Aerodynamics – A discipline swept away?

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ABSTRACT

This contribution is based on the Lanchester Lecture of the Royal Aeronautical Society held in Manchester, UK, in October 2009. The lecture reflected on further possible perspectives for aeronautical research, in particular with respect to aerodynamics. The air transport system of today has matured to very high performance and safety standards. However, due to the ongoing global developments of economy and ecology, new challenges have to be faced. Thus, the relevance of all engineering aeronautical disciplines contributing to the final aircraft configuration is now closely scrutinised, and especially aerodynamics is challenged whether any investment in further research is still justified. In this contribution, it is argued that, when carefully exploited, aerodynamics still offers a substantial technological perspective, well beyond the concepts for the next generation of aircraft as currently being pursued. As an example, the aerodynamics of a forward swept-wing are discussed and it is outlined that, when combining the transonic characteristics of a forward swept-wing with the advantages of natural laminar-flow, considerable improvements in efficiency may be gained. However, this potential may only be leveraged through a strategic, long-term orientation of fundamental and applied research.

1.0 INTRODUCTION

For more than 100 years, aerodynamics has been one of the key disciplines in aircraft design. Only the deep understanding of flow physics and the following exploitation of mechanisms to create forces and moments necessary for controlled flight, allowed the maturation of air transport to the well advanced state of today. However, due to this maturation of the air transport system, the future relevance of all the formerly enabling disciplines is now being challenged. For example, one may be confronted with the question whether aerodynamics is still a discipline with any future potential to be leveraged by further research, or whether it will be swept away into the insignificance of a standard 'teach and apply' technical area. To illustrate the driving mechanisms and their consequences, at first the changes in the process of aircraft design and the current challenges for the air transport system will be outlined. Then today's technological perspectives, i.e. which are the concepts being currently followed to overcome theses challenges, will be assessed. Third, to point out possible future directions beyond those current concepts, technological drivers to improve aircraft performance, which is taken here as efficiency in fuel consumption, will be briefly reviewed. Based on this review of main impact factors for fuel consumption, and a discussion of boundary-layer transition mechanisms and transonic effects on tapered wings, a future technological perspective for forward swept-wings will be derived where aerodynamics is playing the major role for a performance increase. To leverage this potential, a multi-disciplinary approach taking into account the classical disciplines of structures, aeroelastics, and flight control is mandatory. However, without bringing in new technologies such as active flow control by micro-mechanical devices, shape adaptation, and active control of aerodynamic loads and structural properties, the envisaged concept will not be realisable.

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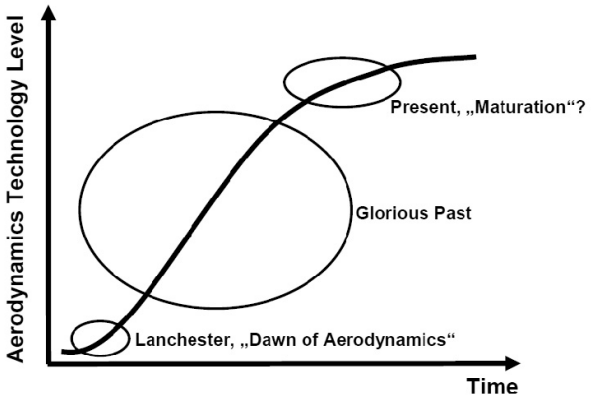


Figure 1. Evolution of aerodynamics technology level. (Sloof, 2002)

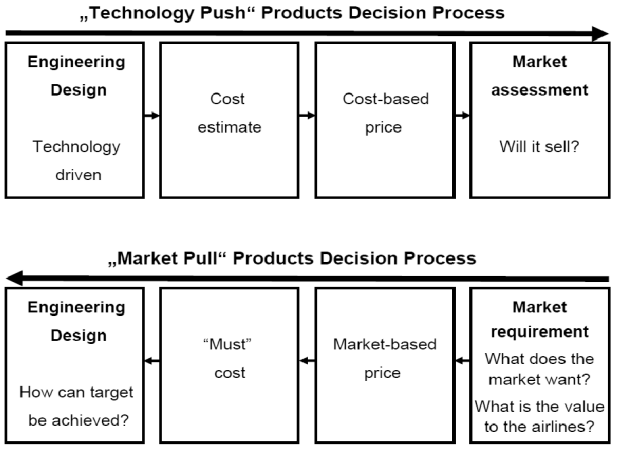


Figure 2. Mechanisms of Products Decision Process. (Rubbert, 1994)

2.0 PAST AND PRESENT SITUATION

Looking back to the end of the 19th and the beginning of the 20th century, when scientists like F.W. Lanchester tried to understand and exploit fluid dynamics for technical purposes[1], and engineers like O. Lilienthal and W. and O. Wright designed and built the first practical flying machines, one may call this era 'the dawn of aerodynamics', see Fig. 1, following Ref. 2. At that time, flying was regarded more or less as a peculiarity, and science, speculation and sheer belief were equally pursued and applied. From then on, mainly driven by the military requirements of two world wars but also by the civil demand for fast and long range travel, technological progress accelerated tremendously. In 1915 H. Junkers invented the cantilever wing, later being used in the Fokker D.VII fighter aircraft, which also featured thick aerofoils with rounded leading edges for superior climb and handling performance. During the 1920s and 1930s, F. Whittle and H. von Ohain worked on the concept of jet engines, and the first turbojet aircraft, the Heinkel He 178, flew in 1939. At the Volta conference in 1935, A. Busemann presented the concept of wing sweep. This was successfully applied to the Boeing B-47 Stratojet, a bomber with a wing sweep of 35° and pod-mounted engines making its first flight in 1947. The idea of supercritical aerofoils was already conceived in the 1940s by K.A. Kawalki, and brought to practical use by R. Whitcomb in the 1960s. These technical developments, namely thick cantilever wings with round leading edges, jet engines mounted in pods under the wing, wings with sweep-back, and super-critical aerofoils, still represent the major design features of today's most advanced civil transport aircraft.

From today's perspective, this time of continuous technological progress may be viewed as the 'glorious past' of aeronautical science and engineering[2], whereas at present the technical development is more and more perceived as being in a state of 'maturation', see Fig. 1. The reason for this perception may be traced back to the fundamental change in the aircraft design process, as described in Ref. 3. In the 'glorious past' of technological innovation the design process was mainly governed by 'technology push' mechanisms, where the introduction of new technologies itself created expanding markets due to new business opportunities. With regard to the air transport system of today, this scenario has changed towards 'market pull' mechanisms, where at first the market requirements are assessed, and then technologies serving these requirements are being identified and pursued by the product manufacturers. It should be noted that in today's design process with its 'market pull' mechanisms, technological considerations may not play the major role in product decisions any more. Economical factors such as manufacturing cost, in-service and maintenance effort, and financing for product acquisition by the customer are equally or even more important than technical aspects like performance in fuel burn, passenger capacity, or travel speed. As illustrated in Fig. 2 following Ref. 3, in a scenario governed by 'technology push' mechanisms, the design process starts with a design mainly driven by engineering considerations, and the final product is then brought to the market with selling arguments mainly based on the technical superiority of the product. Applying 'technology pull' mechanisms as in today's economical environment, this process is completely reversed: first, the relevance of a product will be investigated and the price possibly achievable is evaluated. Only then starts the engineering process with clear boundaries on cost, where the engineering challenge lies in realising the final product in the given cost frame with just sufficient performance.

