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Adaptive Fight Control Actuators and Mechanisms for Missiles, Munitions and Uninhabited Aerial Vehicles (UAVs)

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1. Introduction

The purpose of this chapter is to introduce the technical community to some of the adaptive flight control mechanisims and structures which have either lead directly to or actually flown in various classes of missiles, munitions and uninhabited aircraft. Although many programs are not open for publication, glimpses of a select few have made it to the public arena at various levels.

This chapter is centered on airing several supersystem-level advances to *flight-proven missiles, munitions and UAVs*. Toward that end, basic models were typically used to lay out proof-of-concept flight hardware which was then fabricated, bench and/or ground tested, and incorporated in flight vehicles. In the early years, the adaptive aircraft were often simply flown, just to prove the concept worked. More recently, aircraft using adaptive flight control mechanisms have been flown off against conventional benchmark aircraft so as to demonstrate systemic superiority, thereby proving that flight control systems employing adaptive aerostructures result in some combination of lower power consumption, higher bandwidth, reduction in total aircraft empty weight, greater flight speed, shock resistance, lower part count, lower cost etc. On several occasions, adaptive aerostructures have even been shown to be "enabling;" that is, the aircraft class would not be able to fly without them.

Although adaptive materials have been known for more than 120 years, the Aerospace industry has only more recently become aware of their basic characteristics. Starting in the mid 1980's Ed Crawley's group at MIT laid the foundations of what would become an active and vibrant branch of aerospace technology. With simple experiments on bending and extension-twist coupled plates, this group demonstrated that airloads on aerodynamic surfaces could be actively manipulated by using conventionally attached piezoelectric actuators.[1-3] Although the structures resulting from these projects were not incorporated in flightworthy aircraft, their significance cannot be overstated as they introduced the technical community to the possibility of aircraft flight control with adaptive aerostructures and by doing so effectively started the entire field. Table 1 summarizes a collection of programs which have lead directly to a series of flight proven adaptive subscale aerospace systems.

	Project *p=piezoelectric, s=shape memory alloy c=component testing only f=flight tested v=entire vehicle configuration tested with adaptive device*		Agency/ Sponsor
1	Bending-Twist Coupled Aeroelastic PZT Plate (1985-87)	*c,p*	*MIT*
2	Adaptive Flap (1987-89)	*c,p*	*MIT*
3	Twist-Active Subsonic DAP Missile Wing (1989-90)	*c,p*	*ARO*
4	Twist-Active DAP Rotor (1990-91)	*c,p*	*ARO*
5	Aeroservoelastic Twist-Active Wing (1990-92)	*c,p*	*Purdue*
6	Twist-Active Supersonic DAP Wing (1991-92)	*c,p*	*KU*
7	Constrained Spar Torque-Plate Missile Fin (1991-92)	*c,p*	*KU*
8	Free-Spar DAP Torque-Plate Fin (1992-93)	*c,p*	*KU*
9	Pitch-Active DAP Torque-Plate Rotor (1992-93)	*c,p*	*KU*
10	Subsonic Twist-Active DAP Wing (1993-94)	*c,p*	*WL/MNAV*
11	Subsonic Twist-Active SMA Wing (1993-94)	*c,s*	*WL/MNAV*
12	Subsonic Camber-Active DAP Wing (1993-94)	*c,p*	*WL/MNAV*
13	Subsonic Camber-Active SMA Wing (1993-94)	*c,s*	*WL/MNAV*
14	Supersonic Twist-Active DAP Wing (1993-94)	*c,p*	*WL/MNAV*
15	Supersonic Twist-Active SMA Wing (1993-94)	*c,s*	*WL/MNAV*
16	Supersonic Camber-Active DAP Wing (1993-94)	*c,p*	*WL/MNAV*
17	Supersonic Camber-Active SMA Wing (1993-94)	*c,s*	*WL/MNAV*
18	**UAV with Flexspar Stabilator (*Mothra* 1993-94)**	***v,f,p***	*AAL*
19	Flexspar TOW-2B Wing (1993-94)	*v,p*	*NSF*
20	Solid State Adaptive Rotor (SSAR) (1994-95)	*c,p*	*NSF*
21	Aeroservoelastic Flexspar Fin (1994-95)	*c,p*	*AAL*
22	**UAV with Solid State Adaptive Servopaddle Rotor (95-96)**	***v,f,p***	*NSF*
23	**MAV with Flexspar Stabilator (1994-97)**	***v,f,p***	*DoD CDTO*
24	Barrel-Launched Adaptive Munition (1995-97)	*v,p*	*AFOSR*
25	Smart Compressed Reversed Adaptive Munition (1995-97)	*v,p*	*WL/MNAV*
26	Rotationally Active Linear Actuator (RALA 1995-97)	*c,p*	*WL/Boeing*
27	Pitch-Active Torque-Plate Wing (1997-98)	*c,p*	*AAL*
28	Range-Extended Adaptive Munition (1998-99)	*v,p*	*DARPA*
29	Hypersonic Interceptor Test Technology (1998-2000)	*v,p*	*SMDC/Schafer*
30	**Coleopter MAV with Flexspar Stabilators (1998-2001)**	***v,f,p***	*DARPA*
31	**UAVs with Pitch-Active SMA Wings (2000-01)**	***v,f,s***	*AAL*
32	Light Fighter Lethality MicroFlex Actuator (2000-01)	*v,p*	*TACOMARDEC*
33	Pitch-Active Curvilinear Fin Actuator (2001-02)	*c,s*	*AMCOM*
34	SC Range-Ex Adaptive Munition (SCREAM) (2000-03)	*v,p*	*TACOM ARDEC*
35	Thunder Multilaminate RALA Fin (2000-03)	*c,p*	*AFRL/MNAV*
36	Centerline Precompression RALA Fin (2000-03)	*c,p*	*AFRL/MNAV*
37	Center Pivot Flexspar Fin (2002-03)	*c,p*	*ARL*
38	**PBP StAB (2003-)**	***v,f,p***	*TU Delft/TNO*
39	**Convertible UAV with PBP Grid Fin (2003-)**	***v,f,p***	*TU Delft/KU*
40	**Convertible UAV with PBP Turning Vane Flaps(2003-)**	***v,f,p***	*TU Delft/KU*
41	**Extended-Range Adaptive Gravity Weapons (2003-)**	***v,f,p***	*AFRL/Boeing*
42	**PBP Supersonic NAV (2004-)**	***v,f,p***	*Lutronix*
43	**PBP Morphing Wing UAV (2005-)**	***v,f,p***	*TU Delft/KU*

Table 1. Summary of Adaptive Aerostructures Projects with Direct Connections to Flightworthy Adaptive Uninhabited Aerial Vehicles

