ACTIONNEURS PIEZOELECTRIQUES POUR DU POSITIONNEMENT PRECIS ET RAPIDE

Piezoelectric Actuators for Precise and Fast Positioning

F. CLAEYSSEN, R. LE LETTY, N. LHERMET, F.BARILLOT, H.FABBRO, T. MAILLARD

Cedrat Technologies S.A., 10 chemin de Pré Carré, ZIRST, 38246 MEYLAN Cedex, France
Tel. 33 (0) 476905045 - Fax. 33 (0) 476901609
URL http://www.cedrat.com - Email actuator@cedrat.com

1. Résumé / Abstract

Plusieurs classes d'actionneurs piézo basse tension ont été développées par CEDRAT TECHNOLOGIES pour couvrir des besoins de positionnement précis et/ou rapide. Ce papier discute la capacité de ces actionneurs à couvrir ces besoins et l'illustre à travers des applications diverses (mécanismes, amortisseurs, vannes) dans les domaines de l'instrumentation, de l'espace, de l'aéronautique et de l'automobile.

Several classes of low-voltage Piezo Actuators have been developed by CEDRAT TECHNOLOGIES in order to cover needs for Precise and/or Fast Positioning. This paper discusses of the ability for these Actuators to meet these needs and illustrates it with various applications (mechanisms, dampers, valves) in instrumentation, space, aircraft and automotive industries.

2. Introduction

Multilayer Piezo Ceramics for Actuators (MLAs or CMAs), derived from technology of the high capacitors have been on the market since 1988 [1]. Because MLAs are easy to use and offers many advantages compared to other electroactive materials [2], they have been increasingly used in various actuator applications and contribute to the development of the new field of “smart” or ”intelligent” structures [3, 4].
Using these new piezo materials, several classes of innovative low-voltage Piezo Actuators have been developed by CEDRAT TECHNOLOGIES [5] in order to cover a wide range of needs and applications. Needs can be generally classified either in quasi-static applications where high resolution, precision and stability are looked for, or in dynamic applications where high bandwidth, high frequency, stiffness, resonance operation, ultrasonic operation or short response time in transient operation are desired. CEDRAT TECHNOLOGIES Actuators have been initially developed to meet the most severe requirements of the French and European space agencies (CNES, ESA), for static and dynamic applications. As shown in this paper, these actuators, especially APAs, also meet many requirements in optic, scientific or medical instrumentation, as well as aircraft and automotive industries.

3. Overview of CEDRAT piezo actuators & motors

Direct Piezo Actuators (DPAs) are solid-state linear Actuators. They use only the expansion of the active material, in 33-mode, for producing a useful displacement. This displacement is proportional to the voltage on a 200V range. Typically, the Actuator deformation is about 0.1% (10µm/cm), so DPA displacement are limited to about 100µm. In counterpart, the forces are naturally large, easily higher than 1kN. A first type of conventional Direct Piezo Actuators uses a serial pre stressing (Figure 1) applied with Belleville springs. These Actuators are adequate for quasi-static applications such as micro positioning but not for dynamic applications.

Figure 1. View of a DPA

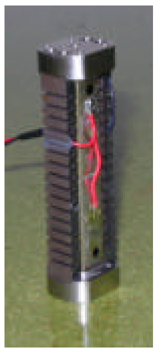


Figure 2. View of a PPA

To overcome this limit, new types of Direct Piezo Actuators called Parallel Pre-stressed Actuators (PPA) [5] have been developed (Figure 2). The pre stress is applied by an external parallel spring. As they are lighter and there is no moving part, PPAs can be efficiently operated in dynamic conditions.

Amplified Piezo Actuators (APAs) are solid-state long-stroke linear Actuators (Figure 3). They are based on the expansion of the active material and on a mechanism for amplifying the displacement. This amplified displacement is also proportional to the voltage on a 200V range. The advantages of APAs are their relatively high displacements combined with its large forces and compact size along the active axis. It leads to Actuators deformation comprised between 0,3% (30µm/cm) to 3% (300µm/cm). So, their stroke may achieve up to 1mm. Other details such as design principle and product performances have been already described [6,7].