The air transport system of today reached its very high performance and safety standards, its customer friendly business model, and its mass transportation capability only by being consequently transformed from a 'technology push' to the 'market pull' orientation. This orientation towards 'market pull' mechanisms has a substantial impact on the engineering design process. To achieve product competitiveness, consequently all classical disciplines of aircraft design are now being challenged: what relevance does a discipline have with respect to the 'market pull'? Today, the 'market pull' may be considered to be driven mainly by either economical, ecological, or sociopolitical boundary conditions, or by combinations of these. Based on the prevailing boundary conditions, two simple market scenarios may be derived: when product performance meets market demand, the 'pull mechanism' is to compete via cost, or, when the product performance is inadequate with respect to the demand defined by the boundary conditions, to compete via technology. From today's perspective, having achieved such a high state of maturity of the air transport system, one may be tempted to only pursue directions such as 'cheaper to produce, cheaper to operate, more comfortable to use'. Consequently, for aerodynamics the question arises whether this discipline is still of relevance in any 'market pull' scenario, or whether it will be considered as being technologically sufficiently exploited, and no further investments in any technological research will be required in the future. If the latter were true, aerodynamics would degenerate from a scientific discipline into a 'teach and apply' technical area which is just considered on a teaching level in engineering education, but no effort would be spent anymore in further scientific and technological advancements. Clearly, an answer to this question strongly depends on the particular 'market pull' scenario, i.e. whether the performance of the product is seen as sufficient to meet market needs, or whether there are future challenges which are not yet addressed.

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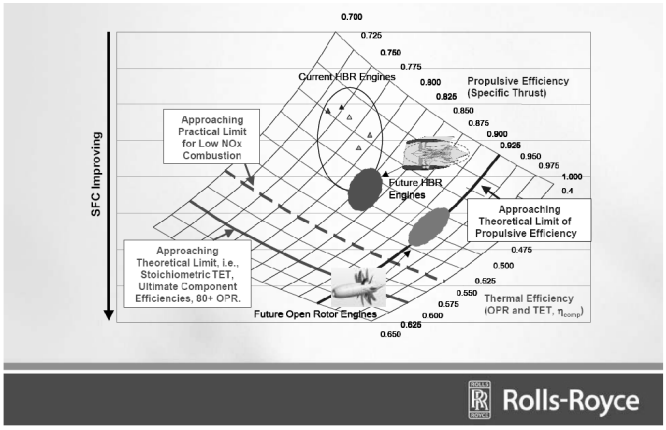


Figure 3. Effect of thermal and propulsive efficiency on fuel burn. (Rolls-Royce, 2007)

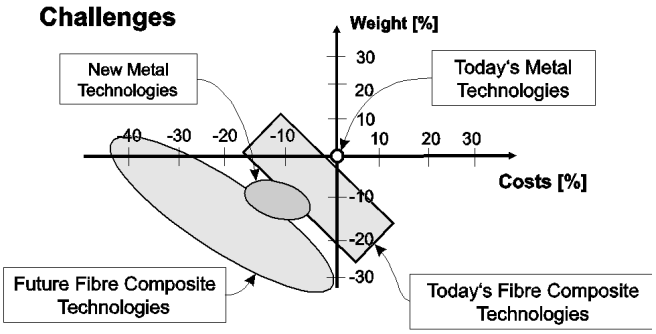


Figure 4. Weight saving potential of new materials. (DLR-Institute of Composites and Adaptronics, 2007)

Due to the ongoing global developments of economy and ecology, the air transport system of today faces new challenges. In the year 2000, the 'group of personalities' of ACARE (advisory council for aeronautical research in Europe) formulated the so called Vision 2020, which defines specific technological targets for the air transport system to be met in the year 2020[4]. As the most challenging target one may view the anticipated 50% reduction in CO_2 production, which essentially translates into a 50% reduction in fuel burn. This target was mainly motivated by the prognosticated scenario of global warming, which may present a severe challenge for human activities concerned with the use of fossil fuels. However, besides this ecological boundary condition which led to the target of 50% CO_2 reduction, new sociopolitical and ecological boundary conditions evolve. To restrain carbon-dioxide production, emission trading may become an integral part of the economics of the air transport system and may alter the direct operating cost breakdown considerably. Furthermore, the volatility of fuel prices, which in the year 2007 led to up-and-down changes by more than an order of magnitude, poses severe risks to the whole business model of the air transport system, since often the profit margins are only in the range of a few percent. Finally, also the air transport system has to address the basic scenario of limited energy resources, which ultimately will influence the standard of living in the so called developed societies. Driven by this set of boundary conditions for future operations, the reduction of fuel burn has become the challenge with the highest priority. Consequently, technological solutions for fuel burn reduction need to be established, and the question arises whether the concepts currently pursued are providing sufficient product performance for this 'market pull' mechanism. Driven by the 'market pull' mechanisms of cost and capacity in the last 50 years of the jet-age, civil transport aircraft evolved from the de Havilland Comet with somewhat more than 50 passengers to today's A380 being capable of transporting more than 500 passengers. Therefore, the specific question of today is, whether the technical solution for the new 'market pull' scenario of drastic fuel burn reduction lies in a step-by-step development of conventional technologies, or in a substantial change of the technological directions traditionally followed.

3.0 TODAY'S TECHNOLOGICAL PERSPECTIVES

For a first order identification of those factors mainly relevant for fuel burn of a typical transport aircraft mission, climb and descent can be neglected and only the cruise segment may be regarded. This leads to the well-known Breguet range equation, for which the main consequences may be summarised as

$$\frac{\text{Mission Fuel}}{\text{Distance}} \approx \frac{SFC}{V_{cruise}} \times \frac{W}{L/D} \qquad \ldots (1)$$

where SFC denotes specific fuel consumption, W represents the aircraft weight, V_{cruise} is the cruise speed, and L and D represent lift and drag, respectively. L/D expresses the aerodynamic efficiency of the aircraft, i.e. the glide ratio, and it should be noted that at cruise lift has to always balance the weight of the aircraft. The term *mission fuel* is representing the total amount of fuel burned during cruise, and *distance* is the corresponding cruise length. From expression (1) it follows that to reduce the amount of fuel required to fly a fixed distance, specific fuel consumption, weight, and drag have to be minimised. Furthermore, expression (1) shows that the cruise speed should be maximised; this is a consequence of the fact that the classical Breguet equation considers power or efficiency, i.e. work per time, and not only work or energy. If solely the amount of energy (i.e. fuel) required for the mission is considered, it can be shown that the cruise speed is not a free parameter in the Breguet equation, but the specific aircraft under consideration has to fly at its optimum speed resulting from the particular design. However, it should be noted that even with fuel burn reduction as highest priority, for economical viability the cruise speed, i.e. efficiency of the transport system, will still be a decisive market factor.

The identified main factors for fuel burn reduction, namely specific fuel consumption, weight, and drag, are addressing the technological areas of propulsion, structures, and aerodynamics, respectively. When additionally taking into account efficiency, maximising cruise speed addresses propulsion and aerodynamics, since the propulsion system has to provide enough thrust to overcome drag at higher speeds, and aerodynamics has to keep compressibility effects such as wave drag at minimum. Today, there are mainly three technological concepts pursued to achieve fuel burn reduction, the development of engine concepts like contrarotating open rotors (CROR) to reduce specific fuel consumption, the use of new materials like carbon fibre reinforced plastics (CFRP) to reduce structural mass, and laminar-flow control (LFC) to reduce aerodynamic drag. All disciplinary issues of these concepts like material technologies, production technologies, acoustics, aerodynamics, etc. have been researched for a substantial amount of time, and now the emphasis is on bringing such concepts towards product maturity.

