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VISCOUS DRAG REDUCTION IN AERONAUTICS
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ABSTRACT

Paper summarizes the state of the art in aeronautical viscous drag reduction across the speed range including natural laminar flow, laminar flow control, transition delay at hypersonic speeds and both passive and active turbulent drag reduction. Up through transonic speeds LFC is essentially "market ready" for most applications, as is riblets for the turbulent case. The remaining issues regarding these approaches concern questions of economic feasibility and the enhancement thereof. Paper also describes several emerging drag reduction approaches which are either active or reactive/interactive and the synergistic combination of advanced configuration aerodynamics with viscous drag reduction approaches.

INTRODUCTION

Aerodynamic drag is historically and conveniently separated into pressure or form drag [including interference and roughness drag], drag due to lift, shock or compressibility drag, and viscous or skin friction drag. Except for helicopters and military aircraft with external stores which can still exhibit appreciable levels of pressure drag, cruise drag for most subsonic aircraft consists primarily of friction drag and drag due to lift. For supersonic cruise aircraft, shock drag is the same order as [vortex] drag due to lift and friction drag, and assumes increasing importance as Mach number increases into the hypersonic arena.

The importance of and possibilities for viscous drag reduction were first seriously identified in the late 1930's, primarily as a result of two developments, successful drag "cleanup" 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 a 'given' beyond a Reynolds number of 2×10^5. Such a low transition Reynolds number was common in the wind tunnels of the period, which typically exhibited stream turbulence levels the order of 1 percent or greater. In flight and low disturbance tunnels, with stream disturbance levels the order of .05 percent, transition could occur well beyond Reynolds numbers of 2×10^6. The earliest research in aeronautical viscous drag reduction addressed the issue[s] of transition delay, initially via favorable pressure gradients on the essentially unswept wings of the day. Later, in the 1950's and 1960's, suction was utilized in research efforts to address the cross flow instability problem endemic on swept wings. Such wings, along with jet engines, enabled the current long haul civil aviation 'golden age' where, since the 1950's, aviation has replaced steamships and rail for passenger long haul.

This early research on transition delay was termed laminar flow control, with "natural" laminar flow defined as 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., U.S., 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] [Ref. 1]. However, the critical [for application] maintenance and reliability issues were never, at least up to the mid 1960's, successfully addressed. Various "real world" problems such as insect debris and other roughness and occurrence of waviness under loading, all exacerbated, initially, by low cruise altitude/high unit Reynolds number in the 1940's and early 1950's [and later by wing sweep], kept laminar flow control ['LFC'] in the category of a "laboratory curiosity". The continued availability of inexpensive petroleum in the 1960's, coupled with these unresolved reliability and maintainability issues caused an essential hiatus in LFC research from the mid 1960's to the mid 1970's, closing off what might be termed the initial period of viscous drag reduction research [which was almost exclusively LFC-related, see Ref. 2]. The research in turbulent drag reduction [TDR] during this period from the late 1930's to the mid 1960's 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 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.

The Arab oil embargo of the 1970's and the consequent increases in the price of jet fuel triggered a renaissance in viscous drag reduction which is still extant. This renaissance began, for both LFC and turbulent drag reduction, at the NASA Langley Research Center. Technology and approaches initially explored/developed at Langley in the 1970's to early 1980's have spread throughout the world, with active viscous drag reduction programs now underway, for example, in Japan, China, France, Britain, Germany, and Russia, as well as in the U.S. [e.g., Refs. 3-6]. The Langley viscous drag reduction [VDR] efforts begun in the 1970's focused from the first on two key issues 1) maintenance and reliability concerns for LFC on supercritical, swept airfoils [applicable to both CTOL and subsonic-leading-edge SST/HSCT aircraft] and 2) possibilities that non-smooth surfaces with specific geometric characteristics could provide, via interference with the turbulence dynamics/ coherent structures, turbulent drag levels below canonical smooth surface values. By the late 1980's both of these major issues had been addressed, the first via several flight experiments and the second via the invention of several non-smooth turbulent drag reducing surfaces, notably "riblets," along with flight tests thereof.

Much of the technology developed during this remarkably fruitful period in VDR [from the mid 1970's to the late 1980's] is documented in several excellent books, courses and conferences [e.g., References 7-21]. The purpose of the present report is to briefly summarize and analyze VDR research with emphasis on developments since the late 1980's in the areas outlined on Table 1 and provide some conjectures concerning future possibilities including configuration issues/synergisms. The importance of this technology arena is attested to by the direct benefits which can accrue in terms of energy conservation/

pollution reduction, national defense and industrial competitiveness/"economic warfare" as well as the breadth of application possibilities--aircraft across the speed range, missles, munitions, and launch vehicles, as well as a wide range of non-aeronautical uses. Examples of potential benefits from VDR research include 25 percent [or more] reduction in aircraft fuel burn and payload doubling for air-breathing launch vehicles (see References 22 and 23 for typical LFC application benefits). VDR is a major component of a rapidly growing field of technology which might be termed "designer fluid mechanics" and which includes, besides VDR, mixing enhancement, separated flow control, vortex control, turbulence control, anti-noise/other favorable wave interference and even designer fluids. From a systems/design point-of-view benefits from viscous drag reduction can be utilized for one or more of the following; longer range, reduced size/weight, increased speed, reduced fuel consumption/pollution and reduced initial unit cost. On the military side additional benefits can include decreased observability and increased sensor and weapon effectiveness.

LAMINAR FLOW CONTROL

The nominal transition process involves initial disturbance fields which are internalized, via a process termed "receptivity" by the body viscous flow and subsequently amplified by various linear and non-linear mechanisms at rates dictated by details of the mean flow development and the nature and magnitude of the initial/internalized disturbance fields. The parameter space is immense. Initial disturbance fields can involve both stream and vehicle-induced fluctuation fields and can include modes such as acoustics, dynamic vorticity, entropy spottiness, particulates, vibration, electrostatic discharge, concentration fluctuations and even brownian motion. Several of these disturbance fields are generally present simultaneously. Receptivity and amplification behavior can be influenced to first order by parameters which affect the mean flow development such as spatial distributions and level of Mach number, pressure gradients, wall temperature, angle of attack, wall mass transfer, roughness/waviness, curvatures, chemistry/energy level, bluntness, shock waves, etc., with different functional dependencies for the various linear and non-linear instability modes [e.g., Reference 24].

