

# Adaptive structures: Moving into the mainstream

It has been known from the very beginnings of aviation that significant efficiency and maneuverability benefits can be realized by small, controlled deformations of flight surfaces, especially a wing's leading and trailing edges. One challenge facing current research in aircraft development is improving the technology that changes the shape of these control surfaces, especially since the current flaps can generate a substantial fuel-consuming drag when deployed.

Advances in the design synthesis of jointless compliant mechanisms for applications to adaptive structures have identified a simple, elegant, yet robust alternative to conventional mechanisms. This approach promises a lightweight, smooth, continuous airfoil with enhanced flight characteristics including significant reduction in drag and improved maneuverability. Furthermore, smooth and continuous shape morphing allows the airfoil to adapt effectively to different flight conditions rather than sacrificing performance with a fixed geometry airfoil or drag-producing hinged flaps.

The Wright brothers' original prototype flyer had a "saddle" that allowed Orville, the pilot, to adjust trim on the ends of the wood and fabric wings by changing his body position. This approach was possible because the wing structures

were designed to be flexible and the aerodynamic pressures were exceptionally low.

As aircraft design evolved to provide for constantly increasing engine speeds and load capacities, designing for flexible wings was discarded due to ever-expanding performance demands. The result is that today's aircraft employ rigid, hinged flaps, ailerons, and other control surfaces that approximate (albeit crudely) optimal airfoil shapes.

### Early morphing efforts

Ideally, aircraft wings should alter their shape discreetly; they should "morph" as needed in response to changing flight conditions to maximize fuel efficiency and flight performance. However, morphing wings have been an elusive goal for aircraft designers, and many attempts by industry, academia, and national labs have not yielded a practical design.

In the mid-1980s, the Air Force Research Laboratory, partnering with NASA, modified and flight-tested an F-111 in a program called Mission Adaptive Wing (MAW). Using conventional rigid-link mechanisms and fiberglass flex-panels, adaptive wing geometry proved its aerodynamic superiority over conventional leading- and trailing-edge flaps through most of the F-111 flight profile. Unfortunately, drawbacks in the design, specifi-

cally increases in weight, complexity, packaging, and mechanical performance, significantly offset the aerodynamic benefits and impaired further development.

After the MAW program results became available, German researchers affiliated with Airbus began exploring variable-camber wing technology for long- and medium-range transport aircraft. Their analysis suggested that a 3-6% reduction in fuel burn might be possible. But the added structural mass required to position their conventional high-lift flaps for camber change at cruise conditions limited the fuel savings to more like 1%. Without some fundamentally new technology, this level of improvement was not sufficient to continue work on the project.

Nevertheless, the goals of reduced fuel consumption and lower drag continued to attract interest, especially among government research agencies. By exploiting elasticity of the underlying structure using compliant mechanisms, we developed variable geometry airfoils in the Mission Adaptive Compliant Wing (MACW) program which was funded by the Air Vehicles Directorate of the Air Force Research Laboratory, the same organization that funded the earlier MAW project.

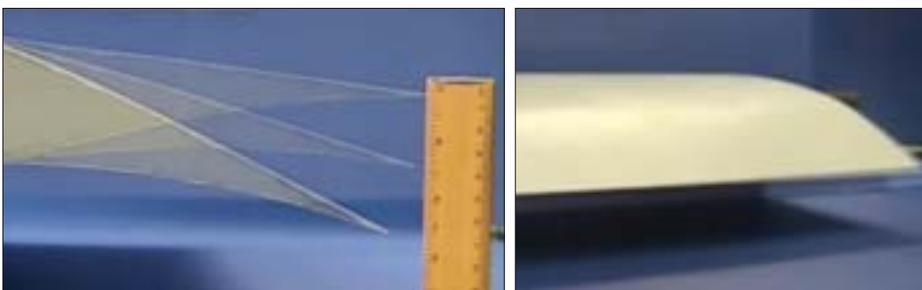
### Distributed elastic shape morphing

The MACW program uses jointless compliant mechanisms to morph shapes on demand—a concept pioneered by the first author, who founded FlexSys five years ago to explore practical applications. The basic theories on the design of compliant mechanisms were transformed to precise and practical shape morphing applications by Joel Hetrick at FlexSys.

