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Abstract

Drag reduction for aerial vehicles has a range of positive ramifications: reduced fuel consumption, larger operational range, greater endurance and higher achievable speeds. The aerodynamic drag breakdown of a transport aircraft at cruise shows that the skin friction drag and the lift-induced drag constitute the two main sources of drag, approximately one half and one third of the total drag. The paper summarizes the state of the art in aeronautical drag reduction for the `conventional' drag components of viscous drag, drag due to lift and wave drag, and also will give an overview of the results obtained for the different mentioned topics and will try to evaluate the potential gains offered by the different technologies.

Introduction

The importance of and possibilities for viscous drag reduction were first seriously identified in the late 1930s, primarily as a result of two developments: successful drag `clean-up' efforts which minimized pressure drag, thereby enhancing the importance of (residual) viscous drag, and the realization, via development of low disturbance facilities and flight transition measurements, that turbulent flow was not necessarily `given' beyond a Reynolds number of order 2×10^5. Such a low transition Reynolds number was common in the wind tunnels of the period, which typically exhibited stream turbulence levels on the order of 1 per cent or greater. In flight and low disturbance tunnels, with stream disturbance levels on the order of 0.05 per cent, transition could occur well beyond Reynolds numbers of order 2×10^6 (Bushnell, 2003).
Drag is at the heart of aerodynamic design. The subject is fascinatingly complex. All aerodynamicists secretly hope for negative drag. The subject is tricky and continues to be controversial. It's also terribly important. Even seemingly minor changes in drag can be critical. For example, on the Concorde a one count drag increase (ΔC_D = .0001) requires two passengers, out of the 90~100 passenger capacity, be taken off the North Atlantic run (Strang and McKinlay, 1979). In design studies a drag decrease is equated to the decrease in aircraft weight required to carry a specified payload the required distance.
The economic viability and future survival of an aircraft manufacturer depends on minimizing aerodynamic drag (together with the other design key technologies of structures, propulsion, and control) while maintaining good handling qualities to ensure flight safety and ride comfort. New designs that employ advanced computational aerodynamics methods are needed to achieve vehicles with less drag than current aircraft.
Initial drag estimates can dictate the selection of a specific configuration concept in comparison with other concepts early in the design phase. The drag projections have a huge effect on the projected configuration size and cost, and thus on the decision to proceed with the design (Hendrickson et al., 1997).
The environmental factors, such as noise, air pollution around airports and impact on climate change, which are well underlined in Green (2003), will also play an important role for future growth of the civil aviation. The impact of air travel on the environment will then become an increasing powerful factor on aircraft design. It is also important to recall the main goals of the vision 2020 launched by the European commission (2001) : a 50% cut in CO_2 emissions per passenger kilometer (which means 50% in fuel consumption in the new aircraft of 2020) and an

80% cut in nitrogen oxide emissions. These objectives cannot be reached without breakthrough in today technologies.

Drag reduction is a great challenge but there is certainly room for improvements. The drag breakdown of a civil transport aircraft shows that the skin friction drag and the lift-induced drag constitute the two main sources of drag, approximately one half and one third of the total drag for a typical long range aircraft at cruise conditions (Reneaux, 2004). This is why specific research on this topics have been initiated researchers and it seems that Hybrid Laminar Flow technology and innovative wing tip devices offer the greatest potential. Aircraft performance improvement can also be obtained through trailing edge optimization, control of the shock boundary layer interaction and of boundary layer separation.

There are two key considerations in discussing drag. First, drag cannot yet be predicted accurately with high confidence levels (especially for unusual configuration concepts) without extensive testing (Sloof, 1988), and secondly, no one is exactly sure what the ultimate possible drag level really is that can be achieved for a practical configuration. To this extent, aerodynamic designers are the dreamers of the engineering profession.

The earliest research in aeronautical viscous drag reduction addressed the issues of transition delay, initially via favourable pressure gradients on the essentially unswept wings of the day. Later, in the 1950s and 1960s, suction was utilized in research efforts to address the cross-flow instability problem endemic on swept wings. This early research on transition delay was termed \`laminar flow control' (LFC), with \`natural' laminar flow defined by pressure gradient controlled/delayed transition and \`forced' or active laminar flow obtained via suction. This technology offered large gains in aircraft performance and was actively pursued, at various times, in many countries, e.g. the United States, Britain, France, Germany, Japan and Russia. This research demonstrated that, in carefully controlled experiments, transition could be delayed for appreciable distances with consequent large decreases in viscous drag (compared to the turbulent level) (Bushnell and Tuttle, 1979). However, the critical (for application) maintenance and reliability issues were never, at least up to the mid 1960s, successfully addressed. Various \`real world' problems, such as insect debris, other roughness and occurrence of waviness under loading, all exacerbated, initially, by the low cruise altitude/high unit Reynolds number prevalent in the 1940s and early 1950s (and later by wing sweep), kept LFC in the category of a \`laboratory curiosity'. The continued availability of inexpensive petroleum in the 1960s, coupled with these unresolved reliability and maintainability issues, caused an essential hiatus in LFC research from the mid 1960s to the mid 1970s.

The research in turbulent drag reduction (TDR) during this period from the late 1930s to the mid 1960s consisted primarily of roughness reduction, the implicit assumption being that a smooth surface exhibits the lowest turbulent drag level. Some effort was also expended on TDR via reduction of the wetted area. The turbulent skin friction reduction associated with mass injection was also known, as was that due to adverse pressure gradients. The use of the former was obviated by the high ram drag associated with air collection for injection.

Increases in the price of jet fuel triggered a renaissance in viscous drag reduction which is still extant throughout the world, reinforced more recently by \`global warming'/environmental issues, with active viscous drag reduction programmes now underway, for example, in Japan, China, France, Britain, Germany and Russia, as well as in the United States. Much of the technology developed during this remarkably fruitful period in viscous drag reduction (from the mid 1970s) is documented in excellent books, courses, reports and conferences (Thibert et al., 1990; Szodruch, 1991; Priest and Reneaux, 1992; Giho, 1988; Hough, 1980; Sellin and Moses, 1989; Bushnell and Hefner, 1990; AGARD reports: 1984, 1985, 1977, 1992; Fiedler and Fernholz, 1990; Tuttle and Maddalon, 1993; Barnwell and Hussaini, 1992; Hefner and Sabo, 1987; Wagner et al., 1989; Holmes et al., 1985; Wagner, et al. 1990; Arnal and Bulgubure, 1996; Schmitt and Hinsinger, 1996; Cousteix et al., 1993; Gad-el-Hak et al., 1998; Thiede, 2000; Choi, 2000; Jahanmiri, 2010).

For supersonic transport (SST) fuel is approximately one half of the gross weight and the fuel reserves required for landing exigencies are on the order of the payload weight. A one per cent drag decrease corresponds, approximately, to a 5-10 per cent increase in payload. Historical approaches to wave drag reduction include area ruling, wing sweep, reduced thickness, wing twist/camber/warp via linear theory and favourable wave interference (Bushnell, 1990; Kuchemann, 1978; Kuchemann, 1962).

Vortex drag due to lift (DDL) is of major interest for both subsonics and supersonics, but the arena has not been worked significantly in years except for winglets and a `zoo' of other tip devices. The classical linear theory approaches of increased aspect ratio, lower lift coefficient and elliptic load distribution are utilized to the extent permissible by structural considerations and overall design (Rokhsaz, 1993; Spillman, 1987; Henderson and Holmes, 1989).

The aim of this review paper is to highlight the state of the art in aeronautical drag reduction, and also describe several emerging drag-reduction approaches that are either active or reactive/interactive.

Basic concepts

Aerodynamic drag generally consists of friction drag and pressure drag. Friction drag is determined almost entirely by the state of the boundary layer (laminar, transition or turbulent), and does not vary greatly between subsonic and supersonic flight. On the other hand, pressure drag increases markedly at supersonic speed due to shock waves generated by the airframe and propulsion system. The increased drag is called "wave drag". Aerodynamic drag is also divided into zero-lift drag and lift-dependent drag components. In general, friction drag is treated approximately as zero-lift drag, because friction drag is not sensitive in the change of angle of attack, namely lift condition being satisfied with attached flow condition. Shock waves are produced by deflections of the flow by airframe volumes, such as the cross-sectional area distribution of the fuselage and the thickness distribution of the wing, and by lift generation. The former corresponds to zero-lift drag and is called "wave drag due to volume". The latter is lift-dependent drag called "wave drag due to lift". Furthermore, lift-dependent drag includes a component called "induced drag" at subsonic speed, which is generated by trailing vortices such as wing tip vortices.

These components of drag are shown in Figure 1.

