Challenges & Needs for the Understanding of Combat Aircraft Aerodynamics

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ABSTRACT

The future air-combat scenery sees an emerging change in air-combat tactics due to stealth and modern missiles. Fast, visual encounters could be decided by very rapid instantaneous maneuvers at high angle-of-attack and transonic speed for shooting advantages being finalized by rapid missile exchanges. Controlled vortex flows also at higher transonic speeds must be mastered for controlled motions about all three axes. The aircraft planform, wing-sweep and the leading-edge type have to be arranged for the mutual benefit of these complex flows throughout the flight envelope also regarding signature considerations. Often controlled flight limits are reached at sideslip conditions. Here asymmetric vortex instabilities cause unstable rolling moments together with adverse yaw. To push these limits an extended understanding of vortex separation, their interaction and breakdown is necessary. The probing of the design aerodynamic characteristics is to be assisted by modern flow simulation tools to be validated on the basis of appropriate physical understanding.

1.0 AERODYNAMIC COMBAT AIRCRAFT DESIGN

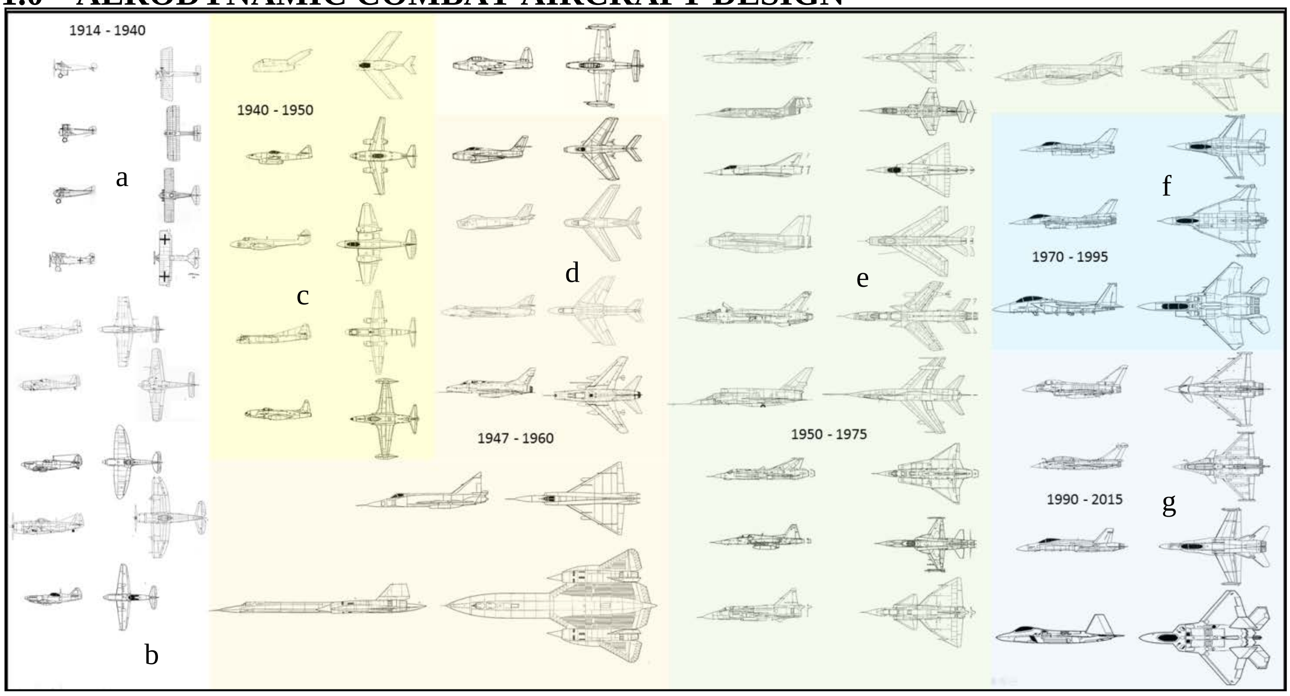

Fig 19-1.: History of Aerodynamic Combat Aircraft Design

From the very beginning of flight stability and control capabilities were the prime aerodynamic objective for the performance and even more so the maneuverability of combat aircraft [1]. Attached flow and/or controllable separation effects [2] are the key to the agility of any aircraft namely combat aircraft whose prowess is the combination of speed, specific access power, lift to drag ratio, agility and stealth capabilities.

The first combat aircraft (Fig. 19-1 a) [3, 4] caused more fatalities from of loss of control during take-off rather than from air-combat maneuvers. High lift conditions at maximum power often led to flow separation at wing-tips overpowering the control elements. Asymmetric wing flow separation provoked spin-entry due to asymmetric induced drag which had to be overcome by directional or vertical tail and rudder stability and control. Eventually unrecoverable spin ensued and had to be avoided by skilled human control.

The ongoing development of propeller fighter design (Fig. 19-1 b) [5–8] brought the design of wing twist, slotted outer wing panels or outboard leading-edge flaps and sharpened inboard wing-root profiles which alleviated the problems. The measures provided attached flow conditions in the most vital roll control element areas, the pilot being forewarned by buffeting caused by at the inner wing sections. High speed demands (Fig. 1 c) into the transonic regime saw the drastic reduction of the relative airfoil thickness with their sharpened nose shapes aggravated the situation even further.

The advent of the first swept wing jet-aircraft (Fig. 19-1 d) [9-14] added to the flow separation issue at the vital outer wing areas. Together with the up-wash caused be the induced effects of the forward inner wing area together with a span-wise boundary layer build-up called for more drastic measures by the introduction of adjustable leading-edge slats and even more pronounced wing twist. The ever increasing speed demands into the supersonic regime [13-16] – even more pronounced by the slenderness demands of area-ruling [15-17] – changed the relation of the combat aircraft inertias from yaw to roll of approximately 1-2 to about 4-6 for the arriving supersonic aircraft.

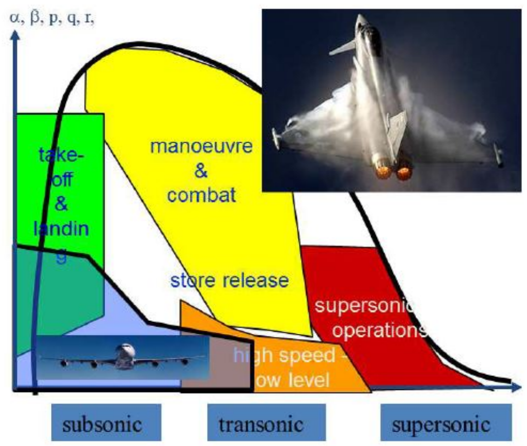

Fig. 19-2: Typical Agility Envelope of a Modern Combat Aircraft

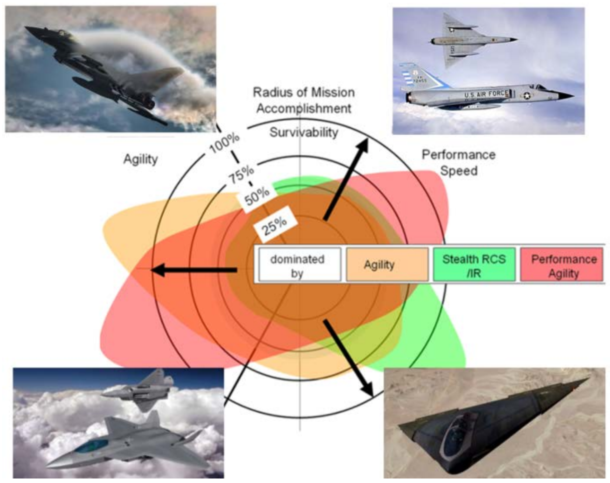

Fig. 19-3: Performance, Maneuverability and Signature of a Modern Combat Aircraft

Adverse yaw and roll stability and control issues usually were countered by vortex generator arrays, fence systems or the well proven leading-edge slats. Means of effective flow control devices (Fig. 19-2) were thought eventually to improve the aerodynamic characteristics by keeping performance capabilities high. Eventually very effective but highly complex slat, flap systems together with active circulation control devices were introduced. Rather large vertical fins and horizontal tails emerged for sufficient stability and control for maneuvering conditions.

The designers of legacy supersonic jet combat aircraft (Fig. 19-1 d, e) soon selected delta-wings [13, 14, 18-20] and their derivatives for their high speed slenderness allowing for large absolute wing-root thickness benefitting internal volume and structural strength countering wing bending moments. Leading-edge shaping - e.g. via conical camber - not only helped to exploit leading-edge suction for drag reduction at trans- and supersonic speed but also to delay pitch-up tendencies caused by uncontrolled separation.

