In-flight identification of conditions leading to an aircraft deep stall

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Abstract

Deep stall consists in a stable equilibrium at high angle-of-attack for which a fatal issue is almost unavoidable. It is thus helpful to identify in-flight critical parameters in order to warn the pilot as soon as possible on the forecoming hazardous situation and to allow him to take an important decision.

Civil transport airplanes with T-tail are mainly considered. This type of aircraft can meet deep stall when the wake of the main wing flows over the tail and render it ineffective. A fighter with canards may also be affected by such a phenomenon. The criteria are applied on the observed behaviour and may be helpful during flight tests for example. (The design phase is not here the core objective of this study.)

On the one hand, the damping of the short period mode is a valuable indicator. Due to the loss of the tail efficiency and the lower lift coefficient derivative due to angle-of-attack in deep stall, the damping of the short period mode proves to be much smaller.

On the other hand, the characteristics of the equilibrium at medium angle-of-attack (saddle node equilibrium) allow to draw a quick conclusion once the airplane flew near this point. Indeed the phase portrait in the (α, q) plane reveals some typical features which may be exploited to diagnose a future attraction towards the deep stall equilibrium.

Moreover the robustness of the criteria is examined with several parametric variations (static margin, etc.) and some noise is added (simulating captor or turbulence properties).

Finally, the different criteria are shown to help pilots and in-flight engineers detecting sufficiently early the conditions leading to deep stall during flight (tests) at high angle-of-attack.

1. 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 point of view of flight dynamics, 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 about a possible forecoming deep stall.

The main objective of this work is to find ways to identify in-flight conditions leading to deep stall. Normally an aircraft is designed so as to avoid these nefast opportunities by directly limiting the reachable angle-of-attack. But once in an aft-centered specific configuration or during flight tests aiming at opening the stall domain, it is intesting to have some indicators at disposal warning as soon as possible of the predicted fatal issue in order to allow the pilot to react adequately while it is still possible or easy to make something concrete.

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

The analysis is based on two features. One concerns the damping of the short period mode. The other one deals with the properties of the equilibria and the implied behaviour in the (α, q) phase portrait. An identification algorithm is then presented. These items are used for the analysis of concrete situations. Some noise is also added to test the criterium robustness.

Finally, the method reveals to alert well in advance situations leading to deep stall without any a priori information on the aircraft.

2. Modelling a deep stall prone aircraft

The longitudinal flight dynamics is the restricted frame of this study that is to say no lateral movement and no asymmetric stall for example are taken into account. Thus the chosen dynamic model involves aerodynamic velocity V, angle-of-attack AOA α, flight-path angle γ, pitch rate q and height h as state variables and elevator δ_e, thrust throttle δ_x as controls.

$$X = \{V, \alpha, \gamma, q, h\}, U = \{\delta_e, \delta_x\} \tag{1}$$

As far as the aerodynamics is concerned, the NASA wind tunnel experiments for a Learjet aircraft[1] is exploited for the static part i.e. $C_L(\alpha, \delta_e), C_D(\alpha, \delta_e), Cm_{static}(\alpha, \delta_e)$. This static part of the pitching moment determines the AOA equilibria. Deep stall occurs when there exists a stable equilibrium at high AOA for a given elevator, center of gravity and configuration (flaps up/down, etc).

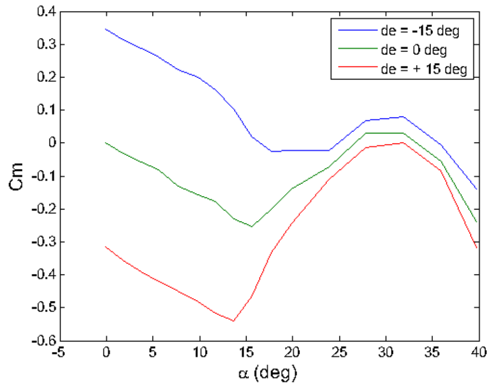

Figure 1: Pitching aerodynamic coefficients for Learjet aircraft with flap down[1] for different elevator angles (full pitch up, neutral, full pitch down) with the center-of-gravity at 25% of the chord

The loss of the tail efficiency in deep stall also affects the pitch rate derivative Cm_q of the pitching aerodynamic coefficient. Indeed the tail creates normally a lever arm opposite to the aircraft movement along the y-axis due to a modification of the effective incidence. The effect of deep stall is visible for a range of AOA and is approximated like in[3] for study purposes.

