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NASA's Morphing Project Research Summaries in Fiscal Year 2002

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Langley Research Center, Hampton, Virginia

February 2005

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Space Administration

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Acknowledgments

The many excellent researchers whose work is compiled in this document are the real "authors" of this document and are the key behind all of the technology breakthroughs in the project. In addition, the Morphing Project Team, who provided invaluable technical guidance in developing and implementing the project, deserve considerable commendation. They are: Mr. Anthony Washburn, Dr. Lucas Horta, Dr. David Cox, Dr. Robert Bryant, Dr. Jamshid Samareh, and Ms. Nancy Holloway. Their vision, technical breadth and depth, people skills, and leadership talent are exceptional. Dr. Richard Antcliff, Dr. Darrel Tenney, Mr. Thomas Sutter and Mr. Long Yip have also provided much appreciated sage advice and camaraderie. Ms. Fran Sabo diligently served as the program analyst for the project. Perhaps most notably, Ms. Sherry Cox assembled, edited, and finalized the current document. Without her efforts this document would not be possible. The authors wish to say a very sincere thank you to all of the above people.

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Abstract

The Morphing Project at the National Aeronautics and Space Agency's (NASA) Langley Research Center (LaRC) is part of the Breakthrough Vehicle Technologies Project, Vehicle Systems Program that conducts fundamental research on advanced technologies for future flight vehicles. The objectives of the Morphing Project are to develop and assess the advanced technologies and integrated component concepts to enable efficient, multi-point adaptability (morphing) in flight vehicles. In the context of the project, "morphing" is defined as: efficient, multi-point adaptability on flight vehicles and it includes small-scale and large-scale, structural and fluidic approaches. The current document on the Morphing Project is a compilation of research summaries and other information on the project from fiscal year 2002. The focus of this document is to provide a brief overview of the project content, technical results and lessons learned from fiscal year 2002. At the time of publication, the Vehicle Systems Program (which includes the Morphing Project) is undergoing a program re-planning and re-organization. Accordingly, the programmatic descriptions of this document pertain to the program as of fiscal year 2002.

Table of Contents

Project Introduction

The Breakthrough Vehicle Technologies Project, led from the NASA Langley Research Center in Hampton, Virginia, is a part of one of NASA's Aeronautics programs entitled Vehicle Systems. The objectives of the Breakthrough Vehicle Technologies Project is to investigate and develop emerging vehicle technologies and tools that will radically change the way future aircraft are designed, built, and operated. Deliverables are technologies for various vehicle components and sub-systems, such as new ultra-light weight materials; computational models and design tools; and smart sensors and actuator systems. Exit criteria are normally demonstration of a technology at or below Technology Readiness Level (TRL) 3 to 4, showing the feasibility of an approach in a laboratory environment. Exit criteria also include evaluation by independent peer reviewers to determine whether a given technology warrants further investigation.

The current document focuses on the Morphing Project one of seven elements of the Breakthrough Vehicle Technologies Project. While there is no formal definition for the word "morphing," it is usually considered to mean significant shape change or transfiguration. In the context of NASA's Morphing Project, "morphing" is defined as: efficient, multi-point adaptability on flight vehicles and it includes small-scale and large-scale, structural and fluidic approaches. In defining "morphing" in this manner, *efficient* denotes mechanically simpler, lighter weight, and more energy efficient than conventional systems; *multi-point* denotes accommodating diverse (and sometimes contradictory) mission scenarios; and *adaptability* denotes extensive versatility and resilience. The major benefits of morphing for the flight vehicle include extensive adaptability, aggressive efficiency improvements, and new mission scenarios. While all flying vehicles must be adaptable to a certain degree to safely adjust to different flying conditions such as take-off, cruise, maneuvering, etc., the technologies under development in the Morphing Project are focused toward going beyond the existing boundaries in vehicle adaptability while specifically addressing system efficiency. Thus, the project is directed towards long-term, high-risk, high-payoff technologies, many of which are considered "disruptive" technologies.

Since many think of "morphing" as primarily large shape change, it is important to note that NASA's Morphing Project intentionally incorporates both micro fluidic and small and large-scale structural shape change to address the intertwined functions of vehicle aerodynamics, structures and controls. For example, morphing on some flying vehicles may be addressed through strategic application of micro flow control with or without relatively small (yet difficult) structural changes.

The objectives of the Morphing Project are to develop and assess the advanced technologies and integrated component concepts to enable efficient, multi-point adaptability (morphing) in flight vehicles. The three focus areas of the project are: adaptive structural morphing; micro-aero adaptive control; and biologically-inspired flight and control systems. These areas are supported by the core enabling areas of smart, nano and biologically-inspired materials, electronics, and systems studies (called "smart technologies"). Figure 1 graphically depicts the major elements of the project. This multi-disciplinary approach provides exceptional opportunities to seek new innovations that may only be possible at the intersection of disciplines. Hence, cross-disciplinary teams (across the different focus areas) are frequently employed for several reasons: to foster multi-disciplinary research, to more appropriately address complex problems, and to stimulate new ideas.

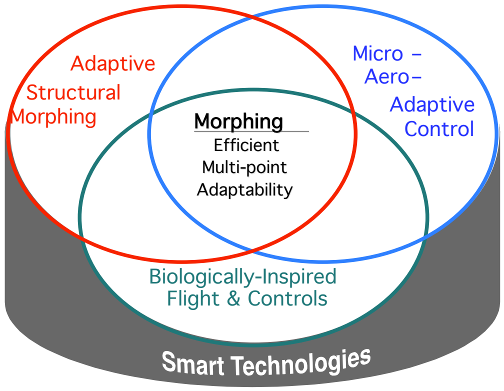


Figure 1. The Major Components of NASA's Morphing Project

The individual focus areas in the project provide a "working group" environment for technology development. The adaptive structural morphing area encompasses developing and testing adaptive multifunctional wing concepts that can efficiently adapt to different flight conditions using approaches beyond conventional control surfaces. The research in micro-aero-adaptive control[i] focuses on dynamically altering the aircraft global flowfield by interacting with and controlling localized flow instabilities and flow structures. The biologically-inspired flight[ii] systems effort focuses on understanding and applying lessons learned from biology (not on mimicking biology). The smart technologies area includes systems studies, materials research to develop new smart materials for actuation and sensing, actuator packaging concepts, microelectronics for powering smart materials and developing and applying advanced controls approaches for morphing vehicles. Multi-disciplinary optimization is used throughout the project in several aspects including developing integrated design tools and optimizing actuator and sensor usage.

Technical challenges are addressed in the project through an iterative, low technology readiness level, research approach that includes: (1) creating new technologies (such as actuators, structural concepts, or control approaches) in response to systems studies and needs in the project; (2) addressing application issues (such as electronics or design tools) to evaluate what is needed to make the technology work; and (3) assessing functionality (integrating technologies into component hardware and demonstrating new capabilities) to understand the nuances of how, when, where, and why the technology works. Experimental demonstrations take place throughout the technology development cycle and not only at the end of the cycle to provide feedback on relevant application and feasibility issues. These issues are then fed back into the project as new technical problems to be addressed. In general, technologies are continually added and removed from the project by using both formal and informal technology assessments and annual reviews that are conducted by an integrated project team that leads and implements the project.

The major deliverables of the project are: technologies that enable new or significantly enhanced vehicle capabilities; tools to use the technology (hardware, software, and guidelines); and demonstrated results (both good and bad). These deliverables are typically transferred through one of several methods: (1) patents and then licenses, (2) collaborative agreements and planned informal information transfer with other organizations, (3) transitioning design tools to commercially available codes or other "easy to apply" analytical methods, (4) periodic, planned overview papers to summarize available technologies as well as numerous detailed technical reports (see the Appendix), and (5) sponsored research initiatives with external groups. The collaborations mentioned above are used extensively in the project. These collaborations are with other NASA programs and projects, other government agencies and industry and are employed to provide technology pull and technology transfer opportunities. University grants (over 25 grants) are also used across a broad range of technical disciplines to provide new ideas and an opportunity to work with leading professors and future engineers. The Appendix lists the external connections throughout the project. Another excellent source of new ideas is the Morphing Project Lecture Series where speakers are invited to visit Langley Research Center and provide research updates, technology summaries, new concepts and discuss relevant technology issues. The list of speakers for fiscal year 2002 is provided in the Appendix.

This document represents one of the methods of transferring information on the technologies developed in the project. It provides a snapshot of the research status as of fiscal year 2002, written by each individual lead researcher in the project. Reference 26 provides a similar report for fiscal year 2001. This report focuses on technical accomplishments and lessons learned and not on programmatic topics such as milestones, budget, etc.

Work Packages and Lead Researchers in Fiscal Year 2001 in the Morphing Project

Micro-Aero Adaptive Control - Anthony E. Washburn

Periodic Excitation for Forebody Vortex Control	D. Bruce Owens
Fluidic Thrust Vectoring using Separation Control in a Nozzle	Jeffrey D. Flamm
Circulation Control for Enhanced Vehicle Performance Using Pulsed Blowing and Pneumatic Flap Concepts	Gregory S. Jones
Flow Control Using Detonation Actuation	J. Philip Drummond
Closed-Loop Control of Cavity Shear-Layer Instabilities	Michael A. Kegerise
Simplified High Lift System	LaTunia Pack-Melton
Smart Surfaces for Drag Reduction	Michael Walsh
Active Transonic Drag Reduction Through Shock Spreading	William E. Millholen
Use of Surface Plasma for Flow Control Applications	Stephen P. Wilkinson

Smart Technologies - Robert G. Bryant

BIOSANT FY 2002 Accomplishments	Emilie Siochi
Miniaturized Morphing Electronics for High Voltage and Sensor Integration	James F. Bockman
Exploratory Optimization Techniques for Conceptual Design	Sharon L. Padula
Flight Control Using Distributed Morphing Effector Arrays	David L. Raney

Adaptive Structural Morphing - Lucas G. Horta

Kinematic Studies of New Morphing Wing Concepts	Jocelyn Pritchard
Morphing Technologies for Composite Wing Structures	David M. McGowan
Multifunctional Adaptive Structures	Travis L. Turner
Adaptable Metallic Materials and Structures	Eric K. Hoffman

Biologically-Inspired Flight Systems - David E. Cox

Dynamics and Control of Resonant Flapping Micro-Aerial Vehicles	David L. Raney
Autonomous/Collaborative Control of Aeroelastic Fixed Wing Micro Aerial Vehicles: Flight Dynamics, Simulation, and Flight Control	Marin R. Waszak
HECS Wing Development and Morphing Implementation	Barry S. Lazos
Airmass Guidance	David E. Cox

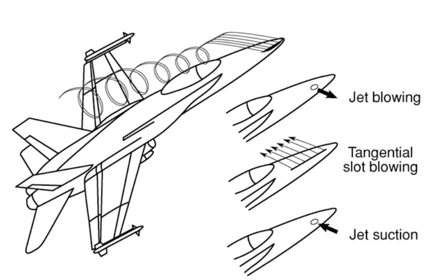
Table 1. Work Packages and Lead Researchers in Fiscal Year 2002 in the Morphing Project

Micro-Aero Adaptive Control FY 2002 Research Summaries

Periodic Excitation for Forebody Vortex Control

D. Bruce Owens, 757-864-8450, d.b.owens@nasa.gov
Vehicle Dynamics Branch, Airborne Systems Competency

Background Information:
At a significant angle-of-attack, a forebody will shed vortices. If the forebody is a significant distance from the center-of-gravity of the vehicle, mechanical and continuous blowing pneumatic devices have shown that these vortices can be manipulated to produce favorable yawing moments. As depicted in the figure, various forebody controls have been studied over the years. Yaw control is significantly augmented at high angles of attack by these devices. Unfortunately, some of the controls are complex, and system power requirements are costly. The current research was conducted to study the potential benefit of using periodic excitation via pulsed blowing.



Objective of Current Work:
To evaluate using advanced fluidic effectors to create periodic excitation for the purpose of forebody fluidic control in a simple, lightweight, and seamless manner for aerospace vehicles. The yaw control produced by manipulating the forebody vortex flow field will be shown to provide control power for enhanced maneuvering.

Benefits Over Existing Systems:
The potential benefit would be adequate yaw control with a reduction in the required power from the aircraft system.

Previous Work on this Work Package:
During FY 2000, an existing generic fighter model was modified to accept a synthetic jet actuator into the chined forebody. The characterization of the actuator mounted on the two different types of nozzles (normal and tangential blowing) was accomplished using a hot wire anemometer, and the velocity fields around the actuator/nozzle configurations were documented at a wind-off condition, and the actuator frequency effects were also measured and documented. Wind tunnel testing was conducted in the 12-Foot Low-Speed Wind Tunnel. These tests showed, using a flow visualization technique, that blowing using the synthetic jet was able to create an asymmetric vortex flow field around the forebody of the model. Surface pressure measurements confirmed the flow asymmetry. However, no measurable yawing moment coefficient was produced.
During FY 2001, a tangent ogive forebody for a generic fighter model that is characterized by its 45° cropped delta wing and single vertical tail (see figure 1) was designed and built. A Siemens natural gas fuel injector produced the pulse blowing. This actuator generates higher velocities and flow rates than the synthetic jet actuator.

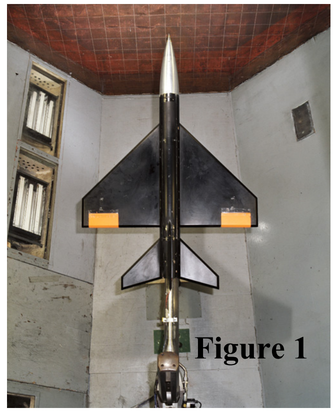


Figure 1

The forebody was designed with numerous parameters: blowing location (circumferentially and longitudinally), blowing direction, nozzle size and shape, forebody apex shape (rounded to pointed), fineness ratio, multiple simultaneous blowing locations, blowing rate, blowing frequency and duty cycle (figure 2). Instrumentation for the model included a standard six-component strain gauge balance and steady pressure measurements on the forebody.

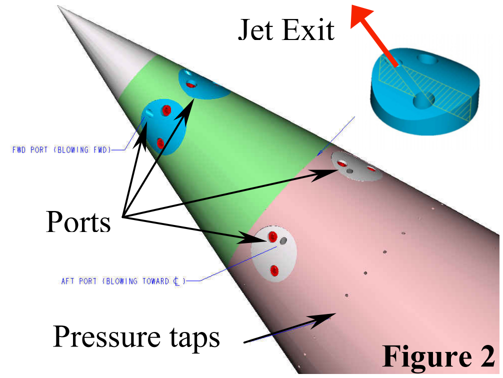


Figure 2

Current Year Accomplishments:
Using the aforementioned generic fighter model and actuator, a test was conducted in the NASA Langley 12-Foot Low-Speed Wind Tunnel to study the potential benefits of pulsed blowing. The 6-week wind tunnel test was completed in August 2002, where all of the aforementioned parameters were investigated. In addition to pulsed blowing, the actuator was electronically modified to provide steady blowing. This was done to ascertain any potential benefits over steady blowing. Figure 3 shows a comparison of the amount of yaw control from pulsed blowing verses that from maximum rudder deflection. As shown, the blowing provides even more yaw control than the rudder and does so in the angle of attack range where the rudder is ineffective. Unfortunately, the pulsed blowing showed no significant decrease in the amount of mass flow rate required to produce the same level of yaw control as steady blowing.

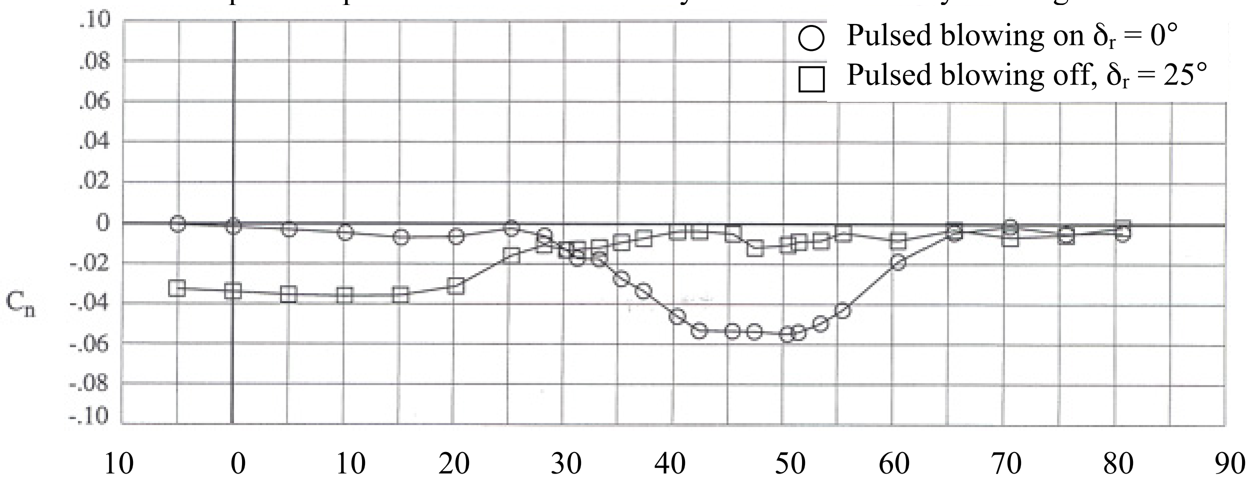


Figure 3 α, deg.

Lessons Learned:
Line pressure, frequency, and duty cycle were expected to either decrease the flow rate to make the blowing more efficient or create a method for modulating the yawing moment. Although these parameters contributed to a reduced flow rate, they did not appear to have a significant impact on directional control, and only radial location provided any incremental changes in yawing moment.

Future Work:
Future plans include final data analysis of the wind tunnel test data of the current configuration.

