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Flow Control Applications

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Table of Contents

Abstract

Flow control has a long history with many successes across a plethora of applications. This report addresses the characteristics of the approaches that are actually used, why they are used, the many approaches that are not used, and why. Analysis indicates ways forward to increase applicability/usefulness, and efficiency of flow control research. Overall, greater and more effective progress in flow control requires utilization of far more detailed information early in the research process regarding application details and requirements.

Introduction

Flow control subsumes all types of technical flow control including laminar flow control, mixing enhancement, separated flow control, vortex control, turbulence control, heat transfer control, favorable wave interference, designer fluids and much more. Also included is the vast preponderance of extant industrial flow control technology which involves valves and fluidics, for which there is immense literature and technology including active control. The vision for designer fluid mechanics includes, for example, the enablement of improved high lift, vectored thrust, drag reduction (e.g. viscous, form, drag-due-to-lift), signature reduction, enhanced combustion, reduced noise and pollution, improved flight/engine controls, reduced buffet, flutter and fatigue, heat transfer control and a host of manufacturing, process and application specific benefits.

The Following is an Attempt at a Taxonomy of Designer Fluid Mechanics:

<u>Flow Control Applications</u> – Aeronautical Vehicles, Ocean Vehicles, Architectural Aerodynamics, Land Transport, Bioengineering, Pipelines, Chemical Processing, Propulsion and Power, Manufacturing/Industrial Processes, Space Access/Re-Entry, and HVAC

<u>Types of Fluids Controlled</u> – Gas, Liquid, Plasma, Multi-Phase, Newtonian, Non-Newtonian, and Designer Fluids

<u>Types of Flows</u> – 2-D, 3-D, Entire Speed Range, Laminar, Transitional, Turbulent, Attached, Separated, Vortical, Shear Layers, Jets, Wakes, Free Surfaces, Steady, Unsteady, Shock Waves, and Electromagnetic (EM)

<u>Control Actuator/Effector Approaches</u> – Suction, Injection, Sweeping Jets, Fluidic Oscillators, Synthetic Jets, Rigid Surfaces, Body Forces, Surface Motions, Porosity, Energy Addition/Subtraction, Discharges, Combustion, Piezo-Electrics, Plasma, Lasers, Additives, Acoustics, and Multi-Phase

<u>Control Logic</u> – Passive, Active, Reactive, and Artificial Intelligence (AI)/Learning

<u>Flow Phenomena Controlled</u> – Cavitation, Drag-Due-To-Lift, Flames/Fire, Aeroelasticity/Flutter, Wall Friction, Heat Transfer, Mass Transfer, Loading, Combustion, Mixing, Acoustics, Wave Drag/Shock Phenomena, Particulates, Electrostatics, Icing, Erosion, Propulsion, Flow Separation, Phenomena Involving Vortices, Jets, Wakes, Signatures, Controls, Buffet, Fatigue, Stall, Surge, and Vibrations

<u>Purpose of Control</u> – Performance, Efficiency, Vehicle Dynamics, Noise Reduction, Environment, Climate, Weather Effects Mitigation, Cost Reduction, Sensor Improvement, Safety, Accuracy, Wake Vortex Mitigation, Thrust Vectoring, Emissions, Load Alleviation, and Observability

One can readily identify three generations of designer fluid mechanics devices and approaches. The first generation is still being utilized. These first-generation devices are typically relatively simple, inexpensive, passive, rigid, and, if active, are quasi-steady state. The second generation is currently still emerging and involves active control using usually simple systems and the application of evolving smart structures and materials for variable geometry requirements. The third generation is of significant research interest currently. It involves the vision of active control including highly non-linear complex/large degree of freedom dynamic systems such as transition to turbulence, turbulence, change of flow orientation, control of periodic separation and reattachment (e.g. dynamic stall) and flow separation. The taxonomy is indicative of the parameter space with regard to designer fluid mechanics approaches and applications. The present paper addresses the issue of application and usefulness for these various approaches (i.e. what determines which, if any approach, is ultimately employed or deployed along with putative solution spaces at the systems or configuration level).

References 1-32 address the utilization aspects of flow control and references 33-83 provide a cross section of review papers and books documenting extensive compilations of flow control research in the large. These references document the wide spectrum corpus of the current and previous flow control activities and accomplishments. As in any emerging field, only a few of these studies address the real-world conditions in total. However, the existence of an extensive array of company flow control patents indicates serious interest and possible detailed application studies by industry. It is of interest to observe what has changed and not changed with regard to flow control as a discipline over these last decades.

What Has Changed

There has been an explosion of small low Reynolds number air vehicle applications (e.g. the unmanned air systems, on demand mobility, urban air mobility, personal air vehicles [UAS/ODM/UAM/PAV] ongoing revolutions in aeronautics). These are usually prone to flow separation and therefore separated flow control approaches could probably be efficacious. Also, applications at a small scale do not involve major financial investments and serious study of several approaches and associated optimization is therefore more easily accomplished. These smallish vehicles, up to scales carrying several humans, should eventually constitute a fleet of many millions and a new air-mobility aero market in the trillion dollar range, i.e. some half of the global auromobile market as they increasingly replace ground transportation and doubling the current commercial aero markets. The knowledge acquired on the small, and mostly experimental, vehicles may eventually penetrate the major aerial transport system that employ large and expensive airplanes.

Major improvements over the decades in computing machinery and computational fluid dynamics (CFD) have enabled computation to replace much of the time and cost associated with experiments. CFD validation is still a challenge but potentially could be used to evaluate flow control concepts and address control approaches that would be difficult to test experimentally. Also, far greater detail is available from computation than experiment, including detailed dynamics.

Miniaturization, a result of information technology (IT), printing, Micro-Electrical-Mechanical Systems (MEMS), and control effectors enables greater coverage and usually lower cost. The use of natural flow instabilities to augment control authority provided a paradigm shift for conceptual active flow approaches. This shift at the research level led to the implementation of active and reactive control methods.

The improved understanding of the flow physics, coupled with improved computational ability, increased the knowledge of detailed flow dynamics. This enabled control approaches tailored to alter causative dynamic flow physics as opposed to just the mean flow. The approach to flow control also has changed. Instead of simply adding momentum to compensate for the viscous and turbulent depletion, active flow control utilizes the prevailing instabilities in the flow to augment the control input. Consequently, a small input level of order (ε) can generate a large change of order (1).

What Has Not Appreciably Changed

Control approaches are studied mainly at low Reynolds number and on a small scale. The literature and research development efforts with regard to applications in the real-world are sparse. Some critical end use metrics, including cost, weather effects, maintenance, favorable energetics, the engineering "illities," robustness, etc. are hardly ever seriously considered at the research level. Flow control research is targeted primarily at specific flow issues as opposed to at the systems level, systems, and configuration opportunities. There is usually a lack of sufficient risk reduction, scaling or consideration of real-world application and enablements.

The Flow Control Application Filters

In the emerging climate of global econometrics, the rate of technological change and innovation (as opposed to invention) is an important issue. The dominant market metric is a combination of product price/cost and features, which can be addressed technologically via a combination of product and process innovation. The technology development literature suggests that a concept/idea must transit successfully two filters between conception and application.

The first of these is a technical filter which addresses the questions "Does it work and does it violate any technical laws?" The second filter is an overall technological one plus economic considerations and determines whether the concept makes sense in the real world in terms of market, affordability, engineering-illities, safety, environmental issues, etc. In other words, "Will the concept transition successfully to the market?" Experience indicates that the first filter only fails 5% of the ideas, while the second filter fails nearly 95% of the rest. The second filter failures are legion, the canonical industrial experience is thousands of ideas required to, after several stages of triage, result in a single market viable new product. The commercial aircraft industry in the western world is currently dominated by two companies: one in the USA (Boeing) and another one in Europe (Airbus), with two emerging companies in the east (Comac & Irkut in China and Russia). The market is huge with plenty of orders for everyone for the foreseeable future so the motivation for change and risk taking is small. Even in the military market an introduction of a new airplane to service may take 20 years and its procurement may last for another 30 years (e.g. the F-16 was produced in 1973 and it is still produced today while the V-22 flew in 1989 and only half of its initial orders are fulfilled at this date).

