Piezoelectric Actuators and Future Motors for Cryogenic Applications in Space

Christian Belly*, Francois Barillot* and Fabien Dubois*

Abstract

The purpose of this paper is to present the current investigation and advancements with piezo actuators or motors in a cryogenic environment especially from the space application point of view. Established performances obtained on cryo-dedicated Amplified Piezo Actuators (APA®) are given and extension of their capabilities is detailed using piezo motors, or Stepping Piezo Actuator. The Stepping Piezo Actuator (SPA) principle is shown in two innovative configurations, fully compatible with a cryogenic environment.

Introduction

High-precision piezoelectric-based mechanisms have already proven their capability to meet requirements for space applications in common temperature ranges. A new step is now underway to improve their operational range down to temperatures nearing absolute zero. Based on the latest experimental results, this paper presents this emerging capability for piezoelectric-based actuators, motors and mechanisms to meet this need.

First, Amplified Piezo Actuators are presented, and especially their cryo-dedicated version, with measurements down to 40K. Then, APA® integration within a piezo motor is shown, and experimental data, including low temperature (90K) experiments, are presented. After that, two new motor configurations are presented, with ambient behavior explanation before setting the perspectives offered by those newly available technologies.

Piezo Actuators in a Cryogenic Environment

Amplified Piezo Actuators

Amplified Piezoelectric Actuators (APA®) are linear actuators offering large deformations (from 1 to 10%) and medium strokes (up to 1 mm) [1]. They have been designed with an efficient mechanical amplifier and a pre-stress applied to the piezo ceramics. This design choice was performed initially to meet space requirements in order to offer a good ability to withstand external vibrations (due to launch). As a consequence of their pre-stress, they can perform the full strokes not only in static conditions but also in dynamic conditions including resonance and fast transient motion. As additional benefit, they are extremely reliable (lifetime is more than 10^{10} cycles), they have passed many aerospace qualifications, and they are selected in many EU and U.S. space missions [2]. Using the ability of APA® for dynamic motions, various mechanisms have been built: fast piezo shutters, fast tool servo, circuit breakers, micro scanners, proportional piezo valves, and piezo generators. APA® samples are visible on Figure 1.

Cryo Performance of Dedicated Amplified Piezo Actuators

The ability of piezoelectric ceramics and stacks to work in a cryogenic environment has already been shown in previous work [3]. Acquired knowledge has been used in order to design cryo-dedicated actuators, using an ingenious combination of materials in order to control thermos-mechanical behavior. In this study, several actuator characteristics, such as stroke, capacitance and creep are studied versus temperature, in a temperature range going from ambient to 40K. The interest in this knowledge is mainly valuable in terms of cryogenic-dedicated design.

---

* Cedrat Technologies, Meylan, France

Proceedings of the 43rd Aerospace Mechanisms Symposium, NASA Ames Research Center, May 4-6, 2016

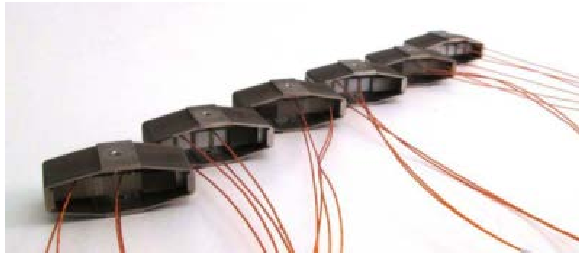

Figure 1. Cryo-dedicated Amplified Piezo Actuators

To be compatible with a vacuum and low temperature environment, an interferometric sensor FPS3010 has been used [3]. It provides reliable measurement from ambient to 40K.

Stroke is one of the main performance characteristics of piezo actuators. It is well known that stroke is reduced with low temperature. Stroke is measured using full stroke sinus command. Amplitude is extracted from the interferometer sensor (Figure 2). Full stroke drops from 95 µm to 37 µm (39%) for supplier #1 whereas it decreases from 81 to 17 µm (20%) for supplier#2.

