Active Materials and Actuators

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Piezo actuators and piezo motors

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The aim of these lectures is to present piezoactuators, transducers and motors developed by CEDRAT RECHERCHE (France) in order to cover a wide range of needs and applications. Static and dynamic characteristics of piezoactive actuators were investigated. Advantages, disadvantages and field of applications of such actuators were discussed. Since amplified actuators are compact and robust, their role in various applications was examined. Active control of vibrations was also briefly considered. The presentation is simple and includes many illustrative figures.

1. Piezoelectricity: old effect, new materials, new actuators

1.1. Introduction to piezoactive materials

In 1880, the Curie brothers first examined the piezoelectric effect on crystal materials, which have the ability to produce electrical charges in response to externally applied forces. This is called the direct effect. This effect is reciprocal; that is, the piezoelectric material changes its dimensions under applied electrical charges.

In 1922, Langevin proposed the first Actuator based on crystal materials. To enhance its efficiency, this Actuator was driven at resonance. The discovery of piezoelectricity in PZT (lead titanium-zirconate) in the late 1960's increased the number of applications for industrial use. Piezoelectric transducers based on bulk PZT rings have been developed for sonar, ultrasonic welding, ultrasonic cleaning applications, etc. Sensor technology using piezoelectric ceramics (pressure or force sensors, hydrophones, accelero-meters ...) have matured.

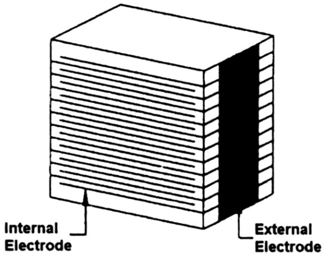

FIGURE 1. Schematic view of a MLA.

Using piezoelectric bulk PZT rings, Actuators for positioning purposes have also been studied. However, to obtain the desired deformation level for this type of applications, it is necessary to use large input voltages. For instance, 0.5 mm thick PZT rings require an excitation voltage of approximately one thousand volts, which is clearly too high for several practical purposes.

Multilayer Actuators (MLAs), derived from the high capacitor technology, have been on the market since 1988 (Fig. 1). Because MLAs are easy to use, they have been increasingly used in various applications. The required excitation voltage of 200 Volts is well adapted to modern electronic.

1.2. Characteristics of piezoactive materials

Piezoelectric materials are crystalline solids whose asymmetric structures create an electric dipole moment in the crystal lattice, which is sensitive to both elastic strain and applied electric field (Fig. 2).

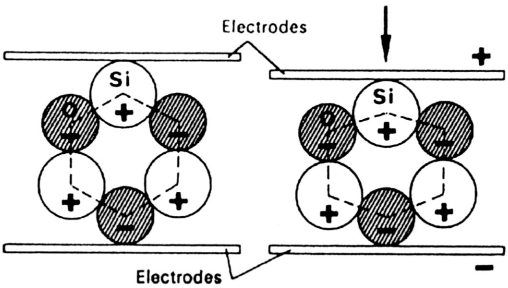

FIGURE 2. Piezo effect on the crystal structure (example of the quartz).

PZT materials are ferroelectric materials under the Curie temperature: the poling process gives the material its remanent polarization. During the poling operation, the material is subjected to a high electric field at the Curie temperature. If the material is subjected to a temperature that is greater than its Curie temperature, it is no longer piezoelectric. It can be repoled to be piezoelectric again in some conditions.

Stresses and strains are related to each other by the Young's modulus of the ceramic. In addition, a stress generates an electrical field through the inverse piezoelectric effect. Since the ceramic is a dielectric medium, the electrical displacement is related to the electrical field. These relationships can be combined in several sets of equations.

For example:

$$\begin{aligned} S_\alpha &= S^{\mathrm{E}}_{\alpha\beta} T_\beta + d_{n\alpha} E_n, \\ D_m &= d_{m\beta} T_\beta + \varepsilon^{\mathrm{T}}_{mn} E_n, \\ \alpha, \beta &= 1, \ldots, 6, \qquad m, n = 1, 2, 3, \end{aligned} \tag{1}$$

where: $\mathbf{S}$ – strain, $\mathbf{T}$ – stress, $\mathbf{D}$ – induction, $\mathbf{E}$ – field, $\mathbf{S}^{\mathrm{E}}$ – compliance at constant field, $\mathbf{d}$ – piezoelectric strains per unit of field, $\boldsymbol{\varepsilon}^{\mathrm{T}}$ – permitivity at constant stress.

The previous equations can be combined to define the electro-mechanical coupling coefficient, which can be seen as the ratio of the convertible energy to the total energy supplied to the Piezoelectric Actuator. Practical values of the material's coupling coefficient can be higher than 50%, but in Actuators, or in resonant transducers, the effective coupling factors k_{eff} are usually lower. The electromechanical coupling coefficient should not be regarded as the Actuator's efficiency. The set of equations shown above does not take into account any losses.

Commercial piezoelectric ceramics can be classified as soft-type or hard-type materials based on the ease or the difficulty of depolarizing them. Table 1 lists some typical properties of piezoactive materials (Fig. 3).

TABLE 1. Properties of piezoactive materials

Materials	Control field E electric H magnetic	Young's modulus at constant field (GPa)	Mechanical quality factor Qm	Electro-mechanical coupling coefficient k33 (%)	Quasistatic maximum strain (ppm)
BULK PIEZOELECTRICS					
PZT-8	*E*	*74*	*1000*	*64*	*+/- 11*
PZT-7	*E*	*72*	*60*	*67*	
PZT-4	*E*	*66*	*50*	*70*	*+/- 15*
PZT-5	*E*	*48*	*75*	*75*	*+/- 30*
MULTILAYERED PIEZOELECTRICS (MLAs)					
Soft-type	*E*	*45*	*25 - 50*	*70*	*1250*
Hard-type	*E*	*62*	*200 - 50*	*60*	*80*
MAGNETOSTRICTIVES					
Terfenol-D	*H*	*25*	*10 - 20*	*70*	*1600*

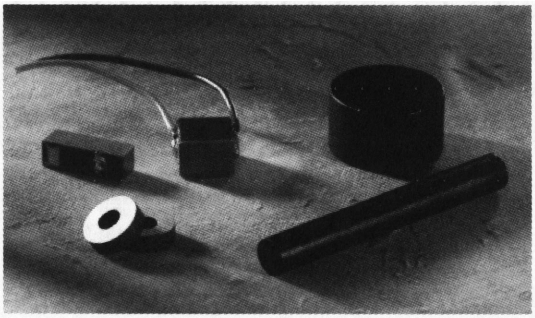

FIGURE 3. View of piezoactive materials.

Magnetostrictive materials like Terfenol-D are also studied at CEDRAT RECHERCHE. They expand when subjected to a magnetic field. Despite the losses occurring in the excitation coil, Actuators based on this material may be well suited for very low-voltage or power applications. Customised Actuators and transducers based on this material are built by CEDRAT RECHERCHE on request.

Electrostrictive materials, such as PMN-PT also exist in Multilayer technique. This material displays a low hysteresis (< 2%), but is much more temperature dependent than PZT material.

1.3. Introduction to CEDRAT piezoactive actuators, transducers and motors

Using these new piezo materials, several classes of low-voltage Piezo Actuators have been developed by CEDRAT RECHERCHE in order to cover a wide range of needs and applications. These Actuators have been initially developed to meet the most severe requirements of the French and European space agencies (CNES, ESA), so they offer optimised properties.

1.3.1. Direct Piezo Actuators (DPAs). DPAs are solid-state linear Actuators (Fig. 4). They use only on the expansion of the active material, in 33-mode, for producing a useful displacement. This displacement is proportional to the voltage on a 200 V range. Typically, the Actuator deformation is about 0.1% (1 μm/mm), so DPA displacement are limited to about 100 μm. In counterpart, the forces are naturally large, easily higher than 1 kN. These Actuators are optimized for quasi-static applications such as micro positioning.

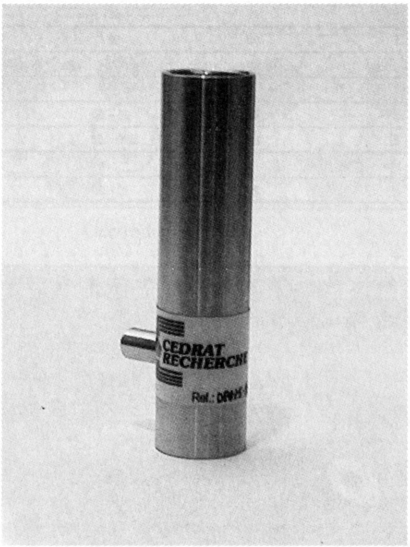

FIGURE 4. View of a DPA.

1.3.2. Amplified Piezo Actuators (APAs). APAs are solid-state long-stroke linear Actuators (Fig. 5). 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 200 V 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 of 1% (10 μm/mm). So, their stroke may achieve more than 500 μm.

As APAs are compact they can be stacked in series for reaching strokes up to 1 mm.

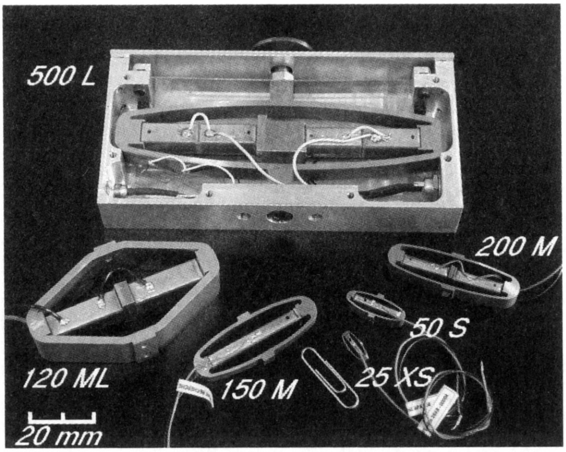

FIGURE 5. View of different series of APAs (XS, S, M, ML, L).

As APAs are robust, they can also be used in dynamic applications, including resonant devices. In this last case, the voltage to apply for getting the maximum stroke is very small (about 1 to 10 V).

1.3.3. Ultrasonic Piezo Actuators (UPAs). UPAs are low-voltage compact generators of ultrasonic vibrations (Fig. 6). They are special versions of APA, optimized to get their useful resonant mode in the ultrasonic range (above 20 kHz). Their active axis are short (typically less than 40 mm), but they produce quite high vibration level (10 to 20 μm) using low voltages (about 1 to 10 V).

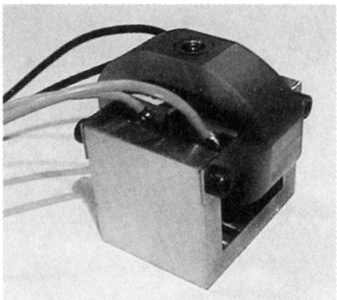

FIGURE 6. View of an UPA.

