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A REVIEW OF THE INFLUENCE OF HIGH ANGLE OF ATTACK AERODYNAMICS ON AIRCRAFT DYNAMIC STABILITY

ABDUL HAMID A. GHMMAM

ZDOBYSŁAW GORAJ

Institute of Aeronautics and Applied Mechanics
Warsaw University of Technology

This paper presents a review of the most important flow phenomena associated with flying at high angles of attack, as well as behavior of aerodynamic stability derivatives under such flight conditions. A short note is given of problems encountered by todays fighter aircraft, when flying at a high angle of attack. Discussion of reliable aerodynamic and flight mechanics models is also included. The paper emphasises the fact that, for a correct prediction of aircraft motion at high angle of attack, significant changes in aerodynamic stability derivatives should be taken into consideration. New concepts in combat aircraft design require more attention to be given to the prediction of aircraft dynamic behavior at extreme maneuvers. At the early stages of the developing program, where wind-tunnel results are still not fully available, simple and reliable computational and prediction techniques of non-linear aerodynamic characteristics are required. In some flow regimes, especially for thin wings having sharp leading edges and/or tips the nonlinear Vortex Lattice Method can be recommended as giving load distribution and stability derivatives in good agreement with the experimental results.

Notation

α	–	angle of attack
β	–	angle of side slip
C_{l_β}	–	rate of change of rolling moment with the angle of side slip, similar definition for other derivatives
$\dot{\alpha}, \dot{\beta}$	–	time rate of change of the angles of attack and side slip, respectively

p – roll rate
q – pith rate
r – yaw rate
δa – aileron deflection
δr – rudder deflection
δe – elevator deflection

1. Introduction

Jet fighters appeared at the end of the World War II. Since then, they were a subject of an extensive research activity. Contribution from different fields has led to the amazing achievements in the field of combat aircraft.

Aerodynamics, above all, plays a cardinal role in design. The behavior of combat aircraft at high angle of attack, which is a fundamental criterion for high performance aircraft, is above all an aerodynamic problem. Stability and control coupled with aerodynamics, under these terms the ability of the aircraft to return to the reference flight condition automatically or with the intervention of the pilot is studied.

As it is well known, the main function of a fighter aircraft is to fulfill the mission as effectively as possible. This requires various maneuvers at different attitudes. Flying and maneuvering at high angles of attack has become the heart of research for more than two decades.

Aerodynamics and flight mechanics at large angels of attack, received attention, because of their decisive role in the aircraft behavior under the extreme flight conditions. In this work, a review of essential aspects relevant to high angle of attack aerodynamics and flight mechanics is given.

2. Remarkable aerodynamic phenomena at high angle of attack

For accurate prediction of the aircraft motion at high angle of attack, it is necessary to understand the aerodynamic phenomena related to flying at high angle of attack, due to the role this phenomena play in aircraft dynamics.

The following phenomena should be recognized, for high performance configurations (cf Boer and Conningham (1990)). Long pointed nose, sweep back wings, and sharp wing edges are typical of today's fighter configurations, other aerodynamic components such as vortex generators, and canard control surfaces have been utilized in the latest fighter aircraft generations. Therefore, these complex configurations are subjected to a complex flow field which can be described briefly as follows:

- As the angle of attack increases from small to moderate – flow separation over different components of the aircraft, such as wings, tail surfaces, fore body, starts to take place.
- As the angle of attack α increases – the cross flow around the fuselage starts to sweep the boundary layer towards the leeward side of the wing, then gradually rolls it up to a pair of vortices.
- With further increase in α – these vortices become non-symmetric, and at nearly the same time, wing leading edge vortices are formed.
- Increasing α even more – these vortices become unstable, and then they break down, at a certain point on the wing chord (vortex burst).
- Sometimes, the flow over the wing and the body may interact, which makes the flow field much more complex.
- The aforementioned phenomena can appear in both steady and oscillatory flight. For oscillating motion, the effect is much more evident, because various vortices change their lateral positions as a function of the angle of attack, which itself is a function of time. Different regions of flow as the angle of attack is changing from small to high and the Mach number is changing from zero to supersonic flow are shown in Fig.1 (cf Rom (1992)).

In short, flow regimes on slender configurations, which are typical for today's fighters, can be distinguished, as a function of the angle of attack as the following:

a – Very low angles of attack: attached, symmetric, steady flow, linear variation of, say, lift force with α.

b – Low angels of attack: attached, symmetric, steady with closed separation bubbles, nearly linear variation of aerodynamic forces and moments with α.

c – Moderate and high angles of attack: separated, symmetric, rolled vortices in steady flow, non-linear variation of aerodynamic forces and moments with α.

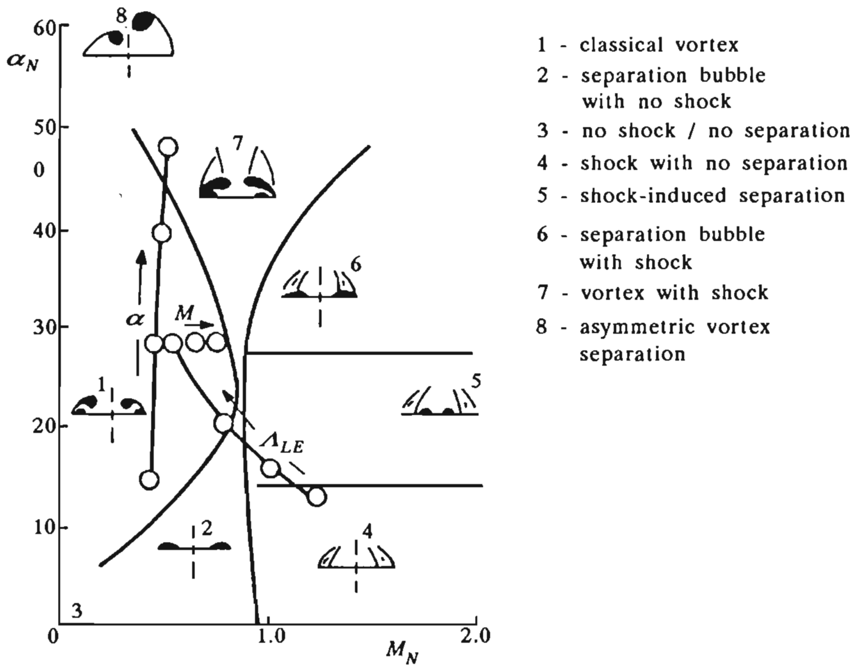

Fig. 1. Classification of flow structures over slender sharp-edge delta wings, see Rom (1992)

d – High angles of attack: separated, asymmetric, rolled up vortices in steady flow, non-linear variation of forces and moments with angle of attack.

e – Higher angles of attack: vortex break down, non-steady flow, loss of lift.

f – Very high angles of attack: separated flow, non-steady turbulent wake, post-stall aerodynamic characteristics.