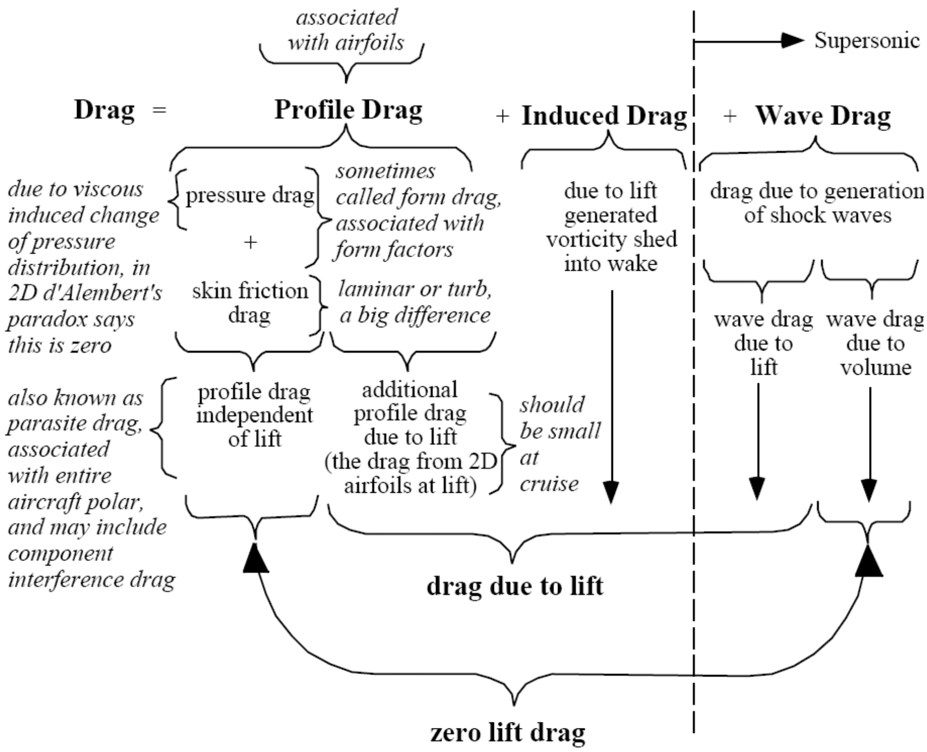

Figure 1: A broadbrush categorization of drag.

Basic drag nomenclature is frequently more confused than it needs to be, and sometimes the nomenclature gets in the way of technical discussions. The chart in Figure 1 provides a basic classification of drag for overview purposes. The aerodynamic configuration-specific approach to drag is not covered in fluid mechanics oriented aerodynamics texts, but is described in aircraft design books. Two good references are the books by Whitford (1987) and Huenecke (1987). An approach to the evaluation of drag performance, including the efficiency achieved on actual aircraft, was presented by Haines (1968). The most important overview of aerodynamic drag for design has been given by Küchemann (1978) and should be studied for a complete understanding of drag concepts.
The broadbrush picture of drag presented in Figure 1 (Hendrickson, 1997) suggests that wave drag appears suddenly at supersonic speeds. A more refined examination shows that wave drag arises at subsonic speeds when the flow accelerates locally to supersonic speeds, and then returns to subsonic speed through a shock wave. This leads to the presence of wave drag at subsonic (actually, by definition, transonic) freestream speeds. This initial drag increase, known as drag rise, is followed by a rapid increase in drag, and is an important consideration in the design of wings and airfoils. The Mach number at which the rapid drag increase occurs is known as the drag divergence Mach number, MDD. The increase in drag occurs directly because of the wave drag associated with the presence of shock waves. However, the drag also increases because the boundary layer thickness increases due to the sudden pressure rise on the surface due to the shock wave, which leads to increased profile drag. Lynch (1982) has estimated that at drag divergence the additional transonic drag is approximately evenly divided between the explicit shock drag and the shock induced additional profile drag. Several definitions of the drag rise Mach number are commonly used. The specific definition is usually not important because at drag divergence the drag rises very rapidly and the definitions all result in similar values of MDD.

Skin friction drag reduction

Two methods are generally considered for skin friction drag reduction. The first one aims at reducing the turbulent skin friction while the second one aims at delaying transition to maintain large extent of laminar flow.

1. turbulent skin friction reduction

As mentioned by Wilkinson et al. (1988), a large proportion of the energy expenditure for all types of transportation (air, sea, land) and for many industrial and propulsion processes is simply to overcome turbulent skin friction. The payoff from invention and development of successful approaches can conservatively be estimated in the billions, irrespective of which country's currency one considers. The approaches of research choice prior to the late 1970s involved either laminar flow control (LFC), which had fairly severe limitations as to application (surface finish/unit Reynolds number, disturbance environment, etc.), or techniques to alter the average flow/drag directly such as (a) wetted area minimization, (b) reduced roughness, (c) use of a "Stratford closure" (adverse pressure gradient), (d) mass injection, and (e) bubbles to reduce the average near-wall density in water (Bushnell, 1985). An exception was the use of polymers to affect, in an unknown manner, the turbulence field directly.
Also Bushnell (2003) points out that, turbulent drag reduction (TDR) is a key issue in aeronautics in that in many applications/flow situations it is simply not possible to establish/maintain laminar flow and therefore some mitigation of turbulent drag levels must be sought. Such situations include flight at very high unit Reynolds numbers where the requisite smoothness requirements become difficult-to-ridiculous (e.g. low altitude cruise missiles, which also fly in the `bug layer'). Additional cases where LFC is contravened include surfaces with large innate roughness such as most aircraft fuselages (due to pitot probes, windshield wipers, doors, windows, etc.), as well as intersection region `contamination' areas and surfaces subjected to other `bypass' inducing flow features such as erosion, shock interaction, high noise levels and

mass efflux from the surface. Since the laminar level is not available in these cases, the amount of drag reduction is not nearly as large as in the case of LFC, but is still of considerable technological importance (e.g. local skin friction reductions of 5-30 per cent versus the 50-80 per cent available from LFC). A successful campaign to reduce turbulent drag is one that approaches the problem via a large number of methods, as many of the techniques work in localized areas or circumstances. Reducing skin friction is relatively simple; flow separation can provide negative skin friction, but at the expense of rather large pressure drag that is far larger than the original friction drag.

Turbulence management represents another class of means for reduction of friction drag or, more in general, for turbulent boundary layer manipulation (Slooff, 2002). For aeronautical application of (turbulent) friction drag reduction devices 'riblets' and 'Large Eddy Break-Up Devices (LEBUs)', in that order, are probably the most important (Bushnell and Hefner, 1990). Both riblets and LEBUs recognize the knowledge that the large eddies in the boundary layer cause most of the turbulent friction drag. In the case of riblets the development of large eddies is constrained by longitudinal, stream aligned, V-shaped grooves. In the case of LEBUs the boundary layer flow is streamwise-periodically straightened by small, surface-parallel, wing-like devices in the boundary layer. Research on riblets and LEBUs has been going on for more than a decade and it has been demonstrated, both in the wind tunnel and in flight that net friction drag reductions up to about 5% can be realized. It seems, however, that due to increased cost of ownership (manufacturing, in particular for LEBUs) and high vulnerability (maintenance cost) the net overall economics are in the red.

Vortex generators represent another means of turbulence management, with a different objective. They have been and are still widely used for (locally) postponing boundary layer separation and, through this, for improving low-speed and/or high-speed stall characteristics. The mechanism is to make the boundary layer more resistant to separation due to adverse pressure gradient by generating streamwise vortices near the edge of the boundary layer that 'reenergize' the boundary layer flow. This at the expense of additional drag resulting from the increased surface friction of the boundary layer flow as well as the frictional resistance and vortex drag of the generator devices themselves. The more recently developed concept of 'smart' vortex generators is a little more closely related to the notion of turbulence management. The basic idea here is to postpone separation by stimulating the development of (very) large eddies within the boundary layer through small generating devices with less additional drag. Both mechanical (Lin et al., 1994) as well as pneumatic (Seiffert et al., 1993) (small jets) devices have been proposed for this purpose. The concept of 'smart' vortex generators is sufficiently interesting for further investigation. Of particular interest is the question whether, if adopted from the outset as an additional 'variable' in the design space of an aircraft (rather than as a 'deficiency curing' device that is applied afterwards), 'smart' vortex generators would lead to better overall aerodynamic/economic performance.

Zheng and Yan (2010), categorize turbulent drag reduction methods as: active control, passive control and interactive control. For active control, turbulent drag reduction can be achieved by changing the flow properties or behaviour. The former can be realized by adding extra substances into the flow, which includes bubble, particle, polymer solutions and surfactant (referred as "additives"). The latter can be done by imposing external force and mass, such as Magnetohydrodynamic (MHD) control and mass injection. Passive control involved with the wall modification by changing the wall structure and adjusting attack angle, passive control includes the employments of riblets, large eddy breakup device (LEBD), convex curvature, wavy wall and adverse pressure gradient. Compared to active control, the advantage of passive control is reducing the viscous flow drag in a passive way where the drag reduction effect is immensely shown under certain designed flow conditions. Interactive control is defined as observing the coherent turbulent structure and controlling turbulent boundary layer by adopting physical or thermal activities in wall surfaces, includes wall oscillation, wall heating/cooling and compliant wall. The interactive and active controls achieve drag reduction in a controllable way suitable for varying flow conditions, while passive control is suited for designed flow conditions due to the

passive style of bearing flows. Considering the input of extra power or mass, passive control is more energy-saving than interactive and active controls due to the absence of extra input.
Among the turbulent drag reduction techniques, riblets have been the most widely investigated method of drag reduction (Walsh, 1983; Viswanth, 2002). Over the last 60-70 years, it has been widely and intensively studied from a wide range of aspects. Riblets with the shapes of rectangular, triangular, semicircular, trapezoidal, and scalloped-shape have been studied in terms of the drag reduction performance. In addition, the impact of the geometry variation of riblet surface on the drag reduction has also been reported by Merkle & Deustch (1992). Obviously most of studies carried out so far have been directed towards the turbulent flow drag reduction. Conclusions widely agreed by many of the relevant studies have been drawn that the drag reduction effect in turbulent flow is related to the dimensionless geometries of riblet structure.
Inspired by the functions of sharks skins, riblet surfaces have been studied and applied to wall structures to reduce turbulent flow drag (Zheng and Yan, 2010). However, whilst structural similarity has been obtained it lacks true mimicry. The drag reduction using "Smart Surface", (Figure 2) is a new proposed composite surface that combines the riblet with an elastic coating. The "smart surface", inspired by the self-adjustable skin of marine animals such as the dolphin, is designed to modify the traditional riblet technique and enable it to "sense" and interact with the flow by adjusting the wall structure according to the flow condition (Figure 3).

