Research Activities within NASA's Morphing Program

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Abstract

In the last decade, smart technologies have become important enabling technologies that cut across traditional boundaries in science and engineering. Here smart is defined as the ability to respond to a stimulus in a predictable and reproducible manner. While multiple successes have been achieved in the laboratory, we have yet to see the general applicability of smart technologies to actual aircraft and spacecraft. The NASA Morphing program is an attempt to couple research across a wide range of disciplines to integrate smart technologies into high payoff applications on aircraft and spacecraft. The program bridges research in several technical disciplines and combines the effort into applications that include active aerodynamic control, active aeroelastic control, and vehicle performance improvement. System studies are used to assess the highest-payoff program objectives, and specific research activities are defined to address the technologies required for development of smart aircraft and spacecraft. This paper will discuss the overall goals of NASA's Morphing program, highlight some of the recent research efforts and discuss the multidisciplinary studies that support that research and some of the challenges associated with bringing the smart technologies to real applications on flight vehicles.

Introduction

The Aerospace Vehicle Systems Technology (AVST) Program office of the NASA Office of Aero-Space Technology has been developing coordinated research programs in which individual disciplines are supported in a collaborative environment to foster the development of breakthrough technologies. As part of AVST, the goals of the Morphing program at the NASA Langley Research Center (LaRC) are to develop and mature smart technologies and address the multidisciplinary issues associated with their efficient use to provide cost-effective system benefits to aircraft and spacecraft. The program seeks to conduct research that will enable self-adaptive flight for a revolutionary improvement in the efficiency and safety of flight vehicles.

The Morphing program is an inherently multidisciplinary program, and has been built around a core discipline-based structure to provide the fundamental technology base. This maximizes the leveraging of all technology developed in the program, and more fully integrates the output of each part of the program. The key disciplines in the program include materials, integration, structures, controls, flow physics, and multidisciplinary optimization. The discipline-based research activities are integrated to support the program application areas that include active aerodynamic control, active aeroelastic control, and other aerospace areas. Smart technologies are currently under development for each application area. In some cases, the smart technologies are consolidated into devices that have local sensing and feedback control. For many applications, these devices will modify local phenomena to support a macroscopic strategy, such as flow separation control for advanced high lift systems. Consequently, a combined approach to control systems and system identification is being used in the Morphing program to address the control laws and controller responses required for the individual devices, as well as addressing global requirements for distributed arrays of devices to achieve an overall system benefit. Furthermore, a research area in the Morphing program referred to as "integration" is targeted at developing smart devices via a mechatronics-based design approach and devising embedding strategies. At the system level, multidisciplinary design optimization will take advantage of the tools developed in the program to optimize the component technologies and provide a systems approach to component integration.

This paper highlights some of the research activities in the Morphing program beginning with the research on smart materials and fiber optics. Various application areas are also discussed herein including a summary of some of the issues associated with final application of smart technologies on aircraft and spacecraft. Although specific application areas are summarized in this paper, much of the research on the development of enabling technologies can be applied to a wide range of engineering applications.

Smart Materials Research

The foundation of the Morphing program at NASA is research on smart materials to develop actuators and sensors for aircraft and spacecraft applications. Three aspects of smart materials research at NASA are summarized herein: advanced piezoelectric materials, fiber optic sensors, and development of smart devices. Research in the area of advanced piezoelectric materials includes optimizing the efficiency, force output, use temperature, and energy transfer between the host structure and the piezoelectric material for both ceramic and polymeric materials. Fiber optics research is focused on non-destructive evaluation of the composite cure process and monitoring the health and configuration of aerospace structures. Device development research in the Morphing program integrates smart materials (actuators and sensors) into devices that are designed to address specific engineering applications.

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Advanced Piezoelectric Materials

Piezoelectric materials have been identified as a promising actuator technology for numerous flight vehicle applications including active flow control, active noise control and active aeroelastic control. However, many potential applications require displacement performance larger than that currently achievable in conventional piezoelectric materials. Researchers at NASA LaRC have developed a high-displacement piezoelectric actuator technology, THUNDER (THin layer composite UNimorph ferroelectric DrivER and sensor) to meet these high displacement requirements. THUNDER actuators are unimorph-type actuators, which consist of a piezoelectric ceramic layer bonded to one or more non-piezoelectric secondary layers. Because of the use of elevated temperatures during consolidation, internal stresses are created in the layers of materials; these internal stresses significantly enhance displacement through the thickness of the actuators. Currently, the processing, characterization, and modeling of these high-displacement actuators are under investigation. References 1-3 contain more information on THUNDER devices and their application.

