Research Article

Solid State Adaptive Rotor Using Postbuckled Precompressed, Bending-Twist Coupled Piezoelectric Actuator Elements

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This paper is centered on a new actuation mechanism which is integrated on a solid state rotor. This paper outlines the application of such a system via a Post-Buckled Precompression (PBP) technique at the end of a twist-active piezoelectric rotor blade actuator. The basic performance of the system is handily modeled by using laminated plate theory techniques. A dual cantilevered spring system was used to increasingly null the passive stiffness of the root actuator along the feathering axis of the rotor blade. As the precompression levels were increased, it was shown that corresponding blade pitch levels also increased. The PBP cantilever spring system was designed so as to provide a high level of stabilizing pitch-flap coupling and inherent resistance to rotor propeller moments. Experimental testing showed pitch deflections increasing from just 8° peak-to-peak deflections at 650 V/mm field strength to more than 26° at the same field strength with design precompression levels. Dynamic testing showed the corner frequency of the linear system coming down from 63 Hz (3.8/rev) to 53 Hz (3.2/rev). Thrust coefficients manipulation levels were shown to increase from 0.01 to 0.028 with increasing precompression levels. The paper concludes with an overall assessment of the actuator design.

1. Introduction

For more than two decades, adaptive rotors, flaps and helicopter flight and vibration control systems have been actively pursued by a small army of technologists scattered around the world. The work of Crawley and his team at MIT in the mid-1980s laid the foundations of adaptive aerostructures by investigating the properties of bending and twist-active plates [1–3]. These early studies lead to several broad reviews which examined material properties and their associated energy and power densities when used as actuator elements [4, 5].

1.1. Adaptive Flaps. The earliest twist, camber, and bending active aerodynamic plates were followed by the first of the adaptive flap studies [6]. A host of adaptive flaps flowed into the technical literature at a steady rate from the early 1990s through their implementation in a full-scale rotor test bed (right) [7–19]. Through much effort it was shown that blade loads could indeed be manipulated as fast as 4/rev with

appreciable deflection levels. However, the weight, cost, and complexity issues still prevent full transition to prototype flying aircraft and serial production aircraft. Efforts with “Smart Active Blade Tips” (SABT) showed good results, but fell prey to the same issues as conventional flaps, but with exacerbated propeller moments. Given that for every 1 unit of mass added at the 75% radius (and further out) it takes on the order of 3 units (or more) of structural mass to distribute the load into the airframe, the weight penalty alone of active flap systems is considerable. Because rotor blades are some of the most expensive items on any given rotorcraft, a sizable cost penalty because of the integration of expensive adaptive actuators is quite daunting. Still, much research regularly appears in scattered literature with new flap and actuator configurations (Figure 1).

1.2. Twist-Active Rotors. Just after the twist-active plates of Crawley, De Luis, and Lazarus were published, a series of studies were put forth on twist-active missile fins, wings,

FIGURE 1: “Smart” rotor equipped with active flaps [18].

FIGURE 2: First twist-active rotor (1989) [20].

and rotor blades [20–25]. These 20+-year-old studies also included the first patent (which was also the first IP royalty-generating patent) on adaptive aerostructures to be issued. The earliest work of 1989 showed that essentially “microscopic” twist deflections could be generated [21, 22]. Clearly, these $\pm 0.2^\circ$ deflections were not enough for full cyclic or collective. However, they were enough to kick off the field. Twist active rotor research continued through the 1990s with expansions of the Directionally Attached Piezoelectric (DAP) elements from the first 35% of the chord (for proper blade balance as seen in Figure 2), to much greater distances along the chord. Although destabilizing because they shift the center of gravity aft of the aerodynamic center, they did increase the ± 0.2 degree deflections substantially to roughly $\pm 0.3^\circ$ at the same field strength [23]. Twist-active rotor research reached a zenith in 1999 when the largest model to date was wind tunnel tested [24]. Although large-scale experimentation with twist-active rotors has come to a grinding halt, there are occasional technologists who revisit this technology [25]. As with the adaptive flap designs, the weight, cost, and complexities have been shown to be simply prohibitive.

