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Deep stall characterization and identification algorithm on a T-tail aircraft model

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ABSTRACT

Deep stall is a kind of stall affecting aircraft longitudinal dynamics in which the pitch up/down command is almost ineffective. The flight of the tail inside the separated wake of the stalled main wing could be considered as an explanation for the phenomenon. It implies a stable equilibrium at high angle of attack.

The analysis is first performed from the observation that the different possible types of time evolutions in the (α, q) phase portrait are only in limited number.

Then the damping of the short period mode near deep stall is noted to be smaller than the one at low angle-of-attack.

At the end, the analysis of the dynamics proves to allow the identification of critical deep stall prone flight conditions without any a priori information on the aircraft.

INTRODUCTION

Deep stall is a kind of stall affecting aircraft longitudinal dynamics in which the pitch up/down command is almost ineffective. It was first observed during a BAC 1-11 test-flight leading to crash. The flight of the tail inside the separated wake of the stalled main wing could be considered as an explanation for the phenomenon. This wing-tail interaction can cause severe degradations on tail aerodynamic performances. From the flight dynamics point of view, it corresponds to a stable equilibrium state at high angle of attack. This dangerous situation implies high descent velocities with no easy recovery procedure.

When designing such an aircraft, the main issue concerns the horizontal and vertical locations and the dimensions of the T-tail or the place of aft mounted engines. They are the design factors promoting deep stall risk for an aircraft.

In this study, we focus our attention on the dynamics of an already built aircraft which flies in the neighbourhood of deep stall. This can be the case in flight tests for example where many configurations are evaluated and especially critical ones where the limits of the aircraft are tested and the flight domain is explored for the first time. The objective is to identify some relevant parameters which warn the pilot of a possible forecoming deep stall.

NOMENCLATURE

α	Angle-of-attack
δ_e	Elevator angle
δ_x	Throttle setting
ρ	Air density
C_L, C_D, C_m	Lift, drag, pitching aero coefficient
c_w	Reference chord
q	Pitch rate
S_w	Reference surface
T	Thrust
AOA	Angle-of-attack

1. GENERAL ISSUE

The non-linear aircraft behaviour of the longitudinal motion linked to the short period mode can be described in the (α, q) phase portrait using a reasonable decoupling hypothesis. The elevator δ_e is the relevant control as it determines the aerodynamic coefficients and especially the pitching moment (but marginally at high incidence, the thrust can also have an impact).

In the work presented here, a flight dynamics model is constructed so as to include the aerodynamic specificities of deep stall.

Then the analysis is performed. It is first based on the diagnosis that the different possible types of time evolutions in the (α, q) phase portrait are only in a limited number.

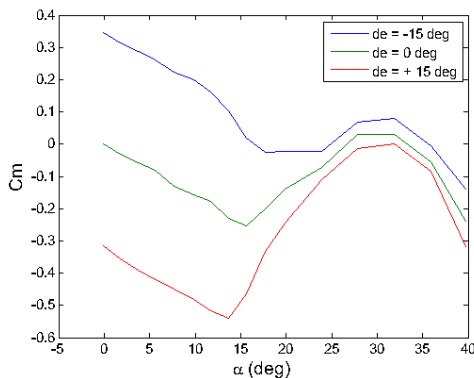
Secondly the characteristics of the dynamic behaviour of the longitudinal short period mode near deep stall show some differences which can be used to make discrimination with the short period mode oscillations at low angle-of-attack.

At the end, the analysis of the dynamics proves to allow the identification of critical deep stall prone flight conditions without any a priori information on the aircraft.

2. MODELLING

The core of the longitudinal flight model used here is analytical. The involved state variables X are velocity, AOA, flight-path angle, pitch rate and height and the commands U the elevator δ_e and the thrust throttle δ_x .

$$X = \{V, \alpha, \gamma, q, h\}, U = \{\delta_e, \delta_x\}$$



- Figure 1. Pitching aerodynamic coefficients for Learjet aircraft with flap down [1] for different elevator angles (full pitch up, neutral, full pitch

down)

The aerodynamic coefficients of the overall aircraft model are taken from NASA wind tunnel experiments for a Learjet aircraft [1] for the static part i.e. $C_L(\alpha, \delta_e)$, $C_D(\alpha, \delta_e)$, $Cm_{static}(\alpha, \delta_e)$. A dynamic part is taken into account for the overall pitching aerodynamic coefficient by means of the pitching coefficient derivative $Cm_q(\alpha)$ due to pitch rate whose model looks like the one found in [3] approximately (or [4]). Finally, with the coefficient derivative Cm_q from the figure 2,

$$Cm(\alpha, q, \delta_e) = Cm_{static}(\alpha, \delta_e) + Cm_q(\alpha) \cdot \frac{c}{2V} q$$