The early discovery of the non-linear lift characteristics of controlled leading-edge flow separation rolled up into stable longitudinal vortices [2, 21-23] eased the exploitation of their high angle of attack (AOA) suction lift at take-off and landing speeds. Depending of leading-edge sweep these benefits may be curtailed by the vortex breakdown phenomenon. Longitudinal vortices travelling into adverse pressure gradient field experience the abrupt change of their structure of jet type into a reversed flow bubble, thereby drastically reducing the suction on the underlying wing-surface. This may lead to lift reduction and even more so to severe pitch-up situations.

Demands for affordable superior fighter agility [24-26] led to double delta, strake trapezoidal or canard delta wing configurations (Fig. 1 e, f) exploiting the potential of controlled vortex flows for high lift and maneuverability. However, vortex breakdown [27-32] also causes adverse roll at sideslip and eventual loss of directional stability of the vertical fins. Meticulous shaping work eventually was performed to push towards the maximum controlled lift conditions. Powerful tail and fin arrangements together with automatic leading-edge slats and eventual passive flow control devices allowed for a widened envelope up into the maximum lift area before stability and control issues may have ended the safe flight regime. Very good knowledge of the complex vortex flow systems eventually allows the extension of the maneuvering flight envelope into even higher post stall AOA-regimes [33-45]. The more efficient measure is the support of vortex flow areas which stabilize the roll- and yaw-conditions and the preservation of aerodynamic efficiency. The provocation of vortex breakdown by so called vortex fences or spoilers may have stabilizing effects but at the cost of reduced efficiency.

Fig. 19-4: Rapid Stealth Air-to-Air Scenarios

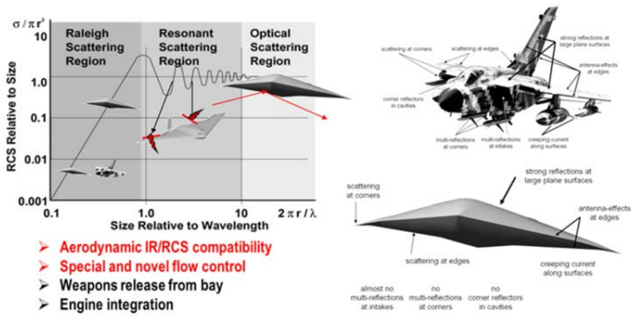

Fig. 19-5: Shaping Effects of high RCS-Requirements [49]

Modern and emerging combat aircraft (Fig. 19-1 f, g) [46] have to cover an even wide scope of performance and maneuverability (Fig. 19-2), eventually also considering signature restrictions (Fig. 19-3) and to meet range and payload capacities. Latest developments in the air-combat scenery see an emerging change in air-combat tactics due to stealth tactics and modern missiles. These may change classic BVR-encounters as well as dog-fights. It may be foreseen that fast visual encounters could be decided by very rapid instantaneous maneuvers at high AOA (Fig. 19-4) and transonic speed for shooting advantages being finalized by rapid missile exchanges. To these ends vortex flows must be mastered also at higher transonic speeds where complex shocks of cross-flow type and spiraling shape may interact with the vortices sensitivity or even may be caused by vortex breakdown. To achieve favorable aerodynamic properties these flow-features must be incorporated into the aircraft planform, wing-sweep and -profiles, the leading-edge type, eventual strakes and the like.

Stealth compatibility (Fig. 19-5) [46-49] manifests into more blended configurations, wing sweeps tend to be increased, horizontal and vertical tails tend to smaller sizes, and compromises have to be thought for control surfaces. The higher the RADAR cross section (RCS) demands are being set, the more restricted the application of legacy flow control devices (e.g. strakes, notches, fences) become. Just to mention here, infrared (IR) signature may add to these problems with regard to heated structures and nozzle flow arrangements.

The link in between design shaping and aerodynamic characteristics and more importantly vice-versa found little attention outside industrial design offices. Here rules and procedures for aerodynamic and flight physical definition for conflicting requirements are to be worked out. They have to scout and explore for robust areas in the design space. The economic probing of the aerodynamics is accessible by modern flow simulation tools and sophisticated test-facilities. Validated computational fluid dynamics (CFD) prediction capability for vortex flow topics for risk reduction and reliable design turnaround times exist, however need further enhancement with regard to turbulence modelling and efficient integration into the overall design process.

2.0 FLIGHT MECHANICAL REQUIREMENTS

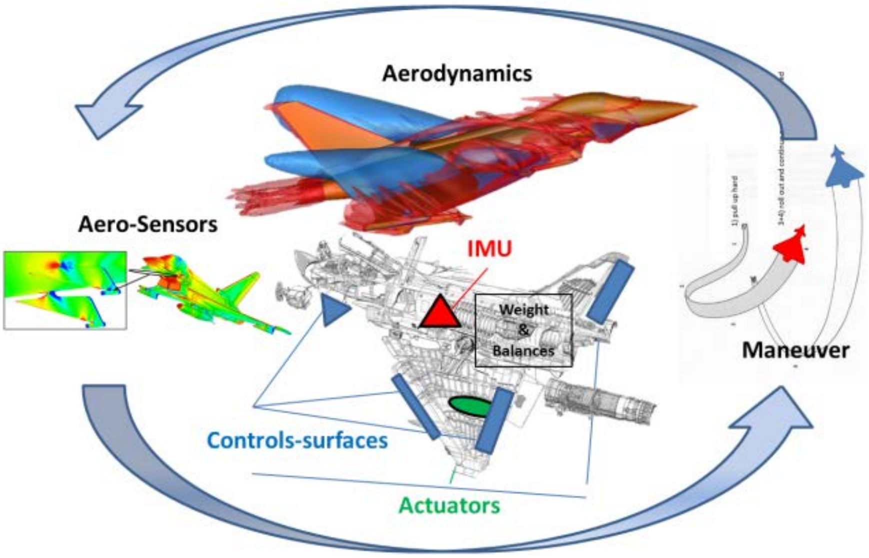

Fig.19-6: Elements of a Modern Flight Control System FCS

The development of flight control systems (FCS) (Fig. 19-6) [50] from mechanical system with full servo, full authority analogue FCS to digital full authority fly-by-wire FCS allowed for relaxed or even unstable flight-physical layout [51]. This provided levels of increased performance and maneuverability into the transonic and supersonic regimes of the flight envelope. However, FCS only can provide safe agility when stability and control is provided through a controllable aerodynamic behavior [51]. The dynamic interplay of the aerodynamic characteristics, the actuators, control surfaces, the aero-elastic effects, the aircraft's inertia and the reliability of air-data information requires are certain piece wise linearity in which the aerodynamic flow may be the dominating challenge.

The flight dynamical consequences [51] are described by the combination of the lateral and directional derivatives in yaw $Cn\beta$ and roll $Cl\beta$ (Fig. 19-7) in the dynamic derivative $Cn\beta dyn$. While the yawing derivative diminishes with the cosine of AOA, the rolling moment derivative increases with the AOA sinus, it becomes dominant. This is enhanced by the relation of the yaw- and roll-inertia for modern combat aircraft lying in between 4-6 typically. At lower and medium AOA the aircraft remains stable as long as the windward side wing is raised and the yawing moment turns the aircraft into the wind, with a stable $Cl\beta$ being negative and a stable $Cn\beta$ being positive. For unstable configurations the longitudinal controllability calls for sufficient pitch-down control power throughout the flight envelope.

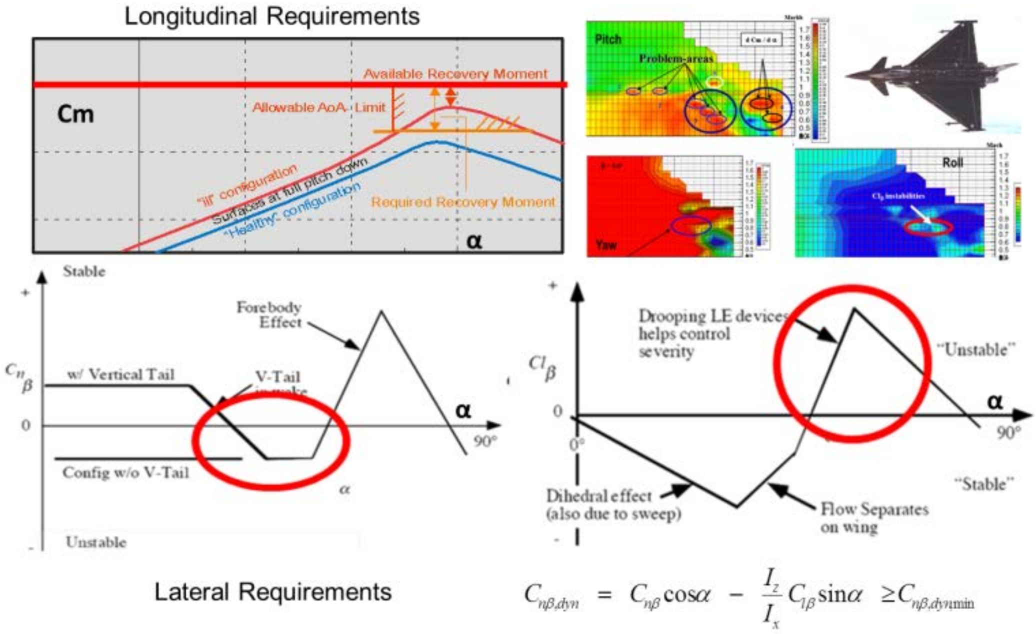

Fig. 19-7: Requirements for Longitudinal and Lateral Stability and Control [51, 52]

The aircraft shape and its control devices must allow for the smooth transition from attached flows to controlled separation into the favorable formation of leading-edge vortices [52, 53]. However, the phenomenon of vortex breakdown causes abrupt reduced local suction effects, causing pitch-up, roll- and yaw-instability.

