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NEW DIRECTIONS OF RESEARCH IN AERONAUTICAL ENGINEERING – BREAKING THE BARRIERS[1]

ZDOBYSŁAW GORAJ

Institute of Aeronautics and Applied Mechanics, Warsaw University of Technology

e-mail: goraj@meil.pw.edu.pl

The paper reviews selected areas of aeronautical knowledge and technology, which play an important role in the progress in the whole branch. Among the discussed component technologies and facinating areas of research there are: super manoeuvrability, aerodynamics of vortex structures, new materials, smart structures, thrust vectoring flight control, low observability, unmanned aerial vehicles and ultra high altitude aircraft. The technologies discussed are in no way exhaustive but attempt to illustrate diversity both military and civil aviation. The paper is probably a little bit biased because of author's scientific interest in aerodynamics and flight dynamics. One of the aim of this review is to put the emphasis on the outstanding progress in aeronautics. In some cases one can talk about breaking the barriers. Among such barriers there are: flying at the post-stall range of angles of attack, controlling the flight path directly by thrust vectoring, being "invisible" for radar, flying at ultra high altitudes being driven by a piston engine – propeller power unit. The progress in aeronautics observed nowadays is not such spectacular as it was during passing through the sound barrier, but is still very impressive, important and continuous. Very often the progress in one field is possible due to achievements in the other one. An extensive review of bibliography recently published and related to the subject completes the paper.

Key words: aeronautical engineering, desing, computational fluid dynamics, manoeuvrability

1. Introduction

During the last decades we have observed an outstanding progress in aeronautical sciences. Fascinating achievements in Computational Fluid Dynamics

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(CFD), super manoeuvrability and high angles of attack, advances in material sciences, so-called smart structures, rapid development of the ultra high altitude aircraft and remotely controlled unmanned aerial vehicles – all these factors create the challenging world of aeronautics. Paper presents author's view on overall development of Aeronautical Sciences and in this sense it is selective, non-objective choice. The emphasis is put on these fields of aeronautical technology, which can contribute to general progress in the field and sometimes to breaking the barriers. Today barriers are not such exciting as those met at the beginning of aviation – a possibility of flying in the machines heavier than air or to fly faster than the sound speed. We will mention about four such barriers: to fly at the post-stall angles of attack [1,2], to control the flight path directly by thrust vectoring, to be "invisible" for radar, to fly at high altitudes being driven by a piston engine – propeller power unit. All these challenges are driven by military needs. Probably some of them will be applied to civil aviation sometimes in the future. For example, flying at ultra high altitudes using piston engines means flying "non expensive". It is very attractive for; e.g., investigators of the stratosphere physics, weather forecast needs, detecting of forest fires and support in directing the fire-fighters, monitoring of highways traffic. The progress in selected fields of aeronautical technology is possible due to outstanding achievements of other disciplines of technology, i.e. microelectronics, controls, material sciences, etc. On the other hand, it issues new, fascinating challenges to farther development of flight dynamics, aerodynamics, aeroelasticity, smart structures, etc. It accelerates to development in specified fields; e.g., super manoeuvrability, performances of unstable aircraft, stability of vortex structures, flutter of composite structures of high aspect ratio. In the paper we limit our considerations to super manoeuvrability, aerodynamics of vortex structures, development of new materials, smart structures, thrust vectoring flight control, low observability, unmanned aerial vehicles and, ultra high altitude aircraft. The main objectives of the paper are: short presentation of the most important areas of research in aeronautical engineering, responsible for the overall progress in the whole branch and an extensive review of the recent bibliography, as exhaustive as it is possible in this, rather limited presentation.

2. Important features of high angle of attack flight dynamics and aerodynamics

2.1. Flight dynamics

The appearance of new highly manoeuvrable air-to-air missiles and new on-board digital systems capable of receiving very weak reflected signals, resulted in a change in air fighting tactics. According to the new concept of air fighting, manoeuvring should enable the aircraft to "catch" an enemy aircraft in its sphere of successful shooting, being itself out of the successful shooting sphere of the enemy aircraft. It can be achieved due to extending the range of angles of attack or sustained manoeuvring at flight speed higher than that of the enemy aircraft (manoeuvring at supersonic speeds).

Flying at high angles of attack may involve some adverse effects, such as wing-rock, tail-buffet, nose-slice or spin departure phenomena. The manoeuvres may be restricted by inefficiency of the available control surfaces, causing insufficient pitching moment or inadequate roll response. Let us look at aerodynamics of high-alpha manoeuvres and start from the steady flight under these conditions. The flow around an aircraft is largely separated, unsteady and contains one or more vortex systems shedding from forebody and leading, side and trailing edges, respectively. As the angle of attack increases, these vortices can become asymmetric, even though the angle of sideslip remains zero. As alpha increases even further, the vortices undergo a breakdown. It starts somewhere in the wake and gradually moves forward towards the nose configuration. The vortex breakdown may cause major effects on the aerodynamic loads and render all aerodynamic characteristics highly non-linear.

Let us now look at an unsteady angular aircraft motion. Since the flow at higher angles of attack can be asymmetric even at zero sideslip, the forces and moments derivatives with respect to small disturbances of motion (so-called stability derivatives) have to include the aerodynamic cross-coupling between the lateral and the longitudinal degrees of freedom. The cross-coupling stability derivatives are of the same order of magnitude and importance as the classic, longitudinal or lateral derivatives.

