PIEZO QUALIFICATION FOR SPACE APPLICATIONS

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Abstract

Piezoelectric actuators are generally deemed good candidates for driving compact and efficient mechanisms, offering advantages like fine precision, fast time response, low power consumption, cost and easier implementation. But to meet space applications needs, devices have to comply to many other requirements besides functional ones. So, a significant job was performed to study their capability to withstand space environment various constraints. Qualification tests results of a piezo manufacturing source would be here sum up and few recommendations highlighted. Today several mechanisms developments using piezo technology are on-going in the space sector. After a brief recall of Cedrat Technologies's Amplified Piezo Actuators original design, this paper presents the work spend on a fine positioning mechanism development for instruments on-board satellites. Development steps and tests results of the engineering model of this compact and innovating XY stage, will be used to point out some technical drivers in space applications.

1. Introduction

CNES is the French Space Agency, which has one major role in Europe promoting space applications and industry. One corner stone of this job is to investigate how to take profit of new or rising technologies such as piezo-actuators…

This kind of material are generally deemed good candidate for driving compact and efficient mechanisms, offering advantages like fine precision, fast time response, low power consumption, cost and easier implementation.

Mechanisms are considered as various systems including a moving part and that could be on a satellite: a cryo-cooler, a reaction wheel, a solar array driving system in space, a payload deployment arm, an antenna pointing mechanism or a fine positioning system for scientific instrument....

But to comply to space applications needs, devices have to comply to many other requirements besides functional ones.

That is the reason why the first part of this conference paper will present the significant job performed to qualify a piezo manufacturing source concerning material processes and quality insurance rules, but also to test its capability to withstand space environment requirements in terms of vibrations at launch, thermal range, radiations, high vacuum but also humidity during integration phase on Earth… Results of all these tests would be summed up and few recommendations for their use highlighted.

After a brief recall about the original 'Amplified Piezo Actuators' family designed with Cedrat Technologies, a fine positioning XY stage development description is finally proposed to underline some technical issues and drivers for space mechanisms. Main characteristics budget will be sum-up and a particular emphasis will be laid upon tests sequence and results on the 200µm stroke XY stage engineering model.

2. Piezoelectric multilayer component space evaluation

There is currently no normative standard to select a piezoelectric multilayer component or to characterize it, although a European standard is in preparation [1].

However in space field, European Cooperation to Space Standardisation documents establish the normative rules to qualify materials or EEE parts. In our case, multilayer piezoelectric ceramic stack is considered by electrical and manufacturing similarity as a single multilayer ceramic capacitor.

After a technical selection step of a kind of ceramic, basic procurement quality needs have been covered by its manufacturing processes examination. A set of piezoelectric PZT multilayer parts has therefore been subjected to various environmental conditions to help defining reliable conditions of storage and use for space applications.

Regarding Assembly, Integration and Test (AIT) activities on ground, piezo ceramic behaviour under DC voltage and humidity was studied. The health status of the few ceramic parts tested was characterized by their electrical admittance, maximum stroke and leakage current measurements.

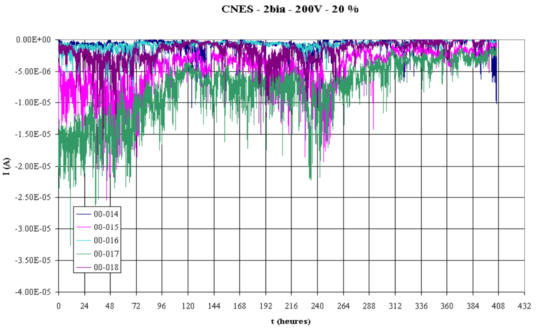

Fig.1 : Leakage current during life testing in air

Results show no degradation for tests performed under dry air (RH<20%), with a current leakage limited to less than few µA. However, working under higher humidity rate, very repetitive ON/OFF switches or during a 100 hours continuous use at maximum constant polarisation could lead to piezo ceramic electrical breakdown. Indeed, facts proved that this kind of failure is not always linked to leakage current value and to Corona effect. To the contrary, coating insulation and perviousness properties seem to be a clue element. So to be conservative, during satellite integration under clean room conditions with RH<50%, piezo continuous use at voltage up to 200V is recommended during periods of only less than one week each Nevertheless, other tests demonstrate that 10 billions of dynamic cycles at maximum stroke are achievable with suitable precautions.