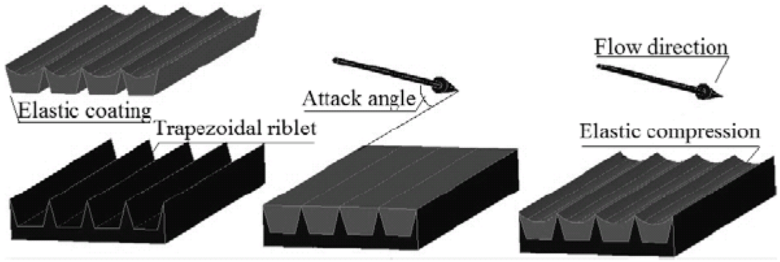

Figure 2: Structure of "smart surface", (a) the components (b) Before compressed, (c) After Compressed.

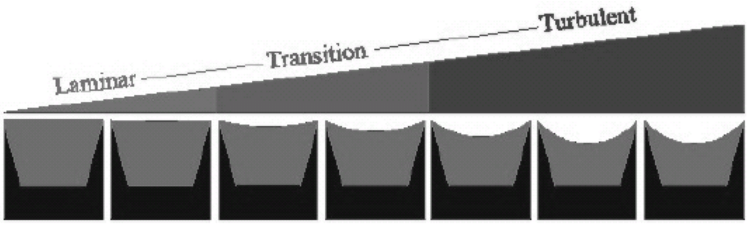

Figure 3: Compressions under different flow regimes

A deformable active skin actuated by active materials has been proposed by Mani et al. (2008) for a flow control technique that holds promise for large reduction in turbulent skin friction drag. Theoretical analyses of two design principles have been performed and were compared with FEA to come up with a parameterization of the deflection amplitude and the natural frequency in terms of the model dimensions. The work efficiencies of the force based actuation scheme was found to be higher than those of the moment based actuation scheme from a structural point of view. Three different possible skin designs (that implement either of the two design principles) utilize SMA (shape memory alloy), piezoelectric C-block and piezoceramic stacks for actuation, respectively (see Figures 4, 5, and 6). It can be generally summarized that for applications in which the required actuation frequencies are low (order of 50 Hz for slow UAV applications), the SMA based actuation technique holds the greatest promise, whereas for applications involving high actuation frequencies (several hundred Hz, for airliners and military aircraft applications), the piezoelectric actuator based systems would be more appropriate. A mechanically actuated skin based on cam action has been designed and manufactured to test the validity the drag reduction technique prior to actual development of the active skin.

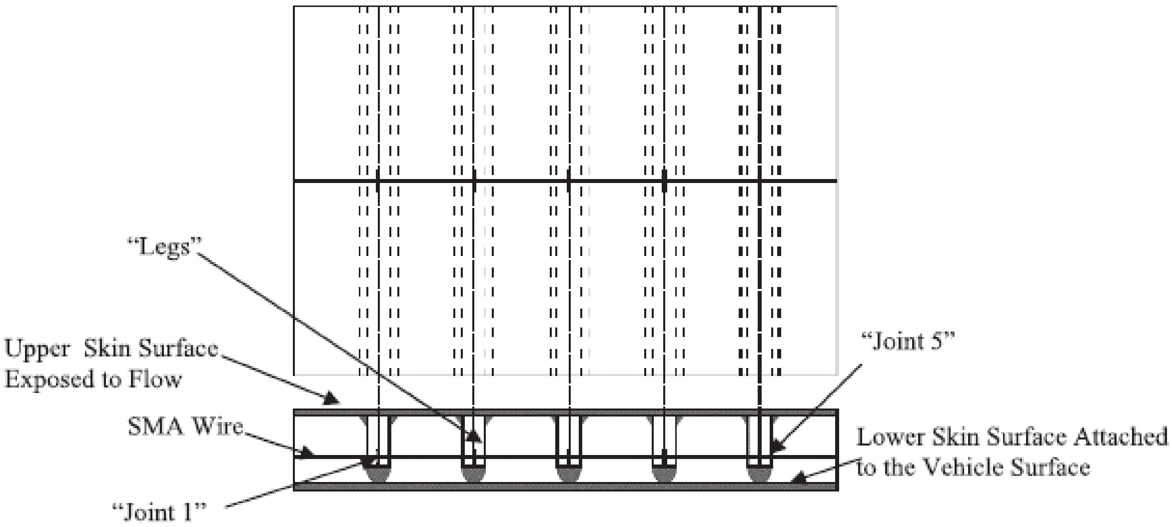

Figure 4: Cross section and top view of SMA actuated active skin.

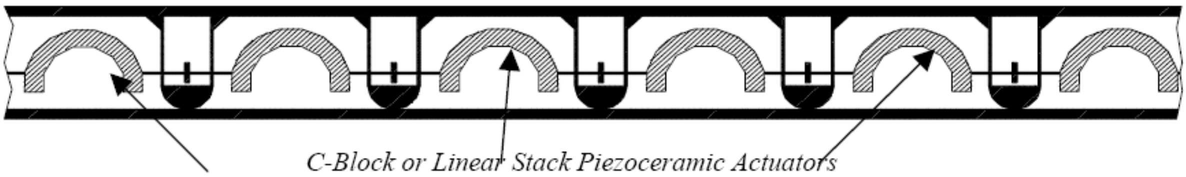

Figure 5: Piezoelectrically actuated active skin.

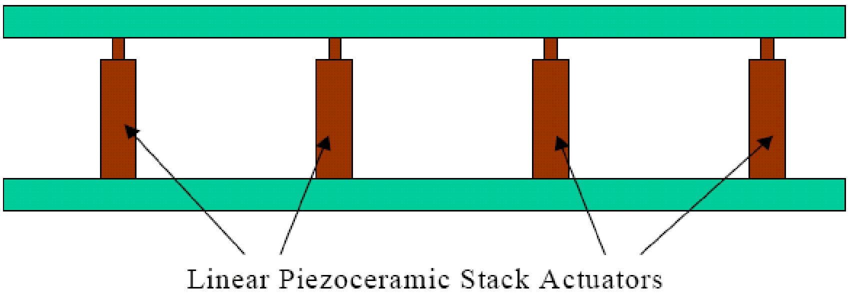

Figure 6: Skin design with linear piezoceramic stack actuators oriented perpendicular to the skin.

2. Laminar flow control technology

A substantial reduction in fuel consumption and in CO2 emissions will certainly require the adoption of laminar flow control in order to reduce the skin friction. For small aircraft with low swept wing (at Reynolds numbers below about 20×10^6 and leading edge sweep angles not in excess of about 20 degrees), laminar flow can be maintained by shaping the airfoil (NLF concept) and this concept is currently considered for new small jet aircraft. However for high Reynolds number and high sweep encountered on a large transport aircraft, suction has to be applied (Reneaux, 2004).

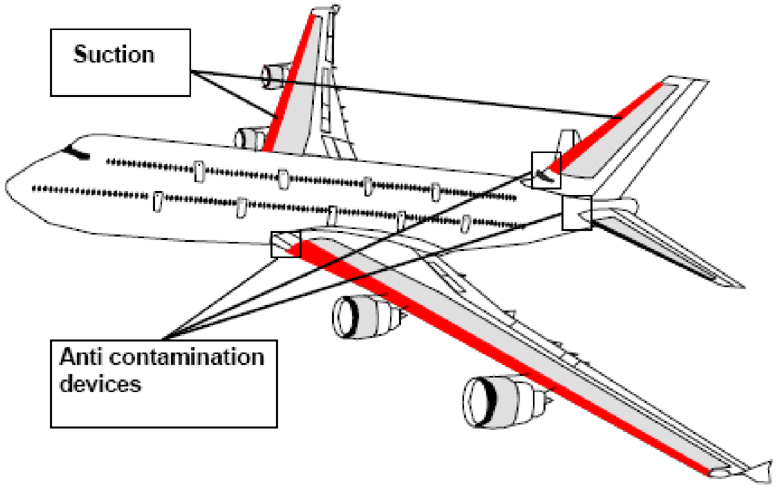

Figure 7: Hybrid Laminar Flow concept (Reneaux, 2004).

