

Cryogenic Piezo Characterisation and Integration in Fine Steering Tip/Tilt Mechanism

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Abstract:

High precision cryogenic applications are demanding domains that require precise knowledge of component performance. In the case of active components such as piezoelectric actuators, such knowledge includes stroke, capacitance and Coefficient of Thermal Expansion (CTE). These parameters are difficult to define with precision because of the combination of small displacements and low temperature sensor compatibilities. A high stability and low sensibility test bench is required to obtain such results.

This paper details a test bench design and the results obtained with CNES on a two piezo ceramics stacks, from 2 distinct suppliers. Integration into dedicated cryo actuators is also proposed as well as the associated cryo performances. The use of such cryo compatible actuators is detailed in a fine steering tip-tilt mechanism designed to reach very high resolution and stability for the ESA EChO space mission.

Keywords: Cryogenic, Piezo, Tip-tilt, Fine steering mechanism.

Introduction

This paper concerns piezo actuators in cryo conditions as those of EChO space mission. It is divided into two main sections.

The first one deals with cryogenic piezo ceramics characterisation. This part details a dedicated test bench design developed with CNES and gives the results obtained on two types of piezo ceramics. Functional characteristics, such as full stroke, hysteresis and capacitance are studied in a temperature range from ambient to 40K.

The second part concerns a cryogenic tip-tilt mechanism for ESA. Adapted to very high precision motion within a low temperature ambiance, the mechanism design and associated testing apparatus are presented.

Cryogenic characterisation

Test bench design

Low temperatures and high precision impose strong constraints on mechanical design and sensors. This section describes the test bench philosophy. High precision (down to sub micrometric measurement) is achieved, using vacuum and low temperature environment compatible interferometric sensors FPS3010. Thermo mechanical behaviour is obtained using a differential structure test bench. Coupled with axisymmetric mechanical structure, the proposed test bench allows measuring small dimension variations, as well as long term variation (such as thermal changes). The test bench is visible in Fig. 1.

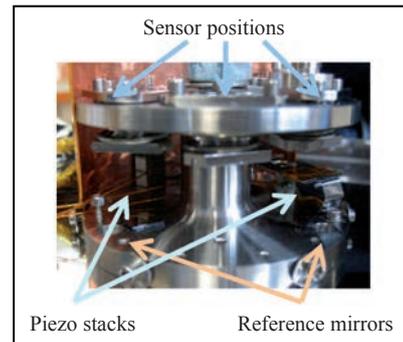


Fig. 1: Cryo characterisation test bench

Several piezo characteristics, such as capacitance [1], stroke [2], are studied versus temperature, in temperature range going from ambient to 40K. The interest in this knowledge is mainly valuable in terms of cryogenic-dedicated design.

Coefficient of Thermal Expansion (CTE) has not been measured during this test because of test bench unexpected results. Indeed, reference mirrors don't give similar feedback during the entire temperature range (from 300K to 35K). This leads to high uncertainty. Therefore, dilatometer has been used to obtain information on this characteristic from ambient to 150K.

Characterisation of two ceramics stacks from two different manufacturers is performed. This helps to compare the performance of each within a given cryogenic environment.

Stroke

Stroke is one of the main performances of piezo actuators. It is well known that stroke is reducing with low temperature, however, dimensioning of a dedicated cryo actuator needs precise data. Therefore, stroke is measured using full stroke [-10;+150V] sinus command. Amplitude is extracted from interferometer sensor. Full stroke drops from 12 μ m to 4 μ m (30%) for supplier #1 whereas it decreases from 10 to 2 μ m (20%) for supplier #2. tests are made on empty stack and preloaded piezo stacks.

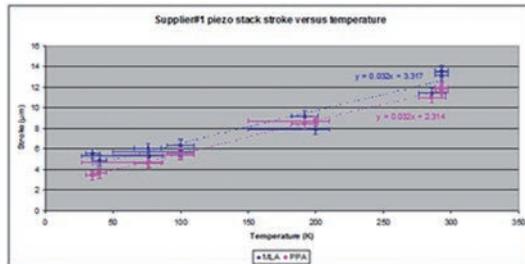


Fig. 2: Stroke versus temperature for supplier #1

Hysteresis

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 Fig. 3 that hysteresis reduces its amplitude with decreasing temperature. Moreover, supplier #1 actuators are producing higher hysteresis. This one reaches 20% of full amplitude compared to 10% for supplier #2.