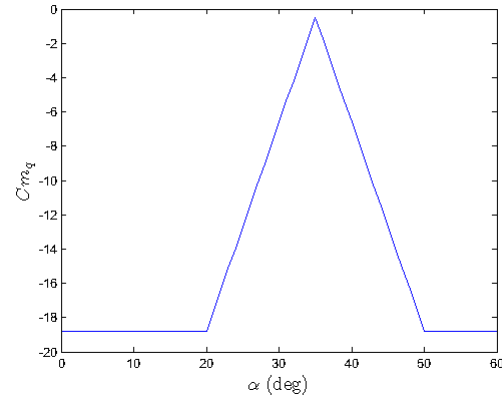


Figure 2. Pitch rate q derivative of the pitching coefficient Cm_q in function of the angle-of-attack α including deep stall effect used for this study

The other aircraft data are provided by [11].

Instead of considering an overall flight dynamics model, another method to build such a model is to take an (aerodynamic) model for each element and to add interactions between main wing and tail. In this case, the downwash angle due to main wing and the dynamic pressure ratio between both wings include the effect of deep stall.

We can note that the exploited models are dedicated to theoretical studies since the sensitivity to the pitch rate of the aerodynamic (coefficients) renders well the physics but is approximate (or even a little bit exaggerated) and does not come from experiments or modelling works.

After the rapid presentation of the exploited model, we focus ourselves on the main objective: the analysis of the dynamics by means of the phase portrait and of the longitudinal modes properties.

3. TYPICAL PHASE PORTRAIT

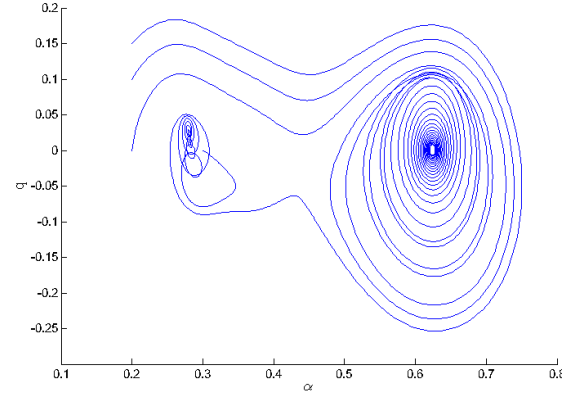
When considering the typical phase portrait of a deep stall prone aircraft with its three equilibria, we can make several observations.

Concretely the T-tail aircraft gives raise to deep stall for several configurations of elevator angles and static margins. For such critical cases, there are three equilibria for one fixed elevator angle δ_e such that the overall pitching moment is zero $Cm(\alpha, q = 0, \delta_e) = 0$: the classical low AOA equilibrium, an unstable equilibrium at medium AOA (a so-called saddle-node associated to one positive and one negative real eigenvalue) and the deep stall one which is the stable equilibrium at high AOA [9]. From classical flight dynamics considerations, we know that there is static stability of an equilibrium when the α -slope of the pitching coefficient is negative: $\partial Cm / \partial \alpha < 0$.

On the one hand, when converging towards a stable equilibrium point, it is visible that the angle of attack for which $\dot{\alpha} = 0$ (equivalently $q = 0$) are becoming closer and closer.

On the other hand, in the neighbourhood of the (saddle-node) equilibrium, all the trajectories are attracted and then repelled from the (saddle-node) equilibrium [9] (at medium AOA). As shown in figure 3, the trajectories remaining at the right of the saddle-node equilibrium and in a delimited (by the stable manifold) region converge into the high AOA equilibrium. The other trajectories converge towards the low AOA equilibrium [10].

This statement allows predicting the convergence towards the equilibrium at low or high angle-of-attack, once the airplane flew near this saddle-node (right, left, up, down). It is also possible besides to foresee the future attraction point by studying also the evolution of the AOA α values for $\dot{\alpha} = 0$ or $q = 0$.



- Figure 3. (α, q) typical phase portrait (of an aircraft which is prone to deep stall)

After describing the possible encountered time evolutions, we will analyze next the short period mode properties.

4. SHORT PERIOD MODE CHARACTERISTICS

Classical flight dynamics theory states that the short period mode involves the AOA α and pitch rate q and that its movement is decoupled from the phugoid. The figure 3 shows that the decoupling of the dynamics with the (α, q) variables is quite a reasonable assumption. The simulation of the 2-state system seems quite close to the one of the complete 5-state system. There are only few cases where the trajectories cut themselves for example.