3.0 VORTEX FLOW SYSTEMS – KNOWLEDGE AND GAPS

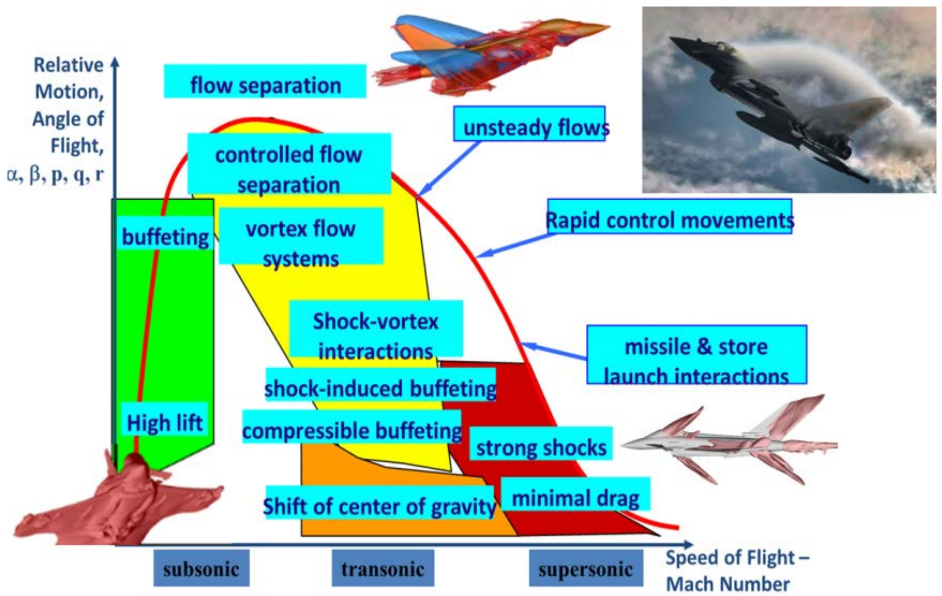

Fig. 19-8: Aerodynamic flow phenomena in a typical combat type agility envelope

The aerodynamics design of combat aircraft has to cover a multitude of flight conditions as shown in Figure 19-8. Supersonic speeds e.g. for super cruise will call for area-ruled shapes [14-16], while the wing and empennage planforms as well as the control layout should provide the basic needs for robust medium and high AOA agility well beyond maximum lift at sub- and transonic speeds. At the same time the largest possible wing aspect ratio together with a blended wing-fuselage shape would help to increase range and endurance aspects. While supersonic performance and stable vortex-flows for stability and control considerations would support the slender wing concept, endurance and range prefer the high aspect ratio wing for induced drag reduction. The compromise may be found in the combination of trapezoidal or delta wings of low sweep with leading-edge extension strakes or canard configurations.

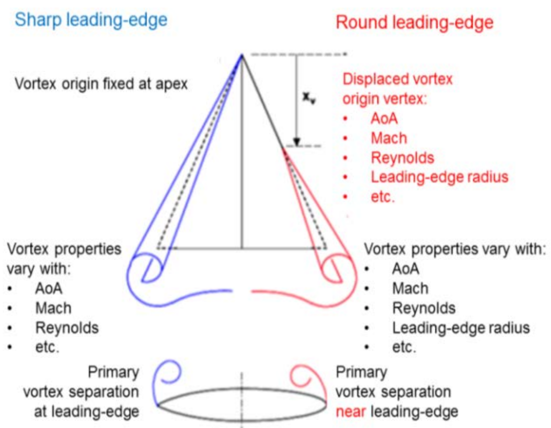

Fig. 19-9: Conditions of Leading-Edge Vortices [54, 55]

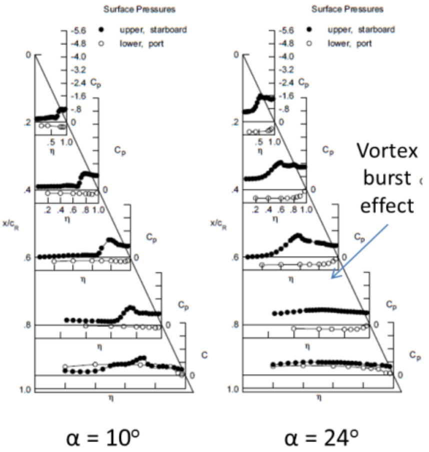

Fig. 19-10: Vortex Flow Induced Pressure Distribution [55]

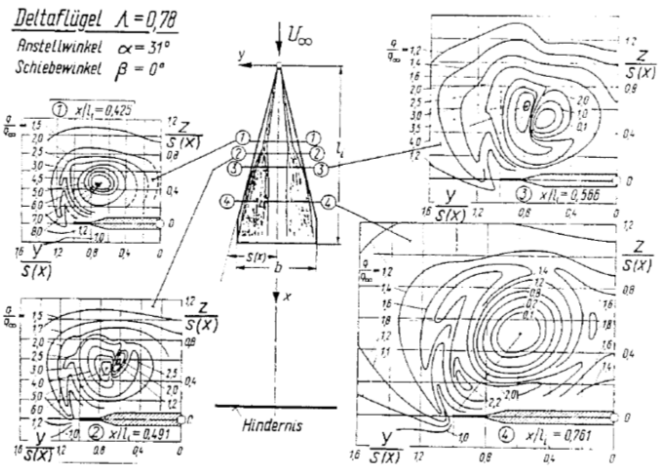

Bild 76a: Staudruckverteilung in Querschnitten um einen Deltaflügel [3].

Fig.19-11: Vortex Breakdown Flow Field [31]

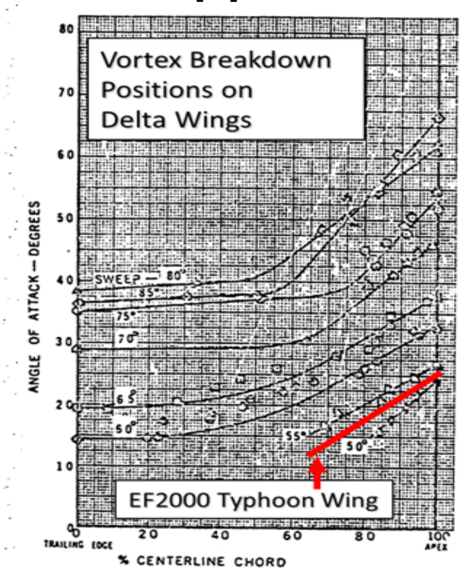

Fig. 19-12: Progress of Vortex Breakdown with AOA for Delta Wings of Low and High Sweep [29]

In the early 50-ties, some otherwise very successful and prominent combat aircraft designers [58] were rather doubtful about the delta wing shape, regarding the straight low aspect ratio wing with very thin airfoils being superior at supersonic speeds. However, the multipoint demands soon converted them to the delta shape which overcame its rather low lift-curve slopes by the theoretical reasoning and experimental finding of the controlled leading-edge vortex flow separation (Fig 19-9). Their high circumferential velocities induce high suction peaks (Fig. 19-10), thereby providing extra non-linear lift [2, 25, 26, 39, 54-57, 59-61].

Depending of leading-edge sweep [29] these benefits may be curtailed by the vortex breakdown phenomenon (Fig. 19-11). Longitudinal vortices travelling into adverse pressure gradient field experience the abrupt change of their structure of jet type into a reversed flow bubble, thereby drastically reducing the suction on the underlying wing-surface (Fig. 19-10). This may lead to lift reduction and even more so to severe pitch-up situations. The higher the leading-edge sweep the more stable the vortices with breakdown occurring at higher AOA. Lower sweep increases the vortex strength but at the expense of its stability causing breakdown at lower AOA. Figure 19-12 gives an overview of forward movement of vortex breakdown, advancing towards the wing apex with increasing AOA.