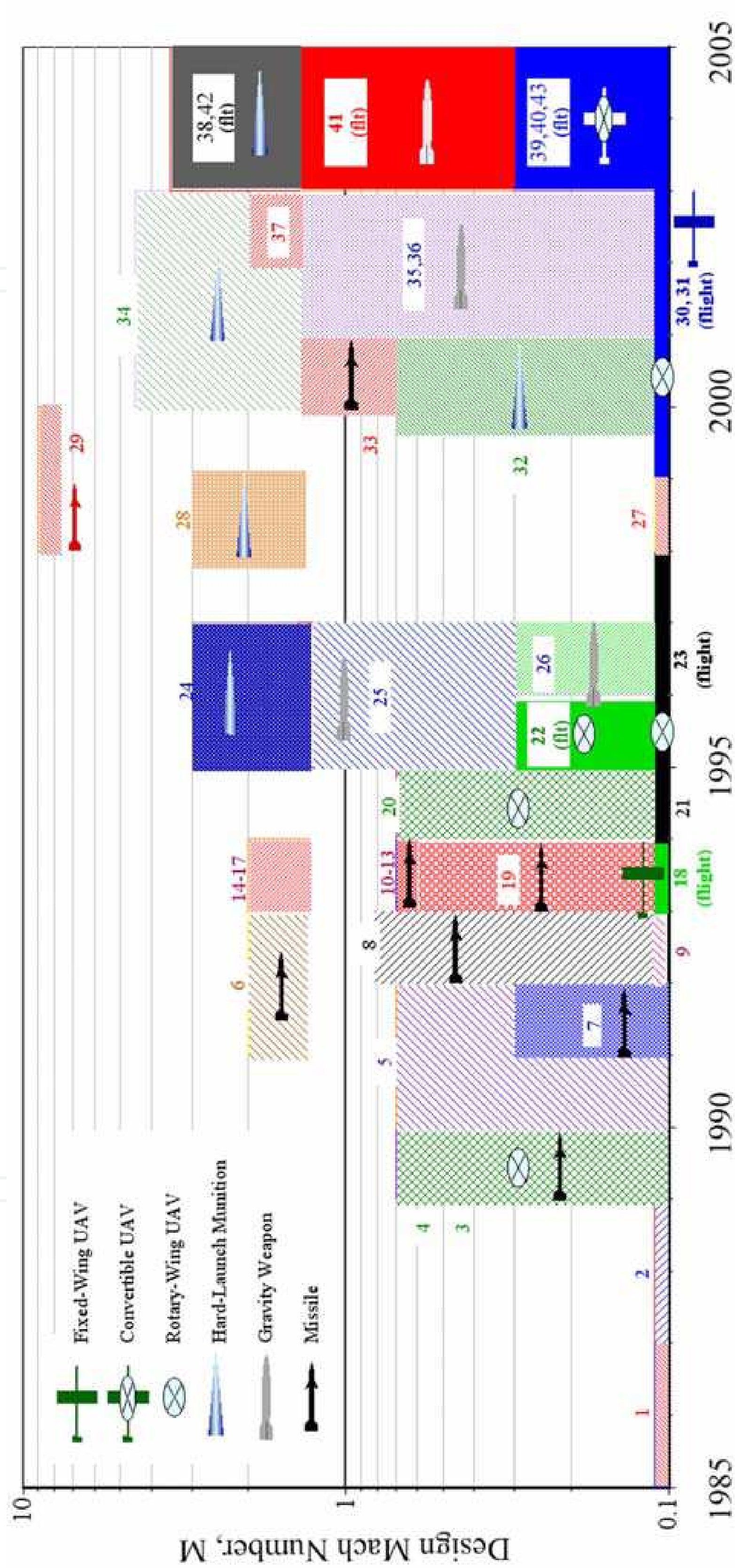

Fig. 1.1 Historical Overview of Adaptive Aerostructures Projects with Direct Connection to UAV Flight

2. Missile, munition and supersonic Uninhabited Aerial Vehicle (UAV) flight control

In the late 1980's, up through 1990, a series of flight control mechanisms were being explored which could drive flaps with piezoelectric bender elements.[4] Although these flight control devices were tested on a small scale, the goal of the investigators was to eventually transition these devices to full-scale, inhabited aircraft.

In 1990, a paradigm shift took was triggered which lead one branch of adaptive aerostructures technology down a large scale/inhabited aircraft path, the other to uninhabited aircraft. The driving philosophy behind the split was simple:

- *Aircraft will benefit the most from this line of technology when adaptive materials can be integrated into aircraft primary structure.*
- *Because there is no current or planned FAA/MilHandbook5 database for materials certification, these materials -by law- will not be allowed in primary structure of FAR 23/25, 27/29 certified aircraft and will not allowed in the primary structure of most inhabited military aircraft because structural designers have no A- or B-basis mechanical properties to lay out designs with.*

Because this philosophy split occured so long ago, the uninhabited branch of technology has had ample time to mature and be demonstrated in flight, thankfully, without the myriad of restrictions which begjile their inhabited counterparts. Among the uninhabited aircraft which were and still are being robustly pursued in this obscure corner of the adaptive aerostructures world are missiles, munitions and UAVs of many sizes. Because funding for military research was comparatively easier to obtain, some of the first applications development efforts were centered on missile and fin research. These eventually matured into system-level designs, bench test and eventually flight tests.

2.1 Early fin and wing designs

In 1990, an important advance in piezoelectric actuation was made.[5-8] The invention of Directionally Attached Piezoelectric (DAP) actuators allowed otherwise isotropic piezoelectric elements to behave as if they were highly orthotropic. This was achieved by attaching piezoelectric elements along a longitudinal axis, leaving the sides free to expand or contract and thereby effectively nulling the lateral stiffness of the element while maintaining the longitudinal stiffness. This property was especially important as it allowed direct active manipulation of structures in twist, rather than just bending. Eventually, DAP actuators were developed with Orthotropy Ratios, OR in excess of 100 which makes them to this day one of the preferred actuator classes for twist activation, especially when cost, robustness and ease of manufacturing are considered. This high OR allowed both coupled and uncoupled structures to be directly manupulated in twist for the first time. If one considers an active laminate with an isotropic active material bonded to an uncoupled substrate, one can see clearly from laminated plate theory that the shear and twist activation terms are zero for CAP elements and non-zero for DAP elements:

Conventionally Attached Piezoelectric Actuators:

$$\left\{\frac{N}{M}\right\}_{CAP}=\begin{bmatrix} A_{11} & A_{12} & 0 & B_{11} & B_{12} & 0 \\ A_{12} & A_{11} & 0 & B_{12} & B_{11} & 0 \\ 0 & 0 & 2A_{66} & 0 & 0 & 2B_{66} \\ B_{11} & B_{12} & 0 & D_{11} & D_{12} & 0 \\ B_{12} & B_{11} & 0 & D_{12} & D_{11} & 0 \\ 0 & 0 & 2B_{66} & 0 & 0 & 2D_{66} \end{bmatrix}_{CAP}\begin{Bmatrix} \Lambda \\ \Lambda \\ 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix}=\begin{Bmatrix} (A_{11}+A_{12})\Lambda \\ (A_{11}+A_{12})\Lambda \\ 0 \\ (B_{11}+B_{12})\Lambda \\ (B_{11}+B_{12})\Lambda \\ 0 \end{Bmatrix}_{CAP} \quad (1)$$

Directionally Attached Piezoelectric Actuators:

$$\left\{\frac{N}{M}\right\}_{DAP}=\begin{bmatrix} A_{11} & A_{12} & 2A_{16} & B_{11} & B_{12} & 2B_{16} \\ A_{12} & A_{22} & 2A_{26} & B_{12} & B_{22} & 2B_{26} \\ A_{16} & A_{26} & 2A_{66} & B_{16} & B_{26} & 2B_{66} \\ B_{11} & B_{12} & 2B_{16} & D_{11} & D_{12} & 2D_{16} \\ B_{12} & B_{22} & 2B_{26} & D_{12} & D_{22} & 2D_{26} \\ B_{16} & B_{26} & 2B_{66} & D_{16} & D_{26} & 2D_{66} \end{bmatrix}_{DAP}\begin{Bmatrix} \Lambda \\ \Lambda \\ 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix}=\begin{Bmatrix} (A_{11}+A_{12})\Lambda \\ (A_{22}+A_{12})\Lambda \\ (A_{16}+A_{26})\Lambda \\ (B_{11}+B_{12})\Lambda \\ (B_{22}+B_{12})\Lambda \\ (B_{16}+B_{26})\Lambda \end{Bmatrix}_{DAP} \quad (2)$$

In the late 1980's it was not readily apparent which among the many approaches to adaptive flight control would actually work in a real flight environment. Several important papers relating aeroelastic tailoring, geometric sweep and aeroelastic coupling were authored, comparing CAP and DAP elements.[9-11] These papers showed that with aeroelastic coupling, small deflections could be aeroelastically magnified to control authority levels which were consistent with aircraft flight control.