3.1 Propulsion

With respect to the propulsion system, the trend towards CROR concepts becomes apparent when regarding the thermal and propulsive efficiency as sketched in Fig. 3 taken from Ref. 5,

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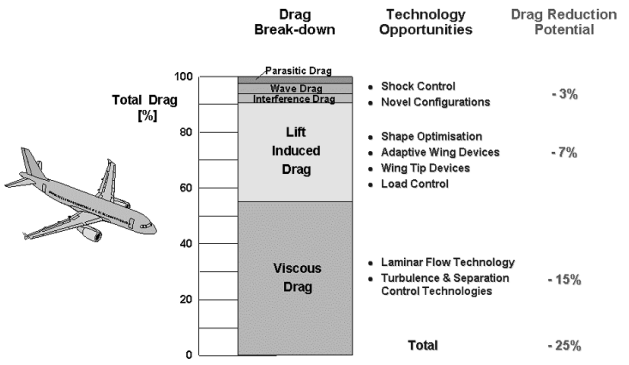


Figure 5. Technological potential for aerodynamic drag reduction. (Schrauf, 2005).

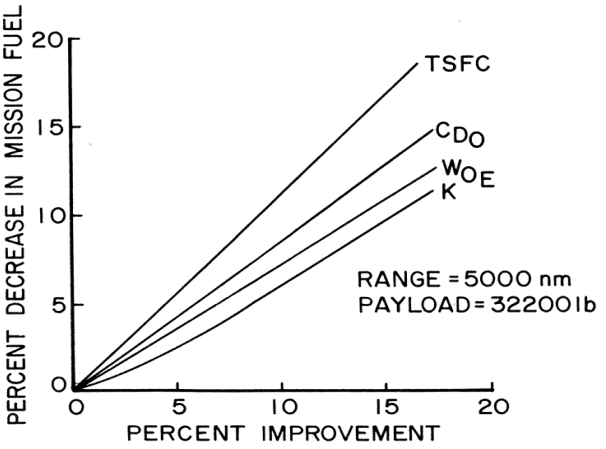


Figure 6. Main impact factors for fuel consumption. (Nicolai, 1975).

courtesy of Rolls-Royce. Fuel burn can be decreased by increasing propulsive efficiency, which essentially means increasing the bypass-ratio. This directly leads to large fan diameters, i.e. high-bypass-ratio engines (HBR), or ultimately to open rotor concepts when nacelle weight and drag become prohibitive. The increase of thermal efficiency is equally beneficial for fuel burn, and it can be achieved by higher overall pressure ratios (OPR) and turbine entry temperatures (TET). Research on CROR or unducted fan (UDF) concepts dates back to the 1980s, and in 1987 an UDF engine was flight tested by General Electric on an MD-80. CROR concepts promise a potential of 15-20% reduction in specific fuel consumption, however they are associated with severe challenges with respect to interior and exterior noise, and safety where blade loss has to be addressed. Other challenges arise from the aerodynamic and structural integration of such engines into the airframe. Additionally, due to the large rotor diameters and the resulting transonic effects on the rotor blades, cruise speeds probably will have to be reduced to Mach numbers of around M = 0·75. It should be noted that the principal technological concept, namely increasing propulsive efficiency by contrarotating propellers, is also a concept being more than 50 years old. Representing a typical transport aircraft, already the Tupolev Tu95 of 1952 featured contrarotating propellers, and this aircraft was well known for fuel efficiency, but also for substantial noise generation.

3.2 Structures

Carbon fibre reinforced plastic (CFRP) materials or composites promise a substantial potential for weight and cost savings, as is illustrated in Fig. 4 from Ref. 5, courtesy of the DLR-Institute of Composites and Adaptronics. Today, the use of composites represents the essential feature of new aircraft products such as the Boeing 787 and the Airbus A350, all of which still have to enter service. A preliminary design study performed at DLR showed that for a 250 passenger aircraft on a trip of 4000 nautical miles, a reduction of primary structural weight by 30% results in a 15% decrease in fuel burn[5]. It should be noted that successful leverage of the potential offered by composites requires substantial accomplishments for all elements of the complete structural process chain, from materials, design technology, manufacturing, to mass production. Only this will allow CFRPs to become a viable alternative for commercially successful products. A major technological step for composites was achieved with the introduction of fibre reinforced plastics, allowing the 'Tayloring' of materials for the specific application. In aviation, it was first applied with glass reinforced plastics to high performance sailplanes like the Phoenix built by the AkaFlieg Stuttgart in 1957, and the LFU 205 single engine General Aviation aircraft from 1968. The next milestone was the introduction of carbon fibres, as accomplished by the AkaFlieg Braunschweig for the wing centre part of the twin-seat sailplane SB-10 from 1972, which lead to an increase in stiffness and reduction of weight, thus enabling the realisation of extremely large aspect ratio wings.

3.3 Aerodynamics

It is well known that for aerodynamic drag reduction, the establishment of laminar-flow holds a substantial potential. Fig. 5 from Ref. 6 shows the typical drag breakdown for transonic transport aircraft, and it can be seen that about 50% of the total drag is comprised of viscous drag. The figure also illustrates the technological opportunities for drag reduction and the corresponding potentials. It shows that reduction of viscous drag bears the largest potential, and the most prominent technology to achieve this is laminar-flow control. For sailplanes, natural laminar-flow is the state of the art, achieved by designing favourable pressure distributions and manufacturing surfaces of highest quality. However, with respect to civil transport aircraft, such a state has so far not been achieved. For such aircraft, the substantially higher Reynolds numbers, boundary-layer instability effects on swept-wings, and issues of manufacture and operation still present severe technological challenges. Despite the fact that a total drag reduction in the order of 15% may be feasible, the surface requirements with respect to smoothness and waviness are extremely high, and the corresponding challenges for economical production have not yet been overcome. Furthermore, the problem of degradation or contamination of the aerodynamic surfaces by insects and dust during climb and descent still lacks a practical solution. The leading edges of laminar-flow wings must be without any steps or gaps, which usually are a consequence of integrating deicing systems or slats for highlift devices. Additionally, when systems for boundary-layer suction shall be applied, system weight and energy consumption become a major concern for not counteracting the savings achieved by drag reduction. As such, the industrial realisation of laminar-flow control has been postponed after several attempts, since market conditions did not favour the necessary investments. Perhaps the North American P-51 Mustang may be viewed as the first successful industrial laminar-flow aircraft, since the aerofoils used in the wing design allowed for laminar-flow. However, it may be doubted that manufacturing quality and maintenance were sufficient to establish this under practical conditions. In parallel to the UnDucted Fan activities of the 1980s, DLR performed first flight tests on its ATTAS aircraft with a laminar glove to establish a database for theoretical design methods in 1987. Until the year 2000, substantial research and development efforts were undertaken in Europe[7] and

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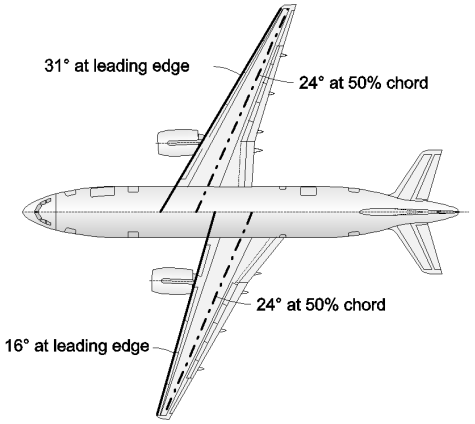


Figure 7. Geometry of tapered swept-wings.

