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EXPERIMENTAL ASSESSMENT AND FURTHER DEVELOPMENT OF AMPLIFIED PIEZO ACTUATORS FOR ACTIVE FLAP DEVICES

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Abstract:

RPA (Rotor à Pales Actives) Franco-German project was launched three years ago to study the possible benefits of implementing active trailing edge flaps on a helicopter main rotor. The main expected effects concern the decrease of BVI noise in descent flight and the improvement of the dynamic behaviour of the rotor throughout the largest possible flight domain. The technological solution adopted to deflect the flap of an 1/3rd scale rotor demonstrator, uses an off-the-shelf elliptic amplified actuator, from Cedrat Recherche Company, driving an innovative patented mechanism. The device has been tested as well on the BRAVoS hover rig to assess the influence of centrifugal loads as in the S3 MA wind-tunnel to evaluate the maximum flap deflections with respect to actuation frequencies and Mach number. Extrapolation to scale 1, which must take into account distinct typical constraints, is not purely homothetic and requires further developments for the actuator which are under way, especially in order to respect the mass specifications.

Introduction

Electro active materials and hybrid components integrating them have been initially developed for the needs of the navy detection (sonars), the medical imaging and low speed sub-micro positioning. The idea to use them as actuators for the dynamic shape control of structures, with a notion of high mechanical power capability, compared to hydraulic devices, raised less than about a ten years ago. This activity, strongly encouraged from its start by the helicopter community, also begins to trigger some interest for the control of vortices moving on small lift surfaces of fixed wings in the airplanes, missiles and drones domains. The advanced concepts of self-adaptive control of helicopter rotor blades, taking benefit of the so-called smart materials, have been in fact strongly considered to solve the following problems of increasing difficulty: improvement of the aerodynamic efficiency by delaying the stall limits , reduction of vibrations to improve cabin comfort and gun shoot accuracy, and reduction of noises caused by particularly intense vortex-blades interactions during descent flight. These electrically driven actuators, requiring little space with a quite interesting volumic energy ratio and having a short response time, are attractive for the manufacture of reduced scale demonstrator. At full scale, these clean and compact devices, which can be largely distributed are considered to be also able to advantageously replace classical hydraulic or electromagnetic solutions thanks to clearly higher volumic and mass powers, admissible force densities and operating frequencies, but some technical limitations and onboard flight constraints nevertheless exist. In the two cases, but much more at full scale where the problem of mass limitation is severe, due to the actual principle and energy storage capability of these materials, energy recovery from working structural parts can and will have to be addressed. The technical specifications for reduced and full scale are not basically the same and the transposition of the devices from one scale to the other is not immediate as far as the corresponding technology doesn’t necessary exist yet on the market and as the development costs of such systems may drastically become prohibitive moreover without the guaranty of a satisfactory reliability.

The first results obtained in the second phase of the RPA project on a wind tunnel scale rotor blade section with an active flap, in order to validate the predictions of the numerical simulations made in the first phase, are already quite satisfactory even if some improvements still have to be done. An off-the-shelf elliptic amplified actuator, from Cedrat Recherche Company, was chosen for the active system which was separately tested under centrifugal and aerodynamic loads. A good behavior under centrifugal loads was noticed. Performance under aerodynamic loads, satisfactory at low Mach numbers, remains to be improved at higher speeds. If a weight excess is not too critical on a reduced scale model in order to demonstrate the merits of some advanced concept, even if it may influence the desired effect, it can’t be tolerated on a manned full scale prototype. These requirements explain the reasons of the studies which have been undertaken in order to decrease the weight and consequently to increase the mass energy efficiency of the existing elliptic actuator, in two ways: an optimization of the elliptic geometry which has allowed to obtain a noticeable gain and the use of composite material which undoubtedly allows to reach another gap order.

Actuators and electro active stacks

Solid state actuators have been first developed to produce precise and micro positioning without great energy and power requirements. Several American and European companies propose low (200V) or/and even high (1000V) voltages Direct Piezo Actuators (DPA). They consist in multi-layer piezo ceramics, pre-stressed by serial Belleville springs inside a stainless cylindrical housing. The deformation is typically about 0.1% and maximal displacement is limited to 120 µm. In counterpart, force capabilities are naturally high , generally over 1 kN. These direct linear actuators are adequate for quasi-static applications but not for dynamic ones. In fact the proposed driving electronics are current and power limited and not optimized to control high electrical capacitances. To overcome this limit, Cedrat has developed Parallel Pre-stressed Actuators (PPA) where the pre-stress is applied by an external parallel spring. These actuators, lighter and without moving part, can be more efficiently operated in dynamic conditions.

