Overview of Active Flow Control at NASA Langley Research Center

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ABSTRACT

The paper summarizes Active Flow Control projects currently underway at the NASA Langley Research Center. Technology development is being pursued within a multidisciplinary, cooperative approach, involving the classical disciplines of fluid mechanics, structural mechanics, material science, acoustics, and stability and control theory. Complementing the companion papers in this session, the present paper will focus on projects that have the goal of extending the state-of-the-art in the measurement, prediction, and control of unsteady, nonlinear aerodynamics. Toward this goal, innovative actuators, micro and macro sensors, and control strategies are considered for high payoff flow control applications. The target payoffs are outlined within each section below. Validation of the approaches range from bench-top experiments to wind-tunnel experiments to flight tests. Obtaining correlations for future actuator and sensor designs are implicit in the discussion. The products of the demonstration projects and design tool development from the fundamental NASA R&D level technology will then be transferred to the Applied Research components within NASA, DOD, and US Industry.

Keywords: active flow control, separation control, MEMS, review

1. INTRODUCTION

During the 1970's and 1980's a considerable amount of research was performed at NASA Langley Research Center aimed at turbulent drag reduction.[1] Emphasis was on passive flow control methods because of their relative ease of implementation and high payoffs. Riblets and micro vortex generators (VGs) in use on aircraft today are products of that research effort. Advances during the last decade, in the development of dynamic, distributed, and (often) micro-sized systems capable of enhancing our ability to control the unsteady flow in a wide variety of configurations has given rise to a new flow control research effort at NASA Langley Research Center. The emphasis is on active flow control methods, focusing on controlling the unsteady flow in a wide variety of configurations such as engine inlets and nozzles, combustors, automobiles, aircraft, and marine vehicles. Controlling the flow in these configurations can lead to greatly improved efficiency and performance, while decreasing the noise levels generally associated with the otherwise unattended unsteady flow. Depending on the desired result, one might wish to delay or accelerate transition, reduce drag, or enhance mixing. Furthermore, future high-performance aircraft may be able to maneuver with these control systems, thereby eliminating conventional mechanical control systems. Removing conventional controls could lead to significant weight reductions or decrease the aircraft radar signature.

In this paper, the following projects are summarized

(1) the control of instabilities associated with cavity flow,

(2) the control of airfoil flow separation by oscillatory blowing,

(3) the development and validation of on-demand vortex generators,

(4) the application of Micro-Electro-Mechanical Systems (MEMS) sensors and telemetry to determine the aerodynamic state of the flow,

(5) the development and testing of zero-net mass flux (or synthetic jet) actuators for lift enhancement and forebody control, and

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(6) the development and validation of computational tools toward understanding the unsteady aerodynamics associated with these new actuators and for determining actuator requirements for a given objective (e.g., maximizing lift).

2. CAVITY OSCILLATION CONTROL*

The complex flow field that exists over cavities has been the focus of research efforts for many years.[2–5] Flows over cavities are characterized by pressure fluctuations that can be large enough to cause damage to the items contained within the cavities and to the aircraft itself. Weapons bays and aircraft wheel wells are cavities where such problems exist. Passive means[4] of controlling these pressure oscillations have been investigated and are currently used to reduce the pressure oscillations but are usually effective at one design condition and typically result in a large weight penalty. Active means of controlling cavity pressure fluctuations are effective but have never been used due to severe systems penalties involved in implementing these methods. Advances in piezoceramic materials have renewed interest in active control of cavity pressure fluctuations because of their demonstrated robustness and ability to generate large local displacements. Recently, Cattafesta et al.[6] used piezoelectric actuators to control the pressure fluctuations associated with cavity flow at subsonic Mach numbers. The sound pressure level (SPL) in the cavity was reduced by up to 20 decibels.

At the NASA Langley Research Center (LaRC), research is underway to understand and to control the flow field over a cavity in the subsonic, transonic, and supersonic flow regimes. The LaRC Probe Calibration Tunnel (PCT) was modified for cavity experiments. A custom nozzle was designed to accommodate a 6 inch high, 2 inch wide test section with a 2 inch wide variable height cavity. For the cavity research described in the next two subsections, the operating Mach number ranges from 0.03 to 0.9, and the unit Reynolds number ranges from 2 to 11 million/ft.

