Recent Results from NASA's Morphing Project

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ABSTRACT

The NASA Morphing Project seeks to develop and assess advanced technologies and integrated component concepts to enable efficient, multi-point adaptability in air and space vehicles. In the context of the project, the word "morphing" is defined as "efficient, multi-point adaptability" and may include macro, micro, structural and/or fluidic approaches. The project includes research on smart materials, adaptive structures, micro flow control, biomimetic concepts, optimization and controls. This paper presents an updated overview of the content of the Morphing Project including highlights of recent research results.

Keywords: Smart materials, smart structures, micro flow control, biomimetics, adaptability, morphing

1. INTRODUCTION

The National Aeronautics and Space Agency's (NASA's) Morphing Project, led from the 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 advanced technologies and integrated component concepts to enable efficient, multi-point adaptability in air and space vehicles. While there is no formal definition for the word "morphing," it is usually considered to mean large shape change or transfiguration. However, in the context of NASA's research on future flight vehicles in the Morphing Project it is defined as: efficient, multi-point adaptability and it includes macro, micro, structural and/or fluidic approaches. In defining "morphing" in this manner, efficient denotes mechanically simpler, lighter weight, and/or more energy efficient than conventional systems; multi-point denotes accommodating diverse (and sometimes contradictory) mission scenarios; and adaptability denotes extensive versatility and resilience. NASA's Morphing Project strategically incorporates both micro fluidic and small and large-scale structural shape change to address the intertwined functions of vehicle aerodynamics, structures and controls and also to seek new innovations that may only be possible at the intersection of disciplines. The project is directed towards long-term, high-risk, high-payoff technologies, many of which are considered to be "disruptive" technologies. The three focus areas of the project are: adaptive structural morphing, micro-aero adaptive control, and biologically-inspired flight systems as shown in Figure 1. These areas are supported by the core enabling areas of smart, nano and biologically-inspired materials, multi-disciplinary optimization, controls and electronics.

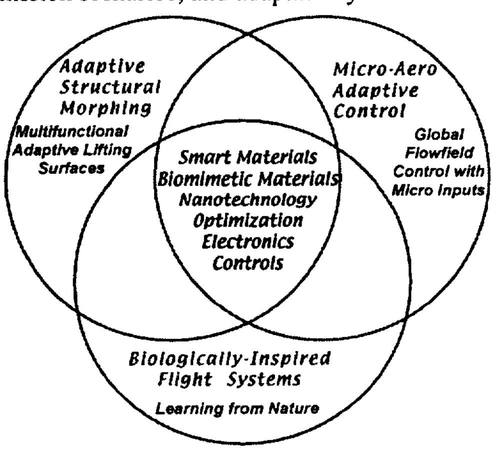

Figure 1: Overview of the content of the Morphing Project.

Though the focus of NASA's Morphing Project is long-term pay-offs, air vehicle morphing is not new, as it was crucial to the success of the first heavier-than-air flight in 1903. Certainly, all flying vehicles must adapt to some degree to accommodate different flight conditions. Some vehicles, such as the variable sweep F-14 and the vertical take off and landing AV8-B Harrier, are capable of more adaptation than most air vehicles. In fact, the key technical challenges that are examined in the Morphing Project, including vehicle control, adaptability, efficiency, and, of course, safety, have long been some of the cornerstone challenges of flight. NASA's role is to explore the potential breakthroughs in vehicle adaptability offered by new, potentially "disruptive" technologies and to lay the technical groundwork for discontinuous advancements in the capabilities of future flying vehicles. Hence the project goals are not only enabling adaptability but also doing so with high efficiency and at many points in the flight regime – a challenge not yet reached in today's flight vehicles. The Morphing Project seeks to understand the science behind efficient multi-point, adaptability in future air and space

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vehicles and to develop and assess the technologies that make it possible. The long-term vision: aerospace vehicles that efficiently adapt to handle diverse mission scenarios. The benefits are diverse but generally include: 1) extensive versatility to accommodate contradictory mission requirements efficiently; 2) significant resilience to accommodate unforeseen problems safely; 3) aggressive efficiency improvements including weight and drag reduction; and 4) new mission scenarios previously deemed impossible. For some applications, specific, quantifiable benefits are available, some of which are mentioned in this document and in the references. As defined above, morphing has applicability to nearly all classes and sizes of flight vehicles, civilian and military.

This document provides an updated overview of NASA's Morphing Project as well as highlights of recent results. To highlight the current work, selected studies are presented as examples; these are not intended to cover all of the possible applications of the technologies. References 1, 2 and 3 provide earlier overviews of the project. Numerous papers discuss results of specific research efforts within the project. The reference list of the current paper provides a listing of many of these research efforts.

2. BACKGROUND

Often called "disruptive" technologies, the application of smart, adaptive, and biologically-inspired technologies to aerospace vehicles brings much promise and controversy to the aerospace community. This dichotomy is not unusual for new technologies. Typically, there is initially "over-selling" of new technologies, quickly followed by controversy as to the real benefits provided by the new ideas. In reference 4 Weisshaar represents this trend graphically as shown in Figure 2 and describes the cycles of optimism and pessimism for new technologies. As mentioned in this reference, two important issues arise in the development of new technical discoveries: 1) the first use of a new technology often leads to focusing research on the newfound issues in using the technology and 2) simply replacing existing systems with the new technology often results in sub-optimal performance. These issues are prevalent today in the application of morphing technologies to aerospace vehicles. Likewise, the opportunity for positive, sweeping change in the aerospace industry is possible if systems-level, multidisciplinary design efforts take advantage of the unique characteristics of the new technologies.