High performance piezoelectric polymers are also of interest to the aerospace community as they may be useful for a variety of sensor applications including acoustic, flow, and strain sensors. Over the past few years, research on piezoelectric polymers has led to the development of promising high temperature piezoelectric responses in some novel polyimides. The development of piezoelectric polyimides is discussed in references 4-6.

A comparison of the characteristics of two new polyimides, identified as P2 and P5, to the only commercially available piezoelectric polymer, polyvinylidene fluoride (PVDF), is shown in Figure 1. This figure shows the value of the piezoelectric constant, d_{31}, as a function of temperature for PVDF, P2 and P5. The polymer structures for P2 and P5 are shown in Figure 2. In general, loss of the piezoelectric effect occurs for both PVDF and the polyimides over time and temperature. However, for PVDF this loss occurs at lower temperatures (approximately 80°C) and is not recoverable due to a loss in the mechanical orientation of the material. Within the operating range of PVDF (approximately 25°C to 80°C) the piezoelectric constant of PVDF is two orders of magnitude higher than those for either polyimide, as shown in Figure 1. Typically, PVDF is not used above 80°C since at these temperatures the polymer begins to loose its mechanical orientation imparted during processing. The material also starts degrading chemically, and aging of the piezoelectric effect is precipitated at these high temperatures.

On the other hand, the new polyimides, P2 and P5 are resistant to temperature effects in this range. For the range of temperatures examined in Figure 1, the polyimides are in the glassy state; hence, they do not deform readily. As polymers approach their respective glass transition temperatures, d_{31} increases due to a decrease in the material modulus making the new polyimides useable in a higher temperature regime. Notice that at 150°C, the piezoelectric constant of P2 is only one order of magnitude lower than that of PVDF. Moreover, at two times the operating temperature of PVDF, the piezoelectric constant of P5 is the same order of magnitude as that of PVDF. Furthermore, any loss in piezoelectric effect in P2 and P5 is recoverable: as amorphous polyimides, P2 and P5 can be regenerated by repoling.

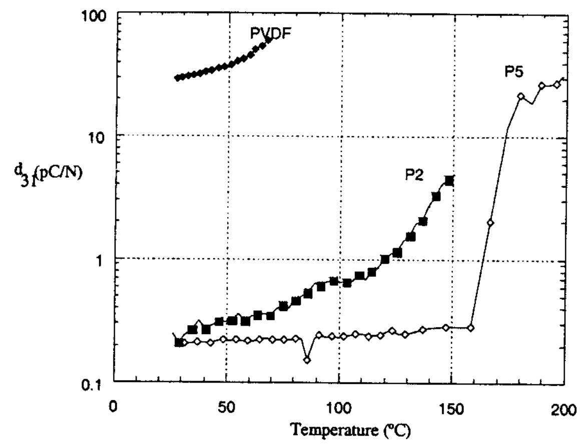


Figure 1 Piezoelectric constant as a function of temperature

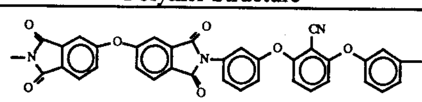
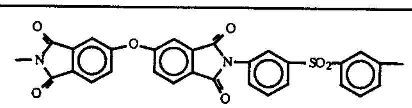
Polymer Structure	ID
	P2
	P5

Figure 2 Polymer structure for P2 and P5

Fiber Optic Sensors

Significant research is also being done in the development of fiber optic sensors for cure, health and configuration monitoring of aerospace structures.[7,8] Currently, techniques are being developed for using optical fibers to monitor composite cure in real time during manufacturing and to monitor in-service structural integrity of the composite structure. A fiber optic sensor is currently under development that is capable of measuring chemical composition, strain and temperature. Both single mode and multimode optical fibers with and without Bragg gratings have been investigated. Chemical spectra of a high performance epoxy resin were obtained using both types of fibers. Temperature and strain measurements were made using single mode fibers containing Bragg gratings and compared to data obtained using conventional techniques and the results showed excellent agreement.[8] Further work is being done on creating a more robust chemical sensing region in the fiber that will better withstand the harsh composite cure environment. A patent application has been filed for the chemical/strain/temperature sensor.

