PIEZO MECHATRONIC BASED SYSTEMS IN AIRCRAFT, SPACE AND DEFENSE APPLICATIONS

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ABSTRACT

In Space & Defense fields, there is a trend for miniaturisation in active optics, fine instruments, robotic missions, micro-satellites, UAVs, MAVs which directly impact on the design of actuators. A new generation of small and smart actuators such like piezoelectric (piezo) actuators, are responding to this trend, thanks to their capacity to offer high energy density and to support both extreme and various requirements. In Space vehicles, UAVs, missiles, military vehicles, etc., onboard place and available electric power can be very limited. For instance, a micro satellite often must operate all its instruments with less than 100W of power. As a result, allocated electric power per actuator is typically between 0.1 to 10W. This is also the case in small UAVs and in MAVs. Because of the high cost of embedded mass, space & military actuators need also to offer high output energy to mass ratio. One of the main difficulties is often the ability to withstand launching vibrations and shocks. Space environments add other constrains. A clear example is the vacuum conditions, which can induce difficulties to release the heat out off the actuator or for out gassing near optics. Other critical space-related environmental conditions include the thermal operation range required as well as the radiation-resistant requirements. In other situations, actuator strength to humidity is often an issue, especially for piezoelectric ceramics. Thus, the success of the application relies not only on design issues but also on material reliability. Specific actions at this level are needed to be undertaken to secure space projects. To cope with these issues and to illustrate the trend, the piezo actuators and mechanisms from Cedrat are presented. They have been initially developed and qualified to meet space requirements but logically found also applications in defense and micro aerial vehicle fields, for various micro-mechatronic functions. The paper presents typical applications and piezo mechatronic based system such like, piezo micro-scanning stage for IR camera resolution enhancement, piezo active flap on helicopter blade for noise reduction, micro amplified piezo actuator for tilting MAV rotor, hollow piezo actuator for external laser cavity tuning of a space LIDAR, in order to discuss the state-of-the-art performance and deduce further needs.

Keywords: actuation, smart materials, piezoelectric, space qualification, UAV, MAV, mechatronic

1. INTRODUCTION

In Space vehicles, UAVs, missiles, military vehicles, etc onboard place and available electric power can be very limited. Thus, in a micro satellite there is often less than 100W in total for all the instruments. So generally, allocated electric power per actuator is typically between 0.1 to 10W. This is also the case in small UAVs and in MAVs.

Because of the high cost of embedded mass, space & military actuators need also to offer high output energy to mass ratio. One of the main difficulties is often the ability to withstand launching vibrations and shocks. Typical level of vibration is often larger than 20g rms in space. It can be worst (as in missiles) or easier (military vehicles), but the main difference is that the vibrations are combined with the actuator operation, which is not the case in space as the actuator operation is after the launching. Space environments add other constrains. One difficulty is the vacuum conditions, which can induce difficulties for getting the heating out off the actuator or for out gassing near optics. A large variety of situations is met for the thermal range as well as for radiations. At last but not least resistance to humidity is often an issue, especially for piezo ceramics. Success of application relies not only on design issues but also on material reliability. Specific actions at this level may be undertaken to secure space projects.

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2. SPACE QUALIFIED PIEZO ACTUATORS

2.1. Space qualification of the multilayer piezo ceramic

A few years ago, a source of multilayer piezo ceramics for actuators (MLA) was space qualified by French Space Agency CNES and Cedrat [1] but the manufacturer leaves the space market. Instead of qualifying a new manufacturer, a recent solution [2] was to establish a Lot Acceptance Test (LAT) plan. Two sources were selected on the basis of the known reliability of their actuator and the available sizes. The LAT plan covers several tests (electric, mechanical, thermal, life time, humidity, etc.) as well as a Destructive Part Analysis (DPA). A DPA is useful to support failure analysis (for exemple, sources of electric breakdown). Example below (Fig.1) shows porosity which could cause different types of failures.