With the high reliability required, other particularities of space applications is to operate in high vacuum and under radiations:

- Outgassing test shows a compliance to standard rules in term of total mass loss (TML < 0.1%) and condensed mass (CVCM < 0.01%). This able piezo devices to be used in scientific payloads near clean optics,
- A cumulated dose test under a gamma source was performed till 100krad with piezo stacks switched on under 200V DC without any degradation of their characteristics. Studying by analysis also heavy ion effect, piezo multilayer ceramic is globally found insensitive to space radiations environment.

Finally, a life test under a thermal vacuum chamber was done to qualify its operational range use in orbit. It concludes that this piezo multilayer is able to work in a temperature range of [-40°C; +80°C] during more than 2000h for a quasi-static use, which corresponds to operation mode and time often required for most of scientific missions.

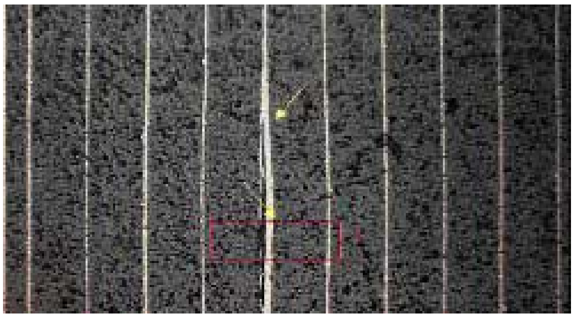

Fig.2 : Micro cut view of a MLA delamination

After this evaluation tests sequence, users guidelines have been defined for space programs together with a FMECA analysis, identifying the main failure modes and their causes :

- electrical breakdown, which is the most probable source of failure and is greatly enhanced by working conditions out of a suitable temperature range, voltage command or mechanical loads and particularly by the presence of humidity [2,3],
- delamination that could appear if any traction effort is applied on the ceramic stack (see Fig.2). Mechanical design has to satisfy this need of stress protection…
- and depolarisation, due to an excessive temperature, but what could be healed applying simple voltage command law.

3. Piezo-actuators design

Before to jump to space mechanisms design, a preliminary job was to robustify and improve displacement capability of the clue elements, that are linear actuators. Their structure is strongly required to be able to protect mechanically the piezo stack.

The original solution of Amplified Piezo Actuator (APA) developed with CEDRAT team during the 90's is based on the flexural-extensional principle of an elastic shell without hinge.

Even though this work has been widely published [4], the main features to remind must be pointed out:

- a good compacity relative to their stroke, achieving deformation of about 1%,
- a simple internal design and an easy interface to the user mechanical and electrical system,
- a ceramic preload sizing with the shell structure, which protect the piezo stack in a certain extend from external bending or twisting moments,
- an ability to be operated in a wide frequency range, from quasistatic till ultrasonic applications.

Modularity of this design allows the development of a whole actuator family, tuning easily characteristics depending on the functional needs required.

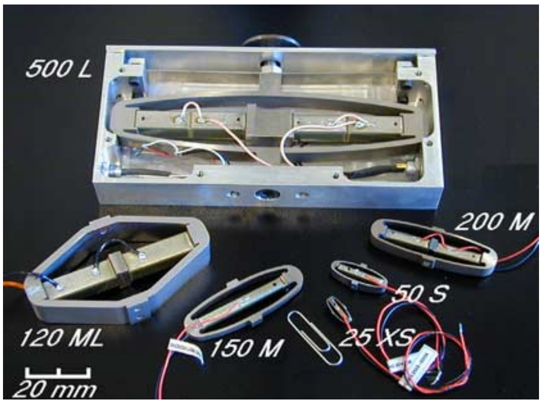

Fig.3 : View of different APA series (XS,S,M,ML,L)

Last R&D improvements in 2000 regarding the preload system drove to ML-PP upgraded series. For instance, the APA 120ML-PP actuator produces up to 120µm of free displacement and withstand till 1800N of force in its translation axis, instead of only 870N in previous ML design.