It should be emphasized that in flow regimes described in items c÷f the strong nonlinearities between angles of attack and forces and moments can be observed. In a÷c flow regimes the panel methods are successfully applied (cf Goraj and Pietrucha [12], Kandil et al. (1976)). Even for leading-edge and tip separation in the sharp edges case prediction of the total aerodynamic loads and stability derivatives is numerically possible with good accuracy (cf Kandil et al. (1976)). Nonlinearities are caused by the crossflow and vortices shedding up from the leading-edge and tip sharp edges. Primary, secondary and even tertiary vortices were observed (cf Kandil et al. (1976)). Fig.2 shows substantial differences between results obtained from the linear and nonlinear

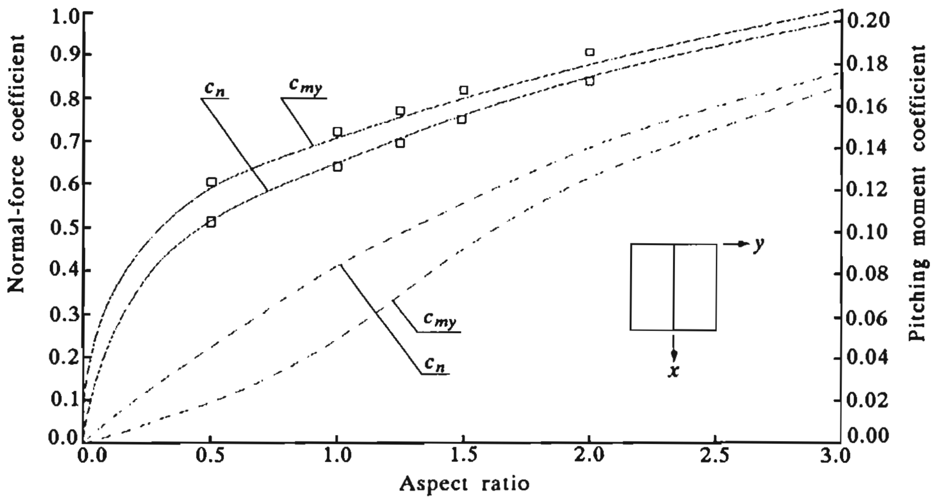

Fig. 2. Normal force and pitching moment coefficients vs aspect ratio at $\alpha = 15°$. Numerical results: linear (broken line) and nonlinear (solid line) Vortex Lattice Methods. Experimental results: □, see Kandil et al. (1976)

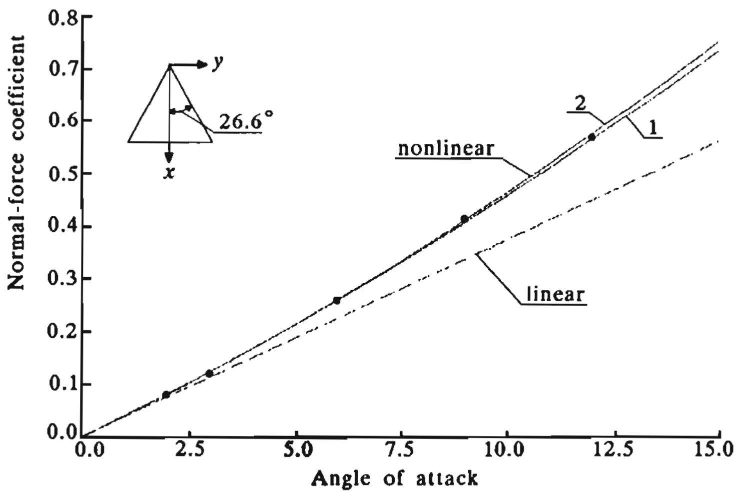

Fig. 3. Normal-force coefficient vs angle of attack, aspect ratio = 2. Numerical results: nonlinear Vortex Lattice Method (solid lines: curve 1 – 5 × 5 lattice, 2 – 6 × 6 lattice), linear (broken line). Experimental results: □, see Kandil et al. (1976)

Vortex Lattice Methods, respectively, for example for the aspect ratio equal to 1 the nonlinear theory gives the normal-lift coefficient value two times higher than that for the linear theory.

It can be seen from Fig.3 that for the angle of attack equal to 20° and the aspect ratio equal to 2 the difference between lift coefficients from linear and nonlinear Vortex Lattice Methods, respectively, is about 25%. It is obvious that corresponding stability derivatives will be different as well.