1.3.4. Ultrasonic Piezo Drives (UPDs). UPDs are low-voltage generators of elliptical ultrasonic vibrations (Fig. 7). They are special versions of UPA, optimized to get two complementary resonant modes in the ultrasonic range (above 20 kHz). They produce vibrations (1-10 μm) with controllable elliptical trajectory, using low voltages (1 to 10 V).

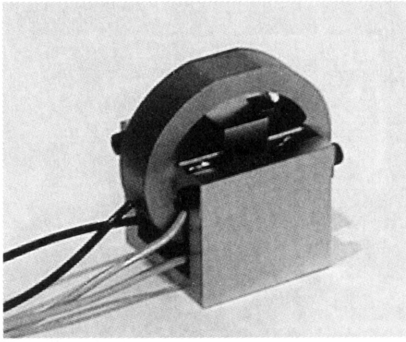

FIGURE 7. View of an UPD.

1.3.5. Linear and Rotating Piezo Motors (LPMs, RPMs). Piezo motors are long-stroke Actuators with blocking force at rest without power supply (Fig. 8). They offer low-voltage actuation (10 V) with unlimited resolution. They exist either in linear or in rotating versions. Both are based on a combination of electromechanical elliptical vibrations (generated by UPD) and friction forces. Strokes of LPMs are typically of 1-20 mm but much longer long strokes are possible. Forces are in the range of 10-50 N. RPMs with customised torque and speed can be easily defined by using standard UPDs and choosing the rotor.

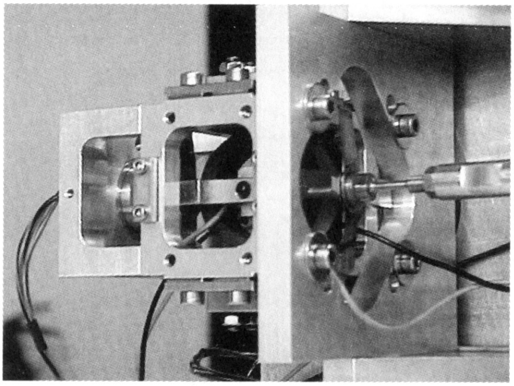

FIGURE 8. View of a LPM.

1.4. Comparison of CEDRAT linear piezoactive actuators.

CEDRAT standard linear Piezoactive Actuators cover a range of free displacements from 10 μm to 10 mm (Fig. 9). They have been designed in order to offer the largest possible stroke keeping a reasonable size. The choice between these different solutions should be made as a compromise between the displacement and the force (Fig. 10).

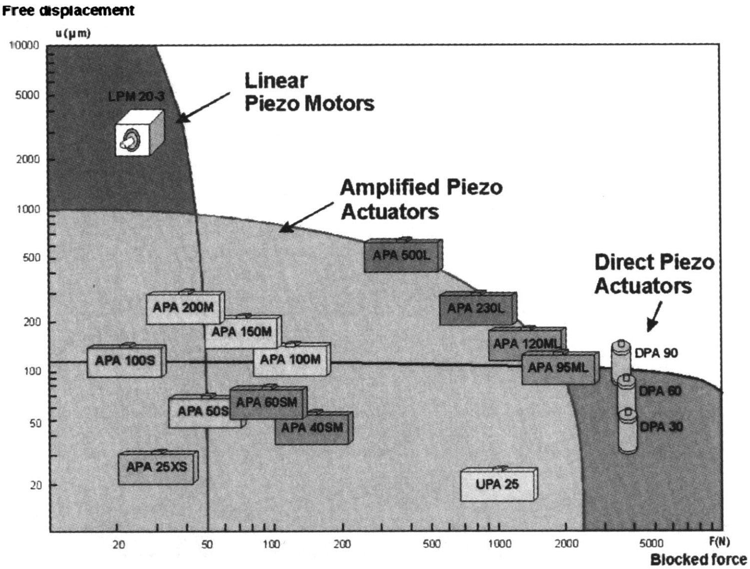

FIGURE 9. Comparison of free displacements and blocked forces of some linear Piezo Actuators (DPA, APA, LPM) of CEDRAT. (The blocked force is the external applied force, which cancels the Actuator's displacement; the free displacement is the maximal displacement without any applied force).

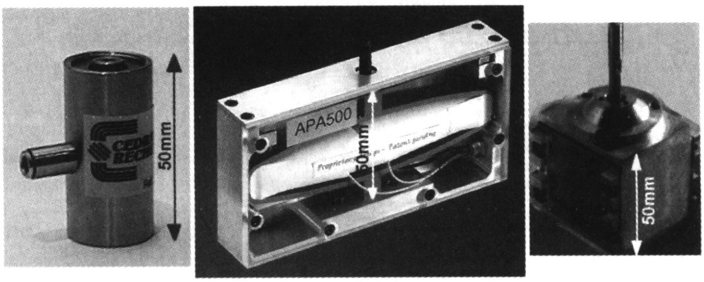

FIGURE 10. Comparison of linear Piezo Actuators DPA30, APA500L, LPM20 of CEDRAT with comparable size (u = free displacement; F = blocked forces).

For example, considering an active height of about 50 mm, one can choose between a DPA30, an APA500L and a LPM20, which offer quite different stroke and force.

1.5. Synthesis of CEDRAT offer

The whole range of CEDRAT's products can be assembled to build a complete mechanism (Fig. 11). Note that mechanisms can produce larger stroke than the used elementary Actuators. All these electromechanical devices can be driven and controlled with appropriate electronics.

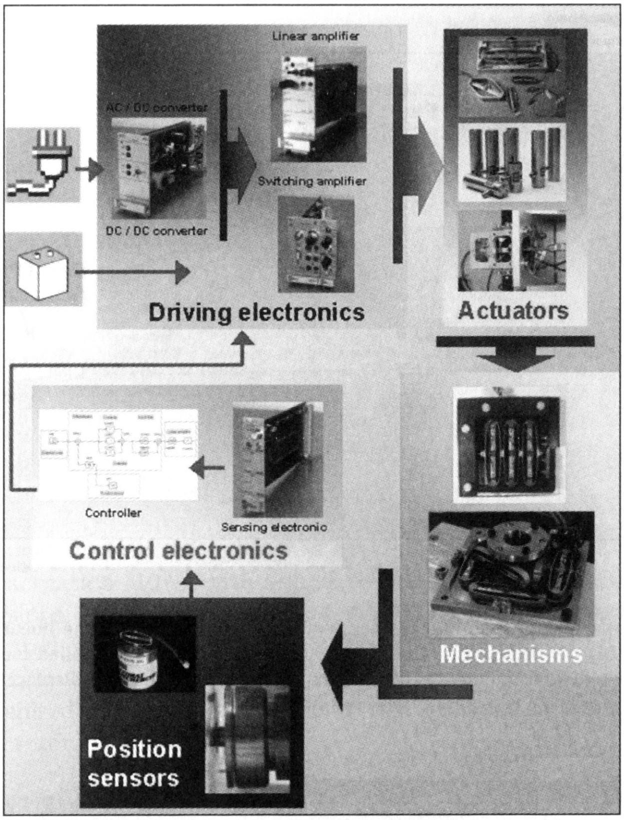

FIGURE 11. CEDRAT's range of products.

Summary

- Several solutions of Piezo actuation exist: the choice depends on the required strokes and force.
- The advantages are a high positioning accuracy, a possible non-magnetic operation, a fast response, a low power consumption...

1.6. Interests and applications of Piezo Actuators

Primary advantages of Piezo Actuators are:

- their solid-state design with no rolling parts, so that they are not subjected to wear,
- unlimited resolution, making them ideal for nano-positioning,
- low power consumption,
- high force/mass ratio, explaining their fast response,
- possible non-magnetic actuation,
- operation in ultra high vacuum.

Piezo Actuators also display several limitations:
- limited displacements range (below 1 mm). For higher displacements, the use of a piezo motor is necessary,
- limited higher temperature $< 100°$, although some progress are being made for automotive applications.

Applications of Piezoactive Actuators are found in various fields of industry:
- mechanical engineering: Positioning of tools, Clamps, Active Wedges, Damping, Active control, Generation of ultrasonic or sonic vibrations,
- microelectronics: Positioning of masks, wafers or magnetic heads, Non-magnetic actuation, Circuit breakers,
- fluids: Proportional valves, Pumps, Measuring, Injections, Ink jet, Droplet generators,
- optics: Positioning of mirrors or lenses, Focusing, Laser cavity tuning, Alignment or deformation of fibbers, Scanners, Choppers, Interferometers, Modulators.

2. Induced Strain Piezoactive Actuators

2.1. Direct Piezo Actuators (DPAS).

Direct Piezo Actuators (DPAs) are the most common type of Actuators (Fig. 12): they consist of a stack of prestressed active material. Conventional DPAs use a serial prestress (Fig. 13). The level of prestress determines the pulling force capability. A more robust technique (widely used at CEDRAT RECHERCHE in power ultrasonic transducer) consists of a parallel prestress with a bolt-tightened steel rod. However, it requires MLA rings that are less common. A third alternative consists in prestressing the MLA stack through an external elastic frame.

DPAs use the expansion of the active material, in 33-mode, for producing a useful displacement. As most of the strain energy is stored into the active material, the effective

FIGURE 12. View of DPAs.

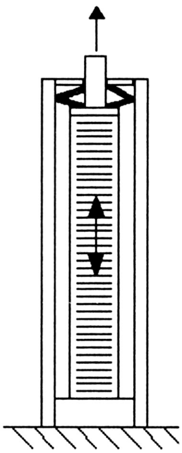

FIGURE 13. Construction schematic for Direct Piezoactive Actuators.

coupling factor of this structure is high, generally higher than 50%, as well the elastic energy per unit of mass.

The displacement is roughly proportional to the voltage, from 0 to 200 V, which can be produced with special power electronics (see section 2.7). The relation between the displacement and the voltage is not exactly linear because of the hysteresis due to the active material. This effect can be well controlled by appropriate feed back electronics (see section 2.8), which linearizes the system behaviour.

As the strain of present piezo materials is limited to 0.12%, the induced displacement is necessarily small, even in case of very long Actuators. Due to non active pieces (end parts, prestress mechanism), the deformation of the Actuator is smaller than that of the material itself, leading to values from 0.08% to 0.10% (0.8 to 1 μm/mm) in the DPA90. Thus, a 100 mm long DPA can reach about 80 to 100 μm. The longest DPAs can hardly be longer than 200 mm because of the risks of fracture in buckling. It is the reason why there is no direct Piezo Actuator of 200 μm stroke available on the market (so APAs offer an alternative solution for these needs). DPAs based on external prestressing frame are currently in development for space applications.

DPAs must be used carefully since they cannot bear any twisting or flexural torque. To avoid this problem, elastic flexural hinges must be preferred. However, these hinges are more difficult to design because they must also be capable of supporting some stiffness. Additionally, standard DPAs have been designed for low frequency operation, typically less than 100 Hz. Amplified Piezoactive Actuators (APAs) are used to circumvent these limitations, because the elastic amplifier can bear transverse forces.