Another important aerodynamic phenomena appearing at high angles of attack are: hysteresis, effect of angular rate and frequency on the forces and moments magnitudes and loss of the effectiveness of the traditional control surfaces. All these phenomena are depicted in Fig.1 and Fig.2. Fig.1 shows static and dynamic breakdown locations depending on the direction of angle of attack changing. The effect of pitch moment frequency on the rolling moment

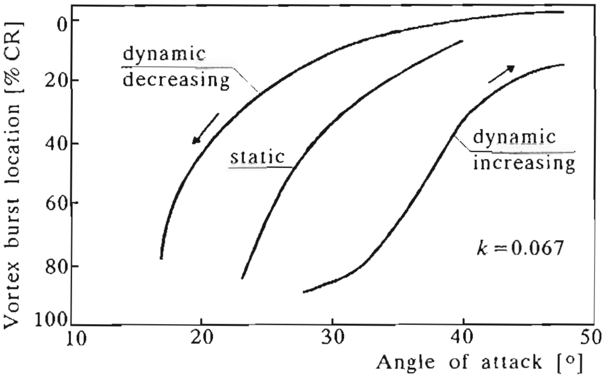

Fig. 1. Static and dynamic location of the vortex burst on a 70° delta wing (after Orlik-Rückemann, 1992)

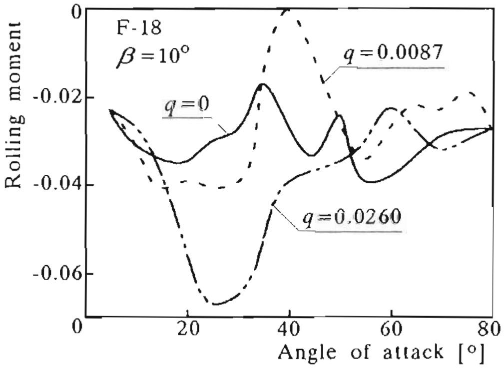

Fig. 2. Effect of positive pitch rates on the rolling moment (after Orlik-Rückemann, 1992)

is presented in Fig.2. Also, a loss of the yaw controllability delivered by traditional ruder is usually significant (cf Orlik-Rückemann, 1992).

To summarise the flow phenomena characteristic for moderate and high angles of attack, we emphasise the important features, different from those known for the small angles of attack:

- for moderate angles – some flow asymmetries, small time lags, moderate non-linearities, extended stability derivatives (which are functions of flight variables and include cross-coupling),

- for high angles – moderate flow asymmetries, significant time lags, large non-linearities (stability derivatives have no physical meaning and a new representation of dynamics is needed).

2.2. Super and hyper-manoeuvrability

At subsonic speeds the manoeuvring at supercritical angles of attack can be realised under two different flight conditions (Herbst, [4]). These states of flight are referred to as:

Super-Manoeuvrability (SM) – if the aircraft can fly at the angles of attack of $60° \div 70°$ with the capability of control in all channels

Hyper-Manoeuvrability (HM) – if the aircraft can fly at the angles of attack of $80° \div 120°$ with the capability of maintaining stability in all channels. In this flight regime the ability to apply a conventional control is usually lost.

In this sense the HM can be considered as the flight regime, in which the dynamic entrance into supercritical angles of attack is possible. It must be emphasised that the SM mode does permit $2 \div 2.5$ times decrease in the space of steady turn. An SM regime can be achieved by some aircraft of the fourth generation; i.e., Su-27 [5,6], MiG-29, F-15, F-16, F-18, and an HM regime can be achieved by Su-27, Su-37 and F-22.

2.3. Requirements for pitching moment characteristic

The necessary condition for fulfilling either an SM or HM regime of flight is the possibility of reaching an angle of attack higher than $60°$. For this aim the aircraft flying at supercritical angles of attack (higher than $30°$) be capable of:

- maintain a state of equilibrium at high angles of attack and
- possess a sufficient margin of pitching moment to rotate the nose down into the initial value of the angle of attack, i.e. α_{bal}.

Fig.3 shows qualitative characteristics of the pitching moment C_m for an aircraft, which is static stable, neutral and static unstable, respectively, all of them with the same angle of elevator deflection. The curves in Fig.3 show

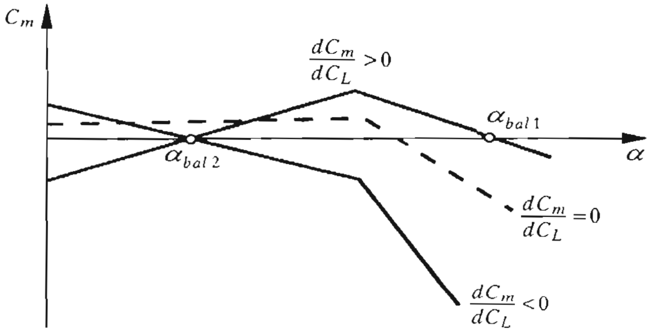

Fig. 3. Qualitative characteristics of the pitching moment for static stable, neutral and unstable aircraft (after [5])

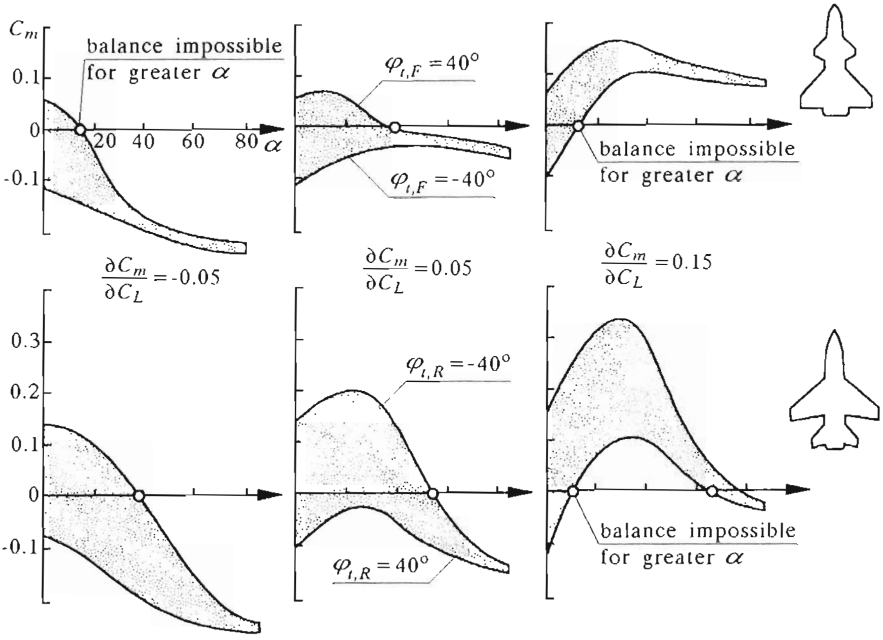

Fig. 4. Forms of pitching moments for classical and canard configurations (after [5])

the fundamental difference between the balances of static-stable and unstable aircraft. The static-stable aircraft with the tail setting angle φ_t = const has only one point of balance α_{bal}, whereas the static-unstable aircraft for φ_t = const has two different points of balance α_{bal}. It means that to realise either an SM or HM regime of flight the aircraft should be static-unstable at lower angles of attack and stable at the higher, post-critical ones.