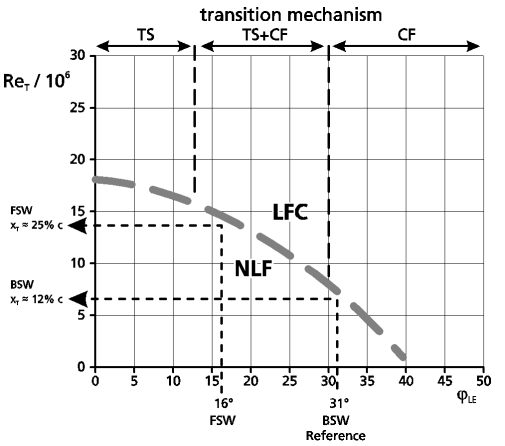


Figure 8. Laminar-flow limits for swept-wings. (Hepperle, 2008)

the US[8] to fulfil the technological requirements of commercially viable laminar-flow control concepts, and the feasibility of laminar-flow control for high Reynolds numbers and swept leading edges could be demonstrated. However, the challenges with respect to manufacturing, systems, and operations were not sufficiently resolved. Today, with the economical and ecological pressure rising to reduce fuel burn, the concept of laminar-flow control is revisited and critical areas are now being addressed in several current research and development activities.

4.0 POSSIBLE TECHNOLOGICAL DRIVERS

Looking at the concepts pursued by today's research and development efforts, it may seem obvious that essentially all promising technological concepts are being followed by now, and one may find oneself being confronted with the question; is there any further technological benefit to be expected after pushing these current concepts to their limits? Or are there still any alternative technological perspectives, legitimating further investments in research and development? To get some orientation on possible technological drivers, it is illustrative to revisit the main factors influencing fuel consumption. From expression (1) corresponding to the Breguet formula, specific fuel consumption, weight, and drag were identified as decisive factors. In Fig. 6, following Ref. 9, the 'leverage potential' of aircraft design parameters such as total specific fuel consumption (TSFC), overall empty weight (W_{OE}), zero-lift drag (C_{D0}), and lift induced drag (K) is sketched. Total specific fuel consumption has a leverage factor of 1, meaning an improvement of total specific fuel consumption directly translates into an equivalent decrease in mission fuel. Reduction in zero-lift drag has a leverage factor close to one, followed by reductions in weight and induced drag. These observations clarify that the most promising disciplines for fuel burn reduction are propulsion and aerodynamics. Aerodynamics contributes twice to fuel burn reduction, first via a reduction potential in zero-lift drag, and second by reducing induced drag. Modern designs such as the Airbus A350 and the Boeing B787 may be considered as quite far advanced with respect to reducing induced drag, especially enabled by the use of multi-disciplinary design tools which allow for the best compromise between induced drag reduction and tolerable wing root bending moment. As a consequence, the main potential to be leveraged in aerodynamics now lies in zero-lift drag reduction. This leads directly to the concept of laminar-flow control, which is again already pursued by current research and development efforts. Thus, specifically for aerodynamics the critical question arises whether there is anything left for future research; are there any concepts in laminar-flow control not yet addressed by today's activities?

4.1 Transition mechanisms and wing planform geometry

To get an orientation for further concepts, it is illustrative to briefly review boundary-layer transition mechanisms and geometrical relations of wing planforms. The main drivers for transition are the Reynolds number, the velocity and pressure distributions governed by the aerofoil shape, and the sweep angle of the wing leading edge. With respect to the flow physics prevalent on typical transonic transport aircraft, three main transition mechanisms can be identified, namely transition caused by Tollmien-Schlichting instability, transition caused by crossflow instability, and attachment line transition. For a wing with an unswept leading edge, only the Tollmien-Schlichting instability is relevant, however for swept-wings all three mechanisms have to be taken into account. The chordwise position of transition can be expressed by a transition Reynolds number Re_T.

$$\mathrm{Re}_T = \mathrm{Re}\frac{x_T}{c} \qquad \ldots (2)$$

In expression (2), Re denotes the Reynolds number based on aerofoil chord length c, and x_T is the chordwise transition location. On swept-wings, transition is strongly affected by the leading edge sweep angle φ_{LE}. In contrast to that, the sweep angle relevant for compressibility effects on transonic wings is not the sweep angle at the leading edge φ_{LE}, but more likely the sweep angle φ_{LE} at midchord, since the shock position typically lies at about 50% chord length.

Geometrically, the sweep angles φ_{LE} and φ_{TE} of leading and trailing edge are affected by the taper ratio λ, where λ is defined as:

$$\lambda = \frac{c_{tip}}{c_{root}} \qquad \ldots (3)$$

with c_{tip} and c_{root} representing the chord lengths at wing tip and wing root, respectively. As can be easily seen from Fig. 7, for a backward swept-wing the leading edge sweep angle φ_{LE} is larger than the sweep angle φ_{50} at midchord. For a forward swept-wing however, this situation is reversed: here the leading-edge sweep angle φ_{LE} is smaller than the sweep angle $\varphi_{50\%}$ at 50% chord length. Concerning wing planforms typical for transonic transport aircraft as sketched in Fig. 7, the influence of taper is substantial; with a midchord sweep angle of $\varphi_{50\%} = 24°$ the corresponding leading-edge sweep angle of a backward swept-wing is $\varphi_{LE} = 31°$, whereas for a forward swept-wing φ_{LE} it is reduced to $\varphi_{LE} = 16°$.

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5.0 FUTURE TECHNOLOGICAL PERSPECTIVES

5.1 Laminar-flow limits for swept-wings

Figure 8 from Ref. 10 gives an overview of the limits of laminar-flow on swept-wings by showing the dependence of transition Reynolds number Re_T on the leading edge sweep angle φ_{LE}. The diagram can be divided into two different zones. A region of natural laminar-flow (NLF), where laminar-flow is established passively by shaping the aerofoil such that favourable pressure gradients are achieved, and a region of laminar-flow control (LFC) where additional active means like boundary-layer suction (hybrid laminar-flow control, HLFC) need to be applied. For further information, at the top of the diagram the influence of leading edge sweep φ_{LE} on transition mechanisms is indicated. For sweep angles approximately less than $\varphi_{LE} = 12°$, transition is mainly governed by the Tollmien-Schlichting instability. For sweep angles between $\varphi_{LE} = 12°$ and $\varphi_{LE} = 30°$, both Tollmien-Schlichting and crossflow instability mechanisms are relevant, and for larger sweep angles the crossflow instability dominates.

Figure 8 clearly shows that if laminar-flow shall be established by passive means only, i.e. staying in the region of NLF, the transition Reynolds number Re_T decreases considerably with increasing leading edge sweep angle φ_{LE}, a leading edge sweep of $\varphi_{LE} = 31°$ leads to transition Reynolds numbers of $Re_T = 7 \cdot 10^6$, whereas a reduction of sweep angle to $\varphi_{LE} = 16°$ yields transition Reynolds numbers closely to $Re_T \approx 15 \cdot 10^6$. For a wing section close to the root of an A320-type aircraft, this leads to transition locations at 25% chord length for $\varphi_{LE} = 16°$, reduced to only 12% chordlength for $\varphi_{LE} = 31°$[(10)].