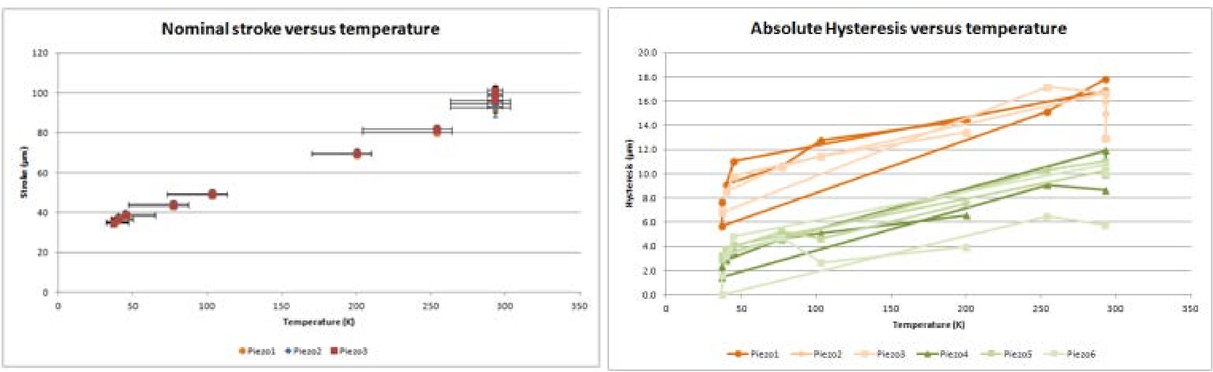

Figure 2. Stroke and hysteresis versus temperature

Stroke measurement is also used in order to obtain hysteresis information. Hysteresis is an intrinsic characteristic of piezo actuators. Two suppliers' preloaded stacks are compared at temperatures from ambient (293K) to 35K. It is seen in Figure 2 that hysteresis amplitude is reduced with deceasing temperature. Moreover, supplier #1 actuators are producing higher hysteresis. Supplier #1 actuators reach 20% of full amplitude compared to 10% for supplier #2.

Piezo actuators are assimilated to capacitance from an electrical driver view. The actuator capacitance is determining the bandwidth of the group {electronic + actuator}, due to amplifier current limit. Therefore, this characteristic is important considering driving philosophy or in the case of charge control of piezo actuators. Capacitance versus temperature is plotted in Figure 3. It can be observed that capacitance tends to stabilize at approximately 20% of its ambient value when decreasing temperature.

Position creep is a slow change of actuator position that appears after a constant voltage has been applied. In open loop operation, position is slightly increasing with time, unfavorable to stability. This creep is generally characterized by a logarithmic law [4]. It has been observed, as presented in Figure 3, that creep increases with low temperature. However, this behavior is removed after cycling. Therefore, cycling seems to be good practice before functional actuation of piezo in a cryogenic environment.

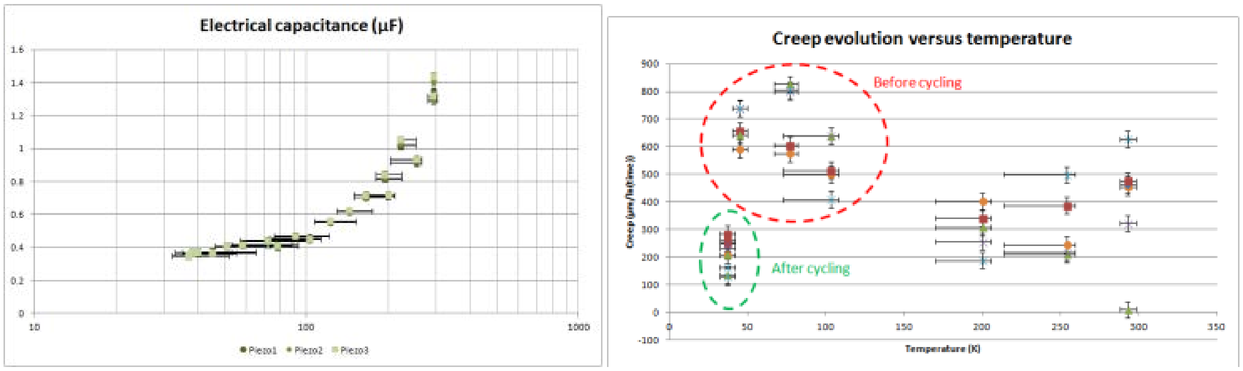

Figure 3. Capacitance and creep evolution versus temperature

Reduction of stroke due to temperature limits piezo actuators even more due to their short stroke. Moreover, even if static power consumption is low, position is not kept when power is cut. Therefore, when larger stroke and/or holding force with no power consumption are needed, piezoelectric motors become relevant.