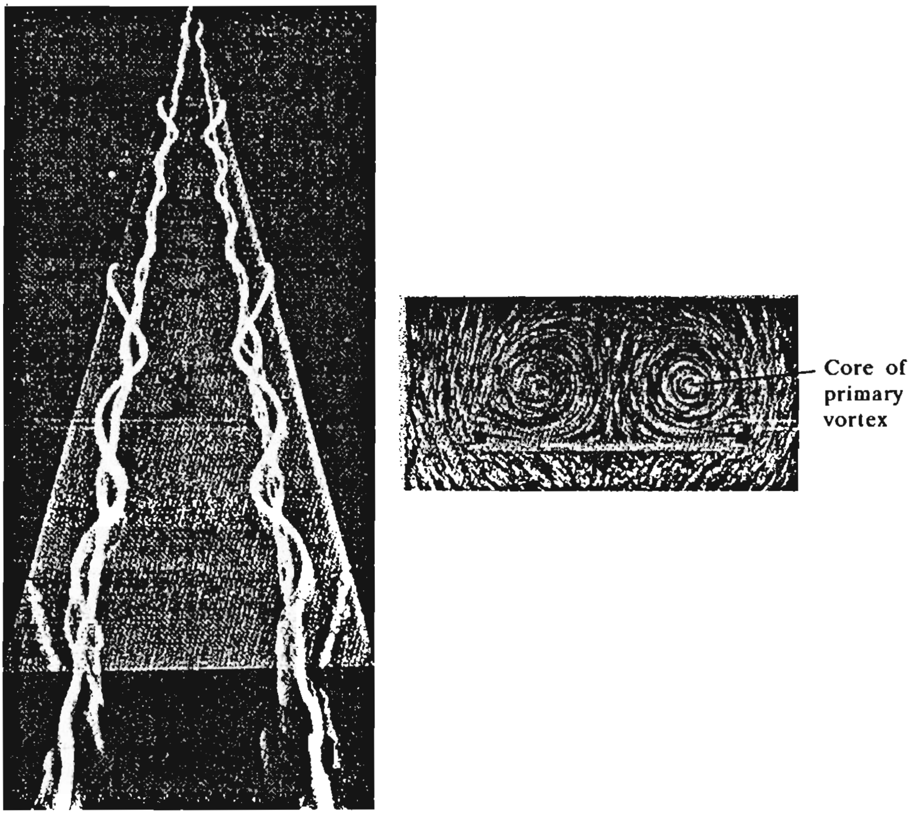

Fig. 4. Visualization of the rolled-up vortices over a delta wing-top view and cross-section view, see Werle (1958)

Transition from one phase to another, sometimes, is not clear. In fact, separation of flow can appear at a relatively small angle of attack, depending on many factors; such as, Reynolds number, imperfections of the surface etc. In general, the behavior is very configuration dependent. Orlik-Rückemann (1973), Orlik-Rückemann and Hanf (1978), Rom (1992) gave more detailed picture of the nature of flow at high angle of attack.

We should note here that all phenomena are very sensitive to any change in geometry, especially of the nose, and the wing leading edge, were different vortices are formed.

In fact forebody geometry is very important since asymmetric shedding of forebody vortices may cause potentially disastrous effects due to the large side force and yawing moment that could be encountered. Some techniques have been in use to alleviate these effects; e.g., modifying the nose shape and introducing small strakes near the tip (cf Chapman et al. (1975); Lowsn and Ponton (1992); Modi et al. (1992)). Fig.4 and Fig.5 illustrate some of these phenomena (cf Rom (1992); Werle (1958) and (1960)).

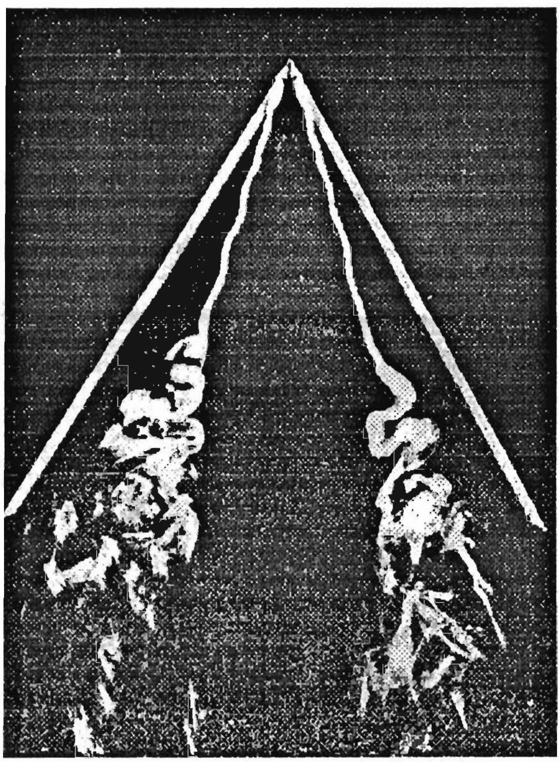

Fig. 5. Top view of breakdown of leading edge vortices on delta wing – symmetric case, no side slip, see Werle (1960)

3. Implications on aerodynamic stability derivatives

A flow with the complex picture described above, which is dominated by the formation and asymmetric shedding of forebody vortices, and the formation and asymmetric bursting of wing leading edge vortices, and interaction with the flow over the wing and other control surfaces, can affect significantly the aerodynamic forces and moments generated on different parts of the aircraft, hence on aerodynamic stability derivatives. Most important of these effects can be summarized as follows:

- **Non-linear variation of stability derivatives with the angle of attack**

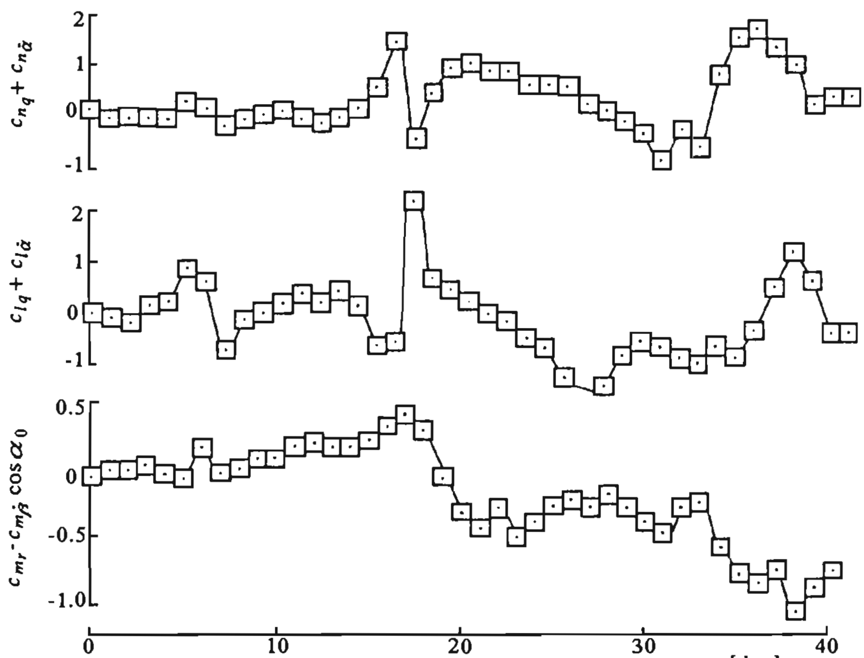

Fig. 6. Dynamic cross-coupling derivatives, wing-body configuration, $\Delta\theta = \Delta\psi = -1$ deg (NAE), see Orlik-Rückemann (1989)

The generation of different vortices shedding over the main aerodynamic surface (wing), causes extra negative pressure over the wing upper surface. This is believed to be the cause for the nonelinear behavior of forces and moments with such flows.

