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Tailplane or main wing stall? LOC-I event due to suspected icing

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Introduction

In January 2017, a business jet was being flown in Norway on a short repositioning flight with two pilots onboard, no passengers or cargo. Initially, the take-off proceeded as normal. As the landing gear was retracted the pilots observed that the airspeed was rapidly approaching the flap limiting speed of 200 kts. As the flaps were retracted at a height above ground level of approximately 2,000 ft, the crew experienced a violent nose-down pitch motion restrained by their seat belts, as the aircraft started banking sharply to the left. A full investigation was conducted by the Norwegian Safety Investigation Authority, supported by industry and academic partners ( ). It is likely that the commander (Pilot Flying) and first officer (Pilot Monitoring) experienced different levels of startle and/or surprise during the upset. Control was regained at a height of approximately 170 ft above ground level. Data from the Flight Data Recorder showed that the aircraft experienced -2.62 G during the pitch down upset and +5.99 G during the pull-out. A tailplane stall due to icing was suspected, however the flight data recorder being limited to 36 parameters was not by its own able to confirm this.

LN-IDB, a Cessna 560 Encore with serial number 560-0637 was manufactured in 2003. The aircraft type is certified for two pilots, commander and co-pilot. The cabin has room for 7 passengers.

Figure 1, Cessna 560 Citation Encore LN-IDB (Hesnes Air As)

The Flight

The crew, which consisted of a Commander and a First Officer, had flown from Bern in Switzerland to Gardermoen with a passenger on board. After disembarking the passenger at Gardermoen, the aircraft was scheduled to be flown to its home base at Sandefjord Airport Torp without passengers on board. The crew had planned to make the ground stop as short as possible and if the weather conditions permitted, they would avoid de-icing. During the ground stop at Gardermoen, only one engine was stopped while the First Officer completed an external inspection of the aircraft. He did not observe any ice or anything out of the ordinary on the areas of the aircraft that could be inspected. According to the crew, the snow did not accumulate on the wings before departure, they could only see melted water on the wing surfaces and therefore decided not to de-ice the aircraft. When the crew requested taxi clearance, they were assigned a different runway than expected. This entailed a longer taxi time and thus longer exposure to the prevailing weather conditions. The aircraft's ground stop lasted approximately 15 minutes at an air temperature of 0°C. The taxiways and runway were covered with 3-6 mm of slush and it was snowing when the aircraft took off. After flying from Switzerland for more than two hours in approximately minus 50°C, the aircraft's surfaces (fuselage and wings) were more than likely chilled.

Initially, the take-off proceeded as normal. Figure 2 shows a plot of the most important parameters retrieved from the Flight Data Recorder plotted over one common timeline (1). The landing gear was retracted and both pilots observed that the speed was rapidly approaching 200 kt, which is the maximum speed with flaps deployed. As the flaps were retracted, the crew experienced a violent nose-down movement and the pilots were "hanging by their seat belts", while the aircraft started sharply banking to the left. Following the accident, data from the Flight Data Recorder (FDR) showed that the aircraft at this moment experienced negative 2.62 G. The Commander did not trust the instruments while the First Officer, which was Pilot Monitoring (PM) had better situational awareness. The First Officer quickly took control and started a pull-out from the dive. The aircraft descended below the cloud base, and even though it was dark, the pilots could glimpse the ground. The control was regained, and the aircraft levelled off 170 ft above the ground. The aircraft was overstressed to 5.99 G during the pull-out. The crew called "MAYDAY" to the Air Traffic Control. The engines were left in take-off position during the entire pull-out and the speed increased to 325 kt. Once control was regained, the "MAYDAY" was cancelled, and the flight continued towards Torp where an approach and landing took place without further problems. The NSIA investigation has not revealed any technical malfunctions in the aircraft and its control systems.

The aircraft's anti and de-icing systems on the wings and tailplane were switched on. The aircraft's tailplane rubber de-icing "boots" were in automatic mode and inactive during the take-off and when the stall occurred. It is NSIA’s (AIBN's) assessment is that the systems were not suitable to remove this relevant type of ice and snow. This accident shows the significance of functioning crew resource management (CRM) in the cockpit when an unexpected and extreme flight situation occurs. In this instance, the First Officer's situational awareness and initial pull-out saved the crew.

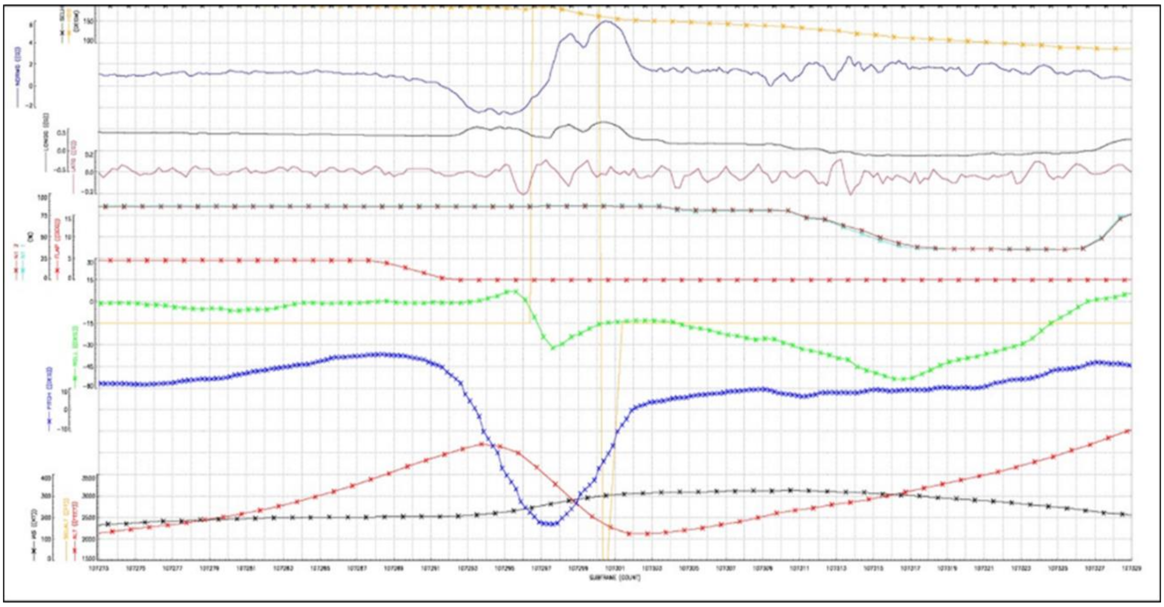

Figure 2, Flight Data Recorder Output (1)

