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Snapshot of Active Flow Control Research at NASA Langley

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SNAPSHOT OF ACTIVE FLOW CONTROL RESEARCH AT NASA LANGLEY

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Abstract

NASA Langley is aggressively investigating the potential advantages of active flow control as opposed to more traditional aerodynamic techniques. Many of these techniques will be blended with advanced materials and structures to further enhance payoff. Therefore a multi-disciplinary approach to technology development is being attempted that includes researchers from the more historical disciplines of fluid mechanics, acoustics, material science, structural mechanics, and control theory. The overall goals of the topics presented are focused on advancing the state of knowledge and understanding of controllable fundamental mechanisms in fluids rather than on specific engineering problems.

An organizational view of current research activities at NASA Langley in active flow control as supported by several programs such as the Morphing Project under Breakthrough Vehicle Technologies Program (BVT), the Ultra-Efficient Engine Technology Program (UEET), and the 21st Century Aircraft Technology Program (TCAT) is presented. On-center research as well as NASA Langley funded contracts and grants are discussed at a relatively high level. The products of this research, as part of the fundamental NASA R&D program, will be demonstrated as either bench-top experiments, wind-tunnel investigations, or in flight tests. Later they will be transferred to more applied research programs within NASA, DOD, and U.S. industry.

Introduction

The National Aeronautics and Space Administration (NASA) recently released an aeronautics blueprint[1] identifying aviation as critical to U.S. economic health, national security, and the overall quality of life. The blueprint also defines the role of the U.S. government in aeronautics research, where NASA serves cooperatively with the Federal Aviation Administration and the Department of Defense. NASA's role is to enable technology and assure that technology flows between civil, military, and commercial sectors in the national interest. This will be accomplished through basic research, high-risk technology, unique facilities and an educated workforce. NASA, furthermore, desires to realign and strengthen its partnerships with other governmental agencies, academia, and industry. It seeks to upgrade its facilities and renew its focus on innovation in engineering tools and capabilities for long-term research in complex aerospace systems. The aeronautics goal then, reduced to two words, is to *Revolutionize Aviation*. The theme objectives of this revolution are emissions, noise, safety, capacity and mobility.

Under the heading of Aerospace Technology, NASA established a Vehicle Systems Program chartered to conduct fundamental research on advanced technologies for future flight vehicles.[2] The structure of the Vehicle Systems Program is shown in Figure 1. At this time active flow control activities at NASA exist in several of the components of this program. These are the Breakthrough Vehicle Technologies Program (BVT), the Ultra Efficient Engine Technology Program (UEET) and the 21st Century Aircraft Technology Program (TCAT). As indicated in Figure 1, the purpose of BVT is to advance fundamental technology and tool development. This translates to a technology readiness level (TRL) of 0 to 4. The purpose of the UEET and TCAT programs is to push promising technologies toward maturity from TRL levels of 3 to 6 through integration of components into systems. A TRL of 6 implies that a system/subsystem model or prototype has been demonstrated/validated in a relevant environment.

Active flow control fits the vision to revolutionize aviation due to the promise of tremendous high-payoff benefits through a concerted long-term research investment. Often however, the benefits are over-sold thus leading to the current controversy regarding the real "systems" benefits provided by these new ideas. These questions can only be answered by improving design and analysis tools as well as experimentally verifying and validating a variety of applications.

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Bushnell[3] suggests that the technical community must push the technology farther to get through the "technological filter."

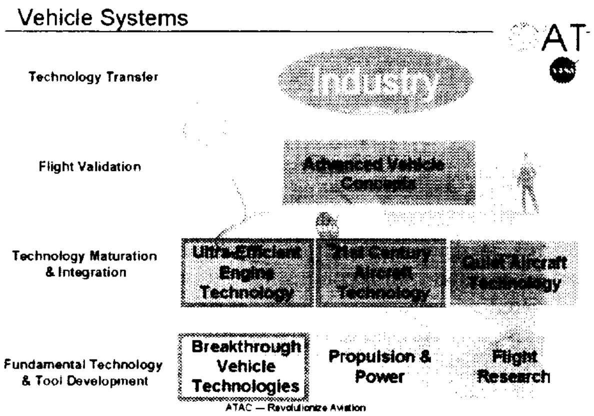

Figure 1. NASA Vehicle Systems Program Structure

Active flow control as a technology is inherently multi-disciplinary in nature requiring expertise in the individual topics of fluid mechanics, advanced structures and materials, controls theory, measurement technology, power electronics, and systems design. NASA Langley (LaRC) is uniquely positioned to address these topics due to the breadth of skill mix and facilities at the center. The cultural challenge of getting the different disciplines to work together as teams is being addressed. It is imperative that each discipline has some understanding of the strengths and limitations of the others so that significant unresolved issues can be addressed in a positive manner. However, to ensure future success, fundamental research within each discipline, such as unsteady aerodynamics and computational fluid dynamics (CFD) code development must not be forsaken.

Background and Organization

In active flow control at NASA Langley, the principle goal is to mature these technologies to the point that their benefits and functionality can correctly be assessed in the preliminary design stage so that NASA's partners can use them. To accomplish this goal, LaRC is striving to advance the state of the art in active flow control over a broad spectrum. Some of the technologies identified include improving design and analysis tools, identifying and using adaptive control strategies, improving flow sensing (to be rugged, reliable, and deployable), developing effective and efficient actuators, and improving the understanding of flow physics and fluid manipulation. At this time, several categories of fluid instabilities are fundamentally known and are being exploited. Actuators and sensors are emerging that take advantage of advanced materials and manufacturing practices. Analysis tools, with sufficient fidelity such as large-eddy simulations and high-order methods, are becoming feasible. To accomplish these goals, LaRC desires to encourage and foster progressive thinking through sharing of resources. We hope to be an intellectual resource for national use and to partner on application specific challenges as well as continuing our benchmark research.

While pursuing a unified effort in active flow control, the goals of several different NASA programs and projects must also be realized. To the best of the authors' knowledge, the major funding sources for active flow control research and related tools are currently the Morphing and the Aerospace Concepts to Test (ASCoT) projects of the BVT Program, the Active Flow Control Element of the Propulsion Airframe Integration Project of the UEET Program, and more recently the Efficient Aerodynamic Shapes and Integration portion of the TCAT program.

Breakthrough Vehicle Technologies Program

The Morphing Project, launched around 1996, is the major funding source for the active flow control activities at LaRC. The Morphing Project objectives are summarized by McGowan et al[2] to develop and assess advanced technologies and integrated component concepts to enable efficient, multi-point adaptability in air and space vehicles. Within the context of NASA's research on future flight vehicles in the Morphing Project "morphing" is defined as: efficient, multi-point adaptability and it includes macro, micro, structural and/or fluidic approaches. The Morphing Project is working toward strategically incorporating both micro fluidic and small and large-scale structural shape change to address the intertwined functions of vehicle aerodynamics, structures and controls. These "disruptive" technologies are also used to seek new innovations that may only be possible at the intersection of disciplines. The three focus areas are: adaptive structural morphing, micro-aero-adaptive control, and biologically-inspired flight systems. These areas are supported by the core enabling areas of smart, nano and biologically-inspired materials, multi-disciplinary optimization, controls, and electronics.

The ASCoT Project's objective is to provide next-generation modeling, simulation, and design tools to increase confidence and reduce development time in aerospace vehicle designs. The area of physics-based modeling is pursuing the development and validation of time-accurate CFD simulations. Turbulence modeling and higher-order methods are the principle focuses for both structured and unstructured codes.