Presented in Fig.4 there are some typical forms of pitching moments $C_m(\alpha, \varphi_t)$ for aircraft of the classical as well as the canard configurations. The curves (from the left to right side) correspond to different margins of static longitudinal stability (from the unstable aircraft $\partial C_m/\partial C_L = -0.05$ to the stable one $\partial C_m/\partial C_L = 0.15$).

These forms of pitching moment coefficients show that the equilibrium of moments for a classical configuration of aircraft is possible in a post-critical range of angles of attack. Also the return to the initial flight condition from high angles of attack $\alpha = 90°$ (i.e. from the HM regime of flight) is possible independently of the effectiveness of tail control surfaces.

2.4. Aerodynamics of vortex structures – burst phenomenon

Three design characteristics are required for an aircraft to be classified as super or hyper manoeuvring. Firstly, a high nose-up pitch control power is needed; secondly, strong lateral stability and control (both static and dynamic) are required; and thirdly, a robust pitch-down must be available. The significance of post-stall manoeuvring as an air-to-air tactic remains a matter of controversy [5,6]. However, one does not have the slightest doubt that it poses interesting scientific problems and stimulates various areas of research. First of all we should determine the vortex system over the wing, find where and how these vortices breakdown and calculate the overall forces and moments, find the conditions for stability, etc. Different formulations are used to predict the location of vortex breakdown, its strength and to simulate the influences on stability.

The most popular theories of vortex breakdown [7] belong to four main classes:

- Quasi-cylindrical approach and analogy to boundary layer separation
- Solution of the axisymmetric Navier-Stokes (NS) equation
- Concept of the critical state
- Hydrodynamic instabilities.

More advanced models, based on the bifurcation theory or using a direct numerical simulation of the problem have also been developed. In most cases, the obtained results are in good agreement with experimental observations, but the predictive capability of these theories is still limited.

The time-averaged incompressible NS equations in axisymmetric coordinate system (see [8]) very often constitute the base for analysis of the phenomenon similar in nature to the boundary layer problem, in addition with the formulae for the swirl motion and radial pressure equilibrium. The common initial and boundary conditions are as follows:

- At the starting stage of calculation are given velocity distributions $V_x(0,r)$, $V_q(0,r)$, $V_r(0,r)$
- Symmetry conditions are established with respect to the centre line $(r = 0)$
- On the outer boundary of the vortex $(r = R)$ the x-wise distributions of velocities and circulations are given (the outer circulation being taken constant in many applications).

The time-averaged NS equations with the above boundary and initial conditions can be solved using the x-marching technique [9] or integral method [10].

However, for aeronautical engineers simpler, faster and also sufficiently accurate numerical codes are of great value. One of such simpler methods [11] proposes a widening of basic capabilities of the non-linear vortex-lattice schemes in order to include the vortex breakdown phenomenon and provide the correct estimation of lift and moment curve. The formulation is based on disruption of the coherent vortical structure and rapid spiralling expansion of the vortex core. Both of then (disruption and expansion) produce a strong reduction in vortex circulation that can be easily simulated. The method, supplied with the classical Nonlinear Vortex Lattice Method [12], makes it possible to determine the wake surfaces, compute the strength of vortices and even to analyse the flight stability. According to the abovementioned method the breakdown takes place at the point (x_{BD}/c) along the chord, where the parameter $\tau(x/c)$ is equal to unity, i.e.

$$\tau(x/c) = \frac{k^2}{c^2}\Big(\frac{\Gamma(x/c)}{\sqrt{2}\pi V_x(x/c)}\Big)^2 = 1$$

where V_x is the velocity component of fluid particle along the vortex core.

A "first order" model of breakdown is based on the decrease in the vortex circulation only

$$\frac{\Gamma_{BD}(x)}{\Gamma(x)} = 1 - 0.6\sqrt{1 - \frac{(x - x_{BD} - 0.2c)^2}{(0.2c)^2}}$$

where x_{BD} denotes the location of breakdown. and $x > x_{BD}$ the chordwise positions we are considering.

The predictions of the onset of breakdown and progression of its location over the wing, by increasing the angle of attack, are shown to be consistent with the experimental data. The reliability of prediction appears to be reasonably satisfactory even when the position of breakdown is near the apex in the first quarter of the wing.

3. Review of the papers devoted to high angles of attack

3.1. Rapid advances in CFD

The position of Computational Fluid Dynamics in engineering analysis has become so powerful that some scientists started to view it as a "third dimension" (see [13]) in fluid dynamics, being the equipollent element together with the classical cases of pure experiment and pure theory. In the late 1950s the so-called "blunt body problem" (cf Anderson, 1995) was a great challenge for the community of aeronautical scientists and engineers. In the excellent book of Liepmann and Rosko (1957) we can find the statement that the blunt body problem "cannot, at present, be theoretically predicted". This problem was solved in 1966 by means of finite-difference, time-dependent code. Today CFD can routinely handle many types of flowfields. Among the problems to be solved at all or to be solved more accurately in the future, there are turbulent flows. This is currently a wide open area of the CFD research. Recently, the Euler or even NS codes for prediction of the flow for wing-tail-fuselage configuration become more and more popular (cf [16÷24]). One of the problems extensively investigated is the flow computing around the close-coupled canard configuration (see, for example, [17,25÷28]). Among various specific problems to be solved, important from the computing efficiency point of view, is still the grid generation. For details see [29÷31]. The numerical results presented in papers recently published are usually compared to the results obtained in wind tunnels or flight tests. Many papers were published to provide a pattern of validation for the CFD methods, for example [32].