In contrast to conventional elastic mechanisms that employ flexible hinges, our algorithms generate designs with distributed compliance for enhanced fatigue resistance and ease of manufacture. Distributed compliant mechanisms get their flexibility from the topology and shape of the whole material cross-section rather than concentrating the flexion to fixed points that can localize fatigue stresses.

This new design paradigm offers additional benefits, since the whole adaptive structure is viewed as a compliant mecha-

*Flexsys' mission adaptive compliant trailing edge was designed for a high-altitude, long-endurance aircraft undergoing  $\pm 10^\circ$  flap deflection with a  $3^\circ$  twist. The airfoil and the conformal flap combination were designed to support an aggressive, 65% laminar boundary layer (chordwise) on the upper surface.*



nism that can move into complex predetermined positions with only minimal force and be locked in place in multiple desired configurations.

In order to morph a load-bearing structure to different shapes or positions, the structure must have optimum compliance for controlled elastic deformation. Development of this concept was funded by the Air Force Air Vehicles Directorate, in the form of an adaptive trailing-edge flap for high-altitude, long-endurance aircraft. The program is slated to culminate in the flight testing of a variable geometry endurance airfoil later this year, to demonstrate compliant wing technology for system application in both military and civil aircraft.

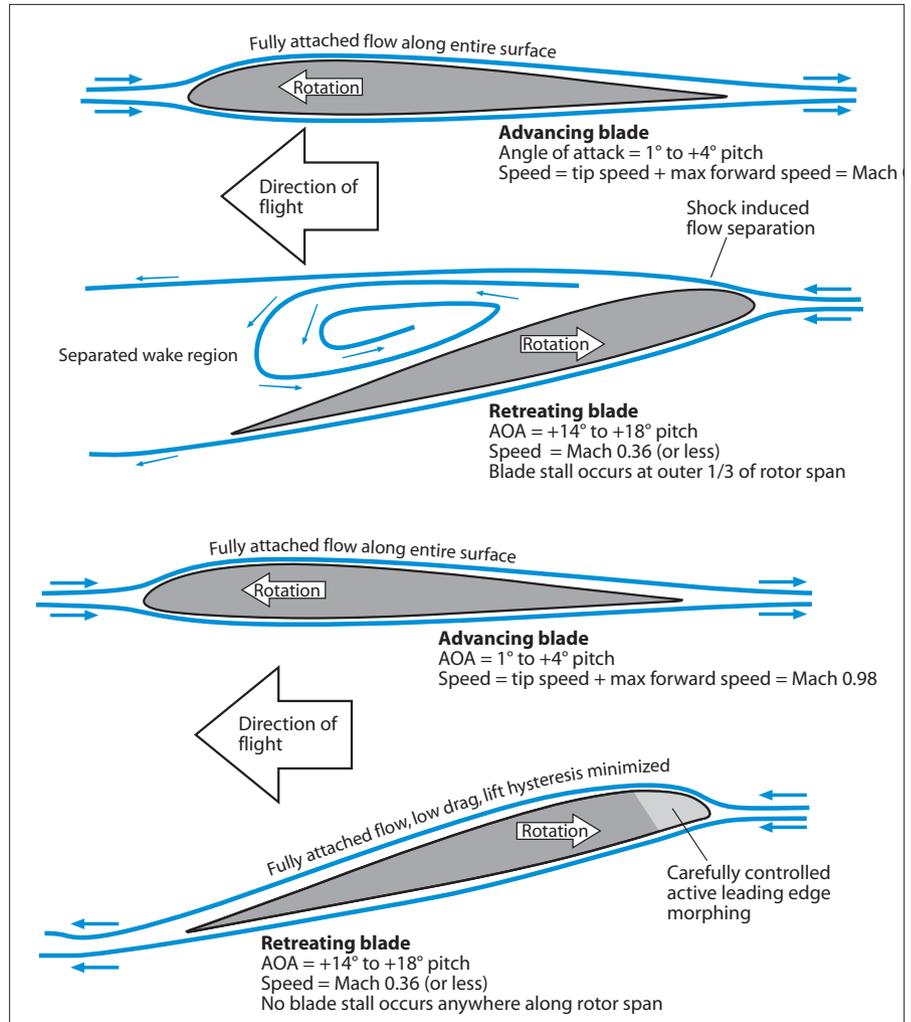
While the current program focuses on a trailing-edge test section, parallel efforts are under way in the development of conformal surfaces for both the leading and trailing edge, and for rotorcraft as well as fixed-wing airfoils. The research is targeted at minimizing the force required to morph surfaces during the full flight profile while maintaining maximum stiffness to withstand all external pressure conditions.

