Manufacture and Properties of First Industrial APA’s Actuators Using Carbon Epoxy Shells

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Abstract:
Future aeronautics will more often use electrical actuators in order to replace hydraulic actuators. Existing Amplified Piezo Actuators APA® with steel shell, delivering among the highest mass energy densities, are good candidates. Lighter carbon shells are developed to further increase their efficiency. For helicopters rotor blade application this evolution is almost unavoidable but is also very interesting for other domains. High modulus and high tensile strength carbon fibres shells have been produced by conventional filament winding, tested and compared. The present final safe choice of a high strength carbon T300 epoxy frame allows obtaining significant gains. The prototype of composite shell APA shows similar electro mechanical performances as existing steel shell APA while being at final 35% lighter. Other first tests as life time and thermal behaviour carried on two composite-shell APAs are satisfactory: They present better thermal behaviour than steel-based APAs. In a nearer future noticeable energy gains of about 20% are still expected and manufacture repeatability is being improved.

Introduction
ONERA activity on Amplified Piezo Actuators APA® from CEDRAT Technologies already well known from other ([1], [2]), was initiated by the opportunity to apply them to the flap motion of active blades of helicopters. Their mode of action at 90° and their performance made them suitable for this application [3]. The main handicap was their weight and the idea of a composite shell was undoubtedly the way to explore. In a first step it had been made choice to fully copy the geometry of the existing steel shell, in order to better compare their efficiency (figures 1 and 2).

![Figure 1: APA500L with steel shell](image1)

The internal profile of the frame is the same for the two shells. Only the external profile of the carbon shell has been progressively increased to obtain the same steel shell stiffness. In further development, the geometry can be sensitively modified to better take into account the specificities of composite and also the problems of mechanical connection.

Since the beginning of works, the manufacturing technique has been improved to insure the repeatability and the reliability of the products.

Manufacture technique
The manufacture of the frame includes two operations: the making of the stacks supports and the filament winding of the frame profile. Filament winding and cure of the carbon composite shells have been realized by Artois Composite Company. Final solution selected for the support material used adequate ceramics machined by wire EDM cutting technique. The steel mandrel whose profile has been drawn to the true interior profile of the existing metallic actuator frame receives the two stacks supports (figure 3). This way allows obtaining as well a perfect parallelism of the two ends and as a direct adhesion of the ceramic to the composite part without any added bond layer. Two lateral caps delimitate the width of the winding. In the present case, the width corresponds to the width of one frame but it can be easily imagined to wind a greater width from which several frames can be cut by disc sawing. This can be interesting when winding angles are involved. The dry mesh of fibre is wet in situ by dipping in a resin bath and then spinning through a calibrated hole before be wound. This way allows using the same resin for several nuances of fibres and vice versa, which are often not easily available on the market. During the rotation of the mandrel, the wet mesh is tightened by a spring mass device which exerts a constant force on the mesh. First carbon shells for carbon fibre comparison used resin...
ACHTUATOR 2012, 13th International Conference on New Actuators, Bremen, Germany, 18–20 June 2012 475

1040 + 1042 hardener from Resoltech. Cure cycle consists in 8 hours at 60°C, followed by a post cure of 3 hours at 120°C. Last shells used resin 1080S with the 1081 hardener. This system can be also polymerized at this same temperature of 60°C. The glass transition temperature Tg can reach up to 110°C.

Figure 3: Filament winding and mandrel
The part is enveloped by absorbing clothes and the cure of the composite is made in a classic oven. For the first prototypes, the resin excess of the external side of the unmolded part is removed by a calibrated automatic slight pumicing. The diameter of the resin calibration hole has been diminished to reduce the resin quantity in order to obtain practically the final thickness and this from the application of the mesh. A higher fibre volume rate is obtained without ripple risk of the tow during the resin flow period and the final sanding operation is needed no longer.

Another quite recent and advanced technique consists in the robotized short mesh placement. This technique must allow achieve a frame profile having as well convex and concave curvatures with a variable thickness answering closely to computation optimization. The wet mesh can be much more pressed on the surface of the mandrel, avoiding the problem of large variation of the thickness encountered with the filament winding. This process allows producing thinner parts of good quality and seems also to be more appropriate for having less degradation of high modulus carbon fibre more brittle during laying.

This process is economic in term of material clippings and allows combining easily different types of materials in a same part.

Electro active stacks
Initially most actuators incorporate soft ceramics stacks to procure long strokes in quasi static conditions. But in principle they are not so adapted to dynamic runs because capacitance and loss factor are very high and current needs increase. Medium and hard nuances would suit better but are not currently available on the market and d33 coefficients are lower. Morgan Electro Ceramics and Noliac propose such materials for stacks (respectively PZT4S and Pz26, Pz27) but generally in smaller sections. Their production is more delicate, not easily found on the market and prices are higher. If for harder nuances d33 piezoelectric coefficient is lower, the total available stroke could be recovered by working on a larger range of electrical field got by an important negative voltage bias ([-150V; 400V], instead of [-20V;150V]). For these hard nuances, stress capacity being higher, the blocking force would be increased.