Usually, the suddenness and magnitude of variation are quite evident, Fig.6. At the non-linear region, stability derivatives undergo big changes even with small change in the angle of attack, e.g., $C_{l_q} + C_{l_{\dot{\alpha}}}$ undergoes big change at α, which equals nearly 18°, it contains even a change in sign. Similar trends are observed for the other two derivatives.

- **Significant aerodynamic cross-coupling**

As a result of non-symmetric flow, an aerodynamic cross-coupling exists, i.e. the resulting of longitudinal forces and moments due to a primary lateral motion, and a secondary lateral reactions as a result to a primary pitching maneuver (cf Orlik-Rückemann (1977)).

Cross-coupling effects are represented by their corresponding stability derivatives; such as pitching moment due to yaw, C_{m_r}, or rolling moment due to pitching, C_{l_q}, etc. Examples of cross-coupling terms are depicted in Fig.6, as measured in wind-tunnel experiments. The combined derivatives are obtained as a result of forced oscillations about fixed axis in these experiments (cf Orlik-Rückemann (1973)).

- **Time-dependent and hysteresis effects**

In the case of oscillating motion, purely unsteady effects exist (cf Lowsn and Ponton (1992)); e.g., derivatives due to the time rate of change in two aerodynamic angles α and β. In the past, with small α, the effects of $\dot{\alpha}$ and $\dot{\beta}$ were either ignored or substituted for by a simple formula. This is no more acceptable at high angles of attack.

In fact, as stated above, derivatives with respect to $\dot{\alpha}$ or $\dot{\beta}$ constitute a part of the results obtained in captive model testing. Getting these derivatives separated from each other is very important, this depends on the development in wind tunnel testing techniques that are being developed for some time.

Hysteresis effects were also observed with respect to both angle of attack and side slip; e.g., the position of the vortex burst, or the value of derivative depends on the direction of motion, weather it is from smaller to higher angle or vice versa (cf Lowsn and Ponton (1992)). One possible interpretation of this phenomenon, is that instantaneous aerodynamic reactions may entirely be independet of the motion variables at the instant considered, but also on the past history of the motion (cf Tobak and Shiff (1981)).

Experimental research has shown that cross-coupling and acceleration effects are comparable, in many cases, to direct and cross derivatives. Wind-tunnel techniques have been in progressive development to enable engineers to correct evaluation of unusual aerodynamic characteristics (cf Orlik-Rückeman and Hanf (1978)).

4. Aircraft dynamic problems at high angle of attack

Fighter aircraft are required to have excellent maneuverability in order to succeed in completing different missions (cf Nguen et al. (1985); Ross and Edwards (1985)). Devices such as limiters of the angle of attack, rate of roll or pitch are introduced to prevent the pilot from placing the aircraft in a region of poor lateral/directional stability (cf John and Kraus (1978); Skow and Titriga (1978)).

Aircraft with poor aerodynamic characteristics, need the control system to provide the required levels of stability in order to prevent the loss of control. In fact if the control system requirements become too restrictive, the ability of aircraft at maneuverability is reduced, so, it is more desirable to have an aircraft configuration with good high angle of attack aerodynamic characteristics with the control system used to enhance the maneuvering capability.

Many accidents,in the history of military flight, most of them were fatal, have been reported. In most cases the claim was put forward on flying at high angle of attack or performing extreme maneuvers where severe degradation in handling qualities is encountered (cf Chapman et al. (1975); Titriga et al. (1975)).

Even though, dynamic problems at high angle of attack are the out come of the interaction between the complex flow field over the aircraft, and the dynamic characteristics forced by the geometry of the configuration, the same phenomena are dealt with in different terminologies. Aerodynamicist talks about flow separation, vortical flows, non-linear reactions, etc, while pilot talks about buffeting, wing rock, spin, etc. However, the major problems that were experienced by pilots can be outlined, as follows:

- **Buffeting**

Buffeting is a vibration phenomenon where irregular flow separation and large pressure peaks are the causative mechanism. Buffeting causes changes in strains and stresses over the aircraft structure, these changes represent considerable danger in terms of flight mechanics and strength. To the pilot sever buffeting impairs concentration and causes serious difficulties in tracking the target (cf Ross and Edwards (1985); Huenecke (1987)).

Intensity of buffeting is measured as an acceleration component in the direction perpendicular to the flight path n_z. Typical ranges of buffet are, from buffet onset $n_z = -0.03$ g to a severe buffet at $n_z = -1$ g (cf Huenecke (1987)). At subsonic speeds, buffeting intensity increases with the angle of attack.

Buffeting could be encountered in transonic speeds. In this case a mechanism, related to formation of a shock wave, is responsible for the phenomenon. Damstrom and Mayes (1971) presented an analysis of flight and wind-tunnel tests to predict the buffet onset in the transonic Mach range. In general, characteristics of structure dynamics are very important in this case.

- **Wing rock**

At moderate angles of attack, experimental studies have shown that wing rock (wing roll oscillations) onset because of pressure changes on the upper surface of the wing near the tip, because of induced change in the angle of attack of the wing panel, which alternately cause leading edge stall and recovery (cf Nguen et al. (1985)). Another probable cause is the asymmetry of wing leading edge vortices in the case of slender wing, or forebody vortices (cf Ericsson (1990)).

Wing roll oscillations are usually accompanied by yawing motion, which makes it more severe. The combined motion is known as the nose slice (cf Skow and Titriga (1978)).