Developing Smart Devices for Steering Optical Mirrors
Another aspect of smart technologies under study is the integration of smart materials into devices to address specific engineering problems. One example of integration for space application uses curved piezoelectric actuators for steering optical mirrors. A prototype system, initially discussed in reference 9, is shown in Figure 3. This mechanism consists of a curved piezoelectric actuator bonded to a polypropylene mount with a mirror attached to the center of the actuator. To get rotational motion of the mirror using the curved actuator, the piezoelectric actuator has individually electroded sections on each side. By applying opposite voltages to each side, one side expands while the other side contracts causing the actuator to flex into an 'S' shape making the mirror rotate.

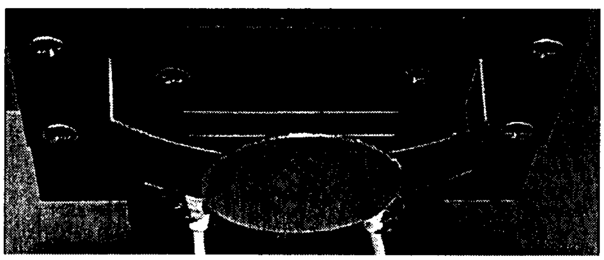


Figure 3 Piezoelectric single axis mirror steering mechanism

The photograph in Figure 4 shows a closer look at the actuator used in the mirror steering mechanism shown in Figure 3. Actuator characterization to predict shape after the consolidation process and performance when driven electrically is discussed in reference 10. Accurate and experimentally validated tools to predict the response of such systems will accelerate integration of these technologies into engineering applications.

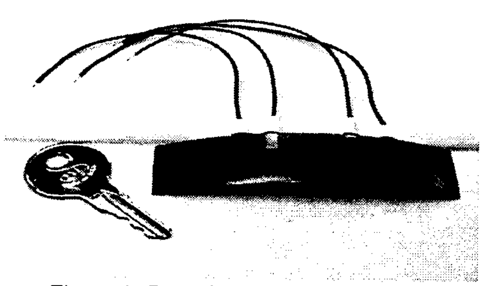


Figure 4 Curved piezoelectric actuator

Novel Actuator Arrays for Active Flow and Flight Control
Recent discoveries in material science and fluidics have been used to create a variety of aerodynamic control devices that have great potential to enable entirely new approaches to aerospace vehicle flight control. A number of flow control actuation concepts were considered including piezoelectric actuators and fluidic effectors which can produce forces and moments by creating small flow distortions over the surface of an airfoil as described in references 11-13. Here an effector is defined as the mechanism that has an effect on the airflow with the purpose of controlling the flow (e.g., a control surface or jet of air) and the actuator is defined as the mechanism that creates the movement of the effector (e.g. hydraulics or piezoelectrics). Fluidic effectors can also be used to alter the degree of separated flow over specifically-designed portions of an airfoil.[14,15] An advanced aerospace vehicle might use distributed arrays of hundreds of such effectors on its surface to generate forces and moments for stabilization and maneuver control, without the need for conventional, hydraulically-actuated ailerons, flaps or rudders as investigated in references 16 and 17.

Development of Actuators for Active Flow Control
An important element of creating a more optimized smart actuation device is using a mechatronics-based design approach. The term "mechatronics" implies the consideration of integrated mechanical and electrical properties, drive electronics, computational control algorithms and hardware, sensor and interface impedance for the purpose of tailoring and optimizing the device design to a specific application. Several smart actuation devices for active flow and flight control are being developed with a mechatronics-based design approach in the Morphing program including synthetic jet actuators and vorticity-on-demand actuators.[18] Coupling mechatronics-based design with more effective piezoelectric actuators, new structural embedding technologies, adaptive controls methods and a systems-based optimization scheme may result in revolutionary improvements in the efficiency and safety of flight vehicles.

Recently, a significant amount of research has been devoted to developing zero-mass synthetic jet actuators for control of flow separation over an airfoil. The actuator is a diaphragm that, when actuated, sucks and blows air through a small orifice. The amount of air sucked in and blown out are equal, hence the name "zero-mass". Figure 5 shows a photograph of one of the piezoelectrically-driven synthetic jet actuators under development and testing. The actuator in Figure 5 is being developed for application to cavity noise control. One of the many challenges with synthetic jets is to get the necessary flow momentum to affect flow over an airfoil at high Reynolds numbers, as discussed in reference 19.