3.2. Couplings between rigid-body/flexible-structure/fluid dynamics

The important direction of research is a multidisciplinary approach to the analysis of vortex structure over lifting surfaces of contemporary combat aircraft. Such an approach allows for including couplings between the outer flow, structure and the state of its strains and rigid body dynamics. The representative papers [33÷37] recently published have showed powerful capabilities of CFD conjugated with solid/rigid body dynamics. A representative example to be solved is the buffet response. A very recent approach consists in sequential solution of three sets of equations on a multi-block grid structure, i.e. unsteady, compressible, full Navier-Stokes equations, aeroelastic equations for tail bending and torsion, and grid displacement equations, used to update mesh coordinates due to grid deflections. The breakdown predicted produces unsteady loads on control surfaces, which, in turn, generate severe buffet on the tails and causes their quick fatigue failure. In [37] used this method, verified by numerous experimental results, for analysis of geometrical configuration of the twin vertical tails of F-117 and F/A-18 aircraft. Some advanced turbulents models (e.g. k-ε) can be used in such computations. Another interesting problem possible to investigate within the frame of the abovementioned model is developing of passive or active control of the tail buffet to suppress its amplitude [38].

3.3. Vortex dynamics

In the early sixties one noticed that potential lift can be strongly augmented by the vortex lift. Since then in many aerodynamic laboratories the vortex structures have been analysed, first of all, versus their geometrical configuration. Vortices generation, their interference, strength and stability have become important scientific and technical problems. Numerous papers, related to this subject, have been published. In the beginning most of them were based on the results of experiments. A typical and characteristic for this approach is the paper [39] which includes both component and complete configuration studies to provide the information necessary for analysis of interaction effects and presents some comparisons between strakes-wing and canard-wing configurations. Only a few correlations with theory, mainly on the basis of the Polhamus' theory [40,41] of a "Leading-Edge-Suction Analogy", were included in the analysis. The same type of analysis is still used, mainly in Russian papers recently published. For example, [42] very interesting results are presented, obtained in TsAGI laboratories and confirmed in flight tests, giving practical directions for geometrical configurations and its influencw on stability. However, most of the recent papers are rather based on CFD and experimental investigations are often used for the validation of the numerical codes. Incompressible unsteady three-dimensional Navier-Stokes equations seem to became a routine tool when investigating the vortex-dominated flows at high incidence and sideslip. Turbulence is modeled in various ways. In [43], which can be considered as representative for a modern approach, an algebraic model to account for the eddy viscosity was used. His computed total pressure coefficient contours, obtained using an implicit upwind-relaxation finite difference algorithm [9,10] are very impressive and consistent with the results of vortex flow visualisation obtained by the use of smoke/laser light sheet technique. A similar approach is presented in [27], where the Reynolds-averaged thin layer NS equations were used to study the detailed effects of canard positioning on the canard-wing-body flow field. According to [27] the viscous modeling is essential to capture some of significant flow features such as vortex-induced secondary separations and other boundary-layer-type separations. The related papers [44,45] present a solution of the flow over delta-wing during-roll maneuver. The unsteady three-dimensional full Navier-Stokes equations, written in strong conservation form were solved using implicit, approximately-factored, diagonal form of the Beam-Warming algorithm. This approach enables to obtain few secondary and even tertiary vortices, very difficult to obtain experimentally. In many papers published recently authors use conservative unsteady Euler's equations. In [46] the flow problem over a delta-wing undergoing pitching oscillation was solved in subsonic case, at a large mean angle of attack, while in [47] solution to the flow problem over delta-wing at supersonic speeds was presented. The main objectives of such studies can be quite different. For example, the authors of [46] tried to find the vortex structure over the wing, pressure contribution across the vortex core and obtain some periodic solutions as well. The primary objective of [47] was to determine the real-flow limitations associated with the high-lift separated supersonic flow.

3.4. Vortex breakdown

Vortex breakdown is of primary importance, especially for high alpha dynamics of super-maneuver aircraft. The phenomenon has been investigated for more than 30 years and many original and review papers dealing the subject have been published. It is rather a general opinion (see, for example, [46,48]), that the Euler equations adequately describe separated flows at sharp edges. For smooth-surface separation, round-edge separation, shock-induced separation, viscous diffusion and dissipation, vortex breakdown, flow transition and turbulence, viscous terms have to be added to the Euler equations to approximate the full NS equations.

The two main parameters influencing strength and stability of the phenomenon are the adverse pressure gradient along the vortex core-line and its swirl intensity which can not go beyond a critical value. It is interesting that the vortex breakdown is insensitive to the Reynolds number and local turbulent properties – these two parameters are responsible for development of the vortex structure [7]. According to different authors, there is only one type breakdown, i.e., bubble type. The spiral and other types are, in fact, only different images of the same breakdown, depending the visualization technique applied. Two different aspects of the vortex breakdown, having strong hysteresis properties, are important – the steady state and the unsteady one, depending on frequency. The unsteady vortex breakdown is dependent on the flow history and its theoretical and numerical simulation has to be based on unsteady aerodynamics [28]. Analysis of vortex breakdown in the steady case (i.e. the wing at steady angle of attack, but it does not mean that the flow over the wing is steady!) was the subject of numerous investigations. The paper [49] published recently is a representative example – unsteady inviscid Euler's equations were used to solve the flow over rather a simplified geometry of the canard-wing configuration. Even in this simple case a mesh of about 1 million grid points was used and the authors had to tackle many numerical problems. For example, the artificial viscosity was used to improve the convergence and various grid topology were studied to suppress the steady state fluctuations and improve the vortex flow resolution. At the same time different experimental methods have been developed. The nonintrusive Laser Doppler Velocimeter method of measurements of velocity field presented recently in [50] can provide a data set for the case of vortex breakdown. Since in numerous papers the compressibility was neglected, the authors of [51] investigated this problem in details. They solved the mass-averaged three-dimensional unsteady Navier-Stokes equations using an implicit Beam-Warming algorithm and the algebraic Baldwin-Lomax turbulence model. For static conditions they found several shocks and the embedded supersonic region in the vortex core for the free-stream Mach number equal to 0.4. Also they detected a strong influence of compressibilty under dynamic conditions, for example, a delay in the dynamic onset of vortex breakdown over the pitching wing. Another, typical representative of the group of papers, where the Reynolds-averaged NS equations are used and vortices evolve as a part of the solution is [52].

A method based on the Euler equations, without specification of the explicit Kutta-Zhukovsky condition to enforce separation, allows for simulation of vortex sheets shedding from the leading edges as well [53].