2.2. Amplified Piezo Actuators (APAS)

The displacement limitation of a DPA can be overcome by using an elastic mechanical amplifier. Various designs, most of them using flexural hinges, have been proposed in the past. Stresses become very high in the hinges during actuation, resulting in fatigue effects.

APAs are based on a shell without any hinges (Figs. 14 and 15). High displacements of APAs combined with high forces show that the proposed Actuators achieve displacement amplifications of 2 to 5 and have a good mechanical efficiency. Thanks to this amplification and their shape ratio, they can achieve deformations of about 1%.

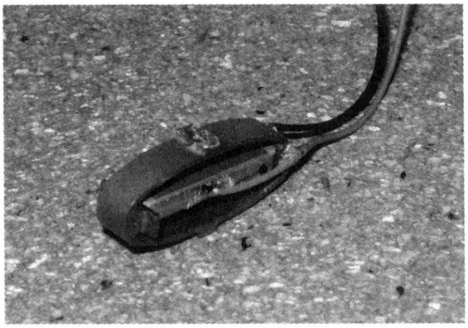

FIGURE 14. View of an APA50S.

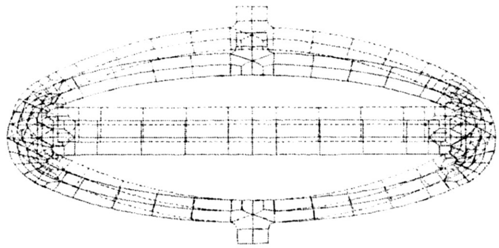

FIGURE 15. Finite element computation of an Amplified Piezoactive Actuator; dotted lines = structure at rest; full lines = structure deformed by the piezoelectric effect (ATILA FEM result).

For example, at 200 V, the APA100S Actuator produces free displacements of up to 110 μm and blocked forces of up to 19N along its short axis, which is only 10 mm high. This corresponds to a deformation of more than 1% along the short (active) axis. This 1% deformation can be found also on large APAs: the APA500L produces free displacements up to 500 μm and blocked forces up to 570 N, along its short axis which is about 50 mm height (Fig. 10).

APAs present the following advantages:

- the Actuators are small and compact relative to their stroke,
- the displacement magnification and the stiffness are functions of the eccentricity of the shell,
- mechanical impedance matching and a good electromechanical coupling are possible,
- it can be operated in a wide range of frequency including the resonance frequency,
- the bending behavior of the shell under the piezoelectric actuation allows for an acceptable distribution of stresses in the amplifier,

- bending and/or twisting moments can be exerted (to a certain extent) on the shell, which prevents the MLA from breaking. From this specific point of view, APAs are considered to be more robust than DPAs,
- the cost of an APA is much lower than direct Piezo Actuators producing the same stroke. This is due to the mechanical amplifier which is less expensive than active materials.

Summary

- The stroke of an APA as well as a DPA is proportional to the applied voltage.
- The hysteresis limits the positionning accuracy. A closed loop can provide an accuracy better than 0.1%.
- The APAs can be driven up to one half of the resonance frequency for positioning applications.
- The APAs can be driven at resonance for vibration generation.
- The APAs are both more robust and cheaper than the DPAs.

2.3. Ultrasonic Piezo Actuators (Upas) and Ultrasonic Piezo Drives (Upds)

Ultrasonic Piezoactive Actuators UPAs have been developed to offer a new solution for the generation of ultrasonic vibrations.

UPA structures are the same as APA structures, but they are maintained on the side of the long axis side in order to decouple the support from the vibration generation (Fig. 16).

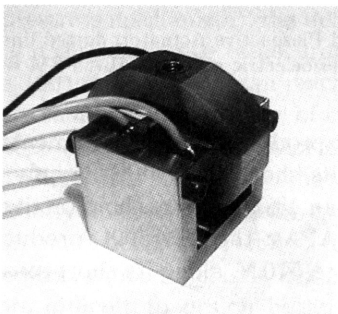

FIGURE 16. View of an UPA.

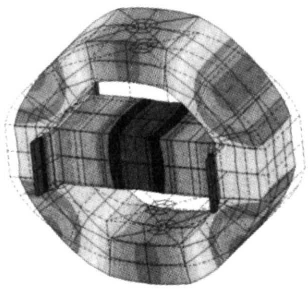

FIGURE 17. Finite element computation of an UPA.

Compared to the Langevin transducers (the most common structure of ultrasonic generation, which are also built under request by CEDRAT RECHERCHE), they offer several significant advantages:

- much smaller size and weight, for the same frequency and displacement amplitude,
- much higher deformations due to the above advantage,
- much smaller voltage (1 to 10 V instead of 200 to 1000 V).

Ultrasonic Piezo Drives UPDs are also ultrasonic vibration generators, but they are designed to produce 2 orthogonal components of vibrations, that can be combined to get an elliptical vibration. They present the same advantages as those listed above. As they are mainly used in piezomotors, their applications are introduced in Sec. 3.

2.4. Static behaviour of Piezoactive Actuators

This section gives some guidelines for choosing the best DPA or APA Actuator as regard a customer's quasistatic application.

In most cases, the displacement ΔU is in the primary interest: it depends on both the applied voltage U and the generated force F:

$$\Delta U = \frac{NV - F}{K}, \tag{2}$$

where N is the force factor of the Actuator and K is the stiffness. The product NV, when the voltage is maximum, is also referred as the blocked force F_0.

$$F_0 = NV_{\max}. \tag{3}$$

It is clear that the displacement ΔU becomes 0, when the generated force F reaches F_0. The Actuator's maximum stroke ΔU_0 is called the free displacement and then equal to:

$$\Delta U_0 = \frac{F_0}{K}. \tag{4}$$

The relation between the free displacement and blocked force can be drawn on the Actuator's load characteristic (Fig. 18).

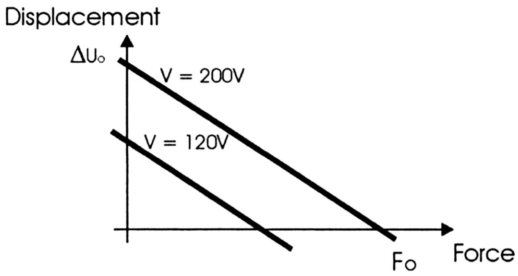

FIGURE 18. Load characteristics of a Piezoelectric Actuator.

If a constant load F (i.e. weight) is smaller than the blocked force or the maximal tensile force, the weight does not affect the stroke of the Piezoelectric Actuator, but results only in a shift of the zero voltage position (Fig. 19) by a distance ΔL:

$$\Delta L = \frac{F}{K}. \tag{5}$$

A very different situation occurs when the Piezoelectric Actuator acts against a spring with a stiffness K_t. The stroke becomes (Fig. 20):

$$\Delta U = \frac{NV - K_t \Delta U}{K} = \Delta U_0 \frac{K}{K + K_t}. \tag{6}$$

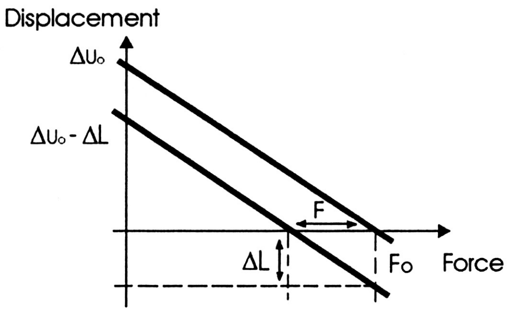

FIGURE 19. Position shift and load characteristics of the Actuator under a constant force.

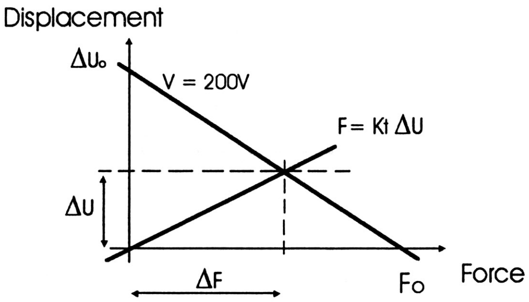

FIGURE 20. Load characteristics under a spring with a stiffness k_t.

Since Piezoelectric Actuators are pre-loaded using a spring, the previous relationship explains why the strain of DPAs is smaller than the active material strain itself.

Piezoactive Actuators can be mechanically arranged in series and/or in parallel. In the first case (Fig. 21a), displacements are added and the force stays constant, while in the latter, the forces are added and the displacement remains the same (Fig. 21b).

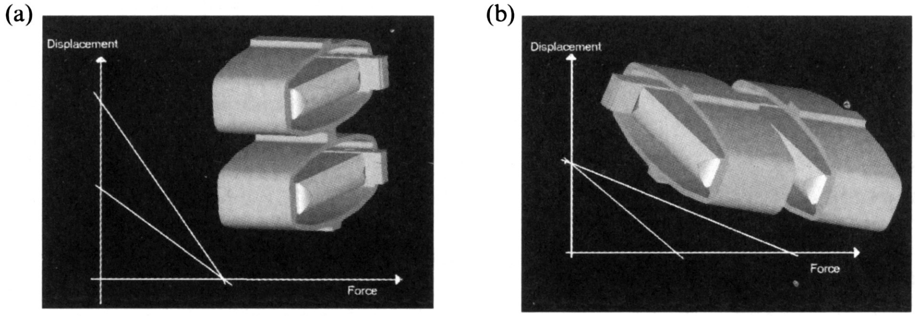

FIGURE 21. Series (a) and Parallel (b) arrangements of APAs.

2.5. Dynamic behaviour of Piezoactive Actuators

This section gives some rules to choose the APA, UPA or UPD Actuators that meet customer's dynamic resonant application.

If either the applied voltage or the external force vary with the time, the displacement still follows the excitations until dynamic behaviours appear. The previous relationships remain valid in the quasistatic bandwidth, which is limited by about half the resonance frequency f_{r0}:

$$f_{r0} = \frac{1}{2\pi}\sqrt{\frac{K}{m}}, \tag{7}$$

where m is the effective mass of the Piezoelectric Actuator (not equal to the total mass of the Piezoelectric Actuator). If the Actuator is loaded by an additional mass M, the resonance frequency f_r then becomes:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{K}{m+M}}. \tag{8}$$

The resonance frequency is also affected by external masses, spring constants or damping effects.

Dynamic operations are more complex because of the acceleration acting on the Piezoelectric Actuator. Displacements (and consequently stresses) can become very high.

