CHALLENGES IN EUROPEAN AEROSPACE
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FLIGHTPHYSICAL ASPECTS AND METHODS OF FUTURE MILITARY AIRCRAFT DESIGNS

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ABSTRACT

Modern multirole combat aircraft have to cover a wide scope of performance and maneuverability imposing challenging flow-control measures to achieve care-free handling and at the same time to meet range and payload capacities. The longevity of such designs has to be achieved by capability stretching not only via equipment modernization but with the same effort by smart aerodynamic enhancers. The selection of which is assisted by modern flow simulation tools and sophisticated test-facilities, however the design and shaping still is an art when complex flows have to be tamed.

Long-range reconnaissance and surveillance tasks materialize into unmanned aircraft of some previously unknown design-space. Fragile, high aspect-ratio configurations – sailplanes only at a first glance -, experience some Reynolds-number effects and become efficient only via the integration of high performance wing technology.

The so called asymmetric war-fare will challenge nowadays surveillance and counter-insurgency capabilities with anti-air-systems. Simple missiles, the adaptation of even older combat aircraft or militarized civil general aviation ones may force higher speed and agility into these platforms and these being combined with some signature challenges.

More and more influenced by compromises in between flight-physics and signature, the requirements of performance, maneuverability and low RCS-signatures must be fulfilled by a common shaping. This may relinquish traditional elements of design in the medium and higher angle-of-attack regime, at sub- and transonic speeds. Constraints are imposed on control-systems. Slats, flaps, roll-devices and classical yaw-controls together with classical flow-control via vortex-generators are undesirable. Here the flight-physical properties must be designed into the plan-form, profiles, twist and a continuous blending of these. This can be achieved only with a deeper understanding of the flows complex behavior to allow for capable and safe designs. Many features of these complex vortex-systems, eventually being combined with transonic effects, especially at the borders of the flight-envelopes, are not yet understood to make the development a straight forward approach.

Very often numerical flow-simulations help to analyze the task at hand properly. However, many challenges only can be accessed and solved by high-fidelity physical models and the simulation of complex geometries.

1 AERODYNAMIC PROPERITES AND MEANSFOR HIGH AGILITY DESIGNS

Legacy combat aircraft shapes were dominated by high performance and maneuverability (Fig. 1). Quite some experience [1-9] was gathered to allow for extreme manoeuvers by very demanding aerodynamic measures to obtain certain superiorities. Increasing stealth requirements manifest themselves into more blended configurations (Fig. 1).

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Most designs can trace their shapes to the findings about vortex-flow-systems [1-4] and their exploitation as design features [4-9]. Often traditional active and passive flow-control devices ranging from slats to strakes, from vortex generators to fences and more extended their flight-envelope into formerly stall and post-stall regimes. Figure 2 gives a coarse overview into a generic agility-, speed-envelope typical for those aircraft.

Figure 1. Legacy (left) F-21, F-4 II, Slat F-4 II, Tornado, F-4 Skyray, EF2000, Rafale and modern combat aircraft (right) F-22, F-35, generic design, B-2, X-47A, X-47B

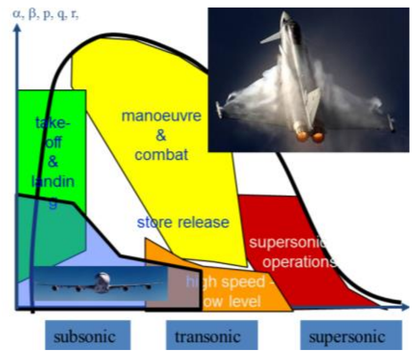

Figure 2. Generic speed-agilityenvelope of modern combat aircraft designs

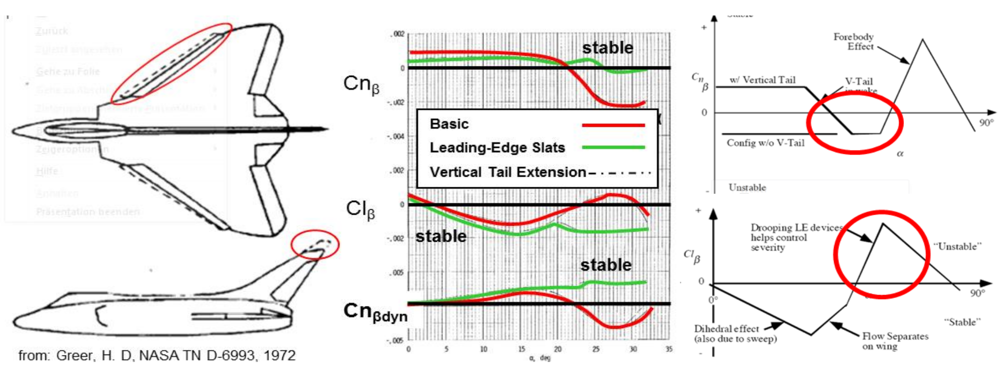

Figure 3. Local yaw- and roll-instabilities on a delta-wing-configuration being cure by a leading-edge slat device. Cnβ, Clβ, $Cn_{\beta dyn}$ shown

Apart from the shaping for drag-reductions of compressible flows, the performance and agility requirements translate into the necessary understanding and proper treatment not only of high lift demands and the provision of fast roll-rates but even more so the handling of uncontrolled and controlled separation [10] and their ensuing interacting vortex-systems, possibly stochastic unsteady flow phenomena e.g. of asymmetric fuselage vortices and dead water flow regions. The successful treatment of which is key to sufficient control-power [11]. Preferably of linear character this allows for an aero-servo-elastic design which can be handled by a safe flight-control-system. It also guarantees for loads-assessments which may help to reduce the structural weight. As indicated in Figure 2 this imposes the need of a wide additional spectrum of aerodynamic and flight-physical knowledge.

The in-depth understanding of these flows is vital for the successful design of these configurations. By this, well balanced, supportive interactions of attached flow, controlled flow separation, the interaction of vortex-systems, the flight-mechanical properties and performance may be optimized throughout the flight-envelope.

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References [10, 11] describe the so called high AoA pitch-recovery, whereas the combined control-power of all pitch-producing devices has to overcome any pitch-up departures, as well as the combined high AoA dynamics of roll- and yaw-instabilities (Cl, Cn), coupled with the relation of the yaw- and roll-inertias, the $Cn_{\beta dyn}$, are explained. At high AoA the classical vertical fin designs may loosen the directional stability and possibly their corresponding control effectiveness due the wing dead-water flow shielding effects. Strong longitudinal vortices even may reverse the fins purpose. Adverse rolling moments caused by asymmetric flow separation and the vortex-breakdown phenomenon can make the aircraft uncontrollable. A historic example (Fig. 3) shows local roll and yaw-instabilities, which prevented high AoA, high lift flight. A leading-edge slat at this compound delta-wing provided the means to stabilize uncontrolled asymmetric separation into mostly attached flow accompanied by some smaller longitudinal vortices.

2 MODERN COMBAT AIRCRAFT AND THEIR HIGH AOA FLOWS

Today higher maneuverability, at higher speeds already use separated flows as part of the design (Fig. 1, 2, 4). Air-combat conditions easily take to trans- and lower supersonics at AoAs only reached at take-off and landing in the early days. CFD-methods are used to probe for the trends of flow features to combine plan-forms, profiles, controls and flow control devices such as strakes, fences, slats and vortex generators at their best.

The Eurofighter Typhoon induces a flow-field of very complex interacting vortex system shown in Figure 4 and 5. The main contributors to lift are the apex and slat vortices (Fig. 6). At these conditions an apex vortex feed is interrupted at the onset of the leading-edge slat. This vortex axis gradually changes direction, rotating towards the free-stream velocity vector, increasing the distance to the wing leading edge and elevating the vortex from the surface, thus reducing the pressure footprint on the wing. Figures 4 and 5 illustrate the interaction of stable and burst vortices above the wing. At first, the slat vortex develops along the leading edge in the classical delta wing sense. However, this vortex is less stable than the apex vortex and bursts at relatively low AoA. The upper wing flow is seen to be dominated by the apex and slat vortices which are easily identifiable close to the leading edge, but increasingly interacting and merging towards the trailing edge. Burst vortices are characterized by lower levels of vorticity in the core. For transonic condition (Fig. 5), a supersonic region in around the wing apex is generated, terminating in a shock system, resulting in a positive pressure gradient that promotes the bursting of both the apex and slat vortices.

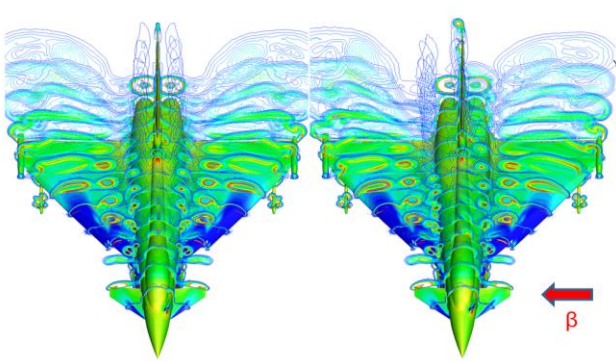

Figure 4. Pressure distribution on a combat aircraft at maneuvering conditions at Mach 0.40, $\alpha = 24.0^o$, $\beta = 0^o$

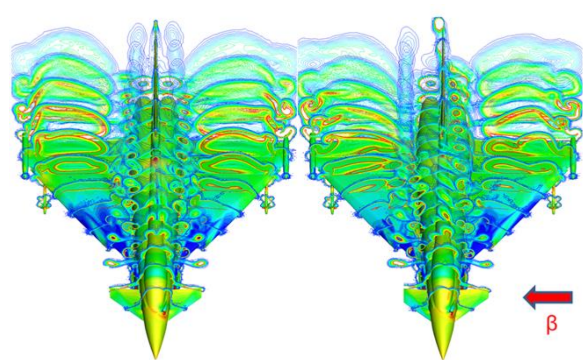

Figure 5. Pressure distribution on a combat aircraft at maneuvering conditions at Mach 0.85, $\alpha = 24.0^o$, $\beta = 0^o$

At sideslip the reduced effective sweep on the windward side, promotes the bursting of the now less stable windward vortex, while the somewhat weaker leeward vortices become more stable according to

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their increased effective sweep. Depending on their relative strength the corresponding rolling moment can switch from stable to unstable within a few degrees of AoA. However, this effect may be very sensitive due to other imbedded effects described now.

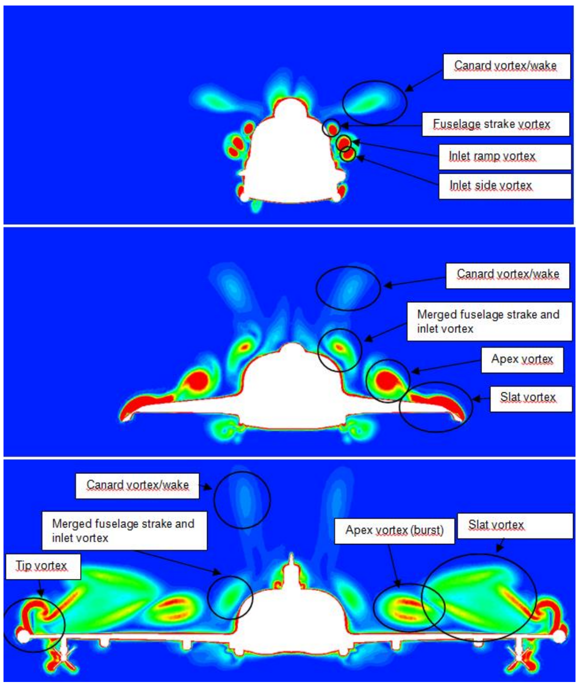

Figure 6. Combat aircraft modified for safe high AoA-flight by the introduction of

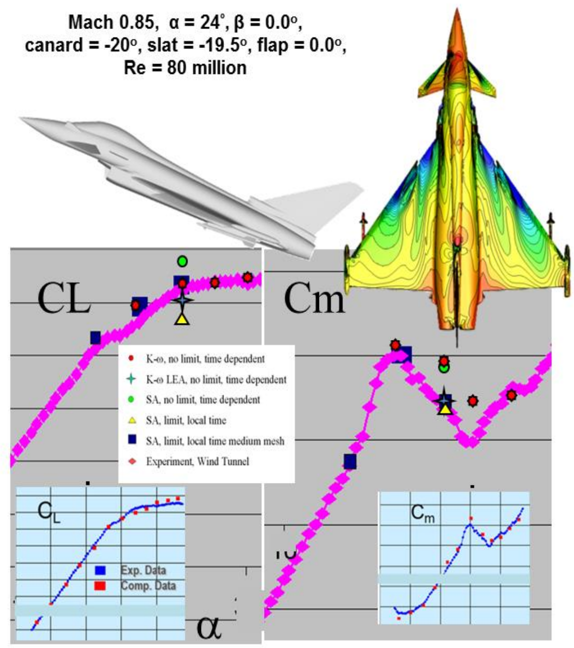

Figure 7. Lift and pitching moment at Mach = 0.85 in a partially trimmed condition (Canard = -20°, Slat -20°)

The interaction of the two main wing vortices increases up to a point downstream where they cannot longer be distinguished from another and merge into a large, chaotic, still rotating, low-energy wing wake (Fig. 6). It appears that the apex vortex burst process is accelerated by this outboard flow-interaction. The direct impact of this interaction on the integral coefficients is however limited since the apex vortex footprint on the wing is small this far downstream. At the wing tip, a classical tip vortex is generated only to be quickly drawn into the remnants of the slat vortex.