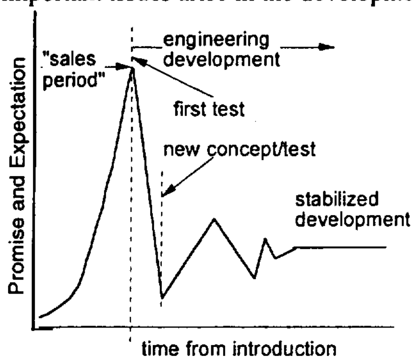

Figure 2: Promise and expectation of new technologies.

Today, many universities, government agencies and industries have conducted research in the area of smart materials and structures, active flow control and biologically-inspired technologies and their application to aerospace vehicles as well as other mechanical systems. Though much research has been conducted, including some significant experimental demonstrations, application of these technologies to aerospace vehicles for large-scale sensing and actuation has only received serious attention over the past decade. NASA's research in the technical areas related to morphing has been ongoing since the early 1990's. As is characteristic of new technologies, much of the current research is focused on addressing the newfound issues in using these relatively recent technologies. Moreover, looking beyond simple replacements to existing systems towards exploiting the unique features of these technologies continues to be a formidable challenge.

While there are a few near term applications of smart materials and structures, active flow control and biologically-inspired technologies to flight vehicles, most of the technologies being researched in the Morphing Project have significant issues still to be addressed before they can be used routinely. For example, some of the major barriers to the advancement of active flow control are insufficiencies in energy efficient flow control actuators with sufficient authority and size and the need for small, robust sensors to measure time-dependent phenomena. In addition, there is generally an insufficient understanding of unsteady and non-linear aerodynamics and consequently, analytical models to predict the interaction of the fluid mechanics with actuation have not been completely developed or validated. Similar analogues exist in the other areas in the project. In structures, for example, basic design principles must be revisited to examine and exploit the new capabilities afforded by tailor-made materials, unique construction capabilities and new actuation approaches. In addition, there are many application issues still to be considered such as lightweight, non-intrusive electronics, reliability and maintainability.

These technical challenges are addressed in the Morphing Project through an iterative, low technology readiness level, research approach that includes: creating new technologies (such as actuators or control approaches), addressing application issues (such as electronics or design tools) and demonstrating new capabilities (integrating disciplines and assessing functionality). Experimental demonstrations are often not the end of a research effort, but rather a critical part of the research iteration where relevant application and feasibility issues are fed back as new problems to be addressed. Numerous collaborations with other NASA programs, other government agencies and industry are used to provide the technology pull and technology transfer opportunities in the Morphing Project. Research topics are investigated from a very low level of maturity to the point where a realistic systems benefit can be determined with a plan for how the concept can be applied in a "real" environment. Upon achieving this level of understanding, the technology is transferred to other users. To provide the broadest dissemination of information possible, research in the project focuses on classes of problems rather than specific engineering problems, although a representative engineering problem is often defined in the research.

As mentioned earlier, the Morphing Project draws on the integration of three crucial technical areas to enable future morphing vehicles: adaptive structures, micro flow control and biomimetics. In addition, these areas are broadly supported by the fundamental enabling areas of smart and biomimetic materials, multidisciplinary optimization, control, and electronics. Both discipline specific research and integrated research efforts are ongoing in the project. Currently, the Morphing Project encompasses approximately 60 person years and a roughly $12 million annual budget, of which roughly a quarter is sent outside of NASA, primarily to universities and some contractors. Over 20 universities and numerous graduate students are funded annually, along with several collaborative programs with other government agencies and industry.

In the following sections of this paper each of the three focus areas of the project (Adaptive Structural Morphing, Micro-Aero Adaptive Control, and Biologically-Inspired Flight) are described with several research efforts highlighted. Following that is a description of the fundamental enabling areas of materials, optimization and control.

3. ADAPTIVE STRUCTURAL MORPHING TECHNOLOGIES

The Adaptive Structural Morphing (ASM) area seeks to develop, assess, and demonstrate adaptive multifunctional wing concepts that can efficiently adapt to different flight conditions to improve the versatility, safety, maneuverability, and efficiency of future aerospace vehicles. The research is focused on approaches beyond conventional control surfaces. Adaptive multifunctional wing concepts may enable missions currently out of reach, as well as new forms of transportation. Due to the broad nature of the work, teams across NASA Langley Research Center including structures, materials, acoustics, fabrication, aeroelasticity, configuration aerodynamics and systems engineering are collaborating in this endeavor.

The ASM area is divided into four major activities: biologically-inspired structural concepts, modeling and validation tools, structures technology development, and wind tunnel system performance evaluation. The areas are organized to advance the technology from concepts to wind tunnel testing. In the biologically inspired structural concepts area, nature is providing guidance for structural concepts and mechanisms for wing structures with unprecedented range of motion while supporting aerodynamic loads. Parallel to the concepts work is the structures technology development task working key technology elements in shape memory alloy and piezoelectric actuators, sensors, manufacturing, and fabrication of components to demonstrate new or improved aerospace structures capabilities. To exploit the full potential of these concepts, validated modeling and design tools are being developed for use in engineering design and to accelerate migration of technologies to applications. As the technology matures, sub-component performance assessments are conducted to determine feasibility and technology gaps. The next step in the technology development cycle is the system performance evaluation under realistic conditions. In particular, this activity supports ground, wind tunnel and, potentially, flight testing of morphing concepts. The performance evaluation effort is a crucial part of the research cycle as it provides vital feedback to other research areas on technology integration, feasibility and application issues. Several highlights of recent work in the Adaptive Structural Morphing area are described below.