The research community is exquisitely familiar with the details of the first, or technical, filter but far less so with regard to the second. A sampling of the components, particularized to aeronautics, of the technological/second filter in terms of its major components (engineering, safety/environment, and economic/business) include the following:

<u>Engineering</u> – Production ability, manufacturability, maintainability, supportability, ability to fly (regulatory restrictions), airworthiness, performance, flexibility, repairability, operability, durability, robustness, compatibility, energetics, volumetrics, part count, complexity, weight, scalability, and responsiveness

<u>Econometrics</u> –Cost(s), potential profit, ancillary side effects, liability, market timeliness, protectability, novelty, availability, complexity, distribution system, risk, regulatory issues, productivity, market pull, and competition

Safety/Environmental – Weather, vortex hazard, stall/spin, flutter, fatigue, reliability, crashworthiness, emissions, and acoustics

Each of these issues obviously has to be particularized with an extensive sub-breakdown for a specific system. As an example of the application of these filters, reference 84 discusses the technical aspects of several wing flow control approaches. Reference 85 then describes a similar, but expanded, set and concludes operational applications of these concepts were quite disappointing, due to lack of integration for the aerodynamic installations with airplane structure and propulsion and flight control systems at the early state of airplane design. A similar story is available for active noise attenuation (reference 86). The application of active attenuators has developed slowly for the following reasons: Insufficient experience of practical installations to permit assessment in real situations, the need to reduce the complexity and cost of the systems, lack of knowledge by design engineers of the potential benefits of active attenuators, and insufficient evidence to convince contractors and hardware suppliers of the cost savings and reliability of active attenuators.

Such comments could be generalized to apply to any designer fluid mechanics or indeed most any new technical approach. It should be noted that large scale research demonstrations, and even research level flight experiments, are usually part of the technical as opposed to the crucial technological filter (due to the typical utilization of breadboard/iron-bird/add-on approaches). Very few, if any, of the technology filter issues are typically addressed in research level flight programs. Designer fluid mechanics is merely one facet of a hugely complex and necessarily interactive aerospace system design process, which, to further complicate matters, can differ appreciably in terms of metrics and their relative importance between military and civilian applications. One estimate suggests 10,000 separate computer programs are run during the design and manufacture of an aerospace system. In general, a bad mark on any one or a number of grey marks on several of the technological filter issues is usually sufficient to obviate use of a particular designer fluid mechanics approach/concept, unless the potential benefits are major enough to justify efforts to attempt to correct the shortfalls. These issues overlay industry proclivities toward conservatism. As competition increases, risk-aversion decreases somewhat. However, in terms of advanced concepts of all types (e.g. flow control/configurational, etc.), the reality is that there are no magic bullets (i.e. approaches which require no research and development, present no problems, and only provide huge (guaranteed) benefits). The evaluation and eventual adoption of a new technical approach/idea/concept is usually a long and arduous process for which the initiators are a key element. They have the physical insight(s) and the motivation to pursue the idea. If such a pursuit included knowledge, study, and problem solving concerning the multitudinous technological filter issues early on, the adoption success rates would increase dramatically. As research on a concept addresses these applications/real-world issues, requisite details regarding requirements and payoffs (or lack thereof) become increasingly competition-sensitive/proprietary and, for Department of Defense-related issues, may even be classified. Therefore, in general, there are no open journals the researcher can consult for this critical second filter information, information which should ideally influence the initial choice, as well as conduct, of the research project. The astute researcher has little choice but to work directly with the end users up front, and at the end of the process the end-user controls the outcome and may delay implementation for a generation.

Flow Control Approaches: Used and Unused

In an attempt to particularize the information in the previous section to the flow control arena, experts in various industries and government were queried with regard to the following: "In your products, what flow control approaches do you use and why do you use these particular ones?" Also, "What flow control approaches do you not use and why do you not use them?" The responses to this query were extraordinarily consistent. The consensus end use metrics included: Low initial cost, favorable overall cost/benefit, competition, operates successfully in "real-world" conditions, demonstrated experimentally at large scale, favorable or worthwhile energetics. The engineering-illities included: Enhances/improves a valuable metric, acceptable "side effects," robust, and acceptable from a legal, regulatory, safety, environmental, liability and acoustic standpoint. These are consistent with the technological second filter elements. Studies of Langley Research Center's attempts to license research concepts generated by in-house research yielded a general theme that (in many cases) the research was simply not carried far enough to allow evaluation of the technological filter issues. More specific comments on particular approaches in the Langley study were: (1) lack of market; (2) not protectable; (3) systems implications unevaluated/unknown; (4) more advanced/alternative solutions already available and (5) narrow applicability.

A comment from the U.S. Navy was particularly interesting in that 95% of hydro benefits in the last decades derived from the use of optional shaping. There are dozens of flow control techniques that have been shown to be effective at the basic research level, and some at the exploratory development and even prototyping levels. Very few have reached optional use.

Reasons for "Why not used?" included: Not robust, did not trade well, and were not "sailor-proof." Also, the NASA Aerodynamics Advisory Panel indicates if the use of a large scale prototype is not feasible (i.e. affordable) in the vehicle development process, and the flow control device cannot be accurately represented at close to flight Reynolds numbers in the wind tunnel (or, reliably, computationally), then the risk factor for these devices is just too great.

Successful/deployed Flow Control Approaches Include the Following:

Blown flaps, leading edge extension, passive ("natural") laminar flow, leading edge "notch" vane vortex generators, NACA flush inlet, flow diverters, variable geometry writ large, base burning, winglets, wing fences, inlet bleed, transition trips, screens/honeycombs, jet injection thrust vector control, spiral chimney bands, anti-noise, polymer drag reduction, shelter belts, super-cavitation, chevrons, shaping/fairing, "no tail rotar" tail boom, spoilers, cyclone combustors, grooved runways, fairings, passive porous surfaces, air injection into hydrodynamic flows, and polymers.

Flow control approaches utilized in nature include shark dermal denticles, swept tapered tips, wing tip feathers, cactus barrels, grooved shells, swordfish/marlin sword, gill efflux, and fairings

Sample Flow Control Approaches Under Study and Development for Many Decades Include:

Suction laminar flow control, circulation control, mission adaptive wing, several wing tip approaches for wake vortex control and/or drag due to lift reduction, jet vortex generators, vortex flap, suction separation control, active compressor stall control, microbubble turbulent drag reduction, phase locked active wave cancellation, spanwise blowing for vortex lift, transverse wall motions, and plasma control

An examination of these lists and the previous discussion herein suggests the following features of a useful flow control approach: Simple and inexpensive in many cases, retrofittable in some cases, passive/rigid (thus far), reliable/simulatable in ground facilities, and well understood and proven.

Some Illustrative Example of Flow Control Visions vs. Reality

Viscous Drag Reduction (VDR)

The general approaches to VDR include reduced roughness, wetted area, viscosity, density, mean velocity, and turbulence near/at the wall. As is well known, there has been very considerable renewed research interest over the past decades in viscous drag reduction, both laminar flow control (LFC) and turbulent drag reduction. The original impetus for this research was the energy crisis of the 70s. In terms of fuel efficiency or initial size/cost reduction payoffs, viscous drag reduction is avowed to have a greater impact than technology advances in propulsion, structures, and materials and even advanced aerodynamics (but not their synergistic combinations). There have been many flight experiments to evaluate various approaches. This flight activity, along with serious progress in computational/predictive capability, has clearly demonstrated that LFC (and riblets for turbulent drag reduction) are through the technical filter yet they are not widely utilized except by the general aviation/ small aircraft community in terms of natural laminar flow, which is the portion of the technology which satisfies the principles of successful flow control devices (e.g. simple, inexpensive, passive, rigid, well understood, and proven). Why is viscous drag reduction not more widely/generally used? The risk is still too large in terms of the various facets of the technology/second filter and, based upon the current knowledge base, the added cost(s) of design, fabrication, installation, and in-service maintenance tend to cancel the value of reduced fuel consumption.