The fundamental issue regarding LFC concerns the identification of the mechanisms responsible for transition in the particular application, especially whether linear instability mechanisms dominate or whether non-linear/by-pass mechanisms are the primary operatives. The term "by-pass" transition is used to refer to any transition process not dominated by a single linear instability mechanism [See Reference 25]. 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 by-pass transition be identified and rendered harmless. As an example, the swept leading edge case has been approached by "bleeding off" the contamination and establishing laminar attachment line flow. This approach may not be feasible for the larger leading edge radius associated with the 600-800 pax transports now on the drawing board and active transition control may be required in the attachment line region also. Once by-pass conditions are circumvented the LFC problem becomes one of stabilizing linear modes. Typical modes and their regime of dominance include; T-S [M< 0(4), 2-D mean flow], Mack modes [M> 0(4), 2-D mean flow], cross flow [3-D mean flow across speed range] and Gortler [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 T-S and Mack modes are, in general, damped by increasing Mach number, whereas the cross flow and Gortler 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 Gortler modes are relatively insensitive to wall temperature. A further example of differing transition delay sensitivities concerns the effect of favorable 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.

Three transition delay/LFC aeronautical applications are currently under active study-subsonic aircraft of all sizes, supersonic transports and aerospace planes/air-breathing launch vehicles. The status and outlook for laminar flow control/ transition delay will be discussed in terms of these three application areas.

Subsonic/Transonic Aircraft LFC

CTOL LFC offers the largest perspective gain in cruise efficiency of any foreseeable single technology improvement/ application for this class of aircraft. To minimize fabrication and inspection problems the currently favored "first step" in the application of LFC to moderate-to-large CTOL transports is a "hybrid" system which utilizes suction near the leading edge (ahead of the front spar) to control cross flow with a subsequent mild (to minimize further cross flow growth) favorable pressure gradient to control T-S waves over the wing box or "wet" (fuel tank) portion of the wing. An even further fall-back position vis-a-vis application of suction LFC is to apply suction control to the upper wing surface only. This approach still provides significant fuel savings as the wing upper surface has the highest edge velocity and hence highest friction drag. In addition the reduction in lower surface smoothness requirements enables [cruise] stowage of insect protection devices deployed during takeoff, wing inspection from, and inspection panels in, the lower surface and reduced initial and maintenance costs. This retrograde approach also removes much of the laminarized region from the foreign body damage which can occur on the lower surface during takeoff and landing.

Real world influences upon the functionality/operability of CTOL LFC systems include surface roughness/ waviness, joints and steps including aeroelastic deformations thereof, flight through ice clouds (less than 50-mile visibility has affected LFC system performance), acoustic fields caused by both engine and airframe and suction related issues such as plenum acoustics, and localized vorticity generation including clogging effects. Of particular concern is recent information regarding possible hypersensitivity of certain swept leading edge regions to even minute roughness with particular spanwise wavelengths [Reference 26]. Experience thus far for the CTOL case, both flight and wind tunnel, indicates that laminar flow can be obtained on modern airfoil surfaces to mid-chord and beyond. The major concern is not, can laminar flow be obtained, but rather can it be maintained, reliably, in an economic fashion. In fact, economics is at the root of the decisions as to whether or not to employ LFC in aeronautics, the economics of the maintenance issues and, more importantly, the economics of the initial capitol cost of the system since over half of the direct operating cost of a new aircraft is the cost of funding to purchase the aircraft. In general, LFC is not a retrofittable technology and current fuel costs are such that initial cost issues are overriding.

The major residual technical transition-related issues for subsonic transport LFC include the question of cross flow/T-S interaction, particularly in the wing-box area, wing surface temperature history/influences and laminarization of the large radius leading edge regions associated with 747 and larger aircraft where, for the first time, we have to address a leading edge which is, without stabilization, turbulent even when spanwise contamination is accounted for. Maintenance suction and/or surface strip heating may be required for transition delay over the mid chord region on these large-to jumbo transport aircraft [due to high mid-chord Reynolds numbers]. Also of technological interest is the extent to which the current criteria for roughness, hole size etc., can be relaxed to reduce manufacturing cost. For smaller sized, lower speed aircraft with low-to-moderate sweep the state of the art is such that "natural" LFC is now a fact, due primarily to improvements in materials and fabrication technology which have provided improved surface finish. In general, a surface which is smooth enough to avoid roughness drag increases in a turbulent flow is also suitable for LFC.

An additional issue regarding the application of HLFC is the requirement for some means of "certifying" the aerodynamic performance on the ground with respect to stability and control, off-design, etc. This function is conventionally carried out in transonic wind tunnels, the issue in this regard for HLFC is the presence of large amplitude acoustic disturbance fields in such facilities which have a first order influence upon the functionality of the HLFC System. These stream acoustic fields have two major sources, diffuser noise, much of which can be reduced with a choke downstream of the test section, and tones from the test section porosity, which can be only partially mitigated. If the walls are closed to reduce noise for HLFC testing, then each test condition/model/ orientation etc., will require a new [and very expensive] liner-which is not a feasible approach. Several alternative approaches to this problem are under consideration including obtaining data at low Reynolds number where the HLFC system will still function even in the presence of high stream acoustical disturbances and using CFD to extrapolate the results to flight, and, alternately, utilizing suction under the turbulent boundary layer to simulate the correct momentum thickness etc., entering the airfoil shock interaction regions. Other aeronautics issues for HLFC include ice protection, high lift and insect protection, all of which are interrelated.