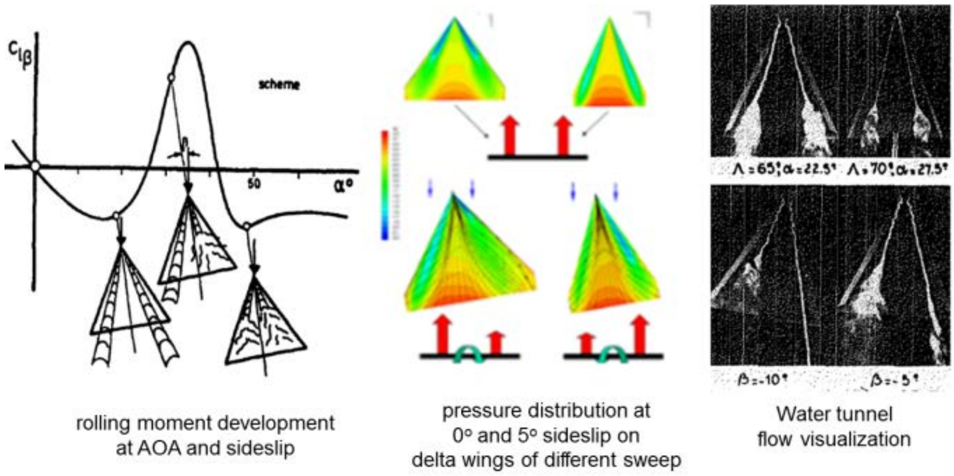

Fig. 19-13: Asymmetric Vortex Breakdown at Sideslip Conditions [27]

Often controlled flight limit is reached at sideslip conditions (Fig. 19-13). Here asymmetric vortex breakdown [27, 32]] causes unstable rolling moments together with adverse yawing reaction. The advancing, windward side wing with its lower effective sweep experiences breakdown conditions earlier than the leeward wing side, which sees an increased effective leading-edge sweep. As long as the advancing wing vortex can produce more lift than the leeward vortex system a stable rolling moment will result, the advancing wing is lifted and the sideslip is converted into an angle of attack [61, 62]. At a certain AOA the advancing wing vortex will breakdown early, thereby diminishing its suction in the apex-region which is overcome by the weaker but stable suction peak over most of the lee-side wing. The rolling moment reverses, while the sideslip angle increases and roll control may be lost, the limits of maneuverability are reached.

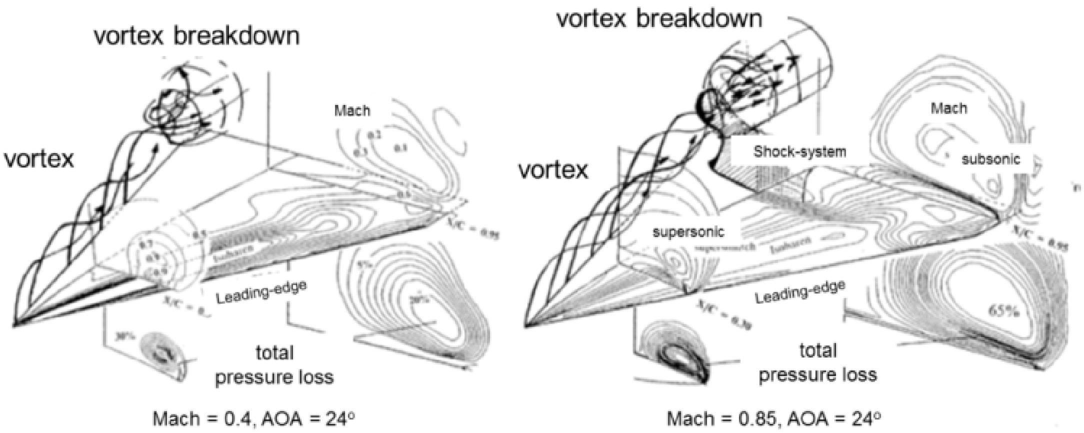

Fig. 19-14: Vortex breakdown at sub- and transonic conditions [63]

Transonic compressibility effects aggravate this behavior (Fig. 19-14) [63-65]. It can become more intense because of the conical character of the flow which brings the vortices closer to the wing surface where the breakdown is more concentrated. Also cross-flow shocks may increase the pitch-effects.

More recently the onset of vortex separation especially on round edged leading-edges, its secondary effects and the development into vortex breakdown even at medium AOA (10° < α < 15°) for delta wings of lower sweep was investigated in more detail (Fig. 19-15) [66-69]. Some similar investigations concentrating onto vortex development were done in [60, 61], however, none explored the upper subsonic and the transonic regime.

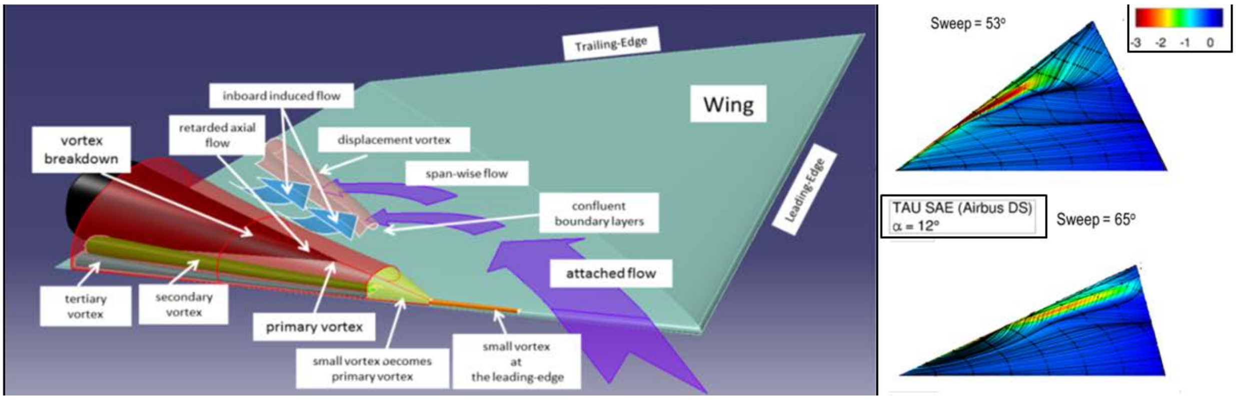

Fig. 19-15: Vortex onset, progression and breakdown at subsonic speeds at AOA 12° [69]

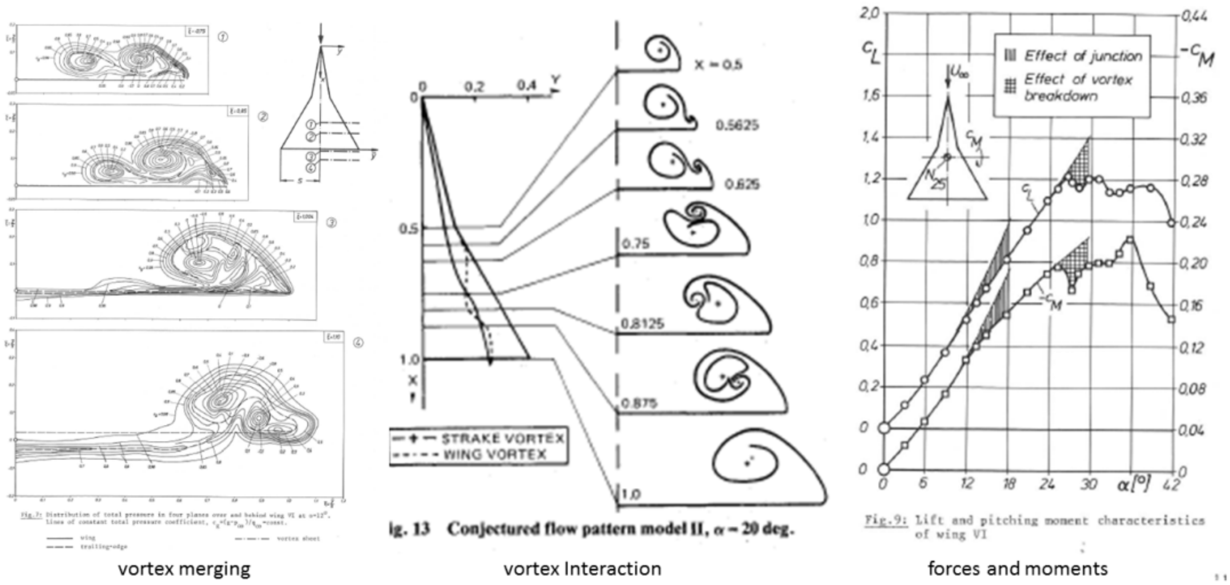

Fig. 19-16: Vortex Interaction of a Double Delta Configuration [70]

Interaction effects among either co-rotating or counter-rotating vortices, vortex breakdown, and their neighboring flow-field, can significantly alter the vortex-induced effects [70, 71]. In some cases the interacting vortices remain side by side, in other cases one vortex will braid around the other, and in yet other cases one vortex will be absorbed by the other (Fig. 19-16). Basic understanding for vortex shock and vortex boundary-layer interactions also is lacking, and these vortex interactions alter other important features such as vortex breakdown and secondary separation.

