight tests and expensive adaptations are to be considered in the detailing phase. As a commercial application, it may serve as a safety asset in creating safety performance beyond legally required performance standards.

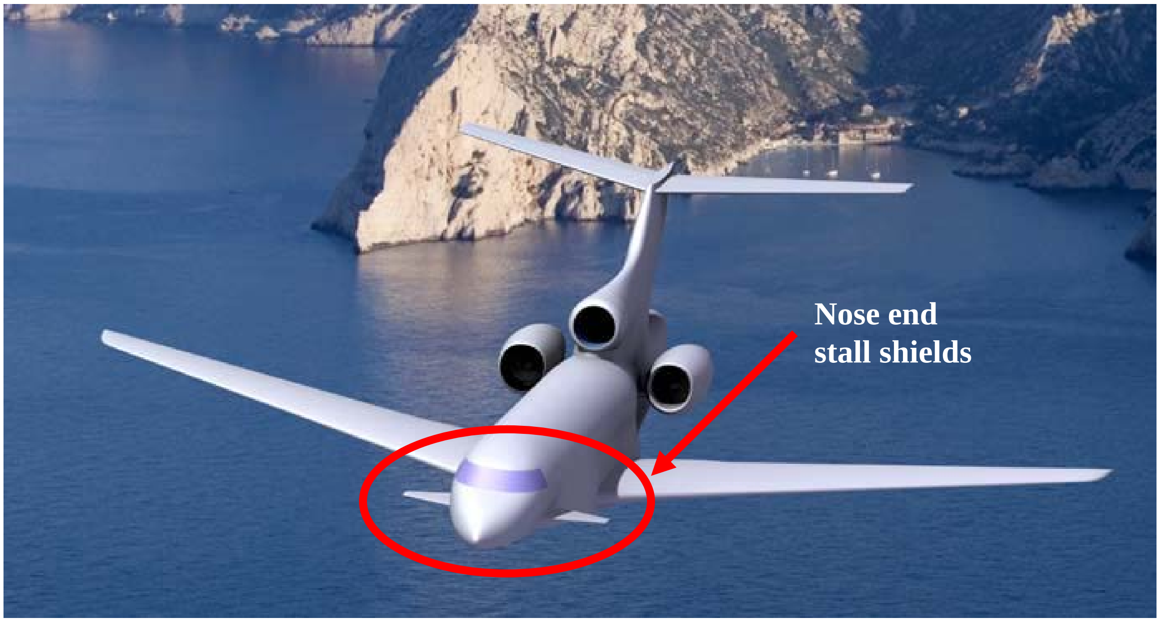

Fig 2. Stall shields at the nose end of a T-tailed aircraft

Such stall shield devices and their control systems should benefit from deploying satellite system by developing avionics applications for ground speed, acceleration, altitude,

positioning and flight attitude identification to provide redundancy in technology over the pitot static data supply. In addition, a direct angle of attack indicator in the cockpit display is preferred to inform the pilot on the actual flight attitude of the aircraft while the stall shield device is operational.
Such a principle of mobilizing rapid deployable control forces in dynamic vehicle control and recovery from unstable and unsafe performance is not unique for the aviation sector. They also have found application in Formula 1 racing by front and tail wings for generating downforce on race cars. In the maritime sea going sector, the sea keeping behavior of fast ships in stern quartering and following waves should be improved. In particular the resistance against large combined yaw and roll motions in conditions with large waves is a known challenge. Hydromechanical research at DUT in cooperation with Damen Shipyards in the Netherlands has demonstrated the feasibility of a vertical controllable bow combined with a 'magnus rotor' bow thruster. In particular for fast vessels with a deeply submerged bow –the axel bow design- excellent test results have been demonstrated in preventing broaching conditions, never approaching seriously dangerous values (Keuning and Visch 2009)

6.2 Feasibility and opportunities

Based on historical information on flight safety issues and accident investigations, the stall shield device has potential for several market segments:

- general aviation, in particular with less experience pilots, manual flight performance and VFR conditions. Stall shields at the tail end could improve stall performance of such aircraft
- small business aviation where stall sensitive configurations exist, combining jet engines with T-tails and swept wing designs. Automatically deploying stall shields on the nose could improve the stall performance of such aircraft
- commercial aircraft, in securing safety as a strategic public value in commercial aviation, balanced against other values such as economy, environment, dealing with performance optimization strategies. Automatically deployable stall shields at the nose and/or tail end could improve the stall performance of such aircraft
- innovations in aviation, based on strategic visions for future developments dealing with hyperbolic flight, smart wing technology, innovative power plants, composites, green and sustainable operations. Stall shields could be an integral part of the design of such aircraft, replacing conventional use of tail surfaces and controls.

In addition to these market opportunities, several scientific uncertainties should be addressed in developing a stall shield device:

- the man-machine architecture and interfacing should address questions such as: manual versus full automation, when and how fast deployable, establishing eventual crisis work loads, maintaining oversight over the actual aircraft state and attitude, identification of critical performance parameters such as angle of attack, speed, attitude, system mode
- providing a proof of concept throughout each phases of design, varying from conceptual assessment until certification processes and standards, testing and flight taking into account validation criteria of safety, costs and lead time, acceptable performance envelope limits

- establishing critical load cases for an encompassing range of loss of pitch control, damage tolerance limits, c.g. range extensions and limits, aircraft stability, trim and fuel economy constraints, structural aspects, construction weight and maintenance issues
- fail safe performance of the device as a ‘’full envelope protection device’’, preventing inadvertently and unanticipated deployment, training requirements, pilot certification and proficiency demands.

7 Conclusions

Assessment of the stall shield as a feasible and desirable innovation should be done in the early phases of its conception. However, discussing the issue of stall and remedies for stall related accidents are not restricted to the aircraft design community. Feedback from operationally highly experienced people such as pilots and accident investigators provide insights in the actual responses of the system under specific conditions that cannot be covered by an exhaustive proactive survey during design and development. In aviation and other high tech industries such insights are derived from beyond design events, -in fact accidents and incidents-. Although such events are frequently addressed as ‘Black Swans’, ‘Unknown Unknowns’, accident investigations however demonstrate that such events can be analyzed along lines of a structured search pattern, disclosing systemic and knowledge deficiencies and creating consensus on conceptual change. A multi-actor assessment should identify strengths and weaknesses, opportunities and threats of the stall shield, providing a safety impact assessment before the concept is released for operations. Case based and evidence based investigations do not only reveal specific issues, but also may lead to more generic insights in system properties such as stall, debating pitch control redundancy, display of critical air data parameters and simulator training issues.
The stall shield concept may serve as an example of serendipity: feedback from accident investigations to aircraft design and knowledge development, strengthening the resilience of a system against critical loads and unforeseen events. Eventually, if the stall shield concept contains inherent deficiencies and design flaws that have not been identified in the design, development and certification phase, they may emerge as accidents during the operational phase. In such a case, the cure could be worse than the cause.

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