Ultra-Efficient Engine Technology Program

The UEET Program was launched in late 1999[4] in response to the growing concern regarding the negative impact of aviation on the environment[5] and to foster revolutionary propulsion technologies. This program has several elements, one of which is to explore the feasibility of the Blended-Wing-Body (BWB)[6,7,8] concept as an efficient alternative to conventional transport configurations. System studies indicate that the vehicle's performance in terms of range can be greatly enhanced if the engines are placed near the surface on the aft end of the vehicle and the boundary layer ingested. In this case, the inlets must be S-ducts with the capability to ingest a boundary layer on the order of 30% of the inlet height. The inlet must perform this task without producing a significant engine performance penalty in terms of distortion or pressure recovery.

The requirements for inlet performance under the severe conditions of an adverse pressure gradient from the S-duct and a very large onset boundary layer flow have led to the consideration of active flow control devices in the inlet to energize and mix the boundary layer. NASA Langley has assumed a lead role in the assessment of active flow control for boundary layer ingesting (BLI) S-inlets under the UEET Propulsion Airframe Integration (PAI) project.

21st Century Aircraft Technologies Program

The TCAT Program was conceived in mid fiscal year 2001 and became it own entity in fiscal year 2002. The purpose of TCAT is to develop and verify critical technologies that provide significant improvements in efficiency and performance by integrating technologies previously developed at low TRL in the BVT Program, the Power and Propulsion Program, or by other government programs. TCAT's focus is mid-TRL integrated demonstrations of active flow control technology, adaptive structures technology, multi-functional structures technology, alternate propulsion (Glenn Research Center), and MDA/MDO design tools assessment/validation.

Research Topics

A matrix of the content of the active flow control activities ongoing or planned at LaRC is shown in Figure 2. The matrix is intended to provide the reader with a quick overview of the different projects that LaRC is pursuing and includes those activities we are funding and/or collaborating on as well. It is not intended to define how active flow control should be organized. The figure attempts to align activities based on predominant physics categories in the columns, while the main intent or purpose of the research is categorized by rows. Some research topics are very general in nature, not fitting well into any matrix, these are included in the boundary layer control column.

The shading indicates the funding source for each research topic as shown by the key located on the lower left side of Figure 2. Efforts that are sponsored as grants and the research topics that are predominantly sponsored by other government agencies are labeled. These items are included for completeness and will be discussed briefly in the following sections.

Flow control activities have been ongoing for many years at LaRC. However, most of the activities summarized here have been initiated in the last 2½ years after a sizeable increase in funds allocated for active flow control. It is anticipated that the current funding level for these activities will remain relatively flat for the next several years. It is also expected that close coupling between active flow control and adaptive structures will be visible in the next funding cycles.

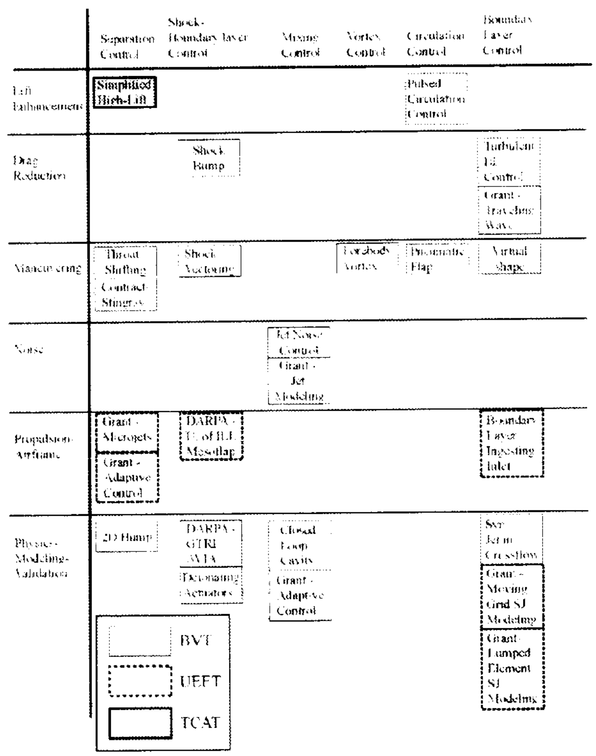

Figure 2. Matrix of AFC Research Topics

The various research topics are summarized in the following sections. The point of contact for each topic is footnoted with their organization if outside of LaRC. The topics are discussed according to the type of physical interaction where feasible, however, there are a few deviations to the intended order. Due to the breadth of the topics covered and overview nature of the paper, little insight into the physical processes is included. The interested reader is referred to the individual references or for a more fundamental overview of projects in the BVT Program to Washburn.[9]

Separation Control

Lift Enhancement

Boundary layer separation and its control are of particular interest in the world of fluid dynamics because separation is so common and so detrimental to efficiency. Active systems that are promising in the laboratory may not be so in reality because the benefits are eradicated due to complexity, maintenance difficulties and low system efficiency. An example of this is the use of steady suction for boundary layer control. However, some methods need to be revisited as new variations are conceived. For example, forced oscillations superimposed on a mean flow that is on the verge of separating have been shown to be very effective to delay turbulent boundary layer separation.[10]

There are several separate efforts ongoing that seek to constructively control the location and/or extent of separated flow in LaRC's active flow control suite. The most visible of these research topics has grown out of a successful partnership between Tel-Aviv University* and NASA LaRC.† This partnership has resulted in many important results helpful to pushing the technology of separation control by oscillatory excitation towards practical application. One of the most important results of the collaboration has been the demonstration of the validity of oscillatory excitation for separation control under conditions often seen on full-scale aircraft. The effects investigated in the 0.3 m Transonic Cryogenic Tunnel (0.3 m TCT) at LaRC include high Reynolds numbers, compressibility, mild sweep (with a geometry specified separation location), and location of excitation slot.[11] Initially, the low Reynolds number experiments of Seifert[12,13] were repeated at chord Reynolds numbers (Re_c) up to 37 million and low Mach (M) numbers to demonstrate the effectiveness of periodic excitation with a fully turbulent incoming boundary layer.[14] The research in the 0.3 m TCT used an oscillatory blowing valve that provided steady blowing and steady suction, an oscillatory disturbance, or a superposition of steady and oscillatory disturbances. Seifert and Pack also found that steady suction and periodic excitation are comparable in effectiveness and the combination of weak steady suction and periodic excitation is extremely effective.

In light of these initial studies, LaRC contracted The Boeing Company to conduct a system study of separation control using unsteady excitation to identify feasible applications with high payoff potential.[15] This study identified simplified high lift as the best candidate for separation control. The concept of simplified high lift is illustrated in Figure 3 and consists of a drooped leading edge and a simple hinged flap. Thus the extended surfaces and tracks are eliminated. Unsteady excitation for separation control is applied near the drooped leading edge hinge line and near the flap hinge line.