Special Investigations: Modelling & Simulation

A review of loss of control in flight accidents where icing was contributory/causal factor was conducted. Theory related to the effects of icing on main wing and tailplane aerodynamics was undertaken and the relationship to stability and control investigated. Due to the limited flight data parameter set, it was decided to use modelling to simulate the effects of tailplane icing and compare with available, known data. Several modelling methods were considered including computational fluid dynamics, scale model wind tunnel testing, scale model flight testing etc. but due to time and cost constraints associated with these methods (2) it was decided to develop a representative (similar but not exact) model using available aircraft design software and desktop mathematical modelling and simulation software. A generic business jet linear flight dynamics model was developed using Matlab/Simulink, aircraft geometry, mass and balance, initial flight conditions from the Flight Data and estimated stability and control derivatives. Aircraft static and dynamic stability of the generic business jet was assessed for a range of tailplane efficiency factors to simulate the effects of tailplane icing.

Methodology

In order to assess the static and dynamic stability, modelling of the total aircraft pitching moment is needed and individual contributions of all major components are required, not simply tail lift and wing lift.

Static Stability

The total aircraft pitching moment about the aircraft's centre of gravity (3) consists of contributions from wing, tail and fuselage (Figure 3). Each contribution generates moments that vary with angle of attack and contributions that are independent of angle of attack (constant). A negative total pitching moment slope represents positive static stability – the aircraft returning to the trimmed flight condition following a disturbance (e.g. sudden change of tail lift).

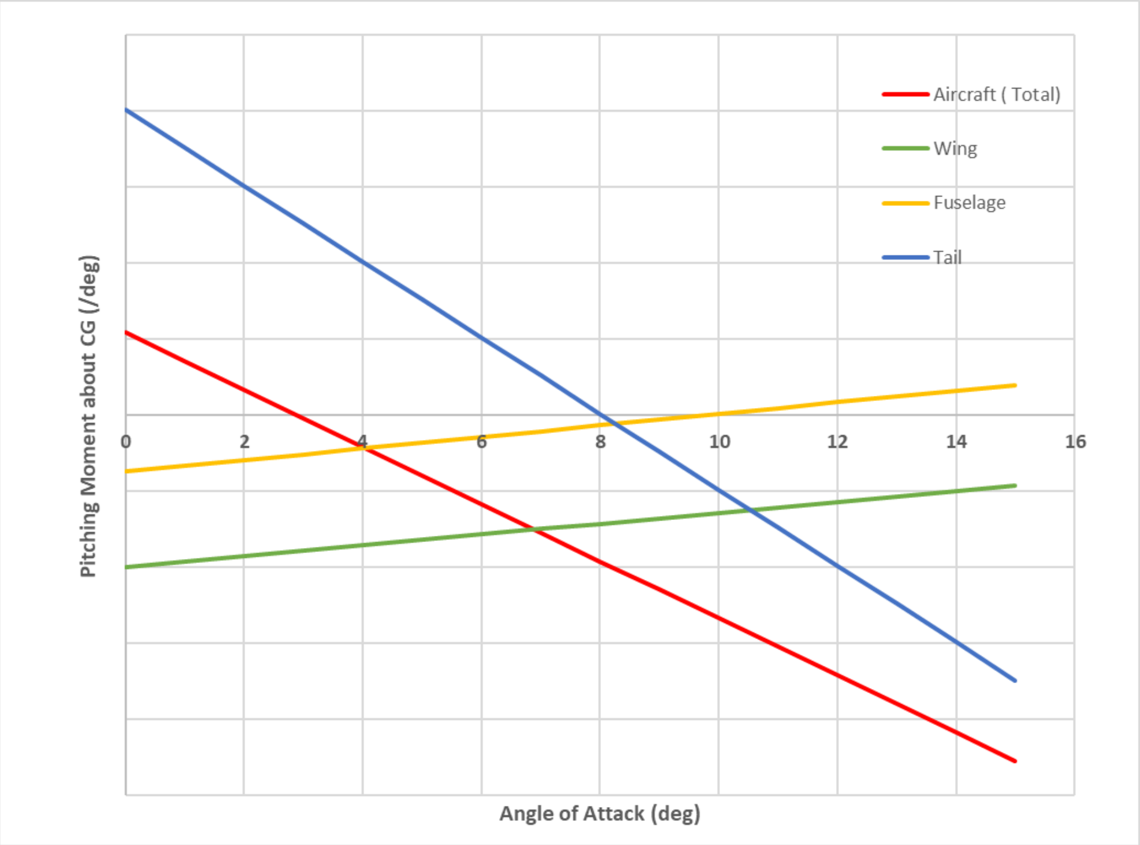

Figure 3, Contributions to Total Aircraft Pitching Moment about the CG

As ice builds up on the tail, it becomes less aerodynamically efficient, increased negative tail lift is needed to keep maintain the trimmed flight condition and, prevent the aircraft tending to nose down and overspeed with flaps extended. This is achieved by increasing elevator trailing edge up to compensate (Figure 4).

When flaps are retracted (Figure 4), the lift generated by the wing decreases and the point of lift moves forward. The aircraft tends to nose UP as the nose down pitching moment due to wing lift decreases. Increased trailing edge down (TED) elevator is required to compensate. At the tailplane, downwash angle decreases hence negative tail lift decreases. The aircraft tends to nose DOWN as the pitching moment due to negative tail lift decreases. This time, increased trailing edge UP (TEU) elevator is required to compensate. The resultant pitching moment about the CG is the net effect of these contributions. The effects due to tailplane are usually dominant (Figure 3).