Rather extensive, and successful, recent LFC flight experiments have now been conducted, originally in the U.S., and later in Europe. References 27-29 provide convenient summaries of these experiments. Flight studies conducted thus far include those involving the NASA Jetstar suction leading edge, which performed very successfully in simulated airline service, both summer and winter, providing major contributions toward the critical maintenance and reliability issues [see Refs. 30 and 31]. In particular this experiment proved the feasibility of a "practical" suction surface [perforated titanium] and the incorporation of suction and de-icing systems in a transport-sized leading edge. In another flight test passive gloves on an F-14 provided transition data at various sweep angles, altering the basic linear instability mechanism from T-S to cross flow on the same test article at similar free stream conditions. Probably the most dramatic flight tests were those conducted on a 757 transport with first passive and then active/"hybrid" gloves. Flight experiments indicate that, for the passive case, wing transition Reynolds numbers of order 15 million are achievable for sweep angles up to the order of 15 degrees, decreasing to the order of 5 million at 35 degrees of sweep. Extrapolation of the hybrid/suction flight data to a new aircraft indicates a 15-percent increase in lift-to-drag ratio if suction is utilized for wings, empannage and nacelles. See References 22 and 33 for the hybrid approach as applied to nacelles. This 757 research showed that laminar flow control was feasible on modern wings with minimal modifications to airfoil shape and surface quality even in the presence of wing-mounted engines. Some earlier studies had assumed that rear engine aircraft would probably be required for successful exploitation of laminar flow transport drag reduction.

The bottom line for CTOL LFC application is that the outlook is significantly improved compared to the 1950's and 1960's, due primarily to improved surface materials and fabrication techniques and a reduction in smoothness requirement due to higher cruise altitude/lower unit Reynolds number. Another major contributor to this improved outlook is the advancements in the e^n class of computational tools for swept wings including initial consideration of roughness effects [Reference 32]. This has also allowed consideration of fuselage laminarization [e.g., References 34 and 35], the eventual application of which will be aided by a trend/initial thinking regarding replacing windows with video screens on the seat backs.

A conceptual "end point" CTOL LFC design has been proffered by Dr. Pfenninger et. al., [Reference 36]. After noting that CTOL cruise performance is maximized at conditions corresponding to near equality of skin friction drag and drag-due-to-lift, they suggest that strut bracing for high speed, long haul transports could offer revolutionary performance when utilized in connection with LFC. Strut bracing allows not only greater span/higher aspect ratio/reduced drag-due-to lift [to correspond to the skin friction reduction of LFC] but also allows thinner wing sections, reduced wing sweep and reduced wing chord-all of which greatly enhances LFC performance. Aggressively designed strut-braced transports could, according to Reference 36, attain cruise L/D values in the range of 40^+, the order of twice the current state of the art. While utilized on commuter aircraft, strut bracing has not been applied to large transport aircraft, probably for two reasons-concern over the wing-strut-fuselage interference drag at near sonic conditions and an aversion to further increases in span due to physical airport gate constraints. CFD has now advanced to the point where the interference problem could certainly be worked, perhaps even yielding a "favorable interference" result. The airport gate issue is more serious but could be approached, according to Dr. Pfenninger, by alternating his high wing, strut-braced machines with conventional aircraft in a "nested" arrangement. An alternative approach to the gate problem is to utilize the structural benefits of strut bracing to install tip region mounted engines which, from Whitcomb, can provide levels of drag-due-to-lift reduction on the order of what can be obtained with increased span.

Another fascinating possibility for CTOL LFC is the augmentation of hybrid/leading edge region suction with [chordwise] narrow heated strips to help control T-S growth over the wing box. This concept was pioneered by the Russians [e.g., References 37-41, see also reference 42] and utilizes the stabilization from wall cooling via upstream wall heating such that the flow is heated and an ambient temperature wall downstream now acts as a cold wall. Since local heating is destabilizing in a [first/T-S mode dominated] gas flow, the narrow heating strips should be placed in a stable region for T-S waves, i.e., in the leading edge suction region, where the anti-icing system may provide a synergistic benefit in this regard. This approach could obviously also be used to laminarize nacelles which would be especially convenient since an obvious source of thermal energy for this purpose is the engine coolant process[es].

HSCT Laminar Flow Control

For supersonic aircraft, the usual LFC techniques of choice are suction and wall cooling [see Reference 43]. The wall cooling approach has been demonstrated by the Russians up to 34 million Reynolds number at supersonic speeds [Reference 44], but the technique is limited to non-hypersonic aircraft and regions of small cross flow as cooling does not significantly damp the cross flow instability [Reference 45]. Cooling does damp the T-S mode including attachment line linear instability, but destabilizes the higher Mach number Mack modes [Reference 46].

The reduced payload fraction of an HSCT [formerly SST] aircraft compared to the subsonic case places an even greater premium upon LFC, which becomes almost an "enabling" technology. Estimates indicate that LFC over half of the [large, highly swept] wings could increase the payload fraction by up to the 0 (50 percent). An additional benefit of LFC for the supersonic case is the reduced skin temperature resulting from laminar, as opposed to turbulent, Stanton number and recovery factor for radiation equilibrium. There are several very interesting design/performance synergisms associated with supersonic LFC including reduced parasitic friction drag for wetted area increases associated with favorable interference wave drag reduction approaches, turbulent skin friction reduction via slot injection of LFC suction mass flow, operation of the suction system at higher suction rates during takeoff as a leading edge high lift device, along with subsequent injection of this mass flow for drag-due-to-lift reduction and/or trailing edge region separation control and, finally, LFC benefits during subsonic overland flight [required due to sonic boom restrictions] [See References 21 and 47-49].

There are several fundamental differences between subsonic and supersonic LFC. These include for the supersonic case a greatly diminished data base [ground and flight], much larger sweep [for volume wave drag reduction] and therefore greater cross flow and consequent greater suction requirement, efficient acoustic radiation from the turbulent fuselage boundary layer onto the wing [which necessitates even larger suction rates] and the prevalence of curved shock waves which constitute an additional source of vorticity and enhancement thereof. A favorable influence of increased Mach number is reduced roughness sensitivity for the case of two-dimensional mean flow with small streamline concave curvature, i.e., in the absence of cross flow and Gortler modes. Due to the relative immaturity of supersonic vs. subsonic LFC there are extensive additional research requirements for supersonic LFC such as perforated suction surface flow physics, including the influences of weak shock waves produced at each suction site, wing-body juncture region turbulence contamination control along the wing chord-of special importance due to the high wing sweep and low aspect ratio, fuselage noise radiation influences, and even the basic instability physics of high speed attachment lines.