The Morphing Project is currently investigating the feasibility of such a system based on the system study recommendations. A 2D model with oscillatory excitation applied on a modern cruise optimized supercritical airfoil is being used. Piezoelectrically-driven synthetic jets provide the periodic excitation. Control of the separation aft of the drooped leading edge resulted in the delay of the stall angle by 1° to 2° and a corresponding increase in the maximum lift coefficient by approximately 10%.[16]

As this technology progresses to higher TRL, the TCAT Program will provide the funding to push to larger scale 3D demonstrations with embedded actuation. In addition to LaRC's internal research goals, TCAT is partnering with The Boeing Company and the DARPA Micro Adaptive Flow Control (MAFC) program to evaluate the application of zero net mass actuation to the high lift system of Advanced Theater Transport vehicle concept for evaluation.‡,§

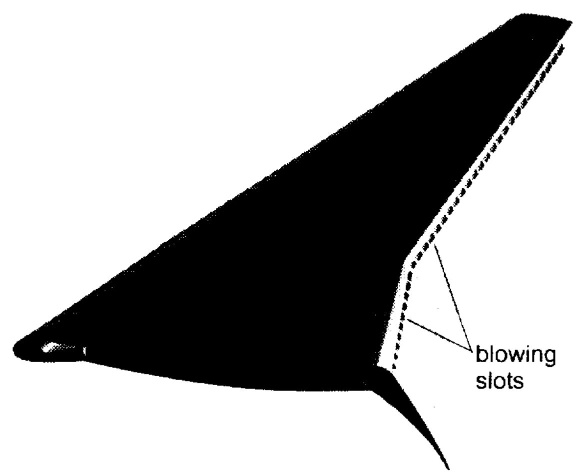

Figure 3. Simplified high lift concept.

Maneuvering

Under a contract awarded to the Georgia Tech Research Institute (GTRI),** researchers are exploring the effectiveness of synthetic jet devices to control leading edge separation on a highly swept UAV shown in Figure 4. These devices will be used at high angles of attack as a maneuvering control effector. This

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† LaTunia Pack

‡ Thomas Austin, Boeing Phantom Works

§ Tony Washburn

** David Parekh, GTRI

application will investigate the feasibility of replacing leading edge high-lift devices for high angle of attack maneuvering and gust load alleviation. This style of distributed vehicle control will be used to study new vehicle control schemes. If the full-scale wind tunnel test planned is successful, the synthetic jet arrays will be installed in the actual flight vehicle. The wind tunnel proof of concept test is planned to occur in the NASA LaRC Transonic Dynamics Tunnel during the fall of 2002. The platform is the Boeing Stingray described by Parekh and Glezer.[17] The full-scale wind tunnel model is currently in construction and will be instrumented with static pressure transducers, unsteady pressure transducers, accelerometers, and an internal strain gage balance. It is expected that there will be four banks of four sets of synthetic jets arranged in a row across the span of each wing. Small-scale tests are underway at GTRI to determine the final placement of the actuators and instrumentation.

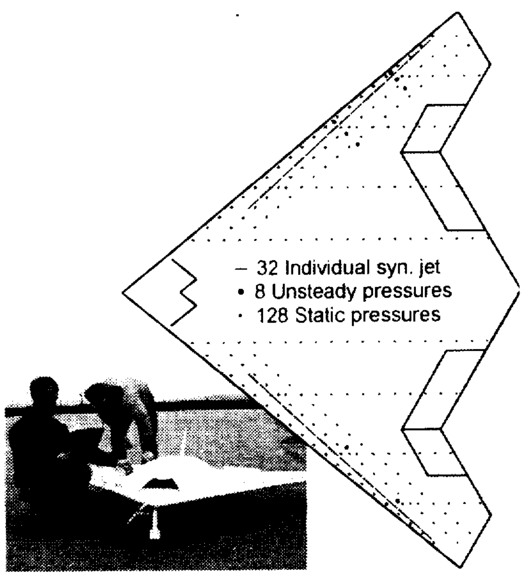

Figure 4. Stingray

Propulsion/airframe Interactions

LaRC is funding two grants with the Florida A&M University* to explore the feasibility of using supersonic microjets in an adaptive control system as an active flow control system. Under the first grant, the distributed supersonic microjet concept is being evaluated for effectiveness in controlling separation under an adverse pressure gradient. This work has just completed the first year of the 3-year grant, and the potential of the microjets as a flow control device has prompted a second grant to develop an active flow control strategy with feedback. This second grant has only recently been awarded.

Physics/ Modeling/ Validation

The prediction of the unsteady actuator flows and their interactions with an external flow field is a critical issue for the design of revolutionary vehicles incorporating flow control. The NASA LaRC Morphing and ASCoT projects have teamed together to address this area. The ASCoT Project is taking the lead in developing and validating time accurate CFD with particular focus on flow and noise control technology. The Morphing project is providing the application focus and the experimental database necessary for the validation effort.

The time accurate computations that are required for flow control are expensive and push the state of the art in CFD. To date, most of the effort in CFD development has been directed toward improving the efficiency and accuracy of Reynolds-Averaged Navier Stokes (RANS) solvers. The geometries and systems that are of interest in flow control are too complex for Large Eddy Simulations (LES) and Direct Numerical Simulations (DNS). The approach in the ASCoT program is toward improving the efficiency and accuracy of current advanced time-accurate RANS solvers by carefully examining the robustness of high-order methods in time and space. This allows much less computational work because larger time-steps can be used in the calculations. ASCoT is also conducting a detailed evaluation of the new hybrid solvers that have been proposed in the last few years. These solvers attempt to seamlessly integrate an LES solution for the separated regions and a RANS solver for the rest of the flow field. Perhaps the best known of these methods is the Detached Eddy Simulation (DES).[18] The ASCoT project is also supporting university research into non-stationary turbulence models for unsteady flows.

NASA LaRC is working toward the development of several benchmark experiments for the validation of time-accurate methods. It requires both computational and experimental researchers to work together to reduce the uncertainties in both the data and computations. The CFD methods need to know all the boundary conditions for the simulations, including inflow/outflow conditions, mass flows, velocity profiles, and facility interference effects. Each group must appreciate the difficulties and limitations of both approaches (e.g. computational and experimental). The experimental validation is a laborious and complex task utilizing multiple measurement techniques to provide an uncertainty bound for the data. Each experiment will use a combination of hot-wire, Laser Velocimetry (LV), Digital Particle Image Velocimetry (DPIV), and a host of surface flow measurements. The set of experiments will include an isolated synthetic jet in both a quiescent and crossflow, and the Hump model described below.

The Hump model shown in Figure 5 was previously tested in the 0.3-m TCT as a flow control experiment by

* Farrukh Alvi, Florida A&M

Pack and Seifert[19,20] at compressible speeds a high Reynolds numbers. They demonstrated that the frequency scaling used for airfoils was also appropriate for the control of the turbulent separation bubble that occurs on this model. With the Hump model the separation is set by the geometry due to the highly convex surface at 60% chord. The uncontrolled flow separates at 65% chord and forms a large turbulent separation bubble, the length of which can be controlled through blowing, suction, or oscillatory excitation at either of two slots located upstream of the natural separation location.

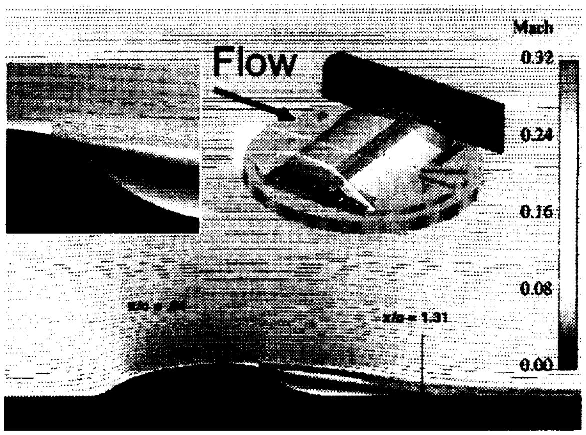

Figure 5. Hump model for code validation with uncontrolled separation. (courtesy of S. Viken).

The prior test was very successful in demonstrating and validating particular aspects of flow control, but lacked some of the information required for CFD validation (e.g. complete boundary condition data). The next round of experiments with this model will be conducted in a low-speed facility with optical diagnostic capabilities. The incoming boundary layer will again be fully turbulent, so that boundary layer transition will not be issue. External actuation will be applied using both steady blowing/suction and periodic excitation. The dataset generated for code validation will consist of DPIV and static and unsteady surface pressures. Additionally, careful attention will be placed on determining and measuring the appropriate boundary conditions, as well as characterizing the slot velocity profile. Flow field maps of the mean and turbulent Reynolds stress in streamwise planes across the model will be developed.