Other types of shell-based actuators are also possible and are used in ultrasonic resonant operations, needing very small voltage (about 1 to 10V) for getting their full stroke. Ultrasonic Piezo Actuators (UPAs) derived from APAs are low-voltage compact generators of ultrasonic vibrations. They can be used at resonance as Langevin transducer, while being much lighter. Ultrasonic Piezo Drives (UPDs) are low-voltage generators of elliptical ultrasonic vibrations looking like UPAs, but including an additional counter-mass. They are used for making Linear & Rotating Piezo Motors (LPMs, RPMs). Both are based on a combination of electromechanical elliptical vibrations (generated by UPD) and friction forces. They offer low-voltage actuation (10V) with unlimited resolution. LPMs are long-stroke Actuators of 3 to 100mm with blocking force at rest without power supply [5]. Forces are in the range of 10 to 50N. RPMs, including miniaturized motors (Figure 4) with customized torque and speed can be defined by using standard UPDs [5] and by choosing the rotor. Piezo motors are developed for high precision positioning applications. Other details such as design principle and product performances have been already described [6,7].

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

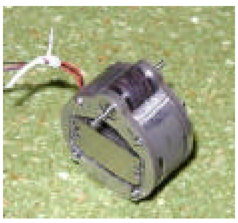


Figure 4. View of a small RPM (Æ20mm)

Although considered as "smart" or "intelligent", piezo actuators can rarely be used for high precision / fast positioning applications without using special cares and additional components.

For fulfilling high precision positioning requirements, a positioning sensor and a closed loop electronic control have to be added to the actuator and its driving elecronics (figure 5). Piezo actuators offer intrinsically a high resolution but a poor precision because of non-linearities, hysteresis and creep. Strain gages have been proved satisfying with precision of 1/10 000 of the full stroke when thermal range is limited. In other cases, absolute sensors such as LVDT and CVDT are preferred.

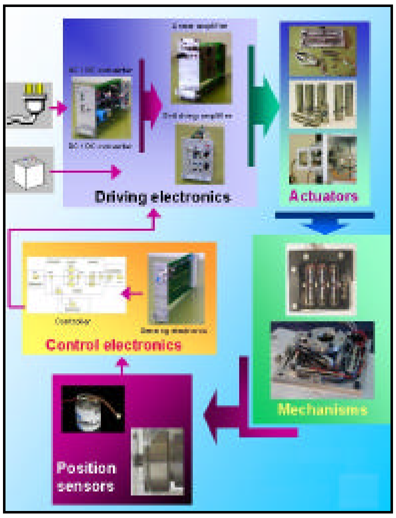


Figure 5. CEDRAT's range of piezo solutions including control loop

For fast positioning applications, several parameters have to be taken into account. Piezo actuators are intrinsically oscillators. When excited by a step voltage, the actuator response includes an overshot and oscillations due to a mechanical resonance and to its damping (Figure 6). The overshoot can strongly damage the piezo ceramics while the oscillations are prejudicial for the system stability. The resonance frequency $\mathbf{f_r}$ depends on the actuator modal mass and the load mass. The damping is depending on the mode mechanical quality factor **Q**. A more complex response may appear when several modes are excited.