Design and testing has accounted for actuator displacement, minimizing shape error, overall system weight, buckling forces, package constraints, overall system complexity, and material fatigue.

Algorithms have been developed for a series of kinematic, geometric, and structural optimization steps to create and refine the structural design.

The success of the wing design is directly dependent on the morphed trailing edge maintaining a balanced aerodynamic pressure distribution along the whole airfoil upper surface. It is also focused on eliminating suction peaks around the leading edge, and preventing abrupt changes in surface slope at the entry to the pressure recovery region. Typically, several iterations are necessary to resolve conflicting design requirements between the aeroelastic analysis and the compliant structure cross section.

Throughout the design process, skin kinematic requirements are considered to ensure smooth, wrinkle-free covering of the underlying structure. These surfaces



Flow-separation on the retreating blade can be avoided by simply morphing the leading edge once per revolution.

must maintain cohesion and flexibility under all environmental conditions, and through the full schedule of conformal movement. A variety of materials are being applied to meet different applications, including aluminum alloys, aluminum-polymer composites, titanium alloys, glass-fiber-reinforced composites, and carbon-fiber composites.

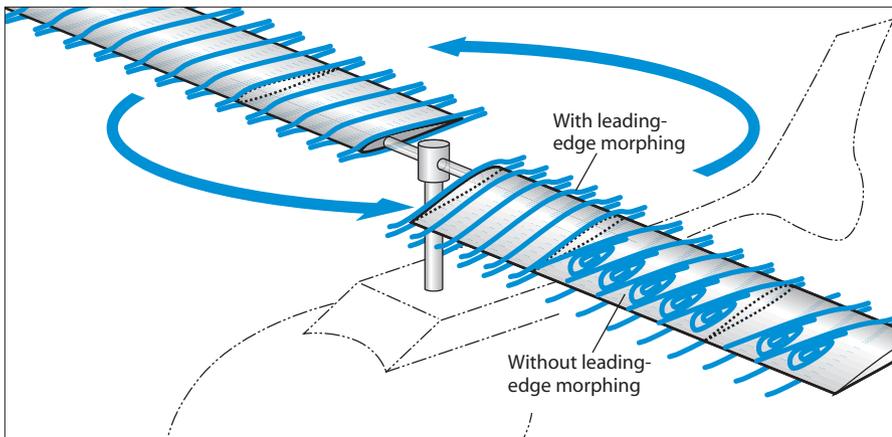
### The fuel/drag challenge

Studies at NASA Dryden show that a mere 1% reduction in drag would save the U.S. fleet of widebody transport aircraft approximately \$140 million/year (at a fuel cost of \$0.70/gal). There is wide agreement that some sort of “smart wing” could provide optimal wing camber with greatly reduced drag throughout a given cruise envelope. For a medium-range transport aircraft with such a wing, the projected fuel savings should be about 3-5%, depending on mission distance.

Although the aerodynamic studies for such a program have projected long-range cruise benefits similar to the German studies, these programs have languished because the smart trailing-edge hardware never matured.

The structural design of a variable-camber trailing edge targeted for a medium-range aircraft has weight and critical flutter speed restrictions competitive with conventional flap systems. For this case, performance estimates indicate fuel savings in the 5% range on a 4,000-n.mi. mission.