Shock/Boundary Layer Interaction

Drag Reduction

LaRC* is working to reduce the cruise drag on commercial supercritical airfoils while flying at off-design conditions using a concept that employs a small local contoured shape change near where the shock impinges on the wing.[21] The application of this technique would be an adaptive bump that would change height distribution as a function of Mach number and lift coefficient to cause a more isentropic compression and thus "spread" the shock. The weaker shock would act as a reduction in wave drag as well as lessen the likelihood or extent of shock-induced boundary layer separation. Therefore, the buffet boundary could feasibly be increased as well reducing fatigue and improving handling qualities. This sort of technique fits well within the Morphing Project vision of seamless aircraft. Promising results have been reported by Bur and Corbel[22] through an investigation of a shock/turbulent boundary layer interaction on a tunnel wall. Rosemann et al[21] report drag reductions in excess of 20% on 2-D transonic airfoil tests.

LaRC is employing a variety of CFD methods to optimize the contour bump shape. These include using an adjoint method and CDISC[23,24] coupled with an unstructured RANS solver (FUN2D[25]) and using CDISC with an integral boundary layer code coupled to an Euler solver (MSES[26,27]). An example of an off-design Cp distribution for the baseline airfoil and an optimized bump shape designed with CDISC coupled with FUN2D is illustrated in Figure 6. The baseline Cp distribution shown in Figure 6 is an example of a condition where a strong shock near x/c = 0.75 causes boundary layer separation on a turbulent supercritical airfoil at a C_l of 0.7 at an off-design Mach number.

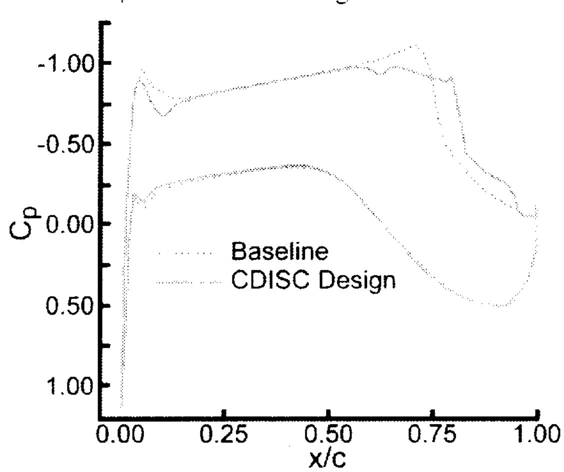

Figure 6. *Cp* distribution for shock spreading bump design

During the optimization cycle, C_l is held constant and the solution is optimized for total drag reduction. The angle of attack is allowed to vary and the surface modification constrained to a region on the aft portion of the upper surface. The Cp distribution for the optimized shape shows a more gradual compression upstream of the shock, a more downstream shock

* William Milholen

position, weaker shock and better pressure recovery indicating an attached boundary layer until very close to the trailing edge. According to the calculations, the optimized bump in this case resulted in a reduction in C_d of 24.5%.

A few different static shapes will be tested experimentally in the NASA LaRC 0.3-m TCT to verify the computational methods. Pending success in that demonstration, multi-disciplinary work will begin to determine how to implement this concept in a practical manner through coupled aerodynamic and kinematic design tools. Additional follow-on research may include active control on the wing trailing edge through either fluidic control or an active trailing edge. In addition the research to address the challenge of integrating deformation and flow sensors into a flexible surface is beginning.

Maneuvering

Another area that seems ideal for active flow control is the topic of fluidic thrust vectoring and throat area control. There are a host of benefits when thrust vectoring is implemented on military vehicles and there is potential to implement it on commercial vehicles to replace trim devices on the wings and tail. The use of fluidic injection vectoring concepts would be beneficial over mechanical devices in terms of signature, weight and drag. Due to these potential benefits, LaRC* is working to develop and demonstrate fluidic injection and fluidic thrust vectoring (FTV) technology for application to a variety of nozzle geometries, configurations, and operating conditions. The general approach in FTV is to implement the vectoring by injecting a secondary stream of air into the primary jet so that the efficiency of the system is maintained at a high level. There are several different approaches that have been attempted including counterflow,[28] shock vector control,[29] and throat skewing.[30]

Counterflow requires very small amounts of secondary flow and produces a ratio of resultant thrust to ideal thrust (thrust efficiency) typically between 0.92 and 0.97. Unfortunately, the jet flow can become attached to the diffuser wall and is difficult to detach. This coupled with the necessity for a long diffuser severely limits useful application of the counterflow technique.

LaRC has more recently been studying the shock vector control technique. This technique consists of injecting the secondary air into the supersonic divergent portion of the nozzle thus causing a shock that skews the flow in the opposite direction. In shock vector control large deflection angles can be achieved (up to about 15° total at a rate of approximately 2° to every 1% of secondary flow mass injected) but with thrust efficiency only in the range of 0.92 to 0.94. The shock vector research at LaRC has had both computational and experimental efforts. In this area, static test experimental data has typically agreed well with computational data using a structured grid RANS solver (PAB3D) with a k-ε two-equation turbulence model for steady fluidic injection. Analysis of an unstructured solver for fluidic thrust vectoring is also ongoing.[31] For yaw control, the shock vector technique is reliable, however, during recent tests[32] using a multi-axis concept it was found that the aft deck greatly affected the pitch vectoring performance. In this application the minimum goal was to achieve pitch deflection angles from ±5° to ±10°. Unfortunately, pitch angles of only +4° and -3° were realized. Therefore the conclusion is that shock vectoring is not effective for this application.

Another concept for fluidic vectoring control is known as throat skewing. This technique, extensively studied by Miller et al[30] is a descendent of the mechanical concepts that demonstrated the improved efficiency of applying control in the subsonic portion of a nozzle. In this technique, fluidic injection is applied near the nozzle throat to shift the sonic line, turn the subsonic flow, and create an asymmetric pressure loading. The turning figure of merit is less than shock vectoring (approximately 1.5° deflection per 1% secondary flow mass injection), but thrust efficiencies in the range of 0.94 to 0.95 are typical for this technique. LaRC has recently started investigating another variation of thrust vectoring that takes advantage of subsonic turning as well.[32] CFD studies to date predict pitch deflection angles as high as 14.5° at rates of 2.1° deflection per 1% secondary flow mass injection with thrust efficiencies larger than 0.97. This technique should be effective for multi-axis vectoring as well. Experiments to validate the computations are planned for fall of 2002.

The effect of the freestream on the deflection angle can be large and detrimental for fluidic injection techniques. Figure 7 summarizes the results of a computational study of these effects on shock vector control at several free-stream Mach numbers. On average, the deflection angles are reduced by approximately 2° at all conditions computed. LaRC is actively working to validate these effects in the 16' Transonic Tunnel. The testing has been delayed due to difficulty with the bellows to bring the secondary air source across the force balance.

Propulsion/Airframe

The oblique shock system in supersonic inlets has typically been stabilized with bleed air. An alternate technique[33] taking advantage of the properties of shape-memory alloys (SMA) and the concept of a porous surface over a cavity near shock impingement was

* Jeffrey Flamm

proposed by a team led by the University of Illinois.* The concept uses an array of SMA flaps over a cavity in the region of the impinging shock to provide mass and momentum transfer thus stabilizing the shock location. The individual SMA flaps (called mesoflaps) are rigidly fixed at their upstream end and are designed to go through an aeroelastic deflection to achieve the proper mass bleed or injection. The DARPA MAFC program has been the primary funding agent for the development of this technology.