The evaluation process required to determine the applicability of LFC to transport aircraft must necessarily include consideration of aerodynamics, weights, mechanical/electrical subsystems, propulsion, structures, manufacturing, safety, reliability and maintainability, marketing, and finance (i.e. components of the second filter).

Remaining Application Issues Associated with Utilization of Riblets Include:

Application installation and removal time/cost, durability/maintainability, cost/benefit tradeoff, substrate inspection, cosmetics/weathering, control surface effectiveness, buffeting, lightning, fluids interactions, operational damage, and clogging

Example Remaining Issues for Hybrid Laminar Flow Control (HLFC) Include:

Insects, lack of a low disturbance large scale, high Reynolds number transonic tunnel, complexity, leading edge device effectiveness, cost/reliability/maintainability, manufacturability, fatigue life, and risk

Over the years, attempts were made to utilize heated body laminar flow control in hydrodynamic applications. The approach worked well in tow tanks but not at sea. Studies indicated that the various particulates in the water column tripped the flow. Yet another instantiation of real-world conditions, this time in the environment, having a first order effect on usability of flow control approaches. Similar real world (flight) effects upon suction LFC in the swept wing x-21 experiments included a requirement for better than 50-mile visibility at high altitudes to avoid laminar flow degradation due to ice cloud particulates. Additional flight issues included acoustic disturbances from the suction system, the propulsion system, and the turbulent fuselage boundary layer, as well as rain/heavy clouds, residual roughness, and insects.

Vortex Control

The diversity and importance of longitudinal vortex control applications are extraordinary.

Examples of Vortex Control Applications:

Submarine hull/sail "necklace" vortices (e.g. noise reduction, effects on control surfaces, drag and propulsion), architectural aerodynamics, wake vortex hazard, turbomachinery optimization, drag due to lift reduction, buffet/wing rock, noise reduction, heat transfer augmentation/reduction, chemical engineering writ large, turbulence/mixing control, scouring, energy separation, benthic oxygenation, and sediment control

Well-known aeronautical examples include: LEX [wing leading edge extensions], geometric discontinuities utilized on fighter aircraft (e.g. F-16, F-18) which provide vortex lift and partially attached lee-surface wing flow for enhanced maneuverability over a wide range of angles of attack

Canards are used on all current European combat airplanes whose main wing has a delta shape and is swept back at approximately 60^o. The tip vortices emanating from the canards have a large effect on the pressure distribution over the wing as may be seen on figure 1, where pressure sensitive paint is used on an airplane model of the Kfir, an F-21 that is a variant of the French Mirage 5 that used the J-79 US made engine and canard. The test was carried out at the University of Arizona and demonstrated the effects of the canard on the flow. It contributed to the leading-edge vortex that is commonly present at these sweep angles, particularly when the leading-edge curvature is large. The strengthening of the leading-edge vortex increases the lift of the wing and provides a sufficient nose-up pitching moment that alleviated the need for a horizontal stabilizer or an inflection at the trailing edge of wing's airfoil section. The incidence of the canard can vary independently of the airplane, thus providing the adequate vortex strength at each attitude.

The Chinese Chengdu J-20 combat airplane has a movable (variable sweep) canard that makes the canard more versatile.

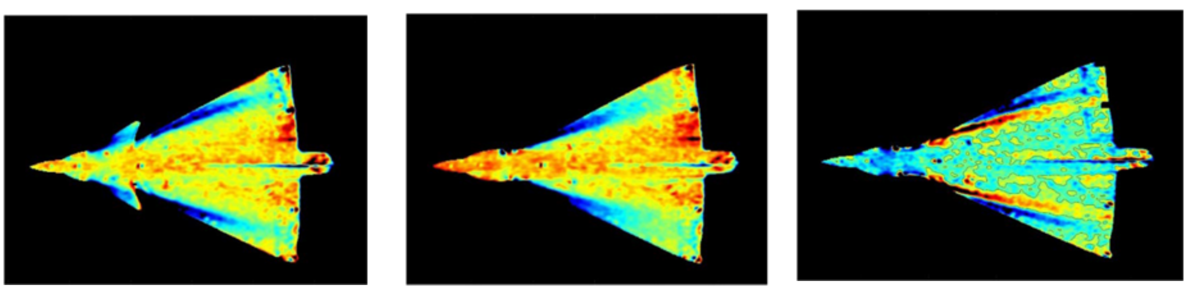

Figure 1: Pressure sensitive paint wind tunnel study of the Kfir aircraft

Over the years, various alternative proposals of the active variety (e.g. moveable geometry, blowing, suction, etc.) have been put forward, researched, and even, in some cases, flown. Thus far, these active approaches have not been extensively applied. In the 1970s, NASA worked a series of fixes to the wake vortex hazard problem and conducted flight tests on a 747 aircraft. The general observation was that differences in detailed geometry and Reynolds number between flight and the then available ground tests were responsible for the often large laboratory-to-flight discrepancies. This provides clear support for the assertion cited previously that adequate ground simulation at near flight conditions is essential, in this case to even sort out the applicable physics, at least part of which was the curvature-induced Rayleigh stabilization of the vortex core. Typical required separation distances between "heavy" and light aircraft observed in the (unmodified) low Reynolds number ground tests were the order of half or less those observed in the (unmodified) flight case. That is, the ground tests did not represent the base flight state correctly. Similar shortfalls in vortex and vortex control have also been observed during marine, especially submarine, applications.

Aircraft High Lift

The conventional approach to civilian aircraft high lift is that of variable geometry utilizing a mix of leading edge slats/devices and trailing edge flaps. The resulting lift coefficient values fall generally in the range of 2.5 to 3.5 (based on the cruise configuration of the wing area) with major cost/weight penalties in terms of a high part count and system weight/volume requirements. The military, which has a requirement for operation of heavy transport aircraft on short, unimproved runways and carrier deck operations has long studied the tremendous benefits of synergistic aero and propulsive interactions for high lift. Probably the most defining/revolutionary approach (in terms of overall performance) to propulsive augmented lift is circulation control, wherein a high-speed jet is positioned near and just above the trailing edge to move both front and rear stagnation points under the wing. This approach can produce CL values approaching 4π. The possible benefits to commercial aircraft and airspace/airport productivity of such a flow control approach are truly revolutionary and the approach transited the technical filter long ago, including flight tests. The requisite small high-pressure feedlines could even become an integral part of the wing structure. Yet, the approach is still not used. This technology, along with thrust vectoring for control and many others, offers synergistic aero/propulsion interactions and are, in the opinion of the civilian industry, too risky even though the fluid mechanists can proffer some obvious risk reduction approaches for engine out such as cross-coupling the engine bleed systems. This is a clear case of the technical community not carrying the work far enough to provide risk mitigation, including invention/development of techniques, to reduce the required efflux flow rates and acoustics.

Scramjet Mixing Enhancement

In 1972, at the Langley Conference on Turbulent Free Mixing, a clear trend was established of reduced mixing for free shear layers with increasing (high speed stream side) Mach number. This result lay essentially dormant for over 10 years until the National Aerospace Plane Program of the late 80s inspired a national effort (Air Force Office of Scientific Research, Office of Naval Research, NASA) in high speed mixing physics and enhancement. The physics responsible for the observed diminution in mixing rate with Mach number was, to a significant extent, delineated/identified, and many approaches proffered/studied by the fluids community to increase mixing at high speeds to overcome this Mach number trend.

Unfortunately, these efforts were largely disconnected from the real world of scramjets, their avowed application. Almost all of the fluids research centered on a clean shear layer without the complicating, but essential, real engine mixing region features such as thick initial turbulent regions, 3-D mean flows with curvature(s), organized vorticity of various types, various wave systems/pressure gradients, combustion, walls, etc., all of which generally cause enhanced mixing and would be expected to overshadow most-to-all of the effects of the various enhancement approaches studied in the clean experiments. In fact, the 1972 “Langley curve” of shear layer spreading parameter with Mach number included an (admittedly sparse) set of data indicating no observable effect of Mach number upon spreading rate for the case of a thick initial turbulent region where the shear layer is effectively forced by a high intensity stream turbulent field with large length scales/broad spectrum. This provides an example wherein the research community did not relate to/include/study the application details, thereby significantly reducing the impact of their work in the real world.