Piezo Motors

An APA-based piezo motor is presented with its working principle. First, low temperature results are presented, giving a first indication about the technology potential. After that, two innovative linear motors, based on a similar principle are presented.

Stepping Piezo principle and low temperature compatibility

Stepping Piezoelectric Actuators (SPA) are long-stroke linear inertial piezoelectric motors for micro/nano positioning applications benefiting from the advantages and the heritage of the APA®. SPA is a way to expand the limited stroke of the APA® to centimeter-length strokes. This feature is achieved using the IDM principle [5].

SPAs are formed of only four parts: the APA®, a front mass, a clamp, and a rod. SPA operates through the accumulation of small steps, using inertial mode, impact forces and stick-slip effects as introduced in [6]. Typically, a slow APA® actuation generates a slow motion of the mass while the rod sits in the clamp. A fast APA® actuation induces a fast motion of the rod slipping in the clamp. This allows getting steps, which gives a long stroke, called the stepping mode (M1). Between each step the actuator is locked in position [7].

The load may be fixed on different positions leading to two different motor capabilities thanks to different modes. In a first configuration offering nano positioning (Figure 4), the load can replace the mass or can be fixed to the mass. So when the long stroke (M1) is performed, the motor can be also operated in a deformation mode (M2) for a fine adjustment. In this case, the stroke is proportional to the applied voltage, which leads to a nanometer resolution and a high bandwidth (limited by motor blocked force). In a second configuration, the load is fixed on the moving rod. In this case, the advantage is a high stiffness, but fine mode is not available.

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

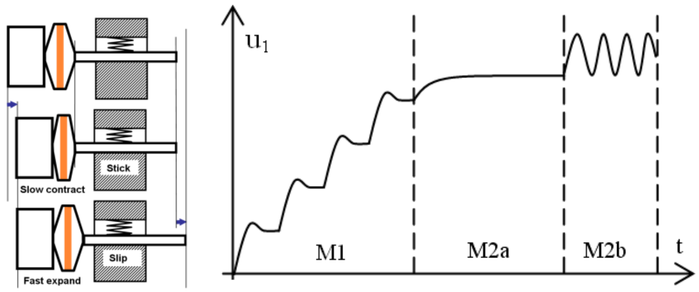

Figure 4. SPA components and principle: stepping mode (M1) and deformation mode (M2)

The large deformation stroke of the APA® is also an advantage. It provides a useful deformation stroke mode (M2). It also contributes in getting good speed in long stroke mode (M1); larger steps per cycle compensate for a lower step frequency. Benefits from amplification in the Impact Drive Mechanism have been demonstrated in [8].

Low temperature tests were performed on a SPA40SM (based on middle range APA®) from 0°C to -180°C, the lowest temperature allowed by the test rig. Speed is affected with a linear speed reduction with temperature. This is fully correlated with actuator stroke reduction. The force results are shown in Figure 5. It can be seen that a drive force reduction is observed at lower temperatures, but not lower than 75% of nominal force achieved at ambient temperatures. However, after every temperature cycle, the performance is recovered upon returning to room temperature, showing no continued reduction in performance after periods of exposure to low temperatures under vacuum.