2.1. Cavity Flow Physics

Active flow control of pressure oscillations associated with flow over a cavity requires an understanding of the mechanisms responsible for the unsteady flow field and the complex feedback mechanisms responsible for cavity resonance. The aeroacoustic feedback mechanisms associated with resonance conditions can drive the sound pressure levels to values greater than 165 decibels. Figure 1 shows a typical vortex structure and impact region at the trailing edge of a cavity with a length-to-depth (L/D) ratio of 4:1. Determining the physics of the feedback should lead to control schemes that will interrupt the resonance, thus reducing the SPL by as much as 20 decibels. The flow fields in cavities with L/D ratios of 8:1, 4:1, and 2:1 are being investigated using hot-wires to measure velocities, microphones to measure unsteady pressure, and schlieren for flow visualization. This flow physics information will help in devising and optimizing control systems for suppression of the SPL in the cavities.

2.2. Cavity Pressure Oscillation Control

Computational studies performed by Lamp and Chokani[7] showed that the SPL in a 2-D cavity could be reduced by introduction of a periodic disturbance below the lip of the upstream edge of the cavity. Lamp is currently performing experimental studies using pulsed injection for cavity pressure control. A pulsed injection valve is being used to generate a periodic disturbance (jet) just upstream of a cavity with L/D ratio of 4:1 at two discrete locations.

3. SEPARATION CONTROL†

The control (or prevention) of boundary-layer separation on two-dimensional airfoils by the periodic introduction of momentum through a slot in the model was demonstrated in low Reynolds number wind-tunnel experiments.[8,9] The technique is effective because it promotes mixing between the higher momentum fluid above the otherwise separated region and the lower momentum fluid near the surface. The enhanced mixing brings the higher momentum fluid

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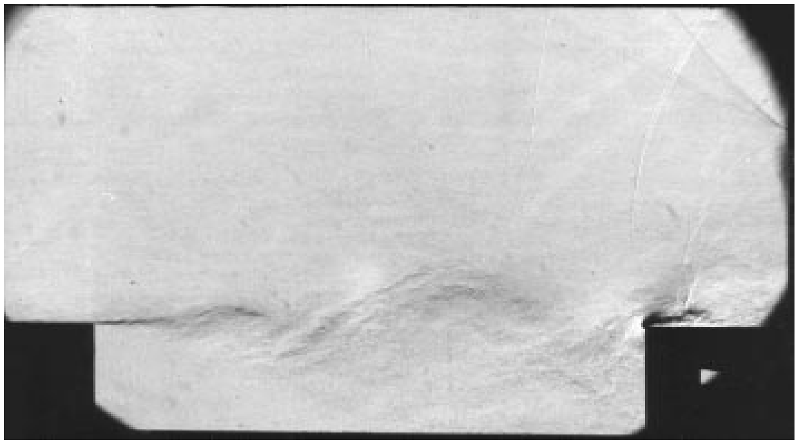


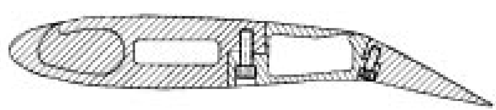
Figure 1. Schlieren photograph of the 4:1 cavity, Mach: 0.74, Re/ft: 6x10^6

close to the surface making the boundary layer more resistant to separation. This active means of control has the advantage of eliminating or reducing separation without the performance degradation at off-design conditions associated with passive devices. Also, the periodic control is two orders of magnitude more efficient than steady blowing traditionally used for separation control.[9,10] A recent paper by Wygnanski highlights research being done using periodic disturbances for active flow control.[11] Research is being performed at NASA LaRC to determine the effect of high Reynolds number on separation control using a periodic disturbance.[10]

The low Reynolds number experiments of Seifert et al.[8,9] were repeated at LaRC in a cryogenic pressurized wind tunnel to enable testing at chord Reynolds numbers as high as 31 million at low Mach numbers (typical of subsonic transport takeoff/landing conditions). Two unswept NACA 0015 models were constructed for the tests. One model had a 0.2% chord wide slot at 10% chord and the other model had a 30% chord trailing-edge flap deflected 20^o and a 0.17% chord wide slot at 70% chord (the flap shoulder) (see Figure 2). Oscillatory blowing through the slot at 10% chord delays airfoil stall, while oscillatory blowing at the flap shoulder enhances the flap effectiveness.