Although DAP elements were first integrated into a subscale missile wing in 1989, a new design incorporating DAP elements on a torque plate was conceived and reduced to practice in 1990.[6-8] This approach allowed large rotations of an aerodynamic shell while the loads were taken up by a high strength internal structure. Figure 2 shows the Constrained Spar DAP Torque-Plate Missile Fin. Because the fin was intended for use in a TOW missile, it was capable of ±5° deflections with a corner frequency better than 30Hz and a maximum power consumption under 50mW.[12-14] During the this program, an important design philosophy was evolved that is still seen as critical advice for adaptive aerostructures designers to this day:

i. Minimize the amount of work done by adaptive materials on passive structure
ii. Employ aerodynamic and mass balancing principles so that the adaptive structures resist only transient external airloads and inertial loads.
iii. Use coefficient of thermal expansion mismatch to precompress piezoelectric actuator elements.

The US Air Force was generous in its support of this area after the concept was initially proven on the bench and the wind tunnel. The first study examining piezoelectric flight control for Air Force missiles was centered on low aspect ratio fin and wing manipulation. In 1993, Wright Laboratory commissioned a study examining DAP and CAP-activated surfaces. This was one of the first times that finite element methods were used to capture the behavior of subsonic and supersonic active lifting surfaces. figure 3 shows a FEM model of a supersonic double-circular arc camber-active DAP fin and NACA 0012 subsonic twist-active DAP fin.[15]

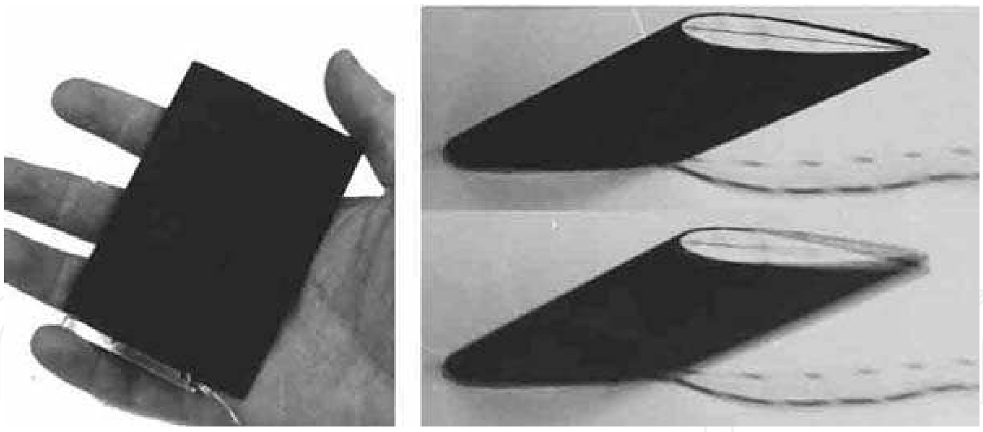

Fig. 2. Constrained Spar DAP Torque-Plate Missile Fin[13]

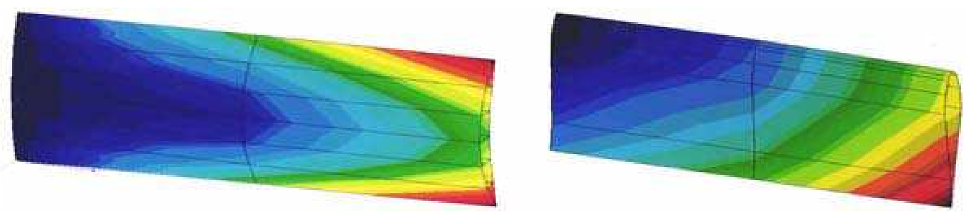

Fig. 3. Finitel Element Models of Active Supersonic & Subsonic Fins[15]

Although the technology worked, at the time it did not work well enough as the levels of manipulation of low aspect ratio aerodynamic surfaces being actuated in twist and camber was simply far too low. Still, for higher aspect ratios, the design was shown not only to work, but work well. However, because most missiles employ low aspect ratio aerodynamic surfaces, a new approach was needed.

2.2 Flexspar: The first flight enabling adaptive system

In an effort to dramatically increase control surface deflections of low aspect ratio fins and in keeping with principles i. and ii above, a new flight control device was invented and reduced to practice. This flight control system would be shown to be one of the most useful and widely used in aircraft employing adaptive materials for flight control. Figure 4 shows the general layout of the device which was designed around a symmetric, balanced airfoil shell.