The unsteady vortex breakdown is much more difficult for investigation and does not have very wide evidence. Some papers were published by Ericsson [54÷58], who focused the attention on highly nonlinear, almost discontinuous, steady and unsteady aerodynamic characteristics associated with the downstream travel of the vortex breakdown. According to his opinion (published in 1996) the flow physics has to be better understood to develop a satisfactory predictable model, therefore, [59,60] are worthy of mentioning. In [59] the authors wrote that the main reason for dynamic breakdown of the vortex is a time lag in separation development and inertial properties of turbulent separated flow. In the second paper [60] they developed an empirical-theoretical model, based on the complex potential. The model was used for wing rock analysis of one degree of freedom. The analyzed phase portraits and chaotic oscillations, compared to numerous experimental results have led the authors to the conclusion that rigid body dynamics coupled with vortex breakdown can detect wing rock motion. Unfortunately, the enclosed experimental evidence is not (in my opinion; also see [58]: "more research is obviously needed before a reliable prediction method can be developed) sufficient to validate quantitatively the proposed mathematical model of vortex breakdown. In [61] it was developed a very simple model either of periodic or ramp burst response, based on the datas ets, obtained in numerous experiments, and on the concept of a transfer function. The results obtained show that the breakdown behaviour may be described adequately with the aid a second order lag model, putting the damping ratio of 1.67 and non-dimensional frequency of 2.0. This model can be used as the first approximation for application in the semi-empirical finding of the breakdown location for the purpose of initial design or performance analysis. Simple criteria for vortex breakdown prediction are given in [11,62,63]. Relevant is also the paper [64], presenting some experimental results and delivering a number of semi-empirical expressions for the cross-flow wake width and correlation of shedding frequency with an inertia parameter, which can be important in the wing rock analysis.

3.5. Advances in aircraft agility and performance

Many papers on high manoeuvre aircraft dynamics have been published, both the original ones and reviews. Especially during last few years these problems have became very popular, after the X-31 – enhanced fighter manoeuvrability (EFM) demonstrator – showed new post-stall flight regime possibilities. Its tests included a sustained flight up to 70 degrees angle of attack and very good pitch, roll and turn rate capabilities under deep post-stall conditions. In the excellent review paper [65] there were presented the essential problems of post-stall flight regime: nonlinear flight dynamics of agile aircraft, various aspects of high angle of attack aerodynamics, condition for pitch recovery and a new role of the vectored thrust – related to tailless aircraft flight and stealth technology. In conclusions the authors stated that the aircraft "demonstrated the feasibility of several advanced vehicle control technologies to greatly enhance manoeuvrability and opened the door for greater challenges ahead". But success of X-31 would have not been possible with no previous studies made in different laboratories over the world. For example, investigations of Orlik-Rückemann [3,66÷68] have been of great importance , especially in respect of dynamic stability at high angles of attack. He defined and tried to measure the so-called cross-coupling stability derivatives. In recently published [69] the author wrote that neither the last encouraging progress in numerical simulation nor wind-tunnel experiment (being not without sources of errors) are not sufficient to predict correctly all important physical flow phenomena responsible for the real aircraft dynamics. In conclusions he wrote that high alpha data measured in the wind-tunnel "should be founded on analyses of the flow physics involved as spurious contributions to measured characteristics and can lead to unrealistic flight predictions". He emphasized the significant role of oscillatory stability derivatives in interpretation of unsteady interference effects and the role of free-flight experiments in data interpretation and code validation. Some recommendations (especially for moderate angles of attack flights) can be found in [70]. Quite interesting possibilities offered when using the captive – and free-model dynamic stability tests (including wind-tunnel free-flight) are presented in [71]. Many specific problems were investigated by different authors. In [72] the "minimum time turning manoeuvre" was considered. In [73] some selected aspects of the tactical utility of X-31 aircraft were considered. In [74,75] some selected manoeuvres of Mig-29 analysed were simulated numerically. A few interesting papers were published recently by Russian authors. For example, in [76] the author approximated the real curves of lift and pitching moment within the full range of alpha degrees and investigated the so-called dynamic entrance into high angles of attack. Many papers were devoted to developing of configurations suitable for post-stall manoeuvrability (cf [6,77,78]). Another interesting aspects of high angles of attack dynamics, considered jointly with the essential features of aerodynamics [5], according to the best of author's knowledge, the first time in public.

Another aspects of couplings between high alpha aerodynamics and vehicle dynamics are presented by Ericsson (1995). The main problems discussed in the paper are: cause and effects of asymmetric forebody flow separation with associated vortices; cause of the wing rock; effect of vehicle motion on dynamic airfoil stall; and exit from subscale tests results to the full-scale free flight results. Some conclusions drawn are rather unexpected, for example, Ericsson wrote that if vehicle motion affected flow separation through boundary layer transition, then the penalty for testing at subscale Reynolds number increased and the test results in some cases showed viscous effects opposite to those observed in a full-scale flight.

Various areas of high angles of attack dynamics have their specialised, sometimes very rich bibliography. For example, the wing rock phenomenon is very deeply investigated. Here we will mention a few papers only [79,80].

In the design process it is important to estimate sensitivity of some agility parameters to primary design parameters. Different aspects of agility and manoeuvrability, and their relation to aerodynamic parameters, control of forebody vortices, aircraft geometric and mass configuration, etc., are given in [81÷98].

3.6. Panel methods used in the high angle of attack aerodynamics

At high angles of attack the flow is highly three-dimensional and only 3D flow field calculation is able to predict the details of such a flow. However, over the last thirty years many aerodynamicists have undertaken numerous attempts to use simple engineering methods (mainly panel methods) to model phenomena of high lift. A typical example consists in simulation of the leading-edge discontinuities, caused by drooped leading edge, usually done to a smoothing of the lift characteristic just above the stall. Details are presented in [99÷101].