Fluidic Thrust Vectoring using Separation Control in a Nozzle

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Configuration Aerodynamics Branch, Aerodynamics, Aerothermodynamics & Acoustics Competency
Stuart K. Johnson, 757-864-9607, s.k.johnson@nasa.gov
Advanced Aircraft Branch, Aerospace Systems, Concepts and Analysis Competency

Background Information:
Studies have shown that thrust vectoring (TV) concepts can provide many benefits to the modern aircraft. Aircraft combat effectiveness is increased with the addition of TV capability to the aircraft's propulsion system. In close air-to-air combat, TV allows the aircraft to operate in the post stall flight regime. This provides a tactical advantage by increasing aircraft agility and maneuverability. A further advantage is gained in long range combat by reducing signature and increasing range. The ability to land and take off from short unimproved runways (STOL) is also improved with TV. Mechanical thrust vectoring techniques have been demonstrated successfully in three recent flight research programs, the F-15 SMTD, F-18 HARV, and the X-31. However, mechanical thrust vectoring techniques have some disadvantages. The mechanical actuators and linkages used to vector thrust add weight and complexity to the aircraft, which in turn increase cost and maintenance requirements. Moveable external flaps work against the design goal of creating a stealthy aircraft and also cause large thrust penalties. These factors have led researchers to investigate novel methods to achieve the same thrust vectoring capabilities without external moving parts fluidic nozzle control - the use of a secondary air stream to influence the behavior of the primary jet. Some of the primary mechanisms for fluidic thrust vector control include shock-vector, sonic-plane skewing, and counterflow. The shock-vector control method (fluidic injection downstream of nozzle throat) offers substantial vector control, but often at the expense of thrust ratio. Higher thrust ratios are generally obtained with fluidic sonic-plane skewing methods (fluidic injection at nozzle throat), but vector control is usually only sufficient for minor cruise adjustments. The counterflow method (suction in a secondary duct near throat) offers large vector angles with little secondary flow requirements, but issues such as suction supply source, hysteresis effects, and airframe integration need to be addressed.

Objective of Current Work:
Develop and demonstrate fluidic injection (FI) and fluidic thrust vectoring (FTV) technology for application to a variety of exhaust nozzle geometries, airframe configurations, and operating conditions. FTV is and will continue to be an enabling technology for seamless flight control because of the inherent advantages and control power provided across the speed range. Especially important is the contribution of thrust vectoring at low speeds (i.e., low dynamic pressure) where other seamless control technologies are either ineffective or extremely limited.

Benefits Over Existing Systems:
Seamless control effector technology will enable fixed external geometry aircraft capable of surviving in the high threat environment of the future. Fluidic thrust vectoring is a critical element in the suite of control effectors that will be required to provide seamless control of those

vehicles especially at specific off-design conditions. Additionally, no known experimental data currently exists for FTV with external flow.

Current Year Accomplishments:
A computational investigation of a two-dimensional, convergent nozzle was completed to assess the use of fluidic injection to manipulate flow separation and cause thrust vectoring of the primary jet thrust. The nozzle was designed with a recessed cavity to enhance the throat shifting method of fluidic thrust vectoring. The structured-grid, computational fluid dynamics code PAB3D was used to guide the design and analyze over 60 configurations. Nozzle design variables included cavity convergence angle, cavity length, injection angle, upstream minimum height and shape (sharp or radius), and aft deck angle and shape. All simulations were computed with a static freestream Mach number (M=0.05) and a nozzle pressure ratio of NPR=3.858. Fluidic injection was simulated with a secondary flow rate of 3 and 6 percent of the primary flow rate, which corresponded to secondary total pressures of 88.79 psi and 177.6 psi, respectively.

A model was designed and fabricated to validate the computational results experimentally. This test is currently in progress.

Lessons Learned:
Results indicate that the recessed cavity does enhance the throat shifting method of fluidic thrust vectoring, which allows for greater thrust-vector angles without compromising thrust efficiency. Pitch vector angles of as much as 14.7 degrees with 6 percent injection have been demonstrated with CFD. This represents a pitch vectoring effectiveness of 2.15 degrees per percent injection.

Future Work:
The computational results will be validated experimentally in the NASA Langley Jet Exit Test Facility (currently underway). Additionally, an experimental test of a fluidic thrust vectoring nozzle concept with external flow will be conducted.

Formal and Informal Documentation Available:
1. Deere, K. A., Berrier, B. L., Flamm, J. D., and Johnson, S. K. *Computational Study Of Fluidic Thrust Vectoring Using Separation Control In A Nozzle*. AIAA 2003- 3803. Proposed paper for 21st AIAA Applied Aerodynamics Conference, Orlando, Florida, June 23-26, 2003.
2. Flamm, J. D., Deere, K. A., Berrier, B. L., and Johnson, S. K. *Fluidic Thrust Vectoring using Separation Control in a Nozzle*. Invention Disclosure LAR 16462-1, August 2002.

External Partners and Their Accomplishments:
Developing Memorandum of Agreement with Lockheed-Martin to jointly investigate fluidic injection and fluidic thrust vectoring technology.

Circulation Control for Enhanced Vehicle Performance using Pulsed Blowing and Pneumatic Flap Concepts

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Flow Physics and Control Branch, Aerodynamics, Aerothermodynamics and Acoustics Competency

Background Information:
Steady State Circulation Control has been demonstrated to enhance aerodynamic performance with $DC_l/Cm > 50$, however mass flow requirements and increased cruise drag have limited its application to experimental aircraft.

Objective of Current Work:
1. The objective of this effort will be to reduce the mass flow requirements by a factor of 2 using unsteady flow control.
2. The Pneumatic flap (dual blowing configuration) to minimize drag of Coanda surface
3. The objective of the acoustic analysis was to develop tools that quantify the effect of configuration on noise radiated and establish a baseline noise radiation pattern for steady and pulsed blowing.

Benefits Over Existing Systems:
The use of Pneumatic High Lift Technology using UCC has the potential to revolutionize aircraft systems by reducing wing area, moving part count, and potential runway take off and landing requirements. Application of this technology is predicated on a reduction in the mass flow requirements with simple flow control technologies.

Previous Work on This Work Package:
1. Design and Fabricate pneumatic flap GACC model with multifunctional capability including high-lift, cruise, and mass flow control. Model includes steady and pulsed blowing - incorporating 20 fuel injectors for pulsed blowing and future span loading
2. Established links to other LaRC CC efforts including Channel Wing (C&I) & the Multi-Gas Generator Fan (MGGF) pneumatic engine nacelle concept (based on GACC)

Current Year Accomplishments:
1. Demonstrated 50 percent reduction in mass flow requirements using pulsed injection (for a given high lift). See figure 1.
2. Demonstrated effectiveness of 2-D pneumatic flight control system for low speed operations. (60 percent drag reduction at cruise). See figure 2.
3. Developed miniaturization of multi-port unsteady pressure system for time accurate measurement of Coanda surface, figure 3.
4. Comparison of steady state CFD and wind tunnel high lift CC experiment show similar trends, and highlight the need to characterize Coanda jet.

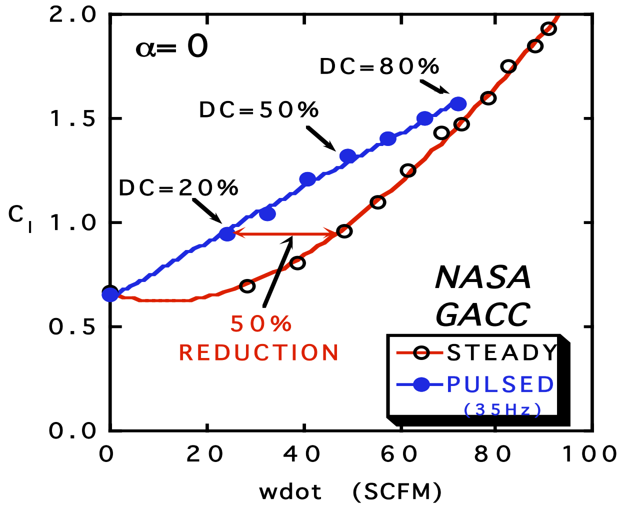

Figure 1. Effect of Pulsed Blowing

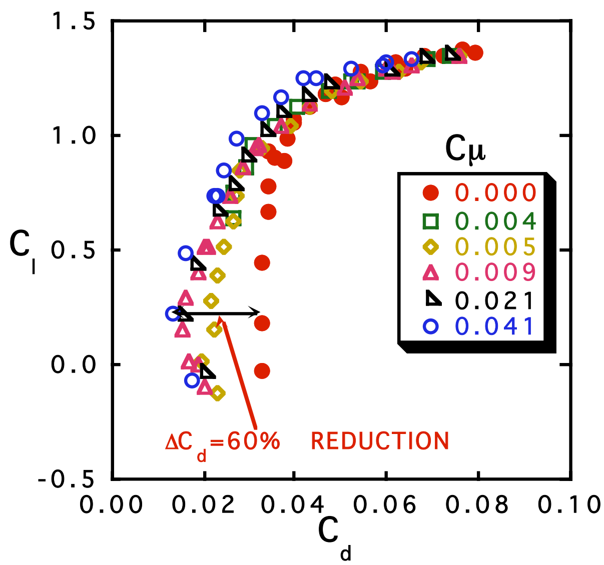

Figure 2. Drag Polar for Dual Blowing

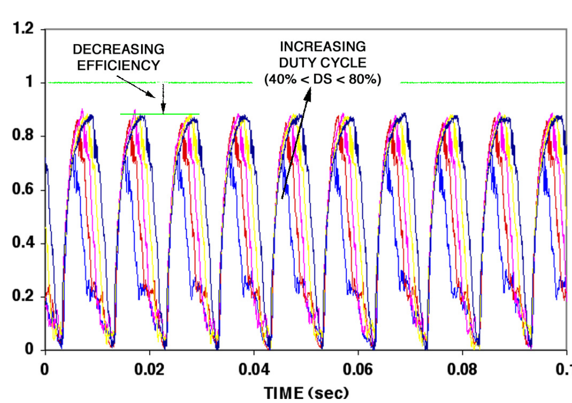

Figure 3. Pulse attenuation due to internal volume and actuator frequency response

Lessons learned:

1. Identified inconsistencies in industry definitions of momentum Cm. This is particularly important in characterizing the effective drag and being able to compare results to conventional and other CC experiments.
2. Actuator systems for CC airfoils must include rapid diffuser and internal plenums to account for time dependent losses associated with the internal volumes and compressible effect, figure 3.

Future work:

1. Establish baseline aerodynamic performance benefits for different CC trailing edge shapes (circular, 2:1 elliptical, & bi-convex). Evaluate GACC for both high-lift and cruise characteristics. Emphasize high-lift and cruise configurations. (CFD & BART)
2. Develop an effort that will focus on large scale issues related to high speed cruise, flight control, and time dependent characteristics, (e.g. shock control, sweep, and load tailoring). (CFD)

Formal and informal documentation available:

1. Jones, G. S., Viken, S. A. Washburn, A.E. Jenkins, L. N. Cagle, C.M. *An Active Flow Circulation Controlled Flap Concept for General Aviation Aircraft Applications*. AIAA Paper 2002-3157, AIAA Flow Control Conference, St. Louis, Missouri, June 24-27, 2002.
2. Cagle, C. M., Jones, G. S. A *Wind Tunnel Model to Explore Unsteady Circulation Control for General Aviation Applications*, AIAA 2002-3240, June 2002.
3. Schaeffler, N. W., Hepner, T. E., Jones, G. S., Kegerise, M. A. *Overview of Active Flow Control Actuator Development at NASA Langley Research Center*. AIAA 2002-3159, June 2002.

External partners and their accomplishments:

GTRI completed wind tunnel test of "Dual Radius" pulsed CCW experiment. Established consulting arrangement with GTRI to provide synergistic approach to development of CCW techniques. Mr. Bob Englar and Dr. Sankar gave symposium LaRC personnel on status of CCW at GTRI.

Flow Control Using Detonation Actuation

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Background Information:
The control of flow separation using unsteady actuators has been successfully demonstrated in both the laboratory and in wind tunnel testing. Zero-net-mass flux and pulsed jet actuators have been successfully employed for separation control, but situations exist where a stronger interaction with the primary flow is desired to achieve a more significant effect.

Objective of Current Work:
Small actuator devices that utilize localized detonation of a premixed fuel-air mixture to periodically inject a jet of gas transversely into the primary flow would produce a more significant jet interaction flowfield. The detonation actuator should extend the effectiveness of jet interaction for active flow control into the supersonic flow regime.

Benefits Over Existing Systems:
A detonation actuator would be capable of producing a significantly greater interaction with the primary crossflow and would be more effective in supersonic flow. In addition, the actuator would be highly efficient in that only a small amount of fuel would be necessary to establish a detonation, producing a strong jet interaction without requiring a high pressure air system or bleed air. The concept is also applicable to inlet and diffuser flow control resulting in more compact devices.

Figure 1. Detonation Actuator Test Rig

Previous Work on this Work Package:
This project was a new start in FY 2002.

Current Year Accomplishments:
The critical element in the success of this research is the design of a small detonation device that can produce a cycle of detonations over the range of frequencies necessary for flow control. Each detonation would result in a region of high pressure combustion products led by a wave that would be injected into the crossflow of the primary fluid in a manner analogous to the pulsed jet. Initial work has involved the fabrication of an instrumented shock tube to facilitate the development of instrumentation and to serve as a reservoir for flow ejected from the actuators. Two actuator concepts are being considered. The first actuator utilizes a spark and fuel injector to control the frequency of the actuator. The second actuator utilizes a spark to initiate combustion, but the frequency of the actuator is controlled by the size of the actuator and the detonation wave speed that is established as the wave repeatedly reflects between upstream and downstream limits.

During FY 2002, a computational technique was developed for modeling detonation flowfields. The detonation code was then used to model a wide class of detonation actuator configurations. From this parameter space, two candidate designs (spark initiated and resonant) were selected and refined. The spark initiated detonation actuator was then further refined with simulations and a final design was chosen for fabrication. The resonant actuator design was also chosen from a parameter space, and further refinement with simulations is continuing on this design. Design and fabrication of the detonation (shock) tube was completed. Design and fabrication of the spark ignitors used to ignite the fuel-air mixture in the actuators, and design and assembly of the associated electronics necessary to control and power the ignitors was also accomplished. Development of the LabView Interface and equipment to control the operation of the experiments and collect the required data was also completed.

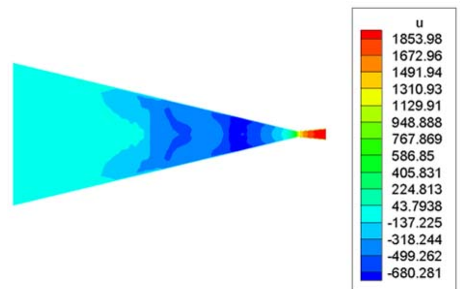

Figure 2. Spark Initiated Detonation Actuator

Lessons Learned:
There are two issues that have developed during the first year of this work. Fueling of both the spark-ignited and resonant detonation actuators must result in a uniform fuel-air mixture that will allow initiation and support of a detonation wave. Mixing enhancement strategies that have been useful in engine designs may be necessary to achieve the required fuel-air mixtures in both actuator designs. The resonant actuator concept must efficiently reflect a detonation wave back downstream to ignite a fresh fuel-air charge while passing a portion of the wave from the actuator into the cross-stream. Simulations are continuing to achieve an enhanced degree of detonation wave reflection before a candidate design is fabricated.

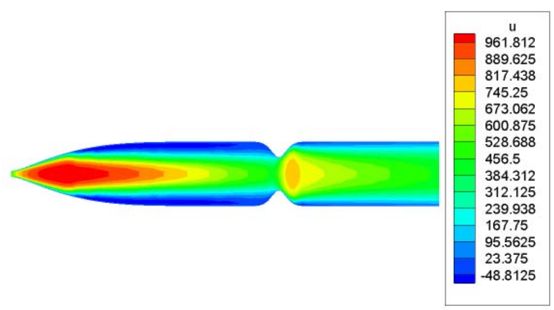

Figure 3. Resonant Detonation Actuator

Future Work:
During FY 2003, testing of the spark initiated detonation actuator will be completed, and the efficiency of the device will be assessed. The resonant detonation actuator design will be finalized, and the actuator will be fabricated and tested. Results from these tests will be used to further optimize both actuator concepts. Development of Schlieren and PLIF diagnostics systems will be completed and installed in the combustion test cell where this research is being conducted and used to visualize the actuator jet–crossflow interaction and separation control.

External Partners and Their Accomplishments:
Professor Andrew Cutler, under a grant with the George Washington University has developed detonation actuator designs, and is conducting experiments in support of the detonation actuator project. He has lead development of the instrumented shock tube to be used in the development and validation of the instrumentation and diagnostics, and to be used as a reservoir for flow

ejected from the detonator. Dr. Cutler has also developed the ignitor system to be used in both actuator designs. Dr. Sean O'Byrne, a National Research Council Fellow, has developed the LabView interface and equipment to control operation of the experiments and to collect the required data. Dr. O'Byrne is also working with Dr. Paul Danehy of LaRC to develop the nonintrusive diagnostics that will be used to study the jet interaction flowfield.

Closed-Loop Control of Cavity Shear-Layer Instabilities

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Background Information: Cavity flows are of critical importance to aircraft programs with weapons bays. In that case, the flow over a weapons bay exhibits large-amplitude, self-sustaining oscillations of a shear layer that are damaging to weapons and sensitive instruments stored within the bay. Current solutions to the problem are based on passive devices that are only applicable for a small range of flight conditions.

Objective of Current Work: The objective of the present work is to use active flow control technologies to suppress the flow oscillations via manipulation of shear-layer instabilities. The end goal is to achieve this suppression over a range of Mach numbers with an adaptive control system.

Benefits Over Existing Systems: Current solutions to the cavity problem are based on passive devices. These devices can minimize the flow oscillations for a given flight condition, but often exacerbate the situation at off-design conditions. An additional drawback of existing passive devices is their inability to suppress the multiple frequency modes that are present in cavity flow oscillations. A closed-loop adaptive control system may address these deficiencies.

Previous Work on this Work Package: In FY 2001, a synthetic-jet actuator for the cavity model was designed and subsequently tested with a simplified digital feedback control system. These experiments demonstrated the feasibility of using closed-loop control for cavity flow-tone suppression. Limitations in the actuator authority resulted in poor control performance at Mach numbers above 0.45.