At resonance, considering a constant voltage amplitude, they are magnified (Fig. 22) by the mechanical quality factor Q_m:

$$\Delta U_0 = Q_m \frac{NV}{K}. \tag{9}$$

The vibration speed Δv is often used in dynamic operation and is proportional to the displacement:

$$\Delta v = 2\pi f \Delta U. \tag{10}$$

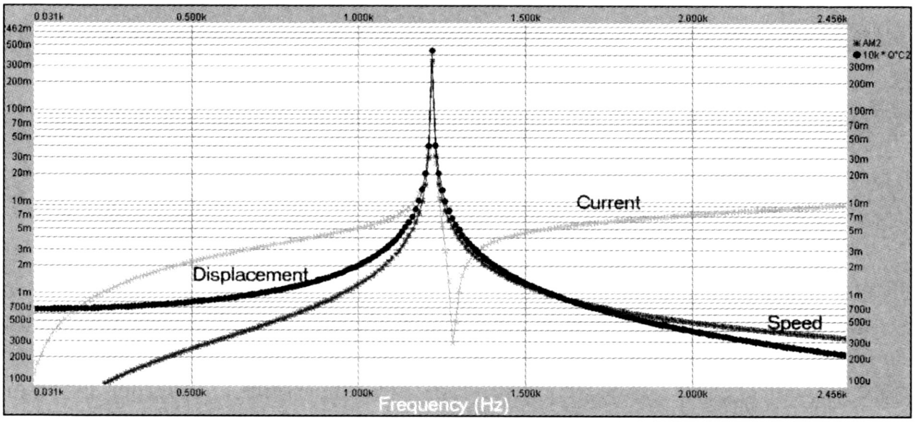

FIGURE 22. Current, displacement and speed of the Actuator versus frequency: the resonance effect can be seen either on the Actuator's speed or current.

The speed variation versus frequency (Fig. 22) exhibits also the resonance phenomena. Values of the Q_m factor depend on many parameters coming both from the Actuator and the load. Typical values are in the range of 20 (high level) to 200 (low level) in free condition. It decreases in case of resistive load (load exhibiting damping or energy radiation).

Due to this amplification and to mechanical limits (see Sec. 2.6), the maximum voltage that can be applied at resonance is much lower than in static condition. Thus, a full stroke of APAs, UPAs or UPDs is achieved in free condition with only a few volts (1 to 10 V). In rough approximation, the maximum voltage at resonance frequency is the maximum voltage in static condition divided by the Q_m factor:

$$V_{\max @ f=f_r} = \frac{V_{\max @ f=0}}{Q_m}. \tag{11}$$

On the APAs radiating in the air, the peak to peak vibration amplitude at the resonance can reach the static stroke at about 10 V_{rms} (Fig. 23). The resonance is also responsible for the overshot and the oscillations, which can be seen on the step response of an Actuator (Fig. 24). This undesirable effect can be controlled with appropriate electric driving or additional damping.

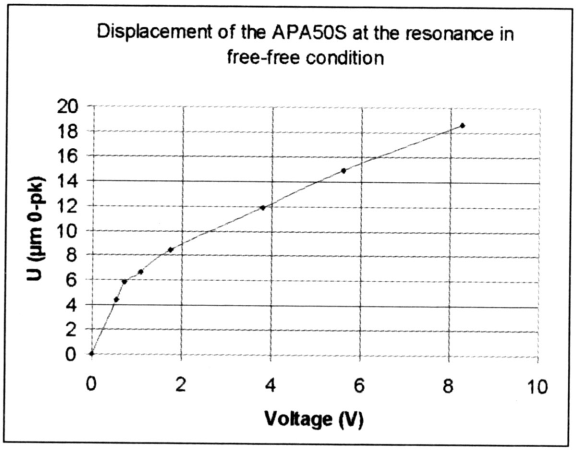

FIGURE 23. Relation between the displacement and the voltage at the resonance.

The time response t_r of the Actuator is limited by the resonance frequency f_r:

$$t_r = \frac{1}{3f_r} \tag{12}$$

In practical situations (due to the current limitation of the driving electronic), one can obtain $t_r = 0.7/f_r$ with a dedicated switching electronic.

Note that the use of Piezo Actuators in dynamic condition (either at resonance or in transient conditions) needs a careful design and a good experience, because of mechanical breaking risks.

Please do not hesitate to contact CEDRAT RECHERCHE for design and tests or to use CEDRAT CADs for preliminary analysis (see Sec. 4).

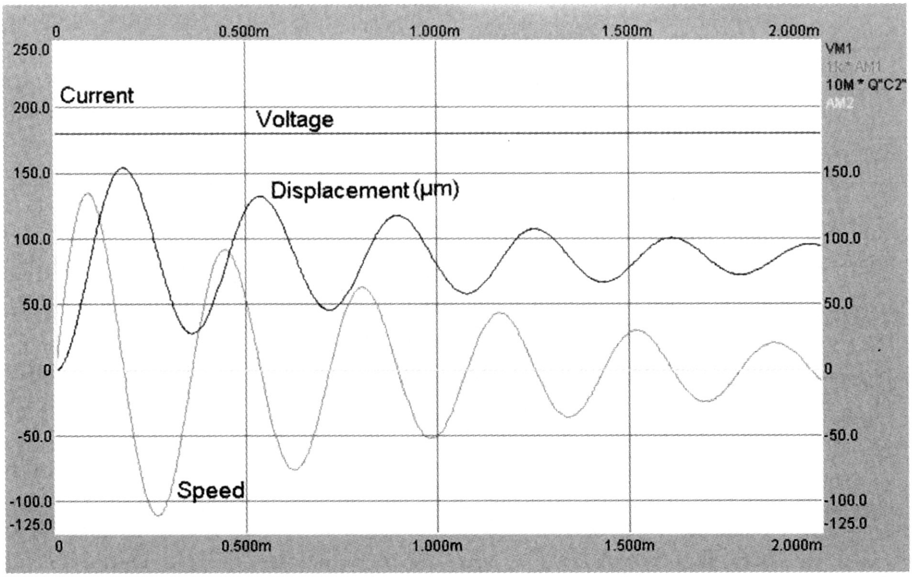

FIGURE 24. Step response of the APA50S Actuator.

2.6. Limitations of Piezoactive Actuators

Piezoelectric Actuators have several limitations that must be taken into account to properly design the applications. These limits are electrical, mechanical and thermal.

The applied voltage is limited to 200 V by the insulating layer. Since the thickness in the layer in the MLA is 100 μm, it corresponds to an electrical field of 2 kV/mm. The applied voltage cannot be decreased under −40 V. Otherwise, the polarization would be reversed (Fig. 25).

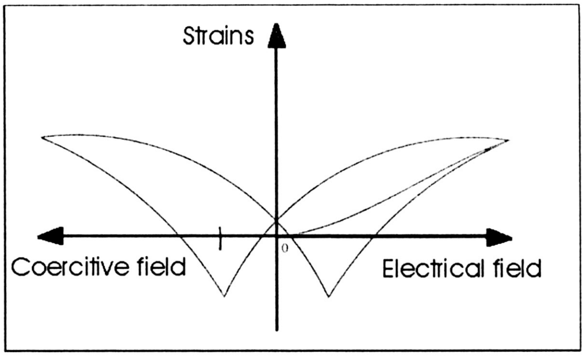

FIGURE 25. Electrical field – strain relation in a piezoelectric material.

Since MLAs are laminated materials, they cannot bear any tensile forces, so that all the Piezo Actuators are mechanically preloaded. Since MLA is a brittle material, bending or twisting moments must be avoided as much as possible, even during the mounting procedure, especially for DPAs. Tensile forces during dynamic operations or switched operations must also be avoided.

Due to the dielectric and mechanical losses, the Piezoelectric Actuator warms up under continuous excitation. Losses are mainly non-linear and depend on the excitation frequency, the voltage amplitude and the humidity. To avoid a depoling effect of the ceramic, the temperature in the Actuator should be monitored to ensure that it stays well below the ceramic's Curie temperature. So typical range of temperatures is $-40°C$ to $80°C$.

There are currently a lot of researchers on materials to be able to produce MLAs displaying higher working temperatures (up to 160°C). On request, CEDRAT RECHERCHE can produce Actuators with these new components.

Similarly, the standard MLAs works at low temperature and have already been tested in liquid nitrogen (77°K, $-196°C$): at this low temperature, the displacement is only one third of the one obtained at room temperature.

The thermo-mechanics may be an issue in the case of a fine positioning application over a large range of temperature: the PZT in the multilayer technique display an expansion coefficient temperature CTE of 3.5 ppm/°K, for temperature well below the Curie temperature. For Amplified Piezo Actuators, since the shell's material has a higher CTE, it results in a negative CTE depending on the shell's amplification ratio. However, the thermo-mechanics of the surrounding parts should also be taken into account.

Summary

- Several limitations apply to the Piezo Actuators: maximum voltage, tensile stress, thermal limits. They should be taken into account in the application design.
- Thermo-mechanics may be an issue in the case of positioning application over a large range of temperature.
- CEDRAT RECHERCHE has a great experience in designing Piezo Actuators or mechanisms taking into account the environment (thermal, random vibrations, lifetime...). See section 4 for more details.

2.7. Driving of Piezoactive Actuators

A Piezoelectric Actuator is a capacitive device, whose capacitance is often very large (as much as 10 microfarads). Such a device is a difficult load for its drive electronics, since a significant charge transfer rate is needed to achieve a fast response. In addition the Actuator will produce electrical energy when submitted to a mechanical load. Linear amplifiers are the most common amplifiers and have high signal to noise ratio. Switched power amplifiers are more efficient under reactive loading in dynamic applications, but are more difficult to control. The general synoptic of the driving system for a piezoelectric system is given on Fig. 26.

One option available on the linear driver is the push-pull operation, which can be used to drive tilt devices or electrically centered mechanisms (Fig. 27).

In dynamic operation, the current i flowing into the Actuator increases linearly with the frequency:

$$i = 2\pi f C V, \tag{13}$$

where C is the quasistatic capacitance of the Piezo Actuator.

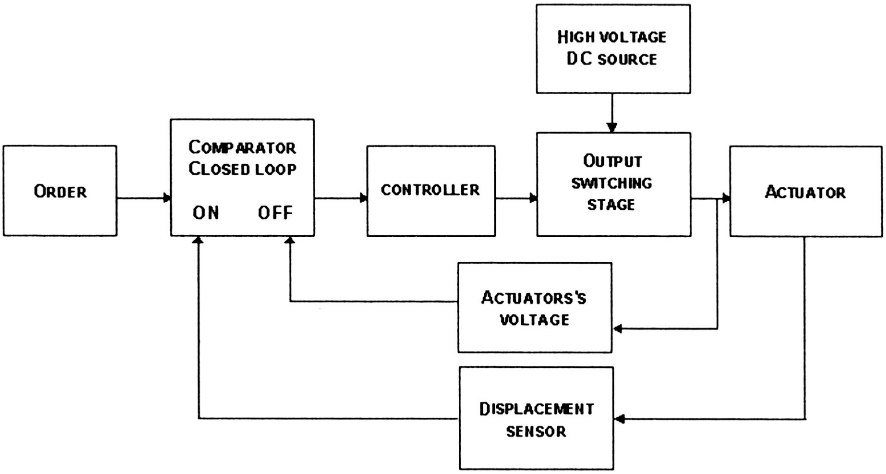

FIGURE 26. Synoptic of a driving system.