Drag Due to Lift (DDL) Reduction

Drag due to lift is a major portion (40% to 45%) of aircraft cruise drag and 90% of takeoff drag due to the requisite high lift levels. The obvious and well used approaches for reduction include increased span, elliptic load distribution, winglets, and distributing lift vertically (e.g. bi planes). There is a plethora of additional DDL reduction approaches, some with considerable research heritage and some more speculative. The tip flow is 3-D and the extant flow angularity can be utilized to either extract thrust or power. Alternatives include formation flying, reduced vehicle weight, tip blowing, rotating tips, porous tips, wing tip engines, joined wing-tail, ring wings, tip sails, vortex diffuser vane, tip turbines and swept back tapered tips, among others.

Several of these require systems level changes in structures/configuration for enablement of such as wing tip engines, ring wings, and joined wing-tail. In general, and curiously, as opposed to the major research efforts focused upon viscous drag reduction, the efforts on drag due to lift reduction has been much less and, aside from mostly improved winglets, not much application. DDL reduction appears to be a major opportunity area for flow control going forward, including study of what has been found to improve lift and reduce wake vortex hazard.

Air Lubrication in Water Flows

The large density difference between air and water is a source of major viscous drag reduction for hydrodynamics. Large laminar and turbulent viscous drag reduction (VDR) can be obtained via adding air near the wall. There are several instantiations of this approach extant, two of which have been applied. The Russian Shkval Torpedo creates an air bubble around the vehicle and attains speeds in excess of 200 knots. Control surfaces are extended out into the water flow. There have been applications at the macroscale scale of air injection for ship drag reduction, usually on riverine and flattish hulls, with greatly increased recent utilization, including 23 vessels across the utilization spectrum, in response to energy, climate realities. Observations at sea indicate reductions of net power requirements by 10% to 20%.

Then there is microbubble air injection, proven in lab experiments, with the major drag reduction levels observed mostly predictable from the mixed density profiles (i.e. air concentration vs. distance from the surface). Another approach is more recent, superhydrophobic surfaces, which are trapped air bubbles at the micro/Nano scales. This reduces both laminar and turbulent drag nicely at low speeds but requires replenishment at higher speeds, particularly in turbulent flows where studies suggest the convected turbulent wall pressure fluctuations lift/remove the air bubbles.

An approach that is speculative is to attempt to extract air bubbles via microcavitation approaches from the usually saturated water column near the surface. This provides continuous “passive make up” air, with various approaches possible and probably worth some study.

Shock Wave Drag Reduction

For supersonic/hypersonic in atmospheric flight, shock wave drag is the order of a third or greater of the total drag. Reducing shock wave drag involves either weakening the shock or utilizing favorable shock interference. An example of the latter is parasol wing design. If the associated shock/boundary interaction flow separation can be controlled, such a configuration has the order of a 25% plus better overall aerodynamic performance than more conventional configurations. Shocks can be weakened by utilizing more gradual flow turning. Interestingly, due to over expansions, there is an optimal bluntness, with some portion of normal shock enabling an overall lower body drag. Such bluntness, vice “sharp”, also reduces heat load and delays transition and improves packaging. Another method of weakening the body shock involves projecting a thin spike such as is used on the C4 and D5 ballistic missiles or injecting a thin stream of liquid water forward or projecting energy upstream. All of these "point" the shock and reduce shock drag as well as heating.

A Detailed Account of Active Flow Control Including Vertical Tail Applications

Turbulence was considered to be random prior to the discovery of the large coherent eddies in turbulent shear flows. These eddies retained their characteristic features over large streamwise distances despite the strong eddying motion that surrounded them. This led the research community to question the validity of the prevailing turbulent models that correlated turbulence to the local mean flow. The corollary of this observation put to test the presumption that all self-preserving (equilibrium) turbulent flows are universal. When the flow at the origin of a turbulent mixing layer was tripped by a piano wire that shed small vortices commensurate with the wire's diameter, the rate of spread of this turbulent flow increased by 30% (Fig. 2). This led to the notion that the mixing layer is sensitive to periodic excitation at its origin (85), suggesting that turbulent shear flows containing an inflection point in their mean velocity profile are susceptible to instabilities similar to the ones observed in laminar flows (86-88). Boundary layer flows subjected to strong adverse pressure gradient have velocity profiles resembling the classical mixing layer (89) and separated flow over a stalled wing is a mixing layer (90). An increase in the rate of spread of such a layer implies that more fluid is engulfed into its large eddies and when this engulfment comes from a limited reservoir of fluid like the one existing on a stalled wing, the pressure over the wing is being lowered by the periodic excitation and that pressure difference bends (redirects) the flow toward the surface, eventually reattaching the mixing layer to it (91). Thus, a novel active flow control (AFC) concept that utilizes inherent instabilities in the flow emerged.

This led to the introduction of periodic excitation (synthetic jets) for control of separation, whereupon the efficiency of the process relies on the natural amplification of the perturbations by the mean flow. Experiments comparing the effectiveness of steady blowing to periodic excitation were carried out, where it transpired that the oscillations reduced the input momentum required to attach the flow by a factor of 5 and more (92).

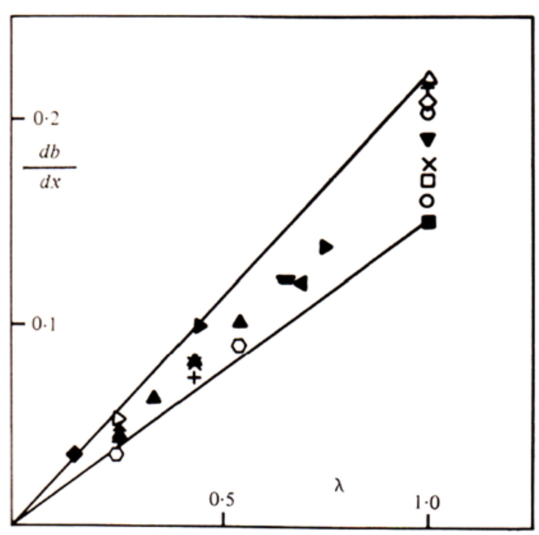

Figure 2: The different spreading rates db/dx of mixing layers versus velocity ratio λ= (U1-U2)/(U1+U2) representing the two streams creating the classical self-preserving, turbulent mixing layer. The various symbols represent different experimental setups.

The idea was pursued at numerous laboratories (e.g. NASA (95); Georgia Tech (94); IIT (95), & industry (96)), and its validity was demonstrated on two airborne vehicles: a “Pioneer” UAV in 1995 (97) and on the XV-15 tilt rotor airplane in 2003 (98]. A blower and a rotary valve powered the active flow control (AFC) system in the Pioneer experiment, oscillating a jet that emerged over a simple flap system. It increased the lift of the vehicle while requiring a relatively small input of momentum coefficient ($C\mu$<1%). The test on the XV-15 was much more extensive. It used 52 electromagnetic actuators that provided the required zero mass flux periodic actuation. The actuators were placed in individual bays near the leading edge of the flaps and emitted their oscillations through a segmented narrow slot. They reduced the download created by the rotor wakes on the airplane in hover by enabling the flap to be deflected at an angle that exceeded the natural separation angle by 15^{o}. Coincidentally, the download alleviation was approximately 17% as was the increase in the Pioneer’s lift, although the configurations and flight test conditions were different.