Current Year Accomplishments: As a precursor to adaptive control, linear quadratic control designs methods were applied to the cavity tone problem. In this set of experiments, the synthetic-jet actuator was installed in the cavity model. Suppression of multiple cavity tones was achieved at Mach numbers of 0.275, 0.35, and 0.45 (figure 1). Closed loop performance was often limited by excitation of sidebands of cavity tones, and the creation of new tones in the spectrum. This behavior illustrates the limitations in linear control design methods that are not able to account for non-linear dynamics, such as the interactions between cavity tones at different frequencies.

To extend control performance to higher Mach numbers, a bimorph cantilever-beam actuator was designed and tested (figure 2). Closed loop control tests were performed with the actuator to demonstrate suppression of cavity tones. Tone suppression for Mach numbers up to 0.60 was achieved. *In situ* measurements of the actuator tip displacement revealed that a tip deflection on the order of 1-3 times the sublayer thickness was adequate for tone suppression.

Real time system identification algorithms were applied to the cavity flow problem. Finite-impulse response (FIR) and infinite-impulse response (IIR) filters were chosen to model the system dynamics. Adaptation of the filter coefficients was achieved with either least-mean squares (LMS) or recursive least squares (RLS) algorithms. FIR filters were unable to capture the system dynamics. IIR filters were better suited, but relatively high order filters (n = 60) were necessary to provide a reasonable model the cavity flow dynamics. In light of this, LMS adaptation may be better suited to the present problem given its computational simplicity and the currently available real-time hardware.

Lessons Learned: The most important lesson learned pertains to adaptive control. It is well known that the dynamics of the cavity flow change with changing Mach number. In the present case it is desired to track this change and maintain suppression of the cavity flow tones. For many adaptive control algorithms, this requires re-identification of the system dynamics as the Mach number changes. Typically, this is performed by introducing a dither signal to the closed-loop system. Amplitude limitations imposed by the actuator, however, prevent this from being realized and therefore other approaches must be considered. The self-tuning regulator (STR) is one possible alternative as it does not require a dither signal.

Future Work: Work in FY 2003 will focus on the application of the STR algorithm and an adaptive disturbance rejection algorithm that uses ARMARKOV/Toeplitz models to the cavity flow-tone problem. The advantage of the later algorithm is that minimal knowledge of the plant is required. The control experiments will be complemented with flow-field measurements (optical deflectometry and PIV) to better understand the physics of the flow control.

Formal and Informal Documentation Available:

1. Cabell, R. H., Kegerise, M. A., Cox, D. E., and Gibbs, G. P. *Experimental Feedback Control of Flow Induced Cavity Tones*, AIAA Paper 2002-2497.
2. Kegerise, M. A., Cattafesta, L. N., and Ha, C. *Adaptive Identification and Control of Flow-Induced Cavity Oscillations*, AIAA Paper 2002-3158.

External Partners and Their Accomplishments: Our partners at the University of Florida are writing the self-tuning regulator (STR) algorithm that will run on our current DSP hardware. System identification algorithms written by this group have been tested on our experimental cavity-flow testbed.

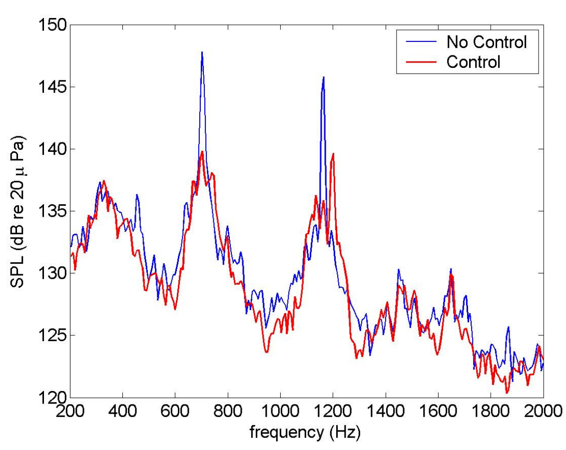

Figure 1: Feedback control of a cavity at M=0.35 and L/D=5.

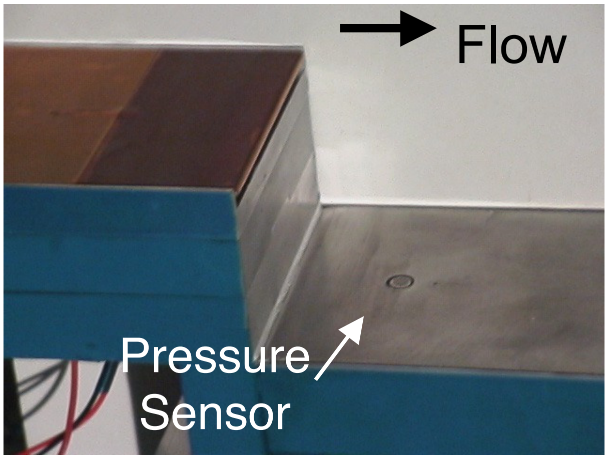

Figure 2: Bimorph actuator installed at leading edge.

Simplified High Lift System

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Background Information:
Conventional high lift systems employ a moveable slat and a moveable flap often comprised of several parts to generate the lift required for take-off, landing and loiter. These complex systems are expensive, heavy and maintenance intensive. A systems study performed by The Boeing Company, following successful demonstration of separation control at flight Reynolds numbers, indicated that significant cost and operational savings could be obtained if the current typical high-lift system could be replaced by a simply hinged slat and flap system with periodic excitation used to control separation. The current effort followed a comprehensive feasibility study at flight Reynolds numbers.

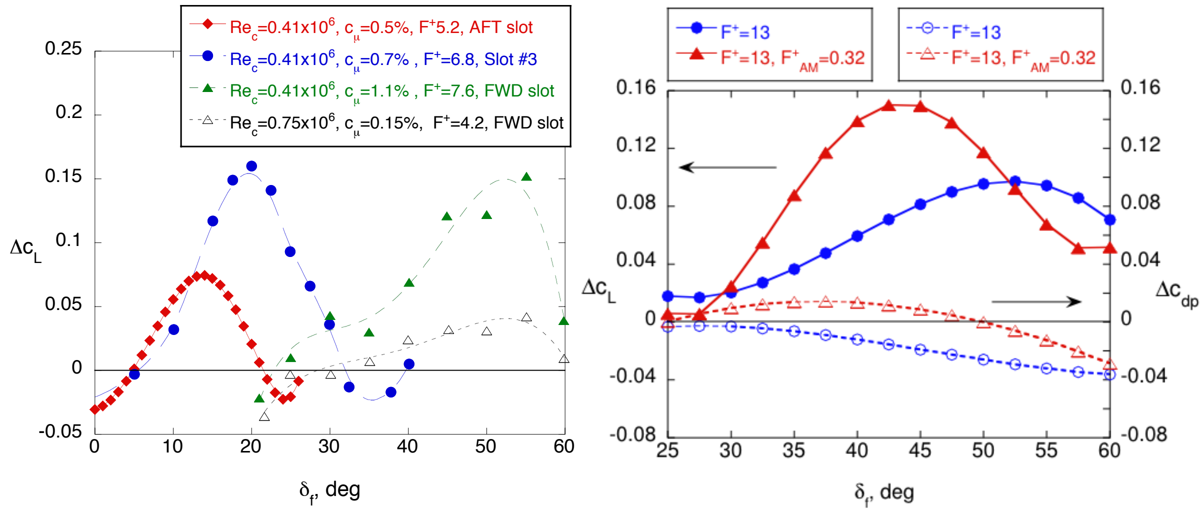
Objective of Current Work:
The objective of the current work is to simplify high lift systems by replacing the slotted slats and flaps with a simply hinged slat and flap and use periodic excitation to the control flow separation at the slat and flap shoulders.

Benefits Over Existing Systems:
Cost weight and operational savings.

Previous Work on This Work Package:
A modified version of the EET (Energy Efficient Transport) supercritical airfoil was tested in the Basic Aerodynamic Research Tunnel (BART). The supercritical airfoil has a simply hinged 15 percent chord leading edge slat that can be deflected from 0 to 30 degrees and a 25 percent chord simply hinged trailing edge flap that can be deflected from 0 to 60 degrees. The test focused on controlling flow separation at the slat shoulder. A piezoelectic actuator was used to produce periodic excitation for controlling separation at the slat shoulder. The primary reason for deflecting the slat is to eliminate the possibility of laminar LE separation or LE stall; thereby increasing the usable range of incidence and therefore the lift generated. For slat deflections higher than 10 degrees, the flow separates from the slat shoulder and the slat actuator is very effective at controlling that separation. With control from the slat actuator stall is delayed by 1 to 2 degrees and the maximum obtainable lift is increased.

Current Year Accomplishments:
The modified EET model was tested in the BART facility with periodic excitation applied on the flap for controlling flow separation. The piezoelectric flap actuator had four alternate blowing slot locations to control flap boundary layer separation over a wide range of flap deflections. Controlling flow separation from the flap was more challenging than control of flow separation from the shoulder of the leading edge slat. Three of the blowing slot locations were tested and figure 1a shows the effective flap deflection range for each slot. Low frequency modulation of the high frequency and amplitude excitation reduced the sensitivity to the slot location (figure

1b). The slots are most effective when separation occurred near but slightly downstream of the slot. Additional data were acquired for the slat actuator and those results were documented and presented at the AIAA 1st Flow Control Conference. A method for the identification of turbulent boundary layer separation was developed and validated over a wide range of flow conditions.



(a) $a=0^o$, $d_s=0^o$ (b) $a=0^o$, $d_s=-25^o$, $c_m=0.55$ percent, $Re_c=0.24\times10^6$

Figure 1. Lift increment due to AFC (referenced to baseline lift) vs flap deflection angle for (a) different excitation slot locations and (b) FWD slot. (Note that AFT slot data in (a) are from curve fits of the controlled and baseline data).

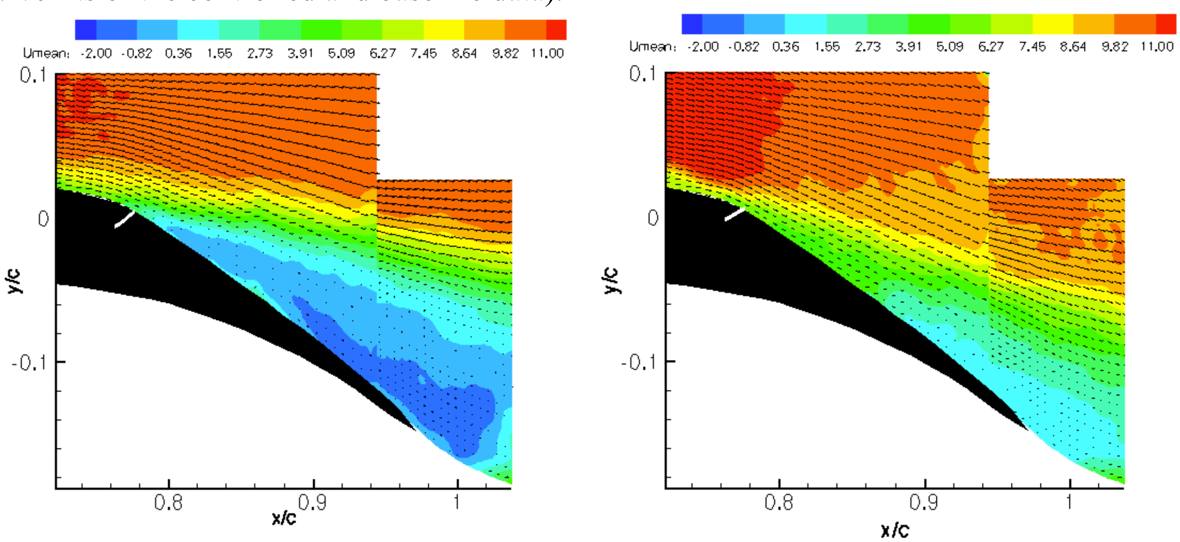


Figure 2. Particle Image Velocimetry of Baseline (left) and Controlled (right) flow fields. $Re_c=0.24\times10^6$, $a=6^o$, $d_s=-25^o$, $d_f=20^o$, $F^+=12$, $c_m=2.5$ percent, flap slot #3 (shown as white-out on black flap).

Lessons Learned:

Hot-film sensors are a useful and economical method of determining boundary layer state.

Future Work:
During FY 2003, the simplified high lift model will be tested with a slat actuator, a flap actuator, and an actuator upstream of the flap. The slat actuator kept the flow attached up to x/c~0.70 and increased lift. With the flap deflected and the flap actuator and flap upstream actuator active it is anticipated that the flow will remain attached to the flap, allowing increased flap deflections and enhanced lift. Flow physics data, due to the interaction of several actuators and the use of complex waveforms, to be gained during the coming test should enable effective and energy efficient operation of the method. Plans are also underway to design and manufacture a larger airfoil for test at higher Reynolds in LTPT in FY 2004.

Formal and Informal Documentation Available:

1. Lin J. C. and Dominik, C. J. *Parametric Investigation of a High-Lift Airfoil at High Reynold Numbers*, Journal of Aircraft, Vol. 33, No. 4, 1997, pp. 485-491.
2. Seifert, A. and Pack, L.G. *Oscillatory Control of Separation at High Reynolds Numbers*, AIAA Journal, Vol. 37, No. 9, 1999 pp. 1062-1071.
3. Seifert, A. and Pack, L.G. *Active Control of Separated Flow on a Wall-mounted "Hump" at High Reynolds Numbers*, AIAA Journal, V. 40, No. 7, July, 2002, pp. 1363-1372.
4. McClean, J. D., Crouch, J. D., Stoner, R. C., Sakurai, S., Seidel, G. E., Feifel, W. M., and Rush, H. M. *Study of the Application of Separation Control by Unsteady Excitation to Civil Transport Aircraft*, NASA CR-1999-209338, 1999.
5. Pack, L.G., Schaeffler, N.W., Yao, C.S., and Seifert, A. *Active Control of Flow Separation from the Slat Shoulder of a Supercritical Airfoil*, AIAA Paper 2002-3156, June 2002.
6. Melton, L. Pack, Yao, C.S., and Seifert, A. *Active Control of Flow Separation from the Flap Shoulder of a Supercritical Airfoil*, Extended Abstract Submitted to the 33rd Fluid Dynamics Conference, Orlando, Florida, June 2003.

External Partners and Their Accomplishments:
The work is performed in collaboration with Dr. Avi Seifert, currently a Professor at Tel Aviv University. Dr. Seifert worked on flow control, in particular separation control, for more than a decade before bringing his expertise to Langley Research Center in 1996, as an NRC research associate. Since 1996 he has worked with Langley personnel in demonstrating that periodic excitation is effective for active separation control at Reynolds numbers comparable to an aircraft at take-off, on swept airfoils, also at compressible speeds, on thick airfoils and applied the method to vector and rotate circular and rectangular turbulent jets.

Smart Surfaces for Drag Reduction

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Background Information:
Turbulent drag reduction has been going on since the early 1970's. Major interest in the early years was polymers and compliant walls. Polymers were found to give drag reductions as large as 80 percent but were only effective in water and oil and required a continuous supply of polymer. Compliant surfaces were found to delay transition and suppress noise on marine vehicles. In the late 1970's and 1980's, LaRC investigated many passive drag reduction concepts for aircraft application. The LaRC work was the impetus for drag reduction programs across the country and Europe. Despite all this work the only successful turbulent drag reduction device that was actually applied to an aircraft was the passive concept of Riblets, which gave drag reductions on the order of 5-6 percent. Indications are that more sophisticated active concepts can and will be required to provide large turbulent boundary layer drag reductions at typical flight conditions.

Objective of Current Work:
The objective of the current program is to explore and develop active and passive concepts for turbulent boundary layer drag reduction that will provide large drag reductions at typical flight conditions. The project is attempting to maximize drag reduction while attempting to minimize the complexity of the drag reduction system.

Benefits Over Existing Systems:
The concepts being studied in the present program will provide much larger drag reduction performance than the 5-6 percent improvement associated with Riblets.

Previous Work on this Work Package:
The initial effort was to determine the state of the art for drag reduction technology. Based on the initial assessment an experimental effort was established to concentrate on near wall modification of the boundary layer using oscillating vortex generators and a traveling wave concept. The main effort on the traveling wave was to be done under grant with Texas A&M University.

Current Year Accomplishments:
Assessment of the state of the art continues and has verified that near wall modification concepts have great potential. In the last year numerous papers have started to become available in which researchers are starting to experimentally assess active modifications of the near wall. CFD for some concepts are indicating drag reductions as large as 70 percent.

Oscillating vortex generators have been purchased and fabricated. The concept of the oscillating vortex generator is that the device generates a vortex and a resultant low speed region downstream. The idea is that the near wall flow structure will be modified and provide skin friction reduction. Figure 1 shows a dye flow visualization from Blackwelder and Jeon. The vortices generated by the device are clearly visible. Figure 2 shows PIV data obtained in a recent experiment using an oscillating vortex generator of similar dimensions. The data indicates that the PIV were capable of resolving the small structures in the near wall region and that these structures persisted for a considerable distance downstream of the device. For reference, roughness heights of fixed devices in wall units < 4 have no effect on the drag of a boundary layer. The oscillation amplitude in figures 1 and 2 is on the order of 1-2 wall units. Efforts are now underway to quantify the changes observed with the oscillating vortex generator.

Lessons Learned:
Active control systems will require small scale actuators and sensors. MEMS technology is the key to providing these sensors and actuators on a scale suitable for typical flight conditions. Although there have been numerous papers on MEMS technology and their application to active control, the devices are not readily available. LaRC's access to MEMS manufacturing facilities and devices needs to be developed.

Future Work:
The oscillating vortex generator concept will be examined in detail for understanding the flow physics that will lead to optimizing the drag reduction performance of the devices. Once optimized, the concept will be applied at higher Reynolds numbers leading to future flight tests of candidate concepts.

External Partners and Their Accomplishments:
The traveling wave concept was being investigated under grant with Texas A&M for use in water application. They were able to design and fabricate a first generation model that would generate a traveling wave with a small amplitude oscillation. Based on **Lessons Learned** with the first model, a second generation model was fabricated. This part of the program will not be funded in the upcoming year.