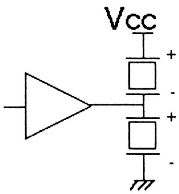

FIGURE 27. Push-pull operation using one electric driver.

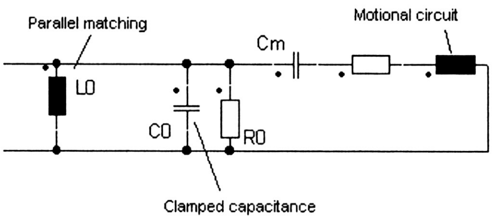

FIGURE 28. Equivalent load for a Piezo Actuator at the resonance and a parallel inductance matching.

Thus, the required electrical reactive power P is equal to:

$$P = 2\pi f C V^2, \tag{14}$$

Inverters are currently used to drive the resonant Actuators. An inductance is generally used to cancel the reactive power (Fig. 28).

2.8. Control of Piezoactive Actuators

MLAs always display an hysteresis, which limits the position's accuracy. Other effects such as creep (which can be understood as repoling process) also limit the Actuator's linearity. Therefore, displacement sensors are often used to insure a linear response of the Piezoactive Actuators through a closed-loop. Among sensors, strain gauges are the most popular because of their integrated features (Figs. 29 and 30). A precision of 1/1000 is usually achieved (SG option). Capacitive displacement sensors can also be used and precision of 1/5000 can be obtained.

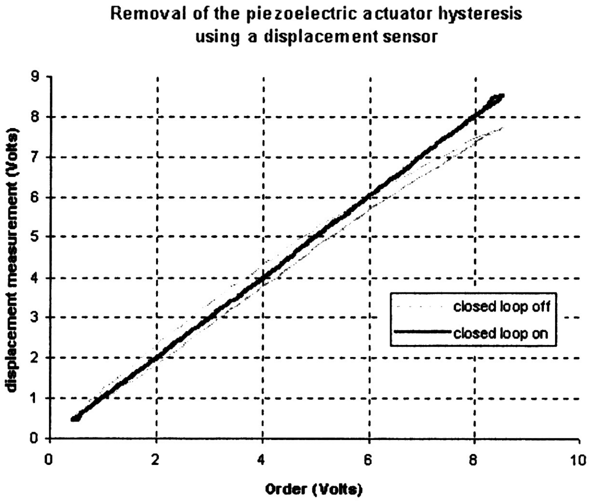

FIGURE 29. Example of an hysteresis removal using a displacement sensor.

FIGURE 30. Example of an APA50S equipped with Strain Gauges.

Summary

- Two types of driving electronics are available: the linear type offers a good signal to noise ratio, while the switching type is more efficient.
- If a high accuracy is required, a closed loop including the Actuator, a position sensor, a controller is necessary to remove the hysteresis.

3. Piezomotors

3.1. General presentation of piezoactive motors

Piezoactive motors use friction between a mobile part (guide, rotor) and a vibrating part (stator) in order to create motion as shown in Fig. 31. The vibrations of the stator are generated by piezoactive materials. The vibrations of the contact points of the stator are such that the trajectory of these points is elliptical. Using friction forces, this vibration drives the mobile part, which is pressed against the stator with a static pre-load F_o. In unloaded conditions, the tangential speed v_{Mt} of the mobile part is almost equal to the tangential velocity of vibration v_{St} of stator (which is the time derivative of tangential component of displacement u_{S} of the stator).

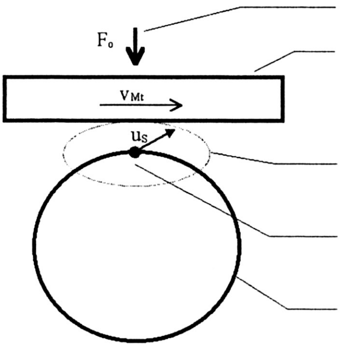

FIGURE 31. Principle of any piezoactive motor.

The advantages of such mechanisms are:

- large holding force or torque at rest, without power supply,
- a large actuating force or torque at low speed,
- potential for silent operation,
- nonmagnetic behaviour,
- short time response,
- very good micro positioning capability,
- high integration capability in application, including "Direct drive" concepts.

The use of this motor in "Direct drive" means that the complete function is obtained without any additional gear mechanism (for speed reduction, or for converting rotation in translation).

These advantages are due to the properties of piezoactive materials. They can produce pressures of 50 MPa, to compare with electromagnetic pressures ($B^2/2\mu_o$) limited to 1.6 MPa. Conversely, because deformations of piezoactive materials are low (section 1.2), displacements are small (a few microns) which accounts for both the low speed and the high resolution in positioning.

Optics is probably the domain where the use of the piezoactive motors is the most advanced. The most famous example, is the CANON camera, which includes an auto focus zoom based on a piezoelectric ultrasonic motor (USM) since 1992.

3.2. Principle of CEDRAT piezoactive motors

Figure 32 shows a principle of stator invented by CEDRAT RECHERCHE, which led to the development of Multi Mode Ultrasonic Motors (MMUM). Two opposing Actuators mechanically excite a ring. These Actuators are electrically excited by two sine voltages with a 90° difference of phase. The tip of the ring describes an elliptical trajectory and can be used to drive a mobile part by friction. This stator provides several advantages compared to other principles. It can work with Actuators excited in longitudinal coupling.

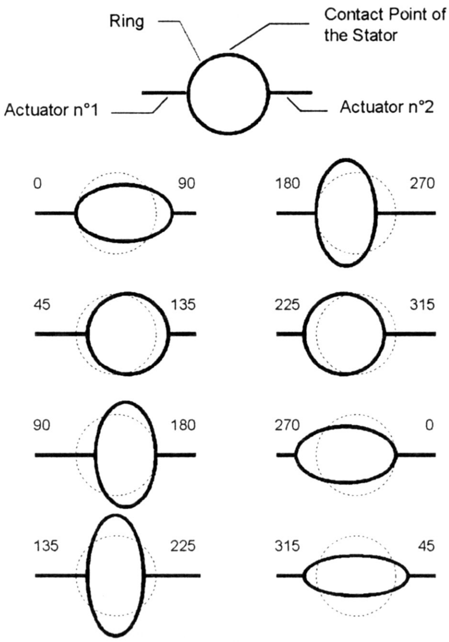

FIGURE 32. Presentation of the structure and principle of the stator of CEDRAT RECHERCHE motor: (the deformed structure at different time step is in continuous lines, to be compared with the structure at rest in dotted lines).

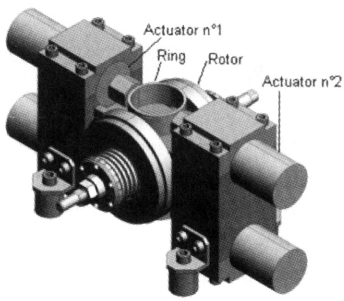

FIGURE 33. Rotating piezoactive motor based on magnetostrictive Actuators.

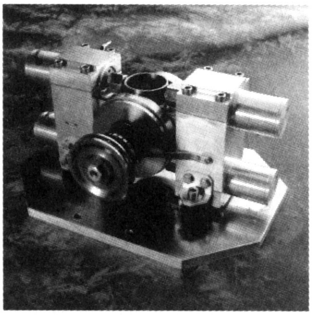

FIGURE 34. Prototype of the previous rotating piezoactive motor, offering a torque of 2 Nm.

The first construction of a motor using this principle in 1993 was made with magnetostrictive Actuators (Figs. 33 and 34). The high actuation torque, which was achieved, demonstrated the interest of the principle. It has also been tested successfully with Piezoelectric Actuators.

3.3. Ultrasonic Piezo Drive (UPDs)

3.3.1. UPD principle. The previous principle of stator has been highly integrated into a new generation of very compact modular stators called Ultrasonic Piezoactive Drives (UPDs). Here, two opposing contact zones produce different kinds of vibration displacements: elliptical, normal, tangential or oblique. The UPD is excited by two electrical ports, which can be fed by low voltage sine waves, either with two phases or one phase. The vibration trajectory is controlled either by the frequency, or by the difference of phase between the two electric ports (Fig. 35).

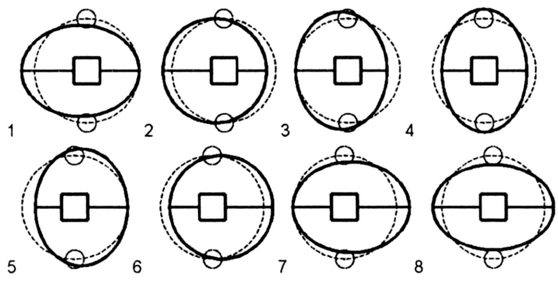

FIGURE 35. Basic principle of the UPD.

3.3.2. UPD elliptical vibration. This principle has been used to define a stator called the UPD20 (Fig. 7) with the aid of the FEM ATILA. It uses two multilayered piezo ceramics of 10 mm in length and a steel shell of about 45 mm in diameter and

10 mm in thickness. The shell is also used to pre stress the ceramics and avoid tensile stresses.

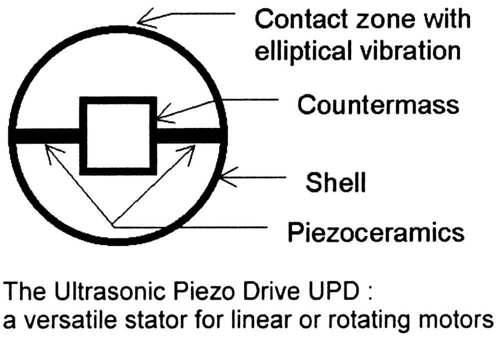

FIGURE 36. Schematic view of an UPD.

The ceramics are deformed in 33-mode close to the device resonances, so that well-coupled large deformations are produced. In these resonant conditions, a deformation up to 1000 ppm is produced in the ceramics using an electric excitation from 1 to 10 V, because of the amplification of strain at resonance. It produces an elliptical vibration within 2-10 μm. For comparison, a voltage of about 200 V is required for the same strain value in quasi static conditions. Working close to resonance is therefore highly beneficial, but needs some care for the control of the amplitude and the shape of the elliptical vibration.

A modal analysis of the UPD20 accounting for the symmetry plane (horizontal), the 3D structure, the piezoelectric effects, the two ports excitation, the dynamic effects and the contact stiffness, provides understanding of the mode shapes: the flexure mode (Fig. 37a) and the translation mode (Fig. 37b).