5.2 Natural laminar-flow on swept-wings

The design of transonic wings is mainly governed by minimising compressibility effects to keep the wave drag at reasonably small levels for cruise conditions. Fig. 9 from Ref. 10 summarises the results of a wing design study for an Airbus A320-type aircraft for a cruise altitude of 10,000m and a cruise mach number of $M_\infty = 0{\cdot}8$. To properly account for compressibility effects, the midchord sweep angle $\varphi_{50\%}$ has to be in the order of $\varphi_{50\%} \approx 24°$. Furthermore, to achieve natural laminar-flow, the pressure recovery was designed to occur at about 65% of local chord length. A conventional wing design for a swept back wing leads to a wing leading edge angle of $\varphi_{LE} = 31°$. Due to the strong influence of crossflow instability, transition occurs at the wing root already at about 15% chord length, and at the wing tip at 61%, as indicated in the upper half of Fig. 9 by the shaded wing area. However, sweeping the wing forward required a leading edge angle of only $\varphi_{LE} = 16°$, resulting in a substantial extension of laminar-flow. At the wing root, transition occurred now at 27% chord length, and at the wing tip at 65%, see lower part of Fig. 9. If the forward sweep is further reduced to $\varphi_{LE} = 11°$, transition may even be delayed to 41% at the wing root. The large increase of the extent of laminar-flow despite the relatively small 5% reduction in leading edge sweep is caused by the fact that for $\varphi_{LE} = 11°$, the main transition mechanism is the Tollmien-Schlichting instability, which can be effectively controlled by the design of favourable pressure distributions.

The results of the design exercise discussed above clearly demonstrate the superior potential of a forward swept-wing in combination with natural laminar-flow. On the one hand even for low leading edge sweep angles, cruise Mach numbers can still be kept close to the level of conventional backward swept-wings. On the other hand, due to the small leading edge angles transition will mainly be governed by Tollmien-Schlichting instability, enabling the design of large regions of natural laminar-flow. Thus, compared to the conventional concepts of laminar wings pursued today, a forward swept-wing with natural laminar-flow offers superior performance. The cruise speeds of today's aircraft can almost be retained, and drag reduction by laminar-flow control can be established without the necessity to apply complex active systems to suppress crossflow instability. It should be noted that the concept of combining forward swept-wings with laminar-flow control was already proposed in 1991 in Ref. 11.

5.3 Aircraft built with forward swept-wings

The concepts of forward swept-wings by itself is not new. Already in 1935 A. Lippisch used a forward swept-wing (FSW) for his tailless sailplane DFS-42 'Kormoran', and in 1942 the jet-bomber Junkers Ju 287 also featured a forward swept-wing. This design was continued in 1946 in the former Soviet Union with the EF 131 and EF 140, and in 1947 W.P. Tsybin used a forward swept-wing for his experimental single jet-engine aeroplane LL-3. Civil aircraft with FSW were the HFB 320 Hansa of 1966, a business-jet type of aircraft with over 50 built, and the V-Jet of 1997. In 1985 the FSW concept was resumed for military aircraft with the X-29 in the United States, and in 1997 with the S-37 'Berkut'/Su-47 in the former Soviet Union. The concept of a forward swept-wing was chosen for various reasons, to achieve a more suitable position for the centre of gravity (DFS-42), to realise a bomb bay or passenger cabin unobstructed by the wing main spar (Ju 287, HFB 320 Hansa), improved stall characteristics (Ju 287, V-Jet), or higher manoeuvrability (X-29, Su-47). However, despite these advantages, the forward

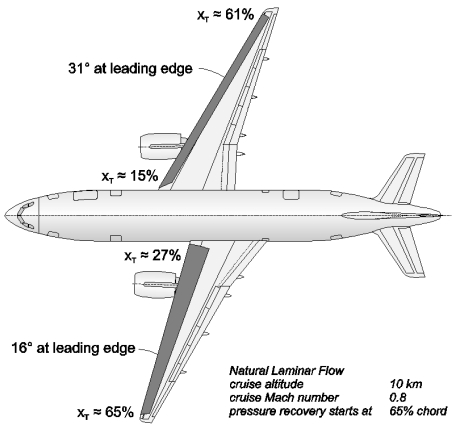


Figure 9. Natural laminar-flow on swept-wings. (Hepperle, 2008)

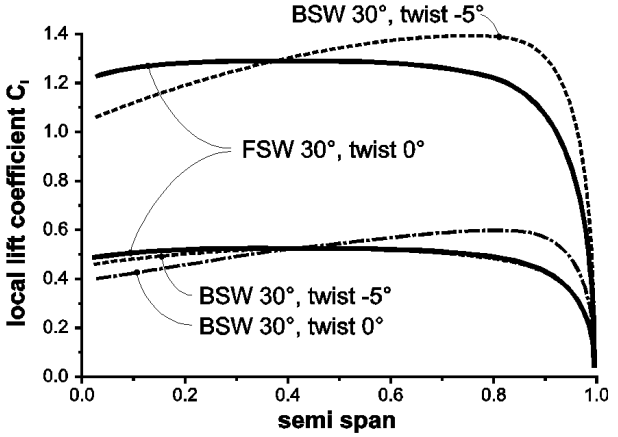


Figure 10. Aerodynamic effect of sweept and taper on local lift distribution. (Hepperle, 2008)

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swept-wing did not become a concept successfully realised in commercial or military aircraft. The reason for this lack of success can mainly be attributed to the well known problem of aeroelastic divergence, where bending of the wing leads to higher local angles of attack, which in turn increase the wing bending until eventually the wing structure fails. Aeroelastic divergence is usually counteracted by increasing the stiffness of the wing structure, resulting in comparatively high wing weight, which then renders the aircraft inefficient.

5.4 Aerodynamics of forward swept-wings

One of the favourable arguments for a forward swept-wing is its beneficial stall behaviour. To illustrate this, Fig. 10 from Ref 10 shows the spanwise distribution of local lift coefficients for a backward and a forward swept-wing at two different angles of attack. Starting with the case of a lower angle of attack, it can be seen that with backward sweep the wing needs a twist of –5° to achieve a reasonable distribution of local lift coefficients (dashed lower curve), whereas the forward swept-wing does not require wing twist (solid lower curve). Without twist applied, the backward swept-wing yields an unfavourable distribution with high local lift coefficients at the wing tip and low local lift coefficients at the wing root, as indicated by the dash-dotted line. If the angle of attack is increased, the situation on the backward swept-wing becomes worse. In the example shown here, even with a twist of –5° the distribution of local lift coefficients exhibits very high local lift coefficients at the wing tip, thus leading to the danger of wing stall at the tip region (dashed upper curve). In contrast to that, for the forward swept-wing with no twist applied, the distribution of local lift coefficients remains benign (solid upper curve).

From these observations it may be concluded that at high angles of attack, which are required for take-off or landing conditions at higher total lift coefficients, the off-design behaviour of backward and forward swept-wings differs significantly. For a backward swept-wing, higher angles of attack lead to high local lift coefficients at the outboard wing, bringing this region to or close to flow separation. For a forward swept-wing, higher angles of attack lead to higher local lift coefficients lift at the wing centre, provoking stall at the wing root.