Direct as well as Amplified Piezo Actuators, based on a multilayer ceramic have become standard products [4], with a manufacturing process and a qualification status under space environment. They could be considered as a good basis to design multi-degree of freedom mechanisms, such as stages or tilting devices for various purposes like positioning or active control vibration [5].

4. Symmetric XY stage development

In a near past, XY stages have been already developed for space scientific payloads, such as a scanner for an Atomic Force Microscope on Rosetta mission [6]. Taking advantage of this heritage, the objectives of the work performed is to design a mechanism which is more simple to integrate and displays a good thermo - mechanical behaviour.

A symmetric centred XY stage has therefore been designed. Two amplified piezo actuators operate in a push – pull mode. It results that the non-energised and energised 0 position are almost equal : this is important for failure consideration and degraded behaviour.

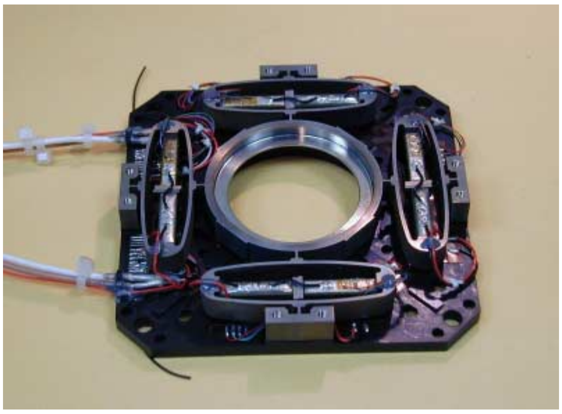

Fig. 4 : View of the damped XY stage

Two kinds of position sensors have been implemented : strain gauges and capacitive sensors.
The general characteristics of the stage are:

- Mass: 300 gr,
- Dimensions: 100mm x 100mm x 22 mm,
- Moving frame diameter: ~50mm

The stage is driven and controlled with a dedicated electronics including:

- a DC/DC converter,
- two channels including a linear AB amplifier, a Strain Gauges conditioner, a filtered Proportional – Integral controller.

Degree of freedom	Value
Translation Tx, Ty	150 µm
Parasitic translation Tz	1.5 µm
Parasitic rotation Rz	5 µrad
Parasitic rotation Rx, Ry	50 µrad
Cross coupling	2.5 % max
Closed loop results on Strain gauges	
Linearity error	< 1% of the total stroke
Stability	35 nm rms

Table 1 : Characteristics of the stage

The stability of the closed loop is affected by the residual micro – vibrations. For a constant order, the residual motion is observed on the capacitive sensors and a spectrum analyser. A residual motion of 35 nm is read, so that a noise to signal ratio around 1 / 5000 is obtained.

Finally, main characteristics budget of what could be at the end considered as an on-the shelf equipment is summed-up.

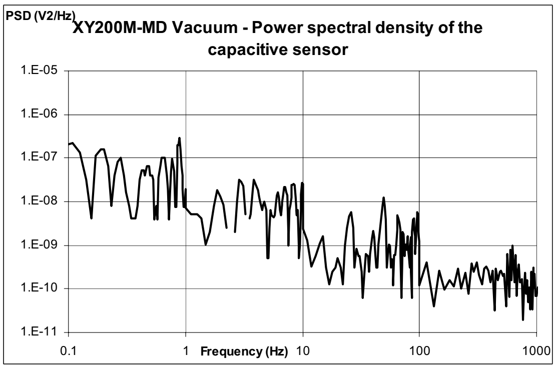

Fig.5 : Noise spectrum read on the capacitive sensors (gain 50 µm/V).

5. How to withstand mechanical loads

In addition to the functional performances required, strong mechanical loads, that space equipment's have to withstand, are also one critical design issue. They are sinus and random vibrations generated at launch phase, or shocks in orbit due to systems unlocking and deployment.