1.3. Solid State Adaptive Rotor. One concept that was intended to skirt the “show stopping” issues associated with adaptive materials mounted on the blades was the Solid State Adaptive Rotor (SSAR) (Figure 4). This design employed DAP torque plates mounted at the root of the rotor system between the hub and the lag hinge [20, 26, 27]. Because no extra weight was added to the blade itself, the mass,

Lock number, cost, and complexity of the blade systems themselves would be no higher than conventional rotor blades. Because the actuator was designed to actively pitch the rotor about the aerodynamic center which was collocated with the line of centers of gravity and counterbalanced with Chinese weights, the only appreciable attached flow moments were inertial. Because the feathering moments were balanced, respectable pitch deflections of 8° peak to peak could be commanded by the small torque plates. These considerable pitch deflections then translated into nontrivial thrust coefficient manipulation levels as seen in Figure 3. Because they were so high, eventually they were woven into the first rotorcraft to fly using adaptive aerostructures for all flight control, Gamara (Figure 5), (below).

The successes in flight test were matched by several overview papers describing the feasibility of adaptive rotors [28–31]. These overview papers described many approaches and listed several different techniques and approaches for achieving flight control. One of the later overview papers summarized not only rotorcraft, but missile, munition, and UAV successes which were numerous by 2004 [32].

1.4. VTOL Microaerial Vehicles, Ultrahigh Performance and Convertible UAVs. Given the very public successes of the SSAR program, the DoD contracted to have a subscale rotorcraft built which actually needed adaptive materials to achieve flight control on the subscale. The “Kolibri” VTOL Coleopter was commissioned by the DoD Counterdrug Technology Office to explore tunnels and stay airborne for 24 hrs [33–37]. It was later understood that these studies were actually the very first Micro Aerial Vehicle (MAV) contracts let by the DoD. These studies eventually enabled free-flight MAVs which used piezoelectric elements extensively in their GNC packages. From 2001 through 2010 a completely new type of UAV has evolved. These new aircraft, first flown under the designation of XQ-138, is capable of hovering in more places than helicopters while pitching over (or converting) to missile mode flight to fly out at tactical missile speeds. Although major DoD elements declined funding, private sources were found and test ranges at Eglin AFB, Florida, Redstone Arsenal, AL and Fort Benning, Georgia gladly hosted the aircraft during some extreme flight tests and demos. It should also be noted that the superior performance of the aircraft also induced all competing UAV manufacturers and Government sponsors to decline *all* flyoff challenges and offers. The US Army’s first exercise with a remote-controlled armored vehicle launching a UAV took place at Redstone Arsenal, AL when an XQ-138 was launched from the turret of an FCS prototype vehicle. Eglin AFB, FL saw the first tandem flights of a Javelin Missile followed closely by an XQ-138 ultrahigh performance UAV flying a Battle Damage Assessment (BDA) mission. Parallel IFF and conversion-stalking missions were also flown for the first time in history by convertible UAVs. 40 mm submunitions were fired from the XQ-138 at Ft. Benning and a Mother-ship drop from 1000 ft AGL was demonstrated. Clearly, the forefront of UAV technology is

FIGURE 3: Solid state adaptive rotor (1996) [20, 26, 27].

FIGURE 4: SSAR thrust coefficient change levels, $\Delta C_T(\sim)$.

being spearheaded by adaptive aerostructures through this class of aircraft (Figure 6).