Although an oscillatory blowing valve was used to generate the periodic disturbance, any type of actuator having similar performance characteristic could have been used. The actuator-induced response was characterized by a nondimensional momentum coefficient $C_\mu \equiv (c_\mu; < c_\mu >)$ and a reduced frequency, $F^+ = f{*}\mathrm{x}_{sep}/U_\infty$, where f is the oscillation frequency in Hertz, x_{sep} is the distance between the separation point (with no control) and the trailing edge, and U_∞ is the freestream velocity. The steady component of the momentum coefficient is defined as $c_\mu = 2(h/c)(U_j/U_\infty)^2$ and the unsteady component is defined as $< c_\mu >= 2(h/c)(< u'_j > /U_\infty)^2$ where U_j and $< u'_j >$ are the mean and phase-locked fluctuating components of the disturbance respectively, h is the slot width and c is the airfoil chord. Reduced frequencies, F^+, of 2 or lower were used for the high Reynolds number test. An oscillatory blowing valve was chosen because it easily generates a steady disturbance, an oscillatory disturbance, or a superposition of steady and oscillatory disturbances. The flexibility of applying different types of disturbances makes it possible to compare the efficiency of the different disturbances as was done at low Reynolds number. Seifert et al.[9] made a comparison of the effectiveness of steady blowing versus oscillatory blowing and found that steady blowing required between one and two orders of magnitude more momentum than oscillatory blowing to obtain the same improvements in lift. Although momentum efficiency considerations indicate the superior efficiency of a zero-net-mass-flux disturbance, low Reynolds number studies have shown that it may be advantageous to superimpose a small amount of steady blowing on the unsteady disturbance. This may help in controlling separation which occurs downstream of the actuator location[8,10]

In a recent report by Seifert and Pack[10] the results from the high Reynolds number experiment are discussed. Most of the test focused on the NACA 0015 with the deflected flap. The flow separates on the flap for this configuration over the entire range of angles of attack tested. When a periodic disturbance is introduced at the flap shoulder,



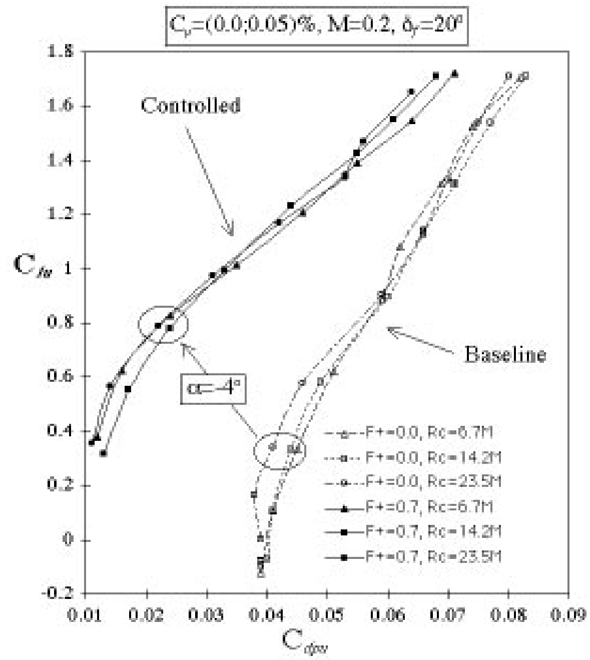


Figure 2. NACA 0015 with 30% chord trailing-edge flap deflected 20^o and slot at 70% chord. Model cavity for 10% chord slot shown sealed as was the case during the experiment. (Seifert et al[10])

Figure 3. Lift vs. Form drag polars for the NACA 0015 airfoil with flap deflected and control applied at x/c=0.7, using the same F^+ and $< c_\mu >$ for different chord Reynolds numbers (Rc). (Seifert et al.[10])

the separation over the flap is delayed, increasing lift and reducing drag. Figure 3 shows a comparison of the lift coefficient (C_{lu}) versus form drag coefficient (C_{dpu}), over a wide range of Reynolds numbers using the same disturbance, $F^+ = 0.7$ and $< c_\mu >= 0.05\%$. The lift and form or pressure drag coefficients are denoted by C_{lu} and C_{dpu} because the wind tunnel data used to compute these values have not been corrected for wall interference. Reynolds numbers of 6.7, 14.2, and 23.5 million (M) are compared in Figure 3 to demonstrate the effectiveness of the control method regardless of the Reynolds number.

The recent wind-tunnel experiment demonstrates that oscillatory blowing is effective at controlling separation at Reynolds numbers corresponding to takeoff/landing conditions of a subsonic transport. Future research efforts will include the evaluation of the technique for control of shock-induced separation as well as the use of the technique for separation control on the trailing-edge flap of a multi-element airfoil. For the multi-element airfoil experiment, piezoelectric actuators will be used in place of the oscillatory blowing valve to generate the control input. Finally, the separation control experiment clearly identified actuator development as a key enabling technology that must be matured before these flow control systems can be considered for realistic implementation and system performance can be evaluated.

4. "ON-DEMAND" VORTEX GENERATOR‡

The on-demand vortex generator (ODVG) is being developed at NASA LaRC for active flow control applications. This novel actuator may be applicable for separation control during aircraft takeoff and landing and drag reduction during aircraft cruise conditions. Unlike conventional vortex generators (VGs) which passively control separation, the ODVG can be optimized at off-design conditions and adds no parasitic drag. In addition, the ODVG requires no external plumbing allowing for reduced vehicle mass and design simplicity.