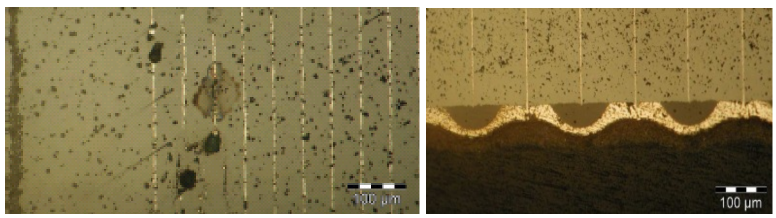

Fig. 1. Examples of DPA for 2 different MLA

Among all tests, the 2000hr humidity tests under DC voltage (150V) revealed the most various failure situations encountered in a MLA. In this humidity test, the actuator is driven under DC voltage while the leakage current is monitored. Typically, the current starts under 0.1mA for all the piezoelectric actuators of the 2 sources, but after some tens of hours, it increases progressively, but with a wide dispersion. The insulation resistance deterioration is permanent after the test. The on/off cycle is the most critical driving mode regarding to humidity resistance. This sensitivity to humidity is still a limitation, which has to be carefully accounted in the lifetime of the applications. Although performed in a space program, these LATs are of interest for other fields.

For applications in devices, there are also mechanical issues to solve: The MLA can bear high compression forces but it is a fragile component while submitted to tensile stress. That is why it is important to pre-stress (to preload) the MLA in order to protect it against the tensile stresses generated by dynamic load from vibrations and shocks. The preload mechanism helps to increase the life time of the MLA and Cedrat Technologies offers 2 different technologies of preloaded piezo actuators, the parallel pre-stressed actuator (PPA) and the amplified piezo actuators (APA).

2.2. Parallel Pre-stressed Actuators & Amplified Piezoelectric Actuators

The piezo actuators should avoid weakness such as pivots [3] to offer long life time in harsh environment. It is the case of Cedrat PPA and APA. The PPA is a preloaded piezo actuator made with a MLA encasing inside a frame of 2 external and parallel springs (see Figure 2).The APAs are Amplified Piezoelectric Actuators offering a large deformation and designed for space applications. The structures and working principle are described in Figures 3 & 4. An elliptical shell pre-stresses (preloads) a MLA along its main axis and amplifies its deformation along its short axis. The shell does not include flexure hinges or hertzian pivots. The ratio of amplification can be from 2 to 10 while keeping an optimum preload level on the MLA and insuring as a consequence a strong capability to withstand and to generate dynamic forces. This piezo technology benefits of a space qualification [1] and a large space heritage, and may apply LATs for MLAs in space or military projects. PPAs & APAs are used in several optics instruments for positioning or scanning applications where compactness and reliability to external vibrations are required.

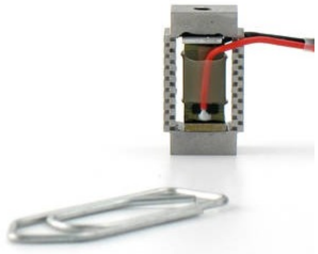

Fig.2. View of a parallel pre-stressed actuator PPA10M

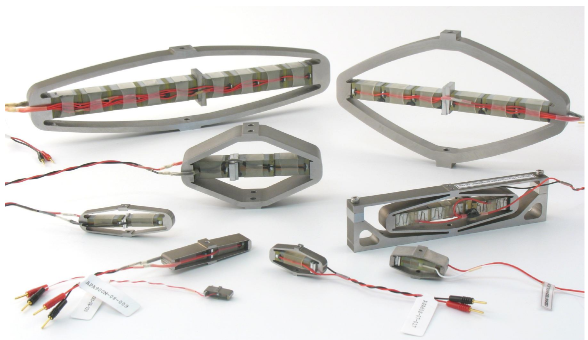

Fig.3. View of different series of standard APAs (XS, S, M, ML, L)

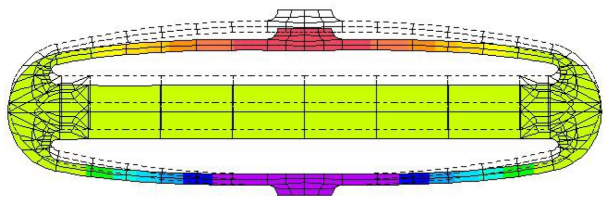

Fig.4. ATILA FEM result on an APA ; Dotted lines = structure at rest; Full lines = structure deformed by the piezoelectric effect

3. SPACE QUALIFIED PIEZO MECHANISMS

A typical mechanism based APAs is the XY stages. The first APA based XY stages have been developed for the European Space Agency for the ROSETTA MIDAS AFM instrument [4,5]. It uses eight APAs and one Parallel Prestress Actuator, PPA. It has successfully passed the launching on Ariane 5 in 2004 and is flying. Using this space heritage, several piezo mechanisms (flight models) have been developed for Eads, Galileo, Nasa, Redshift [6,7,8,9].