The “Achilles Heel” of these tests were the actuators which were heavy and needed maintenance. Various actuator types were considered (e.g. plasma actuators, piezo-electric, mechanical, shape memory alloys, etc.) but none were satisfactory until the rediscovery of the fluidic oscillators (often referred to as the sweeping jet actuators), that almost doubled the download alleviation on the V-22 model. The potential use of these fluidic oscillators is attractive because they are small, have no moving parts, and the air supply required by them is relatively small as well. They can be easily integrated into a wing or a flap. The jets that they emit sweep from one side of the nozzle to the other, therefore interacting periodically with different regions of the flow to be controlled. The fluidic oscillators were developed during the 1950s at the Harry Diamond Research Laboratories and used in analog computers and fluidic amplifiers. They are currently used in automobile windshield washers, shower heads, and irrigation systems. Since these commercial applications involve water, the effects of compressibility were not seriously addressed in the past but this gap in knowledge was recently filled (99, 100)

The use of sweeping jets in the laboratory provided the impetus to put AFC into practice. The most obvious and least risky application is the vertical tail (or stabilizer) of a twin-engine airplane whose size is determined by the eventuality of an engine power loss during takeoff and low speed climb. The vertical tail represents a large surface that is hardly used under normal flight conditions, but it is indispensable during an “engine out” emergency, and is needed during crosswind takeoff and landing. Although seldom used to its full capability, its presence adds drag and weight to the aircraft, thus increasing its fuel consumption. Active flow control (AFC) devices that delay flow separation over a highly deflected rudder may enable a smaller vertical tail to provide the control authority needed during emergency. The purpose of the experiment was to establish the efficacy of a system that uses fluidic oscillators at the rudder hinge. It broke new ground in AFC applications because of the large sweep back of the vertical tail and its relatively low aspect ratio. The natural flow direction over a typical rudder or a flap of a swept back wing is dominated by the spanwise velocity because the chordwise flow decelerates as it approaches the trailing edge, thus providing the Kutta-Joukowski condition. Consequently, a small jet emanating from a point source is able to stop the natural spanwise flow and redirect it downstream along the chord (101). In this sense a jet acts like a flexible fence or a jet curtain and it may be more effective than the large fences currently seen on swept back wings. Initial experiments on typical vertical tail models suggested that very few small jets located near the rudder hinge can provide a large increment of lift (side force exceeding 20%). A collective input momentum of $C_{\mu} \approx 0.1\%$ enabled sparsely distributed jets to redirect the surface-flow and prevent flow reversal thus delaying separation over the rudder.

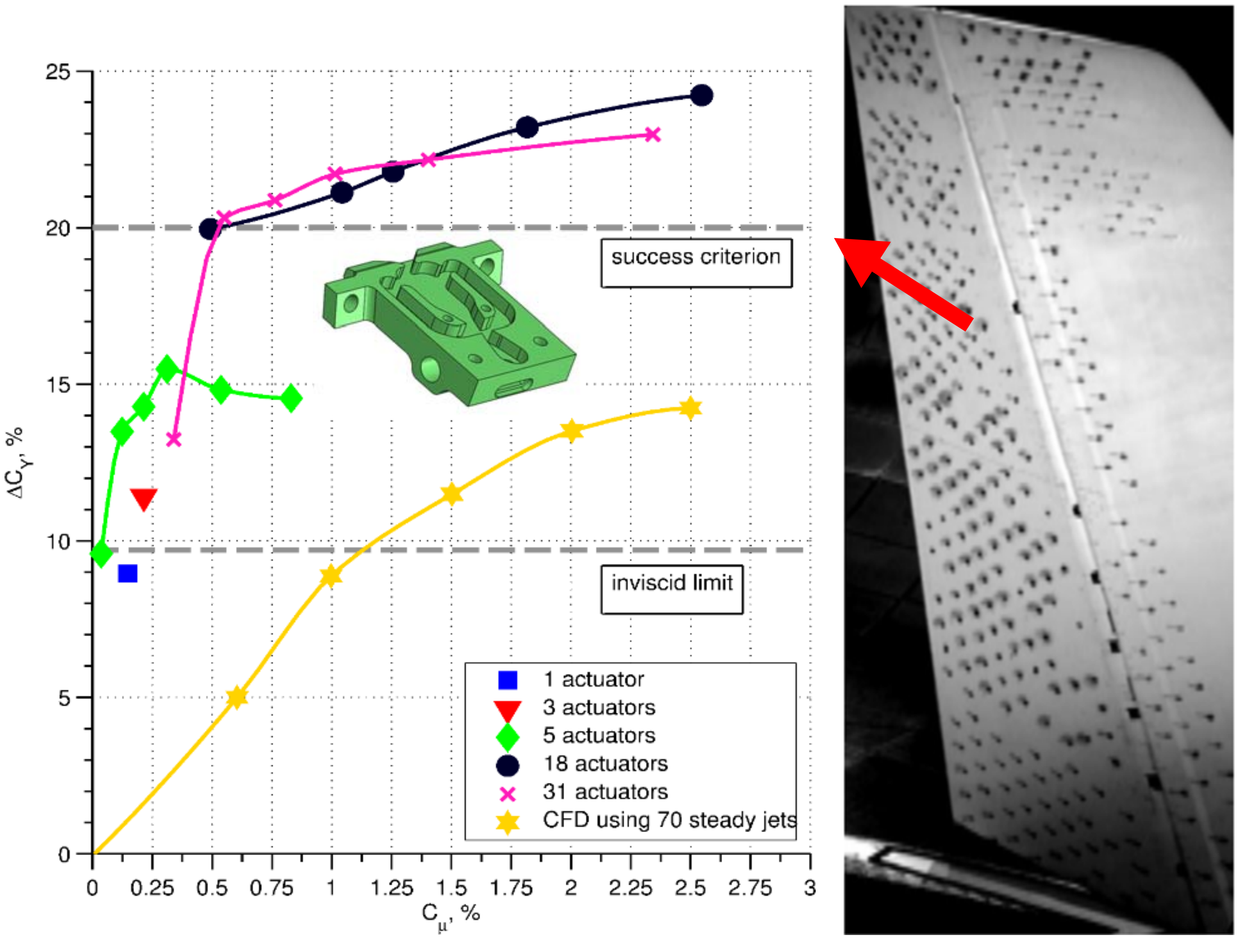

Figure 3: The change of the side force coefficient with cmuat the highest rudder deflection angle when various numbers of actuators were used at NFAC and a typical sweeping jet actuator.

The full-scale tests at the National Full-Scale Aerodynamics Complex (NFAC) (102, 103) confirmed the concept of the fluidic fence but did not attempt to develop it further or optimize it. The purpose of these tests was to prove the viability of active separation control at high Reynolds number (Re) prior to demonstrating it on a Boeing 757 aircraft in flight (104). There were many limitations imposed on the test that precluded a true development of the fluidic fence concept. The test article used was an actual vertical tail that was removed from a mothballed airplane. Its maximum rudder deflection was limited to the existing airplane range of 30^o and it was not modified. There were cut-outs in the rudder that accommodated the rudder deflection mechanisms and those were blocked for a very short time to evaluate their impact on the flow field. These constraints could be relaxed if the tests were to focus on development of a novel AFC technology rather than fulfilling an arbitrary success criterion. Figure 3 presents the change in the side force coefficient normalized by its baseline value as a function of C_μ at the highest rudder deflection angle. It was noted that even a single actuator improved the control authority of the rudder by approximately 9% relative to the measured and predicted baseline value, suggesting that a nozzle whose total area was 1/8 in^2 square can affect a wing whose area is half a million times larger. **This cannot be an issue of classical separation control** because it is impossible for a single wall-jet or even three or five of them to cover a substantial surface area of the rudder. Since the purpose of this experiment was to control separation at high rudder deflection angle and its success criterion for a demonstrative test flight was predetermined, **the discovery of the "fluidic fence" was not recognized by the sponsor nor was it pursued any further**. The CFD support proved to be a challenge. It precisely predicted the baseline results but there were no tools in existence to simulate the time dependent flow exiting the actuators and interacting with the three-dimensional turbulent boundary layer that was either partly or totally separated. Large CFD effort carried out recently simulated the extensive use of actuation on the rudder quite correctly (105, 106). Based on the predetermined success criterion, a 31-actuator array configuration was chosen for the test flight because it resulted in a 20% increase in side force at a side-slip angle of 7.5^o. A TUI-Boeing 757-200 ecoDemonstrator was flown in the spring of 2015 (104). Although the flight test was considered a resounding success, the critics pointed at a heat exchanger located below the APU, mocking the achievement. Two years later it was shown that hotter sweeping jets were more effective than colder ones and the jet flow cooled so rapidly that it did not pose a problem to the rudder structure (102). Flow cones (tufts) placed on the rudder were photographed by a chase plane and shown for reference (104).