Also required are further investigations of the compatibility of HSCT wing designs which are synergistic in terms of LFC and leading edge thrust, as well as research on technology to reduce the required suction mass flow [including utilization of passive bleed where possible and wall cooling or "subcritical" heating strips]. Suction minimization is particularly important for the supersonic case due to the high suction rates required. Reductions in those rates would allow smaller/lighter suction system components, reduced suction system energy usage, reduced laminar skin friction and reduced sensitivity to surface roughness. Safety and stability and control/certification will also have to [ultimately] be addressed.

Dr. Pfenninger's research group at Northrup conducted a series of supersonic suction LFC tests in the conventional [i.e., noisy] AEDC tunnels in the 1960's [reviewed in Reference 1]. In spite of the tunnel noise and high unit Reynolds numbers of these experiments, Dr. Pfenninger was able to laminarize the flow over various configurations [body of revolution, plates with and without weak shock interaction, wings swept ahead of and behind the Mach line] essentially up to the facility Reynolds number limit. These tests proved that supersonic LFC was attainable, but the experiments were limited in that slot rather than perforated suction surfaces were utilized and the model leading edges were thin, i.e., attachment line laminarization was not studied. The maximum Reynolds number at which laminar flow was obtained [limited only by facility capability] was the order of 25 x 10^6 for swept wings and 50 x 10^6 for 2-D mean flow.

Langley is currently involved in a series of LFC flight tests on the wing of the F-16XL Aircraft [Reference 51 and 52] with backup research studies of the leading edge region in the Langley and Ames quiet tunnels. Objectives of this flight test [at M to o[1.7]] include laminar flow to 50-percent chord using leading edge region [and extended] suction panels. This flight test is, however, limited to a chord Reynolds number considerably less than the 140 x 10^6 for "full scale" HSCT configurations. A Russian TU-144 Aircraft is under study as a possible higher Reynolds number follow-on flight test bed. A large scale Mach 2.4 supersonic quiet tunnel with quiet test core Reynolds numbers on the order of 80 x 10^6 is also under consideration for supersonic LFC risk reduction.

Several "enabling technologies" are now in place or emerging which should greatly contribute to the feasibility of supersonic LFC including the success of, and experience gained in, the NASA subsonic LFC Research Program and the development of supersonic quiet tunnels, "smooth" surfaces for high speed aircraft and the e^n and "beyond" design tools. Application of supersonic LFC to a "conventional" HSCT configuration indicates an 8 percent to 10-percent net benefit in GTOW reduction/cruise drag. This is a tremendous benefit level for this class of aircraft. More unconventional supersonic applications of LFC, again by Dr. Pfenninger, [Reference 50] to a strut-braced high aspect ratio arrow wing HSCT configuration indicates phenomenal performance levels. L/D~ o [15 to 20] vs.

the 9 to 11 of conventional configurations [with LFC].

Transition Delay At Hypersonic Speeds

For over 35 years mankind has flown rocket powered slender RV's and/or blunt capsules very successfully in and through the hypersonic regime up to Mach 35 [Apollo lunar return] with very few major problems vis-a-vis transition. This was due to necessarily conservative vehicle design approaches, especially with regard to thermal protection systems. One such conservatism, the assumption of early transition, was required by vehicle surface roughness engendered either by design details to handle thermal stresses, heat shield mass loss, or operational items which impact surface quality such as antennas, handling plugs, etc. This situation vis-a-vis transition in the hypersonic arena is necessarily changing with the advent of research on air-breathing launch vehicles. Such craft are slender 3-D lifting configurations where the forebody is an external inlet with concave longitudinal surface curvature and adverse pressure gradients. The performance requirements for these vehicles necessitates transition delay by "design" for inlet [forebody] surfaces. Preliminary estimates indicate large [up to (50 percent)] changes in payload fraction as a function of transition location. Hypersonic transition physics over such surfaces is both rich and ill-maped. Linear modes which could be present include T-S, 2nd mode, cross flow, Gortler, "supersonic modes," and combinations thereof. Additional concerns include shock interactions [Reference 53], flow chemistry and bluntness effects, the latter of which influences not only the local Mach and Reynolds number [via "entropy swollowing"] but also, due to shock curvature, induces additional off-surface vorticity which can undergo destabilization with subsequent interaction with the body boundary layer [References 54 and 55].

Obvious approaches to transition delay for hypersonic air-breather forebodies [see also Reference 43] includes reduced cross flow [technique utilized in the space shuttle design] and Gortler mode amplification via " 2-D [as opposed to axisymmetric] forebodies and increased longitudinal radius of curvature, along with "smooth" surfaces [$R_k < o[50]$] to avoid roughness-induced by-passes. Transition delay for the inlet cowl and sidewalls is fostered by delaying shock-boundary layer interactions [usually acts as a transition trip, requires extensive further research] avoiding leading edge contamination via reduced sweep and leading edge radius, and reducing corner region disturbance growth via suitable filleting. A transition delay technique noticable by its absence from this listing is suction. At hypersonic speeds the air flowing around the vehicle is simply to hot to take inside. Another transition delay ploy for high speeds is to increase nose bluntness. Unfortunately, while this will appreciably delay transition in many flow situations the accompanying increase in wave drag contravenes its' use.