A variable-geometry trailing-edge surface can minimize drag across the full aerodynamic lift-coefficient range and favorably shift the buffet boundary, providing enhanced operational flexibility. As a next step, trailing-edge variable geometry can be combined with laminar-flow technology by controlling the chordwise pressure distribution consistent with the



Morphing the leading edge of a rotor blade as it approaches the retreating side delays dynamic stall, thereby enabling the helicopter to fly faster, maneuver better, carry heavier payload, and reduce stall-induced vibration.

laminar-flow requirements of variable camber airfoils. This could significantly boost fuel savings potential in the next generation of transport aircraft, perhaps into the 12% range.

In large part, the analysis work has already been done and the adaptive structures design algorithms have been developed and applied with success in endurance aircraft wing geometry. The next step is to bring this advanced military-level technology into the commercial aircraft arena to realize significant fuel savings. It may be worth remembering that the concept of winglets took a long time from ini-

*A laminar-flow flight test model fitted with variable geometry trailing edge was tested in a high-speed subsonic wind tunnel at Wright Patterson AFB in June. The model was scheduled for performance flight test in August on Scaled Composites' White Knight aircraft.*



tial application to the universal acceptance that it enjoys today.

### Rotorcraft applications

Rotorcraft is another category of aircraft where adaptive compliant structures technology offers significant promise. While the research is not as far along as that for fixed-wing aircraft, applying variable-geometry technology along both the leading and trailing edge of rotor blades could have an even greater impact.

An Army-funded research project recently resulted in a variable-geometry helicopter rotor blade section with an embedded compliant mechanism. The variable-geometry leading edge, with  $\pm 0-10^\circ$  deflection capability, modifies the aerodynamics so that dynamic stall on the retreating blade is delayed, giving the craft higher speed and better maneuvering performance.

In this program, we designed and fabricated a 3-ft-span, full-scale chord rotor blade to demonstrate 0-10° leading-edge camber change at 6 Hz (once per revolution). The blade was designed with high-strength materials to withstand pressure loads and centrifugal loads for 4,500 hr of service life (220 million cycles fatigue life).

In a helicopter blade, the blade cross section that is best for the advancing blade is far from optimal for the same blade in its retreating phase. The deficiency manifests itself in reduced lift and a dynamic shock event as the blade azimuth changes, along with vibration stress, audible sound, and structural wear. These

substantially limit the performance in all rotorcraft, such as maximum speed and altitude, as well as impacting the structural life of rotor blades and the cost of operation and maintenance.

The morphed leading-edge structure begins with the airfoil shape optimal for good high-speed performance in the advancing blade phase and then changes to a cambered design that optimizes airfoil performance as the blade retreats. It then cycles back to the advancing blade configuration, once per revolution or at a rate up to seven times per second. This behavior allows the morphing aircraft structure to maintain an optimal profile throughout its entire azimuthal circuit, thereby offering substantial gains in speed and maneuverability (12-25%) and about 10% increase in payload.

The reductions in drag, vibration, and wear will significantly improve performance of next-generation rotorcraft far beyond the current achievable maximum, promising higher speeds, lower drag and fuel requirements, better maneuverability, and quieter operation, not to mention longer usable blade life and reduced maintenance.

Another project is aimed at developing a variable-geometry trailing edge for rotorcraft. This research addresses two additional challenges: producing lift at all rotor azimuthal positions and minimum drag (low-frequency control), and vibration damping using small trailing-edge deflections at five cycles per revolution (high-frequency control).



The successful development of morphing technology will impact not only fixed-wing and rotorcraft vehicles, but other aerodynamic devices such as wind turbine blades. Adaptive airfoils can also improve the performance of air and fluid channels, engine inlets, and underwater vehicles and systems.

In short, better performing airfoils offer a whole new generation of more efficient, quieter, faster, and highly maneuverable and reliable vehicles and systems, yielding a whole new opportunity for industries which are so dependent on fuel efficiency.

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