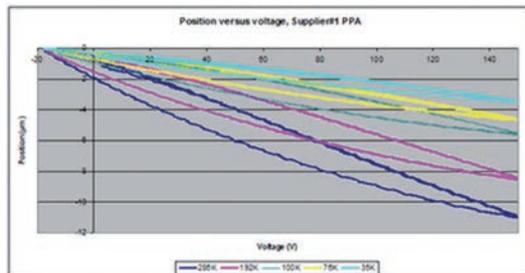


Fig. 3: Hysteresis versus temperature for supplier #1

Capacitance

Piezo actuators are assimilated to capacitance from driver view. The actuator capacitance is ruling the bandwidth of the group {electronic + actuator}, due to amplifier current limit. Therefore, this characteristic is important considering driving philosophy. Capacitance versus temperature for both suppliers' actuators is plotted in Fig. 4. Exponential behaviour of capacitance is visible for each kind of piezo ceramics. Comparison between unloaded and preloaded stacks shows a slight increase in capacitance with preload. It also can be observed that capacitance admits an asymptotic behaviour down to 100K, saturating at approximately 20% of ambient value.

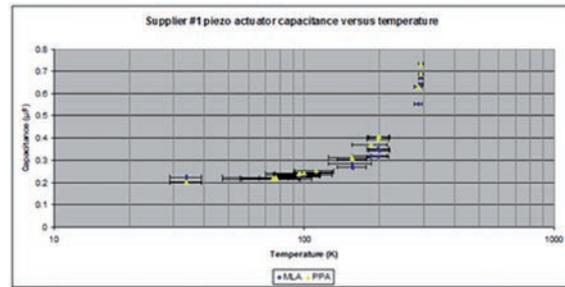


Fig. 4: Capacitance versus temperature for supplier #1

Cryo test bench conclusions

Designed test bench showed limitations facing large thermomechanical variations. Indeed, interferometer lasers need correct alignment to provide reliable and stable output. This alignment may not be guaranteed throughout the 300K to 40K transition. This leads to incoherent measurements that still have to be solved with a future design. However, very low temperature settings are showing good results, allowing data to be obtained for major piezo characteristics, such as stroke, hysteresis and creep (not presented in this paper)...

This kind of information is mainly involved in Hollow Parallel Pre-stressed Actuator (HPPA) or Amplified Piezo Actuator (APA[®]) design, dedicated to cryogenic operations. This leads to applications for cryogenic mechanisms as described in second part of the paper.

Cryogenic mechanism design

The use of Cryogenic Fine Steering Mechanism (CFSM) for astrophysics space mission such as EChO should ensure the stability of line of sight when used in closed loop within the AOCS.

A limited high precision tip tilt mechanism has been designed for ESA to produce +/- 0.75 arcsec Rx and Ry rotation within a cryogenic environment (Fig.7).

The entire CFSM is based on EU components only which make it ITAR free by design. Thermal coupling are minimised: the only source of heat within the mechanism comes from the piezo component. These actuators intrinsically minimise thermal coupling with the mirror since they are based on piezo electric material. In that regard piezo technology displays less dissipation in comparison to other technology such as magnetic actuator.

The CFSM is equipped with four piezo actuators. The control of four actuators in open loop allows them to be driven in a push pull configuration. This opportunity eases the driving approach.

Due to differential thermal expansion and the impact on performance, a cryogenic application requires careful design of the piezo actuator. For Noliac, performance data and experience with the design was acquired in the field of cryostat instrumentation,

space and large science applications [3, 4]. Tests performed on Noliac ceramics encompassed a very wide range of environmental conditions, including temperatures down to 2K, pressure down to $1.3 \cdot 10^{-10}$ mbar and neutron radiation [5]. For the Cryogenic FSM tip/tilt platform, a specific actuator was produced (see Fig. 6.), which included features for optimum performance and reliability in the CFSM application.



Fig. 5: Custom-made piezo stacks for FSM tip/tilt platform and HPPA actuator

The specific features include:

- Double electrode connections (therefore 4 wires per stack) in order to limit the impact of a wire or solder failure +visual check
- UHV-compatible wires and process
- Reduced tolerance on height, flatness and parallelism for ease of integration
- Pre-ageing of 10^7 cycles to stabilise performance
- Additional Lot Acceptance Test (LAT): including spectrum, blocking force, insulation resistance and Destructive Physical Analysis.

Cedrat Technologies proposed to use the space qualified Hollow Parallel Pre-stressed Actuator (HPPA). HPPA is a Direct Piezo Actuator (Fig. 6). The pre-stress is applied through a monolithic pre-stressing body avoiding stick slip effects. These four actuators are integrated into a titanium compliant structure that holds a $\varnothing 60$ mm titanium mirror. The CFSM is design according to the ECSS margin: It is compliant with environmental random vibration ($17g_{rms}$) and shock ($700g / 10$ kHz) without any additional Hold Down and Release Mechanism (HDRM).

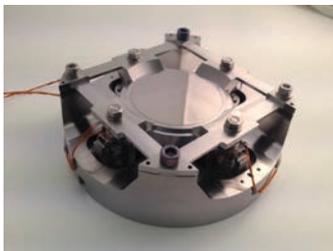


Fig. 6: Fine Steering Tip-tilt Mechanism

Ambient mechanism testing

This engineering model (Fig. 6) is first fully tested at ambient temperature by means of dedicated equipment, instruments and ground support equipments.