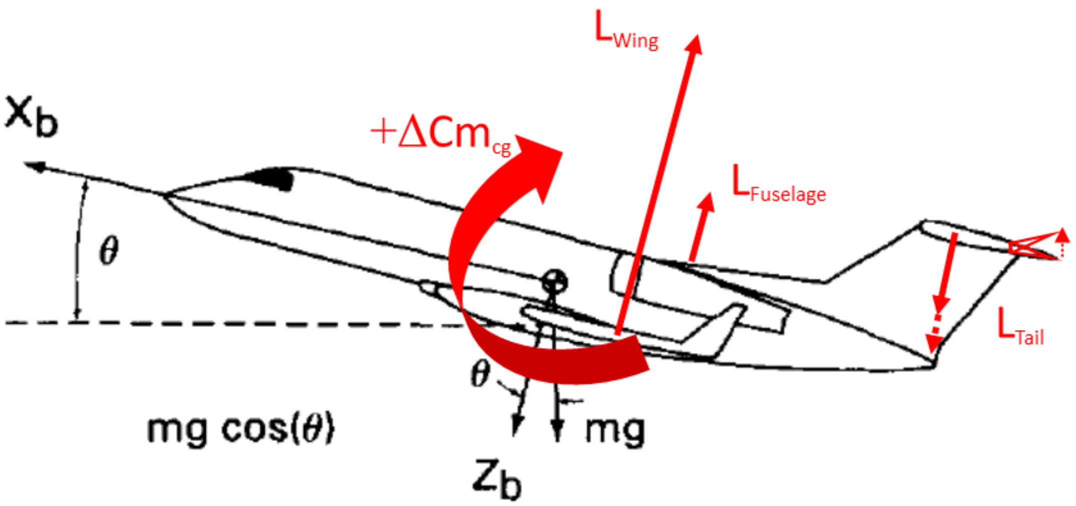

Figure 4, Forces and Moments on an Aircraft and Effect of Elevator Deflection

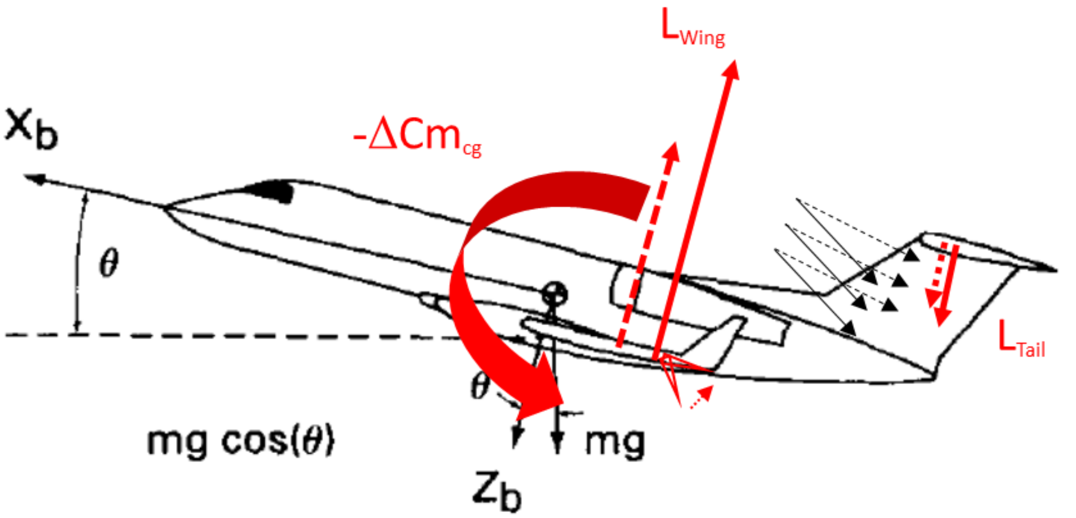

Figure 5, Forces and Moments on an Aircraft and Effect of Flap Retraction

Dynamic Stability

The longitudinal dynamic stability characteristics of the aircraft are dependent upon the airspeed, pitching moment variation with angle of attack, moment of inertia, lift to drag ratio and aerodynamic tail damping.   The system may be exhibit positive, neutral or negative dynamic stability (Figure 6).

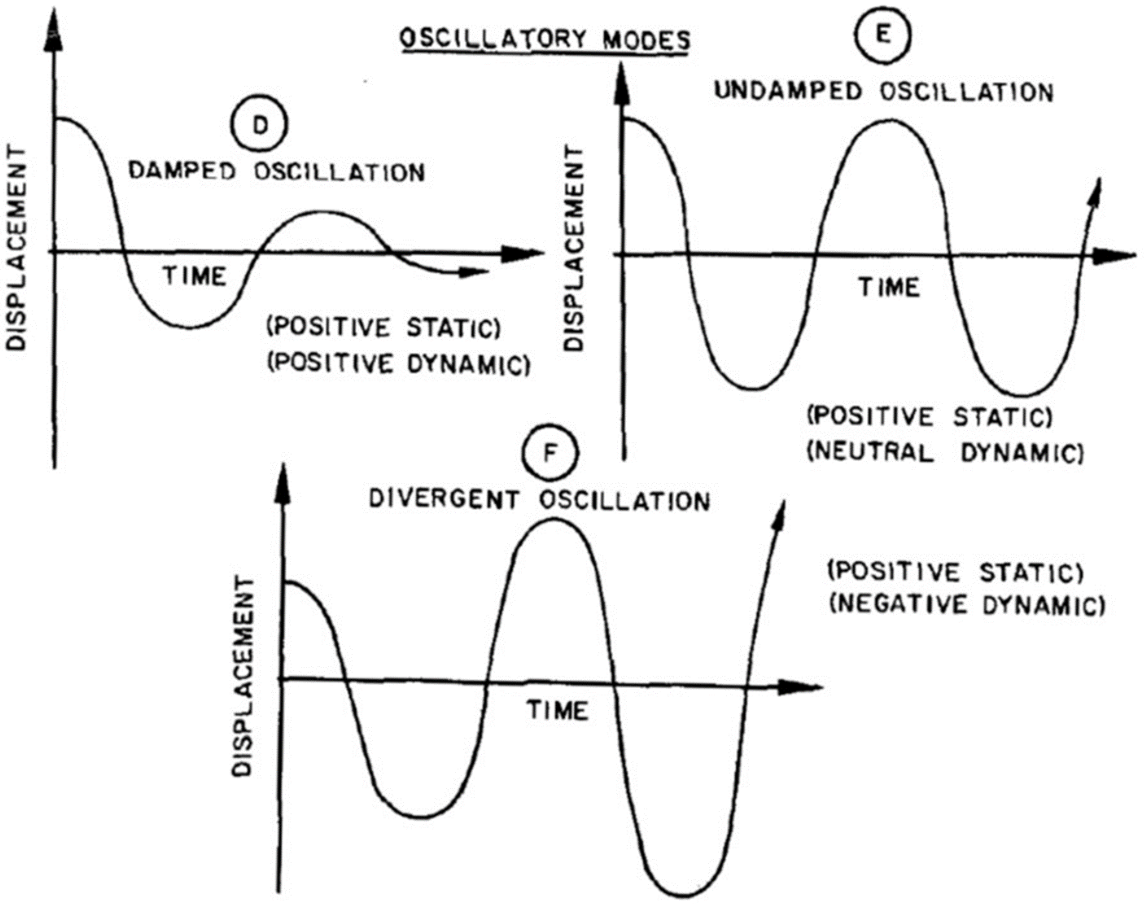

Figure 6, Dynamic Stability (4)