1.5. New Discoveries in Structural Mechanics. Although flight on a 1 m scale was concretely demonstrated as significantly helped by adaptive aerostructures, a new branch of structural mechanics evolved from the mid-1990s through today. In 1997 the first paper describing the superior nature of a new form of structural arrangement was published [38]. Lesieutre et al. showed that by mounting a bending beam, properly the passive stiffness of the actuator, could be nulled. By nulling the passive stiffness the deflections and ultimately the electrical-to-mechanical and mechanical-to-electrical conversion efficiencies could be driven close to 100% [39]. Although Lesieutre et al. primarily used this basic discovery in electrical energy converter, the philosophy of nulling passive stiffnesses is directly transferrable to mechanical actuators. Several related studies were conducted on structures which exhibited negative stiffnesses through

buckling effects associated with snap-through events [40–42]. These were followed by actuator studies on bistable piezoelectric composites which used energy techniques to estimate performance [43–45]. Both the snap-through and bistable studies showed that small amounts of energy invested in piezoelectric actuators could be used to trigger much more energetic processes if the structure and surrounding materials were designed properly.

1.6. Postbuckled Precompression (Pbp) Techniques and Analysis. In 2004 a fundamental discovery was made with respect to piezoelectric actuation. The principles of piezoelectric actuation described in [38] were refined for flight control. Rather than pushing the structure through to a bistable situation, a highly controlled axial force could be used to induce a postbuckling effect. This effect would be seen to drive actuator deflections to very high values, but not sacrifice moment generation capability [46–54]. These PBP structures outperformed any other piezoelectrically driven actuators by factors of 3 and 4. Figure 7 shows the basic arrangement of the bending version of the actuator.

Because the performance of PBP-based bending actuators is shown to be so significantly superior with respect to conventional linear techniques a new incarnation of the above model is explored in this paper. By combining the methods of using Zero-Net Passive Stiffness (ZNPS) structural design (also above), it is possible to null the passive torsional stiffness of the SSAR rotor root actuators of Figure 3. By doing so, it will be shown that otherwise huge deflections can be generated by these “old” actuators if they are just mounted properly between negative spring mechanisms.

2. PBP SSAR Root Actuator Design

Because PBP techniques call for more of a change in actuator design philosophy as much as a change in how adaptive actuators are handled, the rotor of Figure 3 was simply retrofitted with a pair of stiffness nulling springs so as to generate high deflections with simultaneous high moment generations. Figure 8 shows the root section following retrofit.

FIGURE 5: Gamara, the first helicopter to use adaptive materials for all flight control (1996) [27].

The spring stiffnesses and prestress levels were set by analytical modeling and fine tuning during whirl-stand testing. The analytical models called upon were established in [46–52] to determine the amount of axial forces required to fundamentally null the net passive stiffness of the piezoelectric actuator element. The overall PBP assembly design was laid out to provide several overarching properties:

- (i) magnify pitch deflections without adversely affecting moment generation properties of the torque plate;
- (ii) provide a stabilizing effective ∂_3 pitch-flap coupling;
- (iii) balance out attached flow aerodynamic, propeller and passive torque-plate stiffnesses;

- (iv) not significantly impact the weight and hub drag of the assembly;
- (v) allow for easy adjustment during testing to fine-tune the assembly.

The overall design takes advantage of destabilizing spring moments applied at the tip of the torque plate. Figure 9 shows the negative torsional spring arrangement. As the piezoelectric torque plate induces pitch deflections, the two springs generate a nose-up pitching moment which is structurally destabilizing, but when properly “tuned” can be balanced exactly against the passive stiffness of the torque plate laminate. By doing so, the deflections are seen to grow by factors of 3 or more while maintaining the moment resistance capability of the laminate.

FIGURE 6: The XQ-138 ultrahigh performance UAV using piezoelectric elements in the FCS undergoing conversion to missile mode flight, Redstone Arsenal, AL [55].

FIGURE 7: Basic arrangement of a linear postbuckled precompressed piezoelectric beam [46–54].