One of the recent highlights was a demonstration of a high-rate, morphable, hingeless wing, better known as the DARPA/AFRL/NASA Smart Wing tested in the Langley Transonic Dynamic Tunnel (see Figure 3).[5,6,7,8,9,10,11] The Smart Wing program was led by the Northrop Grumman Corporation under a Defense Advanced Research Projects

Agency (DARPA)-funded contract, monitored by the Air Force Research Laboratories (AFRL), and included partnering with NASA Langley Research Center. To achieve the desired high deflection rate, Northrop Grumman designed and built a control surface utilizing eccentuator arms driven by piezoelectric ultrasonic motors. The result was a fast (>70 deg/sec) hingeless control surface that demonstrated deflections of up to ±20 degrees, uniform smart control surface deflections of up to +20/-15 degrees, and 71 different smart control surface spanwise variation shapes were tested at Mach numbers up to 0.8 and dynamic pressures up to 150 psf. During the test, two LaRC-developed model deformation measurement systems were used to measure deflections of the continuous trailing-edge control surface: Videogrammetric Model Deformation and Projection Moiré Interferometry.[12,13] Another collaborative program on a DARPA-funded effort resulted in the demonstration of inlet morphing on a full-scale F-15 inlet. This effort was called the Smart Aircraft and Marine Project System Demonstration (SAMPSON) and was led by the Boeing Company. Wind-tunnel tests demonstrated inlet fore-cowl rotations and nacelle lip rotations of +/- 20 degrees under full-scale aerodynamic loads (M=0.3 to 0.9).[14,15]

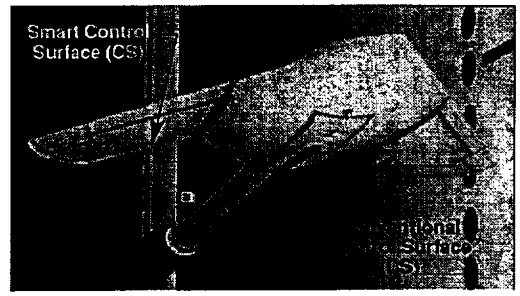

Figure 3: Smart Wing model mounted in the Transonic Dynamics Tunnel at NASA Langley Research Center.

In addition to collaborative efforts, LaRC is also pursuing wing concepts that allow unprecedented shape changes without surface discontinuities through internal efforts. An example of one of these concepts is shown in Figure 4. In this concept, referred to as the fish bone concept, the main load-bearing component resembles the spinal cord of a fish covered with an elastomeric material to transfer pressure loads to the main structure. The trailing edge ribs can deflect up to ± 20 degrees in camber and ± 25 degrees spanwise. Likewise, the leading edge ribs can deflect ± 25 degrees in camber and ± 20 degrees spanwise. Although the configuration was built for assessment and demonstration of the structural concept and not for wind tunnel testing, the departure from conventional design practices is fostering new ideas for improved designs that can provide a technology pull for new smart materials and technologies.

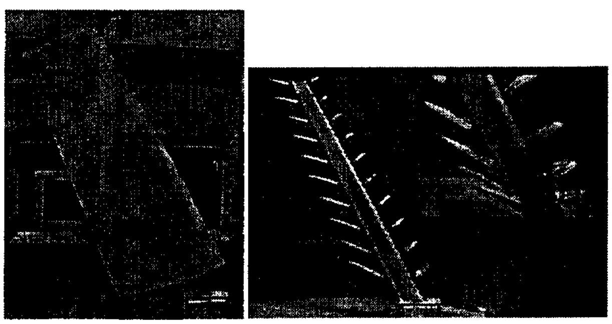
Figure 4: Fish bone wing concept, with and without skin.

Complementary to the concept design efforts is the development of new, more efficient actuation systems. LaRC continues to develop actuation systems using shape memory alloys and piezoelectric materials. In the area of shape memory alloys (SMA), a thermoelastic constitutive model was developed for analysis of SMAs and SMA hybrid composites (SMAHCs).[16] The model is based upon definition of an effective coefficient of thermal expansion and captures the nonlinear behavior of SMAs with temperature, as well as that of other materials in a SMAHC material system. The model is currently under implementation to be used in a commercial finite element code. Numerical studies have been performed using this model that showed substantial control authority of SMAHC structures static thermoelastic and dynamic responses in a weight-efficient manner.[17] SMAHC fabrication techniques were developed to build beam and panel specimens with unidirectional and bi-directional SMA reinforcement, respectively. A sample beam specimen is shown in Figure 5.

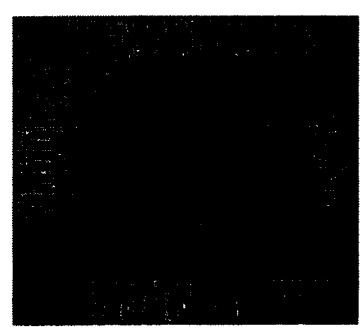
Figure 5: SMA composite panels.