The application of these transition delay precepts for high Mach number air-breathers is enabled by very successful research over the last decade in several areas including extension of the e^n method to the hypersonic, real gas case for the known applicable linear modes, development of M= 6, 8, and 18 quiet tunnels, studies of roughness issues at high speeds and calibration of the n-factor approach with high-speed flight [up to M~20] and quiet tunnel data [Reference 56]. Studies thus far in the quiet tunnels indicate that, for ground facilities at high speeds, quiet flow is required for accurate determination of influences of most configuration geometric changes, angle of attack and wall temperature influences, bluntness effects, and the correct location and extent of the transitional flow region [i.e., that region lying between transition and "fully turbulent" flow]. At hypersonic conditions this transitional flow region can subsume extensive regions of the wetted surface. Quiet conditions are often not essential for high speed swept leading edges, large roughness influences and cross-flow dominated transition.

Reactive/Phase-Locked Transition Delay

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 which "cancels" the growing waves. Such an approach is obviously considerably more complex in terms of practical realization than the methods discussed thus far, all of which influenced the mean flow to reduce growth rate as opposed to directly acting upon the dynamics. Such a dynamic wave-canceling 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. [e.g., Reference 57]. Additional "enabling" technologies for this approach to LFC include the miniaturization of both processors and various types of sensors and actuators which are products of the on-going "electronic revolution." [e.g., MEMS, micro-electro-mechanical systems]. The work on wave cancellation for transition delay is reviewed in Reference 58 for the initial period of research [the 1980's] including extensive soviet work in the area. The conclusions from this initial period indicate that the basic approach "works," both experimentally and computationally, for "simple" wave systems at linear amplitudes if the control is applied early in the amplification process. Since disturbance waves are more or less continuously regenerated, such a control strategy would have to be implemented everywhere downstream of the neutral curve[s].

A key difficulty with the wave cancellation approach is the existence, in applications, of complex initial disturbance fields and multiple [usually 3-D] wave systems. Recent research has begun to address some of these "real life" issues [References 59-65], and their conclusions as to the eventual usefulness of this approach are optimistic. However, wave cancellation has, at least to this point, not been demonstrated to high Reynolds number on an aircraft wing in the presence of "natural"/flight-like initial disturbance fields. Until it is, the technique remains a laboratory curiosity, albeit with interesting promise. The issues of cost, maintenance, safety, efficiency, reliability, etc., for such surfaces have not, to this point, been addressed.

TURBULENT DRAG REDUCTION

Turbulent drag reduction 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 missles, which also fly in the "bug layer"]. Additional cases where LFC is contravened include surfaces with large inate 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 "by-pass" 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 Cf reductions of 5 percent to 30 percent vs. the 50 percent to 80 percent available from LFC.] See References 10 and 66 for discussions/reviews concerning the general problem of TDR in external flows. A successful campaign to reduce turbulent drag is one which 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-far larger than the original friction drag. The techniques discussed herein can, to the best knowledge of the author, provide net reductions in drag as well as local reductions, albeit sometimes after moderate-to-considerable system redesign.

The "point of departure" for turbulent drag reduction in aeronautics is the definition of turbulent friction drag as the area integral of the local skin friction coefficient multiplied by the dynamic pressure. From this definition it can be seen that turbulent drag force can be lowered by reducing, in a net fashion, combinations of wetted area, Cf, and local dynamic pressure. Wetted area reductions are available from, for example, use of active controls or thrust vectoring to allow reductions in control surface size/wetted area, as well as from inventive/innovative configuration approaches. It should be noted from the outset that turbulent drag reduction [TDR] in aeronautics is very different from the hydrodynamic case, where truely huge reductions are readily available via surfactants, polymers, microbubbles/surface boiling and MHD. Such approaches are not applicable to the case of airflow at usual temperatures and pressures.

This TDR discussion will address the various extant approaches grouped under the headings of 1) reduction of near wall mean longitudinal momentum and 2) alteration of turbulence structure via both active and passive means. In general, TDR methodology can be passive, active but steady state, and active-dynamic both phased with, and independent from, the turbulence dynamics. In some sense, even a fixed geometry modification produces a dynamic interaction with the turbulent motions in that they are themselves dynamic. Reduced wetted area approaches will be discussed in a subsequent section which addresses configuration optimization for VDR. Many of these techniques also provide alternative benefits in the areas of acoustics, [self/pseudo and radiated], heat transfer control, sensor improvements and propulsor performance.

TDR Via Reduced Near Wall Longitudinal Mean Momentum

This class of TDR methods is based upon reducing the near wall region longitudinal momentum via direct reductions in wall region longitudinal velocity and/or density. Probably the earliest approach considered was investigated as a result of attempting to avoid separation-utilization of adverse pressure gradients. Turbulence intensity is increased but skin friction is reduced, with the end point being flow separation. The trick is to not accrue the large pressure drag associated with the concomitant increase in displacement thickness for the subsonic case by not approaching the separated flow condition. In supersonic flow this increase in displacement thickness can actually produce a favorable reduction in wave drag. The premier application of this method is to high performance airfoils [e.g., Reference 67]. See Reference 66 for further discussion of adverse pressure gradient possibilities which are, admittedly, a local "fix" to the friction drag problem.

Another "local" approach is the use of surface heating, which directly reduces wall region density/longitudinal momentum. The use of heating is obviously contingent upon the availability of "waste heat," e.g., from engine cooling. The application of this technique to, for example, engine nacelles, would necessitate a major change in the cooling technology for gas turbine engines. Boundary layer "thickeners" also provide reduced turbulent drag. Realizations of this approach vary from simply increasing vehicle size/ Reynolds number to the employment, on axisymmetric bodies, of a small diameter nose extension with considerable length but small wetted area to "age" the boundary layer [see Reference 66].

One of the major, essentially untapped in practice, techniques to reduce turbulent drag via reduced near wall longitudinal mean momentum is wall injection, either normal or tangential [wall wake]. Limited information indicates that, on a per mass basis, tangential injection is somewhat more efficacious for TDR. The amount of drag reduction available is well known [e.g., Reference 68, see also Reference 66], and large. What has mitigated against the use of this approach thus far is, firstly, that this is an "active" method involving significant changes in current practice and, secondly, the requirement for a "low-loss" source of air for injection. Simply taking air on-board via ram devices with their attendant ancillary drag does not yield a net benefit.