The linearization of the dynamics linked to the equations of lift and pitching moment gives analytical estimations of the pulsation ω_{spm} and of the damping ξ_{spm}

$$\omega_{spm}^2 = -\frac{V_e^2 \rho c_w S_w}{2I_{G,y}} \left[c_w \left(\frac{\rho S_w}{2m} C_{L_\alpha} + \frac{T}{m V_e^2} \right) C_{m_q} + C_{m_\alpha} \right] \quad (1)$$

$$2\xi_{spm} \omega_{spm} = \frac{\rho S_w V_e}{2m} C_{L_\alpha} - \frac{c_w \rho S_w V_e^2}{2I_{G,y}} C_{m_q} + \frac{T}{m V_e} \cos \alpha_e$$

where m is the aircraft mass and $I_{G,y}$ is the aircraft moment of inertia about y -axis at gravity center.

We note that the damping of the short period mode is a valuable indicator for the prediction of deep stall. Indeed due to the loss of tail efficiency in deep stall and to the lower lift

coefficient curve slope, the damping ξ_{spm} of the short period mode proves to be much smaller.

Indeed in the analytic expression of the damping ξ_{spm} , the lift aerodynamic coefficient derivative due to angle-of-attack $C_{L\alpha}$ is smaller or negative post stall and the pitching moment derivative due to pitch rate Cm_q is small since the tail is under the main wing wake and thus is inefficient in deep stall.

In the developed model, for an elevator angle $\delta_e = -2.3\text{deg}$, the characteristics of the short period mode are the following ones.

The short period mode corresponds at high angle-of-attack (for an airspeed $V = 83.5\text{m/s}$ at an altitude of 10 km) to the eigenvalue $-0.058 \pm 1.52i$ with a damping $\xi_{spm} = 0.04$ and a frequency $\omega_{spm} = 1.52$ rad/s and at low angle of attack (airspeed $V = 122\text{m/s}$ at an altitude of 10 km) to the eigenvalue $-0.697 \pm 1.76i$ with a damping of $\xi_{spm} = 0.37$ and a frequency of $\omega_{spm} = 1.89$ rad/s.

We observe effectively in this numerical application that the damping of the short period mode is far smaller at high AOA than at low AOA.

The theoretical background is presented and the clues allowing the detection of situations leading to deep stall are described. The summary of this theoretical work help producing an algorithm for the identification of deep stall.

5. PROPOSED DEEP STALL IDENTIFICATION ALGORITHM

After studying the phase portrait and assessing the damping of the short period mode, it is possible to predict if it converges towards the equilibrium at a low or high angle of attack.

In the study of the phase portrait $(\alpha, \dot{\alpha})$, the first step is to determine whether there are three extrema of the function $\alpha = f(\dot{\alpha})$ or not that is to say local extrema $(\alpha_{\min}, \alpha_{\max})$.

If there exists, for continuity reasons, there must also be two extrema of the function $\dot{\alpha} = f(\alpha)$ corresponding to $(\dot{\alpha}_{\min}, \dot{\alpha}_{\max})$.

Next the second step is to study how these angles-of-attack are ordered so as to determine of which type the time evolution is.

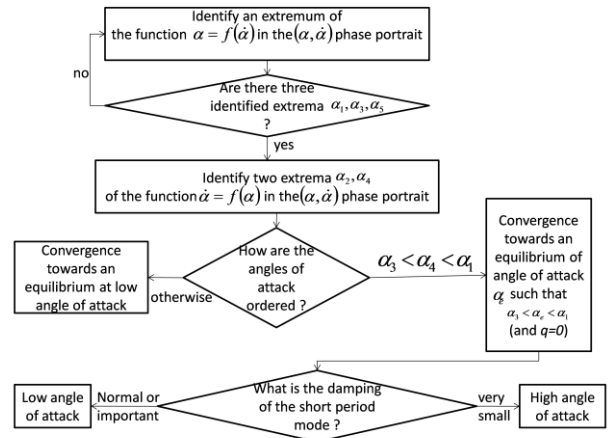
If the case corresponding to figure 5 is observed near the saddle-node where the aircraft flies towards the equilibrium at medium AOA, next is repelled from it and reaches low AOA, then the airplane must fly towards the equilibrium at low angle of attack.

If the case corresponding to figure 6 is encountered where $\alpha_1 > \alpha_2 > \alpha_3$ and

$\alpha_3 < \alpha_4 < \alpha_5$ and the AOA of the extrema are moving nearer and nearer, then the aircraft must fly and convergence towards one of the two stable equilibria.

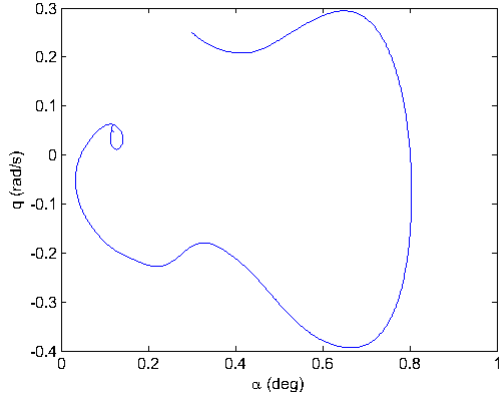
In order to make the discrimination between stabilization at high or low angle of attack, since the damping of the short period mode ξ_{spm} in a configuration of deep stall proves to be far smaller than in a normal configuration, the value ξ_{spm} is used as deep stall indicator.