Representative results from the dynamic experimental tests demonstrated that the fundamental frequency of the beam can be shifted from 26 Hz to 140 Hz and also, the maximum RMS displacement response was reduced by 84% (16 dB). Details of the specimen fabrication procedures, experimental measurements, and correlation studies can be found in references 18, 19, 20, and 21. For panels with embedded SMAs, numerical parameter studies of the vibration and noise transmission control performance were presented in reference 22. Many attributes of SMAs are yet to be fully understood. For example, complex tensile behavior observed in a Nitinol alloy, which showed unexpected dependence on thermomechanical history, was explained through the use of differential scanning calorimetric (DSC) and x-ray diffraction (XRD) studies.[23]

Other actuation systems using piezoelectric actuators are also under investigation at LaRC. In this area, the emphasis was on developing analysis tools to enable reliable system performance prediction using piezoelectric actuation; however, it was not limited to just analysis tools. Work completed includes piezoelectric analysis tools[24] using MSC.NASTRAN[25], a joint effort with NASA Dryden to design and flight-test a piezoelectrically-driven wing for flutter evaluation,[26,27] concepts for self-sensing piezoelectric actuators, piezoelectric shunting for damping augmentation[28,29,] and an improved formulation of electro-mechanical coupling effects.[30] Other related activities include addressing loss of actuator control authority due to fiber delamination near actuators embedded in composite laminates and optimization strategies for improved aeroelastic performance using piezoelectric actuators. As NASA LaRC conducts more research in the adaptive structural morphing area, integration of various technologies is forcing more interdisciplinary activities to better understand the technology payoff. It is clear that integrated analysis tools that include structures, aerodynamics, controls, and optimization must be developed to evaluate new morphing concepts.

4. MICRO-AERO ADAPTIVE CONTROL

The Micro-Aero Adaptive Control (MAAC) element of the Morphing Project is concentrated on an exciting subset of the field of aerodynamics. The term "micro" in the title signifies that the research topics involve a small, low-cost fluidic or shape-change input that can create a large controllable output by taking advantage of unsteady and nonlinear aerodynamics at receptive sites. Thus, the research in MAAC focuses on dynamically altering the global flowfield by interacting with and controlling localized flow instabilities and flow structures. The combination of adaptive structural morphing strategies, such as those described above, and active flow control promise tremendous advances in air vehicle performance and capability, especially when new vehicles are conceived around these technologies. Overview papers by Washburn[31] and Pack and Joslin[32] provide the history of this element of the Morphing Project. The current research in flow control is primarily focused in four general areas: fundamental tool development, performance enhancement, maneuvering control and noise attenuation.

The fundamental tool development area provides fundamental research on actuators, sensors and control theory for computational modeling databases and flow control specific applications. Some actuation concepts in active flow control are synthetic jets,[33,34] pulsed jets,[35, 36] active or vibrating small-scale structures[37,38] and glow discharge or plasma devices.[39,40] Actuation schemes are often the pacing technology in active flow control. Additionally, new small, robust pressure sensors, time-dependent shear sensors and acoustic and optic sensors need to be developed. The Morphing Project is actively attempting to capitalize on NASA LaRC's expertise in fluid mechanics, material science, and electronics to utilize advanced materials to dramatically improve active flow control actuators and sensors. In many cases the major breakthroughs will probably be realized through better actuator and sensor packaging. In addition to the in-house research in this area, NASA LaRC has established several external relationships to pursue the above research areas through cooperative agreements, grants and memoranda of agreement.

Three actuator concepts are highlighted here as examples. Two techniques for fluidic momentum addition to the flow field are synthetic jets (illustrated in Figure 6) and pulsed jets. The unsteady nature of these devices has allowed performance gains to be realized using significantly less energy than is required using steady suction or blowing. The allure of using synthetic jets is that fluidic momentum can be added to a system through electrically-driven wall motion rather than with pressurized air. The synthetic jet design parameters are under study as simplified models for design,[41] for use in closed-loop controls systems and for implementation in computational fluid dynamics (CFD). Pulsed jets are also being used.

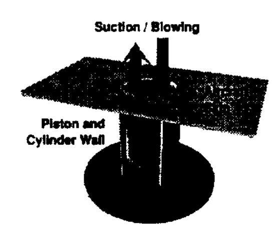

Figure 6: Schematic of simple synthetic jet concept.

A pulsed jet can enhance mixing like a synthetic jet, but with the addition of mass to the flow field as well as momentum. Typically, pulsed jets have more authority but with the cost of pressurized air or fuel lines. The process of detonation is being studied as a potential technique to supply pulsed sources of very high momentum flux. If successful, these devices will most likely be used for high speed and high altitude flight where the conditions for detonation can be realized. Also, an electrohydrodynamic actuator is being developed under partnership between the University of Tennessee and NASA LaRC.[39] This technique relies on a strong electric field to partially ionize air, thus inducing a body force on the flow. This technology is being used to create traveling waves and oscillating walls for turbulent drag reduction.[42]

The performance enhancement area of Micro-Aero Adaptive Control focuses on efficiency and performance improvements via increased lift and/or reduced drag. The most mature area of active flow control is the control of boundary layer separation. One control approach shown to be very effective in delaying turbulent boundary layer separation is superimposing forced oscillations on a mean flow that is on the verge of separating.[43] This approach is effective because it promotes mixing of the high momentum fluid outside the boundary layer with the lower momentum fluid near the surface. Research in the use of forced oscillation for separation control in MAAC addresses application issues through a partnership between Tel-Aviv University and NASA LaRC and is summarized in Seifert and Pack.[44,45] Oscillatory excitation such as that provided by a synthetic jet was shown to be up to two orders of magnitude more efficient than steady suction or blowing.