Other, smaller, vortices are active on the upper flow-field, also identified in Figure 6. While a loaded canard forms tip vortices in addition to the canard wake at large AoA these features quickly ascend above the fuselage and do not appear to strongly interact with other vortices of importance. They are however located close to the fin and have an effect on the local flow in this region, especially at sideslip condition by reducing the fins stabilizing effects.

The so called fuselage strake vortex (Fig. 6) is known to significantly affect the AoA behavior of the configuration at hand. Different to the canard vortex, this vortex does not elevate from the fuselage. Instead, this vortex remains almost parallel to the fuselage axis. Somewhat downstream from the strake, its vortex merges with the two inlet vortices, stemming from the intake ramp and the inlet side. This combined vortex-system appears to remain stable for the significant part of the upper flow-field and interacts with the fuselage side and the fin. Furthermore it interacts with the apex-vortex. Figure 7 gives an impression of the good quality achievable by modern simulation tools as used here [12-16].

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3 DESIGNING CONTROLLED VORTEX FLOWS FOR HIGH AGILITY COMBAT AIRCRAFT

By design, the current standard Eurofighter Typhoon operates within a safe AoA range providing a certain agility level. To increase its agility even further lateral instabilities related to unstable Cl- and Cn-characteristics at sub- and transonic speeds had to be overcome.

After a thorough inspection of the flow structures, by theoretical reasoning and reference to experiences [3-11], CFD-studies and some wind-tunnel-investigations, the addition of wing apex-strakes was proposed for transonic improvements just in between the intake and the wing. The Figures 8 and 9 show a comparison of the standard EF-2000-Tyhpoon and the so called EFEM-Typhoon configurations.

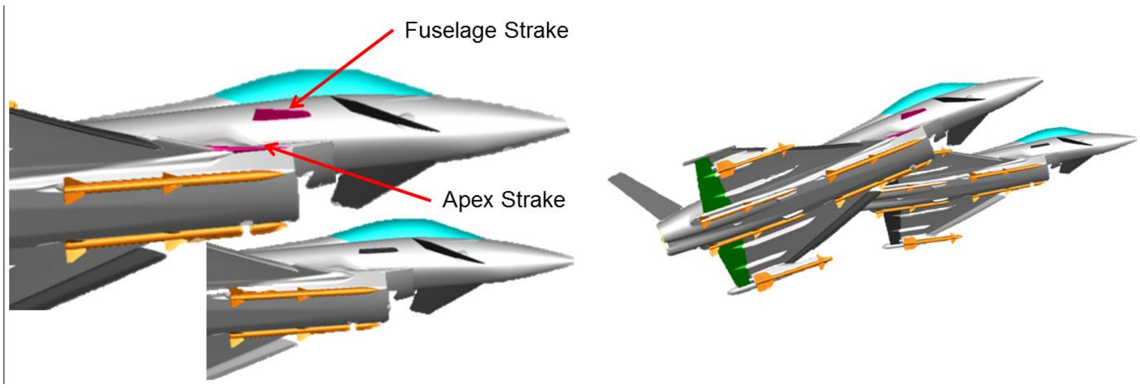

Figure 8. Combat aircraft modified for safe high AoA-flight by the introduction of a triangular fuselage- and apex strake

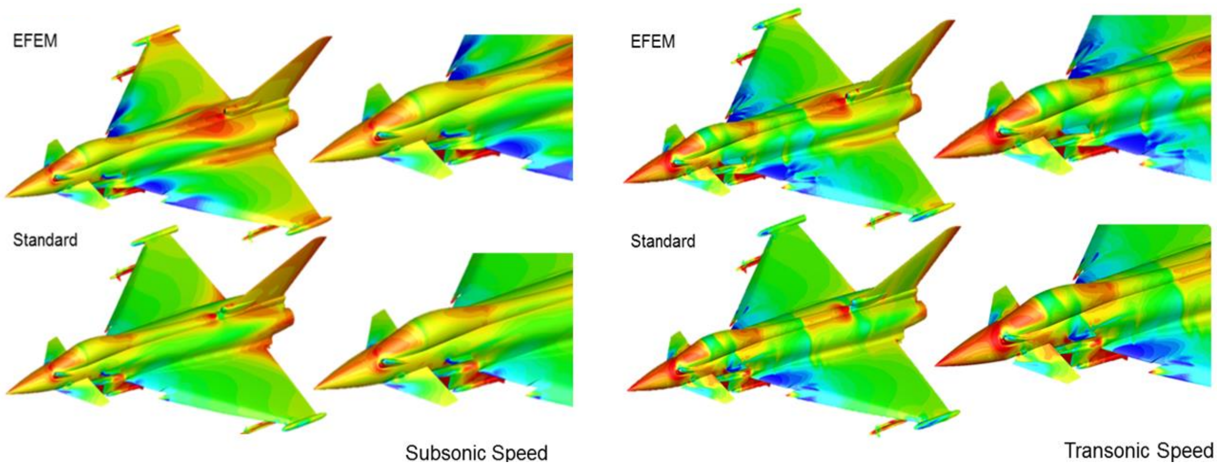

Figure 9. Comparison of subsonic and transonic pressure-distribution in comparison on the EFEM and Standard combat aircraft configuration

The apex-strake creates a small but stable vortex just ahead of the wing. It induces a span-wise side-wash by which the flow on the inboard wing experiences an increased effective sweep, thereby stabilizing the wing vortices up to higher AoA. In a cascading effect also the slat vortex system becomes more stable, delaying the former roll-instability. At transonic speeds the shock-system caused by the inner side of the deployed slat is weakened. The former rectangular fuselage strake on the cockpit side was modified into a delta wing plan-form to enhance the lateral stability at subsonic speed and even higher AoA. Now a rather strong and even more so stable vortex gives impetus to the inboard wing flow thereby

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removing the lateral instabilities almost completely. The comparison of the resulting pressure distributions is shown in Figure 9. The EFEM configuration shows a more favorable subsonic behavior, while at transonic speeds roll stability is produced. At symmetric flight rolling moment excursions almost vanish.

Another possible means to increase the roll stability would have been to change the outboard leading-edge vortex slat with a sharp leading edge of higher sweep to cure the outboard wing flow by providing more stable and stronger controlled vortex flow there. However, this would have resulted in a redesign of the slat-system together with some structural effort in a wing-redesign.

The nowadays standard CFD Navier-Stokes simulations only show the stabilizing effect of the EFEM modifications at a satisfying quality level. For the standard configuration the stability level at lower AoA is being under predicted, while being over predicted in the regimes where experiment and flight test indicate the unstable effects as also known from flight tests. Although the improvement of the aerodynamic means is shown qualitatively, the discrepancy needs to be explained and corrected in future more detailed investigations. Final flight test confirmed the concept and increased the Eurofighters capabilities significantly.

The F-16 XL double-delta aircraft (Fig. 10) is available with free-flight pressure measurements [17]. Its highly swept front wing panel produces strong and stable vortices, while the outboard panel leading-edge sweep is close to vortex breakdown at medium AoA already. The references [18-22] give an overview over multiple investigations which have been performed in recent years to check on simulation capabilities.

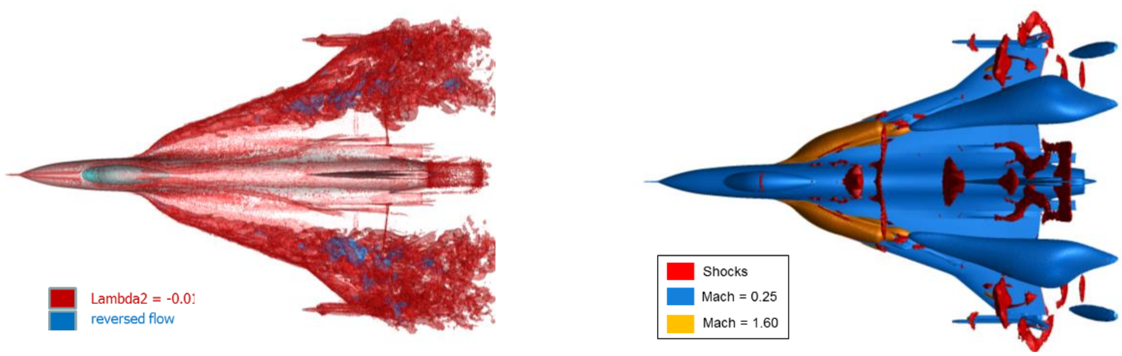

Figure 10. Flow structure around the F-16XL at Mach = 0.242 (left) and Mach = 0.90 (right), α = 19.91°

At subsonic speeds the highly swept, forward part of the double-delta wing was expected to produce an axial jet-like flow as known from slender delta-wings. However, it developed retarded axial velocity distributions in the core, similar to a wake-type flow (Fig. 11). This behavior is caused by the leading-edge inflection shortly after the front end of the leading-edge. Here, the local sweep diminishes and the flow close to the vortex core retards from a jet-like to a wake-like pattern. The further feeding of the forward vortex from the inner wing wraps around this very core, stabilizing the "compound" system as to be expected from a highly swept wing [3]. Only at AoA beyond 20° this vortex starts to burst in the rear part of the wing as indicated in the blue reversed flow areas of Figure 10.

The transonic high angle-of-attack case shows an intense interaction of the vortex-systems with normal and cross-flow shocks (Fig. 10). The inner, forward wing vortex encounters a shock in the middle of the inner wing. Its associated pressure rise immediately leads to a massive flow reversal in the core leading to vortex break down, being accompanied by other small pockets of reversed flow on the outer wing. Also cross-flow shocks can be discerned underneath the primary front wing vortex.

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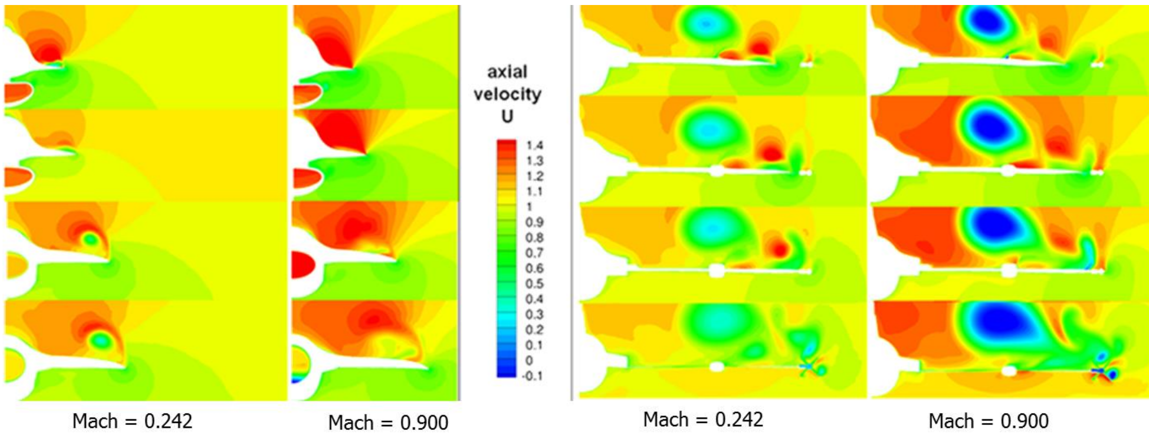

Figure 11. Axial-velocity cross-sections on the F-16 XL at Mach = 0.242 and Mach = 0.9, α = 19.91°

At sideslip conditions the outboard wing panel, being of 50° leading-edge sweep only, shows vortex breakdown already at α = 19.91° on the wind-ward side because of its reduced effective sweep. The advancing wing produces a stronger vortex breakdown effect on the advancing outer wing, while the retarding side shows a stable, not broken down but somewhat weaker vortex-system. Both lee-ward and wind-ward time-averaged pressure distribution results on the outer wing-panel agree well with the port and starboard flight-test sideslip conditions (Fig. 12); more details of which can be found in [22]. The results shown here were performed via a SAS-turbulence model, apparently necessary to account for the more correct simulation of the unsteady effects of breakdown and mutual vortex-flow interaction.