3.1. Tip-tilt mechanisms

Fine tilting movements are also required for several tasks, such as fine pointing [10-11]. A first space flight application is the management of the optical insertion power in the optical fiber. For instance, the PHARAO laser bench is using 10 tip-tilt mechanisms [12]. A double tilt tip piezo micro mechanism has been developed to solve this function. A push pull driving and two independent tilt movement are the key characteristics (Figs 5 and 6). Its first application is on the laser bench of PHARAO by EADS-SODERN [12].

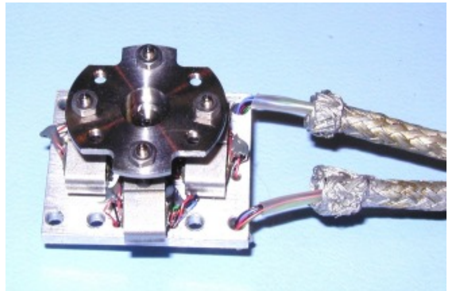

Fig. 5. View of a 3 degrees of freedom double tilt translator mechanism

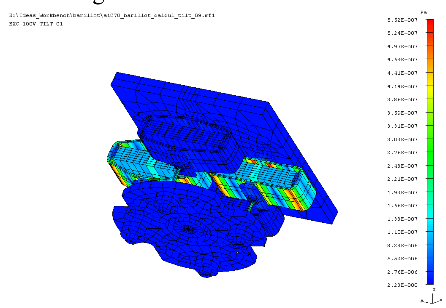

Fig. 6. Finite Element model of the tip-tilt mechanism

When decreasing the size of the mechanism, the shock requirements become more severe. The piezo solution is typically 3 to 5 times lighter than a voice coil solution. The performances are a stroke of +/- 2 mrad, a bandwidth of 1 kHz and stability better than 1 µrad, which is the range of the requirements for laser inter-satellite link. The tip – tilt mechanism DTT35XS is a typical example of a normally centred mechanism, fully qualified (Table 1). Their lightweight characteristic is particularly outstanding.

Table 1. Performances of a tip tilt mechanism DTT35XS and its drive and control electronics

Item	**Units**	**Measured**
Functional performances		
Stroke	mrad	+/- 2
Stability over 1 kHz of bandwidth with Strain Gauges	µrad	1
Accuracy in closed loop	%	+/-1
Bandwidth	Hz	1000
Operational performances		
Lifetime		10^8 full strokes
Environmental performances		
Storage temperatures	°C	-50 / 75
Random vibrations	Grms	41
Shock		200 g @ 500 µs half sine
Interfaces		
Mass	g	15
Dimensions	mm	26 * 23 * 16
Driving electronic		
Primary bus connexion	V	18 - 38
Secondary outputs	V	160, -30, 20, -20
Linear amplifier output current	mA	+/- 30
Linear amplifier phase margin	°	45 mini
Capacitive load	µF	0.2 to 40
Radiations	kRad	10

3.2. Refocusing mechanisms

Future LIDAR instruments [13], typically for meteosat and earth observation use an accurate, single frequency laser source. To overcome a possible deviation of the laser source, a piezoelectric refocusing mechanism is a solution which offers a large bandwidth. Consequently, Parallel Prestressed Actuators, PPA, are well suited to these applications. The pre-stress is essential for a dynamic operation and is realized with an external monolithic spring. It should also be noticed that piezo active tuning filters is also a possibility in the receiving chain: piezoelectric actuators can be used to adjust the length of a Fabry – Perot cavity. A first application is an External Cavity Laser developed by EADS SODERN for the PHARAO Laser source (Fig 7) [12].

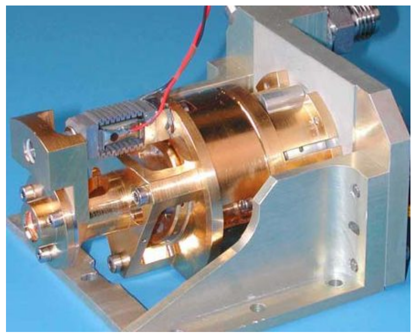

Fig. 7. View of the External Cavity Laser tuned by a piezo actuator (courtesy of EADS SODERN)

A second application is the refocusing mechanism of the laser source for the first European LIDAR ALADIN [14] on board on the AEOLUS spacecraft. The purpose of this LIDAR is to measure the speed of the wind. This application requires a space compatible laser with a very accurate frequency.