The reason for this behaviour becomes apparent by looking at the distribution of upwash and downwash at a wing of finite span. Essentially, this may be traced back to the early observations of F.W. Lanchester in 1907, when he sketched the roll-up of a vortex sheet behind a wing, see Fig. 11 from Ref. 1. The lifting wing may be represented by a discrete model using a finite number of horseshoe vortices. For an unswept-wing as sketched in Fig. 12(a), each streamwise part of a particular horseshoe vortex is accompanied by a similar element of the same length from a neighbouring horseshoe vortex, except at the tip region. This leads to a certain induced velocity field in the vicinity of the wing. Behind the wing, a downwash is created, which by virtue of Newton's action-reaction law is essentially responsible for the generation of lift. At the wing tip, the flow from the pressure difference between wing lower and upper surface causes an upwash, which leads to the roll-up of the vortex sheet behind the wing and establishes the vortices in the wing wake. For a backward swept-wing, this scenario is somewhat different as illustrated in Fig. 12(b). For a small upstream element of those streamwise parts of horseshoe vortices which are lying toward the wing tip, there is no accompanying neighbouring element. Thus, with respect to the situation found on an unswept-wing, the upwash generated by this small element is not balanced by the corresponding downwash of the neighbouring horseshoe vortex. As a consequence, horseshoe vortices lying towards the wing tip encounter a certain amount of upwash from those vortices lying toward the wing root. This in turn leads to higher local lift coefficients in the wing tip region, as discussed in Fig. 10. Sweeping the wing forward leads exactly to the opposite effect: due to the

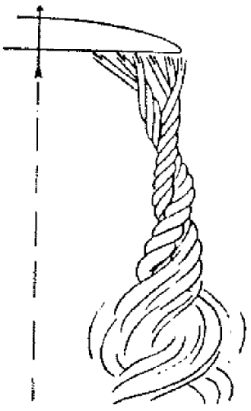


Figure 11. Sketch of wing wake roll-up process. (Lanchester, 1907).

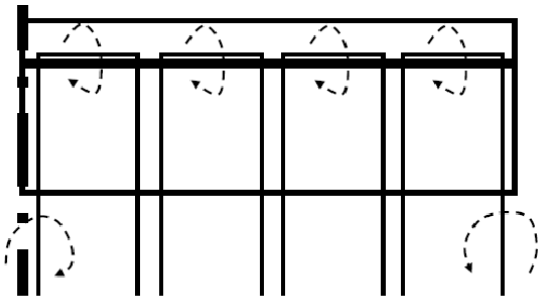


Figure 12(a). Arrangement of horseshoe-vortices on unswept-wing.

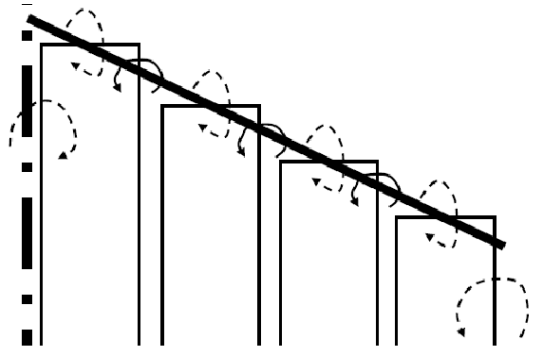


Figure 12(b). Arrangement of horseshoe-vortices on backward swept-wing (BSW).

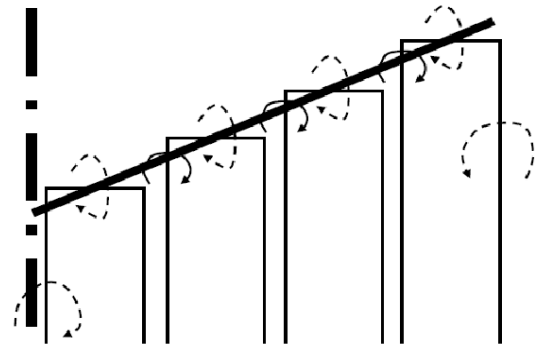


Figure 12(c). Arrangement of horseshoe-vortices on forward swept-wing (FSW).

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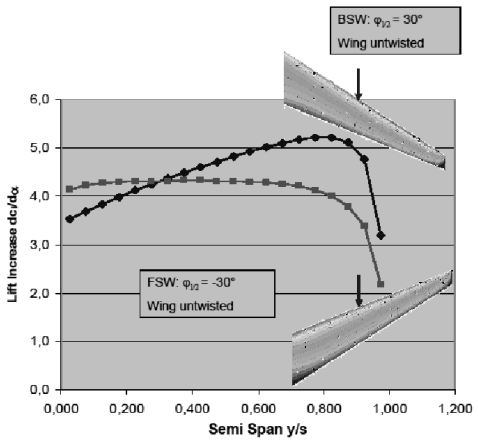


Figure 13. Change of local lift due to change in angle-of-attack. (Horstmann, 2008)

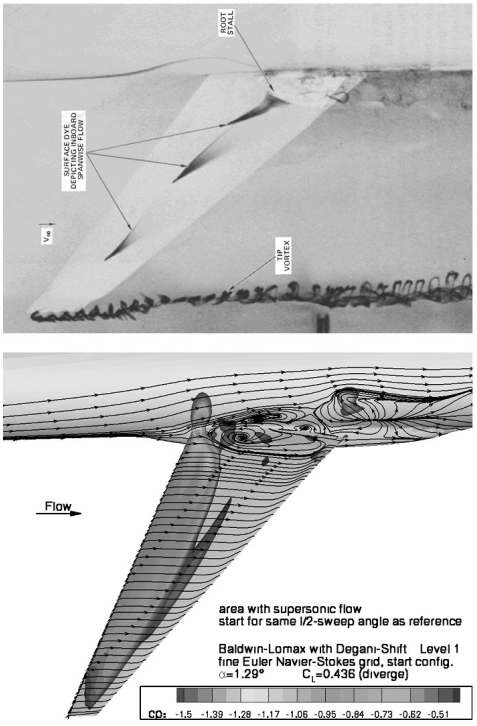


Figure 14. Experimental and numerical results for wing root flow of FSW configuration. (Skow, 1982; Ortmann, 2007)

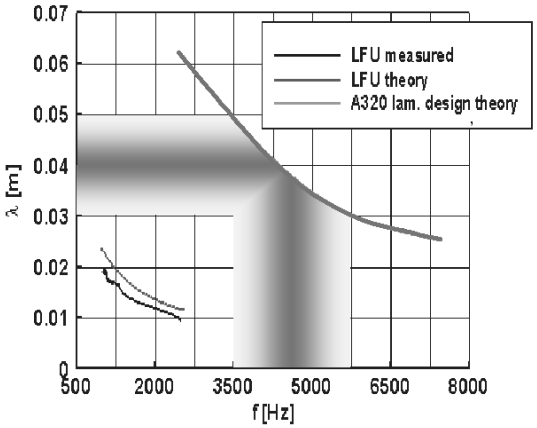


Figure 15(a). Wave lengths and frequencies of Tollmien-Schlichting waves. (Horstmann, 2006)

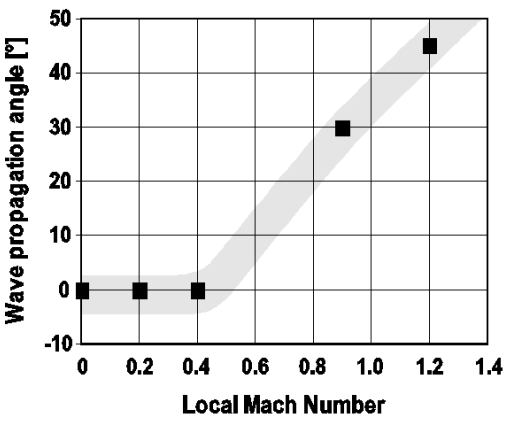


Figure 15(b). Tollmien-Schlichting wave propagation directions (Horstmann, 2006)

imbalance in neighbouring streamwise parts of the horseshoe vortices, the upwash becomes higher at the wing root and lower at the wing tip, see Fig. 12(c).