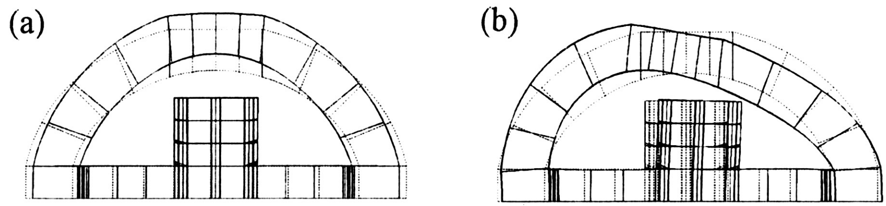

FIGURE 37. (a) Flexural AC-mode, in-phase excitation (ATILA FEM result on half UPD). (b) Translation AC-mode, opposite-phase excitation (ATILA FEM result on half UPD).

An important parameter of the design is the mass of the counter mass. Its value determines the frequency of the translation mode but has no influence on the flexure mode frequency. So it allows for a tuning of both modes. It is possible to use this tuning in the design phase but also in the experimental phase by putting additional masses on the counter mass. The contact stiffness, which can be adjusted with the preload applied between the UPD and the driven part, is another parameter governing the modes.

Indeed, it was chosen to place the flexure and translation vibration modes not at the same frequency. A typical situation of distribution of vibration modes of an UPD20 under pre load is given on Fig. 38. With an in-phase mechanical excitation ($\phi = 0°$) of the piezo stacks (deformation in phase), the Flexural AC-mode is excited alone.

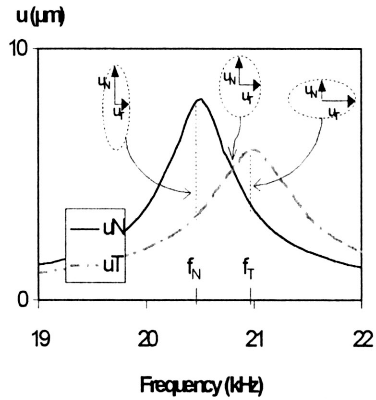

FIGURE 38. Amplitude of displacements of tangential mode u_T and normal mode u_N vs frequency.

It produces a curve of normal displacement $u_N(f)$ with a peak at a resonant frequency $f_F = 21\,\text{kHz}$.

With an out-phase mechanical excitation ($\phi = 180°$) of the piezos (deformation in opposition), the Translation AC-mode is excited alone. It produces a curve of tangential displacement $u_T(f)$ with a peak at a resonant frequency $f_T = 20,5\,\text{kHz}$. With an intermediate phase of mechanical excitation (for ex $\phi = 90°$) of the piezos, both Flexural AC-mode and Translation AC-mode are excited. Thus, there are two available components of displacement, $u_N(f,\phi)$ and $u_T(f,\phi)$ such as:

$$u_N(f,\phi) = \cos\frac{\phi}{2} u_N(f), \tag{15}$$

$$u_T(f,\phi) = \sin\frac{\phi}{2} u_T(f). \tag{16}$$

So, the energy put on each mode and the amplitude of each component can be controlled by the phase. The control of the shape of the elliptical trajectory is due to the shift of resonant frequencies. For example, when considering the mode distribution of Fig. 38, the UPDs are operated close to f_T. The normal displacement is produced at a frequency above its mode f_N and is out of phase with the electrical excitation. The tangential displacement is produced close to f_T and is at 90° with the electrical excitation. Thus the two displacement components are shifted with about 90° phase, which is the last requirement for obtaining the elliptical vibration.

3.3.3. UPD driving and blocking forces. In good conditions (adapted pre-load, use of the two contact zones), the typical value of normal force which is controlled by a UPD20 is equal to 150 N (the force factor multiplied by two and by the maximal voltage). The maximal tangential driving can be equal to the product of the normal force by the friction coefficient of the contact interface between the stator and the mobile part. For instance, with a friction coefficient of 0.3, a blocked actuation force F_{St} of 45 N can be achieved as in the LPM20-3 for instance (section 3.4).

The blocked force F_B at rest without power supply is generally a bit larger than the actuation blocking force F_{St}:

$$F_B \geq F_{St}. \tag{17}$$

For example, in the LPM20-3, it gives a blocked force at rest of 50 N. Linear applications include forwarding devices (such as driving a sheet of paper in a fax machine) and linear Actuators.

The UPD can be also used either to drive different kinds of rotor (section 3.5). In rotating motors, the torque T_R and the rotation speed Ω_R depend mainly of the radius R of the contact strip of the rotor. These parameters are determined from the actuation force F_{St}, the tangential speed v_{St} and the number n of UPD used:

$$T_R = nF_{St}R, \tag{18}$$

$$\Omega_R = \frac{v_{St}}{R}. \tag{19}$$

The blocked torque T_B at rest without power supply is a bit larger than the actuation blocked torque T_R:

$$T_B > T_R. \tag{20}$$

The UPD owns its ultrasonic vibration decoupling means. This is necessary to avoid the transmission of vibrations. Also, the system to apply the preload is not contained in the principle shown in Fig. 35.

Two additional functions are necessary to reach good results:

- a play recovery mechanism to apply the preload and to maintain it in case of wear,
- a rotation blocking mechanism to insure that the driving force provided by the motor is delivered to the load.

Summary

- Piezomotors are driven at the resonance frequency and include a play recovering mechanism. They do not require any power supply to maintain their position.

3.4. Linear Piezo Motors LPMs

Using one or more UPD20 makes it possible to construct compact piezoactive motors such as the LPM20-3 (Linear Piezoactive Motor – Figs. 39 and 40). In the design of this motor, one UPD20 unit is placed between two guiding plates in contact with the ring tips. These plates are pre-loaded against the stator using a play recovery mechanism. In this structure, the stator moves being guided between the plates and drives the output axis in translation. This motor includes an elastic guide, which limits the stroke of the motor to 3mm. In counter parts, it operates without lubricant, which is impossible using conventional technologies (Fig. 40).

The LPM20-3 motor meets the needs of micro-positioning optics and instruments aboard observation satellites. For this reason, its first customer is the French Space Agency (CNES Toulouse). In this application, the real advantages of the LPM20-3 are

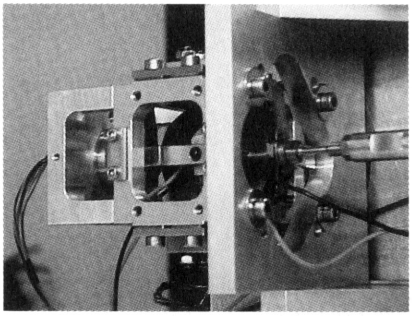

FIGURE 39. Linear Piezo Motor LPM20-3.

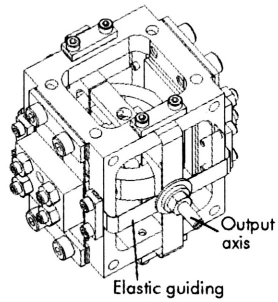

FIGURE 40. Schematic view of a Linear Piezoactive Motor LPM20-3.

a positioning resolution higher than 10 nm (the equivalent precision being obtained with an accurate sensor and a closed loop control); sufficiently high forces to hold loads of several kilograms during ground tests, and low electrical power and voltage requirement. In addition, this motor weights less and is smaller than equivalent conventional (electromagnetic) motors.

A typical load characteristic is shown on the Fig. 41. It is preferable (for tribologic considerations) to work in the first part of load characteristics curve.

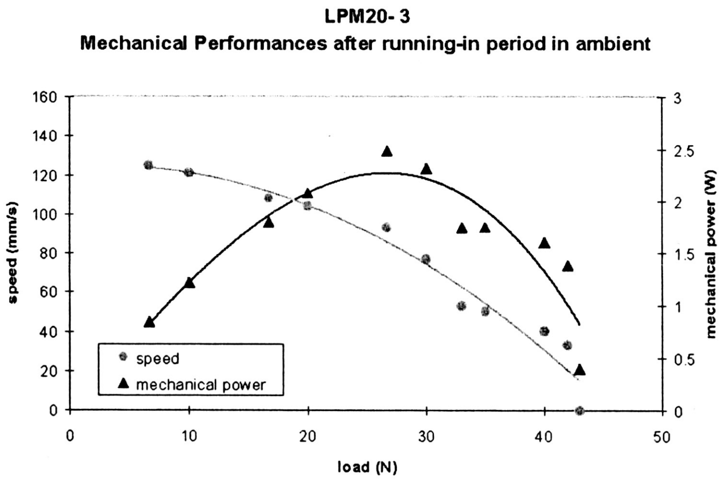

FIGURE 41. Load characteristics of the Linear Piezoactive Motor LPM20-3.

3.5. Rotating Piezomotors (RPMs) and others arrangements

The standard UPD20 unit can be arranged in several ways to obtain various motors, linear or rotary. Some possible arrangements are illustrated on Figs. 42 to 45.

These include the use of UPD20s to drive a roller, a large cup-type rotor, disc-type rotors, or a linear stage.

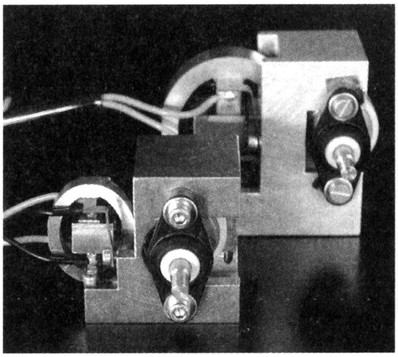

FIGURE 42. RPM based on an UPD20 unit driving an axis through a roller.

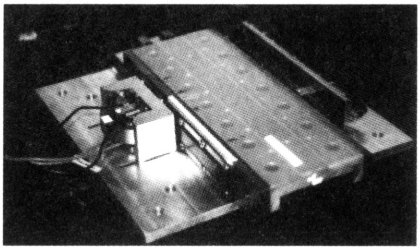

FIGURE 43. Using a UPD20 unit to drive a linear stage on a 100 mm stroke.

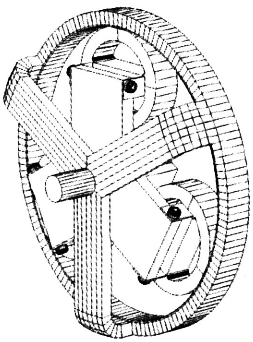

FIGURE 44. Using multiple UPD units to drive a large cup rotor.

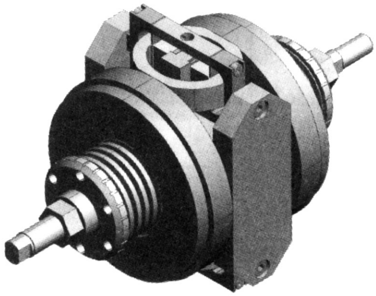

FIGURE 45. Using 2 UPD units to drive a double rotor.

Note that the advantage of the UPD20 units can be clearly seen comparing the motor of Fig. 33 (magnetostrictive version) and the motor of Fig. 45 (based on 2 UPD20 units). Both these motors use 2 disc-type large-radius (40 mm) rotors, but the piezoelectric type is much more compact.

The performance of all these motors can be estimated using the formula given in Sec. 3.3 and the properties of UPD units.