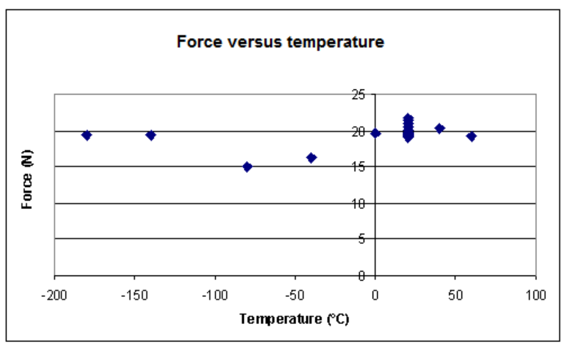

Figure 5. SPA40SM Force versus temperature [9]

<u>Module Stepping Piezo Actuator</u>

In typical SPA motors, the clamp is moving by friction at a variable distance from the actuator. This creates a limitation in stroke, hyperstatism with potential bearing, reduction of force with the distance, and constraints in new mechanisms design. In comparison, Module SPA (MSPA) frees the rubbing contact so the distance between the friction force and the APA® electromechanical force remains at a constant distance. It is able to drive any type of body by friction in linear or rotary motion depending on the guiding.

First implementation is based on a linear piezo stage. This type of stage is relevant for optics motion, or sample positioning, but is currently limited in stroke. The MSPA configuration is used in order to move a 30x30x10 mm^3 device and is presented on Figure 6. A representative configuration using a dummy lens to simulate an optical zoom or focus system has shown its capability to perform long stroke (200 mm) with a speed of 15 mm/s.

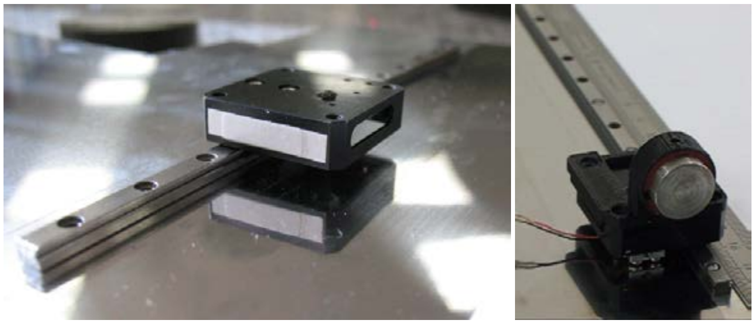

Figure 6. MSPA combined with 200-mm stroke guiding in linear configuration + with dummy lens

Another possible requirement is constant speed all along the stroke. MSPA is used to produce a linear displacement and uses inertia principle to disrupt the friction contact and restart a new ramp of displacement. This creates a linear constant speed displacement for the moving module, or moving mass. Figure 7 presents an example of displacement for a few test masses. Linearity of displacement can be observed. For more stringent requirements, a closed-loop solution has been implemented.

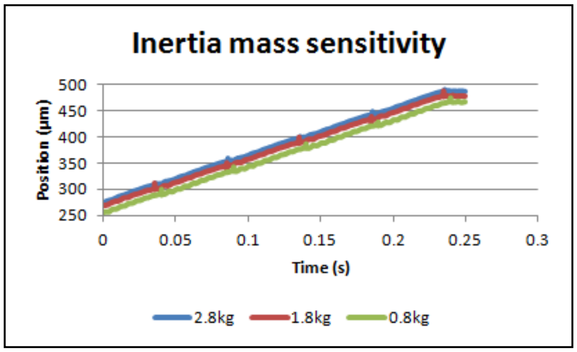

Figure 7. MSPA displacement example

Force Stepping Piezo Actuator

The second type of configuration is also based on Stepping Piezo Actuators. The internal structure of FSPA (Figure 8) allows decoupling high external forces from actuation mechanism making the motor compatible with high load and high levels of vibration. A prototype has been built to support a more than 600-N external force without losing its position.

Figure 8. FSPA motor prototype

Another major advantage of this second configuration is the strong resolution that can be reached. In order to show motor resolution, step-by-step signal is applied and position output is controlled using capacitive sensor. Figure 9 presents the results obtained on the motor. Resolution of steps below 20 nm is shown. This corresponds to a 1.2 µm/min speed. The speed reached with a 20 Hz and full voltage amplitude signal is 75 µm/min.