The overall aircraft pitching moment takes the form:

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

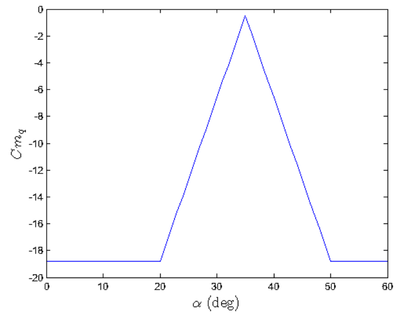

Figure 2: q-derivative Cm_q of the pitching coefficient in function of the angle-of-attack α including deep stall effect (study model)

Aircraft data are provided by[10] which takes also partly its sources from.[1]

After building a study-like aircraft model, the analysis is based on two aspects. On the one hand, we try to identify some properties of the dynamics near deep stall especially for the short period mode. On the other hand, there is an unstable equilibrium between two stable equilibria towards which the aircraft may converge. Their features allow to predict the possible stabilization at low or high AOA.

3. Short period mode characteristics

By linearizing the dynamics of the lift and pitch equations, we can get analytical estimations of the pulsation ω_{spm} and of the damping ξ_{spm} for the short period mode.

$$\omega_{spm}^2 = -\frac{V_e^2 \rho c_W S_W}{2 I_{YY}} \left[\frac{c_W}{V_e} \left(\frac{\rho S_W V_e}{2m} C_{Z_\alpha} + \frac{T}{m V_e} \right) Cm_q + Cm_\alpha \right] \quad (3)$$

$$2\xi_{spm}\omega_{spm} = \frac{\rho S_W V_e}{2m} C_{L_\alpha} - \frac{c_W^2 \rho S_W V_e}{2 I_{YY}} Cm_q + \frac{T}{m V_e} \sin\alpha \quad (4)$$

where m is the aircraft mass, I_{YY} is the aircraft moment of inertia about y-axis at gravity center, c_W and S_W the chord and surface of the main wing, ρ the air density, T the thrust.

Because of the loss of tail efficiency in deep stall and of the lower lift coefficient curve slope, the damping ξ_{spm} of the short period mode is much smaller at high AOA than at low AOA. In deep stall compared to a normal stall where only the lift coefficient curve slope is lower, the pitch damping is also affected and reduced. Thus a very small damping of the short period mode seems to indicate a forecoming deep stall.

Classical flight dynamics theory states that the short period mode involves the AOA and pitch rate 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.

Indeed in the analytic expression of the damping ξ_{spm} , the lift aerodynamic coefficient derivative due to angle-of-attack C_{L_α} 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 $\delta_e = -3$ deg , the characteristics of the short period mode are the following ones. The short period mode corresponds at high angle-of-attack ($\alpha = 34.4$ deg for an airspeed $V = 65.8 m/s$ at an altitude of $6 km$) to the eigenvalue $-0.077 \pm 1.88i$ with a damping $\xi_{spm} = 0.04$ and a frequency $\omega_{spm} = 1.88 rad/s$ and at low angle-of-attack (5.1 deg for an airspeed $V = 122 m/s$ at an altitude of $6 km$) to the eigenvalue $-0.691 \pm 1.59i$ with a damping of $\xi_{spm} = 0.40$ and a frequency of $\omega_{spm} = 1.74 rad/s$. 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 helps producing an algorithm for the deep stall identification.

After analyzing the properties of the short period mode and especially the damping, we will focus our attention on the characteristics of the equilibria (specifically the saddle-node at medium AOA) and of the implied phase portrait.