PROPERTIES	**Piezoelectric**		**Electrostrictive**
	Soft ceramics	**Hard ceramics**	
θ_{Curie}	140 à 200°C	320 à 360°C	N
$\theta_{service}$	70 à 100°C	160 à 180°C	5 à 45 °C
Polarisation voltage	+ 2 kV/mm	+3 à +4kV/mm	
Polarisation duration	**< 20 s**	**5 à 10 mn**	
Operating Voltage **- according to polarity**	200 V max	300 à 400 V max	150 V
- opposite to polarity	**- 20 V** (static)	**- 150 V** (static)	
Stroke (for ΔU= 100V)	**0.050 à 0.060%**	**0.033%**	**0.056%**
Stroke stability with frequency (Δl<10%)	0 - 1000 Hz		0 - 100 Hz
Stroke stability with temperature (Δl<25%)	0 – 100°C		5 – 45 °C
Hysteresis	> 15%		< 2%
Modulus	30 GPa	45 à 60 GPa	110 GPa
Blocked stress	50 à 75 MPa	100 à 150 MPa	
Operating stress (*)	25 à 50 MPa	75 à 100 MPa	
Capacitance (§)	6 à 10 µF	**2 à 3.5 µF**	**25 à 30 µF**
Merit Factor	70 à 100	500 à 1000	
Loss factor tg δ	1.5 à 3 %	**0.2 à 0.5 %**	**8 à 8.5 %**
Heating /20°C (+)	**+50 à + 60°C**	< +5°C	
Response time	< 5 µs		< 100 µs

(*) for the whole stroke - (§) stacks dimensions : 10x10 mm2 - h=25mm
(+) for a continuous running at 100 Hz and for ΔU= 200V

Table 1: *Comparative properties of stack materials*

Amplified Piezo Actuators (APAs), are long-stroke linear actuators. Stacks are pre-stressed inside a steel elliptic frame which produces a natural amplification ratio of the displacement (between 2 and 5 according to the two axes ratio). This principle procures higher deformation level (between 0.3 and 3 %) compare to first types of actuators with only a slight decrease of the force capability.

All these actuators, which have to be much more considered as low speed micro positionners, make use of soft ceramics stacks because of their higher deformation,[1]. For dynamic purposes, hard or half-hard ceramics would have to be preferred because of their low capacitance favourable to low current demands, lower loss factors limiting heat dissipation and higher blocked stresses allowing to support higher external efforts,[2]. Their lack of deformation can be fulfilled by a higher voltage range supply and a possible operation in opposite polarity (Table 1).

The RPA Project

The RPA project aims to evaluate the benefits of active trailing edge flaps mounted on the blades of the main rotor of a helicopter. Two concepts referred to as direct-lift flap and servo-flap were at first considered. The second using a small chord flap and relying of aerodynamic pitching moment to induce blade torsion is finally preferred.

Fig.1: *RPA blade dimensions and flaps localisation*

The overall diameter of the Mach-scaled rotor is 4.2 m. The maximum blade chord is 140 mm. The flap dimensions are 210 mm in span and 21 mm in chord. Significant vibration and noise reductions have been calculated with ONERA numerical simulation codes and expected for three spanwise locations of the flap (figure 1) .

Flap actuation solutions

A large array of solutions was considered during the design phase: hydraulics, electric motors and various smart materials systems such those used or developed by different Universities in U.S (L-L amplification or double X frame),[3]. It appears that APA’s manufactured by Cedrat gives the best results in terms of specific energy. Moreover, the long axis of the elliptic frame can be easily centred along the 25 % pitching axis and the naturally amplified and linear trajectory of the short axis extremity at 90° is favourable to drive the flap.

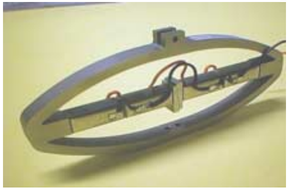

Fig.2 : APA 230

Fig.3 : APA500L

In a first step, APA230 type was selected and was used for centrifugal tests. With the APA500L, recently proposed, the efficiency is nearly doubled. This new actuator, smaller and lighter was used for aerodynamic wind tunnel tests.

Centrifugal tests

A specific model was designed and built to evaluate the capability of the APA230 to sustain the centrifugal loads which it would have to cope with on the future rotor model, [4]. The actuator is clamped on a surrounding rectangular frame on one side and is supported by a centrifugal blade on the other side to withstand the torque generated by the overhang under centrifugal field (figure 4).