In order to overcome several sources of drift, the laser oscillator (Fig.8) is dynamically refocused with a piezo actuator. This application is demanding for the piezo actuator: it requires a bandwidth of 10 kHz and a lifetime of 10^{11} cycles. A dedicated hollow parallel pre-stressed actuator HPPA has therefore been designed (Fig.9).

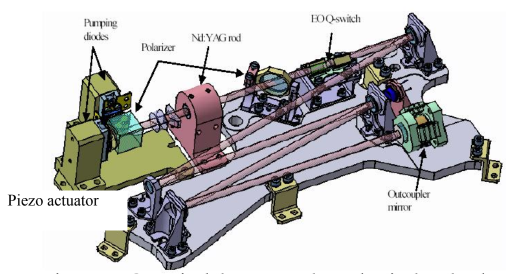

Fig. 8. Dynamic refocusing of the laser master oscillator (courtesy of Galileo Avionica)

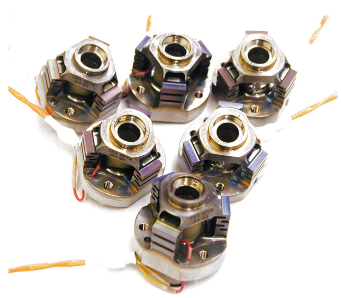

Fig. 9. Set of Hollow Parallel Pre-stressed Actuators (HPPA) for ALADIN

3.3. Optical Path Difference Actuator

The Optical Path Difference Actuator (OPDA) used in the Laser Modulation Unit (LMU) of the Lisa-Pathfinder interferometer has been developed by Cedrat [15] for Oerlikon Space AG who designed the optical configuration. This mechanism is a typical recent application of piezo actuators exploiting several advantages of the Cedrat APA technology. The OPDA is a high-resolution linear stage where the APA and the guiding is monolithically integrated (Fig.10). The OPDA has a stroke of 60 µm and a bandwidth of 10 Hz, in order to moves a triple prism. Most severe issue during the qualification campaign was to guarantee the metrology of the OPDA: the absolute position of the prism along the motion axis max should change less than 10 µm for its complete life (FM acceptance tests, launching and flight life time).

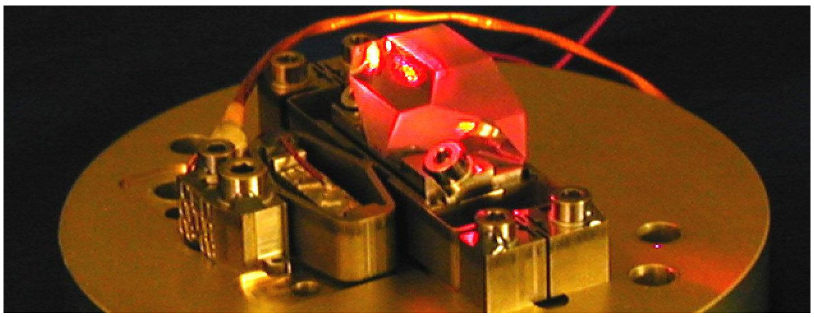

Fig. 10. OPDA with its triple prism

3.4. Linear piezo motors for air, space & military applications

New stepping piezo actuators based on APAs called SPA, are developed with some support from French Space Agency CNES. These miniature piezo motors offer a long stroke (>10 mm), a high miniaturisation (see fig 2.3), a low required current, a nano resolution and space compatibility [16]. These novel SPAs take advantage of Cedrat previous experiences in piezo motors for space environment [17, 18, 19] to comply with worst requirements and to avoid known difficulties meet with standard piezo motors: Generation of dust [20], loss of forces or torque when in vacuum, needing retrofit [21].

Linear stepping Piezoelectric Actuators (SPA) are made up of only four parts (Fig 11): the well-established Amplified Piezoelectric Actuator (APA), a front mass, a clamp and a rod. SPA operates by accumulation of small steps, using inertial mode, impact forces and stick-slip effects as introduced in [22,23]. Typically, a slow APA actuation generates a slow motion of the mass while the rod sits in the clamp. A fast APA actuation induces a fast motion of the rod slipping in the clamp. This way, steps that offer a long stroke are obtained (Fig.12). This is called the stepping mode (M1). Between each step the actuator is locked in position.