4. Time evolutions and equilibria

T-tail aircraft may meet deep stall for several ranges of elevators and static margins. For such critical cases, there are three equilibria for one fixed elevator angle δ_e corresponding to AOA α for which the overall pitching moment is zero $Cm(\alpha, q, \delta_e) = 0$ and $q = 0$ that is to say 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[8]) and the deep stall one which is the stable equilibrium at high AOA. From classical flight dynamics considerations, we know that there is static stability at an equilibrium point when the α-slope of the pitching coefficient is negative: $\frac{\partial Cm}{\partial \alpha} < 0$.

We can distinguish two types of behaviours by analyzing the typical (α, q) phase portrait[9] of a deep stall prone aircraft.

First, when the airplane converges towards a stable equilibrium point, the distance between two angles-of-attack for which $q = 0$ is more and more reduced.

Secondly, in the neighbourhood of the (saddle-node) equilibrium at medium AOA, all the trajectories are attracted by this equilibrium and then repelled from it. The trajectories remaining at the right of this equilibrium stay in the area delimited by the (red) stable manifold which is indeed the basin of attraction of the equilibrium at high AOA.[9] The other trajectories converge towards the low AOA equilibrium.

This statement allows predicting the convergence towards the equilibrium at low or high angle-of-attack, once the airplane flew near this saddle-node. It is also possible besides to foresee the future attraction point by studying also the evolution of the AOA α values for which $q = 0$.

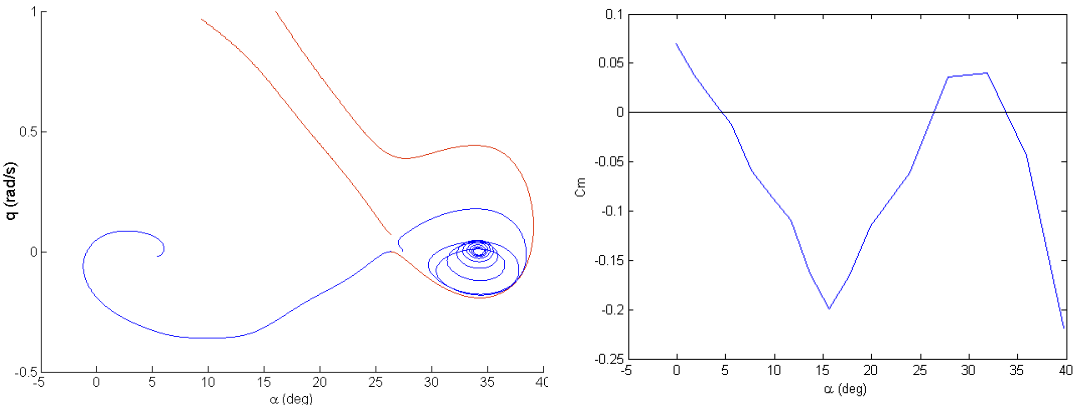

Figure 3: Typical (α, q) phase portrait (of an aircraft which is prone to deep stall) and the associated pitching moment coefficient

Once the characteristics of the possible time evolutions and equilibria are drawn and the properties of the short period mode in the deep stall neighbourhood are pointed out, we try to use these knowledges so as to build an algorithm able to identify a flight in a dangerous situation of forecoming deep stall.

5. Algorithm for the deep stall identification

The algorithm analyzes first the relative positions of the extrema in the $(\alpha, \dot{\alpha})$ phase portrait that is to say of the angles-of-attack for which $\dot{\alpha} = 0$ and $\frac{d\alpha}{d\dot{\alpha}} = 0$. After drawing a conclusion about the possible convergence, the algorithm decides whether the aircraft stabilizes itself at high or low AOA using if necessary the damping value of the short period mode.

For a trajectory in the $(\alpha, \dot{\alpha})$ phase portrait, the algorithm determines first whether there are three extrema of the function $\alpha = f(\dot{\alpha})$. Then, for continuity reasons, if these three AOA $\alpha_1, \alpha_3, \alpha_5$ exist, there must also be two extrema of the function $\dot{\alpha} = f(\alpha)$ corresponding to $(\dot{\alpha}_{\min}, \dot{\alpha}_{\max})$ whose associated AOA are α_2, α_4.