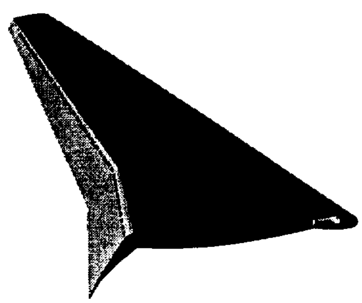
Figure 7: Simplified high-lift system concept with active flow control.

Currently the separation control effort is investigating the feasibility of a simplified high-lift system, as depicted in Figure 7, where synthetic jets provide oscillatory excitation through slots on the flap and just aft of the drooped leading edge. This effort is consistent with the recommendations of a system study sponsored by NASA LaRC[46] that rated a drooped leading edge and a plain flap with active flow control as a top-priority technology to replace the current slotted flap and slat systems on commercial airliners. A two-dimensional model with active flow control applied on a modern cruise optimized supercritical airfoil is being used. Piezoelectrically-driven synthetic jets have provided the periodic excitation. Control of separation aft of the drooped leading edge has resulted in the delay the stall angle by 1° to 2° and a corresponding increase in the maximum lift coefficient by approximately 10%.[47]

Another alternative to conventional high lift systems is circulation control using the Coanda effect. The history of this technique along with many application demonstrations has been thoroughly reviewed by Englar.[48] Although this technique has been shown to produce very high lift coefficients, it does require large jet velocities and, historically, significant compressor bleed air must be available and distributed near the wing trailing edge. Under MAAC, the Morphing Project is investigating the potential benefits of utilizing pulsed blowing in a partnership with Georgia Tech Research Institute (GTRI) to investigate the flow physics behind this phenomenon. The NASA LaRC team is using a 17% thick general aviation airfoil with a circular trailing edge of radius 2% of chord to satisfy the Coanda requirements. The pulsed jet actuation scheme has been able to reduce the required mass flow for a given lift coefficient increase.[49]

Practical implementation of active control and the reduction of viscous drag is probably the most difficult goal in the MAAC suite of topics. However, it is probably second only to separation control in potential payoff for performance enhancement from an efficiency standpoint. Turbulent boundary layer skin friction represents approximately 50% of the total drag of a commercial transport and 90% of the total drag for underwater vehicles.[50] Direct numerical simulations have indicated that turbulent drag reduction on the order of 30-40% may be possible using active control. NASA LaRC is capitalizing on a long history in turbulent boundary layer research and passive viscous drag reduction techniques to pursue active drag reduction experimentally.[51,52,53] Two concepts are under evaluation: traveling waves[37,42] and near wall vortex generators[54,39] using mechanical devices and phased plasmas. Skin friction sensors, direct drag measurements and Particle Image Velocimetry are being used in this research.

The Morphing Project is also working to reduce the cruise drag on a modern transonic airfoil design using a concept that employs a small local contoured shape change near where the shock impinges on the wing.[55] This weakens the shock through a more gradual compression and reduces wing buffet. Optimization of the contour bump shape is being done using CFD. Several CFD designed shapes will be tested experimentally prior to construction of an active bump for experimental testing. Reduction of transonic cruise drag via shock strength reduction not only improves efficiency but also addresses fatigue problems and reduced handling problems associated with wing buffet.

In the area of maneuvering control, the concept of using synthetic jet actuators to create a "virtual shape change" was recently investigated on a NACA 0015 airfoil.[56] The results indicate that synthetic jets with much more authority are necessary to make this approach feasible at reasonable Mach numbers. In addition to the virtual shape concept for maneuvering, fluidic injection is being actively investigated for thrust vectoring as an alternative to mechanical techniques. In fluidic thrust vectoring a secondary stream of air is strategically introduced into the primary jet to create a deflection of the primary jet. When applied to military vehicles, the benefits of fluidic thrust vectoring include improved maneuverability; vertical and short take off and landing; the potential elimination of control surfaces; and reduced signature, weight and drag. The Morphing Project study on fluidic thrust vectoring includes shock vector control[57] and, more recently, throat shifting. In both cases secondary air is injected into the primary jet flow. The shock vector technique injects into a supersonic primary jet and causes an oblique shock and separation to vector the flow. The throat shifting technique injects into the subsonic portion of the nozzle to skew the effective throat and thus vector the flow. Future research plans include examining multi-port injection and unsteady injection and experimentally studying the expected detrimental effect of external freestream flow on the jet vectoring angles.

The fourth focus of MAAC is the pursuit of technologies to alleviate noise through the use of active flow control. The two topics in this category pertain to the sound generated in subsonic turbulent jet shear layers and in resonant cavity systems. These two topics attempt to control fluid instabilities to reduce tonal and broadband acoustic signatures and represent distinctive challenges in the areas of control theory and flow control actuator authority.

The research ongoing in active noise control of both rectangular and axisymmetric jets within the Morphing Project is a multi-pronged effort. One goal is the improvement of unsteady CFD through the use of time-accurate RANS, and Large Eddy Simulation (LES) within the framework of the nonlinear disturbance equations (NLDE) to predict the jet structure development and its control. Secondly, flow field measurements are planned for both cold and hot jets to further improve understanding of the noise sources. Additionally, sensor schemes that can operate in the harsh environment of a hot jet are being investigated. Actuation via piezoelectric devices and phased plasmas is planned. Recent LaRC studies on cavity noise control using active flow control included successfully using several digital controllers to control two modes simultaneously using a synthetic jet actuator at the cavity leading edge.[58] A cantilever beam actuator has been fabricated with in situ deflection measurement for the current series of experiments.