There are two sources of injectant air for TDR which are [relatively] low loss and which can, in a systems sense, provide net benefits. These sources are inlet bleed air from supersonic inlets [utilized for separation control in shock interaction regions] and the suction air from LFC Systems. A third, relatively minor, air source is the efflux from the cabin environmental control system. Preliminary estimates indicate that LFC suction air injected from one or more slots on the forward portion of the fuselage can provide up to a 10 percent fuselage skin friction reduction. Estimates for the inlet bleed air source indicate possibilities for order of 30 percent plus reductions in nacelle turbulent friction drag. [In addition to the already mentioned reduction in shock wave nacelle closure drag from the attendant increase in displacement thickness.] This utilization of bleed air for TDR could significantly mitigate a current problem with this approach to inlet flow control-"bleed drag," which can be as high as 3 percent to 5 percent of airplane drag [Reference 47].

An alternative and much farther term approach to slot injection TDR is to inject helium gas at nearly local stream speed [to reduce mixing] near the front of the fuselage and utilize the reduced near wall density from the lower molecular weight gas to accrue a sizable local fuselage TDR [o[70 percent]]. This would only be feasible if a cryogenic fuel were available to provide a means of separating the helium/air mixture near the rear of the fuselage so that the helium could be recycled/reused. One of the results of such a separation process would be liquid air which could be easily pressurized for subsequent use in a [very different] propulsion system, obviating the need for the current multiple axial flow compressor stages [i.e., variant on a LACE cycle].

TDR Via Passive Alteration Of Turbulent Structure

The premier approach to TDR in terms of research interest is riblets, small longitudinal striations on the surface which, via imposition of a spanwise viscous force, both reduce local skin friction and subject the turbulence dynamics to what is effectively a slip velocity. See References 69 and 70 for premier reviews of riblet research and technology. The net effect is up to a 10 percent skin friction reduction [Reference 71]. This reduction is obtained as a difference between two large changes, almost a doubling of wetted area and a large decrease in friction drag per unit area within the groove. The applicable groove size is the order of 15 "wall units," which for transport aircraft translates into grooves the order of .002 inches. The preferred realization/application technique has entailed utilization of a self-adhesive plastic film with the riblets molded into the surface. However, patents have been granted for several alternative riblet application techniques [laser cutting and fibrous pressed composites, Reference 72 and 73]. Research results obtained thus far, in what became a very extensive international effort after the original Langley work, indicate that the drag reduction performance is relatively insensitive to local flow yaw angle up to o[15 degrees] and moderate pressure gradients. Also, in studies thus far [including flight experience] riblets have not, somewhat surprisingly, appreciably affected wing flow separation behavior. Riblet performance is sensitive to the "sharpness" of the groove peaks. Riblet drag reduction is not, in general, observed in laminar flow and therefore the riblet interaction with the turbulence dynamics is a key issue. The order of 10-percent reductions in longitudinal turbulence intensity are typical over riblet surfaces.

Riblet films have been flight tested on several aircraft and in several countries. When sharply peaked film is used these flight tests, which were carried out at both subsonic and supersonic speeds, have been successful as have extensive [in time] flight experiments aimed at investigating the various maintenance and clogging issues [e.g., Reference 4]. From information available thus far, riblets appear to work across the speed range, at least into supersonic and possibly hypersonic conditions. This is reasonable in terms of the extremely near wall region "radius of action" for riblets, a region which is dominated by low-speed flow due to the no slip condition at the wall. Heat transfer to the riblet peaks becomes a problem in terms of survivability at very high speeds and will ultimately dictate the upper range of usability, speedwise. The riblet film is retrofittable, and has played a role in several well-publicized international sporting events including the Americas Cup and the Olympics. Besides direct [turbulent] skin friction reduction, there are several other benefits available from riblet application including reduced roughness drag via film surface "smoothing," reduced displacement thickness and consequent pressure drag reduction and conversion of pressurized fuselage leakage drag into a further drag reduction via film porosity and consequent spatial distribution of the {inadvertent} mass injection. In addition, the riblet film can be manufactured in various color schemes to save the weight, expense and mitigate the environmental issues associated with fuselage painting as well as retain sufficient transparency to allow structural inspections. There are also indications that riblets, while acting as a transition enhancer, can retard the development of fully turbulent [riblet-influenced] flow, i.e., they stretch out the transition process. This may be of particular interest for engine blade applications.

A key issue in the utilization of riblets for aircraft fuselages, empannage etc., is the application time and cost, including the cost of the capitol which the aircraft represents and which is a major direct cost in airline operations [Reference 74]. Major improvements in riblet application and removal technology are probably possible if the problem is seriously worked [e.g., high speed water jets for removal etc.]. As in the case of HLFC, the issue with riblets is not can net drag be reduced, but can it be accomplished economically, considering all of the initial and life cycle costs. A residual technical application issue is lightning strike effects and electrostatic charge buildup during flight through atmospheric particulates.

From the very first years of the riblet research effort, many attempts have been made to discover/develop alternative micro-geometries which would provide greater drag reduction than the order of 6 percent to 10 percent provided by riblets. Up to this point alternative configurations studied number in the 10's to upwards of 100. The essentially universal observation from this work is that many shapes with dimensions in the range of 5 to 30-wall units will provide net drag reduc-tion in turbulent flows with performance approaching, but unfortunately not exceeding, nominal riblet levels, Reference 75 describes one of the more recent configurations, which in this case was patented, but for which we do not yet have [open literature] performance data. The quest for more efficient micro-geometries is still on-going, but there are no particularly favorable [and verified] results [i.e., greater than 10 percent] known to this author. One possibly fertile area to explore in this regard is that of small-to-moderate sized 3-dimensional "bumps" which subject the near wall flow to a series of oscillatory [in space] in-plane curvatures [see Reference 87]. Examples of such surfaces include marlin [fish] skins and the 3-D surface patterns of Gao [Reference 76], whose results should be independently verified.