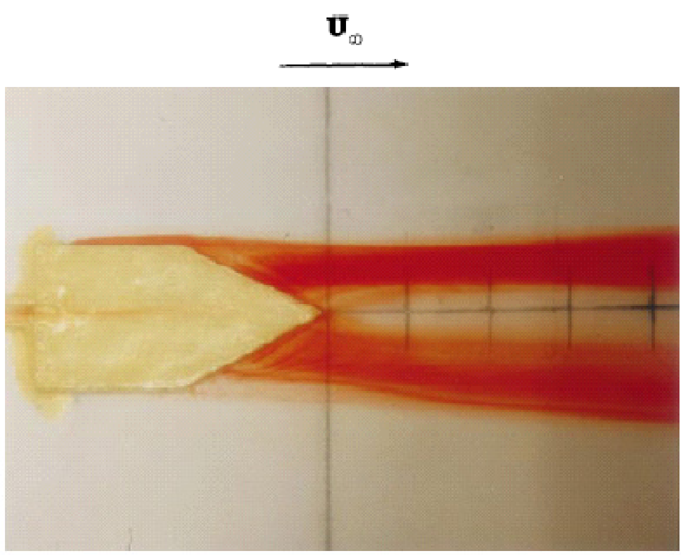

Figure 1. Water flow visualization (Blackwelder and Jeon)

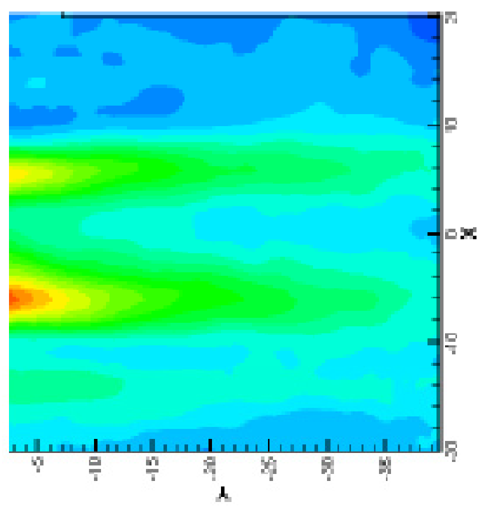

Figure 2. PIV downstream of VG (LaRC)

Active Transonic Drag Reduction Through Shock Spreading

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Configuration Aerodynamics Branch, Aerodynamics, Aerothermodynamics & Acoustics Competency

Background Information:
The area of transonic drag reduction has been a long-standing topic of research, which has been fueled largely by the commercial transport industry. Aerodynamic prediction codes and testing techniques have been developed which allow designers to develop aircraft that perform efficiently at design conditions. Methods to improve the off-design performance of commercial transports are always being examined, as the off-design characteristics often play a strong role in the sizing and range of a given configuration.

One method, which has been proposed to improve the off-design performance of a transonic aircraft, is a wing that can change shape, or "morph" to mitigate adverse off-design effects. A frequent goal of improving off-design performance focuses on reducing drag, particularly the wave drag generated by shock waves on the aircraft. Thus, a wing that could locally change shape to decrease the shock wave strength would be highly advantageous.

The current research examines the size and shaping of a small "bump" on a cruise wing upper surface, as a means by which to spread the shock wave, and thereby reduce transonic drag for off-design conditions. On an aircraft, the bumps would be part of an active system, whereby they would be deployed in an intelligent fashion to minimize drag. Thus, an aircraft designed to take advantage of such an active drag reduction system would have an increased range, and reduced operating costs.

Objective of Current Work:
Develop reductions in transonic drag by spreading and decreasing shock wave strength on an airfoil or wing. The size and shaping of small bumps on a cruise wing upper surface will be examined as a means by which to spread the shock wave, and thereby reduce drag for off-design conditions. Computational Fluid Dynamics analysis codes coupled with various design methods will be used to design and examine the effect of static bumps on the shock wave strength for a two-dimensional airfoil at off-design conditions. Promising geometries will be experimentally evaluated.

Current Year Accomplishments:
A new two-dimensional state-of-the-art transonic airfoil was designed specifically for the contour bump research. The current publicly available airfoils[1] were found to not represent the current aerodynamic design principles. It was realized that designing contour bumps for "old" technology airfoils would result in unrealistic drag reduction values. Thus advice was sought from airfoil design experts at the Langley Research Center and the Boeing Commercial Airplane Group to guide the design of the new airfoil.

The new airfoil's designation is: NASA TMA-0712. The TMA acronym stands for Transonic Morphing Airfoil, while the 0712 signifies a design lift coefficient of 0.70 and a maximum thickness to chord ratio of 12 percent. The design Mach number for the airfoil is 0.76 at a flight chord Reynolds number of 30 million. A multi-point design optimization was conducted using the MSES flow solver and the LINDOP[2] optimizer. The performance of the new airfoil was evaluated using the unstructured Navier-Stokes flow solver FUN2D[3]. The drag divergence characteristics of the new airfoil at the design lift coefficient are shown in figure 1. The off-design condition chosen for the contour bump design is also shown.

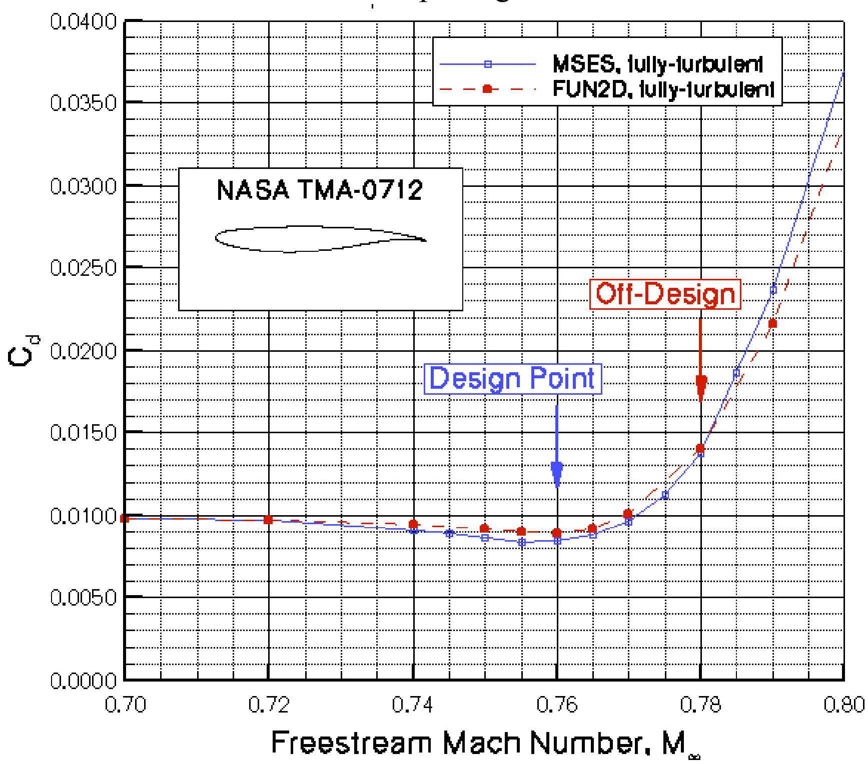

Figure 1. Drag divergence characteristics of the NASA TMA-0712 airfoil (C_l=0.70, Re=30x10^6)

A family of *static* contour bumps has been designed for the new airfoil at the off-design Mach number of 0.78. The LINDOP optimizer and the CDISC[4] design code were used for the design study, which used both the MSES and FUN2D flow solvers. Only the FUN2D results will be presented. Two design approaches have been taken, which encompasses a *near*-term and a *long*-term goal. The near-term morphing goal is a contour bump that would have a length of approximately 20 percent chord and *could* be applied as a retrofit to a commercial transport. The long-term goal is to allow a significant portion of the wing to morph, and the contour bump would be approximately 40 percent chord. Both concepts are shown in figure 2. The latter approach would likely require a new aircraft designed to specifically exploit morphing structures, hence the designation as a long-term goal.

Figure 3 examines the effect of the contour bump height on drag reduction for the off-design case. The design point for each bump family is shown. The contour bumps are clearly capable of generating significant drag reduction, in the range of 12 – 15 percent. The results indicate that the LINDOP optimizer determined the correct bump height, while the CDISC design missed the optimal height slightly. The results are also encouraging in that small variations in bump height do not significantly degrade the contour bump performance. The optimal contour bump heights are on the order of 0.5 percent chord, which agree well with the limited published data[5].

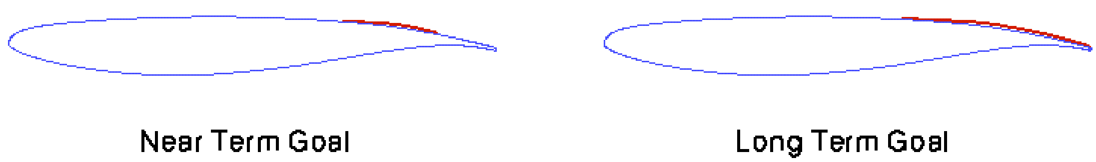

Figure 2. Near term and long term goals for contour bumps.

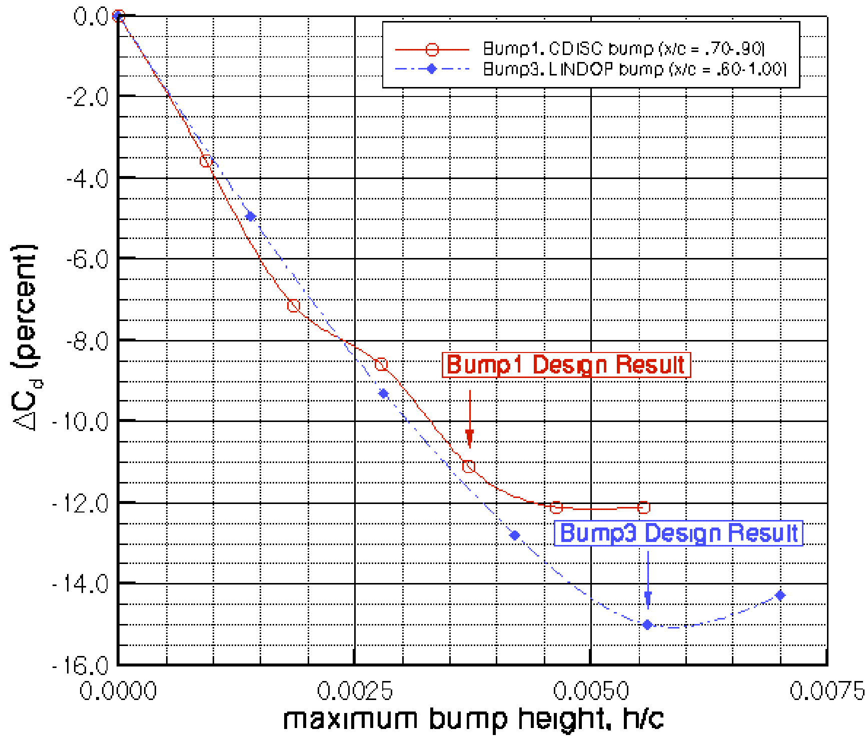

Figure 3. Effect of contour bump height on drag reduction.

Finally, figure 4 examines the effect of contour Bump-1 on the Mach number contours in the vicinity of the normal shock wave. The contour bump has decreased the peak Mach number ahead of the shock wave, and spread the shock to create a lambda-shaped shock wave.

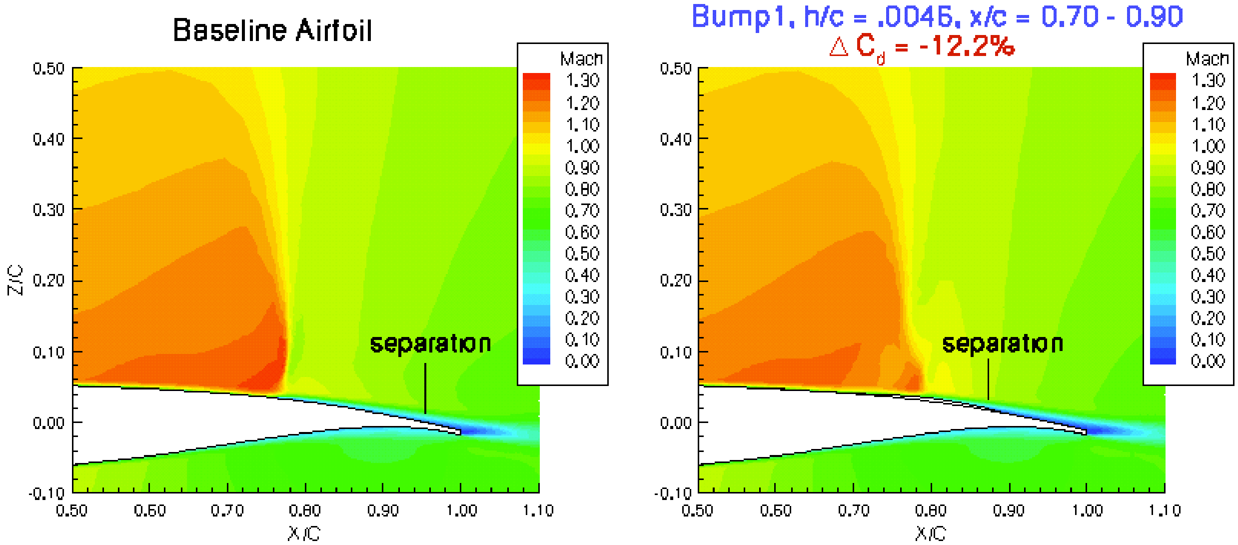

Figure 4. Effect of contour Bump-1 on Mach number contours (M_∞=0.78, C_l=0.70, Re=30x10^6)

Future Work:
The NASA TMA-0712 airfoil and the family of contour bumps will be experimentally evaluated in the NASA Langley 0.3-meter Transonic Cryogenic Tunnel during fiscal year 2003. The wind tunnel model is scheduled for delivery in May 2003. During fiscal year 2002, a new permanent focusing Schlieren system was designed and fabricated for this experiment. This system will provide clear and detailed images of how the contour bumps spread and weaken the shock wave.

During fiscal year 2003, a multi-organizational team of researchers will begin identifying and developing technologies that will enable the development of an active, deployable contour bump.

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3. Anderson, W. K. and Bonhaus, D.L. *An Implicit Upwind Algorithm for Computing Turbulent Flows on Unstructured Grids*, Computers Fluids, Vol. 23, No. 1., 1994, pp. 1-21.
4. Campbell, R. L. *Efficient Viscous Design of Realistic Aircraft Configurations*, AIAA Paper 98-2539, June 1998.
5. Stanewsky, W. *Adaptive Wing and Flow Control Technology*, Progress in Aerospace Sciences, Vol. 37, 2001, pp. 583-667.

Use of Surface Plasma for Flow Control Applications

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Background Information:
Current research explores the flow control uses of the body force due to a non-equilibrium, atmospheric-glow-discharge surface plasma. With proper electrical excitation, model geometry and dielectric materials, it has been demonstrated that a useful, low momentum, uni-directional flow up to about 5-8 m/sec can be generated on a surface with flush mounted electrodes.

Objective of Current Work:
The objective was to try to show whether the plasma could be used to reduce viscous drag due to turbulent boundary layer flow over a flat plate. It is known that mechanical, transverse oscillations of a wall reduces turbulent viscous drag by as much as 50 percent. It was hypothesized that by oscillating the flow close to the wall with the plasma-generated body force, that a similar drag reduction effect could be shown.

Benefits Over Existing Systems:
No viable system for active turbulent drag reduction in air yet exists so no comparison is possible. For plasma-based techniques the pros are mechanical simplicity and robustness. The cons are pollutant generation (primarily ozone and NOx) and operation in high humidity or condensing environments. Since only the pollutant level for the entire application system (i.e., an airplane) is important, the effluent gases from a local plasma are not per se a show stopper. If operability in wet environments proves to be an issue, restrictions on applications would have to be studied.

Previous Work on this Work Package:
Work package efforts in FY 2001 and prior work under DDF/C&I funding was directed at developing the techniques to conduct plasma flow control experiments, study of plasma physics and preliminary studies of turbulent drag reduction and separation control methods. The primary accomplishments were: discovery and patenting of the basic body force generation method (with the University of Tennessee), quantification of the flow forcing effect and demonstration of 2D airfoil separation control.

Current Year Accomplishments:
A method of oscillating the plasma near the wall for a turbulent boundary layer was developed. The primary finding was that the plasma could generate flow oscillations but only effectively at low frequencies. The target specification was 100 Hz. Figure 1 shows the measured frequency response. As seen, there is a fall in oscillation amplitude with the signal reduced by 90 percent at 50Hz, one half of the target frequency. Also, not shown in figure 1 is an unexpected mean flow component that accompanies the oscillation.

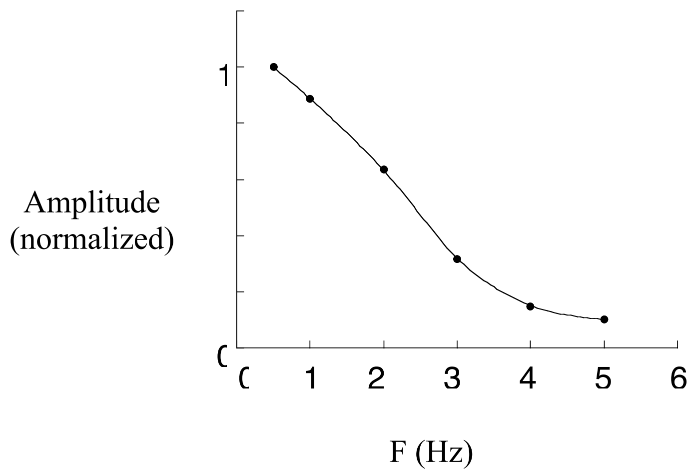

Figure 1. Typical frequency response of plasma induced flow oscillations. Measured with hot wire probe half way between adjacent electrodes. Excitation 6kV rms at 3 kHz.