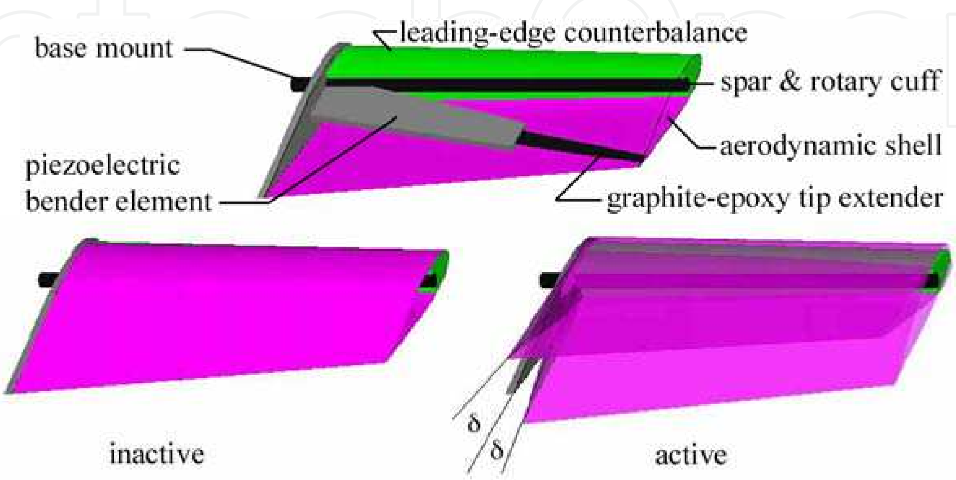

Fig. 4. Flexspar Fin Anatomy

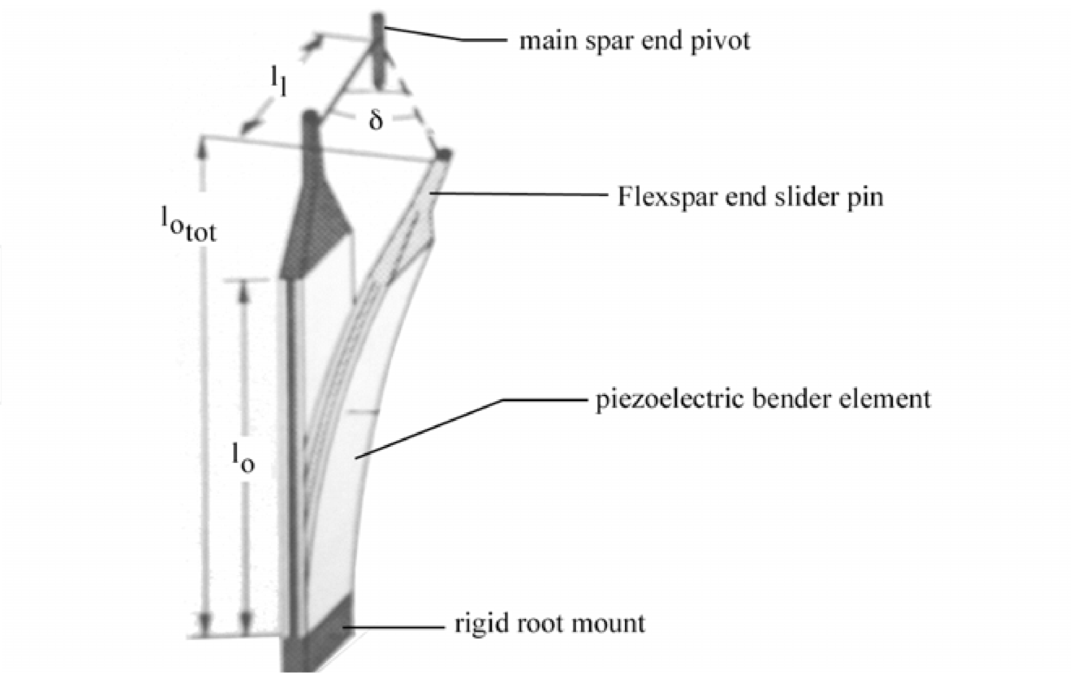

Fig. 5. Tip-Joint Flexspar Fin Geometric Parameters

If one examinies the basic construction of a piezoelectric bender element, then a simple expression can be laid out which relates laminate curvature, k to cure parameters, material characteristics and active free strain levels of the actuator, L. As has been shown over the past 20 years, it is important to use thermally induced precompression in all flightworthy adaptive aerostructures as shown in Equation 3. Equation 4 is the solution of the bending curvature considering a symmetric, balanced laminate composed of two sheets of CAP actuator material bonded on either side of an uncoupled substrate. By using the geometry of Figure 5, the curvatures commanded can be translated into control surface deflections, d. Of course these estimations assume a frictionless, balanced system operating without geometric binding (which typically set in on real systems for rotation angles in excess of 15°.

$$\begin{bmatrix} A_{11}+A_{12} & 0 \\ 0 & D_{11}+D_{12} \end{bmatrix}_{lam} \begin{Bmatrix} \varepsilon \\ \kappa \end{Bmatrix} = \begin{bmatrix} A_{11}+A_{12} & 0 \\ 0 & D_{11}+D_{12} \end{bmatrix}_a \begin{Bmatrix} \alpha\Delta T \\ 0 \end{Bmatrix}_a + \begin{bmatrix} A_{11}+A_{12} & 0 \\ 0 & D_{11}+D_{12} \end{bmatrix}_s \begin{Bmatrix} \alpha\Delta T \\ 0 \end{Bmatrix}_s + \begin{bmatrix} 0 & B_{11}+B_{12} \\ B_{11}+B_{12} & 0 \end{bmatrix}_a \begin{Bmatrix} \Lambda \\ 0 \end{Bmatrix} \quad (3)$$

$$\kappa = \frac{E_a\left(t_s t_a + 2t_b t_a + t_a^2\right)\Lambda}{\frac{E_s t_s^3}{12} + E_a\left(\frac{\left(t_s + 2t_b\right)^2 t_a}{2} + \left(t_s + 2t_b\right)t_a^2 + \frac{2}{3}t_a^3\right)} \quad (4)$$

$$\delta = 2\sin^{-1}\left[\frac{\frac{1}{\kappa}\left(1-\cos\left(\kappa l_o\right)\right) + \left(l_{otot} - \frac{1}{\kappa}\sin\left(\kappa l_o\right)\right)}{2l_l}\right] \quad (5)$$

These expressions have been regularly used for more than a decade to predict Flexspar actuator deflection levels with experimental and predicted results typically within 5% of each other.[16-18]

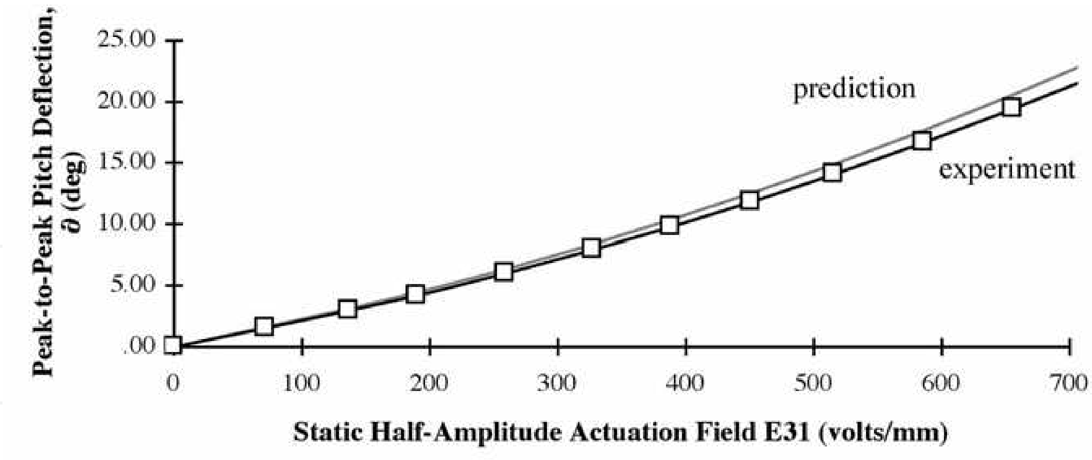

Fig. 6. Typical Flexspar Deflection s and Correlation Levels[17]

The Flexspar actuator configuration is still, to this day, one of the more well used actuation schemes for flight control. It comes in two major variants: the Tip-Joint Flexspar arrangement as shown in Fig. 5. This configuration is particularly well suited to low subsonic flight control using symmetric, balanced aerodynamic surfaces. A high moment configuration called a Shell-Joint Flexspar actuator is used for high subsonic and faster control surfaces. In the Fall of 1994 invention disclosures were submitted to Auburn University where the Flexspar was invented. Because the University failed to either file for patents or revert the rights to the inventors the Flexspar design can now be used royalty-free by one and all. The first missile system to incorporate the Flexspar design was the TOW-2B which used the Flexspar to manipulate wing deflections. Figure 7 shows the TOW-2B missle mounted in the wind tunnel during testing. Because the Flexspar wings were both aerodynamically and inertially balanced and they employed symmetric airfoils, the wing pitch deflections were not affected by airspeed.