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The ODVG consists of a cavity with a flat plate (actuation surface) asymmetrically aligned at the top face such that wide and narrow gaps are formed as shown in the top view of Figure 4. In water tunnel experiments, Jacobson and Reynolds[12] found that a jet-like flow emerged from the narrow gap. Later, experiments by Saddoughi[13] found that a jet-like flow emerged from the wide gap. Computational results by Koumoustakos[14] showed that scaling parameters of the actuator determined whether a jet-like flow would emerge from either the narrow or wide gap. Finally, in still air (or benchtop) experiments at NASA LaRC, Lachowicz et al.[15] used a similar actuator to classify the flow field regimes which are generated by the ODVG. The actuation surface used by Lachowicz et al. was not cantilevered like previous experiments, resulting in fundamentally different actuation. The narrow gap width was held in these experiments and the wide gap, frequency and actuator width were varied resulting in different flow regimes. The typical flow regimes produced by Lachowicz's ODVG are shown in (Figure 5), and include a vertical jet (free jet), an angled vertical jet, a wall jet, and a vortex flow. The resulting flow fields were measured using laser-velocimetry and laser-sheet visualization. A sample vortex induced flow is shown in Figure 6. The ODVG will continue to be developed at NASA LaRC to evaluate to evaluate its performance and application.

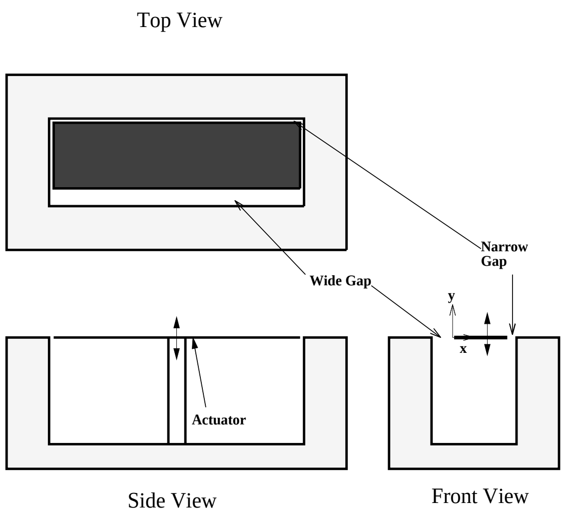

Figure 4. Sketch of ODVG (Lachowicz et al.[15])

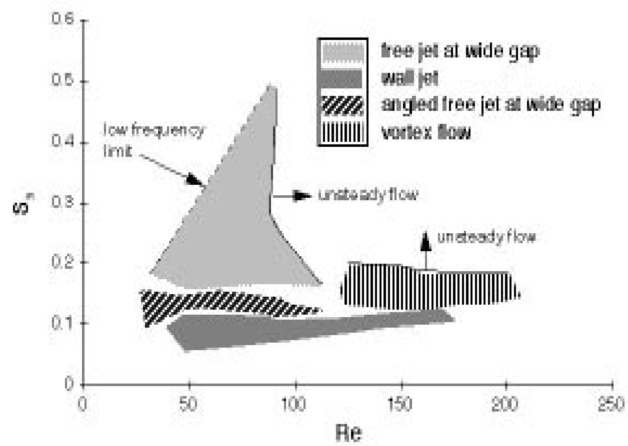

Figure 5. Sketch of induced flow fields by ODVG. (R_e-Reynolds number S_a-Amplitude factor) (Lachowicz et al.[15])

5. SENSOR INTEGRATION AND EVALUATION[§]

In a recent review, Ho and Tai[16] summarized the state-of-the-art in Micro-Electro-Mechanical Systems (MEMS) with application to flow control and identified numerous micro actuators and sensors that were currently available for flow control applications. Because the actuators yield small displacements, their use is presently limited in aerodynamic control to situations where inherent flow instabilities can amplify the small net actuation. The recent development of synthetic-jet actuators, however are the possible exception to this displacement limitation (see section 6 below). Current micro-sensors may soon replace many conventional sensors. Unlike conventional macro-measuring systems, the micro-class of sensors can essentially be non-intrusive to the incoming flow and can provide high-resolution information on the local flow field. Micro-machine technologies have led to the development of a vacuum-cavity based sensor[17,18] and a force-sensing shear stress device aimed at correcting deficiencies in conventional hot-film surface shear sensors (Shajii et al.,[19] and Pan et al.[20]). Ho and Tai[16] also discussed a Wheatstone-bridge based micro pressure sensor that has been integrated into a micro-flow measurement system.