The order of these angles-of-attack helps distinguishing two situations.

After flying near the equilibrium at medium AOA, if the aircraft is repelled from it towards the low AOA region, then the airplane is bound to fly towards the equilibrium at low angle-of-attack.

If the extrema are ordered such that $\alpha_1 > \alpha_2 > \alpha_3$ and $\alpha_3 < \alpha_4 < \alpha_5$ and the distance between these AOA is more and more reduced, then the aircraft must convergence towards one of the two stable equilibria.

Finally, the difference of damping of the short period mode ξ_{spm} in a deep stall prone configuration and in a normal configuration can be used so as to determine whether it stabilizes itself at low or high AOA. Thus the value ξ_{spm} is used as deep stall indicator.

The identification algorithm is summarized in the figure 4.

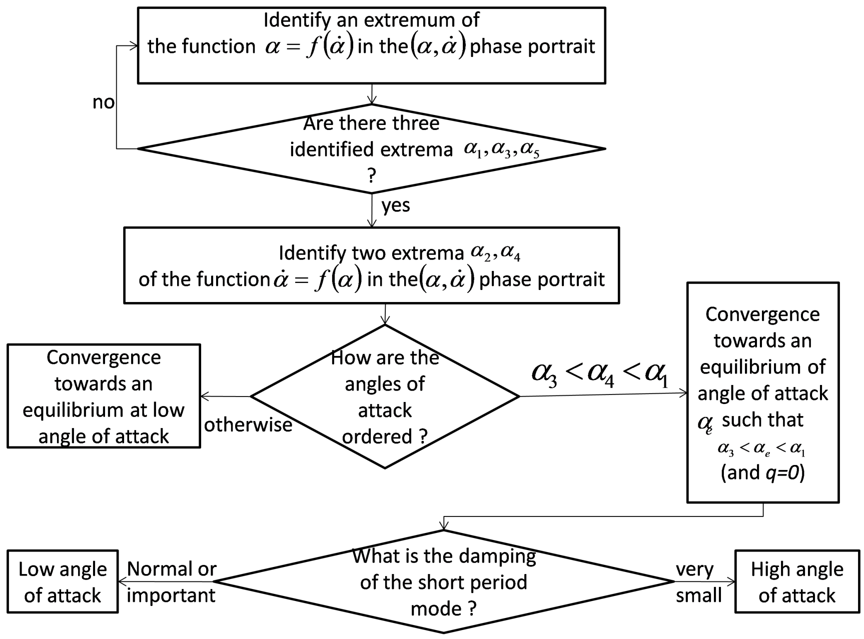

Figure 4: Algorithm for the prediction of deep stall

We present next two cases, one for which the aircraft flies near the medium AOA equilibrium and another one for which the airplane stabilizes itself at high AOA in deep stall.

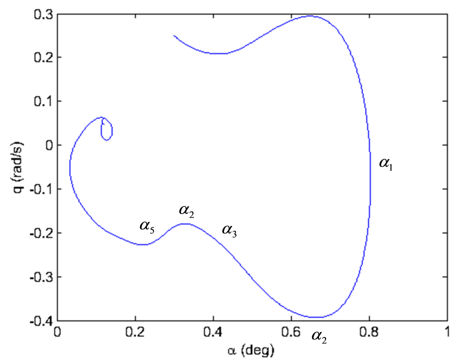

Figure 5: Convergence towards an equilibrium at low AOA after flying near the medium AOA equilibrium

In the figure 5, the AOA for which $\dot{\alpha} = 0$ are $\alpha_1, \alpha_3, \alpha_5$ and the ones for which $\frac{d\alpha}{d\dot{\alpha}} = 0$ are α_2, α_4.

Since $\alpha_3 < \alpha_4 < \alpha_1$, the AOA are not ordered in a progressive manner and the aircrat flies near the medium AOA equilibrium (from higher to lower AOA). This indicates that the aircraft must converge towards the stabilized low AOA.