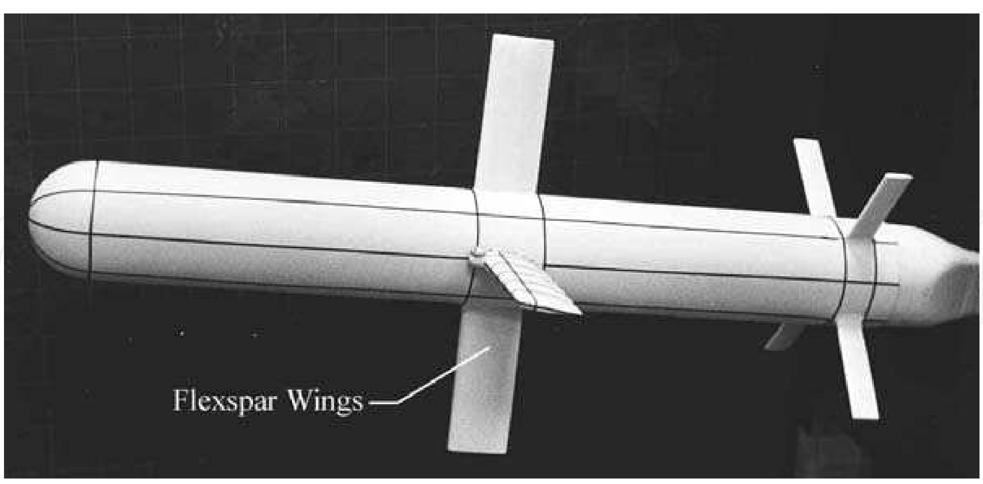

Fig. 7. Flexspar-Equipped TOW-2B Missile in Wind Tunnel

2.2 Cruise missile and gravity weapon applications

2.2.1 Smart compressed reversed adaptive munition

In 1995 the first of the gravity weapons programs was commissioned by the US Air Force employing adaptive flight control mechanisms. The program goal was to compress gravity

weapons into bays the size of the weapon warheads. The driving factor in weapon compression came from the limited size of the F-22 internal weapon bays which were sized for AIM-120 air-to-air missiles, but not the existing slate of minimally compressed gravity weapons. Because conventionally guided gravity weapons of the time could not fit within the bay, a new approach was undertaken. Although a Flexspar configuration would have worked well, an antagonistic piezoelectric actuator was selected to drive a fin set as the design flight speed ranged from mid subsonic through low supersonic. Because of large shifts in position of center of pressure, the transonic flight regime is often the most challenging to flight control actuator designers as large rotations at high bandwidth against high moments are typically prescribed.
Because the designers were allowed to rearrange the weapon configuration itself, a new configuration was developed which took the most advantage of the 1940's-era Mk83 warhead design. This configuration called for a reversal in warhead direction such that the base of the warhead would fly first. This would allow for a stable bluff-body relase (important for weapon egress) and full strakes along the length of the weapon to maintain suitable levels of C_{Na} and provide a housing to accommodate the antagonistic piezoelectric actuators. The entire weapon design took advantage of other artifacts including more than 80 in^3 of volume in large fuse well. Extensive bench and wind tunnel testing showed that full ±10° fin deflections could be resist all airloads without degradation through the transonic flight regime at frequencies in excess of 40Hz. Power consumption studies demonstrated that the actuators could be accommodated over the entire flight duration for less than 2cc of zinc-air batteries.[19,20] Figure 8 shows the weapon configuration and during wind tunnel testing.

Fig. 8. Smart Compressed Reversed Adaptive Munition (SCRAM)[19,20]

Space constraints prevent the full chronicling of the program, but suffice it to say that this effort demonstrated that adaptive aerostructures could be used to increase weapon loadout by an order of magnitude.

2.2.2 Weapon integration and design technology

In 1997, following the success of the SCRAM program an effort was undertaken to provide vernier control for a new family of small penetrator weapons. The canard actuator used a modified form of a shell-joint Flexspar actuator called a Rotationally Active Linear Actuator (RALA). Although this unclassified program is many years old, details are not yet approved for public release.
The actuator set designed for the GBU-39 was intended to enhance terminal guidance and went through extensive bench and wind tunnel testing, showing full deflection capability through the transonic and low supersonic flight speeds.[22,23]

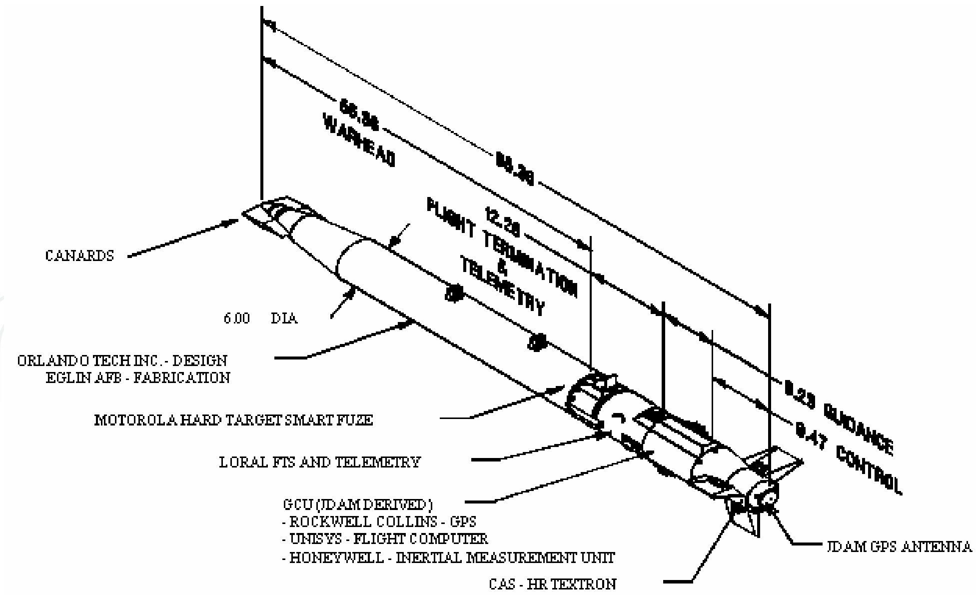

Fig. 9. GBU-39 Small Diameter Bomb with Adaptive Canards[21]

2.2.3 Miniature cruise missile airframe technology demonstrator

Elements of the SCRAM and WIDT programs are currently alive and well in this USAF/Boeing project. Started in 2003, this effort is centered on demonstrating various advanced technologies including an adaptive on an extended range weapon system. As with the GBU-39 WIDT program, technical details have not yet been approved for release.