The high lift aerodynamics has been of primary interest from the very beginning of panel methods development. For example, in the review report [102] an important part of the contents takes just high lift, divided into sections: flaps, wing-jet interactions and vortex lift generation. Partially separated flows were analysed in [103], who showed the possibility of obtaining (using the panel method approach) a flat-top type lift curve that would reduced the aircraft rolling moments when the wing was stalled prematurely. In his analysis he included some viscous effects (for example the location of separation line, known from flow visualization). The very promising approach, i.e. revealing simplicity in use as in most of panel methods, is presented in the report [104] on the high-angle-of-attack aerodynamics. The authors showed that good results for overall loads resulted from the use of Vortex Lattice Method incorporating the Polhamus suction analogy as extended for side-edge and edge-vortex-lift-reduction effects, and by the inclusion of the augmented-vortex-lift concept. Similarly as in [99÷101,105], the prediction method involves the combination of both experimental and analytical information to produce a rational model.

A comprehensive review of prediction methods for the loads acting upon stalled airfoils is presented in [104]. Different approaches, are discussed including viscid-inviscid interaction, and the coupling of boundary-layer theory with an inviscid, potential flowfield representations. Very impressive results of computations, obtained in [104,106,107], for the pressure distributions over the airfoil, being in excellent consistency with the experimental results, are also included in the review.

Important issues of investigations carried out means of panel methods are those oriented to the rolling-up of vortices over, as well as, behind the wings. Numerous papers were devoted to this phenomenon and presented the efficient procedures of its numerical development.

Here, we mention the paper [108], presenting a very simple approach using two-dimensional unsteady analogy in the cross-flow plane, and more refinement, the report [109], based on extension of the Vortex Lattice Method, including the spanwise and chordwise pressure distributions over both the wing and wake. A finite thickness of the vortex wake is being studied assuming that the wake cross-section contains vorticity in an otherwise irrotational field. Many numerical results complete the analysis. An extension to the full aircraft configuration, consisting of bodies and thick wings being at high angle of attack, is given in the report [110]. A local separation is allowed and the separation lines are defined by the locus of minimum C_p locations. The shedding-up vortices are rolling and generate the curved wake. Comparisons with experiments prove high quality of theoretical, horseshoe and source element models, respectively. Relevant are also [111÷123].

4. Advances in materials and structures

Over decades of the aeronautical engineering development it was observed many times that new materials a very important role in the progress played. Extensive use of non-metallic materials in the stressed metallic structures; i.e., hybrid mixtures of metals, polymeric composites, and new generation of alloys, especially, those based on aluminium-zinc, aluminium-lithium and titanium alloys [124], has offered new possibilities of aircraft structures development. Step advances in the polymer have occurred together with introduction of tougher structers based on aramid and polythene fibres or mixed thermosetting and theromoplastic matrices, and also due to the carbon fibres [125]. Ceramics and composites based on ceramic matrices offer a balance between the properties stemming from their covalently bonded structures and exceptional capabilities at high temperature revealed in terms of strength, stiffness, hardness and wear resistance coupled with a relatively low density, being very attractive for high temperature applications, especially in gas turbine components. Unfortunately, the lack of ductility, fracture toughness and resistance to shock held back structural applications until the 1980s, although the ceramic coatings have been used when making critical wear, temperature resistant surfaces, and to reduce corrosion.

Since the use of increasingly efficient electronic systems seems inevitable, so reliance on advanced materials may well diminish. For example, the need for control of observability may become dominated by the electro-mechanical behaviour of materials with measures and countermeasures achieved without resort to passive material-based solutions. On the other hand, smart structures and processes applied to engineering problems such as the suppression of flutter, adaptive lift geometries, and damage sensing structures require new materials of optimised electrical and mechanical properties, see [124].

5. Smart structures

There are two forms of smart structures – Health and Usage Monitoring Systems (HUMS) and reactive skins and structures with control feedback [126]. The way forward seems to be still unclear – some applications are already working succesfully and the other are still a long way off. Fibre optic systems can now measure the strain at a point, and separately temperature, moisture, contamination, damage and crack growth, respectively. Sensors are inexpensive: the Bragg defraction gratings must be the cheapest form of mass producible strain gauge nowadays. There remains the problem of designing cheap and robust connectors to extract the information from the fibres. One of a most difficult ones to lemonitored is barely visible impact damage in a composite structure. An interesting vision of how the civil aircraft of next generation can benefit from smart materials and structures is presented in [126]. Also the other form of smart structures whereby a piezo-electric materials can be forced to strain by changes in an applied voltage seems to be very exciting (see Fig.13 in [126]). This idea seems to be promising in aerodynamic controls with no hinges or mechanical actuators applied and changes in aerodynamic wing sections as the speed passes from subsonic to supersonic flow. Other possible smart wing skin applications would be to control of boundary layers or delay of separation. However, at the moment it seems that smart active skins may absorb more energy than it is saved by the drag reduction [126]. Hopefully, in the future we will see microstructures on the nano scale synthesised down to molecular sizes. It might be feasible to have engineered the surfaces for wear and thermal barriers but also the coatings for switchable antennas, increasing of radar transmittance and solar energy conversion.

6. Thrust Vectoring Flight Control (TVFC)

The advantages of vectored fighters over the Conventional Aerodynamic Flight Controlled (CAFC) fighters have been well demonstrated since 1993 by two experimental aircraft:YF-22 and X-31. The statistical average kill-ratio demonstrated during various combat-types in flight engagements by the thrust vectoring X-31 over CAFC F-18 is 32:1 [127]. Depending on the initial position the results of close-in combat (dog-fight) of 93 engagements during 21 sorties over 6 days are presented in Tab.1.

Table 1

Win for:	X-31	F-18	Neutral
Total result	77	8	8
Line Abreast	63	2	4
X-31 Defensive	10	6	4
X-31 Offensive	4	0	0

TVFC is the technology which allows significantly increased flight safety, agility and kill ratios to be achieved in the post stall domain at subsonic speeds below the so-called corner velocity [128,129]. One of the manoeuvrability coefficients for unvectored and vectored aircraft, respectively, versus the angle of attack is presented in Fig.5. It can be seen that classical fighters (F-15 and F-16) loss completely the roll rate capability as 30° is approached, while F-22 is still capable of producing high roll rates. The TVFC also allows the supersonic turn performance to be significantly improved in comparison with the CAFC-only based aircraft. There are ideas of implementation the TVFC into the passenger aircraft [130], which became unsafe under the high-alfa and spin flight conditions, failing AFC surfaces, low-air speeds, icing conditions and asymmetric loss of propulsion. The TVFC integrated with the active control technologies (ACT) can reduce size, complexity, weight, cost and fuel-consumption due to tailless configurations [129]. Tailless and, in general, reduced-size AFC aircraft reveal almost the same expected air-safety, stability and reliability as the aircraft supplied with the TVFC/AVC. Flight testing of such a dynamically-scaled TVFC/RPV (Remotely Piloted Vehicle) is underway in [130] with tailless F-16, F-22 and B-727. It was proved, [131], that civil TVFC prevented more than 50% of all jet airline crashes as caused by: stall-spin, AFC-failures, icing, windshear, micro-bursts and take-off and landing under strong cross winds, low speed and loss of all airframe hydraulics.