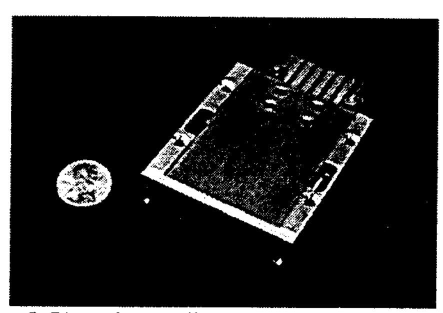
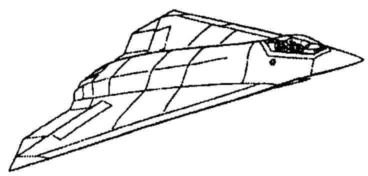


Figure 5 Piezoelectrically-driven synthetic jet actuator

Flight Control Using Fluidic Effectors
A portion of the research in the Morphing program seeks to address controls issues related to the goal of using smart actuators and fluidic effectors for localized flow control and global flight control. Some of the important issues are: how does one determine where to distribute fluidic effectors over the aircraft or spacecraft surface, and how does one use such radically new effectors in a control system to actually maneuver and fly the vehicle? The controls research in the program attempts to address such questions by applying arrays of a generic shape-change actuator to a conceptual aircraft configuration called ICE (Innovative Control Effectors)[20] in a dynamic simulation. NASA is using the ICE design, shown in Figure 6, as an example configuration under a cooperative agreement with Lockheed Martin.



Wing Characteristics
Area .... 75.12 m^2 (808.6 $ft.^2$)
Span .... 11.43 m (37.5 ft.)
Aspect Ratio ... 1.74
Leading Edge Sweep ... 1.134 rad. (65 deg.)

Figure 6 Lockheed Martin Innovative Control Effector (ICE) configuration

An interactive Matlab-based design tool has been developed which allows quick build up and analysis of distributed arrays of small shape-change effectors on the surface of the ICE aircraft. The shape-change effectors in the design tool simulate the virtual shape change created by fluidic effectors (i.e., a small bump on the airfoil). This tool helps the designer to determine placement, size, and shape of the array so that the array can produce the desired forces and moments to maneuver the vehicle. Figure 7 illustrates the graphical user interface for the Matlab-based effector array design tool. The shaded regions in the figure (colored regions on the computer screen) present sensitivity data that indicate the best locations to place the shape-change effectors. The sensitivity data is obtained by differentiating a computational fluid dynamics panel code (PMARC, a Panel Method from the Ames Research Center)[21] using the ADIFOR tool (Automatic Differentiation of Fortran)[22] applied to the ICE configuration model. The sensitivity data consists of the partial derivative of the forces and moments on the aircraft with respect to displacement along the surface normal to every grid point on the aircraft or spacecraft geometry model as described in reference 23.

Using this tool, the designer can quickly build up and analyze an array of shape-change effectors by designating geometry grid points at which he or she wishes to place each element of the array. Once a grouping of shape-change effectors has been defined, the designer can obtain a preliminary prediction of its effectiveness and generate a perturbed geometry grid, which includes the deployed effector array. This geometry file can then be used with aerodynamic analysis programs to further assess the effectiveness of the effector.

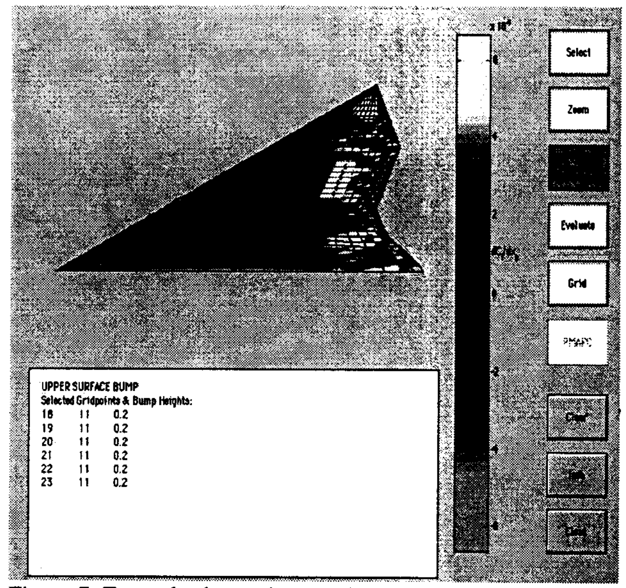


Figure 7 Example shape-change effector array designs applied to the ICE configuration