[§]George Beeler and Scott Anders

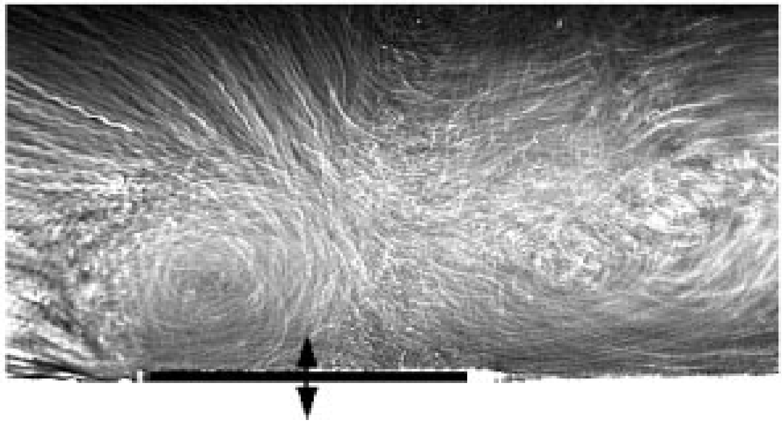

Figure 6. Vortex flow with wide gap on the left and narrow gap on the right. (Figure 5 of Lachowicz et al.[15])

Although a complementary paper in this session identifies the development of advanced sensors, the fluid dynamic contribution to the technology at NASA resides in integration and testing of proposed sensors in a wind tunnel or on a flight-test article. In 1997, shear-stress sensors developed by Rathnasingham and Breuer[21] and Rathnasingham[22] were evaluated in a low-speed, low-Reynolds number wind-tunnel at NASA LaRC. Although the results of that study are not yet available for publication, integration and evaluation of new innovative sensors will continue at NASA.

Future activities include additional wind-tunnel tests of integrated micro sensors and a 1998 piggy-back flight test on a research aircraft at NASA Dryden Flight Research Center to evaluate the use of micro pressure sensors. These new micro sensors may be adequate to replace conventional pressure belts that are intrusive to the external flow and static pressure taps that are embedded in the test article. A second objective of the flight test is to replace conventional integration hardware with telemetry. A schematic of the proposed flight test is shown in Figure 7. When demonstrated, the new sensors could revolutionize the way both wind-tunnel and flight-test measurements are made. In the future, significant cost and time savings could be realized with micro sensors and telemetry.

6. ZERO-NET-MASS FLUX (OR SYNTHETIC JET)ACTUATORS¶

Recent accomplishments by Jacobs et al.,[23] Sutkus et al.,[24] and Wiltse and Glezer[25,26] have demonstrated the use of micro-sized piezoelectric actuators for flow manipulation. The proposed piezoelectric actuator has a net mass flow of zero; however, peculiar to this type of actuator is the resulting jet-like flow fields that can emerge with actuation. Hence, this type of device has been referred to as a synthetic jet. Actuators of this type have generated velocities up to 50 m/s with frequencies in the range of 1 KHz. With further validation, the zero-net mass flux jets may lead to aerodynamic performance benefits through enhanced lift on wings, drag reduction during cruise through advanced active LFC, and on-demand control moments, thereby eliminating or reducing traditional flap/slat hardware.

In cooperation with engineers at Boeing-St. Louis and Georgia Tech, the goals of the NASA use of zero-net mass flux jets, include (1) determining a correlation between the actuator attributes and resulting flow field, (2) determining the consequences of the interaction of a zero-net mass flux jet-like flow with the turbulent boundary layer flow, (3) determining correlations of the actuator attributes with a resulting near-field surface pressure for control-law development (4) determining lift and control-moment initially for an unswept (2D) airfoil model in a low-speed wind-tunnel, and (5) using PIV to characterize select problems in which the zero-net mass flux actuators are successfully used. The zero-net-mass flux actuator testing at NASA has focused on two wind-tunnel experiments, which are described in the remainder of this section.