In the Hybrid Laminar Flow concept, the laminar flow can be maintained by the application of suction in the region of the leading edge to control the development of cross-flow and Tollmien-Schlichting instabilities combined with favourable pressure gradients in the spar box region (Figure 7). It is first necessary to ensure that the attachment line remains laminar and to avoid contamination phenomenon. Anti contamination devices have to be used to avoid the contamination of the attachment line by the turbulent structures coming from the fuselage. Gareth Williams (2010) from Airbus (Smart Fixed Wing Aircraft (SFWA) project) recently in his presentation pointed out that, so far two types of laminar flow technology have evolved. Natural laminar flow, exploiting shape and materials, Hybrid laminar flow, where an active system induces laminarity, typically suction (Figure 8). SFWA investigates the potential of both, but will focus on Natural Laminar Flow as it avoids recognized complexity and weight penalty of the Hybrid counterpart.

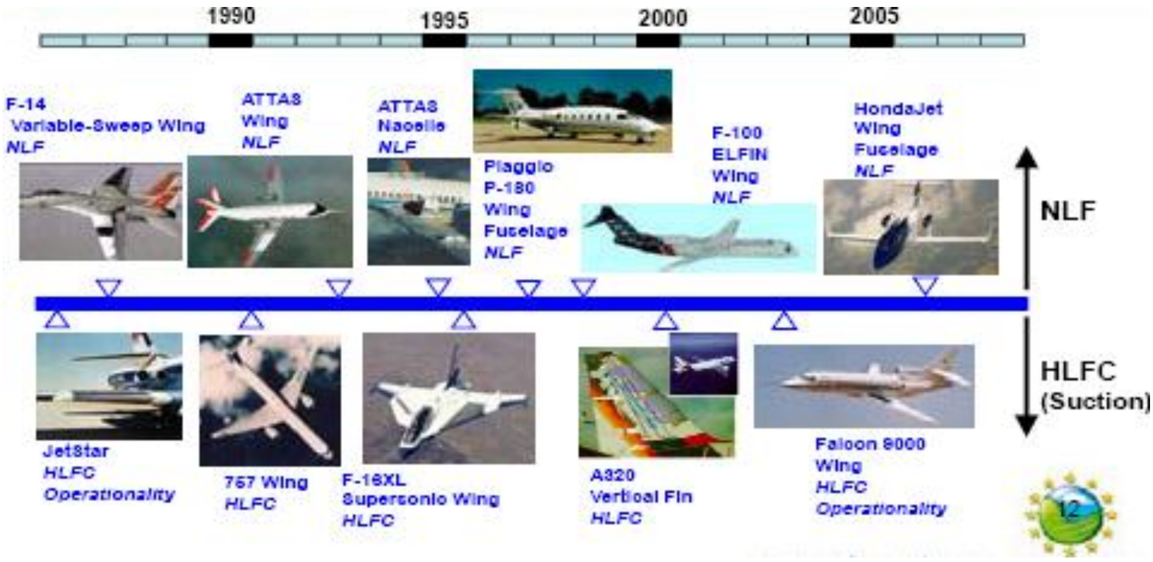

Figure 8: Recent laminar flow demonstrators

While Natural Laminar Flow (NLF) or Laminar Flow Control (LFC) has traditionally been employed to reduce drag for subsonic airfoils, the availability of new materials and fabrication techniques has opened up new vistas in drag reduction through boundary layer flow control. One such method that has shown promise is the Flexible Composite Surface Deturbulator (FCSD) shown in Figure 9 (Sinha and Ravande, 2006a). The FCSD is a micro-structured compliant wall

(Sinha 2003), and interaction of compliant walls with zero-pressure gradient laminar, transitional and turbulent boundary layers is well documented (Bushnell and Hefner, 1977; Carpenter et al. 2001). The uniqueness of the FCSD approach is that it relies on reducing the overall aerodynamic drag by helping maintain a thin layer of separated flow near the surface by attenuating turbulent mixing in this shear layer (Sinha and.Ravande, 2006b). The presence of a varying chord-wise pressure gradient, typical of airfoils and streamlined aerodynamic bodies is essential for this. The FCSD helps maintain a laminar separation bubble-like flow structure, except that it is stretched over a larger extent of the chord. In this manner the bubble behaves as a slip-layer to the external flow and can eliminate skin-friction drag. Laminar boundary layers have lower skin-friction compared to turbulent boundary layers. However unlike the FCSD approach, promotion of laminar flow alone cannot zero out skin friction. In practice, FCSD modification of boundary layer flows significantly lowers skin friction coefficients as evidenced by a speed up of the external inviscid flow. This can help increase circulation and lift generation similar to Liebeck high-lift airfoils (Liebeck, 1973). Such airfoils, however require close control of transition. The FCSD makes transition control less critical, thereby extending the low drag conditions to larger ranges of flight conditions. Also, earlier compliant wall research was done for mainly for water flows since, the mechanical properties of compliant surfaces responsive to air flows would make them extremely delicate and hence impractical (Carpenter et al. 2001). The FCSD has overcome this limitation by its unique construction technique, interaction mechanism and integration with the wing.

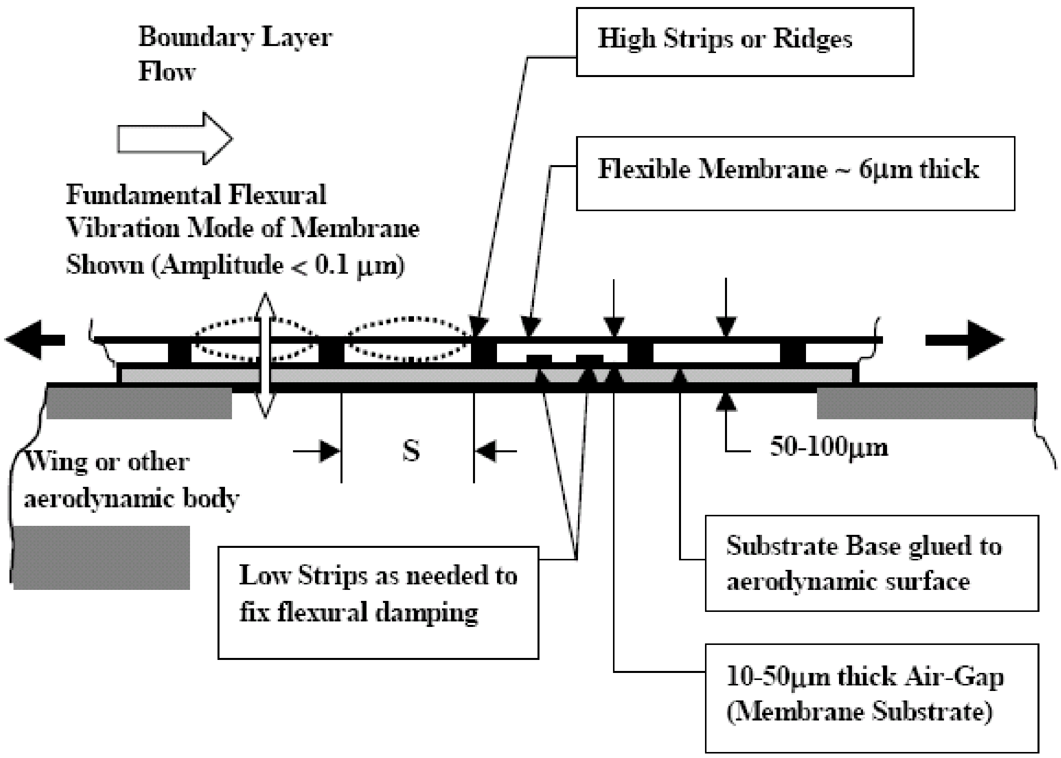

Figure 9: Schematic of the SINHA Flexible Composite Surface (FCSD)

Wind tunnel tests have shown that the FCSD creates a virtual wing profile with a thin region (under 1μm) of dead air along with low turbulence levels all through the chord. The FCSD mitigates the profile drag by stabilizing the near wall shear layer (Figure 10).

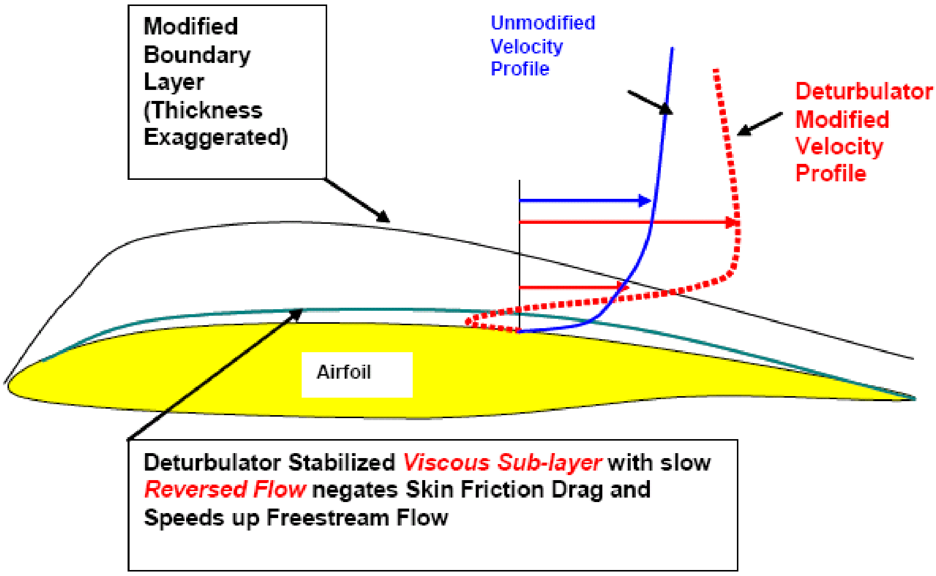

Figure 10: Sketch showing how FCSD reduces drag by maintaining thin stable separated regions.