Give the trimmed flight condition and static stability of the 'generic business jet', dynamic analysis can be undertaken to consider the effects of small disturbances (perturbations) such as turbulence (external) or control inputs (internal). Using defined aircraft notation and axes state variable, control inputs and matrix/vector notations can be defined. Systems with more than one input and more than one output are known as Multi-Input Multi-Output systems (MIMO). Systems that have only a Single-Input and a Single-Output are defined (SISO). The aircraft in longitudinal and pitching motion maybe modelled using a state-space model. The longitudinal aircraft dynamics are linearised about the setpoint (airspeed & pitch) and can be written in state space form:-

$$\dot{\mathbf{X}} = \mathbf{A}_{\mathbf{long}}\mathbf{X} + \mathbf{B}_{\mathbf{long}}\mathbf{u} \qquad \textbf{Equation 1}$$

The elements of matrix A are stability derivatives describing the effect of state variables on forces and moments. The elements of matrix B are control derivatives representing the effects of elevator and throttle commands on the body referenced forces and moments.

Transfer Functions, Elevator to Pitch

Using this matrix method, transfer functions (Input-Output relationships) can be derived using desktop computing mathematical modelling tool Matlab to determine the relationship between Input: Elevator Deflection (η) and Output: Pitch Angle (θ).

Effects of Flap Retraction

The effects of flap retraction can be simulated using a Simulink Switching Model. This type of model enables the dynamic analysis to account for changes in stability & control derivatives as a result of flap configuration changes. Given stability & control derivatives for the selected aircraft, transfer functions can be estimated for different flap configurations and tailplane efficiencies.

Results Analysis

A commercial aircraft software design package (using applied theory described earlier) was used to for modelling of static stability using a 'generic business jet' in a range of conditions similar to the accident aircraft. Dynamic analysis was conducted using custom developed Matlab models and Simulink.

Static Stability

For the 'generic business jet', using the given flight condition of V= 204 KTAS, H = 4,000 ft pressure height, T = 29F, aft CG/low MTOM with flap = 7 degrees, the variation of pitching moment with angle of attack was obtained for a range of horizontal tailplane efficiencies from 1.0 (100%) to 0.5 (50%) to simulate the effects of icing on the aircraft tailplane (Figure 7). The results show that the pitching moment versus angle of attack gradient decreases as the horizontal tailplane efficiency decreases, hence aircraft static stability also decreases as horizontal tailplane efficiency decreases.

The results also show that the angle of attack for trimmed flight conditions increases as tailplane efficiency decreases. Analysis of horizontal tailplane efficiency versus stick-fixed static margin suggests that static margin decreases as the horizontal tailplane efficiency decreases and that the aircraft is neutrally (statically) stable when the horizontal tailplane efficiency is approximately 0.68 for the 'generic business jet' model in given flight conditions (Figure 8).

Further analysis of elevator deflection versus horizontal tailplane efficiency (Figure 9) suggests that increasing UP elevator (-ve deflection) is required to maintain trimmed flight as the horizontal tailplane efficiency decreases. The range of elevator deflection for the 'generic business jet' model was 20 degrees UP and 15 degrees DOWN. The results suggest that as horizontal tailplane efficiency decreases below approximately 0.2 (20%), there is insufficient UP elevator to maintain trimmed flight.