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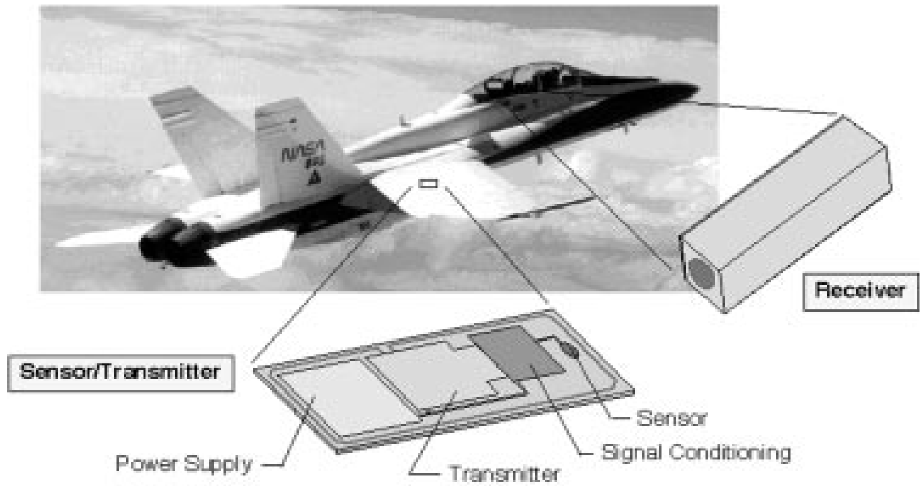

Figure 7. Illustration of flight test of integrated micro sensors and telemetry.

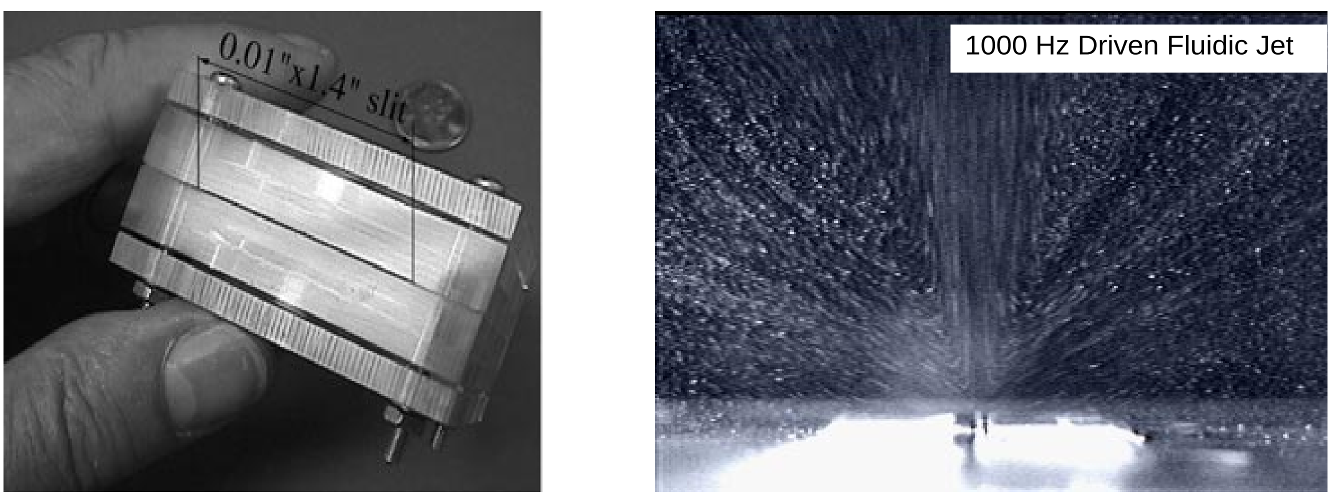

Figure 8. Zero-net-mass flux actuator and induced jet-like flow.

6.1. Circulation Control: 2D Airfoil Experiment

The goal of the 2D (or unswept) wing experiment is to assess the applicability of using unsteady suction and blowing to alter the circulation about a wing to enhance lift. Prior to commencing with the unswept wing experiment, some limited testing of a zero-net mass flux actuator will be conducted on a bench top and in a low-Reynolds number facility (20" x 28" test section). For these preliminary tests, the piston-type actuator will be driven using a shaker and piezo-diaphragm. The flow field with and without the turbulent boundary-layer flow will be analyzed. In preliminary tests, the actuator has a net effect on the boundary-layer flow of producing a local net increase in the displacement thickness of the flow. Hence, an effective shape change could approximate the effect of the actuator in these preliminary experiments.

6.2. Forebody Control

For bodies of revolution at high angle-of-attack, side forces appear in the nose, or forebody, region. Hence, an active control system is desirable that can serve to eliminate the undesirable forces and impose desirable forces (control). In the low-speed wind-tunnel experiments of Roos,[27,28] micro-blowing was shown to be effective for controlling the flow (forces) in the forebody region of bodies of revolution. Because the zero-net-mass flux actuators are locally confined and require no plumbing, the near-term effort at NASA LaRC will focus on evaluating the use of zero-net-mass flux piezoelectric jets for forebody control at high Reynolds number. A chined forebody model geometry that is reminiscent of an advanced fighter forebody region will be tested in the Langley 12-foot Low Speed Tunnel. The removable nose region will enable the incorporation of piezoelectric actuators with variable sized orifice (or slot) openings and positioned at various locations relative to the flow stagnation point.