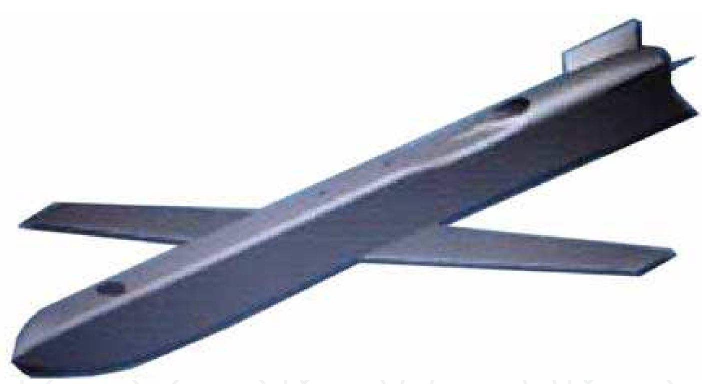

Fig. 10. Boeing/USAF Miniature Cruise Missile with Adaptive Wings[24]

2.3 Hard-launched munitions and supersonic Nano Aerial Vehicles (NAVs)

2.3.1 Barrel-Launched Adaptive Munition (BLAM) program

In 1995 the Barrel-Launched Adaptive Munition (BLAM) program was initated to enhance aerial gunnery by increasing the hit probability and the probability of a kill given a hit in close-in aerial gunnery. To do this, a proof-of concept nontactical round was developed. Figure 11 shows the general arrangement of the test article.[25-28]

The most significant challenges that all hard-launched adaptive munition designs must overcome is clearly associated with launch loads. With respect to launch loads, all flight, storage and handling loads are trivial. In addition to launch loads, the round must also be able to deal with certain environmental factors that are also challenging for aerospace systems. The short summary below illustrates some of these challenges.

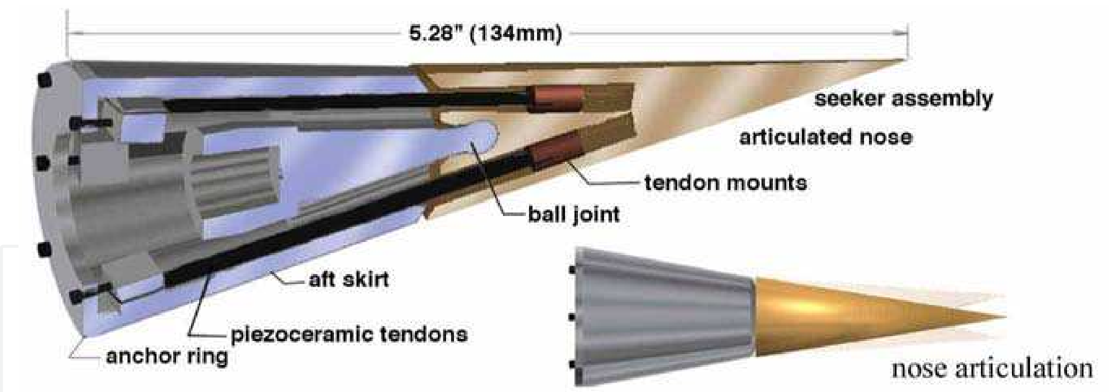

Fig. 11. Barrel-Launched Adaptive Munition (BLAM) Configuration

2.3.1.1 Setback Accelerations

Setback accelerations strongly influence structural layout and material choices and are the driving condition behind length limitations of actuators for hard-launched actuators. Although munitions designers use exacting profiles which are specific to a gun, round, muzzle velocity and charge type combination to predict peak setback accelerations, some basic boundaries can be gleaned from fundamental physics and empirical trends for first-order design. If one assumes a constant acceleration along the length of a barrel (a traveling-charge profile), a round starting from 0 and exiting at a finite muzzle velocity, then a lower bound below which it is not possible to go:

$$a_{\min} = V_{muzzle}^2 / 2L_{barrel} \tag{6}$$

Because there is no upper bound which can be obtained by simple physics, generalized trends from interior ballistic profiles can be obtained. By examining the acceleration profiles of instrumented weapons like the Hypervelocity Weapon System, a rough upper bound can be gleaned for initial design purposes.[29]

$$a_{peak} \cong 1.45V_{muzzle}^2 / L_{barrel} \tag{7}$$

For larger caliber rounds which are currently fielded, setback accelerations on the order of 5,000 – 30,000 g's are typical. The Navy's ERGM projectile is typical of the current families of guided 5″ (127mm) cannon shells and is designed for 12,000g's of setback acceleration while the LCCM projectiles withstand 15,000g's.[30]

2.3.1.2 Setforward, Balloting and Ringing

Although secondary to setback accelerations, setforward accelerations have extremely detrimental effects on hard-launch round components and subsystems. Setforward accelerations are induced as the supersonic round exits the barrel into comparatively still air. This typically causes a large decelration force on most rounds with a pulse of approximately one order of magnitude lower than the setback acceleration. Setforward accelerations are the principal loads which induce buckling and end crush-out failure modes of many families of adaptive actuators. Reference 30 lists the design setforward accelerations for the ERGM round to be approximately 2,500g's.

2.3.1.3 Rotational Accelerations

Most of the gun-launched munitions which are in use today are spin stabilized via the rifling in the barrel. Such rifling induces acceleration rates of several hundred thousand rad/s2. As is the case with acceleration rates, Froude scaling principles hold when arriving at estimates for smaller (or larger) rounds, which indicates that lower caliber rounds will encounter acceleration levels as the reciprocal of the scale factor.

2.3.1.4 Thermal Environment

From Ref. 25 - 28, it can be seen that minimum operational and storage temperatures have a strong influence on the design of the actuator elements as they rely upon CTE mismatch to precompress actuator elements. Precompression levels at depressed temperatures must be carefully matched to thickness ratios and launch accelerations to ensure actuator survival of setback accelerations. Actuator material selection must be made with strong consideration of the operational and storage temperatures. Ref. 30 lists temperature environments which are typical of military munitions as: -40°C (-40°F) to +63°C (145°F) storage -9°C (+15°F) to +63°C (145°F) in a tactical/operational environment. References 30 - 36 lay out many other daunting environmental considerations which must be taken into account when laying out an adaptive munition.

2.3.1.5 Current Progress

The forefront of modern guided round research has progressed far beyond the BLAM which is now more than a decade old. These rounds range in size from just a few milimeters in caliber and up and employ several families of adaptive actuators, guiding rounds with control authorities of just over 1g to many tens of g's. Not surprising, these projects are proprietary and/or restricted by ITARs and EARs. Several scattered efforts have intermittently surfaced, but most projects are still out of the public eye.[36]

2.3.2 Supersonic Nano Aerial Vehicles (NAVs)

The latest international incarnations of hard-launched aircraft comes in the form of supersonic Nano Aerial Vehicles (NAVs). Because conventional, subsonic NAVs are highly sensitive to the many adverse factors which become more severe with reduced scale, it is only logical that many of those problems can be skirted if the NAV is launched supersonically and flown for only a few seconds. The missions for these NAVs is nonlethal and primarily centered on reconnaissance. Figure 12 shows a CAD model of a supersonic NAV.