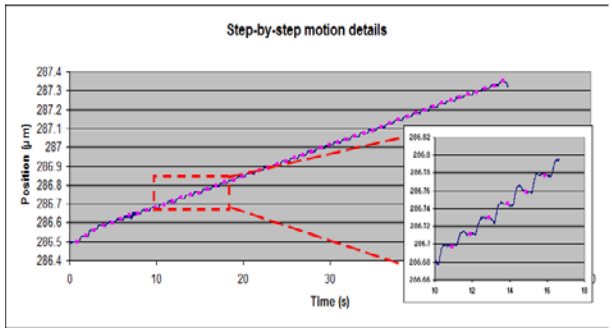

Figure 9. Motor displacement and resolution (mean step = 20 nm)

Cryo applications and perspectives

The presented configurations and associated results are fully compatible with cryo-dedicated actuators. The impact of temperature on SPA motors are mainly about speed (due to actuator stroke reduction), but not on force. Therefore, performances obtained on MSPA or FSPA should be fully comparable and allow targeting specific cryo needs. One example is the GAIA M2M pointing mechanism, with 70-nm resolution on 550-µm travel in a temperature range from ambient to 100K [10]. Other cryo needs have been identified through the EChO mission [3]. Low temperatures (30K) are combined with high shock levels (2000g), targeted by FSPA usage. Typical 10-100 N actuation force and 200-N to 2000-N holding position force are fully in the field of competence.

Conclusion

In this paper, results obtained on cryo-dedicated Amplified actuators are shown with respect to temperature influence from ambient to 40K. Compatibility of performances with positioning application is proven but intrinsic limits in terms of stroke have to be overcome; proposed solution is piezo motor. The SPA concept is reviewed and applications within two new configurations are shown. Interesting advantages and performances obtained at ambient temperature are correlated to a cryo-dedicated Actuator in order to give the reader the potential of the combination of technologies.

Acknowledgment

Cryogenic piezo actuators have been tested within the R&T program from CNES. TV facilities at Toulouse center have been used. The authors want to thank Laurent Cadiergues and Daniel Gervaud for their support.

References

1. Le Letty R., Claeyssen F., R., New amplified piezoelectric actuator for precision positioning and active damping, *Proc. SPIE Vol. 3041 Smart Structures and Materials,* (1997), pp. 496-504
2. Allegranza C, Gaillard L., Le Letty R., Patti S., Scolamiero L., Toso M., ”Actuators for Space Applications: State of the Art and New Technologies”, *Proc. Actuator 2014*, Bremen
3. Belly C., Hihoud M., Pages A., Argelaguet H., Moreno J., Mangeot C., “Cryogenic piezo characterisation and integration in Fine Steering Tip/Tilt Mechanism”, *Proc. Actuator 2014*, Bremen
4. Junga H., Gweon D., “Creep characteristics of piezoelectric actuators”, *REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 71, NUMBER 4*, (2000), pp. 1896-1900
5. Higuchi, T. “Apparatus and method for effective fine movement by impact force produced by piezoelectric element”, (1987) EP0292989
6. Higuchi T., Yamagata Y., Furutani K. & Kudoh K. “Precise positioning mechanism utilizing rapid deformations of piezoelectric elements", *Proc. of IEEE Workshop on Micro Electro Mechanical Systems*, (1990), pp.47-51
7. Claeyssen F., Ducamp A., Barillot F., Le Letty R., Porchez T., Sosnicki O.& Belly C., “Stepping Piezoelectric Actuators based on APAs”, *Proc. Actuator 2008*, Bremen
8. Belly C., Charon W., “Benefits of amplification in an inertial stepping motor”, *Mechatronics 22 (2)*, (2012), pp. 177-183
9. Belly C., Buttery M., Claeyssen F., “THERMAL VACUUM BEHAVIOUR OF A STEPPING PIEZO ACTUATOR”, *14th European Space Mechanisms & Tribology Symposium – ESMATS*, (2011)
10. Compostizo C., López R., Rivera L., “GAIA M2M POINTING MECHANISM QUALIFICATION”, *14th European Space Mechanisms & Tribology Symposium – ESMATS*, (2011)