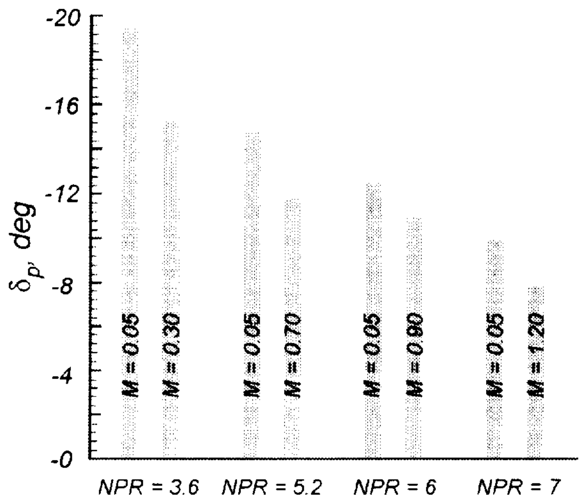

Figure 7. Effect of freestream flow on vectoring performance. [29]

Recently NASA's UEET program† has joined in this research topic by building a supersonic inlet wind tunnel model based on the F-15 inlet and providing in-kind funding to conduct a supersonic wind tunnel test in the NASA LaRC Unitary Plan Wind Tunnel. The inlet model is shown in Figure 8 installed in the wind tunnel. The model was tested with a conventional bleed system designed by NASA Glenn Research Center‡ and a passive porosity panel (PassPorT)§ system designed by NASA LaRC in addition to the mesoflap system for comparison. Data analysis is underway.

Physics/ Modeling/ Validation

In active flow control, actuator authority is often the pacing technology. The Georgia Institute of Technology** and GTRI conceived a high-power actuator based on combustion under the Adaptive Virtual Aerosurface (AVIA)[17] project with funding provided by the DARPA MAFC program. These devices can be very small and are very simple. They use premixed fuel/air and a MEMS spark to ignite the fuel in a combustion chamber causing a deflagration and a release of high momentum flow through the orifice. The pulse rate is dependent of the refill rate of the fuel in the chambers and rates up to approximately 200 Hz have been obtained. Additional information on the capabilities of these actuators can be found in Crittenden et al[34] and Funk et al. [35]

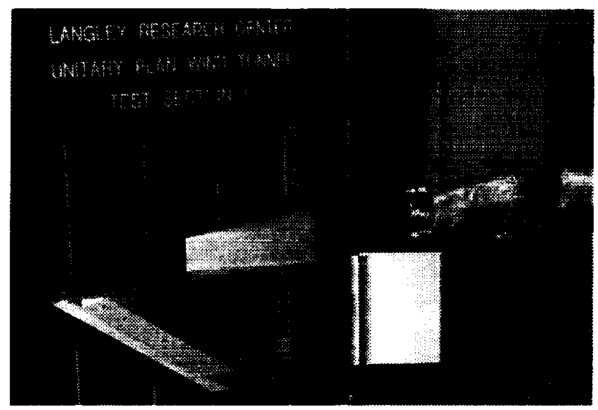

Figure 8. Supersonic inlet for Mesoflap investigation.

LaRC, under a memorandum of agreement (MOA) with Georgia Tech is providing wind tunnel time in the 20" Supersonic Wind Tunnel (20" SWT) to investigate the physics and suitability of this actuator concept to control the location of the shock on a 2D transonic airfoil sponsored by DARPA. The actuators will be located near the shock impingement region. The airfoil angle of attack will be varied as appropriate from 0° to 10°. Surface pressures, phase-locked schlieren, wake measurements, and aerodynamic loads will be obtained during the test which is expected to occur during late summer of 2002.

Research on a new concept for flow control actuators has also recently begun at LaRC. In an effort to develop very high authority actuators for high-speed flows, detonation-based actuators are being investigated.†† Numerical design studies are underway to determine minimum size, spark energy and pressure ratios to create a detonation wave, creating a pulsed jet. Numerical results from the first generation design indicate Mach numbers well in excess of 2 can be achieved with a fairly small device. Experiments on the first generation device are expected to occur in 2002.

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‡ David Davis, NASA Glenn Research Center

§ Steven X. S. Bauer

** Ari Glezer, Georgia Institute of Technology

†† J. Philip Drummond

Shear Layer Control

Noise

The control of the noise generated in a subsonic jet plume is an important and difficult problem as public sensitivity to aircraft noise increases. This is especially true at takeoff when the jet noise is a primary component of the total measured and perceived noise. In jet flows, the shear layer formed at the exhaust tip is highly unstable and rolls up into large-scale vortical structures known to be directly or indirectly responsible or the jet noise generation and jet mixing with the surrounding fluid.

The difficulty of jet noise control is exacerbated because the noise generation is from a noncompact volume of uncorrelated sources that are external to the jet itself. This coupled with the strong directivity of the noise pattern make it hard to correlate the noise, pressure, or turbulence field at a convenient location (under a wing body or on a pylon, for instance) with the peak jet noise direction, which is downstream away from the jet. Also the location where control input is desirable near the shear layer separation location is displaced many jet diameters upstream of the noise sources. Here again a reduced order model to develop a transfer function between the noise generation field and locations where measurements are available may be the key to active control. This model will likely have to be based on physical understanding since the jet noise field is very nonlinear and uncorrelated in some areas.

The research ongoing in active noise control of both rectangular and axisymmetric jets at LaRC under the Morphing Project is a multi-pronged effort.* The research topic attempts to maintain a balance in fundamental flow and acoustic measurements and analysis, actuator development, advanced measurement techniques and control strategy to understand and explore fundamental physics of jet flows in order to develop advanced active control technology.

Two approaches are being pursued. In the first, the shear layer instabilities are being manipulated in a time dependent manner to attempt to reduce the noise generation from the downstream sources. In the second approach, done in partnership under MOA with the Goodrich Corporation, the mean flow is modified using the concept of jet shaping. This is similar to the use of chevrons as noise reducing devices. Eventually, a combination of both techniques may be employed.

A grant to Notre Dame† is in its second year to quantify jet coherent structure via Proper Orthogonal Decomposition (POD). The POD modes are projected onto instantaneous local realizations of the flow to obtain the jet coherent structure in physical space. Significant restructuring of the coherent structure is observed over the range of $3 < x/D < 9$, where x is streamwise distance and D is the jet diameter. Currently the relationship between the coherent structure evolution and the radiated acoustic field is the focus as well as obtaining new data at higher subsonic Mach numbers.

Physics/Modeling/Validation

The control of the development of large tonal and broadband pressure fluctuations that develop as a result of flow over an open cavity is an interesting and challenging problem that LaRC is pursuing. The flow over an open cavity is characterized by a complex process that leads to large oscillations of the pressure, velocity and density fields in and around the cavity through a coupled interaction between the fluid dynamics and the acoustics. The control of this phenomenon involves elements of both free shear flow control as well as noise reduction. For shallow cavities, where length to depth ratio is greater than 1, the frequencies of the tonal oscillations are primarily determined by the Mach number. Cavity flows of this type are pertinent to a range of real-world problems and represent a truly classical adaptive flow control problem. There are a number of research activities in the U. S. addressing the problem through closed-loop disturbance control,[36] high frequency excitation,[37] and techniques to modify the mean flowfield.[38] LaRC‡ is using closed-loop cavity control as a model problem to push technology in wide-bandwidth actuation using advanced materials, and as a testbed to use for the application of various control schemes to fluid problems where actuator authority is limited.