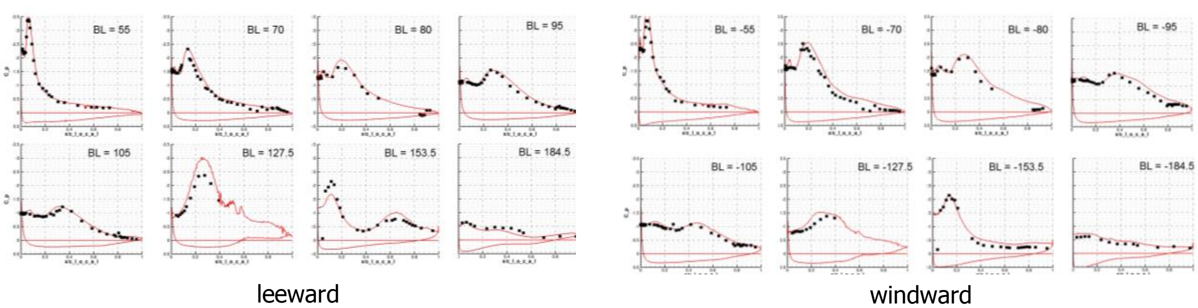

Figure 12. Experimental and computational averaged SAS pressure-distribution on the F-16 XL wing at Mach = 0.242, α = 19.91°, β = 5°

The results show the current CFD-capabilities for configurations which produce flow quite different from many slender wing research shapes. Obviously the interaction of separation and vortex-flows is less entangled than for the more intense highly coupled effects of multiple vortex-systems on wings of only medium sweep in between 40° - 60° as on the canard, delta wing configuration

In the future, the complexity of these compound, highly interacting flow systems such as the retarded axial velocity field on the inner wing vortex should be inspected for its influence of vortex stability and the sensitivity of vortex-breakdown also under the interference of compressible effects for future applications elsewhere.

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4 MODERATELY SWEPT & ROUND EDGED WINGS AT HIGH AOA

Wings of medium leading-edge sweep still hold some problems also for the vortex breakdown behavior at flight Reynolds-number and the associated longitudinal and even more important lateral stability and controllability issues. The influence of changing leading-edge radii on more complex wings still is subject to trial and error design and came under closer scrutiny only recently in some NATO STO-AVT-topics [23-30] to be discussed in a following chapter. Furthermore the effect of optimized leading-edge devices such as slats, strakes etc. has not been probed in detail. Double-deltas and other compound shapes add more to these "secrets" to be lifted to become true design elements even during the preliminary design.

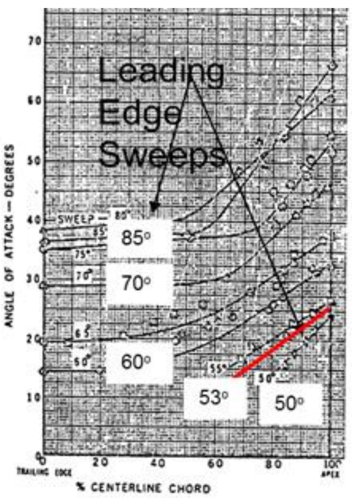

Figure 13. Vortex-breakdown positions on delta wings of various leading-edge sweep [4]

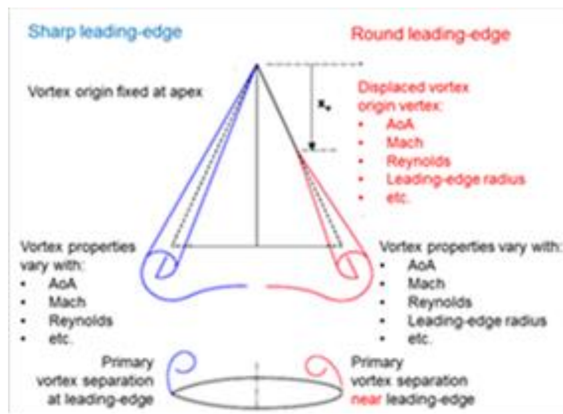

Figure 14. Vortex-flow development at delta wings of sharp and round leading-edges [43]

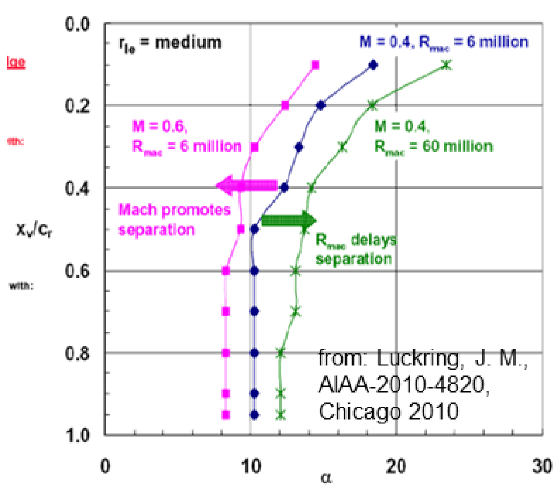

Figure 15. Reynolds- and Mach-number effects on vortex development versus AoA [43]

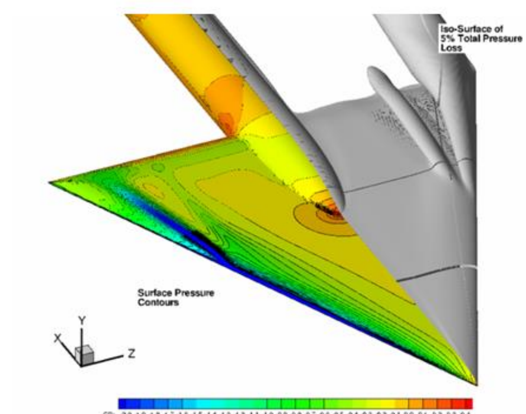

Figure 16. Flow structure of a 65° leading-edge swept delta wing with round leading-edges [40-41]

The past saw quite some investigations into the properties of separated vortex-flows from highly swept (65° and above) configurations. Usually sharp leading-edge configurations have been tested together

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with plan-form variations. Double-deltas and some delta-canards were probed for vortex interaction at medium and high AoA, however, often only at subsonic speeds. By and large their flow-physics are understood and the simulation by high fidelity numerical method predicts them correctly [31-34].

However, the flow around configurations of lesser sweep (45^o – 60^o) still needs quite some clarifying experimental and simulation investigations. Figure 13 shows that the vortex-breakdown of these wings is hardly recorded [3] properly since the development of the vortices and their breakdown may appear almost simultaneously in the rear half of those wings. With rounded leading-edges [35-37] the problem becomes even more compound since the onset of vortices becomes of complex interaction of Reynolds-number and Mach-number conditions (Fig. 14, 15). Figure 16 gives an impression of the part-span vortex onset and with the so-called displacement vortex [32, 33].

Increasing Reynolds-numbers delay the onset of vortices on rounded edges, while higher Mach-numbers provoke an earlier development of vortex systems. Also the basic independence of Reynolds-number of vortex breakdown has been confirmed more than once [4, 5, 10, 37]. The recent STO-AVT-183 [38] dedicated to the "onset and progression of flow separation" on a blunt leading-edge wing of moderate sweep is only a first step to further probe into the intertwining effects, notwithstanding transonic and high Reynolds-number effects. At a first glance the separation of highly and moderately swept wings appears to be very similar, while their developed vortices are quite different in their local flow profiles. The highly swept type shows a more jet-like axial velocity profile [2], the moderately swept resemble a wake-type pattern. Figure 17 gives some first idea of the flow-structure which is under investigation.

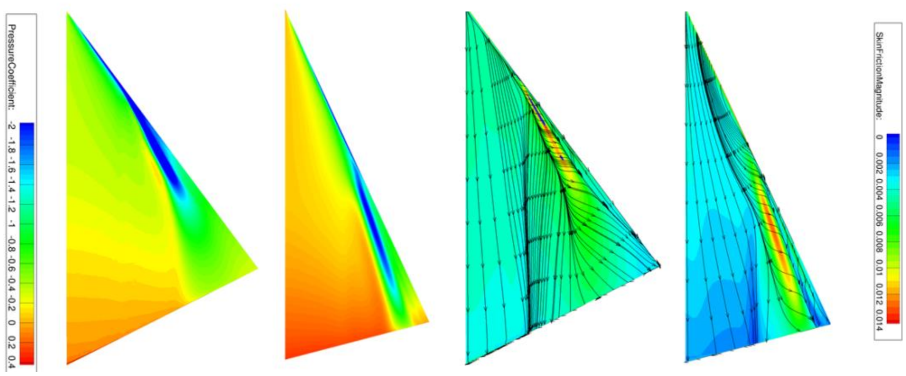

Figure 17. Moderately and highly swept wing with rounded leading-edges with surface pressure and skin-friction-distribution at Mach =0.15, $\alpha = 12^o$, Re = $3*10^6$

Given that most modern combat aircraft wings (Fig. 1) are of the moderately swept type with round leading-edges and some devices such as slats this status is somewhat astonishing. Only recently moderately swept wings with more realistic rounded edges came into focus of researchers. The aerodynamic designer – asked to provide performance, stability & control on real aircraft often is left alone when it comes to tackle and eventually use the vortex and boundary-layer interactions easily to be handled by a flight-control-system; usually without access to experimental capabilities - often late in the design and development process – and then at no cost.

To provide affordable, high performance for superior products the knowhow of high agility design through the sharpening of high fidelity physical modelling techniques and their experimental validation under realistic conditions is mandatory. It is the only economic way to reduce design risks for design to cost approaches.

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Since modern military requirements may result in very specific mission aircraft with very high aspect ratio wings, the paper will now make a short excursion into some of their special aerodynamic problems.

5 HIGH ASPECT RATIO WING CONFIGURATIONS

Special requirements into long-range reconnaissance and surveillance tasks materialized into unmanned aircraft of previously unknown design-space (Fig. 18). Sailplane-like only at a first glance – high aspect-ratio configurations experience quite some shape-changing effects due to their structural flexibility. E.g. wing-bending may result in dihedral effects interfering with lateral dynamics, while the wide span makes the vehicle prone to notorious deep spin. The required long loiter-capabilities (eventually 24+ hours) become efficient only via the integration of low speed, high performance wings with the highest maximum lift potential at very low drag conditions.

Hereby front-loading profiles may be preferred to ease trim-drag reduction efforts. Not only high, but good, reliable maximum lift predictions are essential here to avoid dangerous large-scale stall reactions (Fig. 19). Well-shaped wing-fuselage fairings, together with proper engine integrations are essential to keep additional interference-drag effects at bay. Figure 20 shows trials with a fuselage vortex generator to reduce wing-fuselage junction flow separation effects.