5. BIOLOGICALLY-INSPIRED FLIGHT SYSTEMS

Biomimetics was added to the Morphing Project in fiscal year 2001 after a LaRC study[59] identified several potential research breakthroughs offered by learning from biological systems. The effort focuses on understanding and applying lessons learned from biology and not on mimicking biology. Biologically-Inspired Flight Systems (described in this section) and biologically-inspired materials, called BIOSANT (described in a later section), encompass the biomimetics research in the Morphing Project. Nature provides many examples of systems with multi-functional components integrated into an efficient and often elegant design. These natural systems are optimized against a set of requirements that may be very different from engineering needs, and so direct imitation is not always appropriate. However, in the conceptual design of morphing vehicles several examples of natural systems have led to fruitful areas of biologically-inspired research. The reference by Anders[60] provides an overview of these ideas and several of the current research efforts are described below.

One effort was the use of avian and marine morphologies in the design of low-drag airfoils. Results from an initial survey led to three candidate airfoils that were studied in the Basic Aerodynamics Research Tunnel (BART) at NASA LaRC. All wing configurations had equal planform area and equal aspect ratio and each was compared against a planar wing with an elliptic chord distribution. One wing was configured after a shark's caudal fin; another was a direct scaling and shaping of a typical shore bird's wing in gliding flight. The third wing was inspired through observations of the predominant shape of shore bird wings during flapping flight. This design, named the Hyper-Elliptic Cambered Section (HECS) wing, shows the largest range of benefit with a 14% improvement in lift over drag over the elliptic chord baseline. Details of the HECS design and test results are to be published[61] and work continues to understand the underlying flow physics.

At the more dramatic end of the morphing scale are rapid shape changes that actually create and control unsteady aerodynamic effects. The flapping flight of insects and small birds has long been both an inspiration and a mystery. Although the inertias involved prevent flapping flight from being useful at large scales, studying the phenomena at small scales may lead to a greater understanding of unsteady effects and may find application in general flow control. Efforts within the Morphing Project have concentrated on the use of aeroelastic resonance to achieve flapping motion with a minimum of mechanical drive complexity. Modeling of these systems has also posed a challenge, and research is underway to allow grid-generation and CFD predictions to be made from periodic wing motions whose amplitude and frequency are significant relative to the vehicle's forward speed.

In the area of vehicle guidance, efforts are being made to extend vehicle endurance through energy extraction from the atmosphere. In nature, an albatross is able to make use of vertical gradients in the horizontal wind field over the ocean to fly for hours without flapping. This technique is called dynamic soaring, and can be demonstrated with radio-controlled planes flying in the wind gradient on the leeward side of a hill. Current research involves numerically obtaining optimal trajectories for gliding flight in unstable atmospheres. These trajectories will quantify the potential gain for unmanned air-vehicles and can be used to determine onboard guidance laws.[62]

Finally, throughout the aerospace community there has been interest in building micro-UAV's, vehicles that operate at a size and Reynolds number of small birds.[63] Within the Morphing Project this work has focused on the design of compliant airfoils that, through a passive response, improve stability properties and expand a vehicle's flight envelope. Instrumentation for tunnel testing these vehicles, as well as operational instrumentation, has been investigated.[64,65] Wind tunnel tests have quantified the quasi-static response of these vehicles to different flight conditions and led to the development of dynamic simulation models for a small scale UAV.[66,67]

6. SMART AND BIOLOGICALLY-INSPIRED MATERIALS

6.1 Smart Materials and Actuators

Smart materials research has long been the foundation of the Morphing Project. In this context, "smart" is defined as the ability to respond to a stimulus in a predictable and reproducible manner. Smart materials are also known as adaptive materials, active materials, or multifunctional materials. This class of unusual materials has been available and used effectively for considerable time. However, application of these materials to aerospace vehicles for large-scale sensing and actuation has only received attention over the past two decades. The unique capabilities of smart materials and structures have inspired numerous innovative concepts that are crucial enablers to adaptive structural morphing, active flow control and biologically-inspired flight. The development of new smart materials for actuation and sensing, actuator packaging concepts and micro-electronics for powering smart materials are currently under investigation in the Morphing Project.

The development of active polymers has afforded new materials with increased levels of strain energy and performance over a wider temperature range and allows for the development of platforms beyond that of "unifunctional" electro-active thin films.[68,69,70,71] It is envisioned that these materials will lead to the development of truly smart skins that contain large-scale actuation, sensing, passive electronic components and waveguides integrated into a two (or higher) dimensional architecture.

Actuator development efforts at LaRC have led to several packaging concepts that have extended the operational envelop of piezoelectric ceramics through novel packaging concepts. NASA's THUNDER actuators,[72,73,74,75,76,77] the Macro-Fiber Composite (MFC)[78] and the latest Radial Field Diaphragm (RFD)[79] were developed to solve the common issues associated with durability, flexibility, low displacements and difficult integration into subsystem assemblies. Currently, these new actuators are being integrated into systems that take advantage of their non-mechanical motion to produce lightweight aerospace components and active structures.