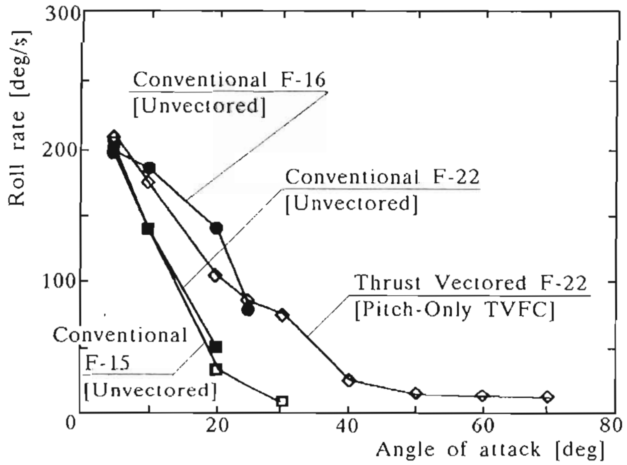

Fig. 5. Decreasing of roll rate at high angles of attack for the TVFC and CAFC (after [128])

7. Low observability

No review of modern combat aircraft would be complete without the stealth consideration, [132]. It is really the single biggest challenge to aerodynamic designers of the near future. Among many signatures of the electromagnetic spectrum the most important for reducing the possibility of detection are currently the radar (Radar Cross Section – RCS) and infrared (Infra Red Signature – IRS). The edge and facet management results in the principal specular and diffractive returns being grouped into particular directions [133]. This leads, in turn, to adoption of the planforms and layouts which may differ significantly from the aerodynamic optimum. Adherence to particular surface curvature requirements results in a tendency towards blended configurations, whilst faceted and chined forebodies generate very strong, interfering vortices. The aligment of surface features in selected directions potentially limits the effectiveness of control surfaces. Non-linear stability characteristics together with the desire to minimise the number of flying and control surfaces (and edges producing the radar returns) usually result in the need to use the automatic flight control system (AFCS) and TVFC. An important role in reducing the radar returns plays hiding of apertures and cavities. Multiply radar reflections within cavities produce strong and essentially omni-directional radar returns. Also ensuring complete obscuration of the engine face from direct sight results in obtained the duct shapes – far from the aerodynamic optimum. Another problems arise with excrescence control and store carriages. The elimination and strict control of excrescences poses some specific design problems (for example, limitations imposed on actuator capabilities, new requirements imposed upon the boundary layer control devices; e.g., air intake boundary layer diverters, fences, strakes and vortex generators). Store carriage design problems, leading and trailing edge treatments and other low observability requirements are discussed in [133] in details.

8. Unmanned aircraft

The idea of unmanned aircraft seems to be very attractive and prospective in the nearest future. The Unmanned Vehicles Handbook 1995/96 includes full specifications of 56 UAV (Unmanned Aerial Vehicles) in production or development [134]. They are used now as UAV, robot aircraft and experimental, scaled aircraft for in-flight testing of new ideas or modern designs, being very often too-expensive for full-scale aircraft testing.

A good example is the Scorpion/Marvel UAV [135], which takes off and lands with its engine elevated to vector thrust for helicopter-like operation. In flight, the aircraft assumes a conventional look for high-speed operation. The design's outer wing panels, called freewings, swing independently of the fuselage and center wing section. The fuselage remains stable as the outer wings rotate to absorb about 75% of air turbulence. In a fixed-wing design, the pounding would be transmitted to the fuselage, causing a shortened lifespan for the structure and avionics. Such stability is critical for shipboard operations, during which the landing deck can pitch and roll. In flight, the stability is a key for the use of laser spot designators for precision-guided munitions. Another example is the X-36 UAV, designed for some fundamental experiments by McDonnell Douglas and NASA [136]. The advanced vehicle lacks vertical and horizontal tails, using instead of that the split-aileron and TVFC concept. This design promises to reduce weight, drag, and radar signature, increasing at the same time range, manoeuvrability, and survivability. Initial tests are concentrated on the low-speed high angle of attack performance. The 28%-scale prototype, designed and built (in 28 months for $17 million) incorporates technical breakthroughs in aerodynamics, propulsion and flight control. Among new, critical technologies at significantly less cost than a full-scale aircraft are:

- Advanced software development tools for rapid avionics prototyping
- Low-cost tooling molds
- Composite skins cured at low temperatures without the use of autoclaves
- High-speed machining of unitized assemblies.

Another example is Israeli HERON I, the medium altitude (10 km) and long endurance (24 hrs) UAV. The super-light structure weight was obtained by the following principles [137]:

- Extensive use of delicate, all composite sandwich skins, reinforced by graphite fiber spars. The central wing, fuselage and booms are made of honey-comb sandwich with very a thin graphite fabric facing
- Highly loaded internal elements such as: fuselage frame, attachments of landing gears, highly loaded webs in the wing are made of graphite fabric facings with a stronger core
- Two integral fuel tanks, one in the central wing and another in the fuselage, are built integrally with the composite structure, without any separate internal bladder
- Hard points and attachments are built into the composite, minimising the use of metallic fittings
- Sizing and tayloring the structure according to a careful stress analysis and experimental verifications.