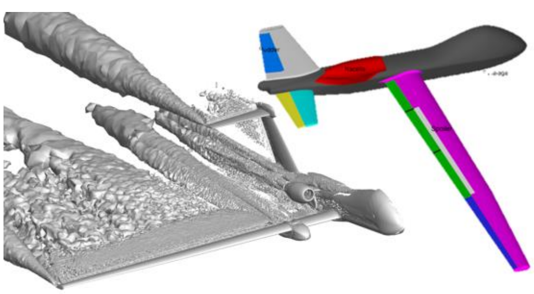

Figure 18. Surveillance aircraft configurations flow field pattern at Mach 0.28, Re = $3.0*10^6$

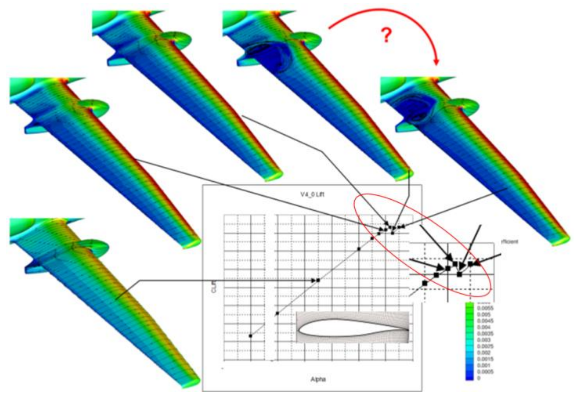

Figure 19. Surveillance A/C wing at high lift conditions, and separation pattern

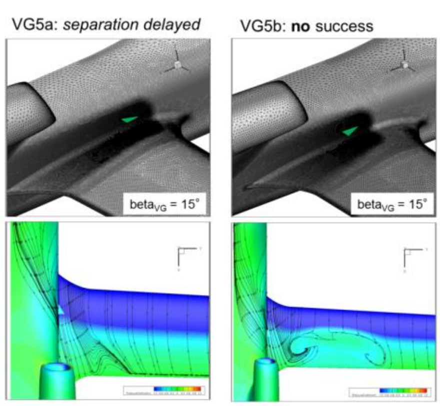

Figure 20. Vortex generator study to reduce separation

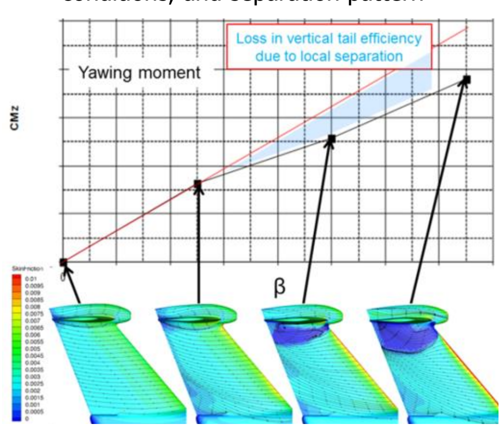

Figure 21. Reduction of vertical tail efficiency at high sideslip conditions

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High altitude surveillance missions require certain minimum speed envelopes to allow for best sensor functioning, while at the same time eventual weapon applications call for good handling characteristics also at medium and low speed not only for take-off and more so landing. To exploit a high efficient wing to the utmost – and with it to provide the smallest, lightest configuration possible – the maximum lift condition has to be secured as early as possible in the design process. Gust and adverse environmental effects have to be regarded through sufficient safety-margins. Interfering fuselage components, which may cause local loss of lift (Fig. 20) may be cured by well selected vortex generators when other means are prevented by other design considerations. Similar investigations may be necessary for certain landing gear, sensor pods and store integrations.

The proper application of laminar-turbulence transition assumptions and the associated turbulence modelling ask for quite some design effort to evaluate maximum lift also quantitatively, while wind-tunnel work requires elaborated tripping techniques. This also has to consider contamination and eventually under icing conditions [40].

Landing and lower altitude operations call for a well selected spoiler system and its applications for safe maneuvering and approach conditions. At the latter the wide flexible wing-span with its large inertias demands well behaved sideslip characteristics close to the ground. Here a tolerant vertical tail fin is essential to counter side-wind and gust effects. Figure 21 shows the eventual loss of yaw-stability, which has to be addressed by proper horizontal and vertical tail combinations; T- and cross-tail shapes must regard the additive effect of intersecting airfoils by displacement bodies or their relative arrangement.

The aerodynamic effects of the very flexible structure also must be investigated and estimated properly. Together with the large roll- and yaw-inertias they may cause considerable flight-dynamical problems, however, to be discussed elsewhere.

Only complete air-superiority makes this kind of aircraft survive its missions. Apart from very high altitude, stand-off distance (HALE-type) configurations any medium-altitude version (MALE-type) easily will be subject to enemy action unless in very asymmetric war-fare. Even this nowadays scenario may see its challenge soon by simple anti-air-systems. Purpose made missiles are under discussion [41]. The adaptation of older combat aircraft or gun-equipped general aviation ones may demand higher speed, agility and possibly add self-defense weaponry onto these platforms together with a combination of signature measures. An effective and efficient system might look different.

6 VERY LOW SIGNATURE AERODYNAMICS

Modern fighters with Mach 2 and 9-G turn-capabilities (Fig. 1) together with air-defense missiles reaching up to Mach 3-4, capable of 20 – 30 G provide a formidable threat. Here, stealth is to defeat the physical principles of the opponent's sensors, especially RADAR. Since radar cross section reduction is very much shape dependent [42] and therefore has considerable impact into the aerodynamic design, jet-exhaust and heating related infrared signature measures are not discussed here. Reducing an aircraft RCS efficiently to very low levels, e.g. some -30dB, its signature is difficult to detect and tracked until the aircraft is close to the threat sensors, cutting detection ranges and reaction times of air-defense inaptness.

Figure 22 gives an overview of geometric features to be avoided for the very low signature configuration design necessary. Corners and edges have to be reduced to minimum, multi-reflections at corners as coming with intakes and cavities have to be discarded. Medium size surfaces ending in points or corners with medium size edges are prone to creeping current and uncontrolled scattering into almost any direction. Vertical surfaces such as the fin and the flat sided fuselage call for harm. All edges are concentrated into as few as possible parallels to focus their antenna-like scattering in a very narrow beam, sweeping it away from the threat RADAR by an appropriate edge direction. Multi-reflections are

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denied by a primarily convex outer shape. The RCS demands for the integration of engines call for highly curved intakes and nozzle ducts to inhibit the direct view onto the engine compressors and turbine faces. While the intake lips also have to align with the limited range of the preferred stealth directions, an intake's close proximity to leading edges may also result in thrust dependent onset flow there, eventually leading to unfavorable intake compatibility and/or even to thrust dependent stability and control issue.

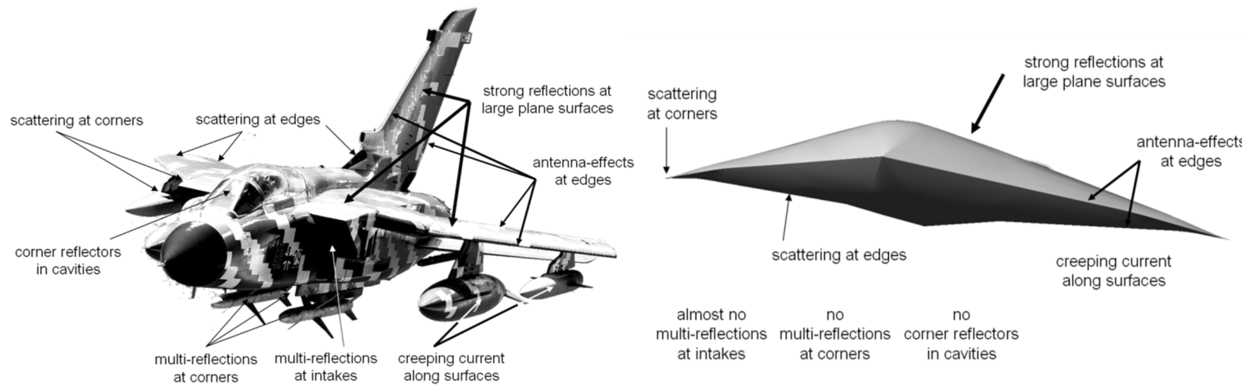

Figure 22. Possible sources of RCS and shaping mean for the reduction to very low RCS [42]

Currently very low signature type aircraft still are situated at the lower end of agility and maneuverability as long as "stealth" may prevent detection and tracking. However, the ongoing development of multi-static integrated air-defense system utilizing also medium and lower band frequencies are a chance to send out fighters for IR or visual contact to destroy mission accomplishment and even survival. Figure 23 gives an idea of the detections capabilities of the RADAR-wavelength with a hind-sight into effects of typical aircraft component dimensions [42] such as controls, intakes etc.

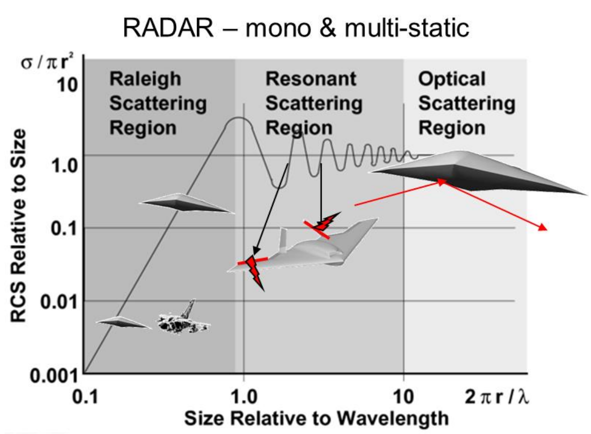

Figure 23. Relative RCS response of relative aircraft and component dimensions

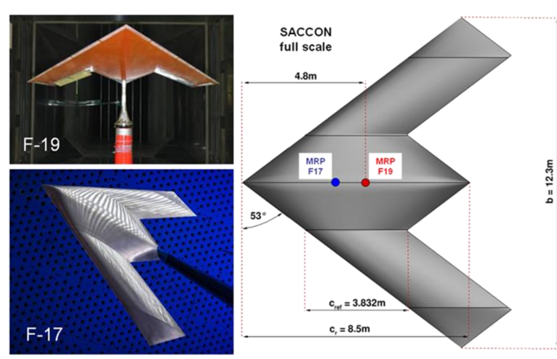

Figure 24. SACCON configuration, low and high speed wind-tunnel models

Here, a higher level agility, increased performance together with good stealth characteristics may provide the superior aircraft. Novel control systems [42, 44] – the size, orientation and principle of which must not resonate with typical wavelength illuminations (Fig. 23) -, possibly in combination with well-shaped more conventional controls, must keep signatures low without penalties in control power.

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Abandoned fins may be compensated by thrust vectoring techniques. However, at least high speed aerodynamic controls must be available because high speed thrust-vectoring would reduce efficiency. Finless configurations may resort to well positioned spoiler-systems and locally induced drag concepts. However, so called split flaps may need relatively large deflections and countering devices may be required to reduce aerodynamic cross-coupling.

While typical RCS scenarios push leading-, trailing- and side-edge sweeps somewhere in between 50^o – 60^o pure deltas, diamond (Fig. 22) and lambda shaped wings (Fig. 24) may allow for reasonable performance and agility plan-forms with inherent flow control [42] by the appropriate leading-edge shaping in all three dimensions, with regard to airfoil, sweep and camber. Since only RCS-compatible aerodynamic controls are thought, classical leading-edge devices such as slats providing gaps, slots, saw-teeth and vortex generators may have to become redundant via a well predictable flow, the conditions of which built into the outer shape for stability and also in support for conditioned control surface efficiency.

Weapon bays are becoming an essential part of stealth store carriage to hide the means to launch weapons by the possible array of effectors, since their geometric combination easily forms multiple corner reflectors. A weapon bay also may open a chance to integrate many access-panels for maintenance and support well hidden inside the air-frame without compatibility implications.

Due to the compactness of very low signature configurations, the associated aerodynamic cross-coupling and mass and balance characteristics, the stability and controllability via a proper FCS-system demand a higher level of detailed understanding and predictability of the aerodynamic behavior. As already mentioned before, especially the roll-instabilities at medium and high AoA due to AoS have to be understood for proper selection, combination and a correct scheduling of active controls, while the directional stability and control still has to find effective means for reduced or disposed fins.