An idea of vortex systems on combat aircraft designed and flown throughout a wide envelope Mach-number and up into the limits of high AOA-stall conditions is given in Figures 19-17, 18-18 and 19-19. The delta-canard configuration [61, 72] shows a very complex mixture of longitudinal vortices together with large areas of reversed flow due to vortex breakdown. The shear-layers of the leading-edge and the slat vortices shown by the lambda-2 criterion wrap around the reversed flow as to be expected for vortex breakdown of a delta-wing with low sweep. Because of the long coupled canard its vortex system hardly interferes with the wing flow. The wing's apex strake area produces additional vortices as does a small but highly important vortex from the fuselage-strake beside the cockpit (Fig. 19-17). Their role is the stabilization of the complete vortex system and avoids adverse rolling moments allowing very high maneuverability and superior agility. The design was achieved by CFD-based investigations into the interference of strake-type vortices reenergizing basic wing without compromising performance demands. A comparison of experiment and simulation of the lift, pitching and rolling moment is shown in Figure 19-18. Here the standard configuration is compared with an agility improved configuration. The aircraft modified with a delta-shaped fuselage strake and the addition of a wing apex strake is roll-stable, thereby extending its possible maneuvering envelope much further than the standard configuration. The latter's instability putting a limit to the maximum AOA, which not only curtails agility but also performance.

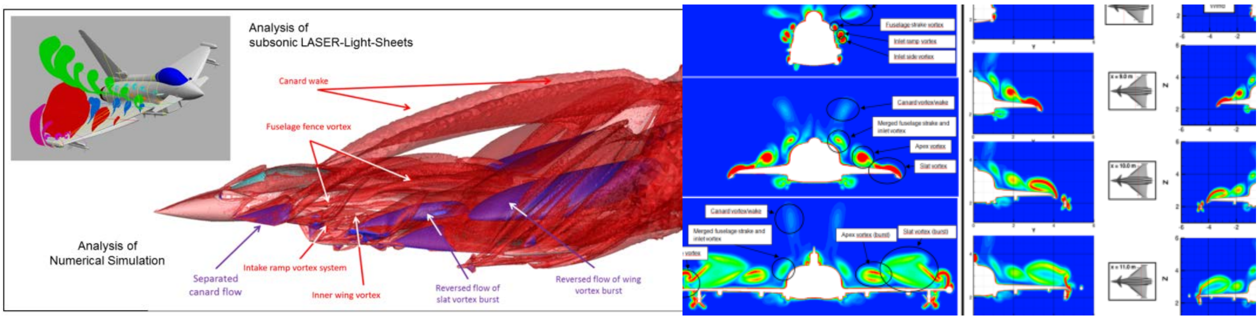

Fig. 19-17: Vortex Systems and Interaction at Very High AOA at Subsonic Speeds [61, 72]

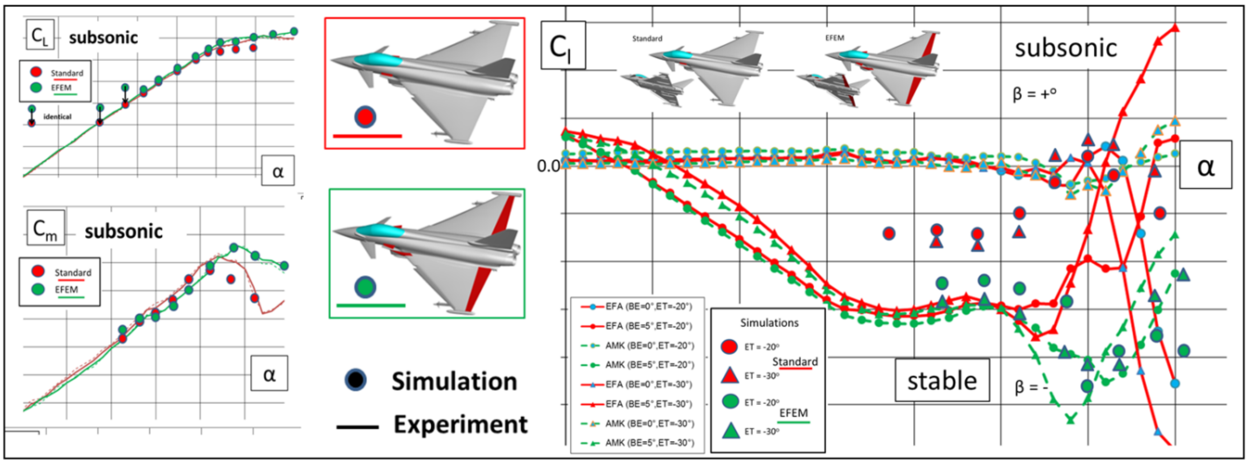

Fig. 19-18: Subsonic High AOA Behavior of a Delta-Canard Configuration [61]

Both configuration simulations show the trends correctly, however, the standard configuration is very far of the rolling moment of the experimental results. Since the computational effort, the mesh quality and the turbulence models applied was almost identical this difference may be claimed to some lack in the turbulence models capability to allow for the proper development of uncontrolled vortex flows, the strake-modified version offering a much better guidance of for vortex separation and interaction of more concentrated longitudinal vortices.

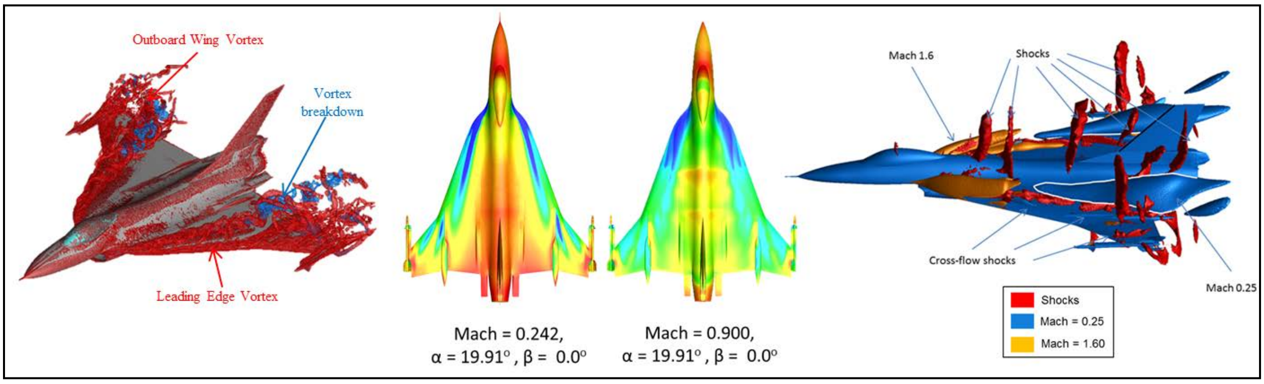

Fig. 19-19: Combat Aircraft Vortex System at Sub- and Transonic Speeds [78, 79]

The double-delta configuration (Fig. 19-19) shows the development of sub- and transonic high AOA flow [73-79]. The inner, highly swept wing causes a concentrated leading-edge vortex which breaks down at the junction of the inner and outer wing panel. The outer wing panel shows a vortex which breaks down very early – shown by the erratic pattern of the vortex-sheets shown by the lambda-2 criterion. A vortex-fence or vortex breakdown fence provides a deliberate destruction of the inner leading-edge vortex to avoid unfavorable sideslip pressure distributions, thereby stabilizing the rolling moment, here at the expense in the wing's performance by the reduction of maximum lift (Fig. 19-19). The transonic case shows the mutual interference of shock systems with the vortex-system. Some shocks are caused by the vortex breakdown flow field, while others are caused by aircraft components or changes of its geometry such as the vertical fin, the end of the cockpit and the kink of the wing leading-edge. The expansion of the flow around the leading-edge vortex into supersonic speeds produces also a cross-flow shock in between the wing surface and the leading-edge vortex.