Wing rock onset is certainly a limit on tracking accuracy. Some aircraft have wing rock which diverges initially and then comes to a bounded moderate oscillations (in roll) amplitude (cf Ericsson (1990)). Huenecke (1987) suggested that roll oscillations of $10°/s$ (degrees per second), is the limit which permits target tracking. Ericsson (1990) discussed the different fluid flow problems which cause wing rock.

In fact wing rock is, in many cases, considered as an alarming mechanism, which provides information to the pilot that he is approaching or exceeding the maximum wing lift. Pulling further into heavy wing rock may initiate a departure from controlled flight, or possible entry to the spin recovery, from which is difficult or some times impossible.

Spin is not considered to be a combat maneuver, or, in other words a maneuver with no tactical utility. In the case of inadvertent entry to spin, recovery should be possible after a limited number of turns and without a large loss in altitude (cf Hancock (1969); William (1971)).

- **Roll reversal**

At certain point, during some maneuvers, the pilot can not use the ailerons as a roll controller, since the adverse yaw rolling moment overcomes the aileron power. This will lead to departure in yaw (cf Hancock (1969); also Titriga et al. (1975)).

In brevity: the characteristics of lateral motion are of the primary concern at high angle of attack (cf Ross and Edwards (1985)), since the departure from controlled flight is usually due to adverse characteristics of some modes of motion (e.g. dutch roll) combined with the loss of effectiveness of both the rudder and the aileron.

Researchers and engineers interested in this area have been trying to find a criterion of assessment the susceptibility of aircraft to departure or possible entry to spin. Some parameters have been introduced for this purpose such as the Lateral Control Departure Parameter (LCDP), which is defined as

$$\mathrm{LCDP} = C_{n_\beta} - C_{l_\beta}\frac{C_{n_{\delta a}}}{C_{l_{\delta a}}}$$

for aileron alone, $\delta_r = 0$.

For stability the LCDP must be positive (cf Skow and Titriga (1978); Huenecke (1987)).

Another parameter $C_{n_{\beta dyn}}$ has been introduced to define aircraft stability about flight direction (cf Skow and Titriga (1978)). Titriga et al. (1975) discussed these parameters also. Fig.9 shows some effects of the relevant stability derivatives on the aircraft lateral/directional motion.

- **Tumbling**

Tumbling is a sustained autorotative pitching motion. Even though most current fighters are not susceptible to this dangerous phenomenon, trends of future designs such as tail-less aircraft, and canard controls, may lead to more tumble prone design (cf Nguen et al. (1985)). More on this subject can be found in the paper by Paulson et al. (1983).

In general, at high angles of attack, trimming in pitch is sometimes a problem. Vectored trust at the nose, and blown high lift canards are currently being investigated as means for trimming in pitch, especially for STOL configurations, Paulson et al. (1983) gives the details of these methods.

Problems with trimming in pitch, have been recently reported with the X-31 research aircraft. As a part of the joint program between MBB[1] and Rockwell Co., in one of the assessment flights (1992) for the X-31, at approximately 60° angle of attack, a nose up pitching moment was encountered, and aircraft was also departed from controlled flight. Those problems were alleviated by introducing body strakes mounted on each side of the fuselage and also a nose area modifications, after which the same maneuver was completed successfully (cf Aviation Week/Space Technology (1993)).

[1]Messerschmitt-Bölkow-Blohm GmbH

Fig.7 ÷ Fig.9 present a good review of different dynamic problems encountered by aircraft as angle of attack increased. Serious degradation in handling qualities could be expected as the aircraft exceeds the conventional aerodynamic limit.

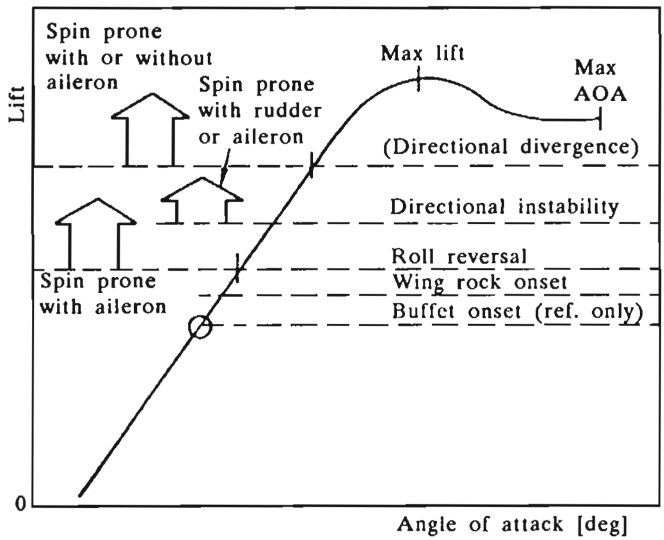

Fig. 7. Usable Lift, see Skow and Titriga (1978)

5. Modeling the aircraft dynamics

Current modern and future generation fighters are desired to have good agility characteristic, which means performing extreme maneuvers at high incidence, besides other requirements such as to maneuver at high rates of turn, and non-zero angle of side slip (cf Orlik-Rückemann (1977); Nguen et al. (1985)).

In the past, with small angle of attack, it was possible to use linear representation of stability derivatives (cf Etkin (1982)). These stability derivatives were calculated using linear methods, or determined in wind tunnel using simple oscillatory testing technique, and dynamic analysis is made at the last stages of design as if no dynamic problems are expected. Also aircraft dynamics is represented in a linear form with two sets of equations describing the aircraft longitudinal and lateral motion, separatly.