The optimized FCSD has the potential of reducing overall fuel consumption of large transport aircraft by at least 10% through retrofitting, resulting in similar reductions in fossil fuel usage and emissions of NOx and greenhouse gases. The enhancement of lift measurements obtained could make the complicated flap structure on a commercial aircraft simpler, thereby reducing the weight and drag of the aircraft. This along with reducing the profile drag and induced drag using the FCSD tape could make the existing aircrafts highly fuel efficient (Sinha and Ravande, 2006a).

As commented by Bushnell (2003), the fundamental issue regarding LFC (Laminar Flow Control) concerns the identification of the mechanisms responsible for transition in the particular application, especially whether linear instability mechanisms dominate or whether nonlinear/ bypass mechanisms are the primary operatives. The term `bypass' transition is used to refer to any transition process not dominated by a single linear instability mechanism (Morkovin, 1984). Examples include early transition induced by roughness/waviness, large initial disturbance fields, spanwise contamination on swept leading edges and finite amplitude mode interactions. Successful application of LFC requires that such causative factors for bypass transition be identified and rendered harmless. As an example, the swept leading edge case has been approached by `bleeding off' the contamination and (re)establishing laminar attachment line flow. This approach may not be feasible for the larger leading edge radius associated with the 600-800 passenger transports and active transition control may be required in the attachment line region also. Once bypass conditions are circumvented the LFC problem becomes one of stabilizing linear modes. Typical modes and their regime of dominance include; T-S (viscous) modes ($M \leq 4$, 2-D mean flow), Mack (compressibility) modes ($M \geq 4$, 2-D mean flow), cross-flow (3-D mean flow across the speed range) and Görtler (longitudinal concave streamline curvature across the speed range). These various linear modes have differing sensitivities and therefore in many cases require differing transition delay approaches. For example, the Tollmein-Schlichting (T-S) and Mack modes are, in general, damped by increasing Mach number, whereas the cross-flow and Görtler modes are far less sensitive to Mach number. Also, wall cooling is stabilizing for T-S waves and destabilizing for Mack modes. The cross-flow and Görtler modes are relatively insensitive to wall temperature. A further example of differing transition

delay sensitivities concerns the effect of a favourable pressure gradient, which stabilizes T-S and Mack modes and destabilizes cross-flow. Suction is a powerful stabilizing influence for all modes, although there is some degradation of suction effectiveness for the case of high Mach number and second mode where the critical layer has moved into the far outer region of the boundary layer. A detail discussion on LFC and HFLC (Hybrid LFC) for different Mach regimes (subsonic/transonic and supersonic transport aircraft) is given in Bushnell (2003).
An alternative approach to transition delay/laminar flow control is to sense, in real time, details of local disturbance growth and input to the local flow a dynamic signal that `cancels' the growing waves in a `phased-locked' manner. Such an approach is obviously considerably more complex in terms of practical realization than other methods, all of which influenced the mean flow to reduce growth rate as opposed to directly acting upon the dynamics. Such a dynamic wave-cancelling approach is intriguing in terms of recent interest and advancements in `smart skins' which attempt to emulate `natural' skin in that the surface constitutes a system of sensors, processors and actuators. Additional `enabling' technologies for this approach to LFC include the miniaturization of both processors and various types of sensors and actuators that are products of the on-going `information revolution' (e.g. MEMS, or microelectromechanical systems).

Lift-induced drag reduction

Another major drag component is the lift-induced drag. The classical way to decrease the lift-induced drag is to increase the aspect ratio of the wing. This has been done in the past and the A340 wing aspect ratio reaches 9.3 (Reneaux, 2004). However, wing aspect ratio is a compromise between aerodynamic and structure characteristics and it is clear that for a given technology there is not a great possibility to increase aspect ratios. The alternative is to develop wing tip devices acting on the tip vortex which is at the origin of the lift-induced drag.
Many wing type devices have been studied these last years at ONERA using the CFD approach and in particular the Euler and Navier-Stokes solvers, and the far-field drag extraction technique (Destarac, 2003) allowing accurate drag predictions to be carried out. Basic studies (Bourdin, 2002) have shown that drag reduction can be obtained with variations in planform geometry along a small fraction of the wing-span and with aft-swept configurations. Furthermore, the Figure 11 presents, as examples among the investigated shapes, the wing tip turbine, the wing tip sails, the wing-grid, the blended winglet and the spiroid tip.

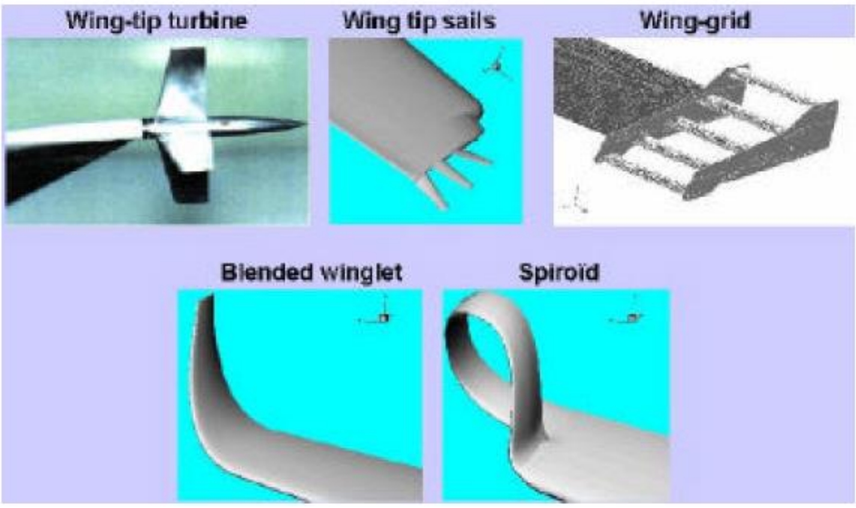

Figure 11: Various wingtip devices investigated at ONERA

The concept of the blended winglet is to modify a large part of the wing tip together with the winglet itself in order to obtain a very smooth blended shape. The blended winglet is expected to be more efficient than a narrow one to reduce the flow acceleration that occurs in the cross-flow curvature and to decrease the vortex intensity as important chord variation is avoided. The spiroid tip is a spiral loop obtained when joining by their tip a vertical winglet and an horizontal one. This unconventional device seems promising to reduce the tip vortex intensity but has a complex geometry difficult to optimize. Design of both wing tip devices were carried out in (Grenon and Bourdin, 2002) using numerical optimization approach and an Euler solver. The pressure distributions obtained on a blended winglet and on the spiroid tip at cruise conditions at M=0.85 are shown in figure 12. It can be seen that in both cases, flow velocities have been limited to avoid wave drag penalties and flow separation (Reneaux, 2004).

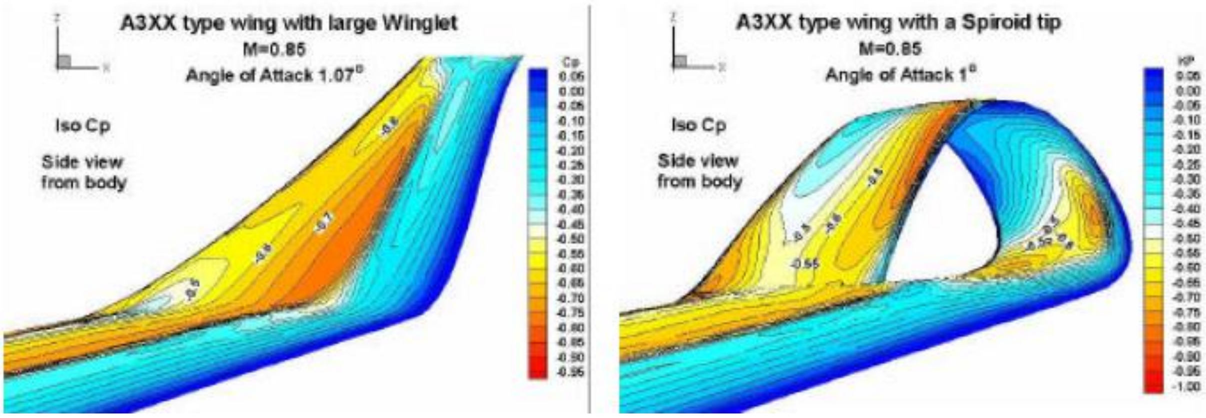

Figure 12: Computed pressure distributions around a blended winglet and a spiroid at cruise.