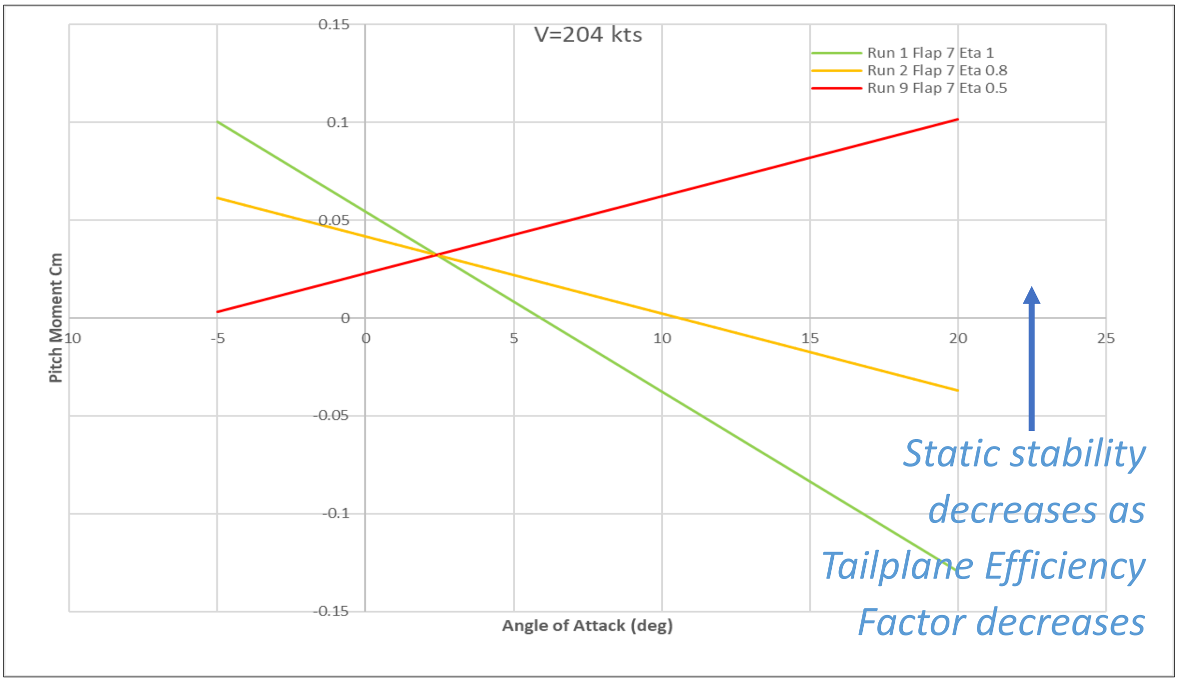

Figure 7, Pitch Stability - Pitching Moment vs Angle of Attack

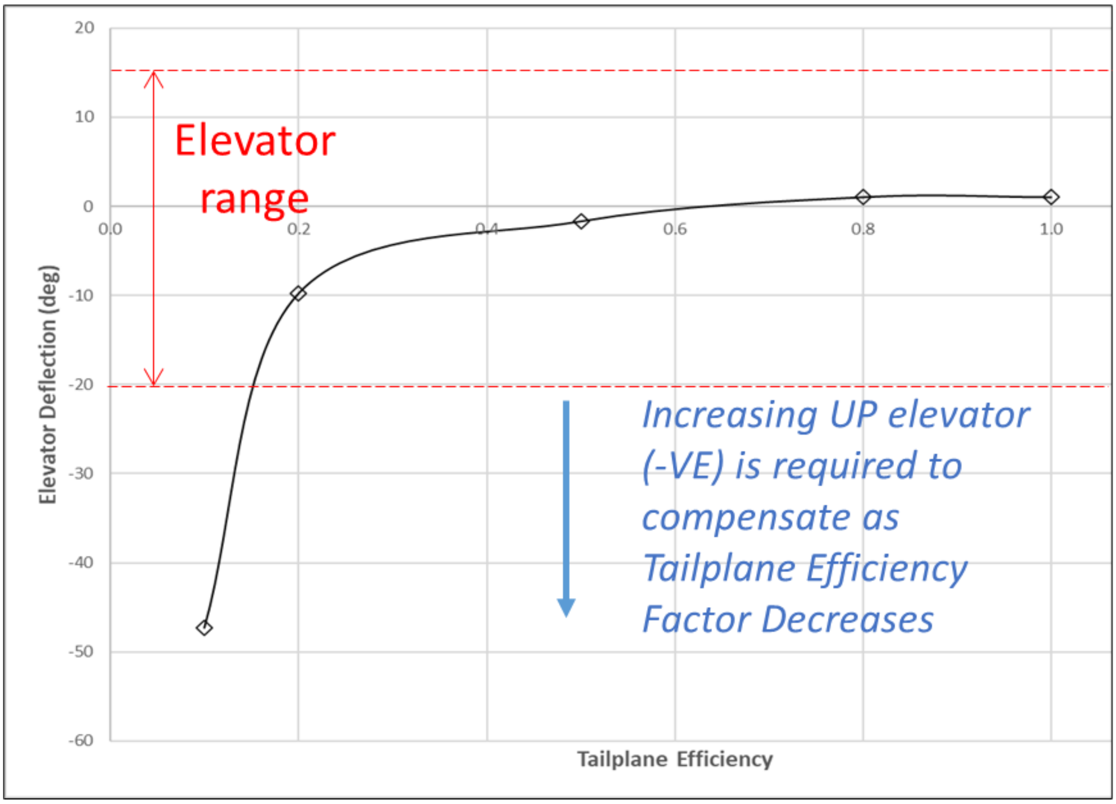

Figure 8, Elevator Deflection vs Tailplane Efficiency

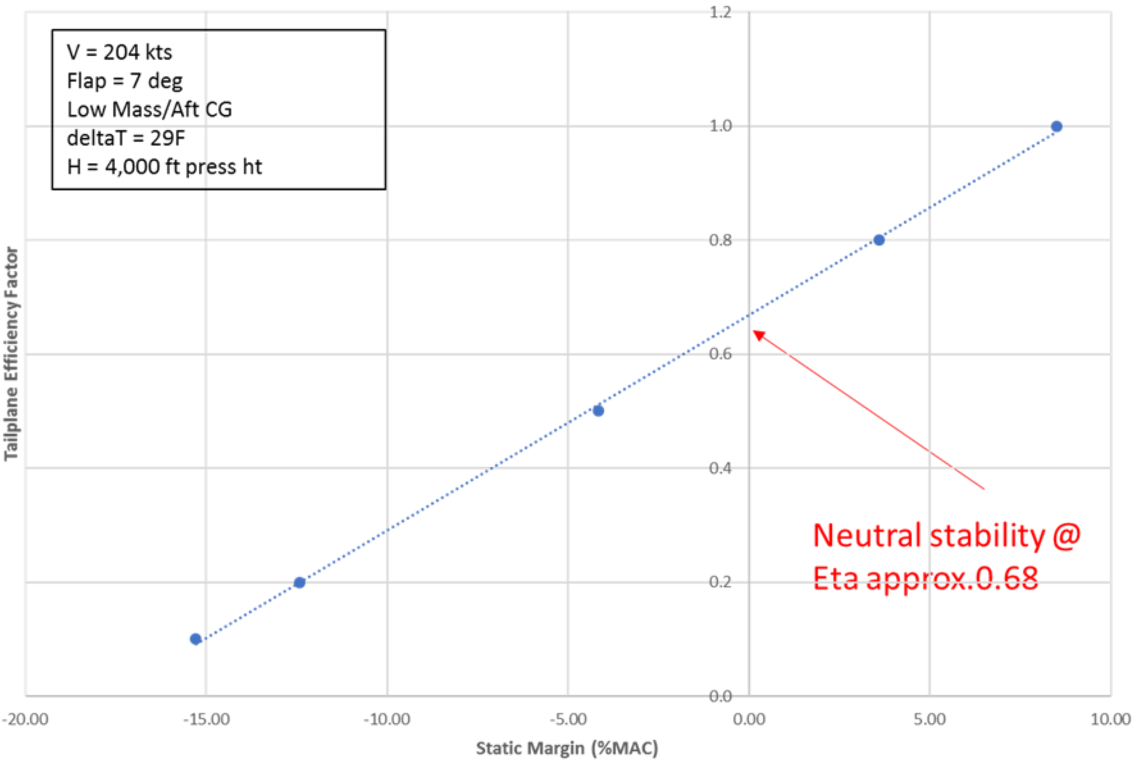

Figure 9, Tailplane Efficiency Factor vs Static Margin

In summary, using established theory and aircraft design application software, for a given 'generic business jet model' it was shown that:-

- Static stability decreases as Tailplane Efficiency Factor decreases;
- Static margin decreases as Tailplane Efficiency Factor decreases;
- Neutral static stability at approx. 68% Tailplane Efficiency Factor;
- Negative static stability at 20% Tailplane Efficiency Factor;
- Increasing UP elevator (-VE) is required to compensate as Tailplane Efficiency Factor Decreases.