In the figure 6, the distance between even AOA α_i (for which $\frac{dq}{d\alpha} = 0$) and the one between odd AOA α_i (for which $\dot{\alpha} = 0$) are more and more reduced (In the demonstrations, using q instead of $\dot{\alpha}$ is equivalent actually). It shows a typical behaviour of convergence.

By calculating the damping of the short period mode next, the asymptotic AOA is predicted i.e. stabilization at high or low AOA. Indeed, at high AOA, since the derivative of the lift coefficient C_{L_α} is reduced or even negative, the damping is always smaller ξ_{spm} than at low AOA. But in deep stall, since the tail is under the main wing wake and thus inefficient, the lever arm due to the tail is clearly reduced. The main factor of the pitching coefficient derivative Cm_q due to pitch rate is also affected. It remains only the potential contribution of the flight control system.

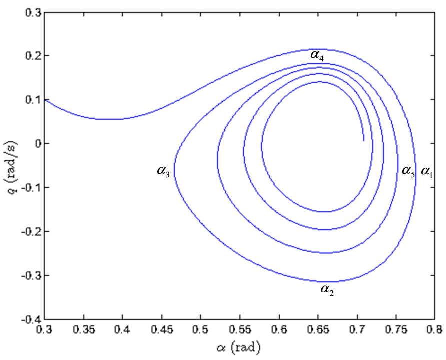

Figure 6: Phase portrait of a time simulation where the airplane stabilizes itself to an equilibrium at high AOA

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 forecoming deep stall and to allow the pilot to react precocely and adequately.

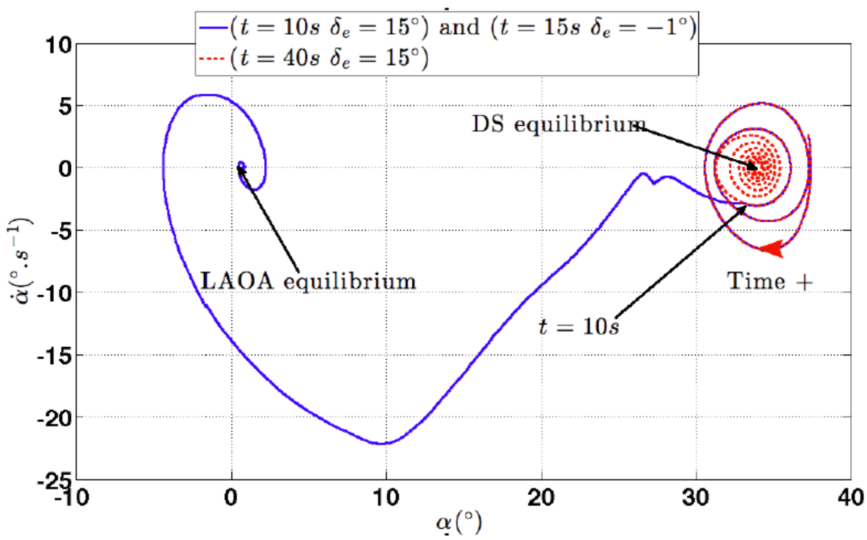

Figure 7: By predicting deep stall precocely, the pilot reaction allows to change the airplane final angle-of-attack

In the figure 7, the pilot of the blue curve is warned of a forecoming deep stall after one cycle of abnormal low damping of the short period mode and makes a pitch down command, contrary to the pilot of the red curve who reacts later and doesn't succeed in avoiding the deep stall equilibrium.

Nevertheless the state values estimated by captors may be noisier in a real case and thus requires adapted filtering so as to determine the motion and the damping.

6. Robustness of the identification

For real data coming directly from captors, the measures of AoA and pitch rate are noisy. It is thus interesting to know if the numerical estimation of the damping is good enough in order to identify a deep stall prone configuration.

Figure 8: Noisy time evolution at high and low angles-of-attack α

From the AOA α evolution with noise, we estimate the properties of the first harmonic. It gives $\xi_{SP} = 0.1176$ and $\omega_{SP} = 1.6963 rad/s$ for the high AOA, $\xi_{SP} = 0.3410$ and $\omega_{SP} = 1.8324 rad/s$ for the low AOA. Even if there is noise, the discrimination with the level of damping is still possible in this illustrative example.