There are two different positions to fix the load, which offer two different running modes. In a first configuration offering nano positioning, the load can replace the mass or be fixed to the mass. Thus when the long stroke (M1) is performed, the motor can also be operated in a deformation mode (M2) for a fine adjustment. In this case, the stroke is proportional to the applied voltage, which leads to a nanometre resolution and a high bandwidth (limited by motor blocked force). In a second configuration, the load is fixed to the moving rod. In this case, one benefits from a high stiffness whereas fine mode is no longer available.

The long stroke stepping mode (M1) is produced by step accumulation with an appropriate 0-150V voltage pattern. The short stroke deformation mode (M2) is produced by deformation of the APA, which is simply proportional to the excitation voltage between –20 to +150V (Fig.12). Only one channel amplifier per SPA is required.

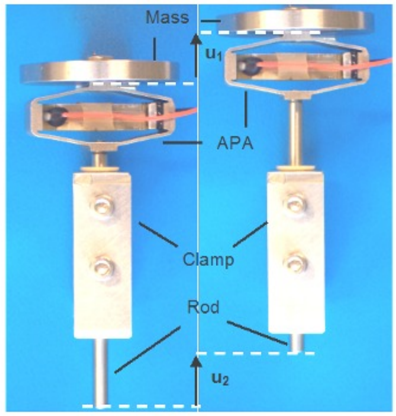

Fig. 11. SPA linear piezo motor components

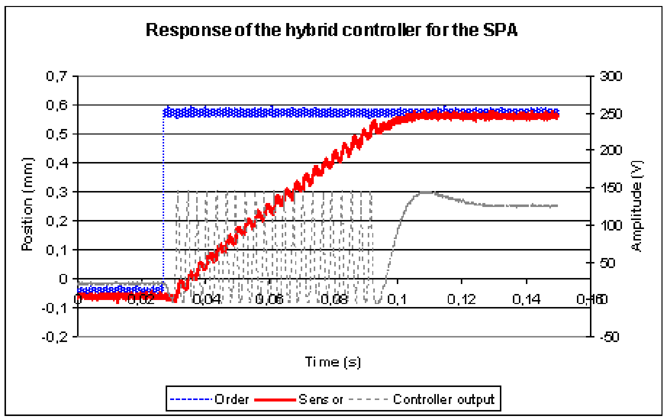

Fig. 12. SPA stroke vs voltage

The newest SPA, the SPA30uXS (Fig.13), demonstrates the possibility to miniaturise the technology (its mass is <1gr), keeping useful actuation properties: An actuation force > 0,1N; A clamping force at rest > 0,5N; A speed > 30mm/s. Several environment test campaigns have been undertaken on different SPA motors, giving promising results. The motor can operate is vacuum condition with no outgassing. Cryogenic tests at -100°C showed the motor speed and force performance are reduced by less than 10% [24]. A test of non-magnetism level has recently been performed for a medical application [25] by placing the motor in a MRI 4.7T magnet from BRUCKER. Conditions for full compatibility with the MRI have been found, showing the motor non-magnetic feature. Several applications have been identified in air, space and military sectors: optic positioning on telescopes, Infra Red camera or laser cavity, actuation of parts in antennas, MAVs, etc. All of these applications require high miniaturisation, low electric power and high precision.

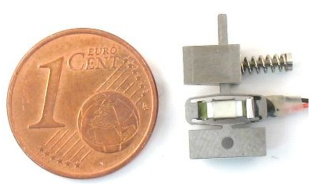

Fig.13. New SPA30uXS linear piezo motor, compared to a one eurocent coin

4. DEFENSE & AERONAUTIC APPLICATIONS

Other defense and aeronautic applications in helicopters, missiles, UAVs, MAVs, re-entry vehicles testing are listed in [26] and some are presented in this section.

4.1. Micro-scanning stage for IR camera resolution enhancement

A recently new military application is a XY piezo micro-scanning stage (Fig.14) used in THALES Infra Red CATHERINE MP and XP cameras (Fig.15) [27]. The micro-scanner includes 4 micro actuators APA25XS acting in a push-pull configuration. APA25XSs are about 6mm in height and 2gr in mass. The central frame which supports the lens can move in X and Y directions with a displacement amplitude of +/– 10 µm, which corresponds to ½ the sensor pixel size.