Dynamic Stability

For model validation purposes, the longitudinal dynamics were analysed by excitation of the Short Period and Long Period modes using the eigenvectors (specific to modes) of Matrix A to specify initial conditions. The variables simulated were relative changes (variations with respect to a trim condition). The results show that for a horizontal tailplane efficiency of 100% the aircraft is statically and dynamically stable with heavy and moderate damping for the SPO and LPO respectively. In addition, the model was independently verified by comparing results to a reduced order model (**Error! Bookmark not defined.**). When the efficiency is reduced to 80%, the response for the LPO is also stable although with less damping of oscillations than the 100% efficiency case (Figure 10). The results of the dynamic stability are in agreement with those of the static stability analysis.

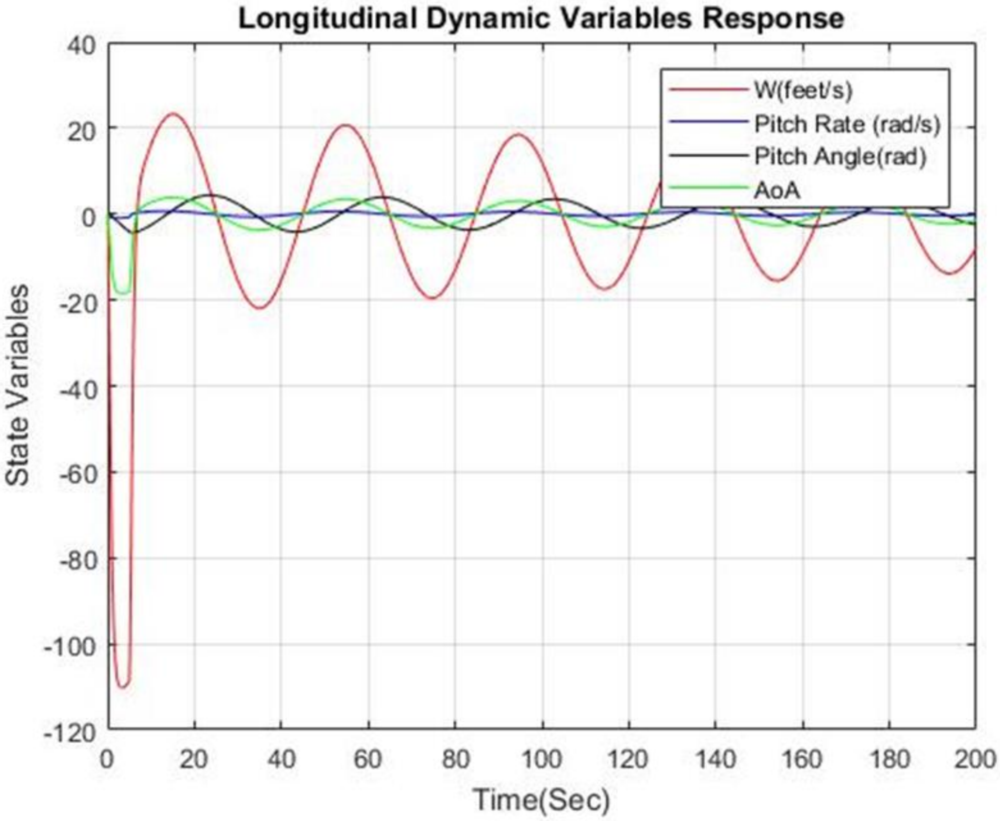

Figure 10, Long Period Oscillation (LPO) with 80% Horizontal Tailplane Efficiency

Effects of Flap Retraction

The results of a flap retraction following a simulated tailplane stall (Figure 11) were analysed with the tailplane efficiency of 100% and the flap deflection of 7 degrees. At t=4 seconds, a tailplane stall was modelled by a step reduction of 50% to horizontal tailplane efficiency, which destabilises the system response. The aircraft pitches down (-30 degrees) within 2 seconds. At t= 6 seconds, the retraction of flaps from 7 degrees to 0 degrees initially helps, but not sufficiently to stabilise the response with 50% tailplane efficiency. The effect of tailplane efficiency on the initial response to a 1 second elevator impulse (Figure 13) shows that at 100% horizontal tailplane efficiency, a large 20deg elevator down during 1 second is needed to initiate a large magnitude but stable phugoid response, which is shown during the first 20 seconds for comparison purposes. At 50% efficiency, a 1 second 2-degree elevator down input destabilises the system with oscillations and at 20% efficiency, 1-degree elevator down is sufficient to produce very fast divergence without oscillations. Load factor changes with 1 second elevator down commands for varying horizontal tailplane efficiencies were also presented (Figure 11). With 100% efficiency, load factor remains very close to 1 with a small elevator command, as expected. With 50% tailplane efficiency, load factor is reduced but changes are small. Major changes to load factor are however obtained with 20% tailplane efficiency and negative G is quickly reached in this case. This is believed to be closer to the conditions experienced during the incident (1).