The other interesting passive approach to TDR via alteration of turbulent structure is utilization of in-plane and [concave] longitudinal curvature [Reference 66 and 77]. Such streamline curvatures can significiently reduce Reynolds stress and wall-skin friction. The obvious difficulty regarding application is the requirement for particular body geometry variations, which impacts the vehicle pressure field, etc. Therefore favorable streamline curvature is another local fix which can be optimized as allowed by the overall vehicle design constraints, [see References 78 and 79]. The longitudinal convex curvature influences upon wall turbulence are large, even very small amounts of flow turning will provide significant stabilization of the outer region flow structures [e.g., Reference 80]. The relaxation distance for such outer layer modifications is the order of 100 boundary layer thicknesses and therefore a local region of wall curvature can influence the wall friction far downstream. What is, however, worrisome, is that similar behaviors downstream of large eddy breakup devices{LEBU'S} are observed to have very little favorable influence on drag for the high Reynolds number [e.g., flight] case [Reference 81]]. The physics responsible for this reduction with Reynolds number in wall region influences from outer region changes is probably associated with the increasing wall-to-outer region scale mismatch with Reynolds number. In flight, the turbulence is produced near the wall at scales of the order of thousands of an inch in a boundary layer which could can be upwards of 1 foot or more in thickness.

The in-plane curvature effects are not yet as well mapped, but have been identified in both experiments and computations [e.g., References 82 and 83]. There has not been, as yet, a concentrated effort aimed at taking advantage of, and optimizing, in-plane curvature physics for TDR.

TDR Via Active Alteration Of Turbulent Structure

There are three extant approaches to active control of wall turbulence structure for VDR, steady state, dynamic but not phase locked and dynamic/ interactive/phased. A viable active steady state approach involves utilizing massive suction [up to o[1.6 delta]] to relaminarize the boundary layer by pulling all of the turbulent fluid into the body. This approach has been shown to work [i. e., reestablish laminar flow] in Reference 84, see also Reference 66. There are several key points to be made regarding this approach to TDR. First, once laminar flow has been re-established, provision must be made for "maintenance" LFC, as the VDR problem is now changed from one of TDR to one of LFC. Secondly, this method can perhaps best be utilized in situations such as on aircraft fuselages where the forward portion of the body has innate roughness elements which trip transition [windshield wipers, doors, windows, pitot probes etc.] but where conditions downstream of the nose region are relatively benign with respect to LFC. An obvious ploy in the fuselage case is to place the relaminarization suction site[s] in favorable pressure gradient region[s] to aid the downstream LFC maintenance problem. Thirdly, the large suction drag engendered in this approach must be offset by downstream LFC drag reduction and utilization of the suction air for either enhanced propulsion efficiency [Reference 85] or slot injection TDR. Another possibly interesting class of active, but not dynamic, TDR approaches involve combinations of pressure and wall temperature gradients which, for compressible conditions, damp turbulence via baroclinic torque effects.

Active TDR approaches which are dynamic but not interactive include oscillatory transverse wall motion [Reference 86 and 87] and dynamic slot injection [References 88 and 89]. At this point both of these methods are represented by extremely sparse results without any real application effort in terms of aircraft TDR. The applicable physics probably involves disruption of the usual turbulence production events via modulation of the instantaneous flow patterns, see References 90 and 91. The oscillatory longitudinal injection approach can possibly be utilized in conjunction with slot injection TDR as discussed herein to increase the efficiency in terms of drag reduction achieved per unit mass of injectant.

The dynamic, phase-locked, interactive control of turbulence structure for TDR is somewhat analogous to the "wave-canceling" LFC approach discussed previously herein. The additional, and extreme, complication in the turbulent case is the necessity of controlling large amplitude, small-scale events/localized instabilities. A major mitigating factor is that complete cancellation of all disturbances is not sought/desired. All that is needed is the disablement or partial replacement of the usual turbulence production events in the near wall region, yielding a lower drag, but still "turbulent" flow. There are two major approaches to the establishment of such a reduced drag state [References 92-95]. In one approach an attempt is made to cancel/invert/counter the developing conditions which incite/allow localized near wall instabilities/turbulence production events. The other approach attempts to establish alternative dynamic flow element[s] which have an innately lower drag state, i.e., eddy substitution. A "halfway-house" approach is to counter flow elements known to be eventually crucial to the wall-region turbulence production processes. An example of the latter would be cancellation of wall streaks via production of longitudinal vorticity with the opposite sign, suitably phased in space-time.

The "vision" for the [quite active] research in this area is a surface with distributed sensors, processors and actuators i.e., "brilliant skins" [Reference 96, see also References 8 and 97]. Research thus far has established theoretical feasibility for such an approach [e.g., Reference 98] and work has begun on physical actuator development [e.g., Reference 99], but the confirmatory experiments have not yet been carried out. Similar comments regarding shortfalls for "real world" applications apply here as in the case of the phase-locked control for LFC. At this point the real-time control of turbulent wall dynamics remains an extremely interesting "vision," with a sizable number of excellent research groups hotly in pursuit.

VISCOUS DRAG REDUCTION VIA AIRCRAFT CONFIGURATION OPTIMIZATION

The VDR approaches discussed thus far have been considered primarily in the context of conventional aircraft configurations. Non-conventional configurational approaches can, conceptually, provide even larger levels of VDR via synergistic application of the techniques discussed herein, reductions in wetted area, flight at higher altitude, or a combination thereof. While conventional aircraft configurations are, after many years of extensive development, at least a local optima for conventional missions, there are open issues regarding the optimal configuration for such "non-conventional" missions as the jumbo [700$^+$ pax] CTOL transports and the HSCT. The Concorde was essentially a linear theory machine. Under the premise of "we build what we can compute," aeronautics has now progressed to the point where non-linear aerodynamics over complex geometry should be studied, particularly for these newer missions. A major departure from conventional wisdom has already been discussed briefly herein--Dr. Pfenninger's strut-braced wings for both CTOL [of all sizes] and HSCT. Other alternatives include spanloaders/blended wing-bodies [for the jumbo CTOL mission], favorable wave interference, supersonic leading edges and multi-stage aircraft. Each of these alternatives have an impact on, and are impacted by, VDR technology and considerations.