The NATO STO-AVT-189 Specialists' Meeting on "Assessment of Stability and Control Prediction Methods for Air and Sea Vehicles" [10, 11] gave a survey of associated flight control rules and demands. The yaw-axis calls for novel directional controls, which must not impair or be disturbed by other controls flow features. The NATO STO-AVT 215 workshop on "Innovative Controls for Military Vehicles", held in 2013, now lay ground for a new STO-AVT-239 task group on "Innovative Control Effectors for Maneuvering of Air Vehicles".

One may cast doubt onto a solely stealth-based survivability strategy; designs combined into a more balanced maneuverability-, performance-, stealth-shape may benefit when seen in the framework of all aspect threats of future air-defense-system [44-46] in which so called passive RADAR-systems, which may draw on the anomalies of the existing electromagnetic mix of the frequencies of fielded military and civil navigation and communication systems.

Given that a future combat aircraft must add higher levels of maneuverability and performance to survive, the aerodynamic shaping will see more challenges by the aforementioned vortex interactions, vortex breakdown and vortex shock systems. Good prediction of separation onset, its progression into vortex systems and stability of these are the key to the proper combination of plan-form shape, leading edge geometry and controls to exploit flow-phenomena at their best throughout the flight-envelope. The pro-active increase of separated flow design knowhow and flow-control techniques also at realistic flight Reynolds-numbers and transonic speeds has to be supported. Means have to be found by a reassessment of highly effective flow control measures blended into the plan-form for future multirole combat aircraft early in the design.

Based on earlier NATO-STO-AVT task groups [23, 24, 31-34] the STO-AVT-161 and the direct follow on STO-AVT-201 [25-30] thought a typical lambda shaped configuration called SACCON (Stability & Control Configuration) to work out the properties of moderate sweep plan-forms with compound leading-edges, varying from sharp at the wing apex to round at mid-span and sharp in the wing-tip area again (Fig. 24). At first subsonic wind-tunnel investigations were combined with high fidelity Navier-Stokes CFD-

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simulations to probe for their capabilities and accuracy as well as to understand the developing flow fields and to explain the aerodynamic characteristics.

Even at low AoA, the chosen configuration's sharp apex region causes a typical vortex, which due to the rapidly increasing leading edge radius in span wise direction is confined to a small region in the front. It leaves the leading-edge and passes down over the configuration. Along the mid-board round leading edge the flow remains attached for now. The leading edge in the wing tip region, being tapered down to sharp again, produces a new, isolated wing-tip vortex. With increasing AoA the apex vortex strength increases, lift and the pitching moment grow linearly. The mid-span, attached flow region disappears rapidly with increasing AoA, leading to a flow with two vortices only. Just before the rearward one starts to develop ahead the moment reference axis, its flow causes a characteristic nose-down dip in the pitching moment (fig. 25). At even higher AoA the front and back vortices merge and are cause for a very rapid pitch-up to be cut off by the breakdown of both and/or the merged vortices. Reference [23] gives more details of these findings as well as a deepened overview of the different simulation efforts. This type of flow developments is quite a challenge to be simulated correctly. While the basic qualitative behavior is generally in good agreement, no simulation was capable to capture the low, medium and high AoA-range satisfactory (Fig. 25). Further details may be found in reference [29].

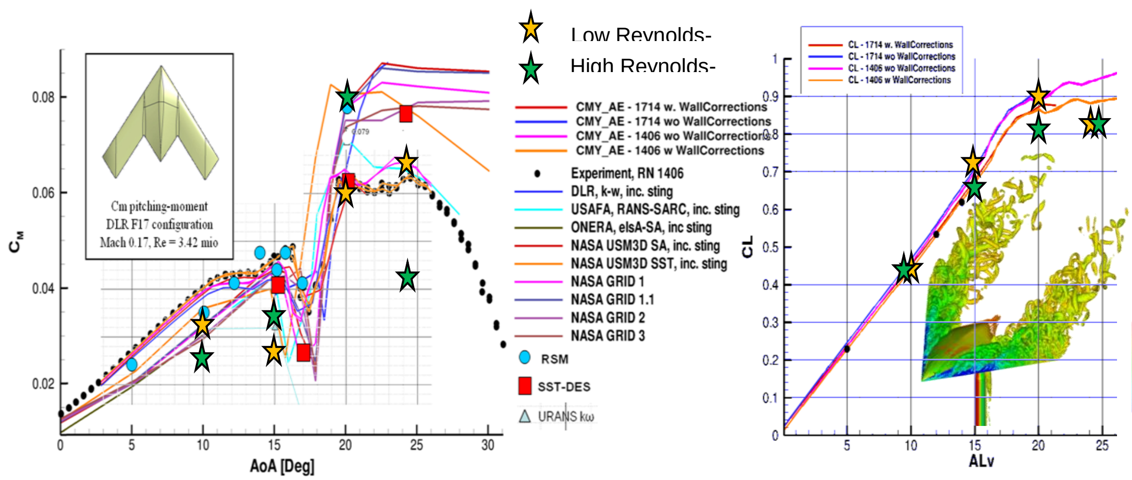

Figure 25. SACCCON lift and pitching moment, comparison of wind-tunnel and simulation

Since industry has to design and develop "free-flight", full aircraft, the question about the aerodynamic properties being scaled by Reynolds number effects comes natural with the wind-tunnel investigations. To rely on low Reynolds number experiments only can be justified when the aerodynamic forces and moments as well as compatibility issues can be secured for the full scale conditions backed by the assumption that the flow structure essentially are identical. CFD-methods could simulate free-flight conditions undisturbed by experimental installations. If the difference of viscous and compressible effects in between low and high Reynolds-numbers could be simulated correctly by the physical modeling capabilities, it can be assumed that the associated changes in the flow features can be covered.

The design offices need to make robust configuration decisions and to obtain a good assessment of the aerodynamic stability & control efficiency to meet the design criteria early on. Therefore the physical properties of the design-space have to be probed. Performed with the appropriate tools to investigate for correct design-trends and gradients, also performance predictions and maneuverability safety issues can be assessed close to the absolute levels and values if calibrated well. Lighter structures could be expected

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on aerodynamic loads estimations being closer to safety factors of 1.0. All this shortens response-time to customer demands and evaluates possible markets before they are closed again.

Configurations with compound leading-edges of moderate sweep as found here, have seen less attention until recently. Interestingly, no simulation of the SACCON was able to capture the low speed, low Reynolds-number pitching-moment correctly. Trials to model the wind-tunnel support or wind-tunnel wall effects failed to explain the differences in the experiment. Also turbulence model studies, ranging from one-equation models to RSM- and DES-approaches [24, 27] were unable to produce a satisfying agreement across the AoA-sweep from totally attached flow type to fully developed vortex flows with breakdown effects beyond α = 15°. When results at low AoA showed reasonable agreement, the high AoA results were far off. Contrary, satisfying results at high AoA were countered with far-off low AoA results. However, the characteristic pitch-down, pitch-up dip around α = 17° was covered fairly well by most simulations. Also the basic lateral behavior was simulated qualitatively correct. Figure 26 shows the switch of the rolling-moment from a stable behavior to become unstable at approximately α = 15° together with the corresponding surface pressure distribution for sideslips around an AoA of 20°.

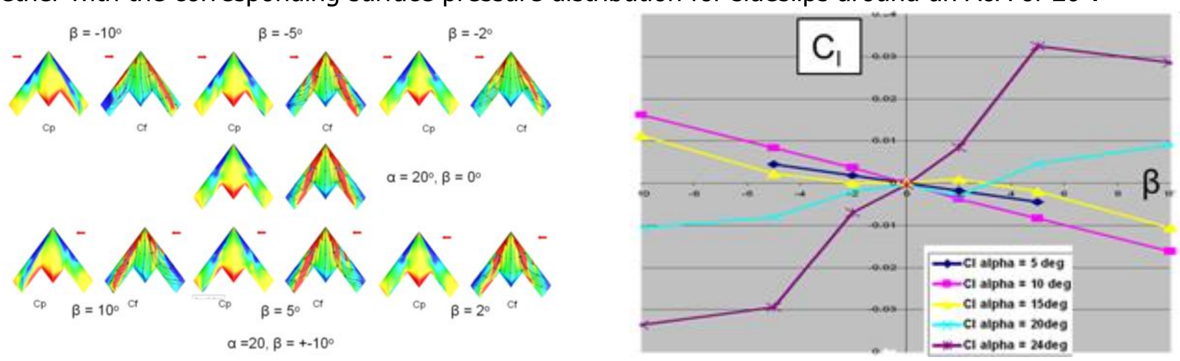

Figure 26. Pressure & skin-friction on SACCON at α = 20°, Mach = 0.17, Re = $3.42*10^6$ and the development of the sideslip rolling moment at different AoA at Mach = 0.17, Re = $3.42*10^6$

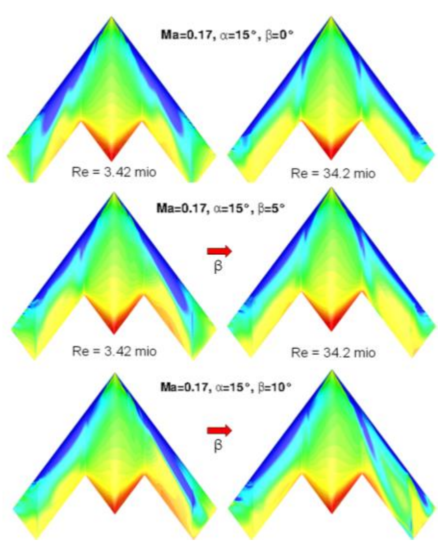

Figure 27. Pressure distribution on SACCON at sideslip at α = 15°, Mach = 0.17, Re = $3.42*10^6$ and Re = $34.2*10^6$

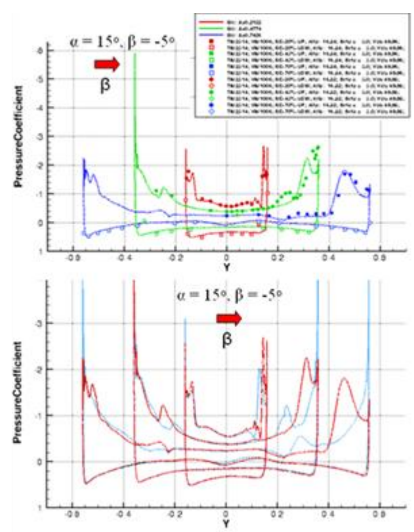

Figure 28. Comparison of the experimental and the simulation SACCON pressure at low Re = $3.42*10^6$ (red) and high ($34.2*10^6$) (blue) Reynolds-number at Mach = 0.17, α = 15°, β = -5°

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An impression of the low and high Reynolds-number subsonic flow structure in the surface pressure distribution at medium AoA and sideslip conditions up to $\beta = 10^o$ is given in Figure 27 at $\alpha = 15^o$. Here the low Reynolds-number shows a developed pair of vortices from the in-board and mid-board wing, while the high Reynolds-number case mostly shows attached flow on the round edged mid-board panel with apex vortex at the sharp-edged in-board part and the out-board tip vortex. At sideslip, the low Reynolds-number flow develops into a single lee-ward longitudinal vortex, with the wind-ward side developing attached flow and its related suction along the leading edge and with remnants left from the in-board vortex. Apart from a stabilized lee-ward, in-board apex vortex the high Reynolds-number conditions show no major leading-edge separation, while the leading-edge flow on the wind-ward side shows the pattern typical for mostly attached flow.

The simulated low, high Reynolds-number pressure-profile comparison confirms these differences (Fig. 28). The wind-tunnel condition simulation at $\alpha = 15^o$ AoA compares well with the experimental results, while the Reynolds-number comparison reveals some distinct differences in the pressure. In line with the findings of higher swept wing flows the higher Reynolds-number case show less and even more so a delayed onset of leading-edge separation into corresponding vortex flows. Since, the developing flow structures are quite different in nature the different Reynolds-number conditions cannot simply be adjusted by some scaling effort. It is necessary that these differences are simulated or measured properly – eventually at free-flight conditions, which means that the use of numerical simulation models should cover the most important features there correctly.

The β-sweep forces and moment characteristics at $\alpha = 15^o$, 20^o show the rolling-moment behavior being only in qualitative agreement with the experiment (Fig. 29, 30). Both, the low and high Reynolds-number simulations follow the same trend. Thus the simulation is a good indicator for important changes in the aerodynamic characteristics here.