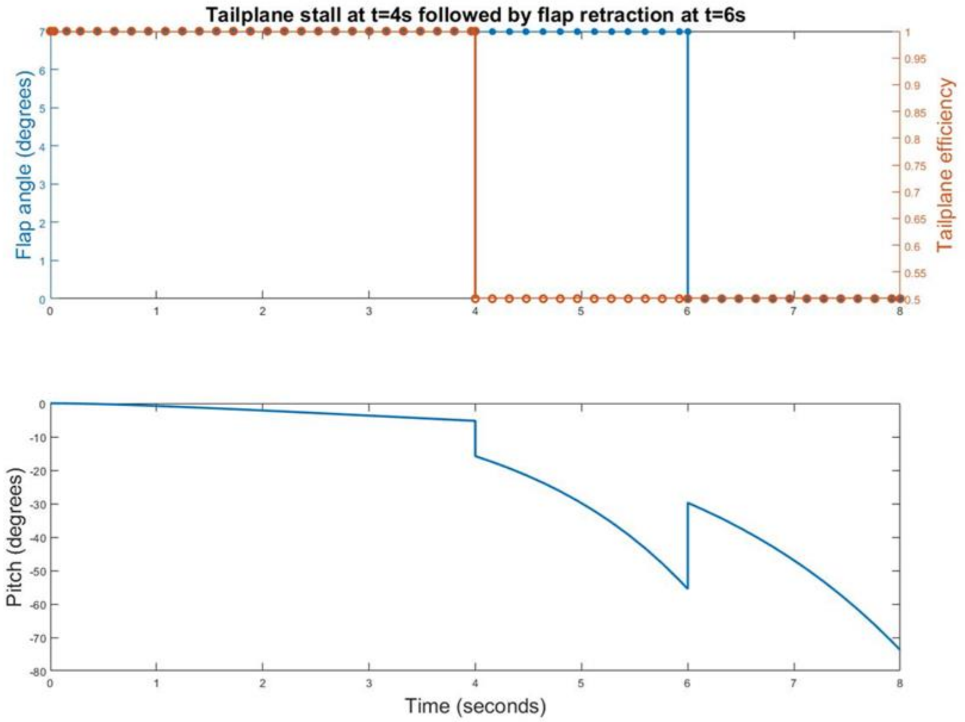

Figure 11, Tailplane Stall Followed by Flap Retraction

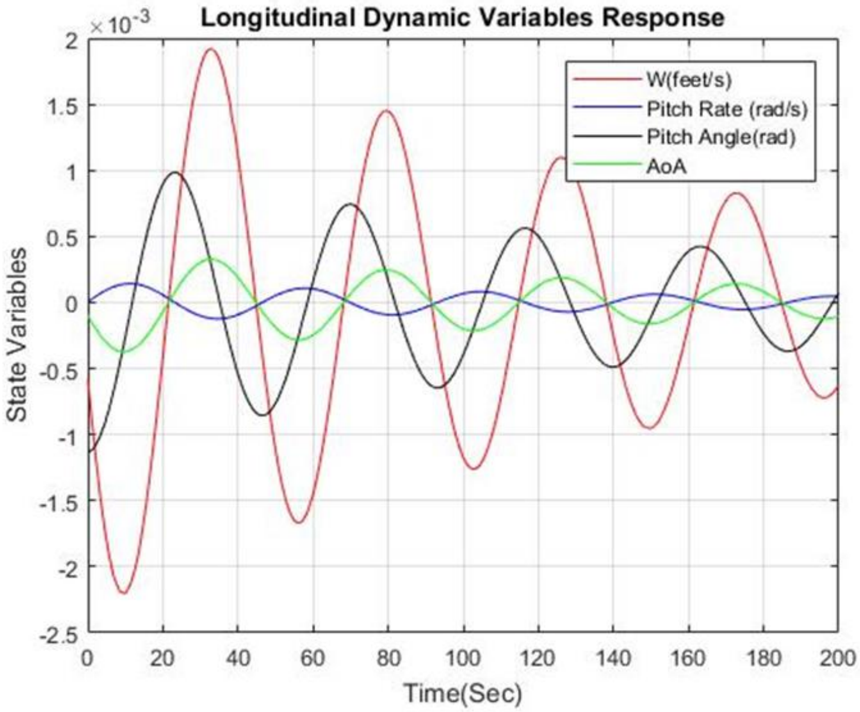

Figure 12, Long Period Oscillation (LPO) with 100% Horizontal Tailplane Efficiency