VDR And Alternative CTOL Configurations

A possibly viable alternative configuration for the conventionally-sized long-haul CTOL transport mission is the strut-braced wing [Reference 36]. Strut-bracing allows thinner, smaller chord, lower sweep and higher aspect ratio wings. The smaller chord, leading edge radius and sweep have a favorable 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. These benefits also carry over into the jumbo CTOL application of strut-braced wings and produce, due to a combination of enhanced HLFC and drag-due-to-lift reduction, very large increases in lift-to-drag ratio at cruise.

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," [e.g., Reference 100 and 101] the major impact of these configurational approaches upon VDR is a sizable decrease in wetted area, as the load-carrying and lift-carrying elements are combined. Unfortunately, their large sweep [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 [Reference 102], [also mitigates spanwise contamination].

VDR And Alternative HSCT Configurations

There are four major alternative HSCT approaches [besides derivitives of 1960's era shapes]. These include multi-stage aircraft, strut-braced wings, favorable wave interference and supersonic leading edge wings. The flying oblique-wing spanloader is also a very serious candidate for cruise Mach numbers less than o[2] [Reference 103]. Modest wetted area reductions are also available from planform variants of more conventional machines [e.g., Reference 104].

Multi-stage aircraft approaches can vary from mid-air re-fueling, through detachable flyback sections with the heavy takeoff gear and high-lift systems, to separate takeoff and landing "piggy-back" vehicles [the latter is discussed in Reference 105]. The flyback option is of interest due to the large HSCT fuel fraction and reduces the landing requirements in terms of high lift and gear capacity as compared to the takeoff case. The use of the flyback section would allow both a much lighter cruise machine and a very aggressive takeoff high-lift system to address the critical takeoff noise problem. The effect of such an approach upon VDR is primarily a reduction in wetted area.

The favorable [non-planar] interference approach utilizes the fuselage nose shock to provide interference lift on the wing and [subsequently via reflection] thrust on the afterbody of the fuselage. Realizations come in many variants with the parasol wing among the most favored [e.g., Reference 106]. These configurations generally require increased wetted area, and LFC provides a means of mitigating the associated viscous drag increases. The supersonic leading edge concepts, by definition, utilize low wing sweep and thin wings. This method accrues additional volume [wing] wave drag and is only viable in terms of allowing natural laminar flow over much of the wing wetted area, aided by the stabilizing effects of the high local Mach number, i.e., VDR is the major rational for this configurational option [Reference 107-109].

Strut bracing for the HSCT allows very significant reductions in both vortex and wave drag-due-to-lift and could be favorable to LFC via reduced chord Reynolds number. Utilization of "reverse" sweep near the wing root [ala M-wing designs] would tend to alleviate the major loss in laminarized "acreage" caused by contamination from the wing root juncture. Natural laminar flow fuselages, perhaps with heating strips for enhanced performance, are of special importance for the HSCT 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 conventional nose bluntness.

CONCLUSIONS

1. Two viscous drag reduction techniques are, at this point, quite mature both scientifically and technologically- HLFC and riblets. There is no longer any serious doubt that these approaches can be made to "work," reliably, in flight, and produce interesting levels of net drag reduction in many aeronautical applications. The remaining technological issues regarding these approaches evolve mainly from economic considerations, i.e., ensuring a sizable/ interesting net economic, as well as drag reduction, benefit. Heated surface strip adjuncts appear to merit investigation for some HLFC applications, notably nacelles and large-to-jumbo aircraft wings.

2. Several turbulent drag reduction techniques can provide localized net drag reductions. Their utilization is a function of local and system design approaches/ details. These methods include mass injection, wall heating, adverse pressure gradients, boundary layer thickeners and streamline curvature.

3. Various alternative advanced configuration approaches have been suggested which could, conceptually, provide significant-to-dramatic viscous drag reduction as well as sizable improvements in other aircraft figures of merit such as gross takeoff weight and drag-due-to-lift. Very preliminary studies indicate lift-to-drag ratios up to double current practice for both CTOL and HSCT. These alternative configuration approaches should be seriously studied to determine their "reality" and the extent to which they can be even further optimized. Such suggestions include spanloader aircraft, strut-braced wings, favorable wave interference, supersonic leading edge wings and multi-stage aircraft.

4. The advent of miniaturized electronics and micro-machining/machinery have enabled consideration of a new class of LFC and turbulent drag reduction approaches based upon sensing and interfering with flow dynamics in a real time/phase-locked manner. The research in this area is at an extremely early stage, the extent to which such approaches can be economically realized for the complex dynamic fields which typify aircraft viscous flows is yet to be determined.

Table 1.- VISCOUS DRAG REDUCTION TECHNIQUES APPLICABLE TO AERONAUTICS

1. "Natural "LFC (airfoils (various applications incl. GA, exec. Jets, commuters, etc.), Supersonics, hypersonics)
   - dp/dx
   - curvature/geometry
   - bluntness(at high speeds)

2. Active CTOL LFC (incl. HLFC)
   - suction
   - heating strips/cooling

3. Supersonic LFC (incl. Synergisms)
   - suction
   - dp/dx
   - wall temperature control

4. Reactive/phase-locked LFC
   - several types of actuators/"effectors" & sensors

5. Turb. Drag Reduction based upon reduction of near wall long. Momentum
   - + dp/dx
   - mass inj. (Normal/tangential)
   - B. L. Thickeners

    - wall heating

6. Turb. DR based upon alteration of turb. structure via passive means
    - riblets(incl. transition region stretchout)
    - streamline and in-plane curvature

7. Turb. DR based upon alteration of turb. structure via active / interactive means

    - interactive control (sensors/actuators incl. Smart materials and micro-machining)
    - oscill. (t-dep.) Transverse wall motion/inj.
    - oscill. Long. inj.
    - suction relaminarization

8. Turbulent D.R. Via configuration optimization
    - active controls
    - thrust vectoring
    - 2-stage aircraft
    - span loaders
    - strut-braced wings
    - supersonic leading edge wings

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