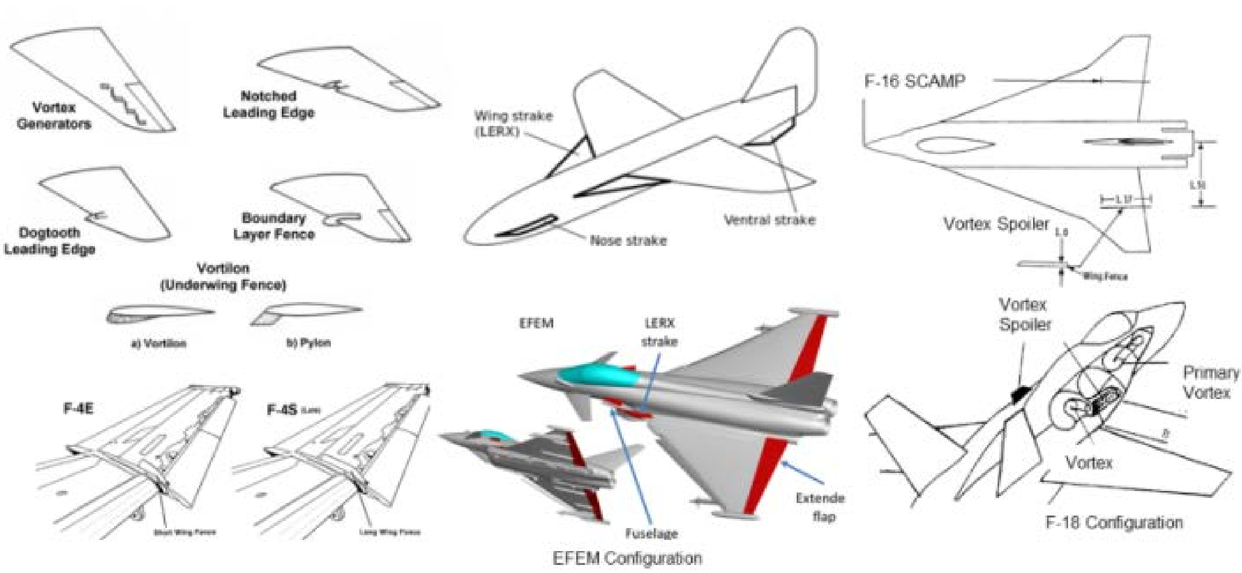

Fig. 19-20: Passive Flow Control Devices to Enhance high AOA Capabilities [25, 26, 37, 38, 42, 61, 83, 85, 86]

Figure 19-20 gives a selection of passive flow control devices which may enhance the stability and controllability of the high AOA flow. To fly beyond maximum lift and the controllability limits means have to be found to delay breakdown on the windward side or to destroy the leeward vortex deliberately. The past saw devices such as canards, strakes and leading-edge slats as well as other means for the individual configuration at hand. Many aircraft are limited to some AOA around 30º. Eventually means can be found to extend or even break through the lateral instability barriers. By aerodynamic means such as an apex strake and a triangular fuselage strake the EFEM-Typhoon fighter increased its agility as shown in Figure 19-18 [61].

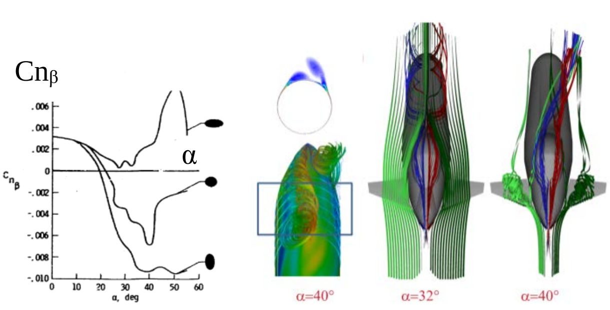

Fig. 19-21: Development of Asymmetric Fore-body Fuselage Vortices

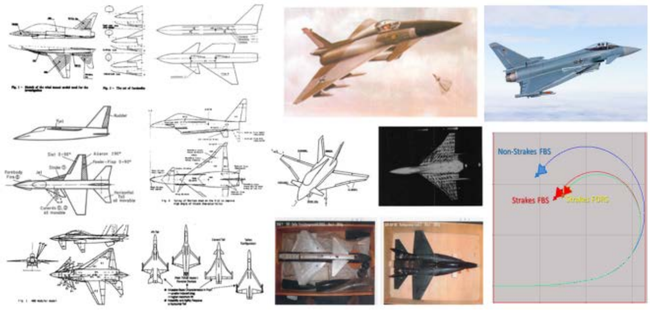

Fig. 19-22: Exploration of Legacy Combat Aircraft Design Space [43-45]

Last, not least to forget are the effects of vortices from slender forward fuselage shapes (Fig. 19-21). Their asymmetric development beyond some AOA of 30º may cause strong yawing-moments eventually even causing unfavorable interference in roll as well. However, well defined forward fuselage shaping – e.g. with a chine or strake - may fix and control these vortices into small but highly stable vortices which could even improve the wing or tail flow conditions.

As already mentioned in chapter 1 together with Figure 19-5, many of these devices may compromise signature – especially RCS – requirements and the aerodynamic layout may have resort to basis wing planform, fuselage blending und airfoil shaping together with means such as slats and spoilers which only may be articulated in the high AOA-regime.

The effort to push the envelope not only performance-wise but also to the brinks of stalling maneuverability may be highlighted by an example of the width of the design space (Fig. 19-22) explored for the Eurofighter combat aircraft. According to the status of CFD and the available computational power most of this work had to be based on expensive wind-tunnel measurements [43-45].

The design problem to shape for controllable vortex systems, which could maximize maneuvering performance, is very much dependent on the basic layout of the aircraft and is very sensitive to details in shape and relative position. Many and even more flow control devices (Fig. 19-20) were thought for specific configurations [80-89]. Intense research and development was dominated by wing-tunnel work only, probing for satisfying shapes, eventually adding expensive add-on solutions in late in the flight-test campaigns [35]. The link in between shape and aerodynamic characteristics and more importantly vice-versa found little attention outside design offices; these often being restricted by cost considerations. Increasing controllability at instantaneous maneuvering flight conditions – eventually regarding stealth restrictions only are achievable with the improved understanding of the onset of separation under the influence of:

- Leading-edge slats and strakes
- The relative sweep and leading-edge shape of double-delta, strake-wing configuration
- The development of vortex flows at medium swept wings (< 55º) with and without strakes

- The interactions of co- and counter-rotating vortices for vortex breakdown control
- The vortex system development at transonic speeds
- The vortex breakdown at transonic speeds together with the mutual effect of shock systems
- The interaction of wing and eventual fuselage vortices

4.0 HIGH AGILITY AERODYNAMICS DESIGN SPACE EXPLORATION

For the development of future advanced combat aircraft the design space – especially for high agility demands - will be prepared via CFD-design exploration [62, 90], supported by validation and check wind-tunnel experiments (Fig. 19-23). A selection of subsonic high AOA stability investigations – centered on delta wing configurations of various sweep (Fig. 19-24) is given as an example from the NATO-STO-AVT-316 research task group on vortex interaction of combat aircraft wings [91]. The CFD results are compared to the subsonic measurements of the Technical University of Munich (TUM) wing-tunnel [93, 94] and for simplicity show only the lift, the pitching moment and the rolling moment from 0º – 40º AOA at 0º and -5º sideslip AOS. Double delta configurations with a leading-edge sweep combination 75º for the strake and 52º for the main wing are compared to triple delta shapes of the same leading-edge sweeps with the first leading-edge also set at the main wing value. The effect of deployed leading-edge slats (set at 22.5º) on the main wing is included as well.

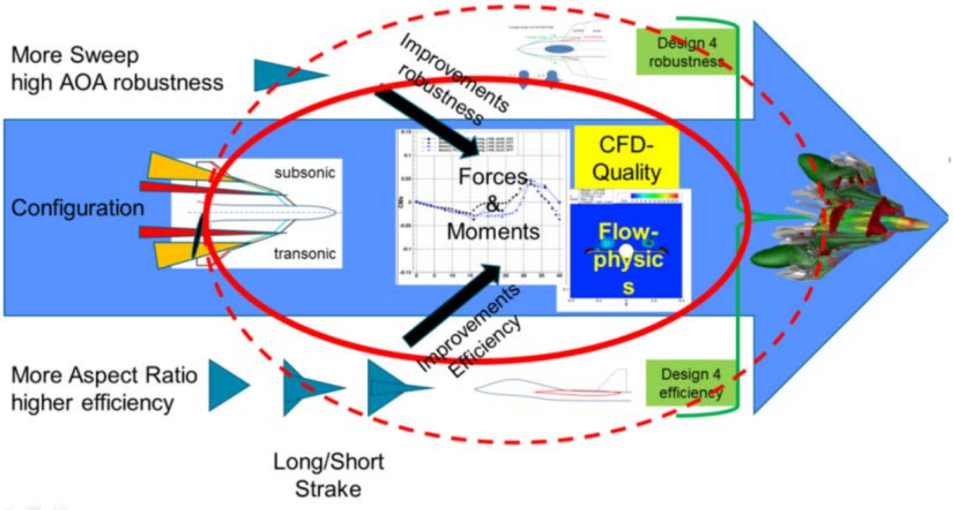

Fig. 19-23: Providing the Design Space for Future Combat Aircraft [62]

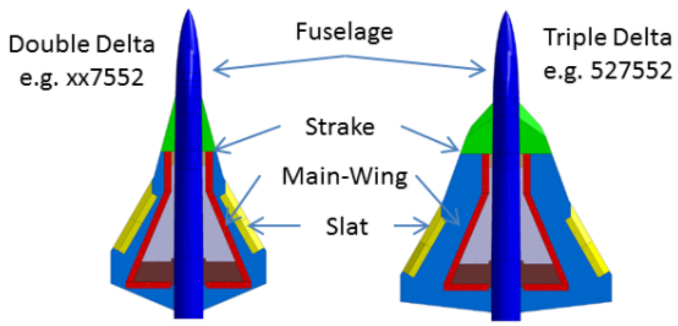

Fig. 19-24: Delta wing configurations for high AOA stability investigations [91]

The overall design objective is the most robust configuration with regard to stability and control while maintaining an overall configuration aspect ratio that offers the least induced drag for range and endurance, naturally regarding the necessities of efficient supersonic flight. The main wing aims for high aspect ratio being supported by a strake configuration allowing for robust high AOA agility with no limits till maximum lift and sufficient controllability beyond. Since air-combat usually starts at high transonic speeds the transonic regime together with the upper subsonic area are of major interest.