7. COMPUTATIONAL TOOLS

Aerodynamic design has a whole new set of challenges with the introduction of unsteady flow control. The fluidic actuators may involve zero, positive, or negative net mass flows. Both fluidic and surface displacement actuators may range in size from MEMS (less than 1 centimeter) to macro devices (centimeters) and have frequencies from 0 to 1 kHz. In particular, Direct Numerical Simulation (DNS) and Large-Eddy Simulation (LES) are required to identify the flow physics governing the organized laminar through turbulent flow fields in the presence of these actuators. For practical designs, a pseudo-unsteady tool such as time-accurate Reynolds-Averaged Navier-Stokes (RANS) must be validated to afford a reasonable design tool. At NASA, DNS, LES, and time-dependent RANS tools are being developed to compute isolated actuator-induced flow fields and configuration- or application-oriented implementations of actuators, sensors, and controls. A schematic of the Navier-Stokes tools and control methodologies related to application-driven objectives is shown in Figure 9.

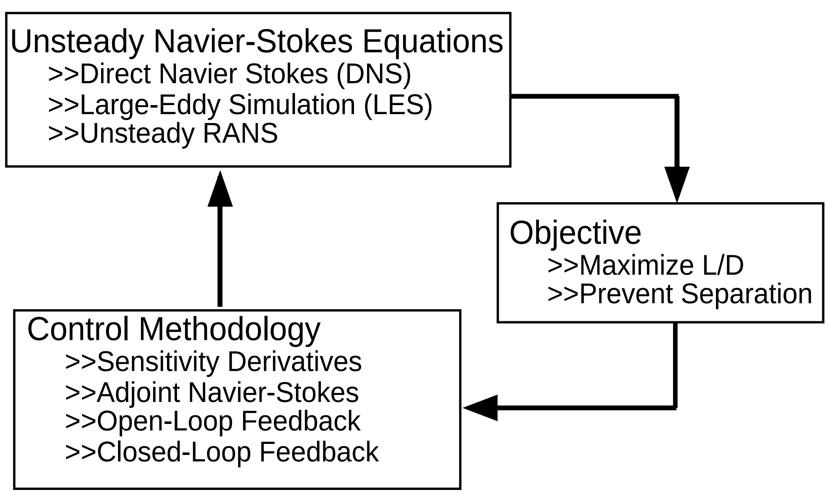

Figure 9. Illustration of relationships between Navier-Stokes solvers, Control Theories, and objective functionals.

7.1. Unsteady Actuator-Induced Flow Control[‖]

To demonstrate the value of DNS in these unsteady, nonlinear aerodynamic problems, simulations were conducted of the flow field induced by a single zero-net-mass flux actuator. With parameters comparable to that used in the zero-net-mass flow actuator (Figure 8), the DNS produced a jet-like flow field a few diameters from the orifice opening. Very near the wall, a slug-like flow was observed.

‖Ronald D. Joslin

The simulation of the more interesting and difficult problem of the actuator shown in Figure 4 was undertaken. The results for the parameter region in which the vortex of Figure 6 is produced are shown in Figure 10. The circular lines represent lines of constant vorticity. Hence, a vortex similar to Figure 6 is found using the DNS tool. Jet-like and wall-jet flows have also been identified using the DNS tool.

Additional two- and three-dimensional simulations will be carried out to further characterize the flows induced with these actuators.

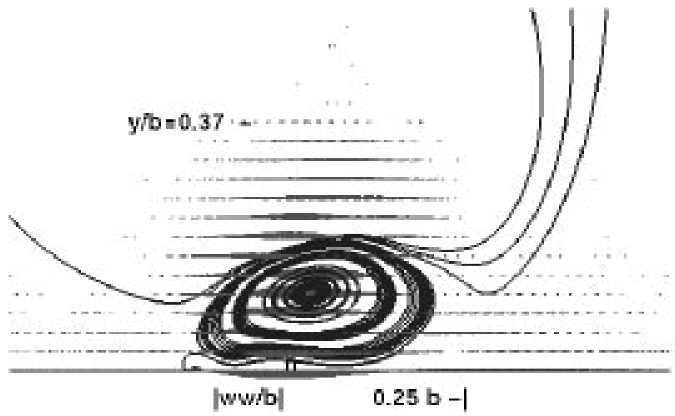

Figure 10. DNS solution of actuator-induced vortex flow. (R=146.9 and S_a=0.13).