The flight test pictures [Fig. 4] confirmed the observations made at NFAC and at the Lucas wind tunnel at Caltech, showing how the rudder flow was redirected by the actuation. Pilot feedback and analysis of the flight data proved the effectiveness of AFC, because a smoother single engine flight was attained that was coupled to enhanced rudder control authority. It resulted in NASA claiming an increase in the AFC Technology Readiness Level (TRL) from 3 to 6. However, the research on the vertical tail was stopped without providing a road map for future optimization and system integration of AFC into the vertical tail or other control surfaces on an airplane.

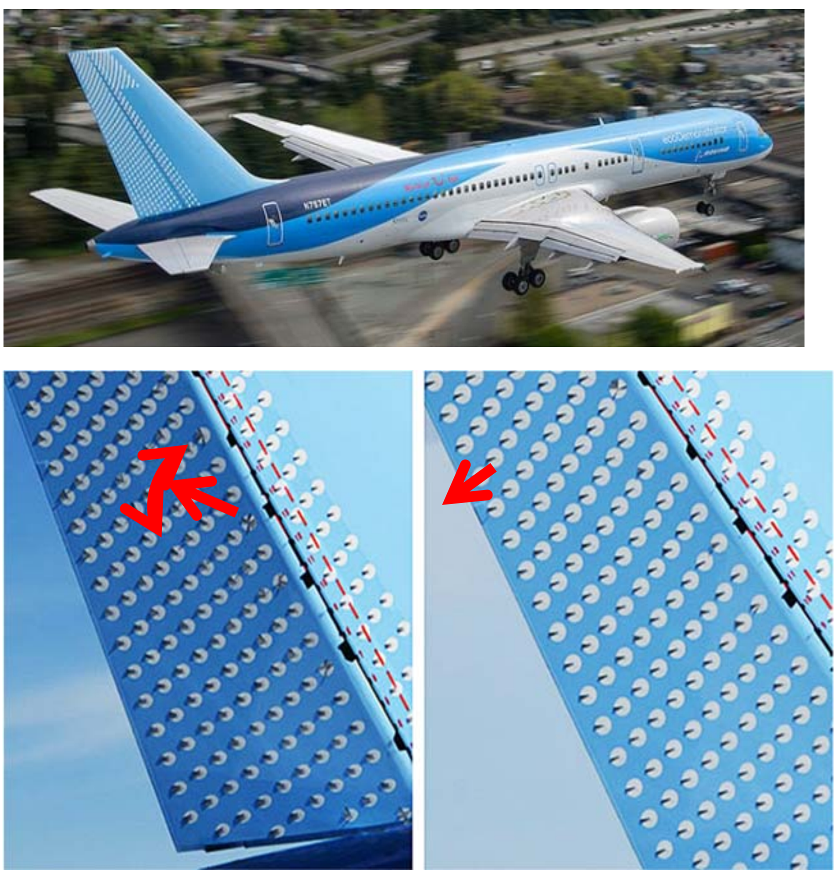

Figure 4: Tuft flow visualization during a test flight of the 757 airplane [104]

If the experiment was repeated today, the elimination of spanwise flow would have been a first order of importance. Since a small number of actuators is required for that task an entirely different air supply could be used and incorporated into the 757-vertical tail. An electrically driven small compressor (see specifications and size in Fig. 5) can supply five actuators on the full-scale tail. It can be easily integrated into the vertical stabilizer as seen below. A small number of these compressors provides safety and redundancy with very low weight penalty. The location of actuation and the direction of intervention (blowing) in the rudder case is obvious because the flow changes direction at the rudder hinge and it is the spanwise flow that has to be controlled first.

The broad purpose of AFC is to extend and augment the capabilities of lift generation by flaps and control surfaces beyond the natural separation of the flow (108). So, AFC may become a tool that interacts with all the other variables affecting the shape of the vertical tail, but the level of that interaction is still to be determined.

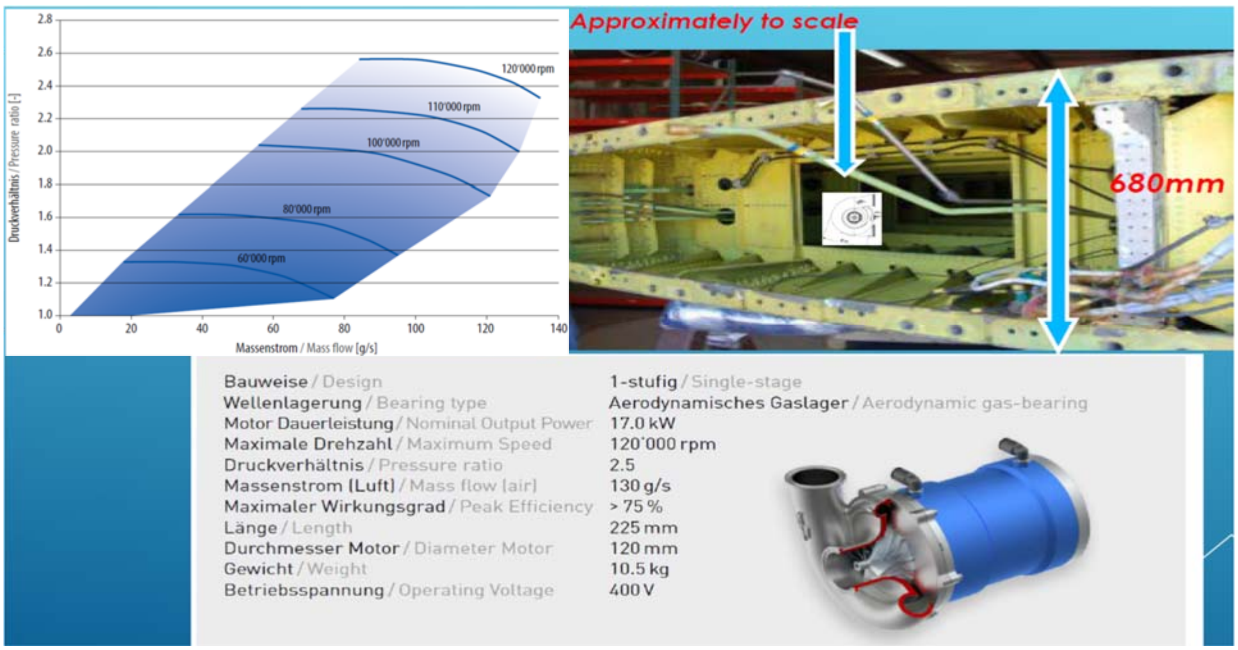

Figure 5 Possible installation of Fischer micro-turbo-compressor in the vertical tail of a 757 aircraft (107)

Potential Systems/Configuration Level Flow Control Enablements

Large performance improvements are potentially possible based upon systems/configuration level applications of flow control. Thus far flow control research has primarily focused upon various classes of flows. There has been little consideration with regard to what could be developed at the systems level if we utilized flow control and deviated from extant, conventional designs.

The All Up Truss-braced Wing

Pfenninger has long advocated strut/truss bracing to improve the performance of conventional transports. The resulting (bending, torsion) structural benefits allow reduced wing weight, thickness, and sweep, resulting in a tremendously enhanced and easily maintained (i.e. reduced sensitivity to roughness/insect remains/ice clouds, reduced cross flow) extent of natural-to-easily forced low drag laminar flow, along with increased span with attendant drag due to lift reductions. The latter allowed a reduction in wing chord, further enhancing the extent of laminar flow, as well as enhanced takeoff and climb performance and reduced vortex hazard. Plenninger's designs for such aircraft yielded lift to drag (L/D) values in the 40s, over twice current levels, with one of his studies which included a laminar fuselage yielding a machine with L/D = 100, 700 Pax and 200,000 Km range. The concept was not, however, adopted primarily because the extensive wingspan did not fit the FAA "80 meter box" for airport gate compatibility, and disbelief that a transonic strut/truss braced wing could be designed with acceptable shock drag (and obtain laminar flow on the strut/truss).