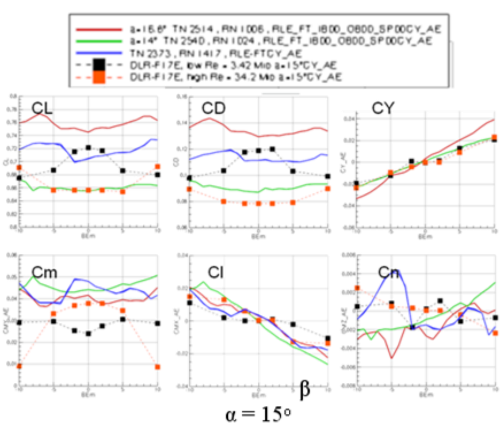

Figure 29. Forces & moments of SACCON at sideslip at α=15^o, Mach=0.17, Re=3.42*10^6 and Re =34.2*10^6 compared to measurements [29]

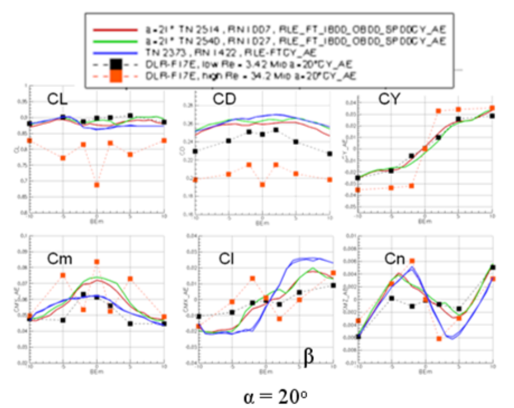

Figure 30. Forces & moments of SACCON at sideslip at α=20^o, Mach=0.17, Re=3.42*10^6 and Re =34.2*10^6 compared to measurements [29]

The very important AoA regime close to the switch of the lateral and longitudinal stability around $\alpha = 20^o$ shows significant Reynolds influence in the lateral behavior. At $\alpha = 15^o$ and 20^o important differences are found in the lift-, drag- and side-force results.

Some transonic cases at Mach = 0.8, in between $\alpha = 5^o$ to $\alpha = 20^o$ were also simulated at the wind-tunnel Reynolds = 12*10^6 and at Reynolds = 120*10^6 free-flight conditions. The experimental lift and drag [27] are predicted very well with both high and low Reynolds-number conditions, indicating that the transonic flow is much less sensitive than the low speed conditions. This is in line with the Reynolds-

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number, Mach-effect assessments [35] discussed before. Obviously this may be applied for the moderate sweep configurations as well. Pitching-moment results also are close to each other. They predict the dip – with a transonic, more stable gradient – fairly well and may provide an early indication to the designer to be prepared for flight control system layout task. As for the subsonic cases the pitch-up is accompanied by lateral instabilities as well, with the rolling-moment indicating quite distinct excursions at high Reynolds-number. At lower Reynolds-number the flows sensitivity to asymmetric conditions may have shifted the same effect to a slightly different AoA than simulated here.

As an example of transonic speed Reynolds-number effects in a compressible flow structure, the skin friction pattern for the case α = 10° (Fig. 31) at Reynolds = $12*10^6$ shows a shock induced pocket vortex [28, 29], which at high Reynolds-number hardly can be discerned. A more detailed description of the shock-induced vortex-system can be found in [28].

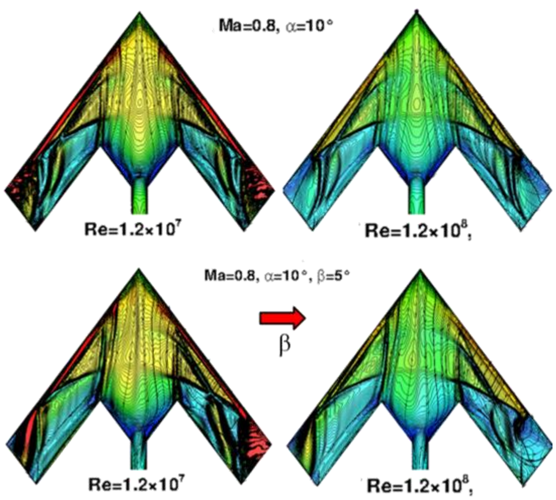

Figure 30. Skin-friction on SACCON at α=10°, Mach =0.80, Re=$12.0*10^6$ and Re=$120.0*10^6$

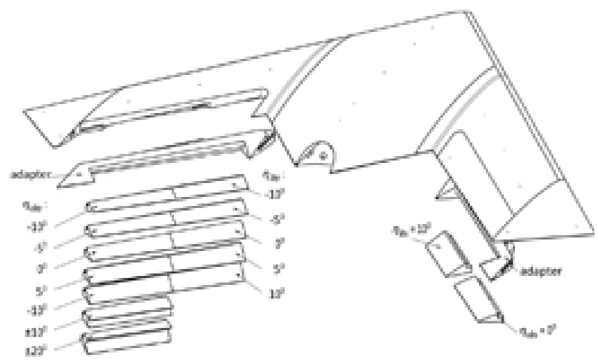

Figure 31. Lambda plan-form configuration SACCON DLR-F17E with trailing-edge control devices [26, 27]

With regard to control-surfaces for the lambda plan form SACCON (Fig. 32), the NATO-STO-AVT-201 group prepared some very detailed experimental and numerical investigation, which have been presented only recently [26, 27, 30]. It turned out that the control-effectiveness was rather poor for deflections below +- 10° and only large actuations of about 20° being more promising. Especially the medium and higher AoA range suffered under flow separation effects. Because of the signature driven control edge-alignment of a more favorable Kutta-condition at lower sweep cannot be exploited, while the complex onset of vortex flows adds to the low control performance at medium and high AoA. However, since low RCS signatures prefer small control deflections the given configuration is not very effective. Figure 33 shows the development of out-, and in-board elevon deflections of +- 5° and +- 10° at transonic speed, which at least beyond α = 10° show a rather erratic behavior even with strong reversal effects, hard to be used by a flight control system.

From a RADAR-signature point of view the most radical configuration is the diamond plan-form, which for flight-mechanical reasons has been adopted in modified form in Figure 22. As a flying wing with a sharp-edged but voluminous profile it provides room for all equipment purposes, from engine to fuel, from weapons-bay to landing-gear etc. Here, only the basic configuration with some control device studies can be shown; any other items currently are confidential.

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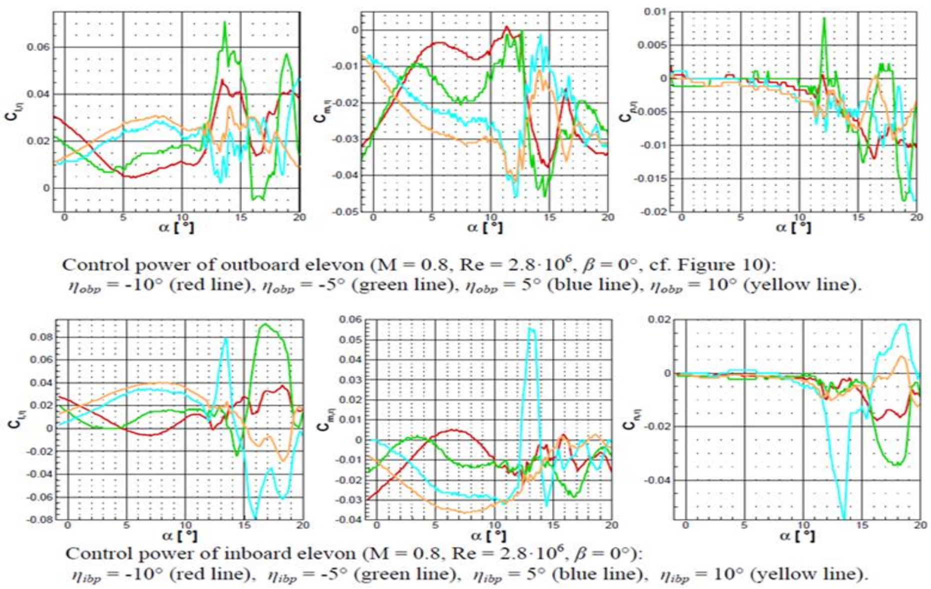

Figure 33. Control power of out- and in-board elevon on the SACCON plan-form at Mach = 0.8, Re =2.8*10^6 [27]

With the signature preserving restrictions given, a flyable configuration has to be found. Figure 34 and 35 depict examples of the basic flow at transonic and subsonic speeds, similar to cruise and high speed maneuver as well as low speed landing and take-off conditions without an adjustment of airfoils, thickness distribution, twist or camber and leading-edge shaping. The outer wing area produces uncontrolled flow separation, being enforced by shock-systems at transonic speeds (Fig. 51). Subsonic, high AoA flight (Fig. 52) shows the effects of vortex breakdown in the wing-tip area as well. These flow features provide unfavorable pitching characteristics, harming roll- and yaw-behavior at sideslip and definitely will impair any flap-spoiler system by separated, uncontrollable onset flow. Numerous configuration studies, especially into the shape of the outer half wing-area were necessary to come up with proper contours to remove strong, sharp pitch-up tendencies as well as the potential of related roll-excursions.

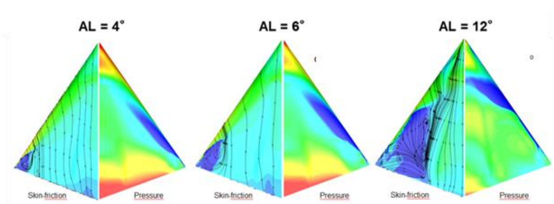

Figure 34. Pressure and skin-friction show the flow-pattern on a basic delta-diamond plan-form at Mach = 0.8

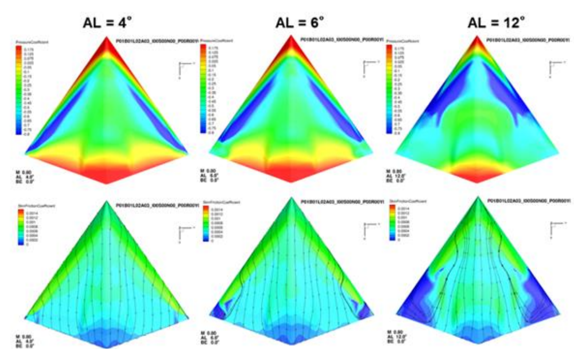

Figure 35. Relaxed pressure and skin-friction pattern on a modified delta-diamond plan-form at Mach = 0.8

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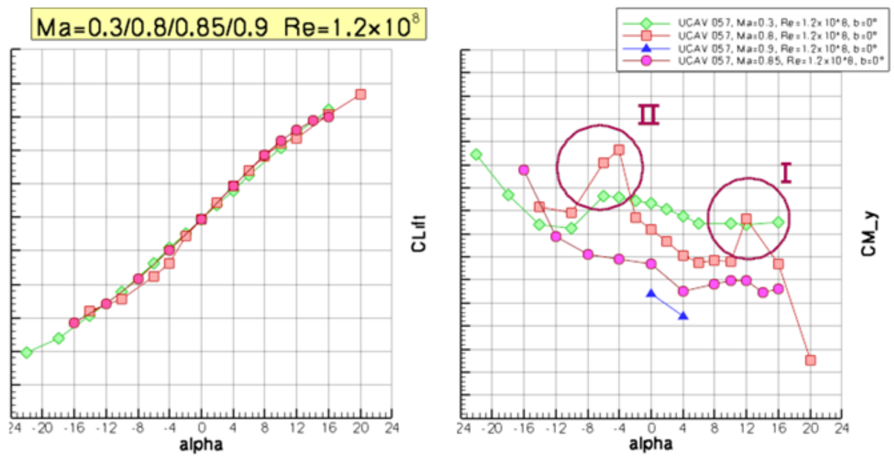

Figure 36. Longitudinal characteristics of a flying delta-diamond configuration at Mach = 0.8

The very much improved longitudinal characteristics of an even more advanced design can be found in Figure 36. It shows a well behaved pitch characteristic in the low and medium AoA-range. Only at Mach = 0.8 two small local pitch-ups (I, II) are left due to other non-plan-form related shaping details, which are not related to the adjustment of thinner and improved out-board airfoil selection and a compound mid-, out-board camber and twist to provide a tolerant baseline shape.
overall lift control via changes of the Kutta-condition.