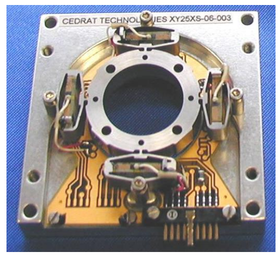

Fig.14. XY micro-scanning stage for IR cameras

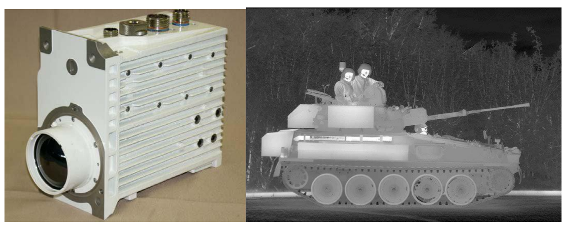

Fig 15. Thales Catherine XP IR Camera & IR Image from the camera

Such micro-scanner improves by 4 the resolution of the camera sensor by over sampling technique: Shifting the image in XY on the sensor, 4 images are taken and combined. Because of the stiffness of the actuator, the unloaded resonant frequency is 2.2kHz. The frequency loaded with a lens is above 1kHz. As the actuators are pre-stressed, the micro scanning can be performed at high frequency, above 100Hz. The pre-stress also allows the XY stages to pass the qualification vibration tests, as requested in the military environment.

4.2. Tiny piezo actuators for MAV

An example of MAV is given by Mufly project lead by ETZH [28,29] which consists in the development of a fully autonomous helicopter (Fig.16) comparable in size and weight to a small bird (<30gr). In this MAV, 2 small (5gr) rotary Brushless DC motors (BLDC) are used to drive the rotor are being optimized in term of power to mass ratios [30]. The rotor is tilted by a set of micro Amplified Piezo Actuators APA – MuXS (0.25gr) combined with a lever arm mechanism (Fig.17). The electronic including micro-controllers is less than 1gr. The Mufly carries a camera and shows enough agility to fly in-door (see video [31]).

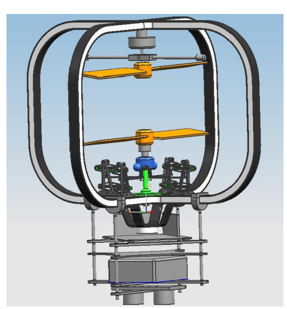

Fig.16. CAD view of Mufly micro-helicopter

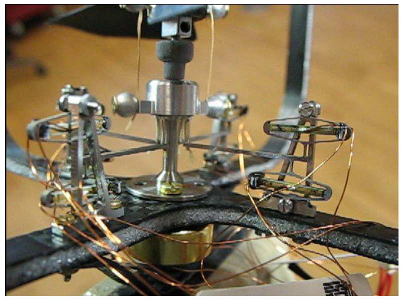

Fig.17. Zoom on actuators of Mufly micro-helicopter

4.3. Piezo actuator based active flap for helicopter

RPA (Rotor à Pales Actives) Franco-German project was launched in 1999 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 uses an off-the-shelf elliptic amplified actuator, from Cedrat Technologies Company, driving an innovative patented mechanism. During centrifugal & wind tunnel testing the APA based active flap worked successfully under 2000g of acceleration [32]. At the present time, a scale one active flap is currently in integration and in test on an helicopter blade (Fig. 18).

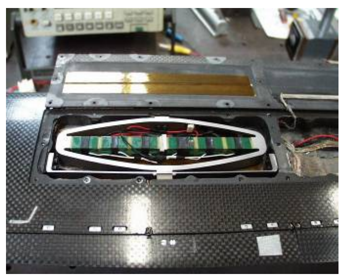

Fig.18. Scale-one APA1000XL-based active flap on Helicopter blade

5. CONCLUSION

Actuation technology is one of the critical fields aerospace and defense applications. During the last years the concept of the more electric aircraft was pushed ahead by industry and scientific community. The adaptation of electric drive train technology to meet with the demanding requirement of aerospace is in the focus of the activities. Besides electro motors, a broad variety of applications have been developed based on piezo actuation. The paper revealed promising application of piezo actuators especially for positioning, micro-scanning, reduction of noise and vibrations. Space field is motivating the emergence of various small & smart actuators. Among these, piezo actuators (APA, PPA & SPA) are expanding in other fields as military benefiting of space heritages and qualifications. The short review, this paper provides, reveals some first success stories from the piezo actuators developed by Cedrat Technologies.

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