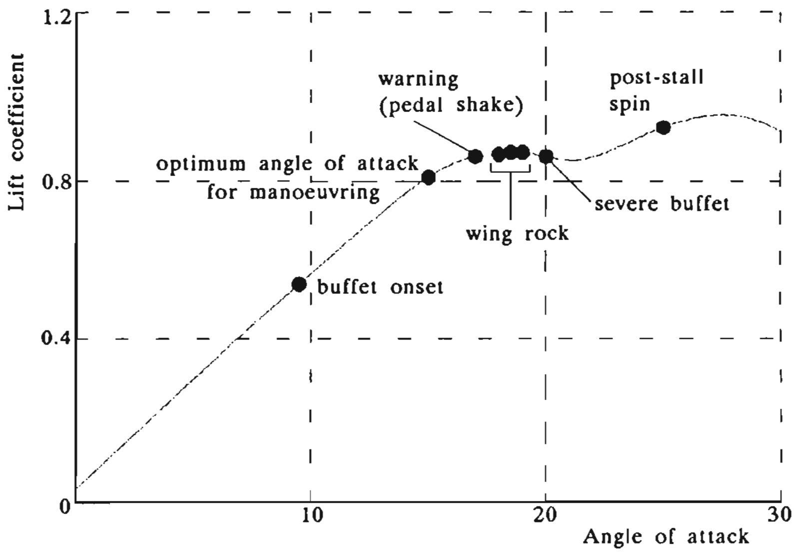

Fig. 8. F-4 at high angle of attack, see Huenecke (1987)

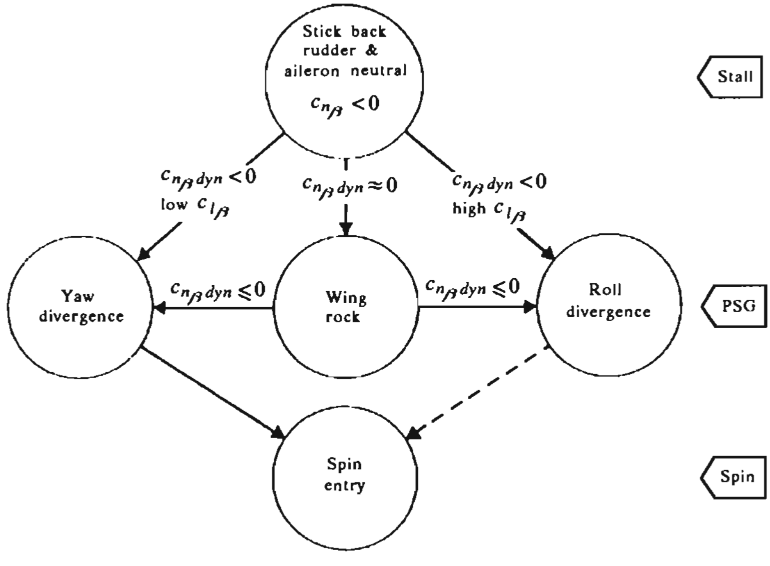

Fig. 9. Aerodynamic effects on open-loop lateral directional mode development, see Titriga et al. (1975)

With high angle of attack, because of the nature of the three dimensional complex flow (cf Almosnino and Rom (1983); Gordon and Rom (1985)), the mathematical model representing the aerodynamics and the flight dynamics of the aircraft must be revised (cf Orlik-Rückemann (1977); Huenecke (1987); Janke and Culick (1994)).

In this case linear representation is no more adequate, and hence an alternative method of representation is needed. In this respect, finding an analytical description of the stability derivatives with motion variables, say, α or β is not readily available (cf Titriga et al. (1975)), simply because of the odd behavior of the flow at high angles of attack. Another technique which has been used in some previous studies of aircraft dynamics, is to local linearize the stability derivative around the trim angle of attack (cf Ghmmam (1990)). With the expansion in the computer memory, variation of stability derivatives with different motion variables may be stored as array of data (cf Ross and Edwards (1985)), that, in fact, would be done at the expense of computer memory space.

With regard to wind tunnel experiments, advanced experimental techniques are required in order to extract full aerodynamic data representative of high angle of attack aerodynamics. A good survey of the present capabilities as well as the future needs are found by Orlik-Rückemann (1973) and (1989).

Having obtained a reliable aerodynamic representation, which contains all significant effects at high angles of attack, an adequate flight dynamic model is also necessary (cf Butler and Langham (1978)). This can be done by describing the aircraft motion with the set of full-non-linear equations of motion, with all the cross-coupling and acceleration terms retained. These equations must be solved simultaneously, since the modes of aircraft motion are highly coupled (cf Kalviste (1978); Huenecke (1987)).

The cross-coupling, in fact, is a character to aircraft motion at high angles of attack, or at any other asymmetric flight condition (e.g., moderate angles of attack and non-zero angles of side slip). Sensitivity studies done in the past, indicated a considerable change in predicted aircraft motion upon the inclusion or ignorance of cross-coupling terms (cf Ghmmam (1990)) gave more details about the relative importance of cross and cross-coupling stability derivatives, for a hypothetical fighter aircraft. Some of these effects, for $2g$ turn refrence flight condition are given in Fig.10.