Previously closed-loop control using asynthetic jet actuator at the cavity leading edge had been established. Various linear controllers were applied from simple gain/delay schemes to generalized predictive controllers. These techniques were able to reduce multiple tones in the spectra by up to about *10 dB*.[39] The actuator authority was limited, and noise reduction could not be established at $M > 0.45$.

Recently, a new wide bandwidth piezoelectric flap actuator (*~1200 Hz*) has been designed using and implemented at the leading edge of the cavity. This actuator is used with an insitu measurement of tip displacement as a direct measure of actuator performance. Using this new actuator, the ability to introduce disturbances into the shear layer has improved, with no degradation in actuator performance up to $M = 0.6$. A second year cooperative agreement with University of Florida§ is to implement adaptive

* Kevin Kinzie

† Tom Corke, University of Notre Dame

‡ Mike Kegerise

§ Louis Cattafesta, III, University of Florida control techniques to active flow control problems. The first problems to be considered are the cavity control problem and then the active jet noise problem. The latest developments in this research can be found in Kegerise et al.[40]

Vortex Control

Maneuvering

It has been demonstrated by Roos[41] and Lee et al[42] that unsteady fluidic injection can be used to control the yawing moment on slender bodies of revolution at high angles-of-attack. A brief investigation was done at NASA LaRC to evaluate the potential of zero-net-mass synthetic jets to control the yawing moment on a chined forebody similar to an advanced fighter forebody in the Langley 12-foot Low Speed Tunnel.* An existing model was selected with a removable nose region that would enable the incorporation of the piezoelectric actuators into the chine. The actuator (four disk diaphragms in one cavity) was installed with slots on the chine leading edge. The investigation included nozzles for both normal blowing and tangential blowing. The chine could also be oriented for a high-chine setting and a low-chine setting. Unfortunately this model did not allow the forcing to be near to the nose of the forebody. Laser light sheet flow visualization and surface pressure measurements indicated that the synthetic jet did have an effect on the vortex structure in the region of the nozzle, however the effect was not significant enough to cause a measurable change in the forces and moments of the forebody.[43] A slender body of revolution wind tunnel model has been fabricated with various fineness ratios and variations in the bluntness of the nose region. A pulsed blowing system employing the fuel injector described by Schaeffler et al[44] will be implemented so the fluidic injection can be introduced very near the apex. The new forebody model will rotate along its centerline to allow variation of the location of injection with respect to the vortex separation line. This research is expected to be complete in 2003.

Circulation Control

Lift Enhancement

A NASA focus on general aviation aircraft technology needs has brought about new research for improving high-lift performance. Consideration of lift enhancement techniques could not preclude circulation control. Although there are examples of other uses of circulation control[45] high-lift has been a main focus. Circulation control has a solid record of producing significant lift augmentation[45] and past techniques have used steady blowing to accomplish this. A new research effort at NASA LaRC† is focusing on using unsteady blowing to produce equal or greater lift increments compared to the steady-blowing case.[46] An example case is shown in Figure 9. For the same flow rate of 1 lbm/s, the pulsed-blowing case results in a 35% increase in C_l over the steady-blowing case. Or, for a constant C_l of 1.0, there is a 45% decrease in mass flow for the pulsed-blowing case. More information on the NASA LaRC effort to develop a General Aviation Circulation Control wing concept can be found in Jones et al.[46]

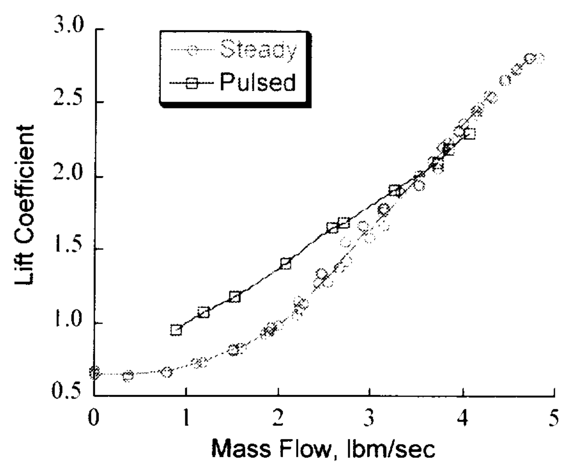

Figure 9. Benefit of pulsed blowing at 30 Hz for $\alpha = 0°$ and $q = 10$ psf.

Maneuvering

Traditional mechanisms for maneuvering a vehicle are generally adequate but are typically not ideal. Their shortcomings vary from application to application but they include the usual issues of complexity, weight, and maintenance. A search for substitute methods of producing changes in aerodynamic forces will consistently produce a list of techniques that will include the powerful technique of circulation control. However, circulation control has historically focused on the low-speed high-lift application. Although there has been some promising results on helicopter blade applications,[47,48] there is comparatively little research in the use of circulation control at high subsonic Mach numbers. For application to wings at transonic conditions, the aerodynamic efficiency (drag) and the necessary air capacity has been a stumbling block for applying circulation control at high subsonic cruise Mach numbers.

* D. Bruce Owens

† Greg Jones

New research at NASA Langley is focusing on using circulation control for mild maneuvering at Mach 0.8.* This research will pave new ground for transonic circulation-control research. The literature is limited for transonic circulation control wings and this new research will help address the shortfall, and it will investigate new possible advances in this area. These new areas are the use of pulsed blowing and the use of dual slots for maneuvering at cruise. Pulsed blowing will be used to drastically cut the required mass flow compared to the steady case. Slots on the upper and lower surface will be used to produce positive and negative lift and to close the wake of the relatively blunt trailing edge of the airfoil to minimize the drag penalty. The transonic airfoil brings about an additional important variable compared to the low-speed case, the effects of the upper-surface shock. The shock and its effect on the downstream boundary layer can impact the ability of the jet to stay attached to the Coanda suface. This of course directly impacts the lift augmentation. An example computational result for blowing from the upper slot at Mach 0.8 is shown in Figure 10. The jet stays attached to the Coanda surface to about 90°-100° for this case. Note that the jet is also performing boundary-layer control as well as producing the Coanda effect. The computational results are obtained with FUN2D.[25] This is the same tool used for the low-speed lift enhancement research by Jones et al.[46] The research will progress to two-slot designs that will be used in a 2D transonic wind tunnel test in 2003.

Boundary Layer Control

Drag Reduction

Practical implementation of active control and reduction of viscous drag in turbulent boundary layers is one of the more difficult goals in the suite of activities at LaRC.† However, it is probably second only to separation control in potential payoff for performance enhancement through an efficiency standpoint. Approximately 50% of the drag of commercial transport aircraft at cruise is caused by skin friction.[49] Skin friction drag is an even greater percentage on underwater vehicles, comprising nearly 90% of the total drag penalty. Therefore, it is easy to see that revolutionary payoffs are possible through the successful reduction of viscous drag.

The turbulent boundary layer is characterized by small three-dimensional vortical structures. These structures are semi-organized into low- and high-speed streaks in the streamwise direction and burst intermittently and randomly in space as well as in time.[50] The general consensus is that the bursting process (where the low speed streaks lift up) is responsible for up to 80% of the boundary layer skin friction. Hence, most active flow control schemes are geared to reducing the number of bursts that occur either through favorable organization of the low- and high-speed streaks, or through their elimination.[51,52,53] Direct numerical simulations have indicated that turbulent skin friction reduction on the order of 30-40% may be possible using active control.