Examples of the utilization of these technologies are the use of the THUNDER devices as active airfoil shape control devices,[80] synthetic jet diaphragms[81] and as flight instrumentation hardware.[82] The MFC has demonstrated utility as an active twist element for rotorcraft blades, an active buffet alleviation demonstrator in a wind tunnel model and as an active vibration suppression device for rigidizable composite tubes.[78]

The microelectronic arena in the Morphing Project has two discrete areas, the development of efficient microelectronics for control and the interrogation of smart materials and the use of new materials in the fabrication of electronic architectures. To integrate smart devices into an aerospace vehicle, specific requirements must be met. The most important being that the electronic hardware cannot have a 120v plug nor be 100+ orders of magnitude larger and heavier than the smart devices it controls. This generally requires that the design of control and power system schematics focus towards efficient, interchangeable commercial off the shelf (COTS) components, depending on the power requirements and bandwidth of the smart device. Electronics issues are a critical factor in the use of smart materials for large-scale sensing and actuation since the electronic architecture greatly affects the response of smart materials. The second area of research in electronics in the Morphing Project involves substituting new materials in the fabrication of electronic architectures to reduce volume. The goal is to use materials that provide some benefit through the "dual use" of active dielectrics. In addition, materials that lend themselves to fabrication techniques that eliminate the bulk associated with electronic hardware and processing steps allow for "on structure" support to make effective use of real estate.[83] The further development of NASA's LaRC-SI is one of these material technologies that is being used to demonstrate higher orders of electronic integration as flex and "on-structure" circuits.[84] Other research being conducted involves electronics as embedded passives that integrate the resistors, capacitors and inductors directly into the dielectric film to decrease the real estate required for densely populated circuits. For all of the electronics research, the Morphing Project draws on the diverse capabilities of the technician workforce at LaRC who have provided invaluable assistance in making actuation concepts into functional systems.

6.2 Biologically-Inspired Materials

The BIOlogically-Inspired SmArt NanoTechnology (BIOSANT) research area was initiated in January 2000. It was conceived to be an umbrella for both biomimetics and nanotechnology research focused on materials development. This effort resulted from the realization that explosive progress in nanotechnology in recent years makes it more reasonable to expect that biologically inspired designs are closer to reality. The goal in BIOSANT is to work at the interface of biotechnology and nanotechnology to generate the revolutionary materials of the future. One area of research where substantial progress has been made is in the development of an electrically responsive micro-air vehicle (MAV) wing. Dynamics and controls researchers interested in understanding flight dynamics of resonant-based flapping flight initiated the research as part of the Biologically-Inspired Flight Systems element of the Morphing Project. The contribution of BIOSANT investigators was the fabrication of a lightweight, electrostrictive material that can be used as a 'tendon' for 'coarse control' and an active wing skin that can be used for finer, dynamic control of the wing. This was accomplished by electrospinning, where a charged solution was spun onto a small MAV airframe. The wing skin is a lightweight, fibrous mat with fiber diameters ranging from 200 – 400 nm. The tendon was made by twisting the electrospun fibers into a thicker fiber. Twisting the fiber affords some orientation of the fiber, yielding a material that was responsive to a 3KV sine wave (peak-to-peak) at about 2.8Hz. A weaker response was observed at a higher frequency for the spun MAV wing skin.[85] Future plans include modifying the electrospinning apparatus to achieve better control of fiber orientation and placement. The work is also being expanded to the investigation of other types of electroactive materials. In an analogous effort, BIOSANT researchers are working with investigators in the Adaptive Structural Morphing element to find materials suitable for the unconventional wing configurations such as the fish bone wing. Current efforts involve the fabrication of models of airfoil components suitable for materials processing investigations. Materials ranging from organic/inorganic hybrids to organic electroactive materials and blends are under study.

7. OPTIMIZATION AND CONTROL TECHNOLOGIES

Two of the critical enabling technologies in the Morphing Project are multidisciplinary design optimization (MDO) and optimal control. MDO is fundamental to the design and operation of future morphing vehicles for several reasons: 1) during conceptual design, MDO balances trade-offs between different disciplines and is crucial to achieving the full potential in areas such as active flow control, adaptive structures and biologically inspired flight; 2) during preliminary design, optimal placement of numerous distributed actuators and sensors in the vehicle ensures efficiency in vehicle design and effectiveness during operation; and 3) during detailed design and operation, MDO enhances flight control algorithms by determining the best set of actuators and sensors for varying vehicle functions.

Over the last several years, MDO research has contributed to morphing activities such as active structural acoustic control, robust airfoil shape optimization, control effectiveness assessment via sensitivity analysis, and actuator placement via multi-objective genetic algorithms. The latter two studies were conducted in concert with optimal control research on an advanced vehicle configuration and will be discussed below. Active structural acoustic control reduces noise inside an aircraft cabin by damping structural vibrations of the airframe. Optimal placement of piezoelectric actuators and microphone sensors played a crucial role in the successful development of this technology that is currently being flight-tested.[86] Robust airfoil shape optimization improves performance over a range of aircraft operating conditions.[87] During the early stages of the design process many parameters (e.g., cruise Mach number) are merely estimates of desired operating conditions. Single point designs using these uncertain parameters can lead to overly optimistic projections of as-built performance. On the other hand, morphing vehicles are highly adaptable and the very idea of designing for normal operating conditions may be obsolete. The ultimate goal is to develop general-purpose robust optimization methods for use in multidisciplinary design. Future MDO research in the Morphing Project will also focus on coupled aerodynamic-structural optimization techniques. Design and analysis tools of varying fidelity are needed to enable morphing research such as finding the optimum wing stiffness and dimensions for micro-UAV.