Strut-bracing is routinely employed on low(er) speed aircraft. The latter objection is probably not valid in light of today's CFD capabilities. In general, we build what we can compute and we were too long constrained in aircraft design to linear theory and consequent "linear thinking." Indeed, lack of adequate/believable "first principles" estimation methods for not only performance but cost(s), maintenance/operability, etc., are a major reason why work on advanced aero concepts has lagged. Our historical systems methodologies were essentially extrapolation and interpolation procedures based upon, and therefore largely restricted to, empirical data for/from the current paradigms. As discussed, the improved computing machine capabilities/mod-sim developments are changing such considerations/judgements in real time.

The span of a truss-braced configuration can probably be doubled and a hinge (already available in industry) utilized to conform to the 80-meter gate requirement. Doubling span would halve Reynolds number on the wing and reduce drag due to lift on the order of 75%. Combining this DDL reduction with the extensive wing laminar flow, results in most of the remaining vehicle drag being fuselage friction drag. Such drag can be addressed in several ways. The most dramatic is to apply boundary layer relaminarization just downstream of the cockpit, forward door. The aircraft nose region with the radome, probes, windshield, wipers, etc. will be turbulent, therefore there will be the need to ingest/take aboard just aft of the forward door 150% plus (to entrain the turbulent "superlayer") of the local fuselage turbulent boundary layer and reestablish laminar flow. The increasing use of personal view screens vice windows greatly eases the task of maintaining laminar flow downstream. The air taken aboard can be slot injected into the turbulent wing-fuselage turbulent flow wedge to accrue local skin friction reduction. The engines can be moved to the rear of the fuselage, surrounded by a Goldschmied shroud. This would enable several interesting/useful functionalities. The engines could be thrust-vectored, obviating the weight/drag of the empennage. The shroud provides copious volume for acoustic treatment(s). The engines ingest the fuselage boundary layer accruing a sizable propulsion improvement. Then there is the oft mentioned, but still under study, "Goldschmied Effect" that purportedly could cancel a sizable portion of the fuselage friction drag. The thought is that possibly/TBD, putting "sinks inside the body" using the cowl could convert the back of the cowl into a stagnation region, thereby producing what Goldschmied called favorable interaction "Static Pressure Thrust."

For long haul transports, the weight of the gear is the order of half the fuselage weight. The gear weight could be reduced in several ways. One is to utilize parachutes instead of super heavy brakes for refused takeoff. Another is to utilize wholly automatic landings with the controls slaved to the altitude/ground proximity and a decent rate to take out the impact loading. All of these benefits greatly reduce vehicle weight overall. These benefits, along with clever vortex flow control and greater span, can reduce wake vortex hazard. Advanced materials on the way to eventual development/invention of structural Nano tubes, along with the possibility of using inflatable inboard wing sections to enable further sweep reductions provide weight reductions, including the truss benefits on wing weight, in the range of 30% to double that. The estimated and computed L/D for these configurations is in excess of 40 to much higher. The resultant fuel burn reductions are, without going to fuselage laminarization but using riblets for turbulent viscous drag reduction, in excess of 70%. It should be noted that we have no detailed studies of truss braced wing truss optimization. The studies thus far have been at the systems not the detailed design level. We have never been here before. Obvious options include pre-stressing, hydraulic dynamic internal pressurization, laminar elements, arching, “Y” intersections with the wing to avoid supercritical flow regions, optimizing the overall number, nature, positioning of the elements, etc. The truss could also be carried out beyond the mid span/wing hinge positions. All of these options and far more are forward work. The recent and ongoing efforts at Boeing on truss braced wing designs employ a portion of the “all up” approaches cited herein. To these flow control approaches for this configuration could be added the recent Corke plasma induced sizable net turbulent drag reduction and some wing tip electric engines for additional DDL for the electric propulsion case going forward.

Double Fuselage

Conventionally, double fuselage/multi-body aircraft have been employed to provide span-load distribution and accrue the associated structural weight benefits (reduced wing bending moment) without going all the way to a “blended wing body”/span loader configuration (i.e. providing such benefits via “conventional” technology). Total aircraft drag is also reduced, primarily due to favorable effects on drag due to lift. An advanced double fuselage approach could attempt to delete the conventional outer wing panels and only retain a largely unswept/long chord wing section between the fuselages. This requires prodigious drag due to lift reduction, a requirement which can be addressed via design of the wing tip fuselages as wing-tip “end plates” and the individual fuselage empennage as “winglets” (i.e. the tails become thrusting surfaces in the presence of the wing vorticity wrapping around the fuselage(s)). For this case, the “midwing” can become the site of the gear (to allow use of conventional runways), with engines “buried” at the rear of the fuselages to accrue the benefits of “boundary layer ingestion” and drag due to lift reduction, with extensive (natural/suction) laminar flow enabled by the largely unswept “midwing.” Spanwise and localized ahead of the neutral curve heating strips in the wing leading edge region would enable, from theory and experiment, longer regions of laminar flow. The approach essentially converts the wing surface downstream of the neutral curve into a “cooled region” as far as the incoming (upstream heated) flow is concerned and for these speeds, in unswept flows, cooling is stabilizing. A major payoff would accrue from making the fuselages detachable/interchangeable to provide a civilian “skytrain” with enhanced productivity. The midwing portion which does all the “flying” could be in the air nearly “around the clock” with interchangeable freighter and/or passenger modules, thereby nearly doubling the productivity/duty cycle and the “return on investment.” Such an approach would allow a restructuring of the airline capital investment, with the airlines “owning” their fuselages and leasing the “midwing” from a “rent-a-wing” company. Obviously, military versions could have cargo, troop, and refueling fuselages--providing a quantum jump in military flexibility and productivity.

The Channel Wing

The channel wing is an example of an advanced configuration which was somewhat ahead of its time. The concept was originally developed, essentially empirically, in the 40s and early 50s as a Short Take Off and Landing (STOL) light aircraft and several versions were flown. This is not just a "paper airplane." The essential technology consists of a semicircular airfoil "channel" underneath, and surrounding on the underside, "standoff" wing mounted engine nacelles such that the engine-induced airflow produces sizable lift on the wing "channel" at zero to low forward speed, providing dramatic STOL capability. Measurements of pounds of lift per horsepower are in the helicopter range. The developers of the configuration claimed, but there was never any satisfactory "proof," perhaps due to "then year" control problems, that the approach was capable of near Vertical Take-off and Landing (VTOL) performance. Development of this concept has been essentially dormant since the late 50's except for Soviet research. Antonov produced an advanced prototype-demonstrator in the late 80's termed the AN 181. The original 40's-to-50's era research on the channel wing was, by necessity, highly empirical and resource constrained. The concept provides a classic example of an approach worth revisiting with updated tools and technology to ascertain the extent to which its STOL performance could approach VTOL. In particular, the incorporation of circulation control in the classical sense (via blowing immediately upstream and above the trailing edge), when combined with the engine-induced flow over the wing, should further augment the lifting capability of the configuration. Also, a serious attempt should be made to reduce the requisite propulsive mass flow currently and historically required for circulation control via "dynamic flow control". Additional technology updates/approaches of possible interest include (power on) CFD (so the approach could be "designed" instead of "engineered"), flow separation avoidance and control, wing laminar flow for cruise performance and inboard strut bracing along with the all-important vehicle controls issues. The potential for such an updated channel wing approach to address the commercial and military "V-22 niche" should be determined as the channel wing could possibly incorporate very interesting lifting capabilities with a fairly high cruise speed at reduced weight/cost compared to the V-22 (with its engine rotation requirements and associated systems penalties).

Extreme Arrow Wing Truss-braced SST

Thus far supersonic transports have not been particularly successful, either conceptually or in actual realizations. The Concord was a technological marvel for its time but was not commercially successful. Similar remarks hold for the TU-144. The basic SST issues are straight forward. The usual many and various aeronautical problems hold and are extended and confounded by the addition of serious wave drag, higher fuel fractions, higher temperatures, and greater weights, which all drive up vehicle cost. Then there are the high-altitude ozone/emissions (especially water) problems, far more incident radiation, and the sonic boom, the latter causing anti-SST legislation. The sonic boom affects both people and things. There has been some success in reducing the “N-wave” peaks that affect people but reducing the low frequency “rumble” that affects buildings is a much more difficult task. Lastly, there is the jet takeoff noise from the engines designed for propulsion at supersonic speeds. There are concentrated studies ongoing of SST business jets, as such smaller vehicles both reduce the massive investment level required to field such machines and also reduce the sonic boom, which is first order dependent upon weight.