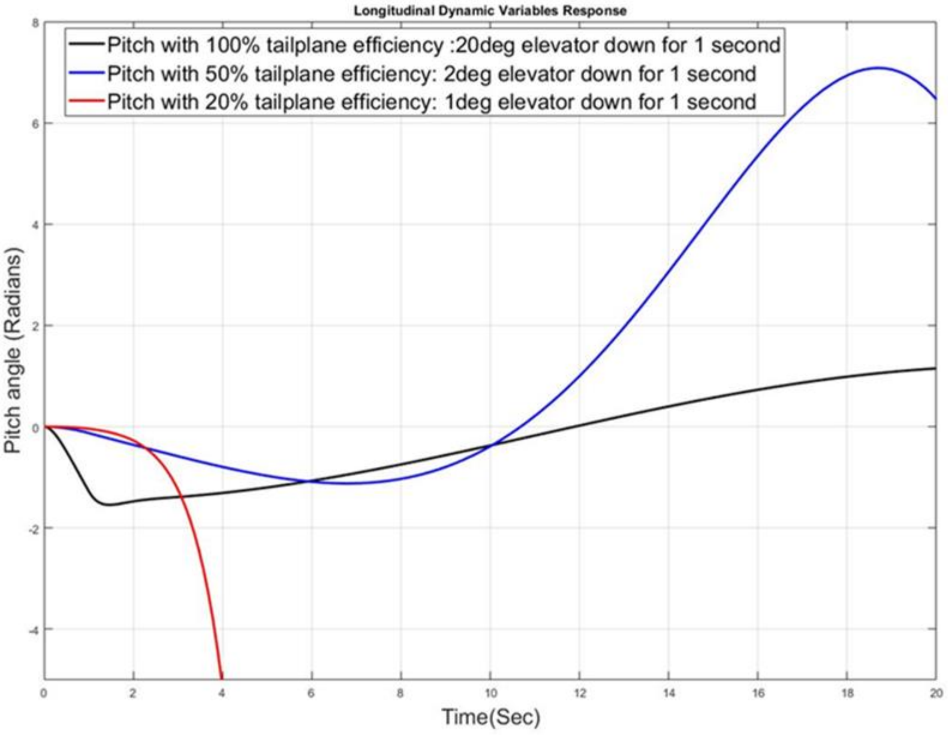

Figure 13, Dynamic Pitch Stability with varying Tailplane Efficiency

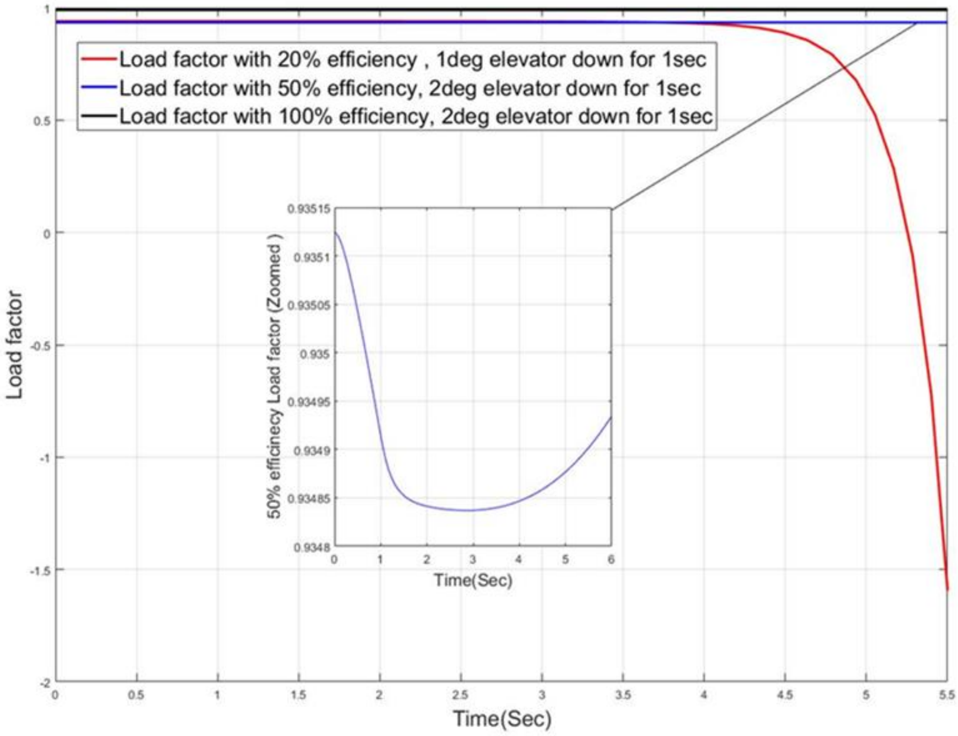

Figure 14, Load Factor with varying Tailplane Efficiency

Summary

Tailplane stall destabilises the system response:-

- Flap retraction reduces angle attack at the tailplane;
- Flap retraction helps initially, but not sufficiently to stabilise the response with 20% tailplane efficiency;
- Aircraft pitch response to elevator commands is unstable when Tailplane Efficiency is 20%;
- Tailplane stall destabilises the system response.

The results showed that static stability decreases as tailplane efficiency decreases, simulating the onset of tailplane icing and that increasing UP elevator (-VE) is required to compensate. At low tailplane efficiency the aircraft pitch response to elevator commands becomes unstable. Flap retraction initially helps, but not sufficiently to stabilise the response with low tailplane efficiency and a tailplane stall destabilises the system response. The safety investigation authority issued a safety recommendation to the aircraft manufacturer, requesting they inform the customers about the nature of the accident and the risk of tailplane stalling.

NSIA Safety Recommendation Regarding Tailplane Icing

Safety recommendation SL no. 2020/01T

On Wednesday, 11 January 2017, the crew lost control of a Cessna 560 Encore at low altitude after take-off. The most probable explanation for the aircraft's sudden dive, is that the tailplane stalled as a result of icing from slush spray from the runway and from falling snow and sleet. The aircraft's rubber de-icing "boots" were in automatic mode and inactive during the take-off and when the stall occurred. Textron/Cessna has informed NSIA that they not previously have experienced loss of control as a result of icing on the tailplane on their aircraft models.

NSIA recommends that Textron/Cessna inform all its customers that operate Cessna Citations about this accident and about the risk of contamination on the tailplane in the form of ice or other substances which can result in the tailplane stalling.

Lessons Learned

In the course of this investigation the following lessons were learned:-

- Tailplane icing events are difficult to confirm since the evidence might not be present (ice accretion);
- Fundamental modelling of effects of icing on tailplane efficiency can be used as an alternative to complex & costly CFD;
- Industry and academic collaboration yields benefits for both parties;
- Industry benefit from expertise not always available in-house;
- Academia benefit from working on a real-world research problem & contribute to knowledge.

Conclusions

The aim of this study was to provide further insight into Loss of Control Inflight (LoC-I)/Upset events in icing conditions. The main objective was to identify the probable characteristics of a LOC-I/upset event due to tailplane icing for a 'generic business jet'. The lack of available stability, control and aerodynamic data for a specific aircraft make/model resulted in a 'generic business jet' model being used for all analyses. Therefore, it has not been possible to replicate exact aircraft dynamics as evidenced by FDR data using modelling & simulation techniques. Flight data analysis and weather reports were used to determine flight conditions to be assessed, static and dynamic stability was assessed using established flight dynamics theory and modelling.

The modelling and 'what-if' trends analysis does however illustrate similar trends to the recorded flight data, particularly in the case of a severe tailplane stall. The degradation/severity of tailplane aerodynamic characteristics due to icing was simulated using an assumed reduction in Tailplane Efficiency Factor and classical theory supported by a commercial aircraft design software package.

The results are applicable only for short time periods after a given disturbance since:-

- A linearised flight model was used about a trimmed flight condition;
- No pilot control inputs were available (e.g. yoke pitch/roll, rudder);
- No external (environmental) disturbance data were available (e.g. turbulence);

The results demonstrate that the 'generic business jet' aircraft used in the analysis is statically and dynamically stable when horizontal tailplane efficiency is high.

When horizontal tailplane efficiency is reduced (simulating a 'tailplane stall'), the aircraft is statically and dynamically unstable, smaller and shorter elevator commands produce large pitch responses and negative 'G' may be quickly reached within a short time period.

As with most incidents and accidents there are multiple contributing factors. NSIA has determined that a probable explanation for the aircraft's sudden dive is that the tailplane stalled as a result of icing caused by contamination from slush and spray from the runway and/or from falling sleet and snow. Was this an infrequent, one of a kind ('black swan') event?. Possibly not. From an NSIA perspective less frequently reported incidents or those where the evidence is not present for sufficiently improving the safety ,can be easily overlooked.

This incident has several lessons learned, the most important being:-

- Tailplane stall due to icing is a real threat;
- Tailplane stall due to icing is a well known cause for accidents during icing conditions;
- The incident highlights the importance of de-icing before take-off in icing conditions;
- The incident underscores the deficiency of the pneumatic boot de-icing systems.

Internationally, ICAO annex 13 (5), and within Europe EU regulation 996/2010 (6), gives rights and responsibilities for involved parties. Any safety investigation is teamwork and benefits from also bringing universities and similar academic environments with their know-how and equipment into the safety investigation.

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