Lessons Learned:
The lack of adequate frequency response and the generation of the mean transverse flow are now understood. The energy available at a given frequency is dependent on the body force amplitude and the frequency response roll-off rate. The body force amplitude may be increased through higher input voltage and a model material with a higher dielectric constant and higher breakdown strength. The frequency response of the flow system can be increased by decreasing target mass flow rate. The issue of the mean flow generation is also understood. As the periodic body force generation increases in frequency, it approaches a continuous or steady state flow. Each of these issues is currently being addressed to improve the techniques performance.

Future Work:
Continue oscillating plasma work as discussed above. Increase pace of the research by seeking computational support for simplified, approximate plasma/flow theoretical models. Extend effort to traveling electrostatic fields to increase magnitude of induced flow.

Formal and Informal Documentation Available:
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2. Wilkinson S. P.: *Investigation of the effect of a oscillating surface plasma on turbulent skin friction*. To be presented at the AIAA Aerospace Sciences Meeting, Reno, Nevada, January 2003.

External Partners and Their Accomplishments:
University of Tennessee PI: J. R. Roth. MOA SAA1-575 under AFOSR funding.
Demonstrated 2D airfoil separation control and proof of concept of electrostatic traveling wave excitation.

Smart Technologies FY 2002 Research Summaries

BIOSANT FY 2002 Accomplishments

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Advanced Materials and Processing Branch, Structures and Materials Competency

The (BIOSANT) research group continued to work on a bioinspired UAV wing with Dave Raney of the Dynamics and Controls Branch. An electrostrictive material capable of 4 percent strain in film form was fabricated into a lightweight membrane using electrospinning. At the end of FY 2001, we were able to demonstrate a small response to a 3KV sine wave (peak-to-peak) stimulus at about 2.8Hz. The goal for FY 2002 was to develop a process by which an electrospun wing with greater fiber orientation can be made. The oriented mat should yield better response to an applied electric field compared to randomly woven mats. At the end of FY 2002, the electrospinning apparatus was successfully modified to include a spinning drum in place of a stationary collector. The drum was capable of rotation at various speeds and side-to-side translation to allow for coverage of a larger area on a target. In addition, the materials tested were expanded to include not just electrostrictive polymers, but piezoelectric polymers as well, so that both sensing and actuating capabilities can be built into the UAV wing. Below are examples of fibers that result from electrospinning the rotating drum in three states.

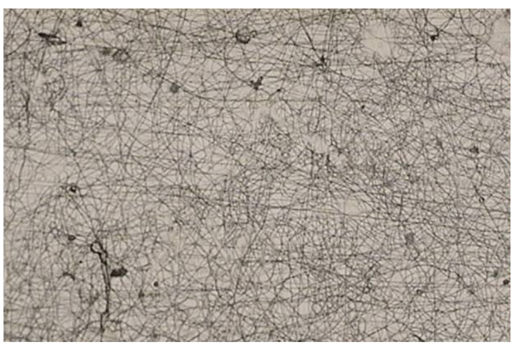

Figure 1a. No rotation

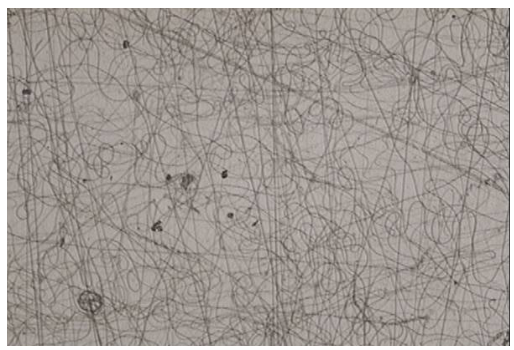

Figure 1b. Mid-range

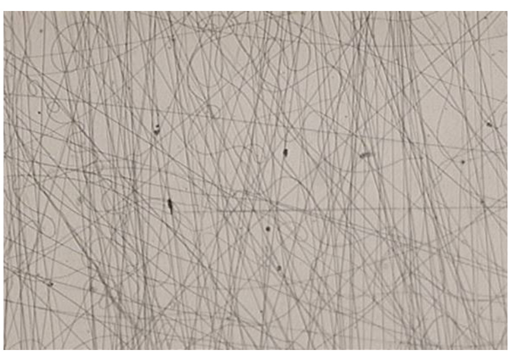

Figure 1c. High speed

Note that as the drum was rotated at the higher speed, greater orientation of the fibers was achieved.

The investigation on processing methods was also expanded to include two other electroactive polymers. It was interesting to note that the conductivity of the polymers used affected their spinnability. The material with higher conductivity was more difficult to spin and had a very narrow window of parameters that yielded good quality nanofibers. (These results were reported at the SDM meeting to be held in Norfolk, Virginia, April 2003.) However, electrospinning was found to induce dipole alignment in this material more efficiently than state-of-the-art fabrication methods. This finding was included in an invention disclosure filed with TCPO and Virginia Commonwealth University is currently pursuing patent coverage for the process used.

Miniaturized Morphing Electronics, For High Voltage and Sensor Integration

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Background Information:
There is a need for small, portable, efficient high voltage amplifiers. This would allow researchers to demonstrate many piezo electric actuator technologies in aircraft and at remote locations.

Objective of Current Work:
To develop small, portable, lightweight, and efficient high voltage amplifiers that work with an aircraft voltage (28V). A battery pack will also be developed for demonstration purposes.

Benefits Over Existing Systems:
As stated above researchers can demonstrate new and existing piezoelectric actuators at remote locations easily. The family of amplifiers is small enough to fit into any suitcase. They are battery powered for portability. As for lightweight, our unit weighs less than 3 pounds, whereas the lightest COTS solution weighs 29 pounds. The power voltage was chosen as 28 volts, this allows the units to be suitable for aerospace applications.

Previous Work on this Work Package:
New work package for FY 2002.

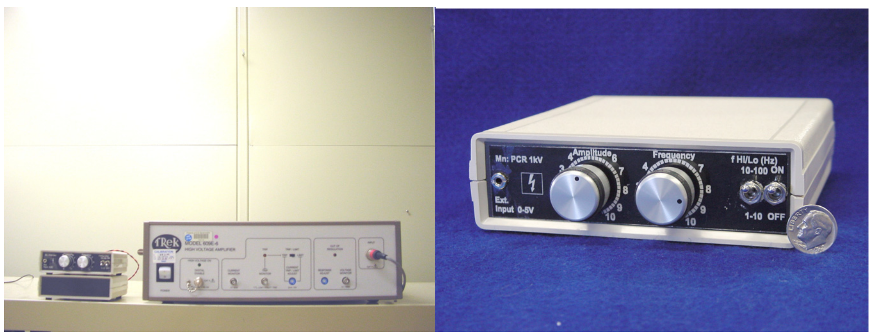
Current Year Accomplishments:
We have developed a family of high voltage amplifiers that fit many applications. The family ranges from 1KV to 6KV peak-to-peak output voltages. The units have built in signal generators that allow them to be used as stand alone demonstration units.
A custom-made battery pack and associated charging system was also developed.

Lessons Learned:
1. Little literature exists on the miniaturization of high voltage amplifiers.
2. Researchers do not fully understand their electronics needs or what the state of the art is capable of supplying.
3. How to significantly extend the bandwidth of a push pull high voltage amplifier.
4. How to package high voltage electronics without ionizing air.

Future Work:
An effort is underway to develop a higher power, smaller, and more efficient amplifier system.

Formal and Informal Documentation Available:

1. High, James W., Wilkie, W. K., and Bockman, James F. *Reliability Testing of MFC Actuators*. The NASA Electronic Parts and Packaging (NEPP) '02 Workshop, Houston, Texas, April 30-May 2, 2002,Bockman, James F. *Push-Pull Coupled Switching Power Amplifier.* NASA Case Number LAR 16454-1, April 24, 2002.
2. Robinson, Paul, and Bockman, James F. *Miniaturizing High Voltage Amplifiers for Piezoelectric Actuators*. The NASA Electronic Parts and Packaging (NEPP) '02 Workshop, Houston, Texas, April 30-May 2, 2002.
3. Wilkie, W., High, J., and Bockman, James F. *Reliability Testing of NASA Piezocomposite Actuators*. Actuator 2002, Bremen, Germany, June 10-12, 2002.
4. Robinson, P., Bockman, James F., and Blackburn, T. *Miniaturizing High Voltage Amplifiers for Piezoelectric Actuators*. Actuator 2002, Bremen, Germany, June 10-12, 2002.
5. Robinson, P., Bockman, James F. *Miniaturizing High Voltage Amplifiers for Piezoelectric Actuators*. First World Congress on Biomimetics and Artificial Muscles, Albuquerque, New Mexico, December 9-11, 2002.



Our Amplifier along side the COTS unit and a close up of one of our units

Exploratory Optimization Techniques for Conceptual Design

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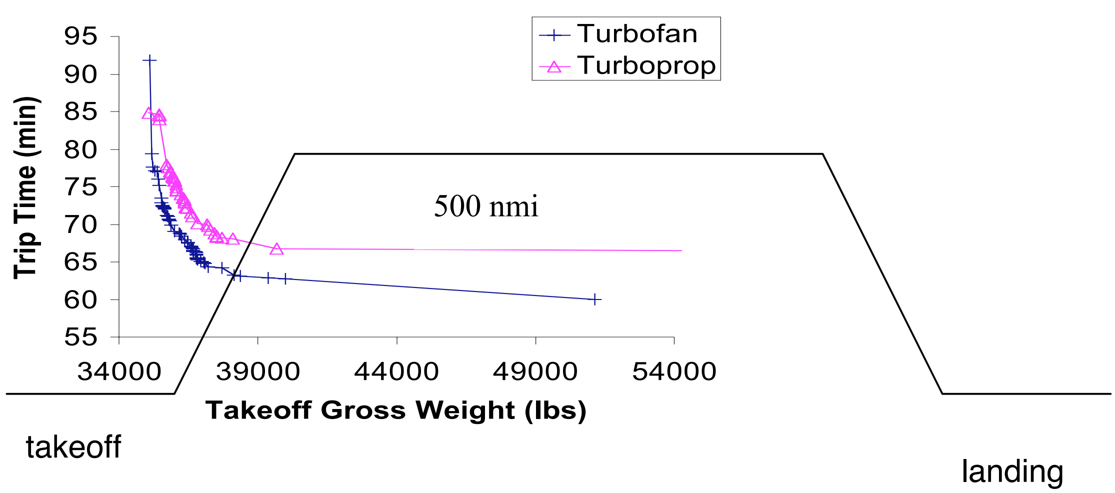
Multidisciplinary Optimization Branch, Aerospace Systems, Concepts and Analysis Competency

Background Information:
To design an air vehicle for diverse mission scenarios, systems analysts need optimization-based tools for trading off one mission goal against another. Some type of exploratory technique is particularly valuable when designing unconventional morphing vehicles where the trade spaces are not well understood. Such information is used to select a few designs for more extensive analysis. Moreover, such information enhances the designer's intuition about the tradeoffs and suggests new opportunities for revolutionary concepts.

Objective of Current Work:
This research tests a new N-branch tournament selection genetic algorithm tool for conceptual design problems. These methods differ from traditional optimization methods in that they generate large sets of comparable designs and they work well even for discontinuous design spaces and discrete-valued design variables (e.g., selection of tail configuration or the number of seats abreast).

Benefits Over Existing Systems:
These methods differ from normal genetic algorithms (GA) in that they allow a large number of constraints and they converge to many diverse solutions.

Current Year Accomplishments:
The 50-seat commuter problem illustrates the power of these methods. The NASA Langley aircraft sizing code FLOPS is used to analyze the 500-nmi range mission. The N-branch approach found 39 turboprop designs and 51 turbofan designs minimizing some combination of the two competing goals of trip time and takeoff weight.



Lessons Learned:
This chart shows typical results for the 500-nmi range mission. Each symbol represents a different candidate design found by the GA. Designs with low trip time and low takeoff gross weight deserve further study. Extensive testing of interesting academic problems suggests that the new N-branch GA approach is ideal for highly constrained problems where the good designs appear in clusters amid large regions of unacceptable designs. On the other hand, the more conventional multiobjective GA approach is ideal when the systems analyst wants to find solutions spread over a large Pareto frontier.

Future Work:
Optimization-based tools for conceptual design form a fruitful new area of research for the NASA. To be practical for Morphing vehicles, these tools must accept probabilistic and expert opinion-based inputs and must contend with computationally expensive and multidisciplinary analysis codes. The present research also can be extended to launch vehicle and satellite conceptual design problems.

Formal and Informal Documentation Available:

1. Martin, Eric T. and Crossley, William A. *Empirical Study of Selection Method for Multiobjective Genetic Algorithm*. Presented at the 40th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, January 14-17, 2002. Also AIAA 2002-0177.
2. Martin, Eric T., Hassan, Rania A., and Crossley, William A. *Generalization of the Two-Branch Tournament for N-Objective Optimization*. Presented at the 9th AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Atlanta, Georgia, September 4-6, 2002. Also AIAA 2002-5430.
3. Crossley, William A., Martin, Eric T., and David W. Fanjoy *A Multiobjective Investigation of 50-seat Commuter Aircraft Using a Genetic Algorithm*. Presented at the 1st AIAA Aircraft Technology Integration and Operations Forum, Los Angeles, California, October 16-18, 2001. Also AIAA 2001-5247.

External Partners and Their Accomplishments:
This research was accomplished through cooperative agreement NCC-1-01042 with Purdue University. William A. Crossley is the principal investigator.

Flight Control Using Distributed Morphing Effector Arrays

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Dynamics and Control Branch, Airborne Systems Competency

Background:
Recent discoveries in material science and fluidics have been used to create a variety of shape-change and fluidic effector devices that offer the potential to enable new approaches to aerospace vehicle flight control. Future aerospace vehicles might use distributed arrays of hundreds of such devices for stabilization and maneuver control, thereby augmenting or replacing conventional ailerons, flaps or rudders. Although several research efforts at universities, government labs and industry are underway to develop and characterize these devices, relatively few activities address the incorporation of such arrays into aerospace vehicle flight control architectures.

Objective and Approach:
This research seeks to develop flight control concepts for aerospace vehicles that utilize flow measurements from distributed sensor arrays and issue commands to large numbers of distributed effectors to achieve a desired control objective. Such control objectives include active separation control, stabilization and maneuver control, disturbance rejection or upset recovery, mission-adaptive performance enhancement, and failure accommodation. Control algorithms are developed and evaluated using computer simulation models, wind tunnel tests, and unmanned aerial vehicles (UAVs).

Benefits:
In addition to the aforementioned control objectives, reduced fuel consumption, enhanced maneuverability, reconfigurability, failure tolerance and mission adaptability are potential benefits of distributed effector and sensor arrays.

Previous work:
Prior work has focused on placement and control design for an aircraft equipped with distributed surface “bump" effectors”.[1-3] The simulation showed that such devices offered promise for seamless aircraft flight control. Previous efforts also provided control support for an active separation control wind-tunnel experiment in Langley's 0.3m cryogenic wind tunnel.[4]

Accomplishments and Lessons Learned:
Currently, research is focusing on the use of a highly instrumented UAV as a testbed for the development of flight control algorithms using distributed shape-change actuator and pressure sensor arrays. The UAV shown in figure 1 will be operated by NC State University under a cooperative agreement with NASA. Also shown in figure 1 is a panel model of the vehicle that was used to create a dynamic simulation for preliminary control law development.

Figure 1. Effector array UAV and panel model used to develop dynamic simulation.

The vehicle is equipped with an array of 12 trailing-edge shape change effector segments on each wing. Distributed pressure measurements will be associated with each independently controlled shape-change segment. The testbed will be used to evaluate a variety of centralized and decentralized control algorithms in the presence of real-world uncertainties and under various failure scenarios.

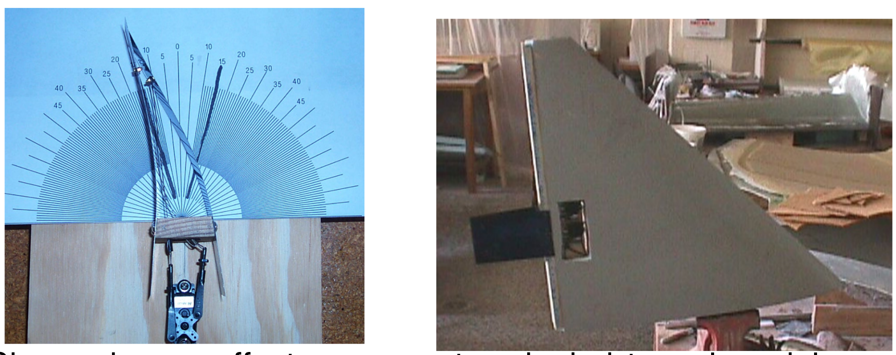

Figure 2. Shape-change effector segment and wind tunnel model used to validate mechanical design of the device.

Control algorithms that use the shape-change effector and pressure sensor arrays are currently under development. Accomplishments during FY 02 included design and fabrication of the actuation concept for the shape-change trailing edge effector segments, wind tunnel testing and validation of the mechanical design (figure 2), and creation of a baseline dynamic simulation model of the UAV for control algorithm development. An earlier version of the flight controls testbed had intended to use a different RPV as the baseline vehicle.[5] That configuration was damaged during preliminary checkouts at NC State, and so the configuration shown in figure 1 was selected as an alternate. It was then necessary to regenerate the preliminary dynamic simulation model for the new configuration. A model of the distributed effector array authority was incorporated into the dynamic simulation of the UAV, and two preliminary control algorithms were implemented to compare centralized and decentralized approaches to allocation for the effector array. Fabrication of the wing structures that incorporate the distributed pressure measurements and trailing edge actuator arrays is currently under way.

Future Work:
The dynamic simulation model will be refined with system identification data from checkout flights of the baseline vehicle. The modified wing sections will then be installed and a new series of system identification flight tests will be performed. The dynamic simulation model will again be updated, and designs for flight control algorithms that use the distributed sensors and effectors will be investigated in simulation and in the UAV testbed.