Four such distributed shape-change effector arrays that were designed using this tool are shown in Figure 8. This figure shows the ICE configuration at a positive pitch and a negative pitch orientation, with the shaded regions indicating the shape change effectors used. These effectors were applied to the ICE vehicle in a simulation and used in a stability augmentation and control system design. The control system deploys the effector arrays in a "quantized" fashion. That is to say that each shape change (modeled as a small bump) in an array is either completely on or off, and more of them are turned on to produce larger forces as needed. Using these effector arrays, the control system is able to stabilize and maneuver the vehicle without conventional moving surfaces such as ailerons or a rudder. The predicted authority of these effectors is still rather low when compared to a rudder or aileron, so the control system generates relatively low-rate maneuvers (roll rates of 5 degrees per second). Future research will focus on experimental validation of the predicted authority of various flow control effectors and on flight control using large arrays of interacting effectors.

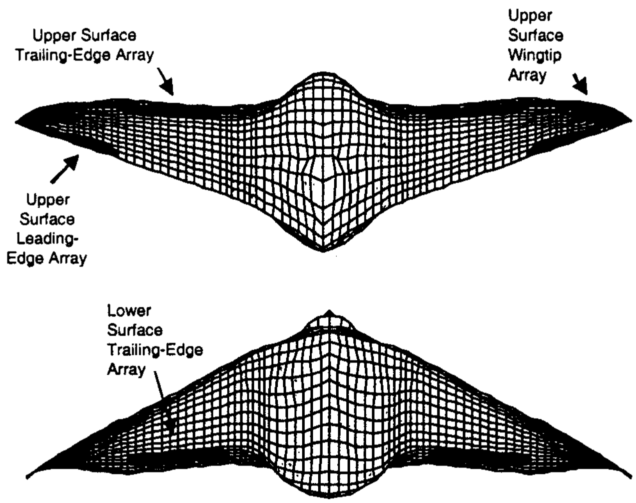


Figure 8 Example shape-change effector arrays design applied to ICE configuration

Integrating Smart Actuators into Structures for Enhanced Performance

Shape memory alloys, piezoelectrics (including piezo fiber composites and single crystals), and magnetostrictive materials have been successfully demonstrated as strain actuators for controlling structural response. At NASA, research on integrating smart actuators and sensors into structures has focused primarily on integrating piezoelectric materials and shape memory alloys. The goal of this research is to advance the technology of embedded strain actuation to a level such that system designers may employ the use of active strain actuation for revolutionary advances in aerospace vehicles. These advances may include significant reductions in structural weight, dramatically increased fatigue life and improved ride comfort. Active strain actuation typically refers to dynamically or statically straining (bending or twisting) a structure to achieve control.

There are numerous challenges in embedding smart materials into composite structures including: electric circuit failures due to dielectric breakdown and arcing, breaking of ceramic wafers and electric leads (particularly in curved surfaces), low performance due to temperature changes or impedance mismatches, and compromised structural integrity due to microcracking and macrocracking in the host composite structure.[24] These complications are even more problematic when high strain, high stress applications are pursued; which is typical of aerospace applications.

Fabrication of Composites with SMAs for Noise and Panel Flutter Suppression

Two aerospace applications being studied at NASA LaRC are noise suppression and panel flutter suppression using embedded SMA wires. Interior noise, sonic fatigue, and panel flutter are important issues in the development and design of advanced subsonic, supersonic, and hypersonic aircraft. Conventional air vehicles typically employ passive treatments, such as constrained-layer damping and acoustic absorption material to reduce the structural response and resulting acoustic levels in the aircraft interior. To prevent the potential destruction of panels that may result from panel flutter, conventional air vehicles employ thickened panels and added stiffeners. These conventional techniques require significant addition of mass and only attenuate relatively high frequency noise transmitted through the fuselage. Adaptive and/or active methods of controlling the structural acoustic response and flutter of panels to reduce the transmitted noise and avoid panel destruction may be accomplished with the use of SMA hybrid composite panels. These panels have the potential to offer improved thermal buckling/post buckling behavior, dynamic response, fatigue life, and structural acoustic response.[25-26]