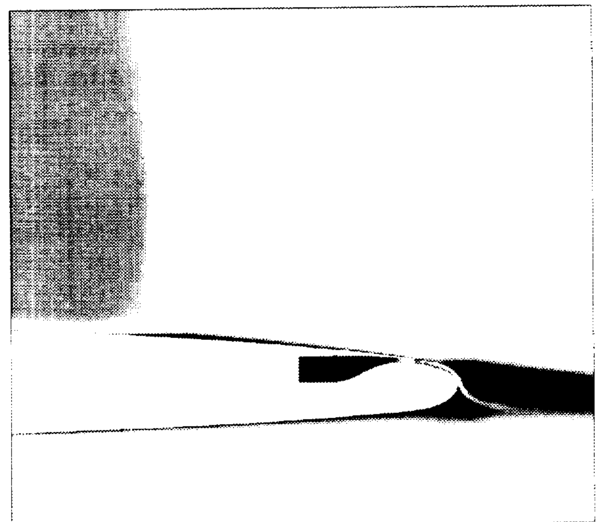

Figure 10. Circulation-control for mild manuevering at Mach 0.8.

NASA LaRC's long history in turbulent boundary layer research and passive viscous drag reduction techniques forms a strong base from which to pursue active drag reduction experimentally.[54,55,56] LaRC is using DPIV, hot-wires, skin friction, and pressure measurement techniques to understand and detect organized structures in the boundary layer. Much of this research is being conducted in the 20" x 28" shear flow facility and the 7" x 11" tunnel. Promising control schemes will be verified on the air-bearing drag balance in the 7" x 11" tunnel.

Recent DPIV results from the 20" x 28" facility are shown in Figure 11. Figure 11 illustrates the instantaneous low- and high-speed streaks in a plane at a height of 7 wall units ($y+$) above the tunnel floor. Data have been obtained at free-stream velocities of 2.5, 5 and 10 *m/s* with the DPIV system. The character of the boundary layer is consistent with established values, the vortex structures are on the order of 20 wall units in diameter, spaced randomly between 80 and 140 wall units apart.

LaRC has used fixed vortex generators (VG) to organize vorticity in the turbulent boundary layer. Each individual VG generates a pair of counter rotating vortices. Combinations of different heights, and spacings were tested at several free-stream velocities. DPIV was able to measure the near wall structures.

* Scott Anders

† Mike Walsh

These experiments are being used to provide guidance for future oscillating VG tests.[57]

A grant to Texas A&M* was established to develop and implement a mechanically actuated active skin traveling wave.[58] LaRC is attempting to design and fabricate a new piezoelectric surface that will produce frequencies from approximately 100-1000 Hz using Macro-Fiber Composite (MFC)[59] technology. Another approach under investigation to actuate traveling waves for turbulent boundary layer control is the use of a phased array of weakly ionized plasma actuators.† Oscillation of the plasma generates unsteady body forces acting on the flow.

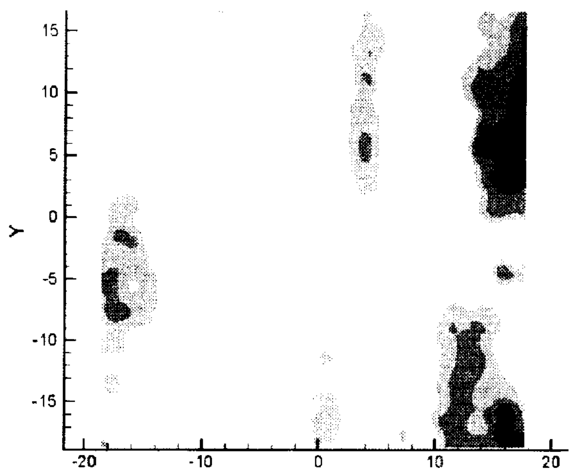

Figure 11. Steamwise velocity in turbulent boundary layer at $y^+ = 7$.

Maneuvering

In the area of maneuvering control through boundary layer control, the concept of using synthetic jet actuators to create a "virtual shape change" was recently investigated on a NACA 0015 airfoil.[60] The results indicate that synthetic jets with much more authority are necessary to make this approach feasible at reasonable Mach numbers.

Propulsion/airframe

The UEET PAI project has several components to support the goals of minimal distortion and maximum pressure recovery in a BLI S-inlet. There is work on-going to establish an experimental high Reynolds number baseline data set for a representative BWB inlet, research in internal flow control actuators and their effectiveness in a BWB configuration, development of sensors and actuators to support the experimental efforts, development of models and simulations to support the design of active flow control systems, and exploratory work in establishing a closed loop control system for the configuration.

A contract was awarded to The Boeing Company to design a generic S-inlet representative of the general class of inlets expected to be used on a BWB configuration. Using this geometry, two test articles have been fabricated by LaRC. The first test article is an inlet to be tested to high Mach number and Reynolds number in the 0.3-Meter Cryogenic Tunnel at LaRC.‡ This test article will provide information with which to correlate the separation and distortion calculations that have been predicted for this type of inlet. Figure 12 shows the schematic of the inlet that is currently being installed in the tunnel.

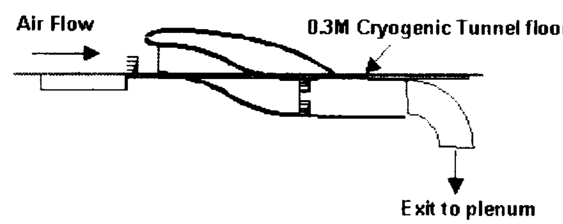

Figure 12. Schematic of inlet installation in 0.3 TCT

Efforts are on-going to explore the effects of active flow control devices on the S-inlet geometry in a less harsh environment. Thus a model is being fabricated for testing in the low Mach number Basic Aerodynamics Research Tunnel (BART) in September 2002.§ This model has the same geometry as the 0.3-Meter Cryogenic Model, but it will be easier to install instrumentation and flow control devices.

As part of the risk reduction effort for the BART testing, several different flow control devices, both active and passive, are being evaluated for their effectiveness in mixing the flow and controlling separation in an adverse pressure gradient along a 2-D ramp in the 15 Inch Low Speed Tunnel at LaRC. The effectiveness of available piezoelectric synthetic jets was determined to be minimal in this environment and not as effective as micro vortex generators.[61] Additional actuator assessment testing is underway using the adverse pressure gradient ramp with steady and pulsed blowing. The initial results of the steady blowing indicate that it may be more effective than the μVGs in establishing pressure recovery; the pulsed blowing testing has not yet started. These flow control devices will be positioned along the inlet and controlled using a closed-loop feedback control system during the BART test later this fall.

In addition to the development of actuators, the advancement of sensors for detection of separation and

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† Steve Wilkinson

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§ Susan Gorton

flow mixing has been supported by the UEET program. In particular, a MicroElectricalMechanical (MEMS) sensor suite was fabricated and evaluated for this application.* The MEMS sensor suite contained six sensors in a 300 micron area. There were two shear sensors, two pressure sensors, and two temperature sensors. The sensor suite was tested in both a zero pressure gradient and an adverse pressure gradient environment. The pressure and temperature sensors appeared to track well with conventional instrumentation, but the shear stress sensor calibration was insufficient to yield satisfactory results. New and different approaches to the shear stress sensor development are being implemented at this time, with some emphasis on direct shear measurement and some concepts using nanotechnology.