Documentation/References:

1. Raney, D. L., Montgomery, R. C., Green, L. L. and Park, M. A. *Flight Control using Distributed Shape-Change Effector Arrays*. AIAA Paper 2000-1560, April 2000.
2. Park, Michael A., Green, Lawrence L., Montgomery, Raymond C., Raney, David L. *Determination of Stability and Control Derivatives Using Computational Fluid Dynamics and Automatic Differentiation.* AIAA Paper No. 99-3136, 17th Applied Aerodynamics Conference, June 1999.
3. Padula, Sharon L., Rogers, James L., Raney, David L. *Multidisciplinary Techniques and Novel Aircraft Control Systems*. AIAA Paper No. 2000-4848.
4. Allan, Brian G., Juang, Jer-Nan, Raney, David L., Seifert, A., Pack, Latunia G., Brown, Donald E. *Closed-Loop Separation Control using Oscillatory Flow Excitation*. ICASE Report 2000-32.
5. Bernatz, Andreas, Hall, Charles Jr., Heinzen, Stearns, Chokani, Ndaona *Design and Flight Testing of a UAV SAS Using QFT*. AIAA Paper No. 2002-0246, 40th AIAA Aerospace Sciences Meeting & Exhibit, January 14-17, 2002.

Adaptive Structural Morphing FY 2002 Research Summaries

Kinematic Studies of New Morphing Wing Concepts

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Background and Objectives:
For years, the idea of having part of an aircraft that can morph from one configuration to another during flight has been an illusive goal. Morphing of a wing requires a paradigm change in the way wing structures are designed today. One such change would require elastomeric skins to allow under-structure mechanisms to move like bones in our body. Mechanism concepts that perform the desired function and analysis tools to guide the design process are under investigation. A key consideration in this design process is to develop systems that allow radical structural changes to occur while performing all of the functions of a conventional wing with little or no weight penalty. Two concepts have been under study at LaRC; a fish bone concept and an articulated truss concept. The fish-bone concept (see figure 1) was the first mechanism design that was built to stimulate ideas in this area. It was used as a focus problem in the development of kinematic models that incorporated both the understructure and the skin surface.

Benefits over Existing Systems:
Most existing wings in conventional airplanes have been optimized for a small portion of the flight envelope. When these same systems are modified to accommodate unanticipated objectives, e.g., wings with folding hinges, the resulting configurations can have significant weight penalties. Single point designs are relatively easy to do well but when conflicting objectives are considered often efficiency of the design tends to be compromised. Our task was to guide the design process using available analysis tools to evaluate requirements for such systems. Systems like the ones being considered herein are not operational and therefore there is little historical data.

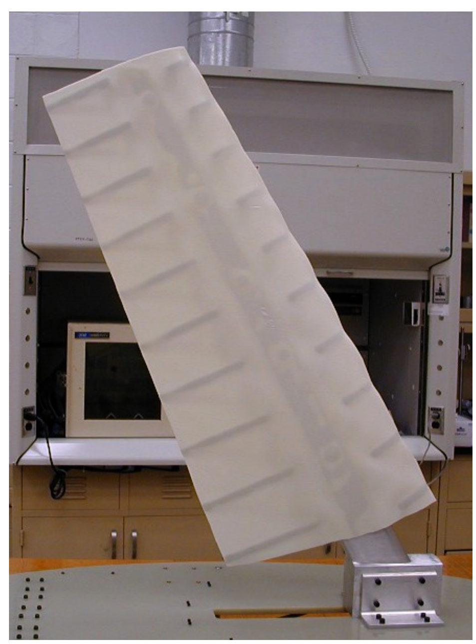

Figure 1. Fish-bone morphing wing.

Previous Work:
For the last few years, different groups within and outside of LaRC have been looking at morphing concepts. More recently, DARPA solicited ideas for potential funding of industry and university partners to develop this technology. Kinematic study of three-dimensional motion of morphing structures has never been done. Commercial codes such as the Dynamic Analysis and Design System (DADS) multibody simulation program have the capability but they have not been applied to this class of problems. Our work in multibody vehicle simulation helped the development of this initial model.

Accomplishments and Lessons Learned:
The fishbone concept is perhaps among the first morphing wing concepts designed and built in-house. It

consisted of a central spar with ribs attached to it through spherical joints. In the photo in figure 1, the wing is covered with a latex skin material. Starting with the engineering drawings, our goal was to create kinematic models for evaluation of actuation requirements under aerodynamic loads. Figure 2 shows the multibody dynamic model created in DADS. The mechanism was driven using two independent inputs and skin effects were modeled using linear tension-only elements. To simulate the aerodynamic forces, unit loads normal and tangential to the wing surface were applied at the center-of-gravity of each rib for lack of a better aerodynamic model. Figure 3 shows a sample set of results for power consumption commanding a harmonic motion. The red line corresponds to power required without skin material, green corresponds to motion with skin, and blue includes unit loads normal to the surface. It is clear that skin materials will play a major role in determining actuator requirements. More importantly, this analysis highlights the need to conduct material testing of skins to properly incorporate their effects during actuator sizing.

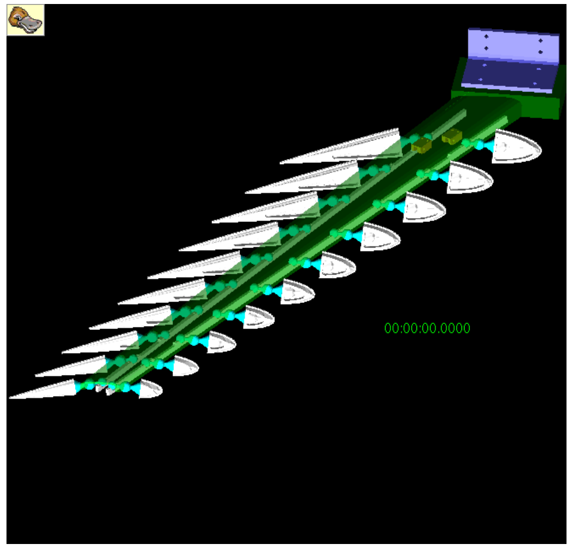

Figure 2. DADS multi-body dynamic model.

Future Work:
Work has shifted to a new articulated truss concept similar to those used by the Japanese for space applications.

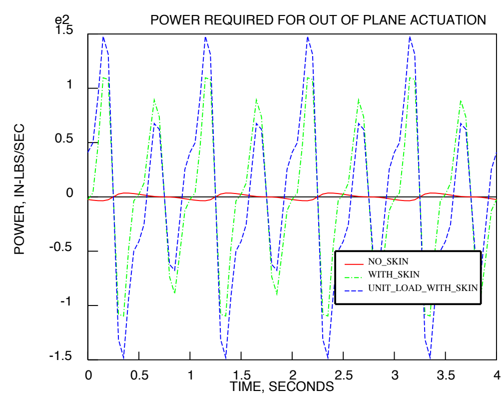

Figure 3. Power requirements with or without skin material.

Morphing Technologies for Composite Wing Structures

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Background Information:
Integration of morphing technologies with passive structural concepts can result in yet to be realized aerodynamic benefits that will result in reduced fuel costs, emissions, and potentially reduced noise. Using well-integrated advanced morphing technologies to reconfigure the vehicle aerodynamic surfaces during flight to optimal geometry's can result in previously unattainable flight regimes.

Objective of Current Work:
Develop validated morphing technologies for aeroelastic and aerodynamic performance of advanced vehicles using composite wing structures.

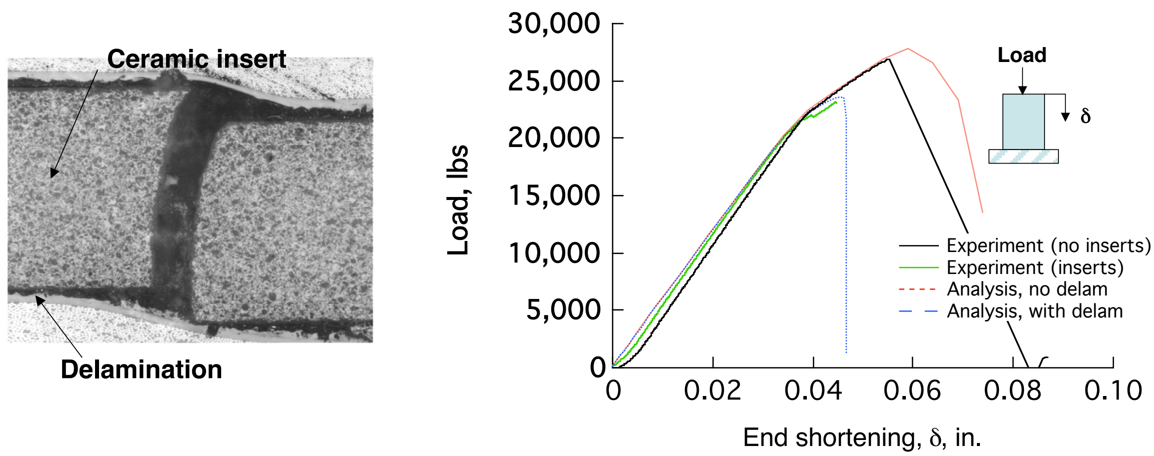
Benefits Over Existing Systems:
Combines passive control (elastic tailoring) with active control (smart structures) technology. Provides enhanced structural analysis capability by developing an SMA modeling capability for implementation into a general-purpose structural analysis code (STAGS) with significant nonlinear analysis capability. This advancement will enable the analysis of complex, built-up structures with embedded SMA actuators to be performed. Advances the state of the art in fabricating composite structures with embedded SMA materials and fiber optic sensors using non-autoclave manufacturing processes. Develops modeling techniques to assess the impact of delaminations between embedded actuators and the host structure.

Previous Work on this Work Package:
Developed analytical models to predict the response of composite laminates with embedded piezoelectric actuators with delaminations present on one surface. Investigated the applicability of using E-beam curing to fabricate unsymmetric laminates. Designed an unsymetrically laminated composite wing box representative of the outer wing box of an F-18. Conducted material property characterization of E-beam cured materials, and began investigating thermal post curing methods for these laminates. Investigated manufacturing techniques for embedding piezoelectric actuators into a composite laminate.

Current Year Accomplishments:
Performed test/analysis of composite beams with embedded MFC actuators with/without simulated delaminations on one surface. Completed test/analysis of composite panels with embedded ceramic wafers representative of piezoelectric actuators. The analysis included failure predictions obtained from progressive failure analysis. Conducted literature survey of actuator technology and identified actuator technology classifications. Developed an SMA modeling capability in the STAGS structural analysis code by adding temperature-dependent material properties for composite materials. Completed fabrication of SMA hybrid composite panels for shape control demonstrations, and completed the initial analyses of these panels.

Continued thermal post cure studies of E-beam cured unsymmetric laminates. Performed initial trials to embed pre-strained SMA actuators into E-beam cured laminates without mechanically restraining the SMA material.

Lessons Learned:
The test/analysis of composite beams with embedded MFC actuators with/without simulated delaminations on one surface validated the modeling technique used to represent the delamination. The results indicate that the presence of a delamination over one surface of an MFC actuator embedded into a composite laminate reduced the effectiveness of the actuator in generating axial displacements in the laminate, and also resulted in unwanted out-of-plane deformations. The presence of embedded ceramic inserts representative of piezoelectric actuators in composite plates reduced the failure strength of the plates by 14 percent. The inclusion of the as-manufactured state (including the presence of delaminations) in the progressive failure analysis dramatically affected the failure predictions. The presence of delaminations between the ceramic insert and the composite panel and the results of the experimental and progressive failure analysis of the panels are shown in figure 1 below.



(a) Cross-section of ceramic insert (b) Experimental and analytical results
Figure 1. Effect of embedded ceramic inserts on structural integrity of composite panels.

Initial fabrication trials to embed pre-strained SMA actuators into composite laminates using E-beam curing were successful. The laminates were cured without mechanically restraining the end of the actuators, and a post-cure strain recovery of the SMA material was demonstrated. Although interface issues between the SMA and composite material were noticed, this result is attributed to the lack of surface preparation of the SMA material prior to embedding it into the laminate. Thermal post-cure studies of E-beam cured unsymmetric laminates have begun to identify the issues that affect the dimensional stability of these laminates.

Future Work:
Continue the assessment of the new STAGS capability to utilize temperature dependent composite material properties. Complete the shape control demonstrations using autoclave-cured SMA hybrid composite panels. Initiate similar demonstrations using E-beam cured panels. Address the interface issues in E-beam cured composites with embedded SMA actuators. Develop, implement, and validate concepts for morphing using actuation devices and systems.

External Partners and Their Accomplishments:
Lockheed – Temperature dependent composite material properties for STAGS
Boeing, Seattle – E-beam curing of laminates with and without embedded actuators

Multifunctional Adaptive Structures

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Background Information:
Novel material systems and structures are needed for multi-mission morphing vehicles. Conventional structures are limited to single point designs and adaptability incurs large design penalties. Morphing concepts necessitate advanced materials and structures fabrication technology, characterization of the material systems and models to predict the behavior of such materials and structures.

Objective of Current Work:
Develop models for adaptive stiffening and shape control applications involving shape memory alloys (SMAs) and SMA hybrid composites (SMAHCs) and implement in general purpose/commercial finite element environments to enable broad use for concept development and structural analysis/design. Develop and refine SMA materials characterization methods to support model development and to facilitate application of SMA technology to morphing concepts. Develop adaptive, flexible skin technology for structural morphing concepts.

Benefits Over Existing Systems:
The LaRC SMA characterization activity is not only supplying property data for model development/validation and applications, but also uncovering unique behaviors not reported in the literature. SMAHC fabrication technology developed in this work package is amenable to automation and is commercially viable. Also the effective coefficient of thermal expansion (ECTE) constitutive model developed for SMAs/SMAHCs is the only known model that has been implemented in a commercial environment. The SMA constitutive model under development at North Western University (under cooperative agreement) is the only known model that is extensible to 3-D and captures the coupled effect of stress and temperature in SMA phase transformations. The thermal control and data logging system, with integrated infrared thermography, will provide a highly stable, accurate, and versatile system for a large variety of test requirements (e.g., automated materials and structural testing).

Previous Work on this Work Package:
A thermoelastic constitutive model ECTE was developed for analysis of SMAs/SMAHCs. Methods for SMA characterization and SMAHC fabrication were developed. SMAHC beam specimens were fabricated and the material system was characterized. The ECTE model was qualitatively validated against experimental results. A contract was established with MSC.Software Corporation to implement the ECTE constitutive model within the standard solution procedures of MSC.NASTRAN. An SMAHC panel specimen was fabricated with bi-directional SMA reinforcement. A LabVIEW-based data logging and thermal control system was developed to automate the measurement of SMA recovery force versus temperature and thermal cycle (referred to as SMAHCTS).

Current Year Accomplishments:
MSC.Software Corporation delivered a Beta release of MSC.NASTRAN with an implementation of the LaRC-developed ECTE constitutive model for analysis of structural concepts involving SMA and SMAHC. Validation of the implementation is underway. The SMAHC panel specimen that was fabricated in FY 2001 was configured for random vibration and acoustic transmission tests. The panel failed by overheating due to a thermal controller problem. Extensive measures have been taken to rectify the thermal control problem including procurement and integration of an infrared (IR) camera for full-field temperature measurement and control. Shape control demonstration specimens have been fabricated (see figure 1), and a test setup is under development (see figure 2). Measurements from these specimens will be used for numerical model validation (for shape control) and application-specific structural concept development. The data logging and thermal control system, SMAHCTS, is under massive expansion to incorporate IR measurements, to add flexibility in system configuration, and to allow variability in system control parameters so that SMAHCTS can be used for a variety of structural test requirements in support of the Morphing Project. An extensive study was conducted to discern the relationship between thermomechanical history, crystalline structure/phase content, and mechanical properties of SMA actuators. This study involved differential scanning calorimetry (DSC), x-ray diffraction (XRD), and thermomechanical testing. The results of this study showed an enormous effect and mechanisms for the variability were identified. A cooperative agreement was established with Northwestern University (NWU) to develop a high-fidelity constitutive model for SMAs. This model will serve as a basis for extending the modeling capability to 3-D, which will be extremely important for some applications. SMA material of several different compositions (shape memory and pseudoelastic) and configurations (round wire, ribbon, and strip) were procured to support adaptive structure concept development for the Morphing Project. Procurement of the pseudoelastic strip material has allowed initiation of an investigation into the feasibility of a layered composite concept for flexible skins.

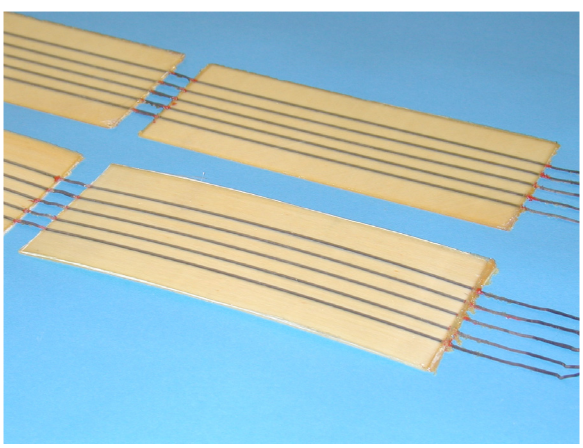

Figure 1. Shape control demonstration specimens

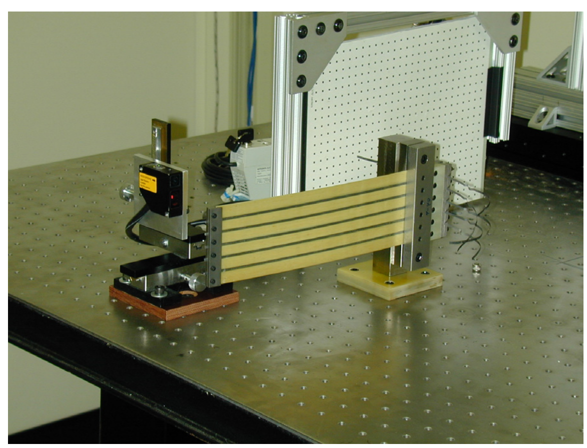

Figure 2. Shape control demo specimen test setup

Lessons Learned:
Thermal control of SMAHC structural concepts can be complicated. Surface-mounted thermocouples can be insufficient in terms of accuracy and reliability. Integrated and distributed measurement is needed. A particularly elegant approach may be optical fibers with combined strain and temperature measurement, which could give full-field strain and temperature measurement for closed-loop shape control and sensing of structural integrity/system state.