9. Ultra High Altitude Aircraft (UHAA)

Current interest in ultra high altitude aircraft stems from their potential value for conducting atmospheric science research, monitoring of highway traffic and military aims. The basic reason for preferring the UHAA to manned aircraft for civilian missions is the long endurance demanded by these missions which imposes unreasonable workload on a pilot. Altitudes of up to 35 km are being targeted by these new designs (Boeing Condor has reached 24 km, Strato 2C driven by two piston engines set the world altitude record for a piston-engined aircraft of 21 km [138], HARVE [139] is designed to reach 27 km). Aerial imaging is the basis for a wide variety of applications [140]:

- Detecting forest fires and support in directing fire-fighters
- Border supervision and prevention of smuggling
- Maritime supervision to detect illegal and accidental oil spillage, illegal fishing, and assistance to trawlers in detecting shoals of fish
- Detecting minerals
- Supervision of building regulations obedience
- Supervision of agriculture development
- Support in case of natural disasters (earthquakes, avalanches, floods etc).

Among technologies critical to high altitude, long endurance flight one can mention the following: propulsion, aerodynamics, structures, electrical system, survivability (for military use), reliability, autonomous control, integration with civil traffic and cooling of systems and payloads.

In [141] it was shown that to minimize the vehicle size and cost it was desirable to use the highest wing loading compatible with the required mission. The most appropriate parameters to analyse and design the wing section for ultra high altitude mission are

$$M = \mathrm{Ma}\sqrt{C_L} = \sqrt{\frac{2W/S}{\gamma p}} \qquad R = \mathrm{Re}\sqrt{C_L}\frac{\rho V c}{\mu}\sqrt{\frac{2W/S}{\rho V^2}}$$

where: Ma – Mach Number, Re – Reynolds Number, W/S – wing loading, ρ – air density, p – pressure, V – speed, c – wing chord, γ – ratio of specific heat, C_L – lifting force coefficient.

For a constant wing loading W/S the parameters M, R are constant at a fixed altitude independently as an aircraft undergoes trim. A few of these parameters are shown in Table 2.

Table 2

Altitude [km]	M	R
15	0.15	1 000 000
25	0.35	500 000
30	0.50	300 000
34	0.65	220 000
35	0.68	200 000

Coupling this high-Mach and low-Reynolds numbers creates a quite new situation for profile designers because of a complete lack in suitable airfoil data, see Fig.6. To keep the flow around the wing subcritical (without a shock/boundary-layer interaction) means that the ceiling have to be limited to about 35 km. Computational studies presented in [141] indicate that 35 km ceiling performances at Ma = 0.60 and Re = 200000 depend on the effective use of transonic flow to enhance transition and reduce separation-bubble losses.

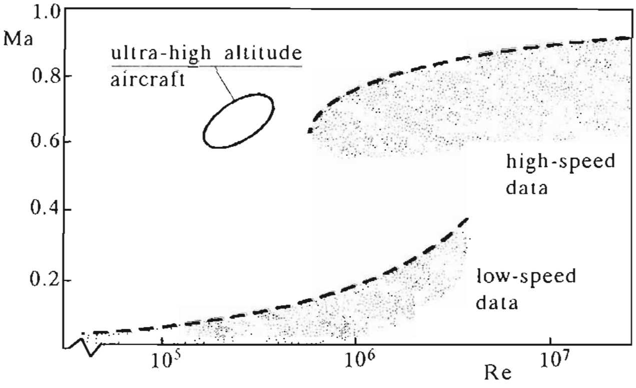

Fig. 6. Limits of available airfoil data (after [141])

Another serious problems are involved by a power plant based on piston engines. The turbocharged piston engines – LYCOMING IO-720 were used in the Grob-Strato 2C and also in the HARVE project [139]. To increase the range and endurance of aircraft an ultra-light-weight design with all horizontal surfaces generating lift was applied [139]. The extremely high lifting surface was achieved due to a biplane configuration. However, the successful design and in-flight testing of UHAA is still an expensive and risky task. This was probably the main reason for the cancellation of very advanced and promising STRATO 2C programme. Teledyne Ryan Aeronautical Company has built the Global Hawk, one-ton payload and long endurance UHAA and is very advanced in testing programme [142]. The first take-off with a payload is scheduled for May 1997.

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Nowe kierunki badań w technice lotniczej – przełamywanie barier

Streszczenie

Praca przedstawia wybrane dziedziny badań i techniki lotniczej, które odgrywają ważną rolę w rozwoju lotnictwa jako całości. Wśród omawianych technologii szczegółowych i fascynujących obszarów badawczych znajdują się: supermanewrowość, aerodynamika struktur wirowych, nowe materiały, struktury inteligentne, wektorowe sterowanie ciągiem, technologia ograniczania wykrywalności przez radary, konstrukcje samolotów bezzałogowych oraz zagadnienia lotów na dużych wysokościach. Przedstawione obszary badań i rozwoju w żaden sposób nie wyczerpują listy ważnych działań decydujących o postępie w lotnictwie, są natomiast próbą pokazania różnorodności stanowiącej o ciągłym rozwoju lotnictwa, zarówno wojskowego jak i cywilnego. Wybór prezentowanych zagadnień jest zapewne dyskusyjny i subiektywny, uwarunkowany naukowymi zainteresowaniami autora skierowanymi na aerodynamikę i dynamikę lotu. Jednym z celów pracy jest zaakcentowanie bezdyskusyjnego postępu w lotnictwie jako całości. W kilku przypadkach możemy wręcz mówić o przełamywaniu barier. Do obszarów "zakazanych" lub niemożliwych do osiągnięcia, leżących za takimi barierami należą: latanie na zakrytycznych (dużych) kątach natarcia, bezpośrednie sterowanie trajektorią lotu za pomocą wektorowania ciągu, skonstruowanie samolotu tak aby był niewidzialny dla radaru lub latanie na bardzo dużych wysokościach samolotem z napędem tłokowym. Postęp w technice lotniczej obserwowany obecnie nie jest może tak spektakularny jak np. w przeszłości było z pokonaniem bariery dźwięku, ale wciąż robi duże wrazenie, jest ważny i nieustanny. Bardzo często postęp w jednej dziedzinie techniki lotniczej jest możliwy dzięki osiągnięciom w innej dziedzinie. Przedstawiona praca zawiera obszerny przegląd literatury naukowej i technicznej odnoszącej się do omawianych działów badawczych, w tym pozycje kluczowe z punktu widzenia postępu we wspomnianych dziedzinach wiedzy.

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