Initial work at NASA LaRC in the fabrication of active composites has focused on the manufacture of E-glass/ Fiberite 934 epoxy panels with embedded shape memory alloys. Quasi-isotropic panels with unstrained SMAs embedded in the zero degree direction have been successfully fabricated. Test specimens machined from a cured hybrid panel are shown in Figure 9. Future panels will be fabricated with prestrained SMA strips. These panels will require tooling which will restrain the SMA strips from contracting during the thermal cure. Panels with bi-directional (0°/90°) SMAs as well as hybrid built-up structures will also be fabricated. All panels will be subjected to various tests to assess their noise, buckling, and fatigue characteristics as compared to baseline panels without embedded SMAs.

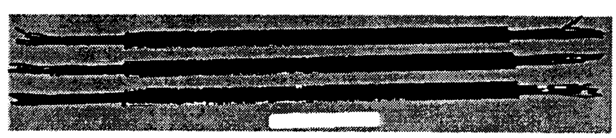


Figure 9 SMA wires in composites

Fabrication, Modeling and Validation of Structures with Piezoelectric Materials

Due to their 20 KHz bandwidth and effectiveness in strain actuation, piezoelectric materials used as actuators have been the smart material of choice for numerous control applications were high bandwidth is required. One fabrication issue that became apparent after experimenting with integrating several piezoelectric actuators into curved structures (which is common in aerospace structures) was the compliance and flexibility of piezoelectric actuators. Figure 10 shows a newly developed encapsulated piezoelectric actuator being flexed without damaging the actuator. This flexibility allows shape forming of the actuator to different contoured surfaces. Another actuator that can be easily integrated into curved surfaces is a fiber-based piezoelectric actuator,[27] where interdigitated electrodes are used to actuate the piezoelectric fibers (see Figure 11). Once integrated into composite structures, these actuators are very effective in controlling structural response as has been demonstrated in laboratory experiments.

Figure 10 Flexible piezoelectric patch

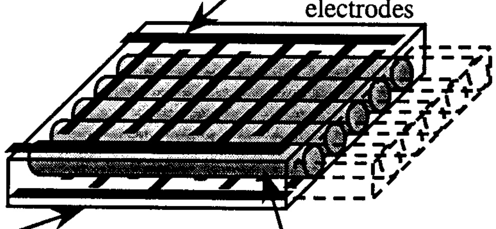


Figure 11 Fiber-based piezoelectric actuator

Fundamental understanding of the behavior of in situ piezoelectric actuators including the development of high fidelity analytical models is extremely important to help bridge the gap between isolated laboratory demonstrations and practical implementation. Towards this end, a number of simple structures are being fabricated at NASA for the purpose of creating a database with test data for model validation. Figure 12 shows a photograph of an aluminum beam with a newly developed piezoelectric actuator bonded to the surface.

Although this particular test-bed is extremely simple, the idea is to investigate modeling of such a system using commercially available analysis tools and to provide a benchmark problem for individuals developing new analysis tools. A second-generation test-bed is shown in Figure 13, constructed with a hollow box cross-sectional area (to mimic more realistic wing-box structures) using composite materials. Localized behavior of actuators and strain transfer efficiencies are being measured to better understand the modeling problems associated with this type of structure. This class of structure presents a different set of modeling and fabrication problems, particularly with strain transfer of piezoelectric actuators when bonded or embedded into composite structures.