7.2. Unsteady RANS**

Recently, Kral et al.[29] and Donovan et al.[30] conducted studies in an effort to validate a time-dependent RANS approach against the available experiments that have tested unsteady suction and blowing actuators. With a single-frequency periodic suction and blowing boundary condition (sine wave), the RANS computation generated the same features of the synthetic-jet (in isolation) experiments by Smith and Glezer,[31] including the turbulent centerline velocity decay rate, approach of a constant momentum flux in the far-field, and mean streamwise velocity profiles. Next, steady and unsteady suction and blowing actuators were used on two-dimensional airfoils to examine the aerodynamic benefits that may be obtained using actuators. Due to local pressure variations caused by the actuators, notable drag reductions were calculated over a large angle-of-attack variation. A computation to mimic the experiments of Seifert et al.[9] (discussed in 3) followed to validate the unsteady RANS approach. At NASA, this effort is being continued to validate and document the use of RANS toward flow control applications.

7.3. Flow Control Theory††

Based on the research of Joslin et al.,[32–34] self-contained automated methodology for active flow control, which couples the time-dependent Navier-Stokes system with the adjoint Navier-Stokes system and optimality conditions, was tested for the problem of boundary-layer transition delay. The problem of boundary layer instability suppression through wave cancellation was used as the initial validation case to test the methodology. The objective of control was to match the wall-normal stress along a portion of the boundary to a given vector; instability suppression was achieved by choosing the given vector to be that of a steady base flow. Control was effected through the injection or

**Craig Hunter and S.S. Ravindran
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suction of fluid through a single orifice on the boundary. The results demonstrate that instability suppression can be achieved without any a priori knowledge of the disturbance.

The methodology was based on defining a control mechanism and an objective for control, and then finding, in a systematic and automated manner, controls that best meet the objective. The dimensions of an actuator are specified on the boundary of the computational domain and the frequency/amplitude vary as defined by the governing equations. In the present setting, an objective functional is defined that computes the difference between the measured and desired state. One may interpret the objective functional as a "sensor". This sensor feeds information to a controller (which is a system of equations) that in turn feeds information to the actuator.

The nonlinear, unsteady Navier-Stokes equations and linear adjoint Navier-Stokes equations are solved by direct numerical simulation (DNS) of disturbances that evolve spatially within the boundary layer (the spatial DNS approach[35]). The coupled system was solved in an iterative manner. First, the simulation starts with no control and the Navier-Stokes equations are solved for the velocity (u, v) and pressure (p) fields. The adjoint equations are then solved for the co-state variables (u', v') and p'. Then, using these adjoint variables, the control (actuator amplitude/frequency combination) is found by solving the optimality equations. The procedure is repeated until satisfactory convergence is achieved.

For all practical purposes, the solutions obtained with the DNS/control theory methodology yield the desired flow control features without prior knowledge of the forced instability. However, the coefficients of the adjoint system are the velocity and pressure solutions obtained from the Navier-Stokes equations for all time and all space. The storage cost associated with this data can be enormous for a three-dimensional application. In addition, the cost to iterate the system becomes formidable for DNS of a three-dimensional application. An alternate, or approximate, solution procedure must be obtained to make this flow control tool feasible for real-world applications. Such approximation procedures are being studied at NASA under the Aircraft Morphing program, whereby the time-dependent RANS approach will be validated. Control theories then will be implemented and tested toward application oriented implementation of actuators, sensors, and controllers.

8. CONCLUSIONS

The present paper has summarized the various active flow control projects in progress at NASA Langley Research Center. Cavity noise suppression using an unsteady disturbance can lead to significant noise reductions compared with uncontrolled noise levels. Separation control during high-lift conditions on an airfoil using a slot- actuator with zero-net-mass flux has resulted in simultaneous drag reductions and lift enhancement. Design and evaluation of actuators will continue until compact, robust and large-amplitude/frequency-variation components become easily achievable. Finally, advanced computational techniques will continue to be employed so that unsteady aerodynamic CFD reaches maturity.

ACKNOWLEDGEMENTS

These research projects were supported by the Aircraft Morphing element of the NASA Airframe Systems Project Office (R&T Base). Gratitude to the following scientists at NASA Langley Research Center for reviewing the sections relevant to their area of expertise. Gregory S. Jones, Mike Kegerise, and Alison Lamp for reviewing section 2, Avraham Seifert (NRC) for reviewing section 3, Chung-Sheng Yao and Jason T. Lachowicz (NRC) for reviewing section 4, Scott G. Anders and George B. Beeler for reviewing section 5, Fang-Jenq Chen for reviewing section 6, and Craig Hunter and S. S. Ravindran (NRC) for reviewing section 7. Gratitude also to William Sellers III, Richard Wlezien, and Catherine McGinley for reviewing the paper.

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