Future Work:
The ECTE implementation in MSC.NASTRAN will be fully validated in comparison to the LaRC in-house code and experimental results for nonlinear static and dynamic structural analysis. The shape control demonstration specimens will be tested to measure full-field deflection, full-field temperature, strain, and power consumption. Measurements from these specimens will be used for numerical model validation (for shape control) and application-specific structural concept development. This test setup will also be used to develop a strain-based, closed-loop deflection control system. The thermal control and data logging system, SMAHCTS, will be completed and used for refined structural acoustic tests on a new SMAHC panel specimen, shape control tests on the demonstrator specimens, and highly refined thermomechanical characterization testing of SMA materials. The 1-D version of the SMA model, developed by NWU, will be exercised in comparison to the ECTE implementation in MSC.NASTRAN and to experimental results to identify relative merits and bounds of applicability. Work on the NWU model will continue to extend the model to 3-D for analysis of structural concepts involving SMA materials in a multi-axial state of stress. A layered composite concept, involving pseudoelastic SMA sheet material, will be investigated for flexible skin applications. Shape control technology will be leveraged to develop adaptive jet nozzle chevrons.

Formal and Informal Documentation Available:

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2. Turner, T. L. *Structural Acoustic Response of a Shape Memory Alloy Hybrid Composite Panel (**Lessons Learned**)*. SPIE's 9th Annual International Symposium on Smart Structures and Materials; Active Materials: Behavior and Mechanics, SPIE Vol. 4701, Paper No. 4701-60, San Diego, California, March 17-21, 2002.

External Partners and Their Accomplishments:
MSC.Software and NWU activity detailed above.

Adaptable Metallic Materials and Structures

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Metals and Thermal Structures Branch, Structures and Materials Competency

Background Information:
Intermetallic Nickel Titanium (NiTi) shape memory alloys (SMAs) exhibit superior shape memory and superelastic properties and have been used in various applications requiring free recovery, constrained recovery, actuation, and superelasticity. NiTi SMAs are typically produced on the macro-scale (wire, ribbon, sheets, rods) using conventional metalworking processes. Due to the inherently high work hardening characteristics possessed by NiTi SMAs, frequent intermediate annealing steps are required during break down of the raw ingot material to final component shape. Machining and joining techniques such as welding, brazing, and soldering are generally difficult. Therefore, although the material is well developed, the current manufacturing procedures for producing NiTi materials are expensive and net shaping is difficult.

Objective of Current Work:
The primary objective of this work is to develop an innovative near-net shape manufacturing process for making shape memory alloys (SMA) for use in control and actuation systems for aircraft applications. Current efforts have focused on direct metal deposition (DMD) techniques including laser engineered near-net shape (LENS) processing for bulk shapes, plasma spray deposition (PSD) for thin sheet and foil applications, and sputter deposition for thin film coating applications.

Benefits Over Existing Systems:
The potential benefit of DMD processes will be likely realized in the fabrication of parts that cannot be readily produced by conventional wrought or casting fabrication processes. DMD processing of bulk materials via LENS processing affords the potential to fabricate nearly fully dense metal parts directly without the use of a mold, mandrel, or other tooling. The use of 5-axis controllers and multi-powder feeders in the LENS units make it possible to deposit a desired powder precisely at any desired location, thereby making it possible to manufacture complex shaped components. PSD offers the possibility of creating foils directly from powders thereby eliminating a number of processing steps. In addition, PSD can be used to spray SMA coatings on other metallic substrates thereby creating a bimetallic foil strip with shape memory response. Thin film NiTi SMAs produced via sputtering possess large energy density and displacement characteristics. Heat transfer is substantially increased in the micro-scale thin film deposits due to the small mass and large surface-to-volume ratio. As a result, power requirements are lowered and frequency response is increased while maintaining large actuation strains and stresses.

In addition, DMD processing offers the potential for producing engineered parts via functional grading of the microstructure and composition. By varying the powder mass flow rate for LENS and PSD processing or target temperature during sputter deposition, it is possible to produce deposits with a gradation in alloy content through the deposit thickness. Since the transformation characteristics of NiTi SMAs are extremely sensitive to alloy composition, it is possible to create integral SMAs with widely varying transformation temperatures. Examples include integrating a superelastic and shape memory composition to create a two-way actuating device.

Previous Work on this Work Package:
This was a new work package in FY 2002.

Current Year Accomplishments:
Fabricated LENS-processed NiTi composition SMA bars from elemental Ni and Ti powder. Characterized the microstructural features, austenite (A) – martensite (M) transformation temperatures, crystalline structure / phase content, and shape memory response of the LENS processed bars. LENS processed NiTi SMA that had been stress relieved and 3.5 percent compressively strained produced a 2 percent strain shape recovery during the M→ A transformation. Developed Radio Frequency (RF) induction PSD co-spray processing of elemental Ni and Ti powders. Fabricated a PSD NiTi SMA foil strip from elemental Ni and Ti powders. Consolidated and alloyed the PSD NiTi foil in vacuum hot press to synthesize embedded microstructures possessing shape change properties. Procured pre-alloyed NiTi powders to be used in the LENS and PSD processing of shape change bulk, foil, and coating materials.

Lessons Learned:
Difficult to obtain the desired aim chemistry for NiTi SMAs using DMD processing of elemental Ni and Ti powders. As-processed LENS SMA components are brittle in nature and require post-processing heat treatment and thermomechanical processing to fully develop the shape memory effect. Residual stresses produced by specimen machining have a major influence on the shape memory transition temperatures and transformation energy. Repeated heating and cooling cycles appear to reduce residual stresses and normalize shape memory transition temperatures and transformation energy.

Future Work:
Develop processing/structure/property relationships for the DMD processing of SMAs using pre-alloyed NiTi powder and target precursor. Demonstrate shape memory response for DMD processed SMAs. Develop processes to manufacture functionally gradient compositions to create in-situ deposits of SMA within a deposited metallic structure.

External Partners and Their Accomplishments:
A grant was initiated with Virginia Tech to develop and characterize ferromagnetic SMAs. Interagency Agreement was renewed with Department of Energy – Sandia National Laboratory for the development of LENS processing of functionally gradient compositions incorporating in-situ deposits of SMAs within a bulk metallic structure.

Biologically-Inspired Flight Systems FY 2002 Research Summaries

Dynamics and Control of Resonant Flapping Micro-Aerial Vehicles

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Background Information:
With uncountable civil and military applications, micro-aerial vehicles (MAVs) represent an emerging sector of the aerospace market and may one day become as ubiquitous as cell phones. Although a number of highly capable MAV designs have been generated by several government-funded and commercial endeavors, these designs rely on relatively conventional scaled-down control approaches, and they do not possess the flight agility and versatility that would enable missions such as rapid flight beneath a forest canopy or within the confines of a building. In order to satisfy such mission requirements, it is likely that μAV designs of the future will exploit flapping flight for extreme agility. Many flying insects generate lift through resonant excitation of an aeroelastically tailored structure: muscle tissue is used to excite a structure which exhibits a particular mode shape that has been tuned to generate propulsive lift. A number of MAV concepts have been proposed that would operate in a similar fashion.[1,2] A resonance-based flapping MAV design would challenge the current state-of-the-art in flight control for vehicles with highly transient flight-dynamic characteristics.

Objective of Current Work:
This work package does not seek to develop a flapping MAV design. The goal is to develop *dynamic models* and *feedback control concepts* for vehicle designs in which resonant excitation of an aeroelastically tailored wing structure is used to generate propulsive lift for an extremely agile MAV.

Benefits Over Existing Systems:
Control over the resonant wingbeat kinematics of an ornithoptic MAV would provide a degree of agility that would enable entirely new mission concepts. Such a vehicle could exploit unsteady aerodynamic factors such as dynamic stall to transition rapidly between hover and cruise flight modes, perhaps also varying its inertial properties by stowing its wings during high-rate maneuvers. Developing methods required to control a highly agile flapping MAV will bolster our understanding of unsteady and nonlinear dynamic phenomena in general, and could also have cross-over application to technologies such as distributed flow control effectors for full-scale aircraft.

Previous Work:
Previous work focused on modification of a latex and graphite-epoxy structural concept from a flexible fixed-wing MAV design from the University of Florida for use in elastodynamic flapping investigations. The structure was modified to create flexible wings that could generate bird-like flapping kinematics when excited at resonance. Later work focused on the use of thin film strain-rate sensors in a tuning circuit that generates a limit cycle oscillation at the resonant frequency of the flexible wing structures.

Lessons Learned:
Current research has focused on the development and operation of a biologically inspired vibrating wing system that provides control over the resonant wingbeat pattern. Key parameters for excitation waveforms that will produce various wingbeat patterns are currently under investigation. A comparison of wingtip trajectories produced by the vibratory testbed with those used by the hummingbird during various flight modes is shown in figure 1. LEDs located at the tips of the wing were used to trace out wingbeat patterns as the structures vibrated at flapping frequencies similar to hummingbirds in the same size range (25 Hz). The factors that are approximately matched in figure 1 include the stroke plane inclination to the body axis of the bird (or testbed), amplitude of the flapping arc, approximate geometry of the wingtip trajectory, and sense of rotation about that trajectory. Note that in forward flight, the wing travels clockwise about the trajectories shown in figure 1, while in reverse flight the wing travels about the trajectory in a counter clockwise sense. Based on these results, it appears that the biologically inspired design of this apparatus has afforded us the desired control over the wingtip trajectory. Such control is a key element in enabling an ornithoptic MAV to maneuver with birdlike agility.

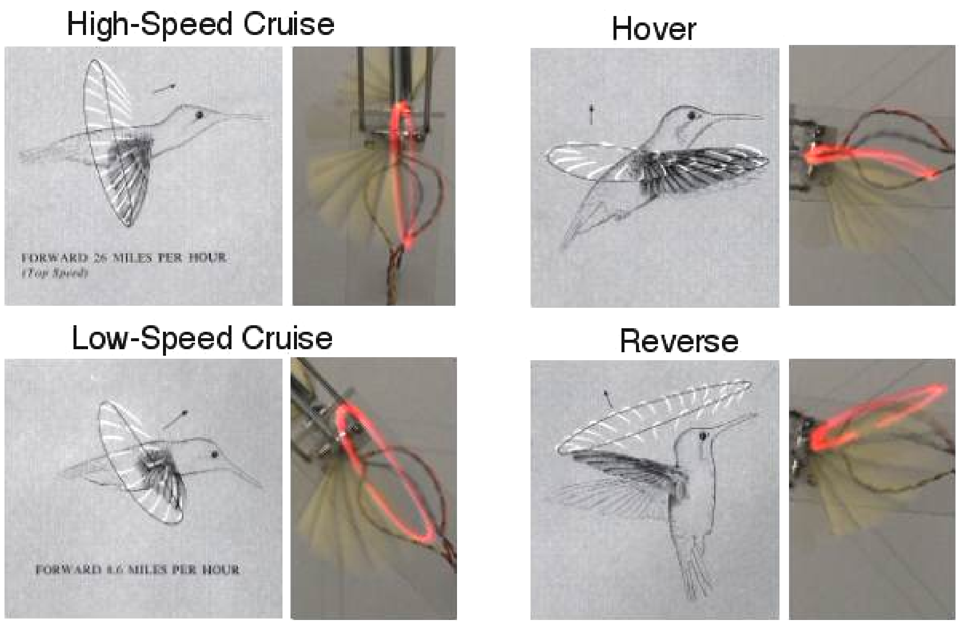

Figure 1. Comparison of wingtip trajectories produced by the shaker-actuated testbed with those used by hummingbirds during various flight modes (Greenwalt, 1990).

Future Work:
Future research will use the testbed to generate actuator force, throw and bandwidth requirements, and will produce calibration data for unsteady CFD codes. A hardware-in-the-loop flight dynamic simulation of an agile ornithoptic MAV is envisioned that will enable the development of flight control designs for such a vehicle.

External partners:
Under a cooperative agreement with Vanderbilt University, NASA is leveraging off previous DARPA-funded flapping flight research to provide information regarding flexible wing design for ornithoptic MAVs.[2] Consultation with researchers at the University of Texas in Austin is

providing mechanization and actuation insights from insect and avian morphological perspectives.

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Autonomous/Collaborative Control of Aeroelastic Fixed Wing Micro Aerial Vehicles: Flight Dynamics, Simulation, and Flight Control

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Micro aerial vehicles (MAVs) represent an inexpensive and expendable platform for surveillance and data collection in situations where larger vehicles are not practical. Many potential uses would require cooperative and collaborative control capabilities so that large numbers of MAVs could be used to cover a large operational area. An aeroelastic membrane wing MAV has been developed with the ability to adapt to atmospheric disturbances via a passive adaptive washout mechanism. This vehicle has been the subject of research to develop the understanding of its flight dynamics and the capability to develop, implement, and test autonomous and collaborative control schemes.

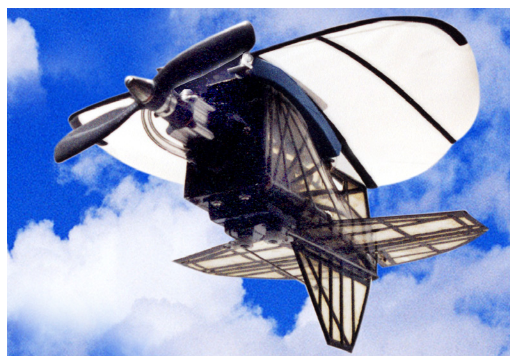

Figure 1. micro aerial vehicle.

Prior research has addressed the behavior of the membrane wing under steady flight conditions. Wind tunnel experiments were conducted in the NASA Langley Basic Aerodynamics Research Tunnel (BART) to identify the way in which the deformation of the membrane wing relates to the aerodynamic forces and moments produced by the vehicle. Data collected during these experiments also provided a basis upon which to develop a dynamic simulation of the vehicle in flight and assess the rigid-body stability and control characteristics of the vehicle.

Stability and control derivatives were obtained from the wind tunnel data to create an aerodynamic database describing the variations in aerodynamic forces and moments as functions of the control surface positions, throttle setting, angle of attack, sideslip angle, and airspeed. The aerodynamic database and the rigid body aircraft equations of motion were used to produce a six-degree of freedom flight simulation of the MAV. The simulation is implemented in Matlab/Simulink™ using a modular structure amenable to future improvements and enhancements.

The simulation model of the MAV was used to perform a number of analyses to assess the stability and control properties of the vehicle. A summary of the modal frequency and damping values for the longitudinal and lateral-direction modes of the vehicle are shown in Tables 1 and 2. Note that the short period mode is stable and lightly damped for all dynamic pressures while the phugoid mode becomes unstable (i.e., negatively damped) at higher speed. The spiral, roll, and dutch roll modes are all stable though the dutch roll mode is very lightly

Table 1 – longitudinal modes.

Dynamic Pressure (psf)	Short Period Mode		Phugoid Mode	
	damping ratio	freq. (rad/sec)	damping ratio	freq. (rad/sec)
1.0	0.13	23.3	0.44	0.85
1.6	0.12	30.2	0.35	0.65
2.0	0.12	32.6	-0.56	0.67

Table 2 – lateral-directional modes.

Dynamic Pressure (psf)	Spiral Mode	Roll Mode	Dutch Roll Mode	
	eigenvalue	eigenvalue	damping ratio	freq. (rad/sec)
1.0	-1.04	-27.7	0.094	21.1
1.6	-1.04	-37.3	0.065	24.2
2.0	-1.02	-42.8	0.050	25.9

damped. The frequency of the short period mode and roll mode time constant are roughly ten times faster than a typical piloted aircraft and the roll mode time constant. This combined with the very light damping of the dutch roll mode make the vehicle particularly difficult to fly. A preliminary guidance/control system has been developed to enable investigations of autonomous and collaborative control issues. The controller is composed of two main parts: an inner-loop measurement-based nonlinear dynamic inversion controller for control of angular rates and an outer-loop navigation command follower for control of wind-axis angles. The measurement-based nonlinear dynamic inversion approach uses acceleration measurements in lieu of a complete on-board vehicle model, this approach is less sensitive to vehicle model errors and can adapt to vehicle failures and damage. The method was extended to accommodate application to systems with fewer controls than controlled variables as is the case for the MAV. The guidance loop was designed to allow the simulation model to be integrated into an existing multiple vehicle collaborative framework. Preliminary results indicate that this is a viable approach for control of MAV's and similar systems. Future efforts will focus on improvements to this approach, robustness analysis, and use of this method as part of a multiple vehicle collaborative control scheme.

Additional experiments and analytical studies of the aeroelastic fixed wing micro aerial vehicle are planned or underway. Future studies will emphasize efforts to develop additional understanding of the physical properties of the membrane wing concept and use this understanding to improve the design of the vehicle and pursue other aerospace applications. In particular, the membrane wing is being used to apply and assess multidisciplinary design optimization methods for nonlinear aero-structure interaction.

The vehicle concept was developed at the University of Florida by a team led by Dr. Peter Ifju. A cooperative agreement (NCC-1-02004) has been established to coordinate development of the vehicle concept and research being conducted at NASA. The University of Florida team has continued to refine the vehicle design and develop related systems and components including electric power, vision-based control, and analysis and design methods.