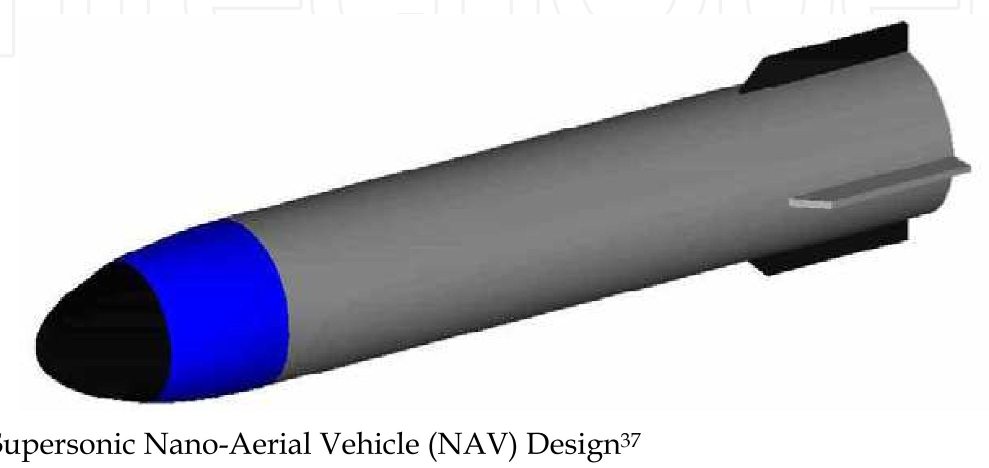

Fig. 12. Supersonic Nano-Aerial Vehicle (NAV) Design[37]

The flight control of these aircraft employ some of the latest adaptive actuators. These advanced "Post-Buckled Precompressed" (PBP) actuators have been shown to generate significantly higher deflections than conventional actuators and are ideal for small aircraft like NAVs.[37]

3. Uninhabited Aerial Vehicle (UAV) & Micro Aerial Vehicle (MAV) flight control

Subsonic Uninhabited Aerial Vehicle (UAV) and Micro Aerial Vehicle (MAV) flight control with adaptive aerostructures draws its lineage back to some early experiments done on flight control devices which produced large changes in commanded lift coefficient. Although flight control mechanisms in rotary- and fixed-wing subsonic UAVs differ sharply, they share some common roots and even took advantage of some of the same families of actuators.

3.1 Fixed-wing UAV beginnings

As part of a National Science Foundation program investigating flight control with adaptive materials, the first fixed-wing aircraft using adaptive materials for all flight control was designed, built and flown in September of 1994. Using a Tip-Joint Flexspar configuration akin to the configuration shown in Figures 4 and 5, the aircraft executed basic maneuvers expected of micro-light aircraft using vertical and horizontal stabilator flight control.[16]

Fig. 13. *Mothra*, The First UAV with Flexspar Stabilators for Flight Control

3.2 Foundations of rotary-wing UAV flight control

The first serious attempts at achieving high control authority deflections of rotor systems was made in 1992. These early efforts employed the same class of torque-plates that drove missile fins, but in the roots of rotor blade systems.[38] Although the first stages of the Solid State Adaptive Rotor (SSAR) was not selected for funding by the US Army, the founding experiments that went into the effort were instrumental in proving its feasibility. In 1994 the National Science Foundation picked up the project and supported it all the way through flight test. Figure 14 shows the earliest incarnation of the SSAR on a hover stand.

The first rotary-wing aircraft to fly using adaptive aerostructures for all flight control took to the air in December of 1996. Space constraints prevent its being chronicled completely, but it employed a pair of piezoelectric DAP servopaddles mounted on a teetering rotor system. The DAP servopaddles were driven by a brush contact assembly which allowed the rotor system to respond to basic cyclic commands at speeds in excess of 2.7/rev. Flight tests were conducted against a benchmark aircraft, ultimately demonstrating maneuver authority nearly identical to the baseline aircraft. The big difference was that the aircraft shed 40% of its flight control system weight, leading to an 8% reduction in total gross weight, a 26% drop in parasite drag and a cut in part count from 94 components down to 5. Figure 15 shows the SSAR aircraft Gamara in on the bench and during flight test.[40]

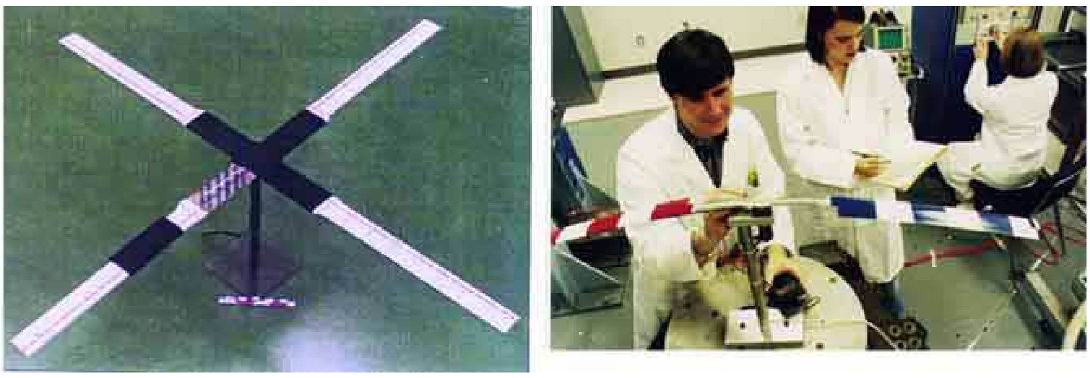

Fig. 14. Solid State Adaptive Rotor with Root Torque-Plate Actuator[38,39]

Fig. 15. Gamara, The First Rotary-Wing UAV to Fly with Adaptive Materials for All Flight Control,[39]

3.3 The DoD's first MAV -- kolibri

In 1994 the DoD CounterDrug Technology Office commissioned a program that would eventually lead to the US Military's first Micro Aerial Vehicle (MAV). In 1995, managers at Lutronix Corp. read about the success of the SSAR program in the technical literature and decided to fold the adaptive technology used in these various programs into their aircraft. The mission specification for the MAV called for a 24hr loiter with acoustic signature levels under 65db at 10ft. Accordingly, an electric-tethered configuration was chosen. Because of the highly constrained rotor diameter and the limited adaptive materials manufacturing techniques of the day, it was decided that instead of a DAP-torque-plate rotor configuration, a Flexspar stabilator configuration would be used. These Flexspar stabilators would be placed in the rotor wash at the bottom of a graphite-truss frame fuselage counterrotating coleopter.

Fig. 16. DoD's First MAV -- *Kolibri* Stabilator, Aircraft & in Flight

Because the *Kolibri* was so severely weight-critical, any opportunity to shed weight was taken. Accordingly, the flight control system was a prime target for weight reduction. Because the aircraft body times to double amplitude were on the order of several tens of miliseconds, extremely fast actuators were a necessity. The conventional servoactuators on the open market were simply not fast enough to catch the aircraft and their weights were prohibitive. Flexspar actuators on the other hand were extremely lightweight with a mass of only 380mg each and exhibited a corner frequency of 47 Hz -- almost double the bandwidth required to maintain flight. So for the first time, adaptive flight control mechanisms were not only enhancing technologies, but they actually *enabled* an entire class of aircraft to take to the air. Not surprisingly, the flight control system also included adaptive materials in the Tokin DO-16 piezoelectric gyros which were used to sense pitch, roll and yaw accelerations.