Advanced configuration SSTs come in five major categories: unswept, thin natural laminar flow wings, parasol wing favorable interference, multistage aircraft, yawed wings and the Pfenninger extreme arrow strut braced wing. The multi-stage approach usually involves a stage which includes the capability to get off the ground with acceptable noise/high lift, and then separates/returns to the airfield. The portion of the aircraft that lands at the end of the flight weighs far less, allowing carriage of lighter weight gear and high lift systems. In-flight refueling is another multi-stage aircraft option. The yawed wing approach uniquely provides a low supersonic Mach number option that is nearly “boomless” and extremely efficient. Of these the Pfenninger extreme arrow strut braced wing appears to have the greatest SST potential, essentially doubling the Concord L/D of 7.3ish. The best NASA did in the High Speed Research program of the late 90s was an L/D in the range of 9.5. The Pfenninger designs proffer values in the range of 14 to 16 plus. The extreme arrow wing minimizes wave drag due to lift and wing wetted area as well as providing a credible span for vortex drag minimization. The short wing chord aids suction laminar flow control. There are mid-wing fuel canisters for favorable wave interaction and load alleviation, with the possibility of natural laminar flow on the forward regions of the fuel canisters and the fuselage. Several approaches utilized to optimize the truss-braced

Conventional Take-off and Landing (CTOL) design can also be applied to this SST, including gear weight reductions via automatic landings and parachutes for refused take off. This is particularly important in the SST case as the gear weight is the order of the fuselage weight. In addition, C-wing tips would reduce DDL. The serious take off jet noise issue can be addressed via an essentially new approach – disabling/reducing the causative turbulence dynamics vice reducing the jet velocity via entrainment using heavy “mixer-ejectors.” Experiments and some theory indicates that the injection of liquid water jets, suitably tailored for effectiveness and minimal water mass flow, can place water droplets in the mixing region of the external jet which reduce turbulence intensity and noise. The water injection produces additional thrust vice the mixer-ejectors that reduce thrust and is a way of “staging the aircraft.” The water utilized during take off does not have to be carried throughout the flight as does the mixer-ejector. Having such a high L/D provides the margins necessary to address the myriad of SST problems.

Probably next-in-line in terms of efficient SST configuration approaches would be the oblique/yawed wing, work on a bi-directional flying wing concept and the NASA N+3 SST studies. The former is due to R.T. Jones and is well discussed in the literature. The bi-directional approach is circa 2011 and involves a design based upon 90-degree rotation of the configuration for supersonic vice subsonic flight. The design thereby provides major alterations in aspect ratio for each speed range, enabling true bi-modal performance with excellent aero performance for both supersonic over water and subsonic over land. The overall approach is similar in philosophy to the variable sweep and yawed designs, but executed in a wholly novel fashion, with efficacy to be determined. Such bi-modal aero performance improves the overall performance for the mission and reduces required fuel fraction.

A Potpourri of Additional Systems Level Flow Control Possibilities Include:

- Spanwise wavy wings deduced from whale pectoral fin turbucules for improved lift and possibly wake vortex mitigation and DDL reduction [Ref. 109]
- A “Grim Wheel,” a flow turned disk just ahead of the internal inlet on a fuselage base engine swallowing the fuselage boundary layer to reduce the inlet flow distortion [Ref. 110]
- Water injection into the jet exhaust shear layer during takeoff to reduce takeoff jet noise via mitigation of the causative jet turbulence, would also both increase thrust and obviate the cruise weight and drag of the takeoff acoustics mitigation mixer-ejector approach for SSTs
- The Lobert Windmill, placing a windmill ahead of the air vehicle to extract energy, reduce the boundary layer external velocity and thereby skin friction on the vehicle; the extracted energy is carried to the rear where it is deposited in the vehicle wake, producing thrust to partially obviate the drag produced by the energy extraction [Ref. 111]
- For ships or submersibles, extract phyto and zoo plankton from the cooling water and cultivate on board drag reducing polymer to obviate having to load the requisite polymer needed throughout the voyage
- Continuous curvature, continuous 2nd derivative surfaces to minimize vortex production; useful to reduce the self-noise on sonar domes and to mitigate hull bilge vortices which reduce propulsion efficiency and create noise. Also can minimize lee side vortices on aircraft
- Turbulence tailoring/control in the combustor of gas turbine engines tailored to improve the performance of downstream turbine stages

- Stopped rotor VTOL, a two bladed large rotor turned by tip fans to obviate a tail rotor. Once aloft, to cruise efficiently, rotor is stopped, becomes the wing. Necessary to rapidly morph the leading/trailing edges of one of the rotors at that point so both rotors are facing the right way. The tip fans become part of the propulsion system for cruise and reduce DDL. A quiet, efficient VTOL with good cruise efficiency [Refr. 112]
- For SSTs, flow separation control at cruise to enable full inclusion of the many inviscid performance enhancements now only partially employed due to flow separation, including leading edge thrust, lift carryover onto the fuselage, carrying more lift on the upper surface, and controlling the shock-boundary layer interactions for parasol wing designs

Concluding Remarks

Research and Development (R&D) of fixed geometry flow control approaches is still occurring, notably the studies of the hump-back whale pectoral fin leading edge turbucles for greater lift and possibly wake vortex hazard and DDL reduction.

Recent apparent breakthroughs in the laboratory regarding large net turbulent boundary layer drag reduction via plasma actuators to induce spanwise motions (65) has, if proven, major implications going forward.

There is a plethora of potential systems level flow control enablements, several positing major benefits.

Boundary layer control by blowing enabled combat jet airplanes of the 1950s and 1960s to operate from shorter runways by increasing their lift coefficient at low speeds. The concepts of boundary layer and circulation control evolved at that time, however, blowing was never considered interactively with other aerodynamic design parameters and it was always applied after the design was frozen. The purpose of blowing boundary layer control was to supplement the momentum loss in the boundary layer and it required a large momentum input to reduce the landing speed by 30mph (e.g. F-104). A novel approach to AFC emerged after it was recognized that turbulent flows are susceptible to instabilities that can naturally be amplified by the flow itself. This enabled a small input level (of order ε) to and provide an output of order unity, thus numerous interacting instabilities were exploited in “simple” two dimensional mean flows and were even demonstrated in flight on a tilt rotor airplane (the XV-15). More recently the focus has been 3D flows on swept wings where one has to maintain trim (i.e. keep the pitching moment constant) over large range of lift coefficients. There is a need to augment the effectiveness of control surfaces through the use of AFC, and in some situations to entirely replace the traditional control surfaces by AFC. Experiments carried out on tailless aircraft models indicate that dynamic tailoring of AFC in terms of momentum input and its location and orientation, provides elegant solutions to problems plaguing such configurations. The research on such configurations is ongoing, with attention being paid to the many real world metrics in order to avoid blind alleys that caused ideas to fail.

The real-world metrics should be considered throughout the R&D process for flow control, from initial ideation through the entire process to application. The flow control R&D journey over many decades now is littered with the carcasses of approaches that were not, for various reasons, suitable for the real-world. A way to make flow control R&D much more effective, efficient, and timely is to do upfront, initial intel – market, application, utilization, technical, competitive intelligence - and utilize such knowledgeability for the entire investigative process from ideation/the decision of which approaches to study, through research and into application. Experience indicates such efforts would be efficacious for R&D in the large, for nearly all purposes, to increase the efficiency and cost effectiveness of R&D investments.

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14. ABSTRACT

Flow control, aka "Designer Fluid Mechanics," has a long history with many successes across a plethora of applications. This report addresses the characteristics of the approaches that are actually used, why they are used, the many approaches that are not used, and why. Analysis indicates ways forward to increase applicability/usefulness, and efficiency of flow control research. Overall, greater and more effective progress in flow control requires utilization of far more detailed information early in the research process regarding application details and requirements.

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