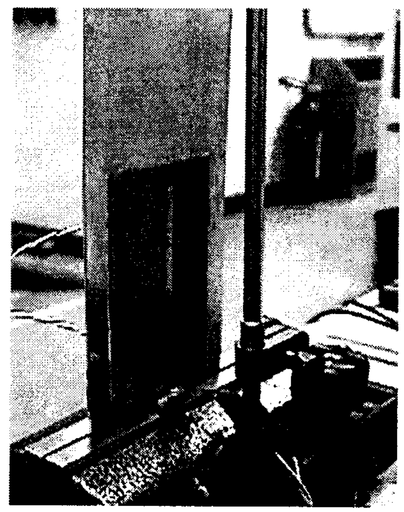


Figure 12 Aluminum beam with surface-bonded piezoelectric actuator

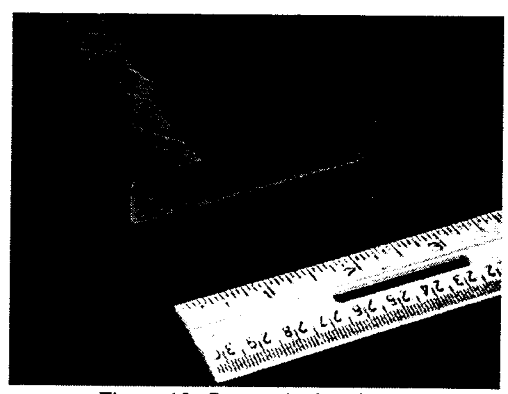


Figure 13 Composite box beam

Using Smart Materials to Control Structural and Aeroelastic Response

The goals of applying smart devices to aeroelastic problems are to control the aerodynamic and/or structural characteristics of air vehicles to improve flutter, gust, buffet and maneuver load behavior of fixed-wing vehicles and reduce dynamics and loads on rotorcraft. In many cases, applications of smart devices will take advantage of the inherent flexibility in air vehicles; using flexibility to create more efficient structural designs. Several analytical and experimental studies clearly demonstrate that piezoelectric materials (piezoelectrics) can be used as actuators to actively control vibratory response, including aeroelastic response.[28] One important study has successfully demonstrated using piezoelectric actuators to control buffeting on the vertical tails of twin-tail, high-performance military aircraft. This international effort includes wind-tunnel testing of a 1/6 scale F/A-18 model experiencing aerodynamic buffet29 and ground-testing of a full-scale F/A-18 airplane using simulated buffet input.[30] Previous studies have also demonstrated active flutter suppression and gust load alleviation using piezoelectric actuators.[31] Piezoelectric actuators have also shown to be effective in active noise suppression.[32]

Depending on the application, there are some important issues in using piezoelectrics as actuators for active control: 1) the potentially large amount of power required to operate the actuators, and 2) the complexities involved with active control (added hardware, control law design, and implementation). Active or passive damping augmentation using shunted piezoelectrics may provide a viable alternative. This approach requires only simple electrical circuitry and very little or no electrical power. A recent NASA analytical study examined the feasibility of using shunted piezoelectrics to reduce aeroelastic response using a typical-section representation of a wing and piezoelectrics shunted with a parallel resistor and inductor.[33] Using Theodorsen aerodynamics, the bending (plunge) response of two aeroelastic models to sinusoidal forcing functions was examined to study the effectiveness of using shunted piezoelectrics to reduce aeroelastic response. These results demonstrate that shunted piezoelectrics can significantly reduce aeroelastic response; for example, reductions of up to 70% in plunging response were realized. Figure 14 shows an example of the results obtained (discussed in reference 33) for the reductions in peak plunging response achieved using the shunted piezoelectrics at several airspeeds. The effectiveness of the shunted piezoelectrics was found to be a strong function of the inherent structural and aerodynamic damping. Thus, this application may not be effective for highly damped structures. However, for lightly damped structures, shunted piezoelectrics provide a simple, low-power, fail-safe vibration suppression mechanism. Follow-on studies are planned to explore developing higher fidelity models and to validate the results via wind-tunnel testing.

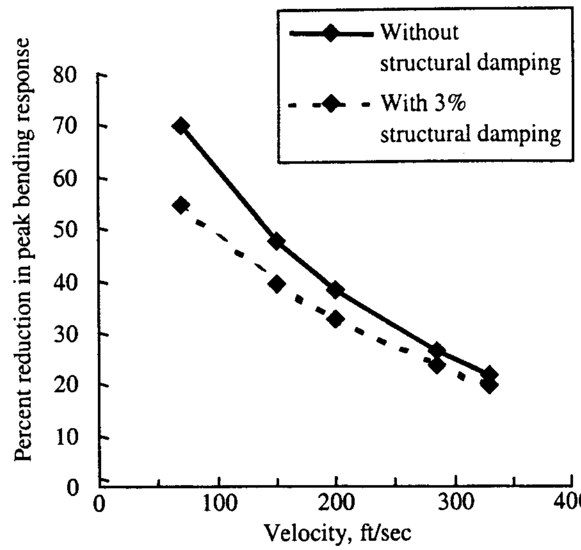


Figure 14 Reductions in peak bending (plunging) response using shunted piezoelectrics