3.4 The first free-flight rotary-wing MAV

Following the success of the *Kolibri,* the DoDCDTO handed the program off to DARPA, thereby kicking off DARPA's much touted MAV program of the late '90's. Although the *Kolibri* satisfied the 24 hour hover endurance requirement with a tether, there was a strong desire to shed the tether. As a result a decision was made to go with an internal combustion engine. Although the boost in power was tremendous, the noise and structural vibrations were also boosted by an order of magnitude. As with the *Kolibri,* Flexspar stabilators and piezoelectric gyros allowed smooth flight in turbulent atmospheric conditions up through 18kt gusting winds. Figure 17 shows the aircraft overview and in flight. Ultimately, the aircraft was the only one of three finalist MAVs which successfully flew at DARPA's 3-day Fly-Off at Quantico Marine Corps Base, Virginia in September of 2000. Fly-offs were also conducted in several other locations including MacDill AFB, Florida, again, with the LuMAV appearing as the only rotary-wing/VTOL aircraft in the air. The aircraft performance specifications included a 15 minute endurance with all-weather capability including rain rates in excess of 12" (30cm)/hr, dust and snow capability through 18kt gust fields, flight in 100°F, 100% humidity environments and 15g wall-strikes. The aircraft was designed to carry a single submicrovideo camera an a GPS navigation suite.[44]

Fig. 17. Lutronix MAV Configuration & Flying at MacDill AFB, Florida

3.5 The XQ-138 convertible UAV

As the LuMAV project came to a resoundingly successful conclusion, a follow-on design was sought. Although the LuMAV was clearly quite capable and flew circles around competitors, it was not selected for follow-on funding by DARPA. Instead, DARPA managers recommended approaching Boeing, which in turn recommended a new corporate partner on the Future Combat System (FCS) program, Singapore Technologies Engineering.

A new aircraft configuration was independently conceived and reduced to practice in the summer of 2001 which employed the best of the rotary-wing and fixed-wing worlds. Impressed with the new aircraft performance and promise, ST Engineering purchased the rights to the aircraft and paid for its production. Initially, the XQ-138, a convertible coleopter, used conventional flight control actuators in its grid-fin empennage and turning vane flaps. Following component development efforts, these actuators were replaced by piezoelectric mechanisms. Figure XX18 shows the overall configuration of the XQ-138.[45]

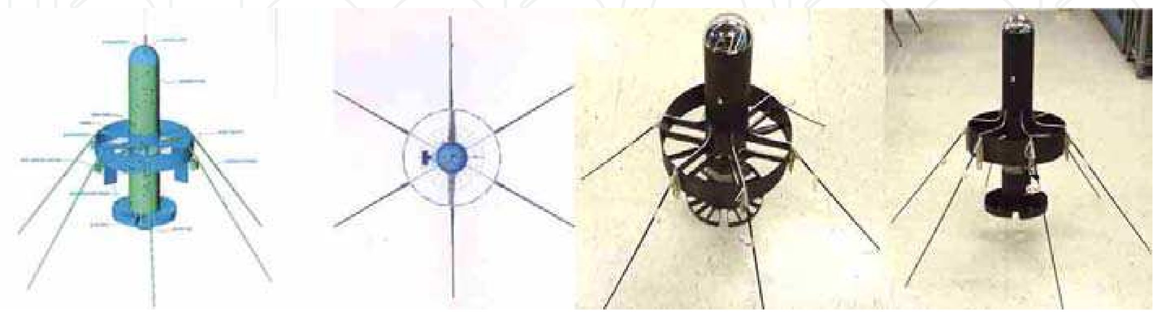

Fig. 18. The 11" Rotor Diameter XQ-138a Overall Configuration

More than 300 flight tests were conducted in all types of atmospheric conditions including gusts through 26 kts, rain at 9"/hr, 100°F (38°C) heat at 100% humidity, winter flights in snow at 22°F (-6°C), dust, sand and finally flight in smoke plumes from exploded tanks. Figure 19 shows a sequence of photos of the aircraft flying off an FCS prototype on Redstone Arsenal, Alabama in April of 2002. These tests were followed by live-fire Battle-Damage Assessment (BDA) tests on the Hellfire Range of Eglin AFB in May of 2002. Although all variants of the aircraft used piezoelectric gyros at the core of its GNC package, the conversion of the aircraft to piezoelectric flight controls lent marked improvements in all aspects, eventually leading to a total empty weight savings in excess of 10% which allowed the range to be expanded by 30nmi to 100nmi and more than an hour and a half of endurance. Variants of the aircraft survive today as Singapore Technologies Engineering's FanTail UAV line of aircraft.

Fig. 19. The Piezoelectric FCS-Equipped XQ-138 Convertible Coleopter UAV

3.6 Low and zero net passive stiffness structures

In 2004 an important innovation was made which dramatically improved the performance of adaptive aerostructures. It was discovered how to simultaneously improve both deflection and force with minimal weight volume and cost penalties.[46] This discovery was shown to dramatically improve flight control actuator performance and has been integrated into a number of flight control systems.[47-53] Several variants of Low Net Passive Stiffness

(LNPS), Zero Net Passive Stiffness (ZNPS) as Post-Buckled Precompressed (PBP) actuator elements have been built into aircraft which are currently undergoing development.

4. Nomenclature

Symbol	Description	Units
A,B,D	in-plane, coupled, bending laminate stiffnesses	N/m, N, N-m
B	actuator width	mm (in)
D_p	actuator power density per unit mass, volume, cost	W/g, W/cc, W/$
E	stiffness	GPa (msi)
F	applied end force	N (lbf)
M	Mach number	~
M	applied moment vector	N-m/m (in-lb/in)
N	applied force vector	N/m (lb/in)
OR	Orthotropy Ratio = E_L/E_T	~
t	thickness	mm (in)
y	out of plane displacement dimension	mm (in)
z	through thickness dimension	mm (in)
α	angle of attack	deg
δ	PBP beam angle	deg
δ_o	PBP end rotation angle	deg
ε	laminate in-plain strain	µstrain
κ	laminate curvature	rad/m (rad/in)
Λ	piezoelectric free element strain	µstrain
σ	stress	GPa (msi)

Subscripts

a	actuator
b	bond
c	cost
ex	external
l	laminate
L	longitudinal
m	mass
s	substrate
t	thermally induced
T	transverse
v	volume

Acronyms

AAL	The Adaptive Aerostructures Laboratory
AFOSR	US Air Force Office of Scientific Research,
AFRL	Air Force Research Lab
AMCOM	US Army Aviation and Missile Command
ARO	US Army Research Office
DAP	Directionally Attached Piezoelectric

DARPA Defense Advanced Research Projects Agency
DoD CDTO Department of Defense CounterDrug Technology Office
FCS Future Combat System
LAV Light Armored Vehicle
MAV micro aerial vehicle
NAV nano aerial vehicle
NSF National Science Foundation
PZT lead zirconate titanate
SMDC Space and Missile Defense Command
TACOM-ARDEC US Army Tank-Automotive and Armaments Command/Armament Research, Development and Engineering Center
TNO Toegepast Natuurwetenschappelijk Onderzoek
TU Delft The Technical University of Delft, Netherlands
UAV uninhabited aerial vehicle
WL Wright Laboratory

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Nonlinear problems in flight control have stimulated cooperation among engineers and scientists from a range of disciplines. Developments in computer technology allowed for numerical solutions of nonlinear control problems, while industrial recognition and applications of nonlinear mathematical models in solving technological problems is increasing. The aim of the book Advances in Flight Control Systems is to bring together reputable researchers from different countries in order to provide a comprehensive coverage of advanced and modern topics in flight control not yet reflected by other books. This product comprises 14 contributions submitted by 38 authors from 11 different countries and areas. It covers most of the currents main streams of flight control researches, ranging from adaptive flight control mechanism, fault tolerant flight control, acceleration based flight control, helicopter flight control, comparison of flight control systems and fundamentals. According to these themes the contributions are grouped in six categories, corresponding to six parts of the book.

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