These aerodynamic effects lead to the well known danger of wingtip stall for a backward swept-wing, and this needs to be prevented by appropriate wing twist and aerofoil design in the outer wing region. However, as shown in Fig. 10, the problem is always prevalent when increasing the angle-of-attack. A forward swept-wing does not suffer from these effects, to the contrary. Here, a potential stall will first occur at the wing root, keeping the flow in the wingtip region attached and the aircraft controllable. Thus, the low speed characteristics of aircraft with forward swept-wings are substantially more benign as for configurations with backward sweep. Note however that in the case of a stall, both wings will exhibit a 'pitch up' tendency because the loss of lift occurs behind the centre of pressure.

5.5 Aerodynamic potential to counteract aeroelastic divergence

The aerodynamic effects dominating the behaviour of swept-wings may be summarised by regarding the spanwise distribution of the change of local lift coefficients due to a change in angle-of-attack, $dc_l/d\alpha$, as displayed in Fig. 13 from Ref. 12: A backward swept-wing, denoted by the blue curve, exhibits very large values of $dc_l/d\alpha$ in the wingtip region, reflecting the strong upwash effects discussed in the previous paragraph 5.4. In contrast, for a forward swept-wing $dc_l/d\alpha$ stays nearly constant along the wing span, as indicated by the red curve in Fig. 13.

The major drawback of forward swept-wings is the effect of aeroelastic divergence: a bending of the wing due to structural loads leads to an increase of wing twist in the outboard region of the wing, causing higher angles of attack and in turn higher loads with even higher bending, until structural failure may occur. Therefore, the stiffness of a forward swept-wing is usually increased by means of a heavier wing structure. Regarding fluid/structure interaction, backward and forward swept-wings show completely contrary effects: For a backward swept-wing, with increasing angle-of-attack high aerodynamic loads occur at the wing tip. Due to the resulting wing bending the wing is twisted such that the local angle-of-attack is reduced: the backward swept-wing essentially acts like a wind vane or weather cock. Thus a geometric effect similar to 'aeroelastic tayloring' is created, without the necessity of special material properties. In contrast to that, for a forward swept-wing the bending causes additional angles of attack, potentially leading to aeroelastic divergence. However, with regard to Fig. 13 it can be observed that

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$dc_l/d\alpha$ of the forward swept-wing is about 20% lower as for the backward swept-wing, leading to a substantial reduction of aerodynamic load increment at the wing tip region when the angle-of-attack is increased. For an efficient structural design, this effect needs be supported by deliberately applying aeroelastic tayloring, where the anisotropic properties of CFRP-materials have to be exploited to achieve a beneficial positioning of the aeroelastic axis. Combining these two aerodynamic and structural effects, there may now exist a potential to also achieve acceptable weights for forward swept-wings. Another potential for counteracting aeroelastic divergence lies in the design of special wingtip devices, which at high angles of attack create favourable torsion moments, and at low angles of attack reduce induced drag.

In the previous paragraphs the beneficial potential of combining a forward swept-wing with natural laminar-flow was outlined. This benefit is enabled by the taper ratio λ, since this leads to the differences in φ_{LE} and $\varphi_{50\%}$, allowing a low leading edge sweep suitable for natural laminar-flow by retaining high transonic cruise speeds. Aerodynamically, low taper ratios generally lead to high local lift coefficients at the wing tip and bear the potential danger of wing tip stall; thus in a purely aerodynamically driven design a low taper ratio is avoided. Structurally, a low taper ratio is beneficial, since the outboard structural load is decreased and the inboard wing thickness is increased, enabling a lightweight structural design. For a laminar, forward swept-wing, there is now also a strong aerodynamic argument to employ low taper ratios due to the difference in φ_{LE} and $\varphi_{50\%}$. Furthermore, for a forward swept-wing the danger of wing tip stall due to lower taper ratios and higher local lift coefficients will be counteracted by the beneficial $dc_l/d\alpha$ distribution. Thus, low taper ratios can be employed with less danger of wing tip stall, allowing for a lighter structural design. This combination of different effects, which is only acting favourably in the case of a laminar, forward swept-wing, should give new potential to explore structural designs for forward swept-wings with comparable weights as to conventional wings. It has to be pointed out that the structural design rules applied routinely for conventional wing concepts may not be adequate to exploit these aerodynamic benefits. However, today's high-fidelity, fluid-structure coupled numerical CFD-CSM (computational fluid dynamics – computational structural mechanics) methods now bear the potential for the accomplishment of an efficient, weight optimised wing construction.

5.6 Design challenges of forward swept-wing configurations

The concept of forward swept-wings poses special design challenges not being encountered when dealing with conventional configurations. As outlined in paragraph 5.4, for a forward swept-wing an upwash effect is created at the wing root. Also the thickness distribution of the aerofoil shapes in this region will differ considerably from the conventional designs of backward swept-wings. Consequently, the wing-body junction requires a careful aerodynamic design with respect to wing twist and aerofoil shape, and the belly fairing has to be carefully adapted to the different operating conditions. Fig. 14 shows the flow field for a forward swept-wing with a conventional design of the wing-body junction, obtained from results of an experimental investigation of Ref. 13 and numerical results from Ref. 14. Another challenge is posed by the design of the high-lift system. For high-lift conditions, the upwash at the wing root is considerably stronger as under cruise conditions, and the wing-body junction has to be adapted to these conditions. Smart leading-edge devices or canard wings may be means to control the upwash field in this region. Furthermore, the trailing edge of a forward swept-wing has a substantially larger sweep, which may lead to premature separation under high-lift conditions.

By regarding the aerodynamic phenomena on forward swept-wings, in the previous paragraphs it has been outlined that on the one hand a substantial potential for performance increase can be leveraged when combining a forward swept-wing with a design for laminar-flow. On the other hand, for transferring this potential into an industrial product which performs under the different flow conditions of practical operations, the development and application of special technical means will be required to efficiently sustain the different flow conditions at take-off, cruise, and landing. Flow control technologies offer the potential to deliberately manipulate flow behaviour, and this technology may be regarded as a decisive factor to fully leverage the potential of forward swept-wings.

5.7 Research opportunities

During the past years, flow control technologies received a considerable amount of attention from the research community. Generally, two areas of flow control may be distinguished: flow control to suppress or delay flow separation, and flow control to reduce aerodynamic drag.