3. PBP SSAR Root Actuator Modeling

The overall design philosophy described above can be fairly easily implemented by simply balancing out forces. If one performs a simple accounting, it can be seen that actuator (a), passive laminate (l), aerodynamic (aero), propeller (prop), inertia, and damping moments about the feather axis should be nulled

$$M_a + M_l + M_{aero} + M_{prop} + M_{inertia} + M_{damping} = 0. \quad (1)$$

3.1. Actuator Modeling. If one considers the first two terms above, they relate to the laminate. By using a simple

linear classical laminated plate theory (CLPT) model, the overall behavior of the symmetrical actuator can be seen in [26, 27]. The techniques of [56] capture the moment balance, considering forces external (ex) to the laminate:

$$\begin{Bmatrix} N \\ M \end{Bmatrix}_{ex} + \begin{Bmatrix} N \\ M \end{Bmatrix}_a + \begin{Bmatrix} N \\ M \end{Bmatrix}_t = \begin{bmatrix} A & B \\ B & D \end{bmatrix}_1 \begin{Bmatrix} \varepsilon \\ k \end{Bmatrix}_1. \quad (2)$$

By expanding (2), the exact structure of the stiffness matrices above can be seen, considering external forces and moments represented by a simple vector

FIGURE 8: Retrofitted SSAR assembly with PBP feather (Pitch) stiffness-nulling springs.

FIGURE 9: Destabilizing compression spring arrangement.

FIGURE 10: Blade pitch results with and without PBP spring compression.

(a)

(b)

FIGURE 11: Solid state adaptive rotor on whirl-stand.

$$\begin{Bmatrix} N_{11} \\ N_{22} \\ N_{12} \\ M_{11} \\ M_{22} \\ M_{12} \end{Bmatrix}_{\text{ex}} + \begin{bmatrix} A_{11} & A_{12} & 2A_{16} & 0 & 0 & 0 \\ A_{12} & A_{22} & 2A_{26} & 0 & 0 & 0 \\ A_{16} & A_{26} & 2A_{66} & 0 & 0 & 0 \\ 0 & 0 & 0 & B_{11} & B_{12} & 2B_{16} \\ 0 & 0 & 0 & B_{12} & B_{22} & 2B_{26} \\ 0 & 0 & 0 & B_{16} & B_{26} & 2B_{66} \end{bmatrix}_a \begin{Bmatrix} \alpha_a \Delta T \\ \alpha_a \Delta T \\ 0 \\ \frac{\Lambda_1 + \Lambda_2}{2} \\ \frac{\Lambda_1 + \Lambda_2}{2} \\ \frac{\Lambda_1 - \Lambda_2}{2} \end{Bmatrix} + \begin{bmatrix} (A_{11} + A_{12})_s \alpha_s \Delta T \\ (A_{11} + A_{12})_s \alpha_s \Delta T \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & 2A_{16} & B_{11} & B_{12} & 2B_{16} \\ A_{12} & A_{22} & 2A_{26} & B_{12} & B_{22} & 2B_{26} \\ A_{16} & A_{26} & 2A_{66} & B_{16} & B_{26} & 2B_{66} \\ B_{11} & B_{12} & 2B_{16} & D_{11} & D_{12} & 2D_{16} \\ B_{12} & B_{22} & 2B_{26} & D_{12} & D_{22} & 2D_{26} \\ B_{16} & B_{26} & 2B_{66} & D_{16} & D_{26} & 2D_{66} \end{bmatrix}_l \begin{Bmatrix} \epsilon_{11} \\ \epsilon_{22} \\ \epsilon_{12} \\ k_{11} \\ k_{22} \\ k_{12} \end{Bmatrix}. \quad (3)$$

Considering a laminate constrained in curvature by high centripetal forces, the laminate twist can be solved as

$$k_{12} = \frac{(E_L(1 - \nu_{TL})\Lambda_1 - E_T(1 - \nu_{LT})\Lambda_2)((t_s + 2t_b)t_a + t_a^2)}{(E_s t_s^3(1 - \nu_{LT}\nu_{TL}))/6(1 - \nu_s) + (E_L + E_T - 2E_L\nu_{TL})(((t_s + 2t_b)^2 t_a)/2) + (t_s + t_b)t_a^2 + (2t_a^3/3))}. \quad (4)$$