Several types of multilayer piezo components, such as N17 from Tokin and NCE51f from Noliac, have been tested but have to be better known with a specific device under high stress level, [5]. The best results are obtained with semi-soft type ceramic, which offers an appropriate compromise between a large strain and a high Curie temperature.

F.E calculations
As described in previous papers, first rough geometrical approach is done with a simple Excel analytical model which makes use of a succession of linear and arch curves, [4], [6], [7].

Fine calculations are after done with Nastran F.E Code and Patran pre-post processor Code. The mesh of the shell and of the sockets is built with linear 8 nodes hexahedric elements and linear 6 nodes tetrahedric elements for the connection of the two parts. Most finite element calculations were carried out in linear. Some non linear calculations give lower values than 8%, [8]. These calculations are intended to verify that stresses in the stress concentration areas are compatible with the yield strength for metals or a secured strength with respect to the ultimate strength of the composite. The setting up of stacks needs a greater level of compression deformation according to the short axis and so of stress of the frame.

These calculations also helped to see the influence of the type of material used for the sockets and the fillets zone and their geometries on the expansion of the great axis, the shrinkage of the short axis and the blocking force, (table 1).

### Table 1: Effect of arm carbon thickness, support and fillet materials on energy shell performances

<table>
<thead>
<tr>
<th>E shell (mm)</th>
<th>Material of support</th>
<th>Material of filament</th>
<th>E (GPa)</th>
<th>d33 (N/m)</th>
<th>Ks (N/m)</th>
<th>Ks Exp (N/m)</th>
<th>d33 Exp (N/m)</th>
<th>Fb (N)</th>
<th>Ky (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4</td>
<td>Steel</td>
<td>Steel</td>
<td>100</td>
<td>6.2</td>
<td>5.25</td>
<td>215</td>
<td>424</td>
<td>2.22</td>
<td></td>
</tr>
<tr>
<td>5.78</td>
<td>Loaded</td>
<td>Loaded</td>
<td>765</td>
<td>2.42</td>
<td>2.37</td>
<td>181</td>
<td>424</td>
<td>2.22</td>
<td></td>
</tr>
<tr>
<td>3.78</td>
<td>Ceramic</td>
<td>Ceramic</td>
<td>100</td>
<td>6.2</td>
<td>5.25</td>
<td>215</td>
<td>424</td>
<td>2.22</td>
<td></td>
</tr>
<tr>
<td>5.78</td>
<td>Cer, B4C</td>
<td>Loaded</td>
<td>681</td>
<td>2.94</td>
<td>2.77</td>
<td>281</td>
<td>576</td>
<td>2.77</td>
<td></td>
</tr>
<tr>
<td>4.56</td>
<td>Loaded</td>
<td>Loaded</td>
<td>765</td>
<td>2.42</td>
<td>2.37</td>
<td>181</td>
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These differences between computation and experience results are nevertheless very important because it takes into account the theoretical composite tensile modulus which is different from flexion modulus. This has itself to be corrected of the probable non homogeneous distribution of fibres across the section.
Static mechanical tests of the shells

First investigations have been made with the M40JB carbon but the latter proved to be particularly brittle to the setting up of the piezo stacks. So other fibres (T300, HTA5241 and IMS5131) have been considered. The numbers of winding turns and therefore the thicknesses are adapted to have identical \(<E,I>\) flexion rigidities with reference to M40JB material (table 2). For each material, two prototypes have been manufactured. Stiffness’s have been measured according the long axis and the short axis. For tension in the long axis, M40JB and T300 present same stiffness, but when acting on short axis in tension or compression T300 is stronger.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Size  (Type)</th>
<th>Fibres per strand</th>
<th>Density (g/cm³)</th>
<th>Modulus (GPa)</th>
<th>Strength (MPa)</th>
<th>Strand winding turns for (&lt;E,I&gt;) CS</th>
</tr>
</thead>
<tbody>
<tr>
<td>M40JB</td>
<td>400 12 k</td>
<td>1.77</td>
<td>317</td>
<td>4600</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>T300</td>
<td>195 10 k</td>
<td>1.76</td>
<td>230</td>
<td>3550</td>
<td>215</td>
<td></td>
</tr>
<tr>
<td>HTA 5241</td>
<td>47 1 k</td>
<td>1.77</td>
<td>230</td>
<td>626</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IMS 5131</td>
<td>410 12 k</td>
<td>1.80</td>
<td>230</td>
<td>97</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T300/11</td>
<td>223 6 k</td>
<td>1.81</td>
<td>284</td>
<td>5590</td>
<td>171</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2: Types of carbon fibres tested**

An important phase is the setting up of piezoelectric stacks. There also, T300 shows the higher ultimate strength and strain values with no degradation up to 1 000 N corresponding to a deflection of 9 mm, (figure 4).