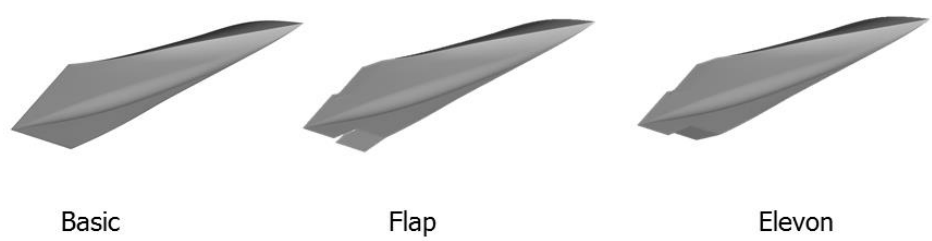

Figure 37. Flap and elevon control-elements on a delta-diamond flying wing configuration

With a better controlled onset-flow, the design of control devices may proceed. Since the leading-edge has to cover both low RADAR-signature and aerodynamic requirements no active control-device is thought there. As classical mechanical trailing-edge devices such as flaps, ailerons and in their combination as elevons (Fig. 37) are the most efficient leverage as pitch- and roll-controls due to their impact onto local and and overall lift control via changes of the Kutta-condition.

As can be seen in the longitudinal characteristics of the delta-diamond flying wing with flaps being deployed at rather modest deflections, almost linear pitch-control power can be provided (Fig. 38).

To discard with a fin and/or rudder novel control elements have to be found, which take over the directional control. While thrust-vectoring may be an integrated approach, off-design conditions as well as high speed thrust requirements call for some aerodynamic yaw control power. To avoid multiple permanent edge reflections other than the leading- and trailing-edge fixed an- or dihedral components have to be replaced by active devices. Aerodynamic cross-couplings should be avoided or have to be compensated by their combination with countering means to produce yawing moments to be reasonable for a flight control system. Figure 39 gives some examples of such yaw-control devices like spoilers, leading-edge rudders differential flap-settings and the like. It turns out that spoiler, orientated parallel to

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the trailing-edge are the most efficient means to provide yaw- or directional control (Fig. 40). However AoAs somewhere above 8°-10° lose their control power due to leading-edge vortex flows which provide an unfavorable onset flow, thereby reducing or even cancelling their effectiveness.

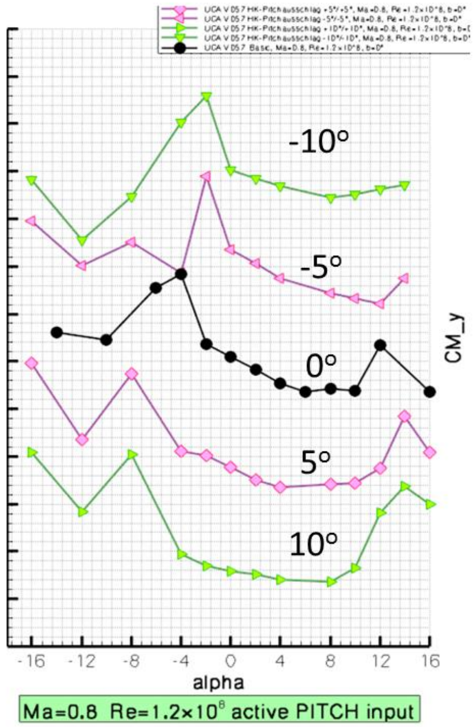

Figure 38. Pitch-control of a diamond-delta configuration at Mach = 0.8

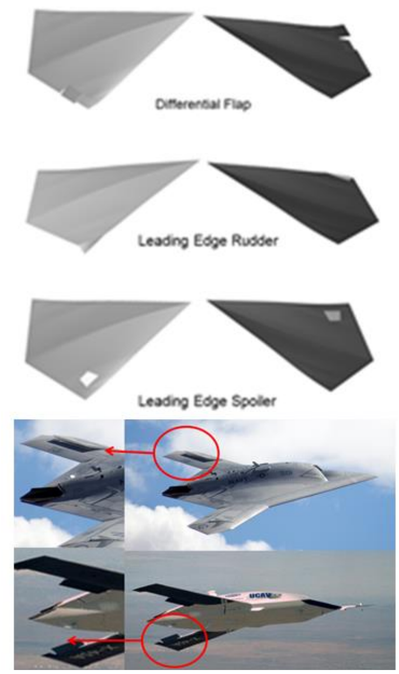

Figure 39. Selection of yaw-control devices: leading-edge, trailing-edge spoiler, split-flaps, differential flaps etc.

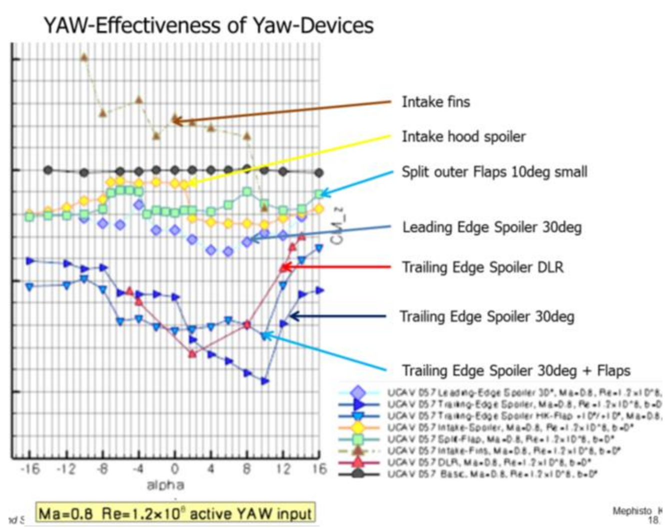

Figure 40. Effectiveness of yaw-control devices at Mach = 0.80: leading-edge, trailing-edge spoiler, split-flaps, differential flaps etc.

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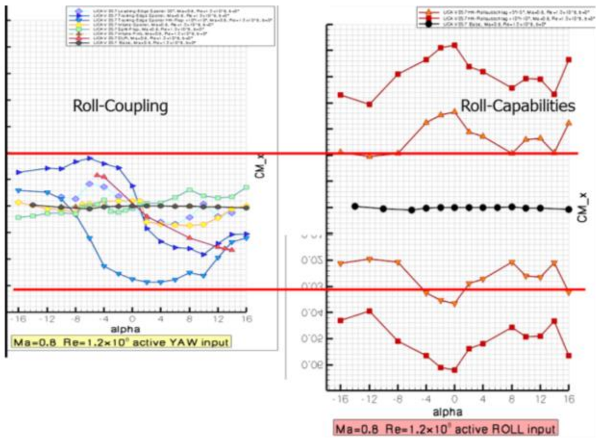

Figure 41. Roll-coupling of various yaw-controls: leading-edge, trailing-edge spoiler, split-flaps, differential flaps to be controlled by elevon roll-capabilities

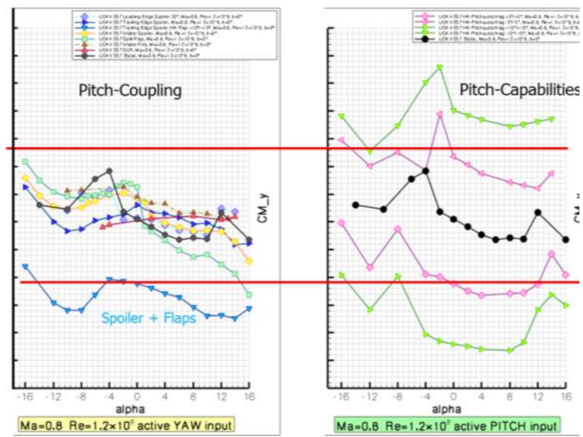

Figure 42. Roll-coupling of various yaw-controls: leading-edge, trailing-edge spoiler, split-flaps, differential flaps to be controlled by flap pitch-capabilities

On fairly compact, small span delta-diamond configurations the yaw control is rather weak with regard to flight-control requirements, which also have to cover gust, hard maneuvers etc. Apart from that all devices provide control power only at rather large deflections, which not only deteriorate flight performance but also may compromise RADAR-signature. Even the rather effective trailing-edge orientated spoilers have to be fairly large and must benefit from the largest span-wise position possible. Larger aspect ratio configurations (Fig. 39), which also benefit from it by increased range and endurance would be a better choice. Other studies into thrust-vectoring control – not discussed here – also show fairly week effects with traditional devices.

While the yaw controls without fins are fairly weak, their roll- and pitch-coupling effects are rather difficult to be overcome by the application of corresponding elevon (Fig. 41) and flap activity (Fig. 42). The complex flow interactions found on tested devices easily develop strong pitch and roll effects which also are non-linear even throughout the lower and medium AoA-range. Proper combinations of control settings are required to allow for a flyable configuration that performs more than cruise. Namely landing procedures and combat manoeuvers will take their toll and will demand signature compromises.

7 SUMMARY AND CONCLUSIONS

Given the recent and future advances in multi-static and passive integrated sensors of developing air-defense systems may again shift the configuration design work into the balance of agility, performance, active counter-measures and some effects of reduced signatures (Fig. 43). While RCS-shaping is here to stay, it will not dominate future combat aircraft designs as some very-low signature shapes may suggest.

A wide spectrum of compressible speed-regimes and many off-design flow conditions, which are prone to flow separation and mutual interference effects, have to be covered. Flight control systems only can provide safe agility, being combined with high performance, when stability and controllability is provided through a docile controllable aerodynamic behavior.

The aircraft shape must allow for the smooth transition from attached flows to controlled separation, such as longitudinal vortex-systems. This includes the organized onset flow for control devices as well as

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the exploitation of favorable interactions of features such as vortex-systems as design elements to restore favorable or deliberately destroy not suitable stability and control moment areas.

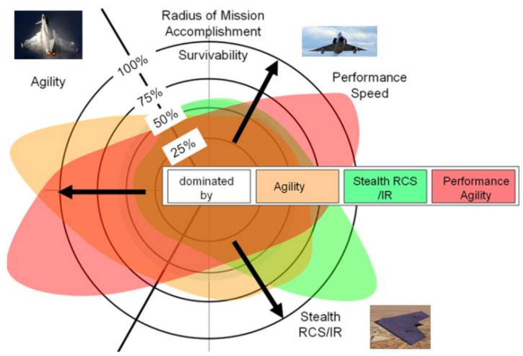

Figure 43. Balance of agility, performance and signature characteristics

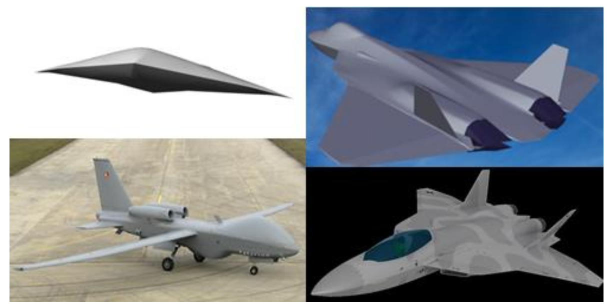

Figure 44. Generic shapes of future combat aircraft

The effect of complex interactions of separation and vortices eventually together with the transition of laminar to turbulent flow needs as much future attention. The same is true for the interaction of small and large scale vortices as seen in the complex flow of combat aircraft. Vortices, shocks systems, their interaction with vortex breakdown foster or diminish the controllability of the flow throughout the whole flight envelope. The understanding of vortex breakdown and its relation to bubble type uncontrolled dead-water flow is another key for improved aircraft shape design. Superior and efficient combat aircraft configurations (Fig. 44) only will be feasible and affordable with a deepened understanding of these physics.

Stealth type configurations for very low RCS are restricted in any use of legacy flow control devices such as strakes, notches etc., anything that disrupts smooth, unbroken edges. Since traditional flow control devices are banned here, the flight envelope must be checked from the regime of attached flows up to the onset and development of cruise-speed shock boundary layer interactions.