Recently, an experimental study has been done on three different types (rectangular, triangular and circular) of winglet (Inam, et al. 2010) to see the potential of winglets for the reduction of induced drag without increasing the span of the aircraft (see Figure 13). The experimental results show that the drag decreases by 26.4%-30.9% for the aircraft model with winglet for the maximum Reynolds number considered in their studies. Also, triangular winglet at inclination five degrees has the better performance giving about 30.9% decreases in drag as compared to other configurations.

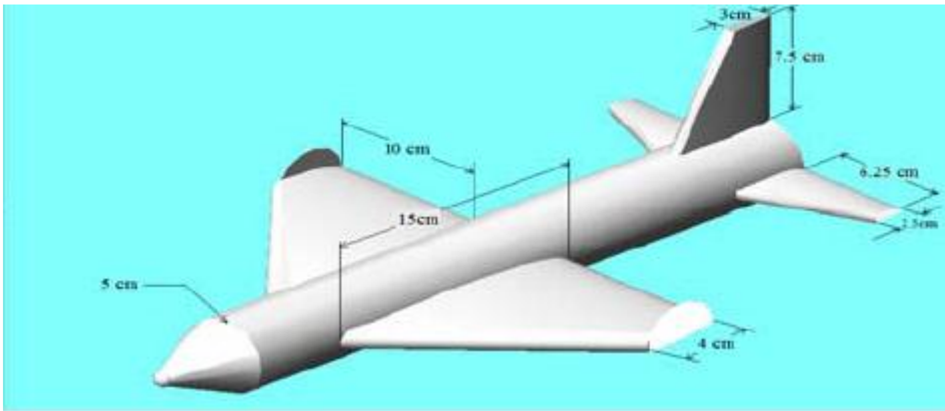

Figure 13: Designed Aircraft model

The induced drag due to lift constitutes approximately 40% of the total drag at cruise and more than 90% of the total drag at takeoff of a typical transport aircraft . An attempt has been made using wing-tip mounted vortex generator method by ManoharaSelvan (2010). This method makes use of the wake of the propeller to counter-act the induced vortex.

The results which are illustrated in Figure 14 show the followings: the linear lift trend followed 0.0013 CL increase per 1000 rpm (a) and the parabolic drag trend followed 0.006 CD decrease per 1000 rpm (b) roughly. As the rpm was increased above 12000, the lift starts to decrease and the drag tends to increase., because of the weak shock formation at the propeller tip (d). The vortex core was observed to move out board with the increase in rpm till 12000. The increase in rotational speed of the propeller makes the core of the induced vortex to attain the free stream pressure faster (e) and (f). The magnitude of the Cp of the leading edge suction peak of wing increases with rpm while the magnitude of Cp of the trailing edge suction peak of wing decrease with rpm. It was also observed that the increase in rpm introduces more high pressure in the lower surface of the wing. The primary effect of the propeller on the tip-vortex roll up mechanism was, it tries to suppress the favourable pressure gradient that drives the flow from lower surface to the upper surface of the wing. The secondary effect was, it tries to suppress the formation of the secondary vortex. Thus, the results reveal that this propeller device can provide an effective means of induced drag reduction.

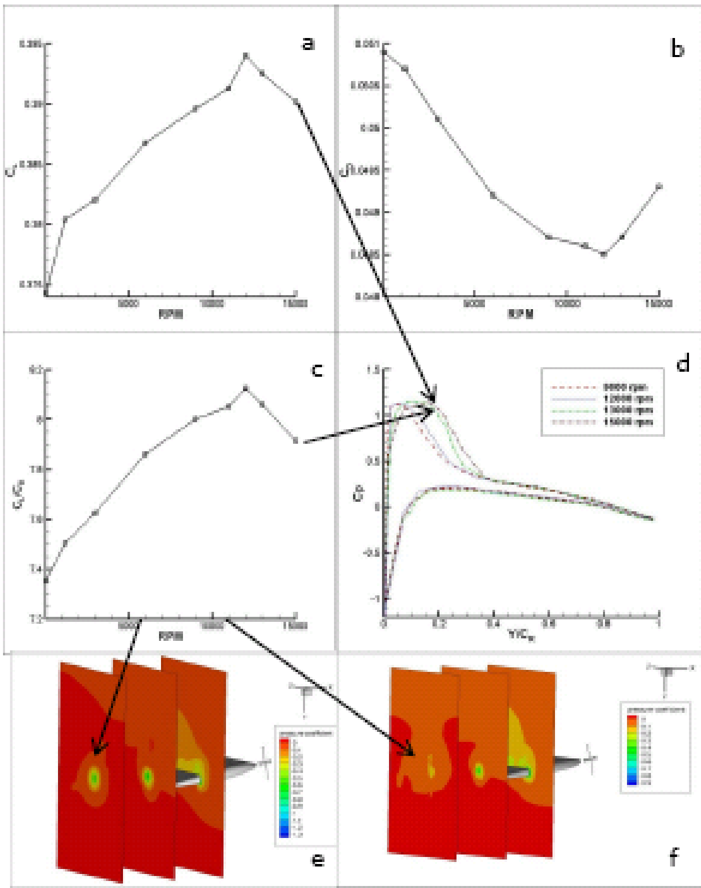

Figure 14: The results of computational analysis for induced drag reduction by ManoharaSelvan (2010).

Classical linearized theory indicates that elliptical loading, increased aspect ratio/span and lower lift coefficient values/reduced weight are the primary approaches to vortex drag due to lift reduction (Henderson and Holmes, 1989). Increasing the aspect ratio/span beyond a certain point obviously becomes inefficient due to structural penalties, while a decreased lift coefficient entails larger wings and both weight and wetted area/ viscous drag increases. Application of the extensive alternative solution set for vortex drag reduction has been relatively sparse (except for winglets) for many reasons, including (depending upon the approach) structural weight, parasitic drag and/or power-addressable in many cases via creative overall aircraft configuration design, as discussed in a subsequent section.

Bushnell (2003) proposes three approaches for reduction of induced drag:

1) Non-planar vortex sheet approaches: relaxing the assumptions of classical linear theory (closed body, no energy addition, planar vortex sheet, etc.) provides alternative vortex drag

reduction possibilities (Kroo et al., 1996; Zimmer, 1987; Ervondy and Linford, 1996; Lam and Maul, 1993; Lyapunov, 1993; Sugimoto and Sato, 1992; Kolobkov and Nikolaev, 1991; Mortara et al., 1992; Jones, 1979; Dehaan, 1990; Lowson, 1990; Ardonceau, 1994; Cone Jr, 1962; Naik and Ostowair, 1988; Lundry and Lissaman, 1968; Van Dam, 1985; Van Dam, 1987; Vijgen et al., 1987). In particular, the use of non-planar lifting surfaces, e.g. distributing the lift vertically through various approaches such as upswept tips and multiple (vertically spaced) wings, can provide sizeable reductions (up to an order of 15 per cent).
2) Energy/thrust extraction from the tip vortex: the vortex that forms at, and downstream of, the wing tip (caused by the tip upwash from the high pressures on the lower surface) affects a smaller percentage of the wing as the aspect ratio increases. A characteristic feature of this vortex formation is flow that is at an angle to the free stream. Devices can therefore be inserted into this flow to produce/recover thrust and/or energy from this tip flow. This (simplistically) is the fundamental rationale behind at least four devices that reduce inducd drag. These devices can obviously also have an influence upon the vortex formation process itself and thus may directly influence induced drag reduction. Such devices include tip turbines for energy extraction, winglets, vortex diffuser vanes and tip sails. The vortex diffuser vane is supported by a spar behind the wing tip to allow the vortex to concentrate before interception. These devices work quite well, depending upon the wing design and tip region loading, and produce on the order of 5-15 percent reductions in induced drag at CTOL (Conventional Take-Off and Landing) conditions. Major application issues for these include, along with the `usual' concerns stated previously, possible utilization as control devices (Rokhsaz, 1993; Spillman, 1987; Whitcomb, 1976 & 1977; Heyson et al., 1977; KC-135 Winglet Program Review, 1982; Yates and Donaldson, 1986; Kuhlman et al., 1988; Hackett, 1980; Webber and Dansby, 1983; Hackett, Feb. 1980; Spillman, 1978; Boyd Jr, 1984; Spillman and McVitie, 1984; Daxi, 1985; Janus et al., 1993; Keenan and Kuhlman, 1991; Eppler, 1997; LaRoche and Palffy, 1996).
3) Alteration of tip boundary condition(s): These lift dependent drag reduction techniques are based upon either eliminating the tip altogether or adding mass (and/or energy) in the tip region. Eliminating the physical wing tips can be accomplished either via the use of `ring wings' or joined wings and tails. Mass addition at/ near the tip can be carried out either via tip blowing (local/remote passive or active bleed) or by the use of wingtip engines, resulting in sizeable (up to 40 per cent depending upon wing design) vortex drag reduction. Passive tip blowing could possibly be approached via wing leading edge ingestion (allowing increased wing thickness), with subsequent tip blowing used to tailor for the production of, and modulated to excite, virulent tip vortex instabilities at landing/take-off to ameliorate the wake vortex hazard. Positioning the engines at the wing tips requires aerodynamic theoretical developments in an open thermodynamic system-as are adding energy/ species as well as mass. Also, the engine nacelle can function as a `tip device' (Degen, 1957; Letcher Jr, 1972; Gall and Smith, 1987; Patterson Jr, and Flechner, 1970; Patterson Jr, and Bartlett, 1987, and 1985; Yuan and Bloom, 1974; Wu et al., 1982 & 1984; Tavella et al., 1985; Chiocchia and Pignataro, 1995; Janus et al., 1995; Johnston et al., 1989; Snyder and Zumwalt, 1969; Kroo, 1984; Miranda and Brennan, 1986; Witkowski, 1989; Gallman, 1992; Loth, and Loth, 1984; Cho and Williams, 1990). There is an additional, wholly `new', potential approach for induced drag reduction. In reference Rossow (1975) oscillatory span load distributions were employed to reduce/obviate the wake vortex hazard. This same approach could well yield interesting levels of induced drag reduction and should be investigated for such.