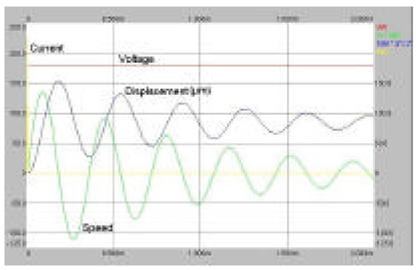


Figure 6. Step response of the APA50S Actuator

Therefore, the use of an actuator for fast positioning needs special cares in electrical drive, damping condition, load guiding…. In practical situations (due to the present technologies of the driving electronic, one can obtain a response time of $\mathbf{t_r = 0.7/f_r}$ with a dedicated switching electronic such as the CEDRAT TECHNOLOGIES switching power SP75. This result has been checked for example on a 6months life time test combining an APA200M and a SP75. This actuator produces displacement of more than 200µm for 180V voltage range. The actuator has been put in free-free mechanical conditions, leading to a mechanical resonance frequency of 3.4kHz in order to increase the number of cycles per second (600Hz, for cycles of 1,6ms). The obtained response time for actuator full stroke with limited overshoot was 200µs (Figure 7). This has been achieved with a good reproducibility and no failure all over the test time leading to a total of 10^{10} cycles. This result is presently applied in fast shutters for optical or X-ray applications such as used in ESRF Grenoble [8].

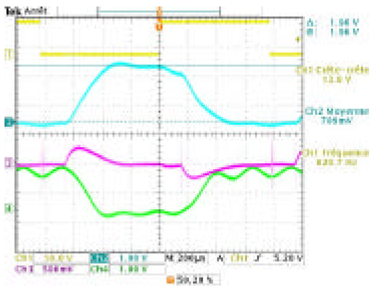


Figure 7. Displacement of an APA200M vs time (From top to bottom: order, voltage, current, displacement)

4. Applications

4.1. Tip-tilt mechanism

As APAs are rather flat, they can be arranged in parallel. It is interesting either for increasing the force or for tilting applications. In this last case the flat structure of APAs allows for placing their actuation axis's close together to get a relatively large tilt angle. Using this possibility, a tip tilt named TT50S has been designed for precise and fast optical deflection. It is based on a 2 standard APA50Ss and a flexural hinge.

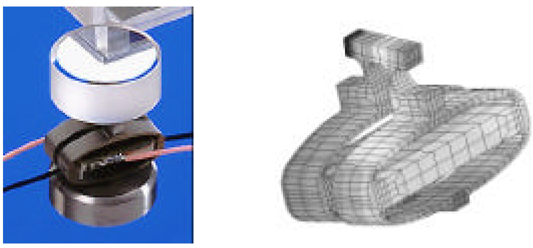


Figure 8. Tip-tilt TT50S (based on 2 APA50S Actuators) and producing an angular displacement of +/- 0.5° and a response time of 400µs, a) Actuator; b) corresponding ATILA FEM modelling [9].

In this mechanism, the Finite Element method is useful for the design of flexural hinges, such as those employed in a tip-tilt mechanism (Figure 8).
The TT50S model is now available as a standard product [5]. Customized tip-tilts, including double-tilt (controlling rotations Rx and Ry, z being the actuation axis) are defined the same way using standard Actuators.

4.2. XYZ mechanisms for fine positionning

An innovating XYZ mechanism has been designed and space qualified within 16 months for MIDAS instrument of ROSETTA space mission under ESA/ESTEC contract. The function of this mechanism is to ensure a very precise scanning motion of an Atomic Force Microscope (AFM) aiming at analyzing the dust of Wirtanen comet. The objective for ESA/ESTEC was to get a lightweight stiff nano-resolution stage able to produce a stroke of [0;+100µm] x [0;+100µm] x [0;+8µm].

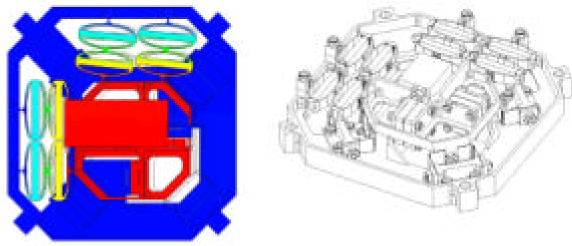


Figure 9. ATILA FEM modelling of the XY stage [9] (a); I-DEAS view of the XY stage (EM) (b)

At first, the engineering model (EM) of an XY stage has been designed and tested [10]. The design work has been performed with ATILA [9] and I-DEAS (Figure 9). The general concept is shown on the Figure 9. It uses 8 Actuators placed in the X and Y directions to provide the required strokes and acts also for the guiding functions, by forming a parallelogram. Flexural hinges are used to decouple the X and Y axis. The construction takes benefit from the planar structure. The shells and the central moving frame were made in one stainless steel part. This is an advantage for the weight but also for reducing the assembling costs.