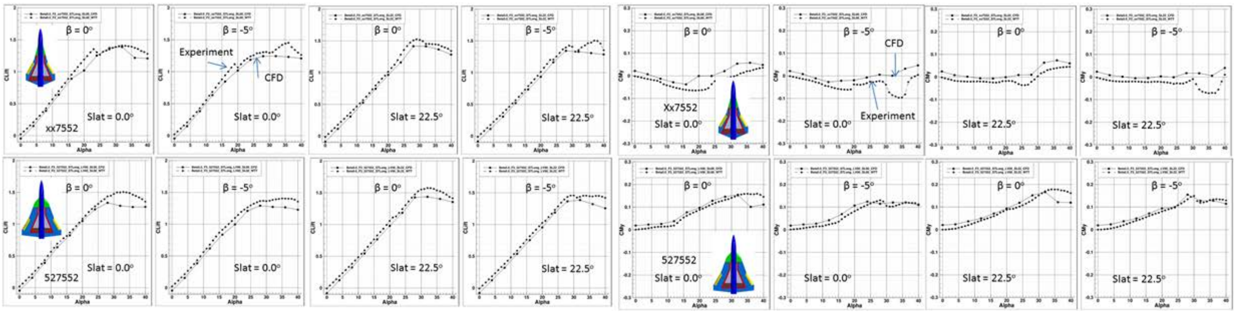

Fig. 19-25a: Subsonic Lift and Pitching Moment versus AOA of Double Delta xx7552 and Triple Delta 527552

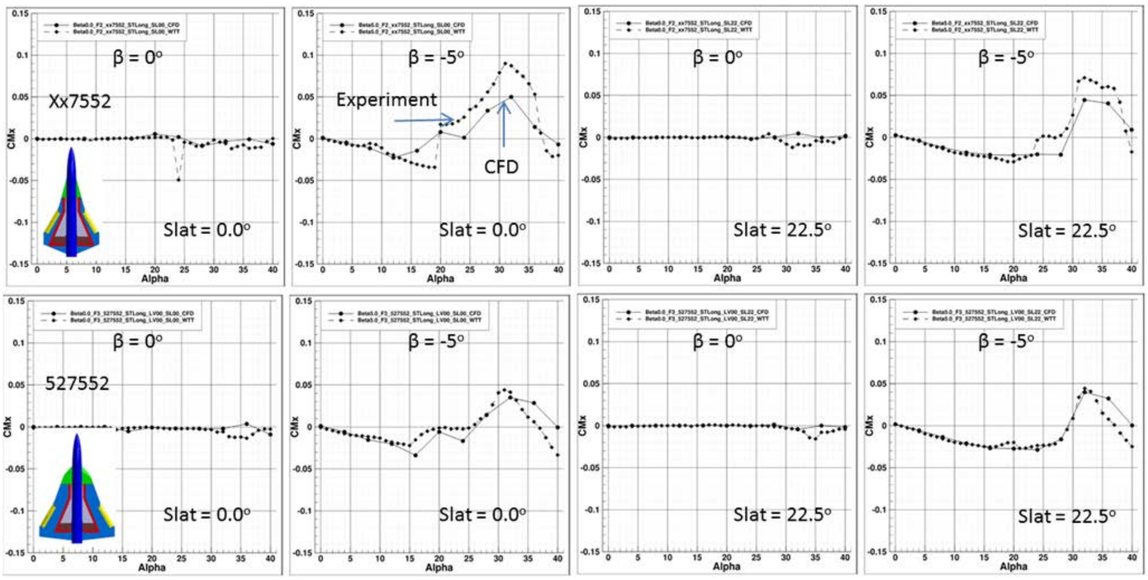

Fig. 19-25b: Subsonic Rolling Moment versus AOA of Double Delta xx7552 and Triple Delta 527552

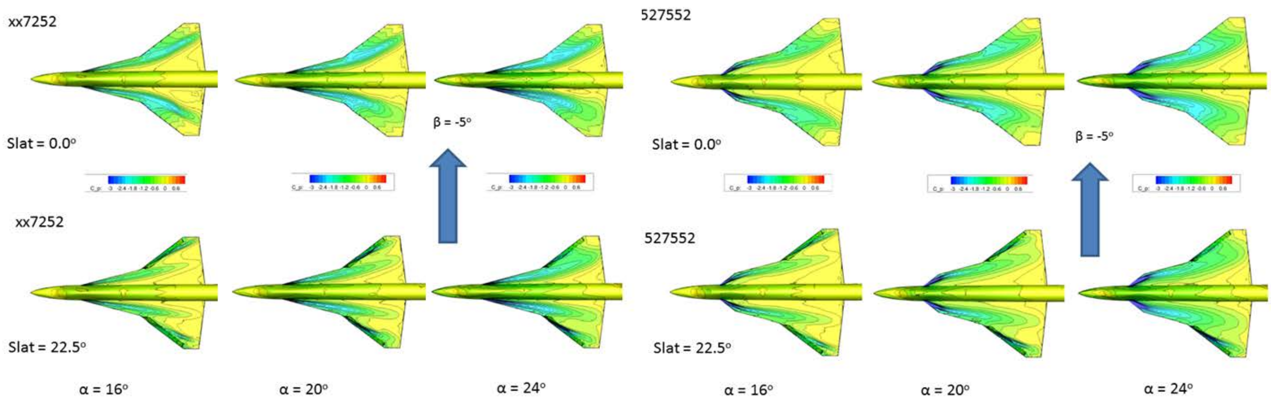

Fig. 19-26: Pressure Distribution of the xx7552 and 527552 Wing Configuration at Subsonic Speed at Sideslip

The subsonic CFD-simulations are compared (Fig. 19-25 a, b) to the experimental results of the delta wing types of Figure 19-24 [93, 94]. Here only the most important stability and control related moments (pitch and roll) are shown, the forces are in good agreement and of similar quality as in Figure 19-18. At lower and medium AOA the CFD pitching moments are very much in line with the experiments, while the high AOA range still shows very similar trends but significant difference beyond the 30o mark. Interestingly the 527552 configuration fares much better, showing only minor differences in between simulation and measurement. The trends of the rolling moment evaluation (Fig. 19-25b) are encouraging in so far that they indicate the occurrence of the developing instability; also the stabilizing effect of the leading-edge slats is given correctly. However, the AOA-position into the unstable flow conditions as well as the local gradients and the absolute rolling moment values are not met with sufficient accuracy to use the results for eventual air-data modules. Other configuration – not shown here – with lower sweep may even show a less favorable agreement, while configurations with higher sweep show a better agreement.

This more favorable, more stable character of the 527552 wing may be attributed to the origin of the strake vortex in the low sweep (52^o) forward area, which already produces retarded, wake-like flow in the vortex core, while the highly swept strake vortex sheet may wrap around and be stabilized by the total pressure losses in its center. Similar effects have been found in the flow field of the F-16 XL investigations [78, 79]. The double delta xx7552 wing produces a jet-like core flow, which may be more susceptible to increasing pressure gradients and with that more to vortex breakdown. The explanation still is subject to research and awaits clarification.

Figure 19-26 show the surface pressure distribution for the configurations discussed with and without leading-edge slats deployed. The range of AOA is selected in the vicinity of the rolling moment cross-over from stable to unstable conditions. Without slat deployment the forward strake vortex soon merges with the main wing leading-edge vortex. At AOA 16^o the merger is almost complete and the pressure distribution shows the unified effect of it. As know from pure delta wings the combined vortex system breaks down on the advancing wing first, while the leeward side still shows a stable system, the suction of which finally leading to an unstable rolling moment. The deployed slats keep the strake and main wing vortices separate until much higher AOA. The slat vortex itself supports a stable roll and AOA-margins up to 10^o are possible.