Wave drag reduction

The `usual' (linear theory) approaches to wave drag reduction include wing sweep, area ruling and reduced thickness as well as wing twist/ camber/warp (Brown and McLean, 1959; Das, 1973; Nastase, 1986; Bos, 1986; Barger, 1992; Chang, 1992). More recently computational fluid dynamics (CFD)/non-linear methods have been applied, resulting in further optimization(s). Classical non-linear wave drag reduction techniques include the use of nose spikes (either

physical or via forward projection of energy, gases or particulates) to extend effective body length, particularly useful on blunt nosed bodies (Berdyugin et al., 1995; Luk'yanov., 1999; Riggins et al., 1999; Hinanda et al., 1986; Karlovskii and Sakharov, 1986; Reding et al., 1977; Arafailov, 1988; Belokon et al., 1977; Krasnobaev, 1984; Georgievskii and Levin, 1988; Kogan et al., 1987), and base blunting, which reduces the strength of the base recompression shock (Chapman, 1955). All of the wave drag reduction methods mentioned thus far involve weakening the shock. There is another whole class of approaches that utilize favourable shock interference. The fundamental approach is simple in concept—utilize shock waves, via reflection/interaction, to create favourable interference either for body thrust or lift, or both. Generally volume distributions are utilized to synergistically create lift and lift distributions are utilized to cancel volume drag. Realizations of favourable interference include ring wings and the related parasol wings, multiple bodies (fuselages, control surfaces, wing pods) and propulsion system interaction. For non-lifting bodies a ring wing can cancel, at design Mach number, the volume wave drag of the body such as the `Busemann biplane', at the expense of increased wetted area/weight, etc. For the lifting case the parasol wing provides both partial cancellation of the body/nacelle volume wave drag and an efficient lifting surface (Kulfan, 1990; Boyd, 1965; Erdmann and Zandbergen, 1976; Johnson et al., 1964; Gord, 1983; Erdos, 1983; Kulfan et al., 1978; Wood et al., 1985; Wood et al., 1983; Bauer and McMillin, 1988; Nielsen, 1985; Wood et al., 1986; McMillin and Wood, 1987; McMillin and Wood, 1986; Dollyhigh and Coen, 1987; Squire, 1965; Suikat and Farokhi, 1988; Sigalla and Hallstaff, 1967; Rethorst and James, 1982; Wood, 1988).
The application of favourable interference would be facilitated by flow separation control and active controls. Various experimental evaluations of favourable wave interference have resulted in far less than the expected inviscid performance levels owing to the detuning and drag associated with flow separation caused by the concomitant shock wave-boundary layer interactions. The plethora of flow separation approaches currently extant (e.g. see references: Gad-El-Hak. and Bushnell, 1991; Jahanmiri, 2010), if employed at cruise conditions, should enable nearly inviscid performance levels. One such approach makes use of passive porous surfaces (e.g. references: Hsiung and Chow, 1995; Bur et al., 1998; Serbanescu and Savu, 1985; Bauer. and Hernandezto, 1988; Nagamatsu et al., 1987). See also references, Gupta et al., 2000; Gupta and Ruffin, 1999; Ruffin et al., 2000, for a `mega bleed' approach to wave drag reduction. Flow separation control utilized during cruise could also greatly increase the percentage of lift carried on the upper surface as expansion waves—as opposed to the lower surface/(shock) wave rider conventional approach. The use of active flow control would allow both enhanced `on design' and improved `off design' performance via shock locus tailoring. As an order of magnitude estimate, parasol favourable interaction wings can provide on the order of 20 per cent improvement in the overall lift-drag ratio at cruise (Bushnell, 2003).
Among the different passive shock boundary layer control concepts investigated, the bump concept proposed by Ashill and Fulker (1992) seems promising. This concept is based on the local modification of the airfoil surface in the shock region. The straight shock is transformed into a lambda shock configuration and its strength is reduced by the presence of the compression waves.

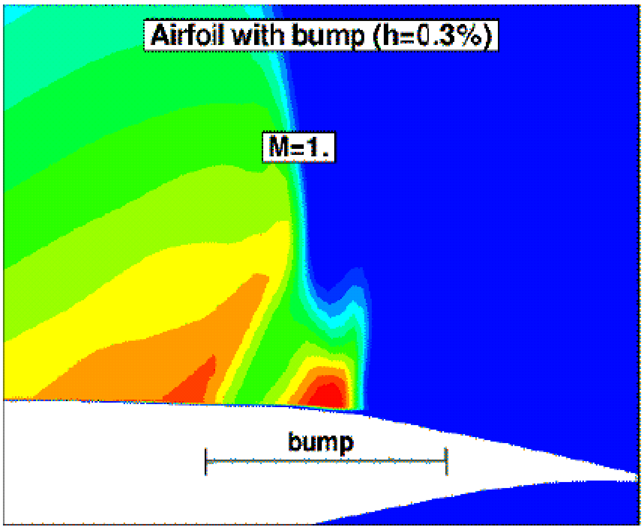

Figure 15a: Navier-Stokes computations around a 2D configuration with bump.

This concept was first applied in 2D on a laminar airfoil in the framework of a cooperation with Airbus Germany. The Figure 15a presents RANS results obtained on the 2D configuration having an optimum bump location and a bump height of 0.3%. It suggests that the shock structure consists of a weak inclined supersonic / supersonic shock originating from close to the leading edge of the bump and intersecting the normal shock wave. Important wave drag reduction and total drag reduction have been obtained on this configuration as shown in Figure 15b.

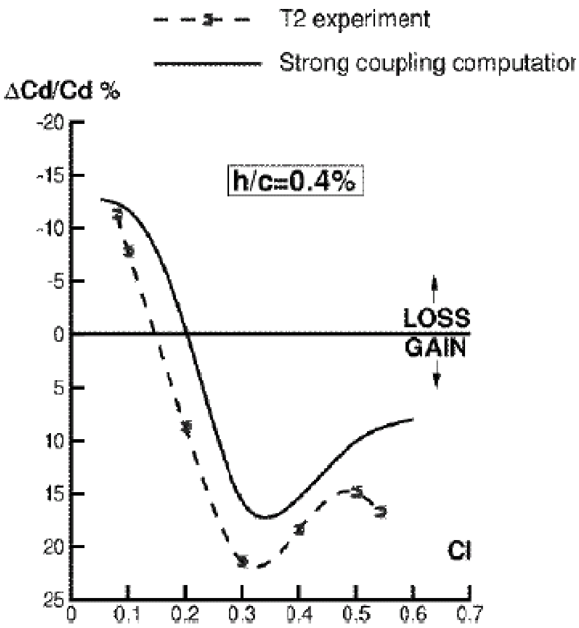

Figure 15b: Measured and computed drag reductions on a 2D laminar airfoil. M=0.77, Re=6×10^6.

New drag reduction technologies

Very recently, as an attempt for supersonic drag reduction in the scaled supersonic experimental airplane project, Japan Aerospace Exploration Agency (JAXA) has developed an advanced drag reduction technique (Yoshida, 2009). JAXA's technique is based on an aerodynamically optimum combination of well-known pressure drag reduction concepts and a new friction drag reduction concept. The pressure drag reduction concepts are mainly grounded in supersonic linear theory and involve the application of an arrow planform, a warped wing with optimum camber and twist, and an area-ruled body. The friction drag reduction concept is a world-first technical approach that obtains a natural laminar flow wing with a subsonic leading edge at supersonic speed. An ideal pressure distribution is first designed to delay boundary layer transition even on a highly swept wing, then an original CFD-based inverse design method is applied to obtain a wing shape that realizes the pressure distribution. Flight data analysis and comparison of flight data with CFD design data validated the drag reduction technique both qualitatively and quantitatively.

Figures 16 and 17 after Yoshida (2009) show each designed configuration and its corresponding drag characteristics. By comparing with a reference configuration designed with a flat Ogee planform and a non-area-ruled body, the effect of each drag reduction concept was estimated as follows: an approximately 11.5 counts reduction due to the warped arrow wing, an approximately 6.7 counts reduction due to the area-ruled body and an approximately 9.1 counts reduction due to the effect of the NLF wing assuming 60% laminar flow over the upper surface.