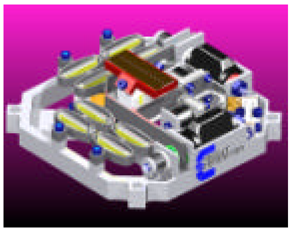


Figure 10. IDEAS CAD view of a piezoelectric XYZ stage qualified for the Rosetta/Midas instrument

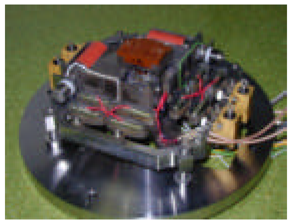


Figure 11. View of a piezoelectric XYZ stage qualified for the Rosetta/Midas instrument

In the Qualification Model (QM) (Figure 10 and Figure 11) customized lightweight direct Piezo Actuator controlled by strain gauges has been implemented on Z axis to replace a too heavy standard direct Piezo Actuator. Two shape memory alloy (SMA) Actuators have also been implemented for the latching mechanism. This stage has passed the vibrations tests at the qualification level, which are higher than usual values, as well as other tests, including a wider temperature range and latching tests. Flight Models (FM) have been constructed and have passed ESA mechanism and instruments acceptance tests. A FM should flow in early 2003 on ROSETTA (Figure 12).

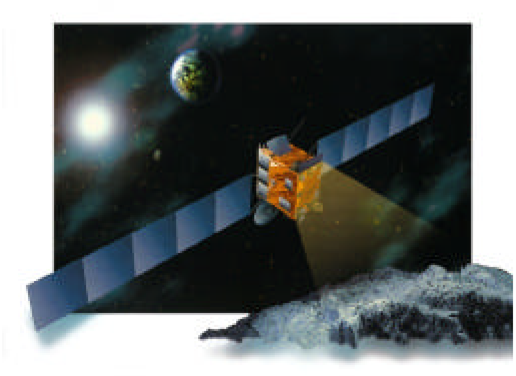


Figure 12. Rosetta spacecraft to be launched in early 2003 (courtesy of ESA)

Industrial and miniaturized versions of this type of XY stage are also now available [5]. The concept used for Rosetta mechanism has been simplified by eliminating functions that are specific to space requirements, in order to reduce its cost. For example a miniature XY25XS [5] able of stroke of [0,+20µm] x [0,+20µm] is shown on Figure 13. An other example of XYZ mechanism based on standard components and developed for an optical application in CNRS/GPS/UP7 is given in [5]. This mechanism is able to perform any stroke into [-100,+100µm] x [-100,+100µm] x [0,200µm].

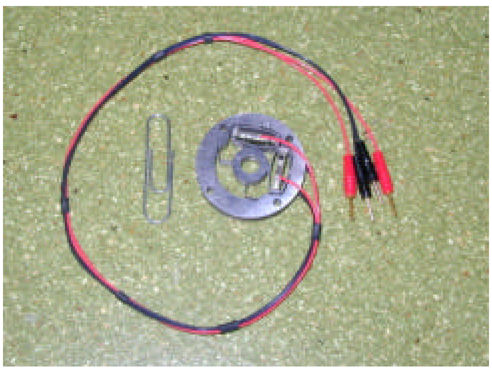


Figure 13. XY mechanism based on 2 APA25XS

4.3. Active control of vibrations

Active control or damping of vibrations is good example of application requiring both precise and fast position controls. The ability of piezo actuators manufactured by CEDRAT TECHNOLOGIES has been successfully demonstrated for this application in space applications at engineering model levels. In a first case, the piezo actuators were used for both the control of launching vibrations and the positioning control in orbit of a telescope mirror [11]. In a second set of space applications, these piezo actuators have been integrated in space truss using active tendons for control of micro vibrations. This application is further presented hereafter.