Several roller-type RPMs based on one UPD have been built and tested. For example the results on a RPM based on one UP20 are given in Table 2. Rotational speed and torque are measured directly on the motor. UPD20 in-situ forces and vibration speed are deduced from these results and from rotor radius. The mechanical power is presently about 2 W. Future works may be oriented to improve lifetime, to reduce size and to refine control of the motor in order to benefit from its high angular resolution. It is developed for the direct drive of axles of instruments. This RPM motor has also been successfully tested for forwarding paper sheet.

Using standard UPDs and by just taking larger rotors (Fig. 46) as in an already tested configuration [6], one can also obtain large torque disc-type motors (Table 2).

TABLE 2. Experimental results of a Roller-type RPM based one UPD20.

RPM blocking torque at rest	Nm	0.22
RPM actuation stall torque (AC)	N.m	0.19
RPM free rotation speed (AC)	turn/s	3.5
RPM resolution (AC)	mdeg	<1
Rotor radius	mm	11.5
UPD20 in situ tangent driving force	N	16.5
UPD20 in situ tangent driving speed	mm/s	250
Supply voltage (AC mode)	Vrms	9

Using this result, a new generation of small RPMs is developed for the direct drive of axles of instruments, for medical, scientific and space applications. For the medical application the objective of the piezomotor was a blocked torque of 8 Nm and a speed of 600 rpm, fitting approximately in a diameter of 20 mm and a thickness of 11 mm. This has led to the design of a new small UPD (13 × 16 × 11 mm) operating at about 60 kHz, driving a rotor of 5mm diameter. Experimental results of the motor in line with the objective.

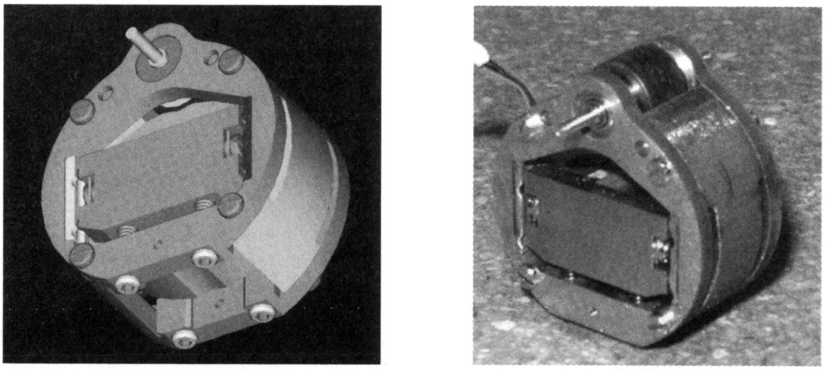

FIGURE 46. Small RPM (⌀ 20 mm) based on one UPD60 (CAD view and hardware).

4. Design of piezoactive devices and customized products

The range of standard Actuators from CEDRAT RECHERCHE is not always to sufficient to cover the specification of the customer application. Several situations may arise:

- the strokes of standard Actuators are not high enough,
- the standard mechanical interfaces are not well suited to the application,
- the application requests a mechanism more complex than a single Actuator,
- a special feature such as non-magnetism is required...

In all these cases, CEDRAT RECHERCHE can provide or help the customer in a fast and cost-effective solution combining its existing products, its experience and its development facilities such as Computer Aided Design-CADs sofwares and test equipments.

4.1. Design tools and test equipments

Piezoactive devices can be designed using numerical tools, as currently done at CEDRAT RECHERCHE:

- the ATILA® Finite Element software is used to model the Actuator behaviours including the piezoelectric coupling, the 3D structure, dynamic aspects and losses,
- the SIMPLORER® software allows to compute the Actuator with its driving and control electronics through block diagrams or equivalent electrical circuits,
- the IDEAS® software is used to develop mechanisms using several Piezoelectric Actuators.

Some examples of application of this CADs are given in the next section. Note that ATILA® and SIMPLORER® CAD programs are commercialised by CEDRAT RECHERCHE and MAGSOFT Corp.

Specialised test equipment available at CEDRAT RECHERCHE is also recommended to build piezo devices:

(a) (b)

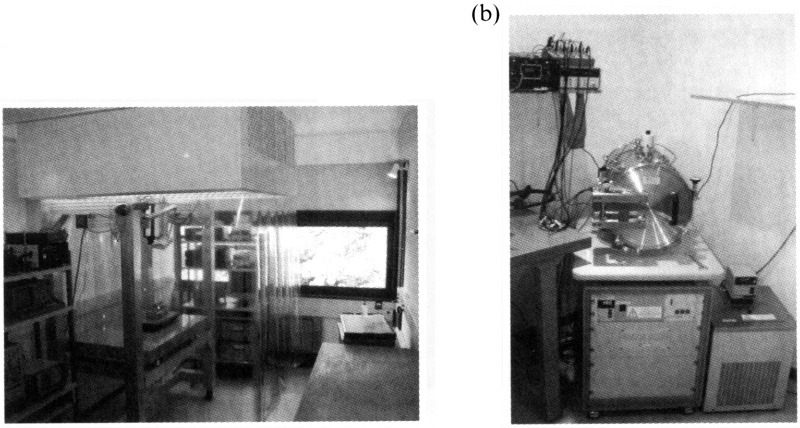

Figure 47. View of CEDRAT labs laser interferometer test bench (a); thermal Vacuum chamber (b).

- HP Impedance analyser is used for measurement of admittance curve, resonance and equivalent circuits,
- Polytech interferometers are useful to measure the Actuator main displacements as well as parasitic displacement with a high precision (Fig. 47a),
- Thermal Vacuum chamber allows for the analysis of the thermal behaviour and/or the effects of primary or ultra vacuum (such as Corona effect) (Fig. 47b).

The piezo devices described in the next sections have highly benefited from all these tools.

4.2. Super amplified Piezo Actuators

As APAs are compact and centered, they can be stacked in series to get a larger stroke. This has been used in a mechanism for a Magnetic Resonance Imaging (MRI) bio medical need for INSERM U438 (French Institute for Medical Research). 3 APA200M-NMs are stacked to get more than 600 μm. A second lever-arm increases the stroke up to 3 mm at 180 V (Fig. 48a), with a sub-micron resolution. Figure 48b allows a comparison between the ATILA model and the measured deformation. The parts including the APAs have been made non-magnetic to fulfil MRI needs. Because of planar design, the APA shells and the lever arm can be manufactured in a single piece to reduce mass and cost.

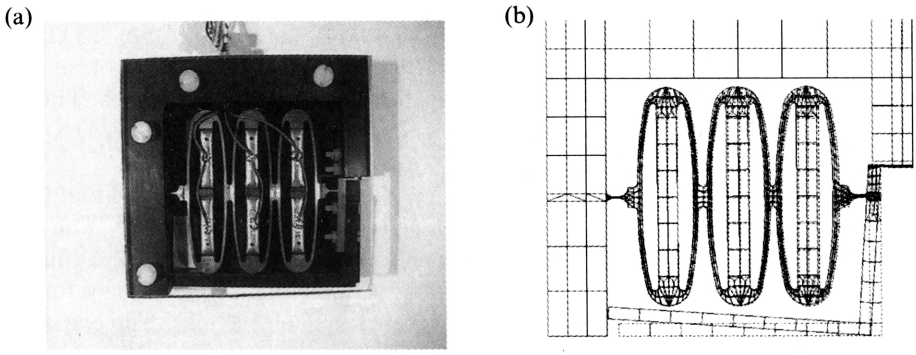

FIGURE 48. Super Amplified Actuators producing 3 mm of stroke and having a resonance frequency of 100 Hz: (a) Actuator; (b) corresponding FEM modelling.

4.3. 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 optical deflection. It is based on a 2 standard APA50Ss and a flexural hinge. In this mechanism, the Finite Element Method is useful for the design of flexural hinges, such as those employed in a tip-tilt mechanism (Fig. 49).

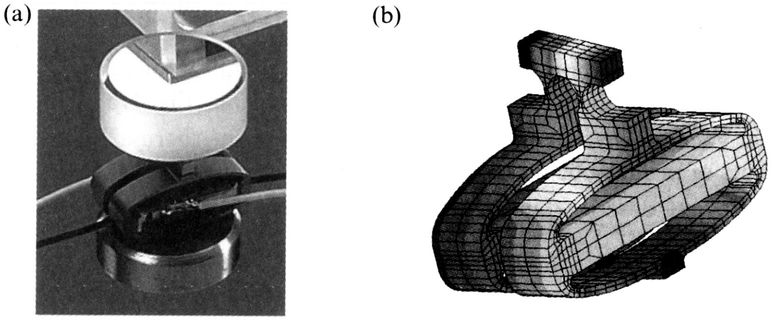

FIGURE 49. Tip-tilt TT50S (based on 2 APA50S Actuators) and producing an angular displacement of $\pm 0.5^\circ$ and a resonance frequency of 1800 Hz: (a) Actuator; (b) corresponding FEM modelling.

The TT50S model is now available as a standard product. Customised tip-tilts can be defined the same way using standard Actuators.

4.4. XYZ mechanisms

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 the 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 in the volume $[0, +100\,\mu\text{m}] \times [0, +100\,\mu\text{m}] \times [0, +8\,\mu\text{m}]$.

At first, the engineering model (EM) of an XY stage has been designed and tested. The design work has been performed with ATILA and I-DEAS (Fig. 50). The general concept is shown on the Fig. 50. 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.

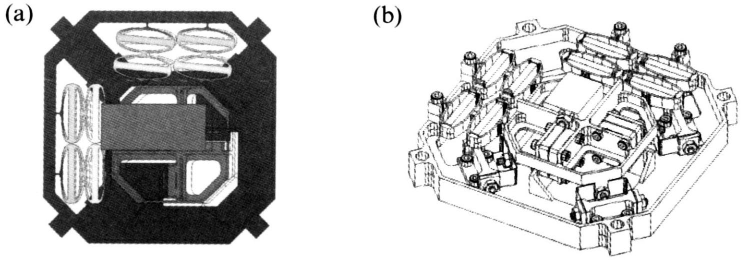

FIGURE 50. (a) ATILA FEM modelling of the XY stage; (b) I-DEAS view of the XY stage (EM).

In the Qualification Model (QM) (Figs. 51 and 52) 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. A Flight Model (FM) is being constructed for implementation in MIDAS and will hopefully flow in 2003 on ROSETTA (Fig. 53).

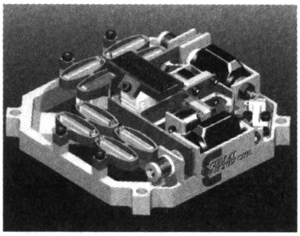

FIGURE 51. I-DEAS CAD view of a piezoelectric XYZ stage qualified for the Rosetta/Midas instrument.

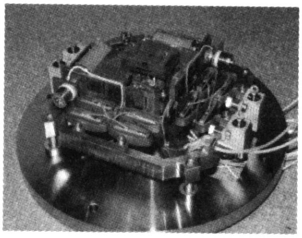

FIGURE 52. View of a piezoelectric XYZ stage qualified for the Rosetta/Midas instrument.