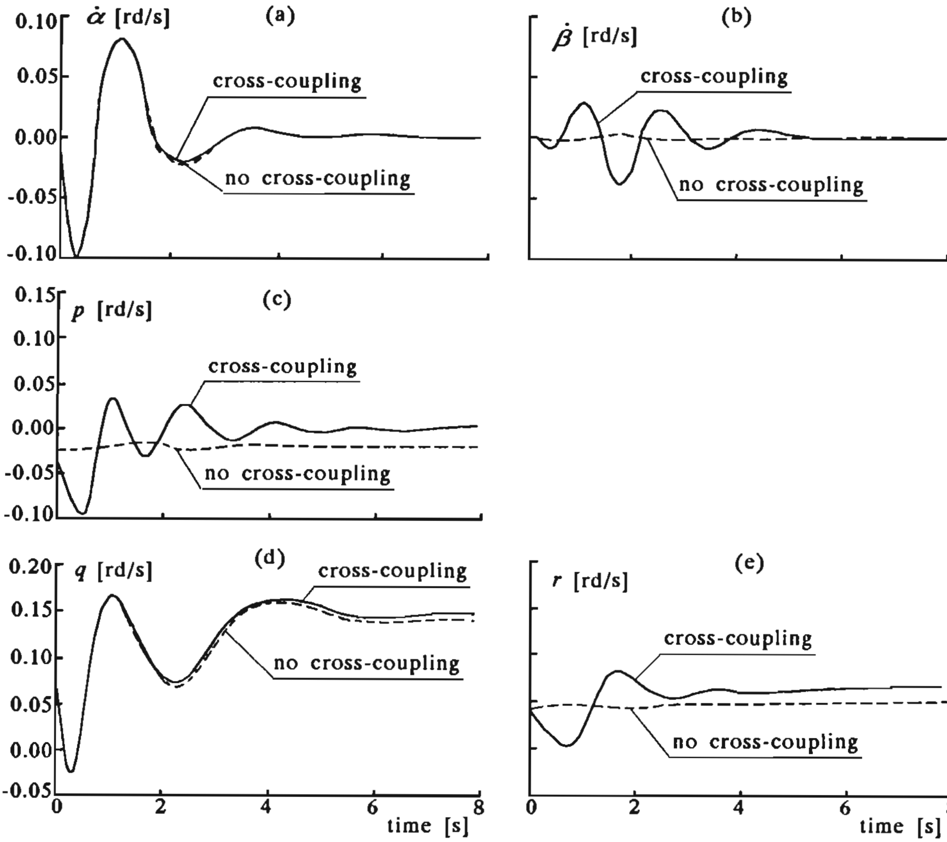

Fig. 10. Effect of cross-coupling in predicted aircraft motion, after Ghmmam (1990); perturbation impuls was: $\delta_e = 3°$ for $0 < t < 0.3$ s and $\delta_e = 0°$ for $t > 0.3$ s

6. Final conclusions and recommendations

Issues related to flying at high angle of attack are multiple and complex. The degree of complexity increases in proportion to the increase in the angle of attack. Having discussed many topics, some general conclusions and recommendations can be drawn from this review:

- Flow at high angle of attack is a complex phenomenon. Degree of complexity increases with the angle of attack. In the case of oscillating motion the flow is even more complex (cf Orlik-Rückeman and Hanf (1978); Huenecke (1987)).

- At high angle of attack cross-coupling, acceleration derivatives, and nonlinearities are significant and should be retained in the aircraft aerodynamic and dynamic stability model. This requires the solution to the full-non-linear equations of motion as one set (cf Orlik-Rückemann (1977); Orlik-Rückeman and Hanf (1978)).

- Since all phenomena are sensitive to any change in geometry, extrapolation from one configuration to another, may lead to poor representation in terms of aerodynamics, hence to poor prediction of the dynamic behavior (cf Orlik-Rückemann (1989)).
- Current and new generations of fighter aircraft are desired to have configurations of acceptable aerodynamic characteristics capable of enhancing aircraft maneuvering capability at large angles of incidence.
- With regard to serious problems that may be encountered at high angle of attack, dynamic study has to be done at early stages in any design and developing program, for high performance configurations, so any adverse characteristics can be early discovered, and then the suitable remedies can be implemented (cf William (1971); Titriga et al. (1975)).
- The preliminary design requires methods that are fast, reasonably accurate, and easy to use so that changes in aircraft configuration can be easily assessed.
- Fast and reliable computational models for calculating non-linear flow over complex geometry are needed. In this respect, non-linear panel methods seem to be promising (cf Kandill et al. (1976); Almosnino and Rom (1983); Rusak et al. (1983); Almosnino (1985); Gordon and Rom (1985); Ross and Edwards (1985); Rom (1992); Goraj and Pietrucha [12]).
- Recent advances in wind-tunnel testing facilities have been reported, were different cross-coupling and acceleration dynamic stability derivatives could be measured. Data obtained from wind tunnel could be used to validate numerical models for flow calculations at high angle of attack (cf Orlik-Rückemann (1973) and (1977); Orlik-Rückeman and Hanf (1978); Ross and Edwards (1985); Boer and Conningham (1990)).
- The basic principles discussed here are applicable to other areas of interest such as missiles and space shuttle, since they are subjected to the same flight conditions; i.e., high angle of attack, or a combination of moderate angle of attack and non-zero angle of side slip (cf Orlik-Rückemann (1977); Ross and Edwards (1985)).

- Finally, subjects related to high angle of attack, are numerous, and in many cases are also complex (cf Modi et al. (1992)), therefore a full coverage of all subjects in one paper is nearly impossible. Nevertheless, the authors tried to find the most important elements of the topic.

References

1. ALMOSNINO D., ROM J., 1983, Calculation of Symmetric Vortex Separation Affecting Subsonic Bodies at High Incidence, *AIAA Journal,* **21**, 3
2. ALMOSNINO D., 1985, High Angle of Attack Calculations of the Subsonic Vortex Flow on Slender Bodies, *AIAA Journal,* **23**, 8
3. *Aviation Week/Space Technology,* Page 29, May 17, 1993
4. BUTLER R.W., LANGHAM T.F., 1978, Aircraft Motion Sensitivity to Variations in Dynamic Stability Parameters, *AGARD-CP-235,* **35**
5. BOER R.G., CONNINGHAM A.M., 1990, Low-Speed Unsteady Aerodynamics of a Pitching Straked Wing at High Incidence, Part I: Test Program, *Journal of Aircraft,* **27**, 1
6. CHAPMAN G.T., KEENER E.R., MALCOLM G.N., 1975, Asymmetric Aerodynamic Forces on Aircraft Fore Bodies at High Angles of Attack-Some Design Guides, *AGARD-CP-199*
7. DAMSTROM E.K., MAYES J.F., 1971, Transonic Flight and Wind Tunnel Buffet Onset Investigation of the F-8D Aircraft, *Journal of Aircraft,* **8**, 4
8. ERICSSON L.E., 1990, Various Sources of Wing Rock, *Journal of Aircraft,* **27**, 6
9. ETKIN B., 1982, *Stability of Atmospheric Flight,* John Wiley & Sons, Inc. New York
10. GHMMAM A., 1987, An Investigation in to the Effect of Aerodynamic Cross-Coupling on Aircraft Motion at High Angles of Attack, M. Eng. Thesis, Dep.of Mech. and Aero. Eng., Carleton University, Ottawa, Canada
11. GHMMAM A., 1990, The Effect of large Angle of Attack of High Performance Fighter Upon the Aerodynamic Stability Derivatives, *Proceedings, International AMSE Conference "Signals and Systems",* Cetenje, Yugoslavia, **5**, 97-110
12. GORAJ Z., PIETRUCHA J., Panel Methods: A Routine Tool for Aerodynamic Calculation: The State-of-the-Art, *Journal of Theoretical and Applied Mechanics,* (submitted in 1993)
13. GORDON R., ROM J., 1985, Calculation of Non-Linear Subsonic Characteristics of Wings with Thickness and Camber at High Incidence, *AIAA Journal,* **23**, 6
14. HANCOCK G.J., 1969, Problems of Aircraft Behavior at High Angles of Attack, *AGARD Do Graph,* **136**
15. HUENECKE K., 1987, *Modern Combat Aircraft Design,* Airlife Publishing Ltd. England