The actuator moment which can be applied by full hard-over pitch commands considering a bending-constrained laminate is shown in

$$M_a = \frac{E_{La} - E_{Ta}}{4(1 - \nu_{LT}\nu_{TL})} (t_s t_a + t_a^2) W_a \Lambda. \quad (5)$$

3.2. External Moments. If one examines the aerodynamic moments, then a simple offset between integrated centers of pressure, elastic axis, and line of centers of gravity can be seen:

$$M_{\text{aero}} = \frac{1}{2} \rho \Omega^2 R_{sp}^2 C_{sp} B_{sp} (x_{cg} - x_{cp}) c_{la} \phi. \quad (6)$$

Of course, the easy (and logical) design decision is simply to collocate the c.g., c.p. and e.a. so as to null those moments. One set of moments which require a bit of orthogonal design stems from propeller moments:

$$M_{\text{prop}} = -m_{sp} \Omega^2 r_g^2 \phi. \quad (7)$$

From (6) and (7) it is easy to see that aerodynamic and propeller moments are both proportional to blade pitch angle, ϕ . Through proper design, it is possible to balance out these two terms by judiciously prescribing the distance between the c.g. and c.p. Of course this is actually a comparatively dangerous move as the system can become dynamically unstable. In the interest of safety, the blade static margin will be set to zero or slightly positive.

4. Rotor Fabrication, Testing, and Results

Because the geometry of the 122 cm rotor model, its fabrication methods and materials are described in [26, 27], the reader is simply referred to those documents. The modified rotor, equipped with destabilization springs is shown in

FIGURE 12: Dynamic response of SSAR and PBP-SSAR Systems.

Figure 8. Two series of tests were conducted: static bench tests and dynamic whirl-stand testing. Laser reflection techniques were employed to measure blade pitch deflections. Quasi-static excitation voltages were passed through the rotor hub at 1 Hz. From Figure 10 it can be seen that both the laminated plate theory and the raw piezoelectric performance line up well (as shown in [26, 27]). As the spring compression levels were increased, deflection levels were seen to grow and grow till the edge of structural stability was reached. Figure 10 shows the results from that “edge.” By employing the practical experience and modeling techniques of [46–52], it can be seen that amplification ratios (AR) on the order of 3.5–3.8 are most generally achieved by bidirectional piezoelectric control actuation. Accordingly, the measured AR of 3.8 is seen to be an excellent achievement for the world’s first torsionally amplified low-net passive stiffness piezoelectric actuator. It should be noted that the amplification ratio of 3.8 is essentially constant over the entire range of deflections commanded and measured.

In addition to amplification of static deflections, the thrust coefficient manipulation levels were also increased

dramatically. Figure 11 shows the rotor undergoing whirl-stand testing, demonstrating thrust coefficient manipulation levels 3.8 times higher than measured in the baseline SSAR laid out 15 years ago.

The dynamic testing showed an interesting trend: a slight reduction in both natural frequency and bandwidth, but maintenance of a high resonance peak as well as good frequency response. Figure 12 shows the dynamic response of the rotor system. The corner frequency of the unmodified SSAR blades and actuators was approximately 63 Hz, while the low-net passive stiffness PBP incarnation of the system achieved a corner frequency of 53 Hz.

5. Conclusions and Recommendations

It can be concluded that zero-net passive stiffness structural modification techniques can be successfully applied to torque-plate-driven rotors. Such successful application leads to dramatically higher deflections with no adverse effects on moment-generation capabilities, indicating higher total work levels available from such a Postbuckled Precompressed (PBP) Solid State Adaptive Rotor (SSAR) design. Pitch deflection levels were shown to be magnified by up to 3.8 times in static bench tests while thrust coefficient manipulation levels increased 2.8-fold during whirl-stand testing. Dynamic testing showed a reduction in corner frequency from 63 to 53 Hz by the use of PBP techniques, which represent 3.8 and 3.2/rev, respectively.

Given the continued success of the SSAR design, it is recommended that such techniques be implemented in larger scale rotors and flying UAVs. The tremendous promise of this technique has the ability to make feasible now what was deemed "infeasible" many years ago.

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