All the work performed allows to predict the forecoming deep stall and to react in advance as in the figure 7. The adequate moment for which the pilot must react sucessfully remains to determine. The subject of the next sections consists in finding the good opportunity and method so as to recover.

7. Recovery

Several recovery procedures are tested since predicting the deep stall is useful only if it is possible to react adequately. First a static recovery is performed with a classical pitch down command. Next a dynamic method based on an oscillating elevator control leads to the airplane recovery.

Once the Learjet aircraft in its flap down configuration with a center-of-gravity at 25% of the chord is stabilized at high AOA, a pitch down command is applied. Depending on the moment when this action is applied, the aircraft succeeds in recovering from deep stall or not.

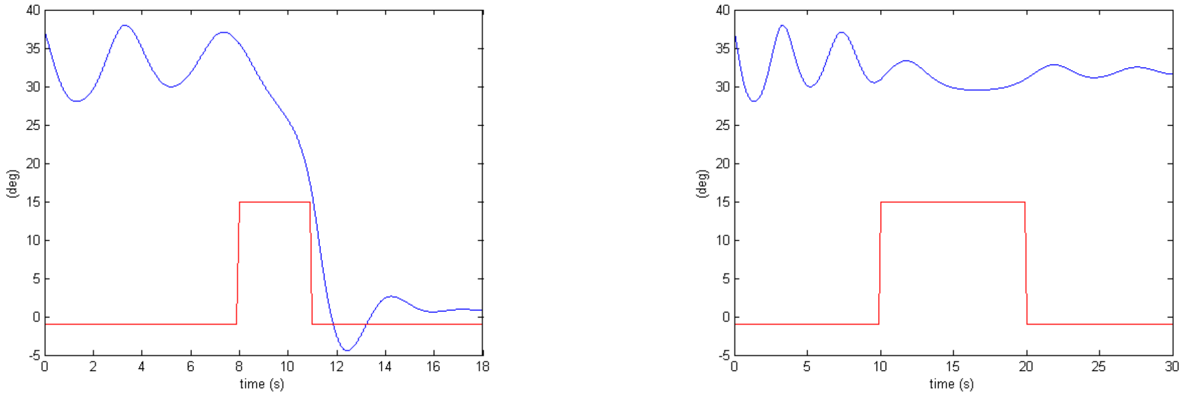

Figure 9: Pitch down maneuver for the Learjet aircraft recovery

It is visible that it is better to apply a pitch down command when the angle-of-attack decreases (with a negative pitch rate) and not when the angle-of-attack increases (with a positive pitch rate).

Besides for the F 16 aircraft, a recovery procedure is described in the NASA technical paper.[11] It consists in making the speedbrakes out and taking benefit from the generated pitching down moment and from the short period mode oscillations in order to create a resonance by an in-phase oscillating action of the pilot.

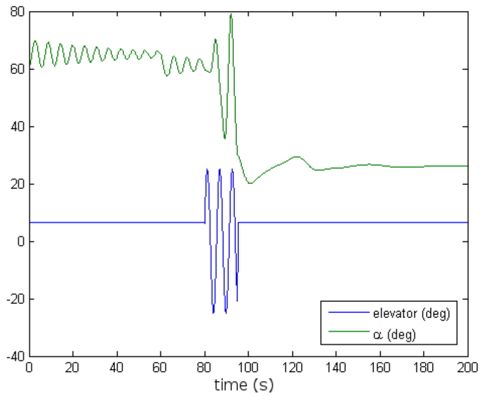

Figure 10: Dynamic recovery for the F 16 aircraft

In the figure 10, with an aft-centered aircraft (37.5% of the chord), the described procedure allows well to recover from the deep stall angle-of-attack.

8. Conclusion

In this study of the dynamic behaviour of a deep stall prone airplane, 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 which is prone (or not) to deep stall. We noted that 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 was built which allows predicting far in advance if an airplane flies towards a deep stall equilibrium or not. Several procedures were also applied so as to recover from a deep stall prone situation.

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