Using Smart Materials to Improve Vehicle Performance

Also within the Morphing Program, NASA has collaborated with DARPA, the Air Force and the Navy in two unique programs investigating using smart materials to improve the performance of military vehicles. The DARPA/AFRL/NASA Smart Wing program, conducted by a team led by the Northrop Grumman Corporation (NGC), addresses the development of smart technologies and demonstration of relevant concepts to improve the aerodynamic performance of military aircraft. Reference 34 provides on overview of the DARPA/AFRL/NASA Smart Wing program. During Phase I of this program, a 16% scale, semi-span wind-tunnel model, representative of an advanced military aircraft wing, was designed and fabricated by NGC and wind-tunnel tested at NASA LaRC's Transonic Dynamics Tunnel (TDT) in May 1996 and June-July 1998. The "smart wing" model incorporated contoured, hingeless flap and aileron designs actuated using built-in SMA tendons. Control surface deflections of up to 10° were obtained. Variable spanwise twist of the smart wing was achieved using mechanically simple SMA torque tubes that employed novel connection mechanisms to effect a high degree of torque transfer to the structure; 3200 in-lbs. of torque was generated by the SMA tubes. Up to 5° of spanwise twist at the wing tip was demonstrated. Under steady-state conditions, 8% to 12% improvements in lift, pitching and rolling moments were achieved over a broad range of wind tunnel and model configurations, in comparison to a conventional design incorporating hinged control surfaces. During Phase II of the Smart Wing program, research and development are focused on the application of smart technologies to uninhabited air vehicles and further raising the technology readiness level of these technologies for future applications.

In the Smart Aircraft and Marine Propulsion System Demonstration (SAMPSON) program, NASA LaRC is collaborating with DARPA and the Navy's Office of Naval Research (ONR) on a team led by the Boeing Company to demonstrate the application of smart materials and structures to large-scale aircraft and marine propulsion systems.[35] This program seeks to show that smart materials can be used to significantly enhance vehicle performance, thereby enabling new missions and/or expanding current missions. Currently, a demonstration of a full-scale adaptive fighter engine inlet is planned for testing in the NASA Langley 16-foot Transonic Tunnel in the Spring of 1999. Smart technologies will be utilized to actively deform the inlet into predetermined configurations to improve the performance at all flight conditions. The inlet configurations to be investigated consist of capture area control, compression ramp generation, leading edge blunting, and porosity control. The wind-tunnel demonstrations will serve to directly address questions of scalability and technology readiness, thereby improving the opportunities and reducing the risk for transitioning the technology into applications. The analytical and experimental expertise gained from the wind-tunnel tests conducted in the Smart Wing and SAMPSON programs are an important part of the technology development process in the Morphing program and provide an excellent opportunity for collaborative research.

Concluding Remarks

The integration of smart technologies into aircraft and spacecraft structures shows the promise of high benefits if the appropriate technological issues are addressed. To effectively approach the long-term technology issues, the Morphing program at NASA Langley Research Center integrates smart material and structures research efforts across many disciplines. For example, coupling mechatronics-based design of smart devices with new embedding technologies, more effective piezoelectric materials, adaptive controls methods and a systems-based optimization scheme may result in revolutionary improvements in the efficiency and safety of flight vehicles. These improvements are not limited to, but may include a significant increase in the fatigue life of structures undergoing high-cycle response (such as buffeting, gust, or acoustic response), a significant reduction in the structural weight of load-carrying components such as wing boxes, and dramatic improvements in high lift systems. Ground and wind-tunnel tests are currently underway in the Morphing program to bring these technologies to fruition. The Morphing program strives to assure the ultimate usability of the technological product of this work and, potentially, have a major impact on air and space travel and the way in which aircraft and spacecraft are manufactured and flown.

Acknowledgements

The authors wish to acknowledge the invaluable assistance of the rest of the Morphing Integrated Project Team: Jean-Francois Barthelemy (Project Manager), Ronald Joslin, Sharon Padula, and Gary Fleming. In addition, the following colleagues provided crucial assistance: Robert Rogowski, Roberto Cano, Karen Wood, Richard Silcox, Mercedes Reaves, Garnett Horner, Barmac Taleghani, and Keats Wilkie.

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