Free-floating space trusses are intended to hold interferometric equipments, which require a very high positioning accuracy and a very low level of vibrations. These equipments find applications in IASI instrument (Interféromètre Atmosphérique de Sondage dans l'Infrarouge) on METOP satellites and in IRSI/DARWIN. Fine mechanical stability in a free-floating space truss is difficult to achieve because this kind of structure is generally large. Consequently it is compliant, it possesses low frequency modes and might be sensitive to thermo-mechanical deformations. A first technique of mechanical control consists in replacing some truss bars by active bars, for example by Piezo Actuators as shown by the CASTOR experiments performed by CNES on the MIR space station.

Figure 14. Space truss from ULB, integrating an active control of vibrations based on tendons actuated by APA100Ms

Another technique consists in adding actuated cables (active tendon concept) between various points of the truss. The advantage of this method is that the truss mechanical properties (the modes base) are not modified and that the implementation of active tendons can be performed at a later development stage of the truss. A demonstrator of an active tendon control of a free-floating space truss was performed by ULB in 1998, on its own funding. The truss is representative of a scaled model of the JPL-Micro-Precision-Interferometer. High damping ratios of the vibration modes were achieved. However, the present active tendon mechanism relies on conventional piezo actuators amplified by a leverage mechanism based on ball bearings. This system is bulky, has a limited lifetime and is not compatible with space requirements and better actuator solutions were wanted [12].

A recent work performed by ULB, Micromega Dynamics and CEDRAT TECHNOLOGIES (Project Coordinator) for ESA/ESTEC (the European Space Agency) has consisted in implementing Amplified Piezo Actuators (APAs), in the active tendon control experiment of ULB and in testing the capabilities to actively damp the whole structure (Figure 14).

The proposed actuator (APA100M) appears well fiited to the need because it is a pulling device. Therefore the heavy leverage mechanism used for the Direct Piezo Actuator (DPA) can be replaced completely by the APA actuator acting directly on the cable structure. As the actuator is still much stiffer than the cable, the reduced stiffness of the APA compared to the DPA does not deteriorate the control performances. Furthermore, the high resistance of the APA to bending moments and transverse forces allows removing the flexures used in the previous design. This is important because, for dynamic applications, these flexures are usually the weak points during fatigue testing.

As a result, it was shown that the use of the APAs of CEDRAT in the active truss of ULB simplifies drastically the hardware implementation of active tendon control system while preserving the control performances of the previous design (Figure 15).

In conclusion, the integration of the APA actuators in the experimental truss was considered successful by ESA and brought a significant improvment on the previous state of the art.

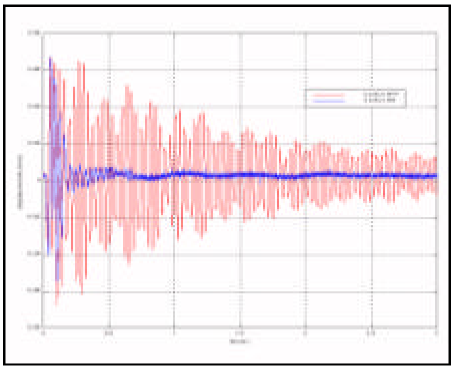


Figure 15. Truss vibration level after a shock excitation, without and with control using APA100Ms