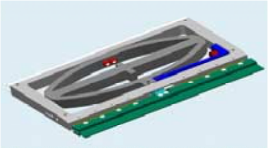

Fig.4: *active flap system*

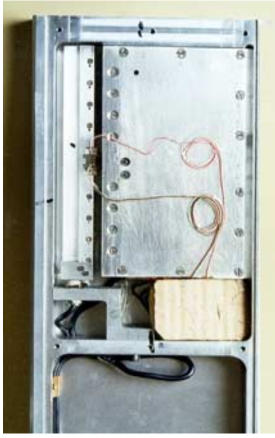

Fig.5: *centrifugal model*

Fig.6: *BRAVoS test rig*

The flap is deflected by means of a lever blade. In fact the flap rotates around a pseudo axis given by the flexion deformation of two composite hinge blades. At rest, i.e without power supplied, the flap lies in the maximum downward deflection. The whole mechanism equipped with a dummy flap, mocking realistic mass and inertia, was installed inside an aluminium frame, closed by trap doors in order to avoid any aerodynamic influence (figure 5). Several sensors recorded various parameters such the flap rotation by two small Hall effect sensors, the effort on the lever blade by a strain gauges bridge and the internal temperature of the closed blade box. The whole model was mounted for the rotary tests atop the BRAVoS rig (figure 6).

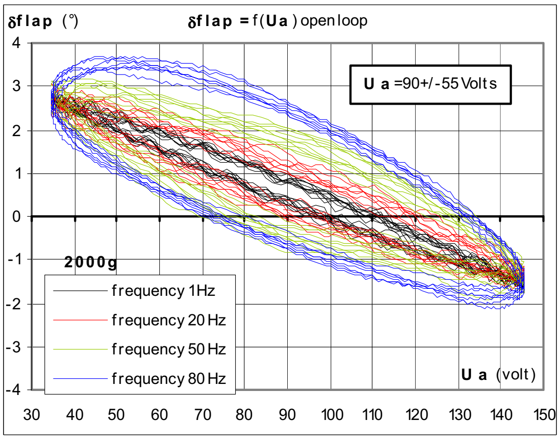

Fig. 7: Flap deflection versus voltage under 2000g

The flap deflection was recorded versus the amplifier voltages at different actuation frequencies, respectively at 0 g and 2000g. The dynamic component was limited to ± 55 V because of the amplifier current limitation. The stroke loss between the two acceleration levels was less than 10% and a good repeatability of measurements without too much noise was observed (figure 7).

Aerodynamic qualification

A 2D-blade section aluminium model incorporating the whole active system and equipped with the previous similar instrumentation has been manufactured (figure 8), [4]. The selected OA312 airfoil with a 140 mm chord exactly matches the future rotor blade model.

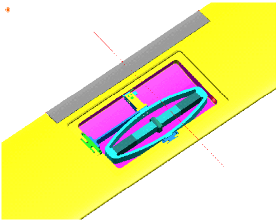

Fig.8: *Flap active system*

Fig. 9: *Model in S3MA*

The tests were carried out in the S3MA blow-down ONERA wind-tunnel located at Modane. A rotating hydraulic jack connected to the left-hand side of the model allows to perform steady and unsteady pitching movements (figure 9).

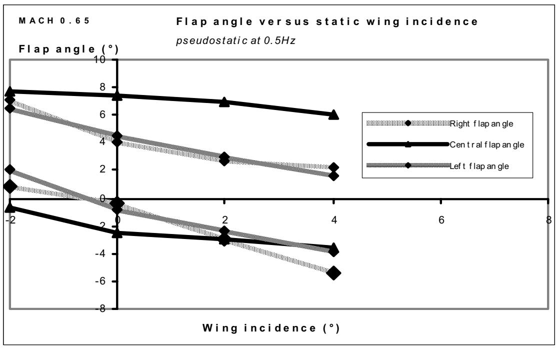

Fig.10: *Flap deflections at Mach = 0.6*

Tests were made at several Mach numbers (0.3, 0.45, 0.65 and 0.80) and several angles of attack. At low Mach numbers, a fairly good agreement can be seen between the three locations of flap deflections measurements. At M = 0.6, (figure 10) the discrepancies between lever blade and flap ends measurements begin to increase and become significant at M = 0.8 .

A comparison of the capabilities of the devices studied at the University of Maryland and at ONERA is given table 2. The use of composite material for the actuator frame is going to allow to multiply by about 2.5 the energy to weight ratio.