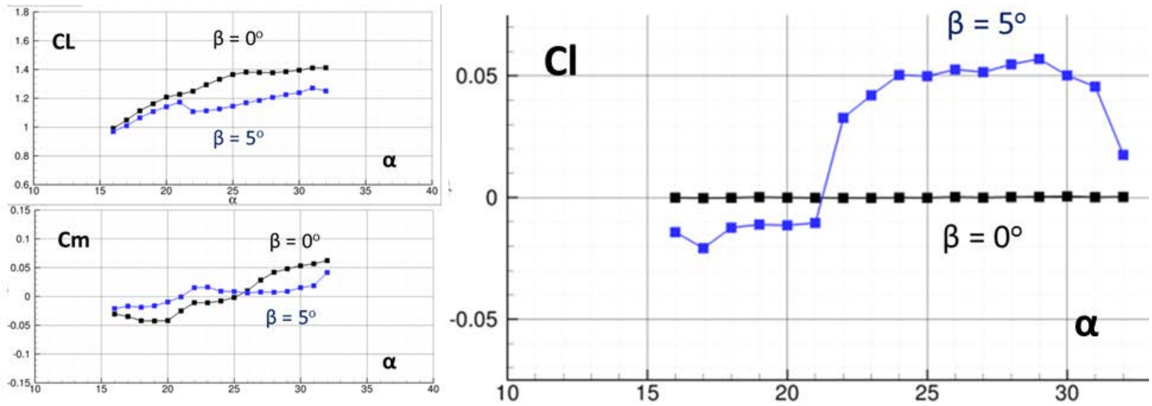

Fig. 19-27: Lift, Pitching and Rolling Moment of the 527552 Configuration with and without Sideslip at Mach = 0.856 [95]

Transonic simulations are shown in Figure 19-27 [94, 95]. In between AOA 20^o and 22^o vortex breakdown of the vortex system occurs shortly after the merger of the strake and wing vortex. As can be seen in Figure 19-28 a shock system develops at the breakdown position. Its reversed flow forms a kind of fluidic displacement shape, the shock of which also reversed the previously supersonic jet-like core flow into a rotating dead water flow regime similar to the delta and double delta result of Figure 19-14 and 19-19.

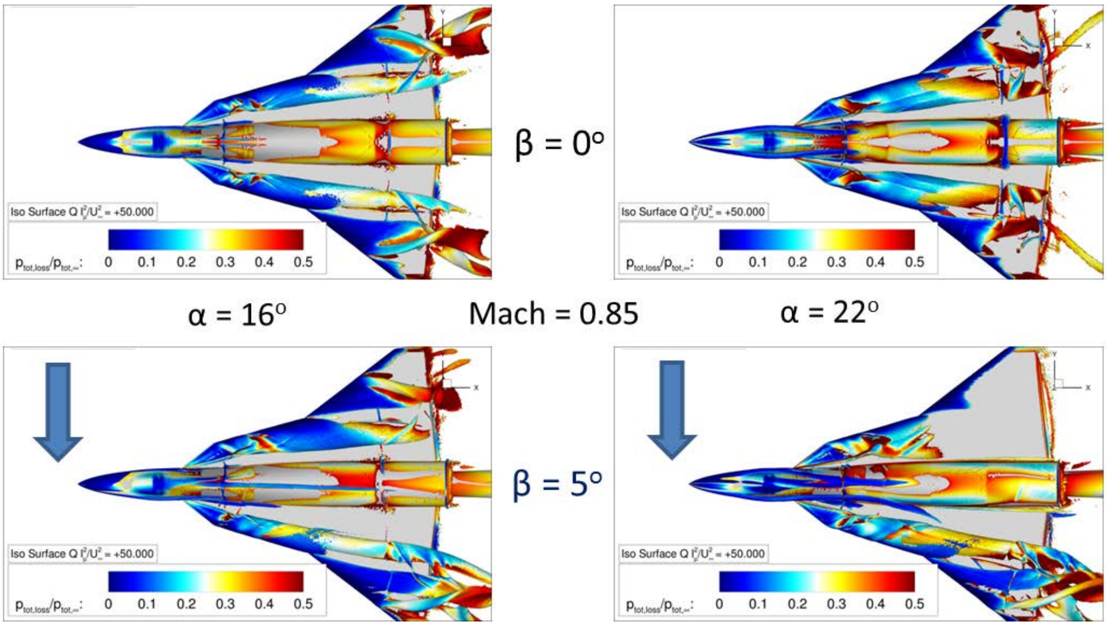

Fig. 19-28: Transonic Flow Field with q-criterion Q * lµ2 / U∞2 = 50 colored by total pressure loss of the 527552 Delta Configuration [95]

Because of its low leading-edge sweep the outer main wing vortex breakdown position at AOA 16° occurs at approx. 50% local wing-depth. At the very same position a weak shock pattern develops across the whole wing-span. At sideslip the advancing wing burst effect becomes stronger and also affects the inboard strake vortex system. On the leeward side the vortices show no breakdown and no shock pattern exists. Increasing the AOA to 22° pushes the breakdown upstream and an even stronger vortex breakdown induced shock systems develops now also destroying the concentrated strake vortex. At sideslip the strake vortex is destroyed much earlier, possibly due to cross-flow shock vortex breakdown interference, while the leeward vortex system appears to be undisturbed. The ensuing difference in lift in between the advancing and the trailing wing side explains the almost discontinuous loss of roll stability (Fig. 19-27).

It must be expected that the complexity of these transonic conditions will increase the effort to install high maneuverability for the agility of future fighter aircraft. The development of steep gradients even at medium AOA together with an eventual coupling of pitch and roll behavior can only be overcome by the understanding of the shock-vortex interactions as shown here. At the same time shapes and means are in demand to cope with these effects to avoid or at least to mitigate the limits of the maneuverability envelope. The knowledge and experience accrued and the latest results by revisiting the high AOA design of wings for highly agile combat aircraft point out how complex vortex flow characteristics can become especially at transonic speeds for even simplified and generic wing configuration. In the view of the design of new-generation combat aircraft, for which increased requirements are also present to the aerodynamic design, the understanding of associated flow field characteristics and the resulting stability and control behavior is thus essential. The transonic regime plays in this context a decisive role, as robust and controllable stability and control characteristics are hardly to reach but contribute to a large extent to agility and maneuverability of fighter-type aircraft.

In current industrial simulations the complete flow-development starting from surface separation, evaluating the development of shear-layers and the formation of vortex-cores up to the breakdown phenomenon usually is treated by one and the same turbulence model Currently most simulations are preformed via one-equation, eventually two-equation models [96, 97]. Although elaborated techniques for the simulation of complete polars – eventually even including control deployments – for turn-around time and economic reasons the standard application of more sophisticated turbulence models such as DES [98] or Reynolds-Stress-Models RSM is forbidding under industrial conditions and the vast amount of configurations and data to be provided and checked. Even these models cannot guarantee the proper treatment of separation, shear-layer roll-up, their interference with other vortices, the viscous effects inside a vortex core especially at breakdown conditions. At higher transonic speeds vortices can be highly influenced by strong expansions and are accompanied by additional cross-flow shocks. How these, as well as the vortex breakdown shocks are treated correctly is subject to further physical knowledge and improved – eventually adapted - turbulence model techniques [99].

5.0 STATUS AND SUGGESTIONS

Till recently the design shaping side which could maximize maneuvering performance saw limited attention. To provide for a high agility design space for the finding of robust, controllable aerodynamics improved and widened knowledge about certain means of flow effectors is necessary. Often expensive add-on solutions had to be introduced late in the flight-test campaign to ensure otherwise guaranteed turn-rates, while the aerodynamicist key expertise to allow for a superior, efficient, flexible and customer satisfying system aircraft had been restricted by low budget, pushing schedules and insufficient multidisciplinary understanding and planning. Increasing controllability also for at instantaneous maneuvering flight at low risk conditions – eventually regarding stealth restrictions - only are achievable without program delays with the improved understanding of the onset of vortex flow separation, their formation, their character and their interference under the influence of aerodynamic means to name only a few such as:

- Strakes and advanced leading-edge slats
- The relative sweep and leading-edge shape of double-delta, strake-wing configuration
- The development of vortex flows at medium swept wings (< 55º) with and without strakes
- The interactions of co- and counter-rotating vortices for vortex breakdown control
- The vortex system development at transonic speeds
- The vortex breakdown at transonic speeds together with the mutual effect of shock systems
- The interaction of wing and eventual fuselage vortices

The application of numerical simulation tools (CFD) with a thorough review of the most appropriate turbulence models for the simulation of:

- Vortex separation onset
- The interference of vortex sheets
- The sensitivities of vortex breakdown
- Vortex-cores of jet-type, wake-type and breakdown conditions.
- Vortex-interaction controlling vortex-breakdown.
- Investigations and data for the transonic regime.
- Adapted and optimized turbulence modelling
- A validation data base: forces, moments, pressure distributions and 3-D flow-structures

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