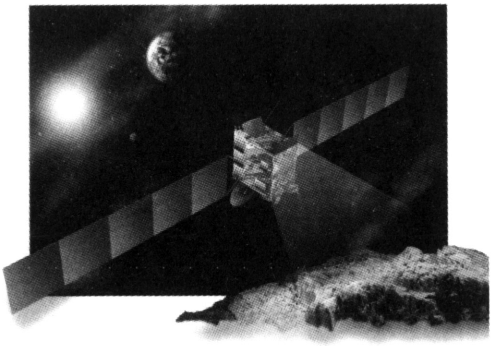

FIGURE 53. Rosetta spacecraft to be launched in 2003 (courtesy of ESA).

An industrial version of this stage, the XY100S, is also available. The concept used for Rosetta mechanism has been simplified by eliminating functions that are specific to space requirements, in order to reduce its cost.

An other example of XYZ mechanism developed for an optical application is given on the Fig. 54. This mechanism is able to perform any stroke in the volume $[-100, +100\,\mu\text{m}] \times [-100, +100\,\mu\text{m}] \times [0, 200\,\mu\text{m}]$. It is entirely based on standard components. It combines a standard XY200M stage based on 4 APA200M for centered XY displacements with a set of 3 APA200M for Z displacement.

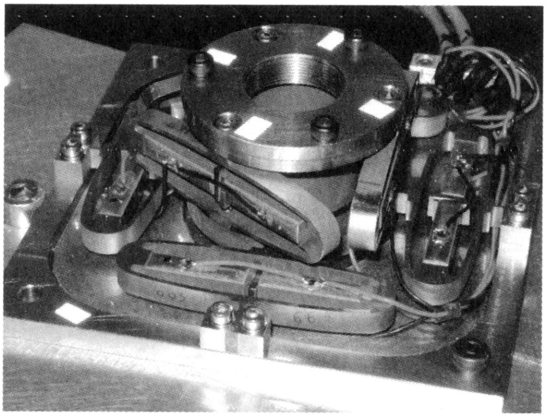

FIGURE 54. XYZ mechanism based on the XY200M and 3 APA200M.

4.5. Active control of vibrations

The new piezo actuators manufactured by Cedrat Recherche have been developed for the positioning control space optic but they are spreading widely in various engineering fields such as precise positioning, intelligent control of shapes and generation of vibrations. Their ability for the control or active damping of vibrations has been successfully demonstrated at the lab scale in space applications. In a first case, the piezo actuators were used for both for the control of launching vibrations and the positioning control in orbit of a telescope mirror. In a second set of space applications, these piezo actuators have been integrated in space truss using active tendons for control of micro vibrations.

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. 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 both bulky, has a limited lifetime and is not compatible with space requirements.

A recent work performed by ULB, Micromega Dynamics and Cedrat Recherche (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.

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. The proposed actuator (APA100M) is a pulling device and experiences an internal amplification mechanism. Therefore the heavy leverage mechanism used for the Direct Piezo Actuator (DPA) can be replaced completely by a 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. 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.

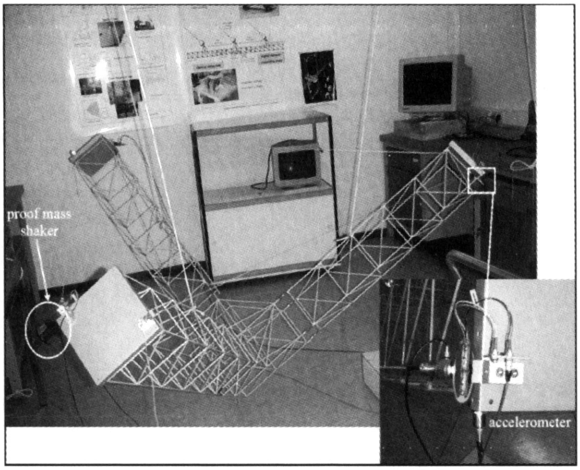

FIGURE 55. Space truss from ULB, integrating an active control of vibrations based on tendons actuated by APA100Ms.

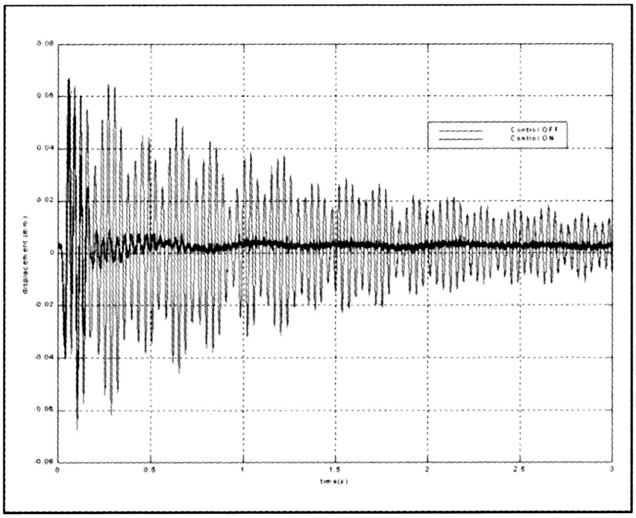

FIGURE 56. Truss vibration level after a shock excitation, without and with control.

4.6. Structural shape control mechanisms

ONERA Lille, the French Aircraft Institute, has developed a tilt mechanism based on APA230Ls for flap control of helicopter blades. ONERA found this solution 3 times more efficient than other tested solutions based on direct piezo actuators. As APAs are robust against transverse forces, they can bear the centrifuge forces. Successful tests at 1000g have been passed.

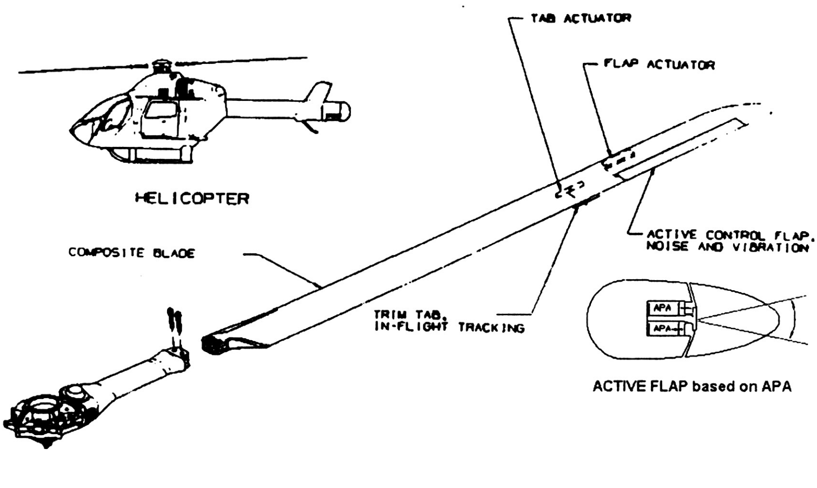

FIGURE 57. Actuation of an Helicoptere flap with 2 APAs.

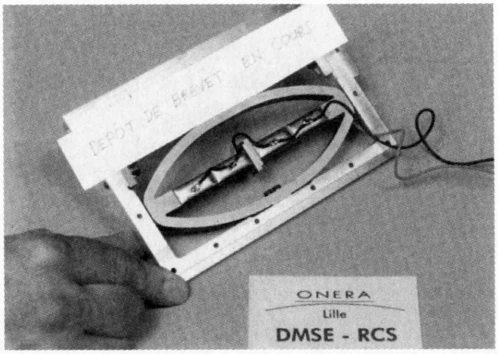

FIGURE 58. Helicoptere flap segment based on the APA230L, as designed by Onera, the French Aircraft Institute.

4.7. Valves, injectors and fluid control mechanims

Cedrat 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 offer a flow control proportional to the applied voltages. Applications vary from flow control in Scientific or Bio Medical Instruments to thrusters control for propulsion of micro satellites.

Piezo Injectors based on APAs offer a a very short response time, while being compact and potentially low cost. Their application for automotive industry is being investigated by CRF (FIAT Research Centre).

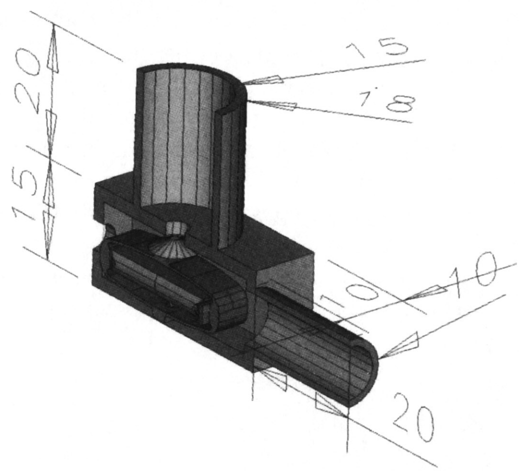

FIGURE 59. View of a proportional valve based on an APA100S for a Scientific Instrument.

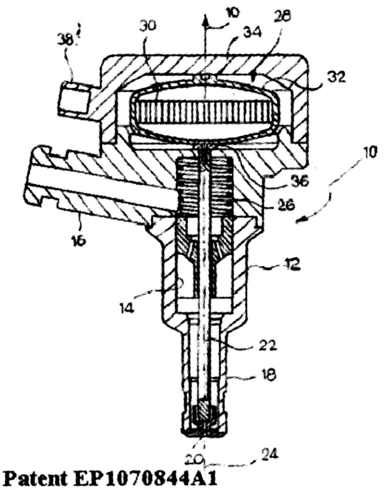

FIGURE 60. Car Injectors based on an APA, according to C.R.Fiat.

5. Conclusion

Several kinds of Piezo Actuators are available, but the Amplified Piezo Actuators APAs are the most widely chosen for building mechanisms because they are compact and robust. Additionally, they can be strongly integrated to get complete solid state mechanisms. This has been shown with super amplified actuators and with tip-tilt for optical, instrumentation and aircraft applications. This has been also clearly shown with a qualified XYZ stage for ROSETTA/MIDAS space instrument. Industrial XY stages and APA-based mechanism benefit of these works and also take advantage of their simple monolithic structure for offering flat, low cost and robust solutions.

Because much more innovative, Piezo motors based on UPDs are developed to customised applications. A great advantage of the Ultrasonic Piezo Drives UPDs is its versatility. The same stator can be used in very different linear or rotating applications, which allows it to fit with customer specifications in a much faster development time than other piezomotors such as TWUM. Due to their extended strokes, their high positioning resolution, their low power consumption Linear Piezo Motors already find several applications in space and in optics in replacement of electromagnets or stepping motors. Rotating Piezo Motors RPM also offer unique capabilities in terms of blocking torque at rest, per unit of mass and in positioning accuracy. Future development at CEDRAT about piezo products will lead to smaller UPDs for miniature motors.

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