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HECS Wing Development and Morphing Implementation

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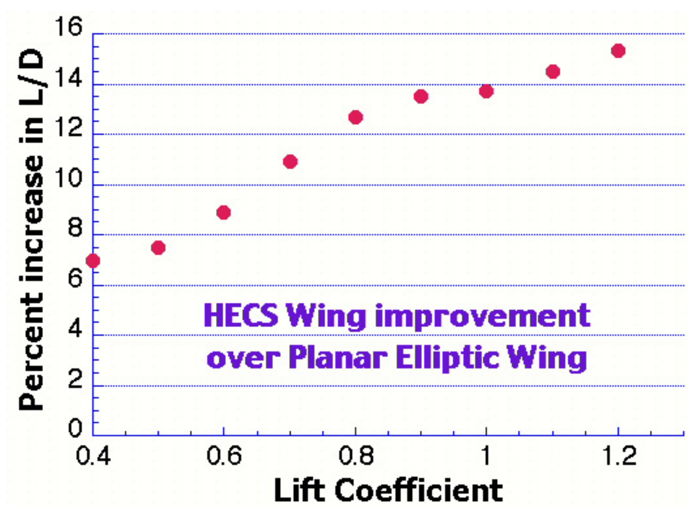
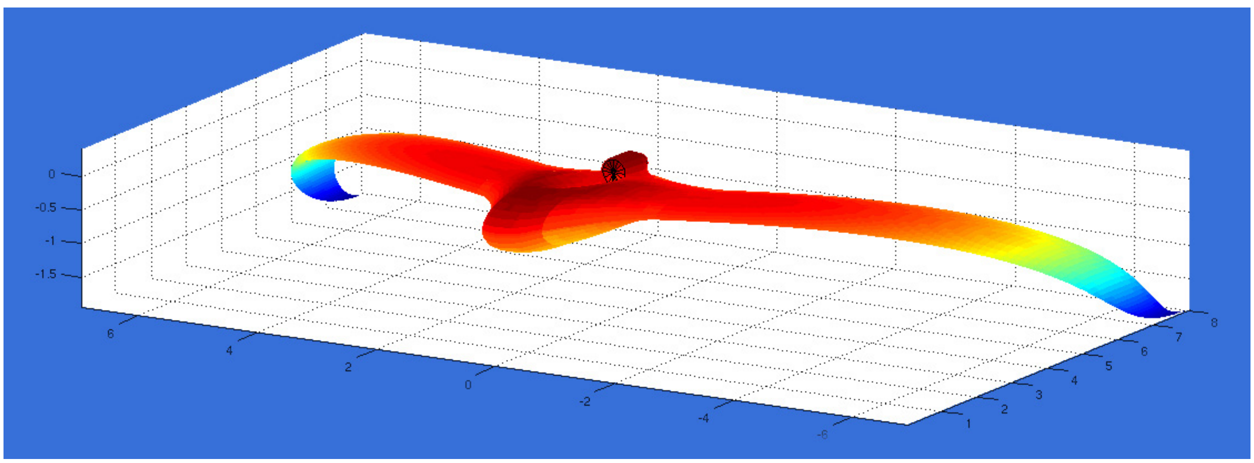
Man has often found inspiration for mechanical systems in nature from avian, marine and land organisms. Some may consider our understanding of natural systems complete, but are there still tricks to be learned? In 2000 NASA Langley took a fresh look at biomimetics to determine the state-of-the-art and consider where there may be gaps in our understanding[1]. The following year, the Morphing Program funded configuration biomimetics research aimed at the study of natural morphologies that may prove beneficial for advanced flight systems. The effort began by concentrating on biologically inspired wing configurations that may provide a reduction in induced drag. Induced drag accounts for as much as 50 percent of the drag of an aircraft in a cruise configuration. Sometimes called drag-due-to-lift, it can be described as lifting energy lost at the wing tips in the form of large counter-rotating vortices. Has nature found a more efficient flying configuration that reduces this energy loss?

In the following years, connections were made with biologists at the Virginia Institute of Marine Sciences, Harvard University and the University of Montana with the intension of determining low drag wing configurations. Wind tunnel tests were then conducted in 2002 to compare three biologically inspired wings with a planar elliptic wing; theoretically considered the best planar configuration for the least induced drag. One of the wings tested was dubbed the Hyper-Elliptic Cambered Span (HECS) due to its continuously varying spanwise camber. Inspiration for its shape came through observations of shore birds during soaring flight and was supported by theoretical work of Clarence Cone[2]. Test results indicate that even though the HECS wing has nearly a 10 percent increase in surface area it can provide a lift-to-drag increase of as much as 15 percent.



While the HECS wing configuration shows promise, there is room for improvement. Along with a significant decrease in induced drag, there is also a decrease in lift. Two approaches are being taken in the current year to improve on its performance. The first is a physics based approach. Two semi-span models are being constructed that will be tested in the Basic Aerodynamics Research Tunnel (BART). One is the planar elliptic configuration, used as the baseline, and the other is the HECS wing. Each will have nearly 150 pressure taps. Investigations into the flow physics associated with each wing will be conducted to determine what differences exist and how they might be advanced. The second approach will be to test various slightly modified HECS configurations. Whether increases or reductions in lift-to-drag are observed, insight will be gained.

The HECS wing shape lends itself to other aircraft improvements beyond drag reduction. With only minor in-flight wing tip adjustments, yaw, pitch and roll control can be accomplished. This will eliminate the need for a conventional tail and result in further drag savings. An effort has been organized in the current year to investigate the feasibility of using such shape changes for aircraft maneuvering. Stability and control analysis of such a vehicle proves daunting since maneuvers would be accomplished through continuous wing morphing rather than discontinuous adjustments to discrete control surfaces, as is conventionally done. Other issues that will be address are the Internal structure and the external skin. Can a feasible internal mechanism be devised that will produce the appropriate shape changes? What kind of skin will withstand the external aerodynamic loads and still provide flexure under internal loads? In the advent of successful answers to these and other questions, North Carolina State University has agreed to provide an existing, flyable UAV sized center body that HECS wings can be attached to for a proof of concept flight (see figure below).



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Airmass Guidance

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Background Information:
Small unpiloted aerial vehicles (UAVs) are becoming increasingly attractive for surveillance, communication, and science missions in both the military and civilian sectors. Although this encompasses a diverse range of applications these vehicles have a common requirement for long range and endurance. A typical mission scenario would involve repeating a waypoint driven flight circuit, or possibly navigating to a particular waypoint and loitering about that area. In such systems time-on-station is often a key factor in determining operational utility.

Objective of Current Work:
The objective of this work is to explore the potential to increase range and endurance by maneuvering the vehicle about a planed flight path, or in the neighborhood of a station keeping way-point, in such a way as to extract energy from the ambient atmospheric velocity field. The most direct approach is to circle in well defined thermals. These rising columns of air can be strong enough to overcome drag losses and increase a vehicle's altitude. Another approach, called dynamic soaring, involves only a vertical *gradient* in a horizontal wind field. Gradient conditions occur on the lee side of a hill or very near the surface over flat areas. Nature's use of these effects can be seen in the soaring flight of large birds. The wandering Albatross lives for days at a time on-the-wing, flying over the open ocean and does much of this just gliding without propulsion from flapping. Ground effects from the ocean's surface give rise to a consistent vertical wind gradient. By flying a spiral path the Albatross is able to gain energy during a downwind segment at altitude, then return upwind near the ocean's surface where the headwind is less strong.

Benefits Over Existing Systems:
In current practice UAV systems make little use of atmospheric conditions in path planning, except possibly to choose downwind landings or avoid adverse weather conditions. Attempts to increase range and time on-station typically involve low drag airfoil designs, efficient propulsion systems, and improved fuel or energy storage. Although these are critical design aspects they are also well-studied areas, and it is difficult to get substantial improvements in performance without incurring traditional engineering trade-offs in the design. An airmass guidance strategy, should one prove viable, would not involve changes to the vehicle design and should find application as a smart-system retrofit to existing or in-design UAVs.

Previous Work on this Work Package:
Previous work in this area involved the development of atmospheric datasets from convective atmosphere simulation programs. These datasets provided baseline thermal strength for systems with boundary level atmospheric dynamics driven by ground heating. In addition to wind strength, physical parameters such as moisture content, and localized pressure were available. Such correlated and measurable variables may be useful for flight systems trying to gage thermal strength and location from on-board measurements.

Current Year Accomplishments:
The primary focus of this year's effort was in the development of an aircraft model with appropriate consideration of the effects of winds aloft that could be used in non-linear trajectory optimization studies. In typical powered flight, speeds of the vehicle are much larger than the ambient wind field and can be described as perturbation effects on a consistent headwind. For the case of efficient soaring flight, the vehicle's speeds is comparable to ambient winds and wind effects must be considered directly. This involves in addition to inertial coordinates and a body fixed coordinates, the introduction of a wind relative coordinate system. Differential equations involving angle of attack, for example, should describe the body relative to an inertial frame; however, look-up tables of aerodynamic performance with respect to angle of attack must be body relative to the local wind frame. These models have been tested in simulated wind fields and produce expected results, as shown in figure 1.

They are also in a form suitable for trajectory optimization. Trajectory optimization allows one to find a flight path, consistent with the vehicles dynamics, that is minimizes energy loss. Figure 2 shows a typical result for a set of optimal trajectories in a vertical wind field. The starting and end point locations are prescribed in the horizontal plane, and flight path angles are constrained to be periodic at the boundaries. As the strength of the gradient increases, the flight path tends more towards dynamic soaring with more aggressive cycling into and with the wind. These dynamic soaring paths, despite a longer flight path, finish with higher altitude and energy than the optimal paths for the lighter wind-gradient cases.

Lessons Learned:
Solutions to the optimization problem are sensitive to details in the problem formulation. This makes use of additional information, such as correlated variables in the atmospheric model difficult to incorporate into the formal optimization problem. Therefore, there still exists a need developing and evaluating a guidance heuristic that will implement a sub-optimal version of these trajectories using on-board information.

Future Work:
To determine a guidance heuristic that will approximate the optimal solutions given the limited atmospheric information available on board the vehicle. These guidance laws need to be evaluation through simulation to determine if the necessarily sub-optimal solutions provide adequate benefits.

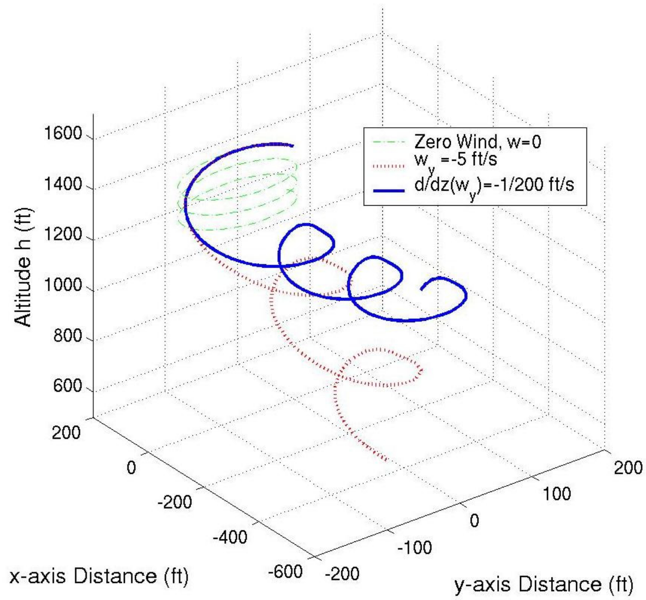

Figure 1. Open loop trajectory of glider model under various wind conditions.

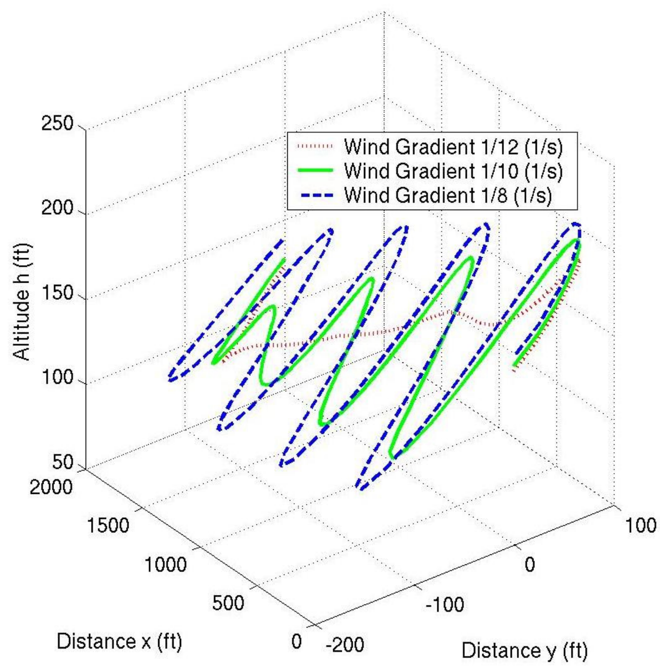

Figure 2. Optimal trajectory of glider for different strength wind gradients

Appendix

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2002 Morphing Lecture Series under the Auspices of the Institute for Computer Applications in Science and Engineering (ICASE)

http://www.icase.edu/series/Morphing/

In fiscal year 2002, a lecture series was continued to broaden our awareness of innovative technologies and approaches. The lectures were conducted through the ICASE group at Langley Research Center.

1. Bewley, Thomas: *Adjoint and Riccati: Essential Tools in the Analysis and Control of Transitional and Turbulent Flow Systems*. University of California, San Diego, October 23, 2001.
2. Carman, Gregory: *Investigating the Passive Damping Properties of Active Materials*. University of California, Los Angeles, October 3, 2001.
3. Carpenter, Bernie: *Shape Memory Actuated Control Surfaces*. Lockheed Martin Astronautics, May 16, 2002.
4. Cesnik, Carlos: *Wing Shape Deformation for High-performance Aerial Vehicles*. University of Michigan, Ann Arbor, June 26, 2002.
5. Chopra, Inderjit: *Review on the Status of Application of Smart Structures Technology to Rotorcraft Systems*. University of Maryland, College Park, October 31, 2001.
6. Grasmeyer, Joel: *Perspectives on Micro Air Vehicles and Electronic Packaging*. AeroVironment, Inc., November 9, 2001.
7. Haller, George: *Exact Theory of Unsteady Separation with Applications to Flow Control*. Massachusetts Institute of Technology, August 15, 2002.
8. Kota, Sridhar: *Compliant Mechanisms: Design Methods and Applications to Shape Morphing Structures*. The University of Michigan, Ann Arbor, May 10, 2002.
9. Lauder, George: *Fish Morphing: Experimental Hydrodynamics of Locomotion in Fishes*. Harvard University, March 15, 2002.
10. Livne, Eli: *Aeroelastic/Aeroservoelastic Challenges in Integrated Shape Design Optimization of Flight Vehicles*. University of Washington, Seattle, September 10, 2002.
11. Livne, Eli: *Towards Integrated Aeroservoelastic Optimization of Strain-actuated Flight Vehicles (A Progress Report.* University of Washington, Seattle, September 11, 2002.
12. Monner, Hans Peter: *Overview of Smart Structures Activities in Europe*. DLR - Institute of Structural Mechanics, Germany, May 30, 2002.
13. Monner, Hans Peter: *Overview of Smart Structures Activities in Germany*. DLR - Institute of Structural Mechanics, Germany, May 23, 2002.
14. Monner, Hans Peter: *Smart Structures Activities at the Institute of Structural Mechanics of the German Aerospace Center (DLR.* Institute of Structural Mechanics, Germany, May 6, 2002.

2002 Morphing Lecture Series under the Auspices of the
Institute for Computer Applications in Science and Engineering (ICASE)

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15. Shkarayev, Sergey: *Experimental and Computational Modeling of Flight of Insects and Design of Micro Air Vehicles*. The University of Arizona, May 15, 2002.
16. Weisshaar, Terrence: *Aeroelastic Tailoring for Energy Efficient Morphing Aircraft - Finding the Right Stuff*. Purdue University, October 25, 2001.

Partnerships and Collaborations in the Morphing Project in Fiscal Year 2002

Air Force Office of Scientific Research
Air Force Research Laboratory
Defense Advanced Research Projects Agency
Department of Energy
George Washington University
Georgia Technology Research Institute
Lockheed Martin
MSC.Software
North Carolina State University
North Western University
Purdue University
Sandia National Laboratory
Tel Aviv University
Texas A&M
The Boeing Company
University of Florida
University of Tennessee
University of Texas at Austin
Vanderbilt University
Virginia Tech

Acronyms

BART	Basic Aerodynamic Research Tunnel
BIOSANT	BIOlogically Inspired SmArt NanoTechnology
CFD	Computational Fluid Dynamics
COTS	Commercial Off The Shelf
DDF	Directors Discretionary Fund
DMD	Direct Metal Deposition
DSC	Differential Scanning Calorimetry
ECTE	Effective Coefficient of Thermal Expansion
EET	Energy Efficient Transport
FI	Fluidic Injection
FIR	Finite Impulse Response
FTV	Fluidic Thrust Vectoring
GA	Genetic Algorithms
HECS	Hyper-Elliptic Cambered Span
IIR	Infinite Impulse Response
LaRC	Langley Research Center
LED	Light Emitting Diode
LENS	Laser Engineered Near-net Shape
LMS	Least Mean Squares
MAV	Micro-Aerial Vehicles
MEMS	Micro Electrical Mechanical System
NASA	National Aeronautics and Space Agency
PSD	Plasma Spray Deposition
RLS	Recursive Least Squares
SMA	Shape Memory Alloy
SMAHCs	Shape Memory Alloy Hybrid Composites
STAGS	Structural Analysis Code
STOL	Short Unimproved Runways
STR	Self-Tuning Regulator
TCPO	Technology Commercialization Program Office
TMA	Transonic Morphing Airfoil
TRL	Technology Readiness Level
TV	Thrust Vectoring
UAV	Unmanned Aerial Vehicle
XRD	X-Ray Diffraction

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14. ABSTRACT
The Morphing Project at the National Aeronautics and Space Agency's (NASA) Langley Research Center (LaRC) is part of the Breakthrough Vehicle Technologies Project, Vehicle Systems Program that conducts fundamental research on advanced technologies for future flight vehicles. The objectives of the Morphing Project are to develop and assess the advanced technologies and integrated component concepts to enable efficient, multi-point adaptability of flight vehicles; primarily through the application of adaptive structures and adaptive flow control to substantially alter vehicle performance characteristics. This document is a compilation of research summaries and other information on the project for fiscal year 2002. The focus is to provide a brief overview of the project content, technical results and lessons learned. At the time of publication, the Vehicle Systems Program (which includes the Morphing Project) is undergoing a program re-planning and re-organization. Accordingly, the programmatic descriptions of this document pertain only to the program as of fiscal year 2002.

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