16. JANKE C.C., CULICK E.C., 1994, Application of Bifurcation Theory to the High-Angle-of-Attack Dynamics of F-14, *Journal of Aircraft,* **31**

17. JOHN H., KRAUS W., 1978, High Angle of Attack Characteristics of Different Fighter Configurations, *AGARD-CP-247,* **2**

18. KALVISTE J., 1978, Aircraft Stability Characteristics at High Angles of Attack, *AGARD -CP-235,* **29**

19. KANDIL O.A., MOOK D.T., NAYFEH A.H., 1976, *Nonlinear Prediction of Aerodynamic Load on Lifting Surfaces, Journal of Aircraft,* **13**, 1

20. LEMAY S.P., BATILL S.M., NELSON R.C., 1990, Vortex Dynamics on a Pitching Delta Wing, *Journal of Aircraft,* **27**, 2

21. LOWSN M.V, PONTON A.J., 1992, Symmetry Breaking in Vortex Flows on Conical Bodies, *AIAA Journal,* **30**, 6

22. MODI V.J., CHENG C.W., MAK A., YOKOMIZO T., 1992, Reduction of Side Force on Pointed Fore Bodies through Add-On Tip Devices, *AIAA Journal,* **30**, 10

23. NGUEN L.T., RAYMOND D.W., BRANDOM M., 1985, Recent Experiments of Unsteady Aerodynamic Effects on Aircraft Flight Dynamics at High Angles of Attack, *AGARD-CP-386*

24. ORLIK-RÜCKEMANN K.J., 1973, Dynamic Stability Testing of Aircraft-Needs Versus Capabilities, *Proceedings of International Congress on Instrumentation in Aerospace Simulation Facilities,* Pasadena, CA

25. ORLIK-RÜCKEMANN K.J., 1977, Aerodynamic Coupling between Lateral and Longitudinal Degrees of Freedom, *AIAA Journal,* **15**, 12

26. ORLIK-RÜCKEMANN K.J., 1989, Implications of Unsteady Aerodynamics to Flight Dynamics, *Proceeding of 7th Applied Aerodynamic Conference, AIAA,* Seattle

27. ORLIK-RÜCKEMANN K.J., HANF E.S., 1978, Experiments on Cross-Coupling and Translational Accelerations Derivatives, *AGARD-CP-235,* **8**

28. PAULSON JR J.W., GATLIN G.M., QUINTO P.F., BANKS W., 1983, Trimming Advanced Fighters for STOL Approaches, *Journal of Aircraft,* **20**, 11

29. ROM J., 1992, *High Angle of Attack Aerodynamics, Subsonic, Transonic, and Supersonic,* Springer-Verlag

30. ROSS J.A., EDWARDS G.F., 1985, Correlation of Predicted and Free-Flight Response of High Incidence Research Model, *AGARD-CP-386*

31. RUSAK Z., WASSERSTROM E., SEGINER A., 1983, Numerical Calculation of Non-Linear Aerodynamics of Wing-Body Configurations, *AIAA Journal,* **21**, 7

32. SKOW A.M., TITRIGA A. JR., 1978, A Survey of Analytical and Experimental Techniques to Predict Aircraft Dynamic Characteristics at High Angles of Attack, *AGARD-CP-235,* **19**

33. TITRIGA A. JR., ACKERMAN J.S., SKOW A.M., 1975, Design Technology for Departure Resistance of Fighter Aircraft, *AGARD-CP-199*

34. TOBAK M., SHIFF L.B., 1981, Aerodynamic Mathematical Modeling-Basic Concepts, *AGARD-LS-114,* 1

35. Werle H., 1958, Aperçu sur les Possibilités Experimentales du Tunnel Hydrodynamique a Visualization de l'O.N.E.R.A., *ONERA Tech. Note,* 48

36. Werle H., 1960, *ONERA Rech. Aeron.,* 74, 23-30

37. William B. Jr., 1971, Influence of the Static and Dynamic Aerodynamic Characteristics on the Spinning Motion of Aircraft, *Journal of Aircraft,* **8**, 10

Problemy aerodynamiki dużych kątów natarcia i jej wpływ na stateczność samolotu

Streszczenie

Praca zawiera przegląd najważniejszych zjawisk towarzyszących opływom samolotów na dużych kątach natarcia oraz przedstawia ważne cechy pochodnych aerodynamicznych stateczności w tym zakresie parametrów lotu. Rozważane są również pewne problemy dynamiki współczesnych samolotów bojowych, operujących na dużych kątach natarcia oraz zagadnienia budowy adekwatnych modeli aerodynamiki i mechaniki lotu. W pracy podkreślono fakt, że w celu właściwej symulacji ruchu samolotu na dużych kątach natarcia, powinny być wzięte pod uwagę, znaczne zmiany pochodnych aerodynamicznych, w odniesieniu do pochodnych klasycznych. Nowe rozwiązania układów konstrukcyjnych współczesnych samolotów bojowych wymagają poświęcenia większej uwagi charakterystykom tych samolotów w manewrach ekstremalnych. We wczesnych fazach procesu projektowego, gdy pomiary w tunelu aerodynamicznym nie są jeszcze możliwe, proste i wiarygodne obliczenia numeryczne nieliniowych charakterystyk na dużych kątach natarcia mogą stanowić cenny materiał pomocniczy dla konstruktorów. Dla pewnych zakresów lotu, szczególnie dla samolotów mających ostre krawędzie boczne i krawędzie natarcia, godna polecenia jest metoda nieliniowej siatki wirowej (NVLM). Rozkład ciśnienia i pochodne aerodynamiczne uzyskane metodą nieliniowej siatki wirowej (NVLM) są w wybranych zakresach lotu w bardzo dobrej zgodności z wynikami eksperymentów.

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