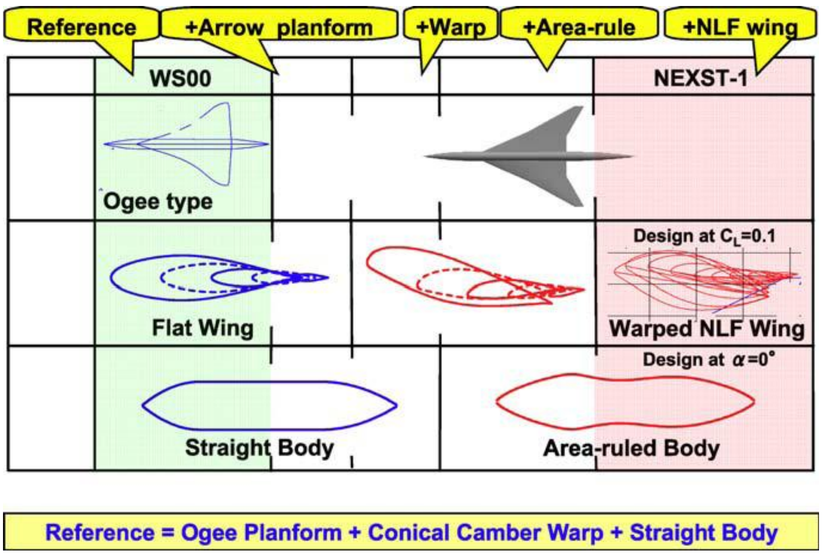

Figure 16: Each configuration based on each drag reduction concept

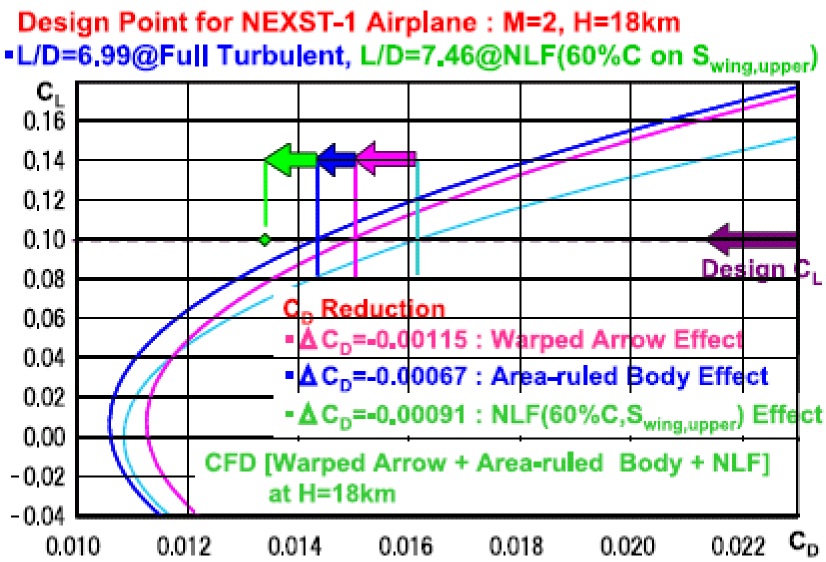

Figure 17: Each drag reduction effect on each configuration.

There are at least four major alternative supersonic transport transport (SST) approaches (besides derivatives of 1960s era shapes). These include multistage aircraft, strut-braced wings, favourable wave interference and supersonic leading edge wings.
As stated by Bushnell (2003), a possibly viable alternative configuration for the conventionally sized long-haul conventional take-off and landing (CTOL) transport mission is the strut-braced wing. Strut-bracing allows thinner, smaller chord, lower sweep and higher aspect ratio wings. The smaller chord, leading edge radius and sweep have a favourable influence upon HLFC, increasing the amount of wetted area laminarized and reducing suction mass flow and roughness sensitivity as well as increasing attachment line stability. Other `strut-related' benefits include large drag due to lift reductions from the wing tip engines and greater span enabled by the strut, as well as large wing weight reductions. Circulation control, powered by the auxiliary power unit, could be utilized on a conventionally sized tail to work the engine-out problem. All these benefits produce very large increases in the lift-drag ratio and range at cruise.

Figure 18: Strut-braced wing concept

Strut-bracing for the SST allows very significant reductions in both vortex and wave drag due to the lift via an extreme arrow configuration and could be favourable to LFC via reduced chord Reynolds number (Pfenninger, 1977; Pfenninger and Vemuru, 1988). Natural laminar flow fuselages, perhaps with heating strips for enhanced performance, are of special importance for the SST, where synthetic vision offers the possibility of fairing windshields, the fuselage projects far ahead of the wing and the doors can be located relatively far aft. Additional transition delay would be available from fuselage nose bluntness tailoring.
The other major alternative configuration for the Jumbo aircraft mission is some variant of the spanloader or blended wing-body, the latter being sometimes referred to as the `civilian B-2'. The major impact of these configurational approaches upon drag reduction is a sizeable decrease in wetted area as the load-carrying and lift-carrying elements are combined. Unfortunately, the large sweep required to control shock drag associated with the requisite thick wing sections (for within-wing passenger transport) are detrimental to HLFC. In research on other configuration alternatives, it has been suggested that forward swept wings would reduce the effective sweep angle, thereby alleviating somewhat the cross-flow laminarization problem (which also mitigates spanwise contamination).
All of these advanced configurations, CTOL and SST, provide large potential drag reductions, along with many other benefits. They deserve serious research effort(s) utilizing modern design optimization technology (e.g. see, Sevant et al., 1999; Oser, 1995; Gage, 1995; Zedan et al., 1994; Martins and Catalano, 1998).

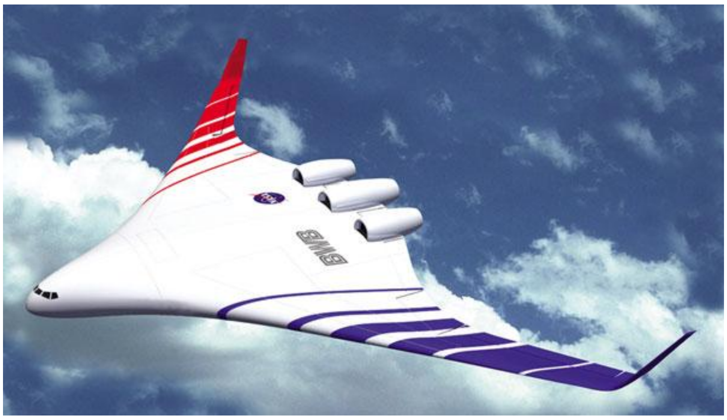

Figure 19: Blended wing-body aircraft.

Reduction of boundary layer separation regions can also be obtained by an active system avoiding the drawbacks of vortex generators which increase the drag coefficient at low lift coefficient. Emerging miniaturized electronics and associated Micro-Electro-Mechanical-Systems (MEMS) technologies can be used to control the flow through an active manipulation of the coherent structures that are developed in the near-wall region of the boundary layer (Reneaux, 2004). Fluidic actuators such as suction/blowing devices offer many perspectives (Warsop, 2001; and 2003). However the concept is not yet mature and the development of this new technology can be pushed by the use of computational tools such as the Large Eddy Simulation (LES). It is expected that high-lift devices can be improved with this technology particularly in landing conditions and that drag reduction can also be obtained through the use of MEMS in the design optimization process.

Concluding remarks

For past few years, drag reduction studies have been oriented towards the investigation of the potential benefits which can be expected by applying various new technologies. The different concepts which have been presented could have the following average potential drag reduction:

- The turbulent skin friction drag reduction by the use of riblets (about 1-2%)
- The hybrid laminar flow technology (about 10%) ;
- The innovative wing-tip devices (about 2%) ;
- The shock control and trailing edge devices which allow to adapt the wing geometry to flight conditions (variation of the lift coefficient or of the Mach number), (about1%) ;
- The sub-layers vortex generators and MEMS technology which can be used to control flow separation.

These technologies can be associated to maximize the drag reduction. Future laminar flow aircraft can, for example, be fitted with wing tip devices and equipped with riblets in the rear part of the wing upper surface.

Several other turbulent drag reduction techniques can provide localized drag reductions. Their utilization is a function of system/configuration design details. Especially interesting in terms of drag reduction performance is the somewhat newer approach involving oscillatory transverse surface motions.

Various alternative advanced configuration concepts have been suggested which could provide significant to dramatic drag reduction overall as well as sizeable improvements in other aircraft figures of merit, such as gross take-off weight (GTOW). These alternatives include spanloaders, strut-braced wings, favourable wave interference and multistage aircraft.

The use of flow control will reduce the system complexity and the structural weight of the aircraft by the use of a smaller wing, a reduced sweep, a thicker wing or smaller and simpler high-lift systems. It is then important to model the effects of sub-layer vortex generators and synthetic jets with the CFD approach. This will allow the gain in performance to be estimated.

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Some applications are borrowed from the work of Reneaux (2004) and Bushnell (2003), and the author has benefited from them in this paper.

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