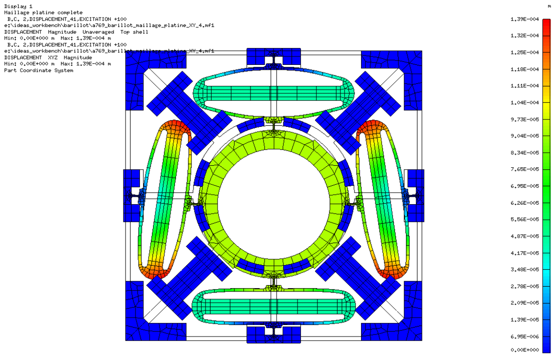

Fig.6 : Finite element simulation of the Y excitation

Studying the mechanism dynamic behaviour and every devices mechanical stresses, one common solution is to stiffen structural parts, implying often volume and mass issues. In this XY stage case, the first eigen mode is at 400Hz for a 100gr payload. However, excitation levels are still too important in this frequency range and the high quality factor of these devices amplify them too much.

Additionally, an other usual idea is to add a locking system to hold moving parts, but it adds complexities to the user's interface and increase the equipment cost. So two alternatives have been investigated...

On the one hand, a possibility to circumvent this problem is to mechanically damp the stage by adding a space qualified potting material in the stage. It results that the quality factors are decreased from about 100 down to 5.

On the other hand, an alternative is to limit the displacement of the payload under vibration by implementing a hard-stop. By experience, this device is rather difficult to integrate :

- a too short distance between the moving payload and the hard-stop will interfere with the functional behaviour,
- a too large distance between them will make the hard-stop no longer useful.

6. Evaluation tests results

The stage was submitted to a qualification campaign including a thermal vacuum tests, a lifetime test consisting in 10^6 full cycles, a sine and random vibration tests and a shock test.

The thermal vacuum test consists in 8 cycles between -25°C and 75°C. The main drawback of a damped solution is that the damping elastomer has a glass transition temperature around 0°C. It turned out that its Young's modulus is larger below 0°C, which means that the stroke is severely decreased below 0°C : at -25°C, the stroke became only 70 µm (40 % of the total stroke at room temperature).

The stage has been submitted to sine and random vibrations. The measured quality factors in the X and Y directions are near 6 (while on an undamped stage it is around 100). In the Z direction, the quality factor is around 25. The values here obtained shows the effectiveness of this kind of approach.

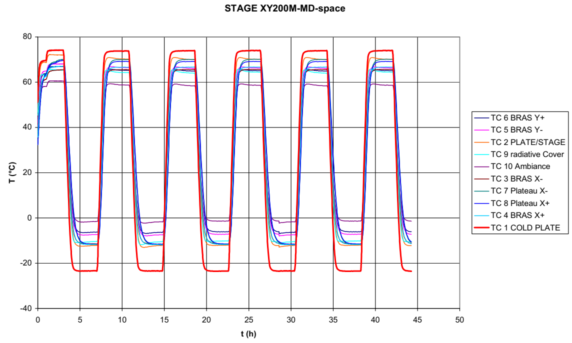

Fig. 7 : Thermal – vacuum cycles

Capacitive sensors seem to be preferable compared to strain gauges for their thermal stability. Strain gauges are still a good solution provided the temperature range is not high and offer a good accuracy since they are shielded by the stage frame.

7. Lessons learned and future development and perspectives

Qualification tests, summarised here before, conclude that kind of Piezo MLA are able to withstand a space environment. However, guidelines have to be take into account, in particular for Assembly Integration and Tests activities on ground. The last piezo developments for space applications, like ROSETTA mission and PHARAO instrument, show its good capabilities to design miniaturised and high precision mechanisms.

One lesson learned concerning the performances required is that control law is not the only clue, like with the choice of the sensor. The mechanical configuration is also very important… For instance, the use of flexible elastic pivots are preferable than hertzian pivots for fatigue aspects and thermo mechanical stability. The collision between the capacitive sensors and their targets on the moving frame that may occur during the vibrations remains a limitation for the payload mass. It can be circumvent by the use of hard – stops currently under study.

Push – pull mechanisms appear to be a good solution to build stable mechanism versus a large range of temperatures. This design philosophy can also be applied to double tilt - tip mechanisms (3 degrees of freedom). This double tilt tip mechanism can be placed on the moving frame of the stage to control 5 degrees of freedom.

Finally, innovating actions to lead about mechanical configuration to avoid locking device and about driving electronics simplification are factors that will promote piezoelectric based mechanisms use. Improvements on quality needed for space applications will profit to other terrestrial markets.

8. Acknowledgement

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9. References

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