4.4. Structural shape control mechanisms

Active control of structure shape is another good example of application requiring both relatively precise and fast position controls. ONERA Lille, the French Aircraft Institute, has searched for a tilt mechanism for flap control of helicopter blades. First actuator requirements were small size along actuation axis, strokes of more than 200µm, forces of more than 1kN and frequency bandwidth of 200Hz, which can be performed by the APA230L. The test of a first flap mechanism based on the APA230L (figure 16) demonstrated this solution 3 times more efficient from the electromechanical point of view than other tested solutions based on direct piezo actuators from competitors [13,14]. As APAs are robust against transverse forces, they have also shown their ability to bear the centrifuge forces of 1000g. Further tests by ONERA are in progress and larger versions of these actuators (APA XL) have been constructed by CEDRAT TECHNOLOGIES for full-scale models of helicopter blades [15].

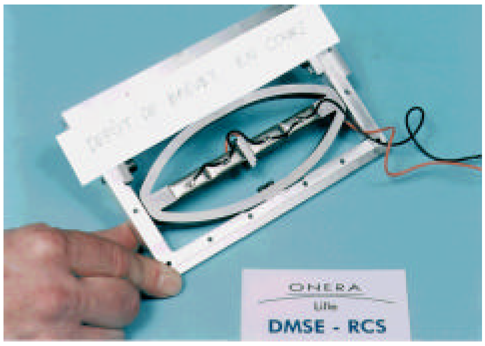


Figure 16. Helicoptere flap segment based on the APA230L, as designed by Onera

4.5. Valves, injectors and fluid control mechanisms

CEDRAT TECHNOLOGIES Products, especially APAs, are also expending in the field of fluid control applications, for example for making Proportional Valves and Automotive Direct Injection. In addition to the previously listed advantages of the APAs, these application take benefit of the fact that the APAs are pulling actuators. This is a key advantage for making normally closed valves, as generally preferred for safety reasons.

Proportional piezo valves based on APA make use of the APA fine resolution to offer a flow control proportional to the applied voltages. Applications vary from flow control in Scientific or Bio Medical Instruments (Figure 17) to thrusters control for propulsion of micro satellites.

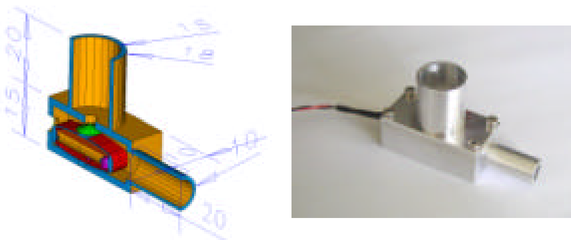
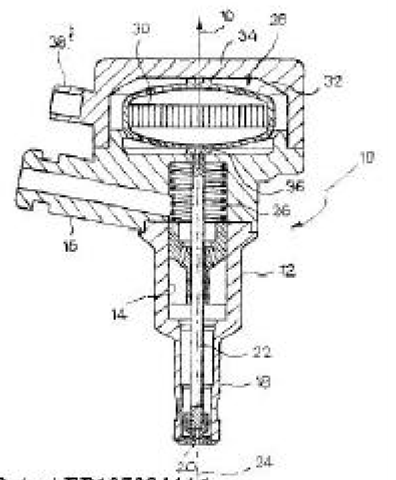


Figure 17. View of a proportional valve based on an APA100S for a Scientific Instrument

Piezo Injectors based on APA make use of the APA fast response, while being compact and potentially low cost. Their application for automotive industry is being investigated by CRF (FIAT Research Centre) [16] (Figure 18). Following a similar approach, short time response actuators are also of interest for droplet generators and ink jet printers.



Patent EP1070844A1

Figure 18. Car Injectors based on an APA, according to C.R.Fiat

5. Conclusion

Several kinds of Piezo Actuators are available from CEDRAT TECHNOLOGIES. However, its Amplified Piezo Actuators, the APAs, are today the most widely chosen in applications because they are compact, robust, low cost, easily integrated and able for covering needs in terms of both precise and fast responses, provided appropriate care and electronics. This has been clearly illustrated with various applications (mechanisms, dampers, valves) in instrumentation, space, aircraft and automotive industries.