7.1 Optimal control using shape change devices

As mentioned earlier in the Micro Aero Adaptive Control area, one of the applications of active flow control may be virtual shape change for vehicle maneuvering. This, of course, may also be accomplished using structural shape change. Thus, future aerospace vehicles might use distributed arrays of hundreds of shape change devices for stabilization and maneuver control, thereby augmenting or replacing conventional ailerons, flaps or rudders. This approach can potentially lead to reduced fuel consumption, and enhanced maneuverability, mission adaptability and failure tolerance. Although several research efforts at universities, government labs and industry are underway to develop and characterize the shape-change devices, few activities address the incorporation of such arrays into aerospace vehicle flight control architectures. Moreover, due to the large number of potential control actuators, MDO is an important and integral part of developing and assessing shape-change devices for vehicle control. Thus far, two UAVs have been studied as representative problems where small shape change actuators may be used for vehicle control. The lessons learned from these studies lay the groundwork for understanding new approaches to vehicle control using many of the morphing strategies mentioned earlier.

Designing a vehicle with novel shape-change actuators has been studied from several facets by researchers at NASA LaRC. This section is an overview of some of those efforts. Topics addressed include: (1) estimating control derivatives based on computational fluid dynamics (CFD) model of the vehicle; (2) estimating control effectiveness for a given array of devices; (3) optimizing actuator and sensor placement; and (4) developing control algorithms using computer simulation models, wind tunnel tests, and unmanned aerial vehicles.

Much of the documented research focuses on optimal placement and control design assuming that the control actuator is modeled as a bump on the wing.[88] The approach is demonstrated on the Lockheed Martin Innovative Control Effector (ICE) model shown in Figure 8. Notice that the effector (actuator) is modeled as a change in height of any grid point. Given a low fidelity model of the ICE configuration, the process consists of several steps. First, automatic differentiation of the CFD code is used to predict the change in pitch, roll and yaw moments with respect to a change in height in any grid location.[89] Next, the predicted control derivatives are used to identify particularly good locations. Then, the control derivatives, plus an estimate of the maximum attainable height change, are used to predict the global pitch, roll and yaw moments for any combination of multiple actuators.[90] Finally, a genetic algorithm (GA) is used to find the best set of candidate locations.[91]

The goal is to minimize the number of actuators required to complete all maneuvers specified by the design team. One excellent set of actuators is illustrated in Figure 8. The stars indicate single actuator locations for which derivatives are available. The black circles indicate the selected locations on the upper surface of the right wing. The GA evaluated 150,000 combinations of 350 actuators out of about 3×10^{99} possible combinations. This approach provides the design team with promising designs for further evaluation.

Existing, low-order CFD codes such as PMARC can be adapted to model shape change actuators. These linear aerodynamic panel methods are inappropriate for detailed study of the flow field but provide quick estimates of control moments. Results of simulation studies indicate that shape change devices offer promise for seamless aircraft flight control.[92] These studies also conclude that additional analytical modeling and experimental testing of shape change devices are needed to improve design confidence.

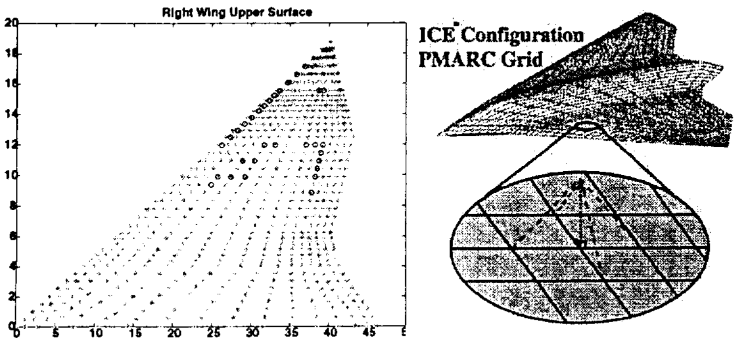

Figure 8: Best locations for actuators based on estimated control derivatives.

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 is a delta planform operated by North Carolina State University under a cooperative agreement with NASA. A panel model of the vehicle was used to create a dynamic simulation for preliminary control law development. Control algorithms that use the shape-change actuators and pressure sensor arrays on the UAV are currently under development. Preliminary evaluations of control authority have been conducted and the resulting control actuator models were incorporated into the dynamic simulation of the UAV. A baseline control algorithm was implemented in the simulation that uses the shape-change actuator array to stabilize and maneuver the UAV. Actuator bandwidth and deflection requirements are being generated from the simulation. Development of the UAV control architecture, sensor and actuator systems is still under way. In addition, an effort is underway to demonstrate feasibility of using adaptive control techniques for flow control. The technique has been used to demonstrate closed-loop control of multiple tones generated by flow over a cavity.[93]

8. CONCLUDING REMARKS

NASA's Morphing Project is developing and assessing a diverse number of technologies to enable efficient, multi-point adaptability in future air and space vehicles. The research in the project focuses on the areas of smart/ adaptive materials and structures, micro active flow control, and biologically-inspired technologies. While many application issues remain in applying these technologies to actual flying vehicles, the potential for broad, significant change in the capabilities of future vehicles remains unbounded. Cross-disciplinary interaction of advanced structures, materials, flow control and even biology offer a fascinating palette for future innovation that has already yielded many crucial findings as discussed herein. Further multi-disciplinary research approaches and, applications of advanced adaptive technologies that are beyond simple replacements of conventional technologies, will likely led to further advancements.

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