This complete algorithm is summed up in the figure 4.



- Figure 4. Algorithm for the prediction of deep stall

After describing the prediction method, it is applied in two concrete situations. The first one is a time evolution where the aircraft flies near the unstable equilibrium at medium AOA. The second one is a flight where the aircraft flies and stabilizes itself in the deep stall equilibrium at high AOA.

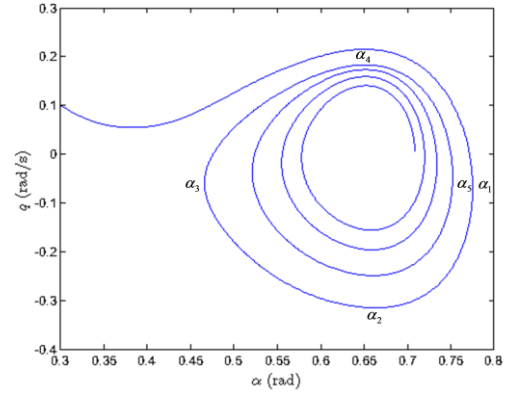


- Figure 5. Phase portrait of a time simulation where the airplane converges to an equilibrium at low AOA after flying near the saddle-node at medium AOA

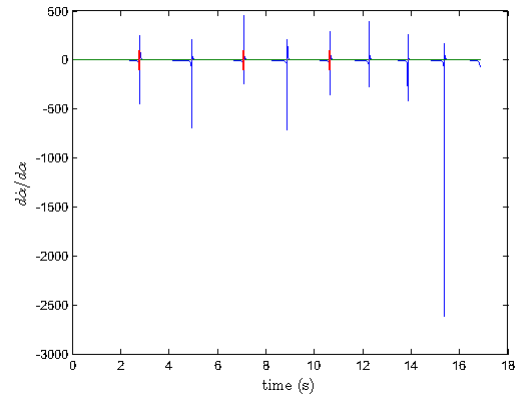
The other case presents a typical phase portrait of a simulation converging towards an equilibrium state (airspeed $V = 81.5m/s$, AOA $\alpha = 0.7rad = 40.6deg$, altitude $h \approx 10km$) in the figure 5. Consecutive AOA for which $\dot{\alpha} = 0$ (or equivalently $d\dot{\alpha}/d\alpha = 0$ or $q = 0$) are $\alpha_1, \alpha_3, \alpha_5$ and the ones for which $\dot{q} = 0$ (or $d\dot{q}/dq = 0$ or $q = 0$) are α_2, α_4 .

Since $\alpha_3 < \alpha_4 < \alpha_1$, the AOA are not ordered in a progressive manner and are closer and closer. This is a feature associated to an aircraft converging towards a stabilized AOA.

We can analyze next the damping of the short period mode. At high AOA, since the α derivative of the lift coefficient $C_{L\alpha}$ is reduced or even negative, the damping is always smaller ξ_{spm} than at low AOA as here where $\xi_{spm} \approx 0.04$. But in deep stall, since the tail is under the main wing wake and thus inefficient, the moment arm due to the tail is clearly reduced. As the main factor of the pitching coefficient derivative Cm_q due to pitch rate, this last one is also affected. (It may remain only the contribution of the flight control system).



- Figure 6. Phase portrait of a time simulation where the airplane stabilises itself to an equilibrium at high AOA



- Figure 7. Local extrema determination and organization for the time simulation in the figure 6

When a stabilization at a low AOA occurs, the damping of the short period mode is far bigger that is to say the stabilized AOA is reached clearly quickly after only one or a few periods. This feature seems quite useful to point out in order to warn the pilot of a forthcoming deep stall. Nevertheless the simulation processed in the figure 7 may be noisier in a real case and thus requires adapted filtering so as to determine the damping and the motion.

6. CONCLUSION

In this study of the dynamic behaviour of a T-tailed airplane in deep stall, several points were dealt with.

First the phase portrait made of the AOA and pitch rate reveals itself to characterize well the behaviour of an airplane prone (or not) to deep stall. The decoupling of (α, q) from the rest of the movement is a reasonable hypothesis. Next the stabilization at low or high angle-of-attack is discriminated by a relevant criterion

that is to say the damping of the short period mode.

At the end, a theoretical algorithm is built which allows predicting far in advance if the T-tailed airplane flies towards a deep stall equilibrium or not.

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