Further actuator developments at CEDRAT TECHNOLOGIES are driven by customer applications. They are oriented toward miniaturisation and always better control, for getting “smart actuators”.

6. Acknowledgements

The authors would like to thank its partners ANVAR, CNES, ESA, Min. of Research & Industry, and ONERA, for their supports.

7. References

[1] U.Dibbern, Piezoelectric Actuators in Multilayer Technique, Proc Actuator 94 Conf, Pub Messe Bremen, pp 114-118, 1994.

[2] Quandt, E., Claeysssen F., Magnetostrictive Materials and Actuators (Review), Proc Actuator, June 2000, Ed Messe Bremen (G), pp 100-105.

[3] C. Niezrecki, D. Brei, S. Balakrishnan, A. Moskalik, Piezoelectric Actuation: State of the Art , The shock and vibration digest, July 2001, pp 269-280

[4] Gobin P.F., Jayet Y., Recent Aspects in French Research on Intelligent Materials and Systems, Proc. Journée S.E.E. 17 June 1999, France, pp. 1-8.

[5] R.LeLetty, F.Claeyssen, Piezo Products catalogue v2.2, Sept 2001, Ed .Cedrat Technologies (Meylan, F), http://www.cedrat.com, 76 p.

[6] Claeyssen F., Le Letty R., Barillot F., Lhermet N., Thomin G., Actionneurs piézoélectrique amplifiés et autres actionneurs grandes courses, Proc MAGELEC, Ed Ensheeit Toulouse, Avril 1998, pp125-130.

[7] Claeyssen, F.; Lhermet N., Le Letty R., Barillot F., Debarnot M., Six M.F., Thomin G., Privat M., Bouchilloux P., Piezoelectric Actuators and Motors based on Shell structures. Industrial and commercial applications of Smart Structures Technologies. ISBN 0-8194-3609 SPIE Conf . Newport beach, March 7-8, 2000, SPIE proc ISSN 1017-2653, Vol 3991 pp202-209.

[8] K. Freund, O.Mathon, Thoughts and first experiments on using crystal-based X-Ray Optics, Proc SPIE Conf. 3451 on Smart Material & appli., San Diego, 9p. July 1998.

[9] N. Lhermet , User Manual of Atila - A 3D CAD Software for Piezo Structures, Isen, Lille (F), Distr. Cedrat, Meylan (F) & Magsoft (Us), 2000.

[10] F. Barillot, R. Le Letty, F. Claeyssen, N. Lhermet, M. Yorck, Design and Test of a XY Piezoelectric Stage, ESA SP-438, 8th European Space Mechanisms & Tribology Symposium, Toulouse, 29th Sept. - 1st October 1999, pp 121-126.

[11] Bruneau H., Le Letty R., Claeyssen F, Barillot F., Application of a New Amplified Piezo Actuator to Semi-Active Vibration Control, Proc. 2nd Int. Conf on Active Control in Mechanical Engineering MV2, ECL Lyon, France, 1997, 6p.

[12] Preumont A, Loix N, Some perspectives of applications of active control to large space structures, Proc 5th Int Conf on Motion and Vibration Control, MOVIC2000, Autralia, dec 2000, 10p.

[13] B.Camus, J.L.Petitniot, Materials and actuators for the Control of Structure Shapes. SEE conf. on Material & components piezo- pyro- ferro electric & applications, INSA, Sept 1999, 4p.

[14] Mercier des Rochettes H., Petitniot H., Materials and actuators for the control of structures, Proc SPIE Conf Newport beach, March, 2001, 12p.

[15] H. Mercier Des Rochettes, P. Leconte, Experimental assessment of an active flap device, to be presented at AHS Conf., Canada, June 2002

[16] Butera, F., Alacqua S., Injector for Internal Combustion Engines, Patent EP1070844A1, Applicant C.R.FIAT, 2000