Reynolds number effect investigations have shown that its influence may not be negligible in the transfer from wind tunnel to real flight conditions. Namely the medium and high AoA regime shows significant differences in the flow and the ensuring forces and moments which cannot be covered by traditional Reynolds number scaling measures. A better understanding of the differences at high and low Reynolds-number is necessary.

Equally important, are the assessment of the limitations and the validity of state of the art CFD-codes to simulate full scale conditions. The physical modelling of the flow effects to be found on military aircraft, their chances and consequences may need a scrutinizing look into locally adaptable turbulence models when ultimate highest fidelity ones cannot be handled by current computational equipment. Current turbulence modelling capabilities, e.g. ranging from SA, to K-ω from SAS-, DES-types as well as RSM-approaches must be probed for to their local and global effects, adjusted, possibly being modified, re-written to prepare them for the flexibility necessary to simulate the intense interactions in proper mesh-resolutions.

For these objectives appropriate experimental benchmarks and detailed investigations are needed, not only for basic shapes, but also for complex configurations. The effect of promising shapes of novel wing-planforms, reflexed leading-edge shapes of compound profile character together with those of leading-edge devices and passive and active flow-control devices such as strake-shapes and position have to fill the future designer shelf before any actual aircraft is demanded.

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Since the industrial design office needs to make correct configuration decisions and to obtain a good assessment of the aerodynamic stability & control efficiency to meet the design criteria early on, the physical properties of the design-space have to be probed. Performed with the appropriate tools to investigate for correct design-trends and gradients, also performance predictions and maneuverability safety issues can be assessed close to the absolute levels and values if calibrated well. Lighter structures could be expected on aerodynamic loads estimations being closer to safety factors of 1.0. All this shortens response-time to customer demands and evaluates possible markets before they are closed again.

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9 REFERENCES

[1] Küchemann, D., "Aerodynamic Design of Aircraft," Pergamon Press, 1978

[2] Hummel, D., "On the Vortex Formation over a Slender Wing at Large Angles of Incidence", AGARD-CP-247, Oct 1978

[3] Wentz, W. H., Kohlman, D. L. "Wind-tunnel Investigations of Vortex Breakdown on Slender Sharp-Edged Wings", NASA CR 98737, 1968

[4] Poisson-Quinton, P., "Slender Wings for Civil and Military Aircraft," Israel J. Technol., vol. 16, no. 3, 1978, pp. 97-131

[5] Polhamus, E. C., "Applying Slender Wing Benefits to Military Aircraft, J. Aircraft., volume 21, no.8, August 1984, pp. 545-559

[6] Chambers, J. R., " High Angle of Attack Aerodynamics: Lessons Learned, AIAA 86-1778 CP, San Diego, 1986

[7] Chambers, J. R., Grafton, S., Aerodynamics of Airplanes at High Angles of Attack, NASA TM 74097, Dec. 1977 (developed for an AGARD-VKI Lecture Series given in April 1977.)

[8] Greer, H. D., Summary of Directional Divergence Characteristics of Several High-Performance Aircraft Configurations, NASA TN D-6993, 1972

[9] Lamar, J. E., "Some Vortical Flow Experiments on Slender Aircraft that Impacted the Advancement of Aeronautics," Aerospace Sciences, Vol 45, issue 6-8, pp 147-168, 2009

[10] Osterhuber, R., Hitzel, S. M., "FCS Requirements of Combat Aircraft – Beneficial Aerodynamic Deliverables," STO-AVT-201 Edinburgh, October 2011

[11] Osterhuber, R., FCS Requirements for Combat Aircraft – Lessons Learned for Future Designs," STO-AVT-189, Workshop on stability & control, Portsmouth, October 2011

[12] Gerhold, T., Galle, M., Friedrich, O., Evans, J., Calculation of Complex Three-Dimensional Configurations employing the DLR TAU-Code, AIAA Paper 97-0167, Jan. 1997.

[13] Gerhold, T., "Overview of the Hybrid RANS Code TAU," in N. Kroll, J. Fassbender (Eds.) MEGAFLOW – Numerical Flow Simulations for Aircraft, NNFM, Vol. 89, Berlin, 2005, pp. 81-92.

[14] Schwamborn, D.; Gerhold, T.; Heinrich, R., "The DLR TAU-Code: Recent Applications in Research and Industry," In proceedings of European Conference on Computational Fluid Dynamics - ECCOMAS CDF 2006, Delft , The Netherland, 2006.

This work is licensed under the Creative Commons Attribution International License (CC BY). Copyright © 2015 by author(s).

[15] DLR Deutsches Zentrum für Luft- und Raumfahrt e.V. Technical documentation of the DLR, TAU-Code, Release 2011.2.0, 2011
[16] Kroll, N., Rossow, C., Digital-X: DLR's Way Towards the Virtual Aircraft, German Aerospace Center (DLR) Institute of Aerodynamics and Flow Technology, NIA CFD Research, Hampton Virginia, August 6-8, 2012
[17] Lamar, J. E., Obara, C. J., Fisher, B. D., and Fisher, D. F., "Flight, Wind-Tunnel, and Computational Fluid Dynamics Comparison for Cranked Arrow Wing (F-16XL-1) at Subsonic and Transonic Speeds," NASA TP 2001-210629, Feb. 2001.
[18] Lamar, J. E., "Cranked Arrow Wing (F-16XL-1) Flight Flow Physics with CFD Predictions at Subsonic and Transonic Speeds," RTO MP-069, Paper 44, 2003.
[19] Obara, C. J., and Lamar, J. E., "Overview of the Cranked-Arrow Wing Aerodynamics Project International," Journal of Aircraft, Vol. 46, No. 2, 2009, pp. 355–368.
[20] Boelens, O. J., Badcock, K. J., Görtz, S., Morton, S., Fritz, W., Karman, S. L., Jr., Michal, T., and Lamar, J. E., "Description of the F-16XL Geometry and Computational Grids Used in CAWAP," Journal of Aircraft, Vol. 46, No. 2, 2009, pp. 369–376.
[21] Görtz, S., Jirásek, A., Morton, S. A., McDaniel, D. R., Cummings, R. M., Lamar, J. E., and Abdol-Hamid, K. S., "Standard Unstructured Grid Solutions for CAWAPI F-16XL," Journal of Aircraft, Vol. 46, No. 2, 2009, pp. 385–408.
[22] Hitzel, S.M., Vortex Flows of the F-16XL Configuration – CAWAPI II Free Flight Simulations, AIAA SCI-Tech 2014, January 2014, National Harbor, MD, U.S.A.
[23] Schütte, A., Hummel, D., Hitzel, S. M., "Numerical and Experimental Analysis of the Vortical Flow around the SACCON Configuration," AIAA-2010-4690, Chicago, June 2010
[24] Cummings, R.M.; Vicroy, D.D.; Schütte, A.; An Integrated Computational/Experimental Approach to UCAV Stability & Control Estimation: Overview of NATO RTO AVT-161, AIAA Paper 2010-4392; 2010
[25] Cummings, R. M., Andreas Schütte, The NATO STO Task Group AVT-201 on 'Extended Assessment of Stability and Control Prediction Methods for NATO Air Vehicles', AIAA 2014-2000, 32nd AIAA Applied Aerodynamics Conference, June 2014, Atlanta, GA
[26] Huber, K. C., Vicroy, D. D., Schütte, A., Hübner, A., UCAV model design and static experimental investigations to estimate control device effectiveness and Stability and Control capabilities, AIAA 2014-2002, 32nd AIAA Applied Aerodynamics Conference, June 2014, Atlanta, GA
[27] Rein, M., Irving, J. P., Rigby, G., Birch, T. J., High speed static experimental investigations to estimate control device effectiveness and S&C capabilities, AIAA 2014-2003, 32nd AIAA Applied Aerodynamics Conference, June 2014, Atlanta, GA
[28] Zimper, D., Hummel, D., Analysis of the transonic flow around a generic UCAV configuration, AIAA 2014-2266, 32nd AIAA Applied Aerodynamics Conference, June 2014, Atlanta, GA
[29] Hitzel, S.M., Zimper, D., "Model Scale and Real Flight of Generic UCAV and Advance Combat Aircraft – An Industrial Perspective", AIAA 2014-2267, 32nd AIAA Applied Aerodynamics Conference, June 2014, Atlanta, GA
[30] Jirasek, A., Cummings, R. M., Schütte, A., Huber, K., The NATO STO AVT-201 Task Group on Extended Assessment of Stability and Control Prediction Methods for NATO Air Vehicles: Summary, AIAA 2014-2394, 32nd AIAA Applied Aerodynamics Conference, June 2014, Atlanta, GA
[31] Elsenaar, A., Hjelmberg, L., Bütefisch, K.-A., and Bannink, W.J., "The International Vortex Flow Experiment," AGARDCP437, Vol.1, pp. 9-1 to 9-23, 1988.
[32] Hummel, D., "The second international vortex flow experiment (VFE-2): Objectives and first results," 2nd International Symposium on "Integrating CFD and Experiments in Aerodynamics", 5

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- 6 September 2005, Cranfield University, UK. Journal of Aerospace Engineering, vol. 220 (2006), No. 6: 559 - 568.
[33] Hummel, D.: The International Vortex Flow Experiment 2 (VFE-2): Objectives and Overview. In: Understanding and Modeling Vortical Flows to Improve the Technology Readiness Level for Military Aircraft, RTO-TR-AVT-113 (Summary Report of Task Group AVT-113), chapter 17, 2009
[34] Cummings, R. M., Forsythe, J. R., Morton, S. A., Squires, K. D., "Computational Challenges in High Angle of Attack Flow Predictions," Progress in Aerospace Sciences 39 (2003), pp 369-384, Pergamon Press
[35] Luckring, J. M., "A Survey of Factors Affecting Blunt Leading Edge Separation for Swept and Semi-Slender Wings," AIAA-2010-4820, Chicago 2010
[36] Chu, J. and Luckring, J.M., "Experimental Surface Pressure Data Obtained on Delta Wing Across Reynolds Number and Mach Number Ranges," Vol. 1-4, Sharp, Small, Medium, Large Leading Edge," NASA TM-4645, February 1996
[37] Kulfan, B. M., "Reynolds Number Considerations for Supersonic Flight," AIAA-2002-2839, St. Louis, M., 2002
[38] Luckring, J. M., Boelens, O. J., „A Reduced-Complexity Investigation of Blunt-Leading-Edge Separation Motivated by UCAV Aerodynamics," SciTech 2015, AIAA 53rd Aerospace Sciences Conference, January 2105, Kissimmee, FL, U.S.A.
[39] Hitzel, S. M., Boelens, O. J., van Rooij, M., Hövelmann, A., „Vortex Development on the AVT-183 Diamond Wing Configuration – Numerical and Experimental Findings," SciTech 2015, AIAA 53rd Aerospace Sciences Conference, January 2105, Kissimmee, FL, U.S.A.
[40] Seubert, R., Activities within TAECA41 (Aerodynamics & Methods) for the Certification of a Typical UAV for Flight into Known Icing Conditions, Airbus D&S, TAECA41-MEM-037/14, July 2014
[41] Tegler E., "Duck Hunt, U.S. military plans defenses against growing UAV threat", Aviation Week & Space Technology, May 12th, 2014
[42] Hitzel, S.M., Perform and Survive – Evolution of Some U(M)CAV Platform Requirements, NATO-STO-AVT-215 Workshop on Innovative Control Effectors for Military Vehicles, May 2013, Stockholm, Sweden
[43] Hitzel, S. M., "Aerodynamics and RADAR-Signature", Dornier Report, 1988
[44] Engelbeck R.M., "Investigation Into the Impact of Agility in Conceptual Fighter Design", NASA Contractor Report 195079, Boeing Defense & Space Group, Seattle, Washington.
[45] Kopp C., „Replacing the RAAF F/A-18 Hornet Fighter - Strategic, Operational and Technical Issues", AirPower Australia Analysis, 1998
[46] Kopp C. "Assessing Joint Strike Fighter Defence Penetration Capabilities", Air Power Australia Analysis 2009-01, 7th January 2009
[47] Baker C. J. Griffiths H. D., "Bi-static and Multi-static Sensors for Homeland Security", London University College, 2005

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