**Figure 4: Compression to failure tests according to the short axis for various types of carbon fibres**

So Carbon T300 has been selected for next produced and tested parts. Number of winding turns has been increased from 213 to 290 to reach the same tensile stiffness as the steel shell according the long axis.

**Electro mechanical performances:**

Tests results show that identical energy performance (stroke and blocked force) have been finally obtained with a composite shell APA being 35% lighter than a steel shell APA. The free-free resonance frequency has been doubled and the blocked- free frequency has been increased by 9%, (table 3). The composite-shell APAs seem to have a stroke bit larger than the steel shell APAs but some dispersion attributed to the manual process does not allow concluding definitively on this point.

The resonance frequency is not affected by stack pre-stress for the two material shells but it is not the case for the stroke. It has been highlighted that for carbon shell an increase of the stack pre-stress is in favor of a stroke increase of about 0.8 % to 1 % by 1 Mpa step. This effect is about 0.5 % for steel shell. Limitation is due to the ceramics. Total stress exerted on soft ceramics including pre stress has to be limited to 50 MPa. For steel, this possibility is also limited by the possible local plastic deformation of the metal during the setting up of the stacks.

**Table 3: Comparison of main properties of the steel shell and carbon shell actuators**

**Life time and thermal tests**

A life time test is necessary to verify and validate the behavior of the composite over 10⁹ cycles as done for metallic shell actuators. A LA75C amplifier has been used at 70 Hz and performances have been monitored weekly. At this day a total of 567 hours at 70Hz, either 1.43 10⁹ cycles, has been totalized. A slight delamination has been initiated, but without loss of performance, (figure 5). It can be thought that it is due to the fillet sharpness of the ceramic that may damaged the connection area during the implementation of stacks and is also magnified by the high stress concentration factor in this area.

A first thermal test was performed on a free shell to check for the carbon thermal limits. A permanent deformation appears at 90°C and 110 N. Consequently other tests carried on the second shell have been limited to 70°C.

**Figure 5: slight delamination defect apparition after 1.43 10⁹ cycles**
A measurement of the coefficient of thermal expansion (CTE) has been done by two different methods: with a tridimensional displacement measuring system and a capacitive sensor placed inside a climatic chamber. A CTE of 0.7 μm/°C has been obtained for composite compared to a value of 7 μm/°C for a steel shell, leading to a gain of 10 for composite on the [-40°C;+70 °C] temperature range. Moreover, for carbon shell case, the stroke increases with increasing temperature. This effect is due to the fact that ceramics have itself a piezo coefficient which increases with temperature. This effect must also be correlated with the low CTE difference between piezo and composite materials. This effect is not met for steel APA where pre stress decreases with temperature because of a higher CTE of steel.

The modal behaviour of composite shell is a little different of steel shell. At ambient, the coupling coefficient, measured by a dynamic method, is a little lower, 40% instead of 47%, but this difference, which is not yet well explained because stiffness are identical, decreases at higher temperatures.

![Figure 6: Comparison of the modal behaviours](image)

The quality factor of 28 for carbon shell against 44 for steel shell at ambient and which is still better at 70°C (26 against 50) is very interesting, (figure 6). This lower Q factor procures a better damping capacity to composite actuator, attractive in terms of control for rapid positioning such as required for rotor active flaps, robotics, air jets generators,… The bandwidth is increased and work domain can be extended without danger very nearly of the resonance frequency.

Further improvements

Performance gains of at least about 20% are still expected by several ways:
- the choice of an intermediary modulus carbon fibre with a higher modulus and higher ultimate tensile strength,
- a lower resin volume rate, closer to the final rate and enabling to reduce fibres waviness during flow,
- a more efficient connection geometry of the supports bases of the stacks to the inner profile of the composite frame, allowing among other things to exert a higher pre-stress on the piezoelectric stacks.

Conclusions

First results obtained on new APAs actuators using carbon composite shell are very encouraging. Dynamic performances have been noticeably improved. Use of T300 carbon composite has already allowed multiplying the mass energy density by a 1.5 factor. Significant stroke and mass gains are still hoped. The increased resonance frequency, the much better thermal behavior and the lowest quality factor are very attractive for dynamic applications.

The industrial production has been investigated and the quality and repeatability of the parts have been significantly improved.

The recent development of piezo-dedicated high power switching amplifiers (SA75D) from Cedrat Technologies should be also mentioned: Its energy recovery capability will improve a lot the global efficiency of actuation, which is of great interest for blades flaps in helicopters as well as for many other applications. For this reason, the composite shell APAs driven by such switching amplifiers should be tested in the future.

References