In an integral and complementary partnership with the experimental investigations, research efforts in CFD are also supported under the UEET program. The main objective of the computational research is to establish a public-domain, validated design tool for active flow control of inlets.† Towards this end, the Navier-Stokes solver OVERFLOW[62] has been used to validate the implementation of a source-term model of vortex generators. This methodology is based on the work reported by Bender[63] and is being validated by comparison to both computations of gridded vortex generators[64] and to experimental data obtained on a single vortex generator.[65] Steady and unsteady jets are also being added to OVERFLOW to model active flow control devices. The model of the steady jet has been used to predict the effectiveness of an integral controller using pressure differential as the feedback for controlling separation on the adverse pressure gradient ramp. Figure 13 shows the performance of the controller. The unsteady jet model is on schedule to be implemented in OVERFLOW by the end of the year.

Physics/ Modeling/ Validation

Experiments are underway for the development of an experimental database suitable for CFD code validation and modeling of synthetic jet actuators.[44] Detailed and redundant measurements are being obtained for a synthetic jet in quiescent flow using 3 component laser velocimetry (LV), DPIV and hot-wire anemometry. In additional to the flowfield measurements, diaphragm displacement and cavity temperature and pressure are being acquired simultaneously. Both the numerical and experimental groups provided requirements and input for the selection of the synthetic jet configuration used for this dataset. The jet has a 2D slot. Detailed LV measurements with fine resolution (25 measurement locations across slot) have been obtained and sorted into bins with 5° spacing in phase angle.

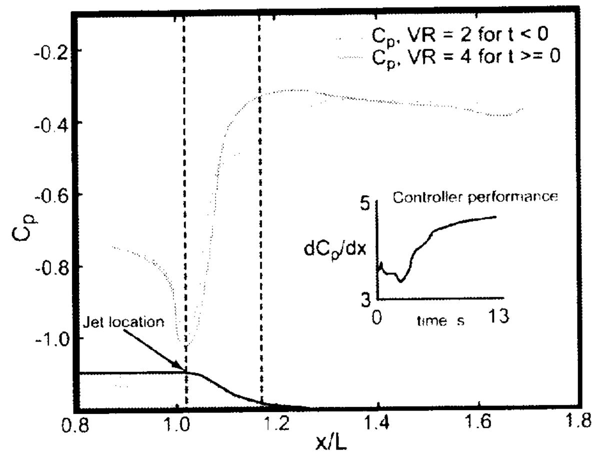

Figure 13. OVERFLOW calculations using an integral controller

In addition to the quiescent flow dataset, the interaction of synthetic jets with a turbulent boundary layer crossflow is under investigation by Schaeffler et al.[44] Measurements have been obtained with Stereo Digital Particle Velocimetry (SDPIV). A 2D slot, a circular orifice and an elliptic orifice were tested at Mach numbers of 0.05, 0.1 and 0.134. An example of the data is shown in Figure 14. The plot shows the mean streamlines and velocity vectors (not every vector is shown for clarity, actual resolution is 200 *µm* between vectors) calculated from the phase-locked measurements. The jet shown had benchtop performance of peak velocity of 45 *m/s*, rms velocity of 16 m/s at an operating frequency of 1730 *Hz*. In the data, the first vector row is 0.0905 *mm* above the wall and the orifice spans from ±2.4 *mm*.

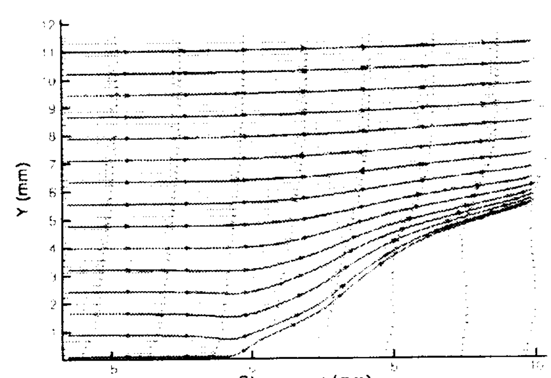

Figure 14. Mean streamlines of synthetic jet in crossflow at $M = 0.05$

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* Seun Kahng

† Pieter Buning

One of the goals of this research is to attempt to develop reduced-order models for use in CFD and validate the methodology. Figure 15 shows the velocity component normal to the wall at a height of 0.05 orifice diameters above the wall as a function of diaphragm phase angle in a $M = 0.1$ crossflow. Notice the complexity of the flow throughout the cycle as the leading edge and trailing edge shear layers interact.

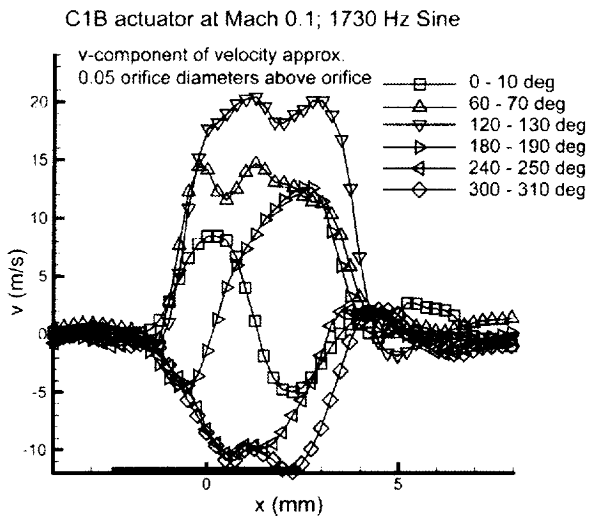

Figure 15. Velocity component normal to wall above synthetic jet in crossflow as function of phase angle.

To further study these complex interactions, LaRC is doing in-house computations* under the ASCoT Project as well as sponsoring a grant to the University of Florida with a subcontract to the George Washington University† to explore the advantages of using a moving boundary, Cartesian grid method (CGM) to analyze actuator design parameters. This work emphasizes the importance of the internal actuator design and the interaction between the actuator and the external flow. A major portion of this grant is to extend the current 2D model of a synthetic jet to a 3D model and to use this 3D model to include a realistic structural model of the piezoelectric diaphragm in the computational model. A detailed, parametric study of actuator design considerations will then be conducted.

This 3-year grant was initiated in 2001, and has just completed the first year. Significant progress has been made in understanding the jet performance in a crossflow and the internal flow inside the synthetic jet cavity.[66,67] The extension to 3D is well underway and is expected to be completed by the spring of 2003.

The University of Florida‡ is in the second year of a 3-year grant to develop design tools for active flow control actuators. The objective of this work is to use lumped element modeling to allow the synthetic jet actuator to be characterized into a set of coupled differential equations. Progress to date has included the development of electro/fluid/structural models of piezoelectric synthetic jets,[68,69,70] the design and fabrication of an experimental synthetic jet for model validation, and the development of a structural dynamic model for the design of piezoelectric flap actuators. The work in the third year of the grant will concentrate on the validation of the model and the comparison of the model with CFD results.

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† Rajat Mittal, The George Washington University

‡ Louis Cattafesta, III, University of Florida

Concluding Remarks

A summary of the various active flow control projects in progress at NASA LaRC has been presented. NASA as an agency has made a commitment to *Revolutionize Aviation.* NASA has also expressed a desire for long term, high-risk, high-payoff research in enabling technologies to achieve this revolution. Active flow control is considered one of these enabling technologies. LaRC intends to continue pursuing active flow control over a broad spectrum off applications. This research will develop and validate design and analysis methodologies, use applications that force integration issues to be addressed, and ensure that appropriate systems analysis is conducted so that active flow control can push through the "technological" filter.

Acknowledgements

The authors would like to gratefully acknowledge the contributions, material, and editory remarks provided by the researchers responsible for the individual topics. The authors also acknowledge the program managers who support the research efforts reported herein. The Morphing Project is led by Anna-Maria McGowan, the ASCoT Project is led by Long Yip, the UEET Program is led by Joe Shaw, and the TCAT Program is led by James Pittman.

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