	Maryland 1/7th scale blade model ***fabricated in-house***	**Maryland full scale blade** ***prototype***	**CEDRAT APA230 For 1/ 2.62th model** *mass production*	**CEDRAT APA500L** mass production	**CEDRAT APA500L x 1.5 Theorical Full scale**	**CEDRAT APA750** **Delivered Full scale**
Actuator technology	Multi-layer actuator configuration (8 layers)	Piezostacks With L-L double Lever amplification	Piezostacks on elliptic housing	Piezostacks in elliptic housing mass production	Piezostacks in elliptic housing	Piezostacks in elliptic housing new model
Voltage (V)	± 134 → ± 400	0 -120	0 - 200	0 - 200	0 - 150	0 - 170
Mass of actuator (grams)	14	634	250	208	700	600
Blocked force (N)	8	53 (*20)	800	570	1250	920
Total stroke (µ)	165	2540 (*889)	230	500	750	1150
Stiffness (10^{-6} N/m)	0.048	0.021	3.48	1.140	1.67	0.80
Resonance frequency (Hz)	beyond 150	beyond 150	800	450	300	218
Energy to weight ratio of Actuator (x10^3 mN/kg)	23.6	53.1 (*28)	184.0	342.5	334.8	440.8
Ratio of Energy.. /L-L Energy..	**0.44**	**1**	**3.47**	**6.45**	**6.31**	**8.30**
Width (mm) (chord axis)	33	71	69	55	82.5	60.5
Length (mm) (span axis)	60	183	140	145	217.5	213.7
Thickness (mm)	2 to 5	19	10	10	15	15
Peak-to-peak flap deflexion	± 11.5°	± 11.5°	± 4.5°	± 6.7° (measured)	±9.5° (extrapolated)	±10.3° (hoped)

* test with spring applied on actuator

Tableau 2: *Capabilities of smart actuators*

Full scale prototype

The transposition of the technical solution to full scale has to take into account various aspects such as the technological and onboard constraints. For weight, technical and cost reasons, five APA750 (APA500 x scale 1.5) and not two actuators will have to be used and a composite frame can't be avoided (table 3), [5].

Specifications	**Model (1 / 2.619)**		**Prototype Scale 1**	
	APA 230	APA500	APA750	APA500 x 2.619
Mass of one actuator (g)	250	208	600	3640
Specific Energy (J/g) **- actuator** **- whole system**	0.184 0.070	0.342 0.116	+ Direct not viable 0.15 à 0.30 J/kg	
Volumic Energy (J/dm3)	0.476	0.894	++	
Centrifugal acceleration	2 300 g		800 +/-30 g ++	
Admissible mass increase	10 à 15 % (350 à 550 grams)		5 à 10 % (2.5 à 5 kg)	
Actuator Mass (g) **Total Mass (g)**	- 500 416 654	500 570	3000 (1960) 5765 (4725)	7280 (4880) 10045 (7645)
Torsion inertia axis	Located at 25% of the pitch axis		Located at 25% of the pitch axis	
Maximal Voltage	unlimited ++		270 V DC	
Power	unlimited		200 à 2000 W by blade total limit : 10 kW max	
Cost of an actuator (x N)	+ 20 kF (X 2)		65 kF (x 5)	Prohibitive (x 2)
Running clearance	-		++	
Max Flap turning (in unloading condition)	+8°/-5° à +10°/-5°		± 5 à ± 15 °	
Hinge moment (blocked moment)	± 0.2 à ± 1.6 m.N realized: 0.50 with 2 actuators		± 15 à ± 80 m.N	
Bandwith	80 Hz (5Ω)		30 Hz ++	
Life Duration	++ 5 h (3. 10^5 cycles) à 115 rd/s		Infinite ('fail safe')	
Environment	Wind tunnel Conditions		-50 à 80°C – 85%RH – saline corrosion	

\- unfavourable , + favourable , ++ very

Table 3: *Reduced scale and full scale specifications*

The effectively delivered APA750 is in fact not homothetic with the APA500 one (figure 11). A thinner frame section along with a smaller short axis have allowed to increase the efficiency.

Fig. 11: *APA750X*

Fig.12: *Composite frame*

First tests of filamentary wounding have been done to manufacture the composite frame. A carbon fiber with an intermediate Young modulus has been chosen (figure 12). A fiber volume of 55% has been obtained. The high specific rigidity is favourable to an increase of the resonance frequency. The higher strength of the carbon epoxy allows to increase the pre-stress of the stacks and to reduce the thickness of the frame. The high conductibility of carbon and the low dilatation in the fiber direction are interesting to improve the positionning accuracy. Efforts still have to be borne on the stacks stand zones.

Conclusion

First results obtained in the RPA project with the combination of the existing Cedrat actuators and the specific transmission mechanism are rather encouraging and are very competitive compared to other solutions studied elsewhere. Even if minor modifications are still required on the system, the centrifugal aspects were rather easily mastered. The behavior under aerodynamic loads has still to be better assessed, especially at high speeds. The geometry and the manufacture of the carbon epoxy composite frame has to be industrially validated. Short term modifications which can allow to hope substantial energy savings concern the nature and the disposal of piezoelectric ceramics of the stacks and a deep modification of the actuator frame profile. Other further improvements will concern the driving electronics and energy recovery as well from the active systems as from the surrounding working elastic structures featuring active components.

References

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