Separation control

To avoid flow separation, today's research is directed towards active systems with actuated suction or blowing devices such as 'massless' or pulsed jets, see Ref. 15. The main principle is to counteract the momentum loss in the boundary layer by transporting fluid with higher momentum into regions closer to the surface. The target of such flow control means is to replace current high-lift slat/flap devices to avoid the high mechanical complexity and high weights associated with classical high-lift systems[16]. However, these 'classical' systems are well advanced and matured. Therefore, any new system must offer a substantial benefit for the final product, either with respect to lower production cost or with respect to higher performance, before a change from these matured systems will be considered by industry, and already some scepticism is voiced in the research community with respect to the potential success in applicability[17]. For a forward swept-wing, the situation with regard to the applicability of flow control changes considerably: in this case, flow control will not be a replacement of current technologies, but it plays the role of an enabler. Deliberately designed and constructed flow control mechanisms such as investigated in e.g. Ref. 18 shall be able to overcome the challenges at the wing-body junction of a forward swept-wing configuration: the main design of this area will be made for cruise conditions to minimise drag, but for high-lift conditions separation has to be suppressed to achieve reasonably high total lift coefficients. Here, a flow control mechanism which does not incur additional drag at cruise conditions such as classical vortex generators, but which will be activated only at take-off or landing, can play a decisive role to ensure the competitiveness of the forward swept-wing concept.

Active laminar-flow control

With respect to drag reduction, flow control mechanisms include techniques such as wave drag reduction by shockbumps[19], turbulent drag reduction by affecting coherent structures through surface textures like riblets[20], or laminar-flow control by either passive or active means. Active laminar-flow control becomes a necessity when very high Reynolds numbers as on large, long range transport aircraft are encountered. The major direction followed in active laminar-flow control is boundary-layer suction[7,8], generally applied locally close to the leading edge, followed by a run of natural laminar-flow. This combination is called hybrid laminar-flow control (HLFC). With HLFC, the Tollmien-Schlichting instability (TSI) as well as the crossflow instability (CSI) can be damped, and such systems are under research for some time now. Here, the complexity of manufacturing the suction surfaces at the wing leading edge, and the power to drive the suction pumps are of considerable concern. Another emerging route towards laminar-flow control is active damping, such as investigated e.g. in Ref. 21, where small, micromechanically fabricated sensor and actuator fields are employed to directly counteract evolving Tollmien-Schlichting instabilities. On a forward swept-wing, leading edge sweep angles low enough to avoid CSI may be

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achieved without too much compromising cruise speed, and mainly TSI has to be dealt with. For very high Reynolds numbers, this allows the design of HLFC devices which facilitate the integration of de-icing systems or slats, thus reducing system complexity substantially. Furthermore, the forward swept-wing offers the potential to employ future concepts of active damping, despite their restriction to damping Tollmien-Schlichting instabilities only.

Wave propagation characteristics

Up to now, laminar-flow control by actively damping Tollmien-Schlichting instabilities has been performed for incompressible boundary-layers under laboratory conditions only, and the propagation characteristics of disturbances was considered as more or less being two-dimensional. As was shown in the flight tests of Ref. 22, already on the wing of a low speed aircraft the disturbances do not travel as well aligned two-dimensional waves, but as wave packets with a particular spanwise distribution. Thus, special sensor and actuator systems will be needed to allow for the deliberate employment of damping mechanisms, and the system layout will require a thorough understanding of all local flow features. The situation becomes even more complicated when dealing with the flow conditions of typical transonic transport aircraft. Figure 15(a) and Fig. 15(b) from Ref. 23 show the propagation characteristics of Tollmien-Schlichting waves for different flow conditions. Figure 15(a) displays the correspondence of TS frequencies and wave lengths measured in the flight test with the low speed aircraft of Ref. 22, theoretical estimates for these conditions, and for conditions of the design of a laminar wing for an A320-type aircraft[23]. Frequencies and wave lengths roughly increase by a factor of five for application on the A320-type aircraft. Furthermore, theoretical estimates show that when the local Mach number increases above M = 0·4, the wave propagation direction of disturbances changes from 0° (i.e. flow direction) to angles of up to 45°degrees, see Fig. 15(b). Today, these mechanisms of disturbance propagation in compressible transonic boundary-layers are not well enough understood to derive design criteria for active damping systems. Therefore substantial effort in basic fluid dynamical research is required, and it should be noted that here especially designed flight tests with carefully developed measuring systems will be necessary to detect and quantify the disturbance topologies.

Numerical simulation

The industrial realisation of the laminar, forward swept-wing requires the availability of advanced design tools to succesfully tackle the truly multi-disciplinary design challenges of such concepts. This holds especially for the coupling of aerodynamics and structures, but it also includes flight mechanics and active load control systems. A promising area to provide these design tools is numerical simulation. Today, computational fluid dynamics (CFD) is mainly used as a tool for design support, but in the future the potential for multi-disciplinary analysis and optimisation will be exploited. The perspective of numerical simulation lies in the possibility to realise the vision of digital flight, i.e. to perform the design, assembly, and flight testing in the computer before the first non-reversible decisions about the use of hardware are made[24]. The potential for numerical simulation is mainly based on Moore's law[25], which predicts a doubling of the number of transistors per square inch every 18 months. Basically, this can be translated into a similar increase in computational power, and if one assumes that computational power doubles every two years, than a computation which will need 30 years of computation time today, can be achieved in 30 years within 8 hours[24]. However, the computer architecture will differ substantially from today's state of the art, and a direct application of the software in use today on the hardware of tomorrow will not be possible. It is therefore the challenge of future research and development efforts in numerical simulation to leverage this tremendous potential of computational power for the application in the design processes of tomorrow.

6.0 CONCLUSIONS

Today's air transport system is highly efficient and matured. This highly evolved state resulted from the transition of the 'technology push' scenario, where new markets were established by new technological possibilities, to a 'market pull' orientation, where the introduction of new technologies is decided by the requirements of an established market. Over the last decades, the 'market pull' requirements more or less 'designed' the highly efficient shape and structure of today's air transport system, and for those market requirements the system may be regarded as having reached an almost optimal state. However, new market factors like the volatility of fuel prices, and the more and more severe requirements of ecological compatibility are changing the long time constant 'market pull' mechanisms, and reduction of fuel burn is becoming of utmost importance. Currently, the technologies under consideration to reduce fuel burn are contra rotating open rotors, carbon fibre reinforced plastics, and laminar-flow control, and today's research efforts are concentrated on pushing these concepts to their limits.

The concept of a forward swept-wing with laminar-flow control represents a technological perspective with a potential beyond that of these current efforts. Such a concept will allow natural laminar-flow at cruise Mach numbers in the range of present turbulent, swept back wings. Furthermore, since crossflow instabilities may be controlled by the reduced sweep of the leading edge, the transition mechanisms are mainly governed by Tollmien-Schlichting instability mechanisms. This allows the use of locally restricted HLFC-systems, and to consider future concepts of active damping, thus holding promise to efficiently extend laminar-flow to very high Reynolds numbers. However, a forward swept-wing faces substantial technological challenges. These may be overcome by deliberately using the potential of flow control technologies for separation suppression, aeroelastic tailoring and multidisciplinary design to counteract aeroelastic divergence, and numerical simulation for risk reduction and optimisation of the aircraft design with respect to all relevant disciplines. Therefore, the challenging question 'Aerodynamics – A discipline swept away?' may be boldly countered with the response 'By no means: Let's sweep it forward'!

It has to be emphasised however, that the potential of such a laminar, forward swept-wing will not be leveraged by 'off-the-shelf' solutions. With respect to the involved technologies, being it aerodynamics, materials and structures, or systems, the clear definition of a well-balanced strategy in basic as well as in applied research is required. This includes the clear dedication to a continuous research effort over a substantial time period; the often observed on/off switching of research activities as frequently performed in the past will not enable the necessary progress: all the 'low-hanging fruits', which may be easily available by short time efforts, have already been picked.

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