The power consumption is measured in piston mode at 10Hz (Fig. 7). It displays less than 1mW dissipated power at ± 0.75 arcsec ambient.

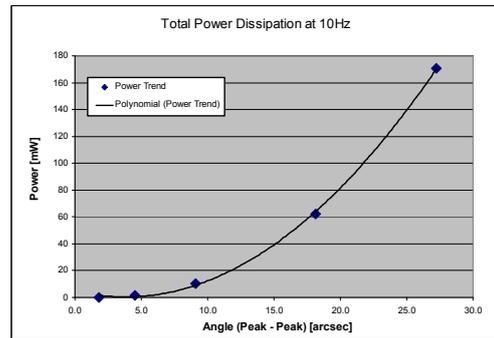


Fig. 7: CFSM power consumption in piston 10Hz.

The CFSM resolution is obtained by measuring the signal to noise ratio of the command chain. The HP35665A Signal analyzer is used in AC mode. The power output is acquired along a 16mHz to 100Hz bandwidth to trace the resulting PSD (in nV^2/Hz). Then, the equivalent electrical noise in μV_{rms} is computed.

The measurement gives an SNR equal to 107.5dB corresponding to a noise of $375\mu V_{rms}$. The maximal stroke being 42arcsec for 170V, the CFSM resolution is then $92.2 \mu arcsec$.

Table 1: Ambient performances of CFSM

Performances	Value
First Eigen frequency	2610 Hz
Max Tip/Tilt range (170Vpk-pk)	± 20 arcsec
Max. Piston range (170Vpk-pk)	$\pm 4.50 \mu m$
Sensitivity to gravity	$< 70nm$

Cryo mechanism testing

With the objective of characterizing the thermo-mechanical performances of the CFSM under cryogenic temperatures two main activities were performed:

- Design of a dedicated MGSE for cryotesting activities
- Cryogenic Test campaign elaboration

A MGSE was designed whose main design drivers were to eliminate distortions and/or non desired movements which could modify the actual performances of the CFSM. For this purpose, all the parts of this MGSE are made of the same material of the CFSM, Ti6Al4V, this included all screws, to avoid differential contractions and therefore removing any induced stress.

The main performances to be verified during cryogenic test campaign were: Resolution (± 0.001 arcsec equivalent to ± 0.14 nm for 30mm mirror radius), Range of CFSM (± 2.48 arcsec), Max Angular drift & piston drift, Lifetime (full stroke at nominal operating frequency: 2 months on ground, 5.5 years in orbit).

Some of these performances are critical requirements, for example the verification of the angular resolution, which is equivalent to 0.14nm linear resolution at 30mm radius. This resolution is current state of the art for sensor technology. For this reason specific high accuracy instrumentation was selected including capacitive sensors and optical interferometer and Autocollimator.

Additionally the testing methodology was defined, taking into account the following error sources: Thermal instabilities during cryo testing which can lead to measurement inaccuracies; Non representative interface that could drive to non-representative thermo-elastic behaviour; Mechanical and electric noise that could affect the measurement accuracy.

Cryogenic tests Results

Cryogenic tests have been carried out inside a Cryostat chamber at 30K stabilized temperature, where the CFSM was assembled on a dedicated opto-mechanical MGSE structure as shown in Fig.8.

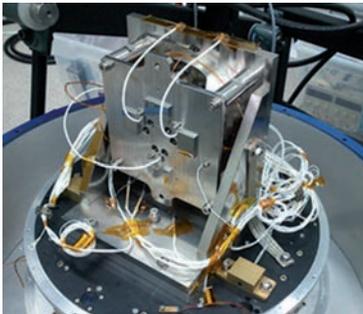


Fig. 8: Cryogenic Set up

Angular and linear performances of the CFSM were measured at its nominal operation temperature (i.e. 30K) obtaining the results summarized in Tab.2.

Table 2: Cryo performances of CFSM at 30K

Performances	Value
Nominal Frequency	10 Hz
Nominal Tip/Tilt range	± 0.75 arcsec
Max. Tip/Tilt range	± 6.21 arcsec
Max. Piston range	± 1.57 μ m
Resolution at max. Tip/Tilt range	± 2.2 marcsec
Power consumption per actuator at nominal movement	0.467 mW

Resolution shown in Tab.2 is given at the maximum Tip/Tilt range this is improved when the movement range is decreased, reaching resolutions of 1 marcsec at ± 2.25 arcsec (much higher than the nominal range). Resolution measured is also directly depending on the electronics resolution, for that reason, improvements of this part would improve the total mechanism resolution.

Parasitic motions of the CFSM in open loop were also measured at cryo temperatures obtaining results below $\pm 0.1 \mu$ m and ± 0.29 arcsec during Tip/Tilt movement at its maximum range.

A specific test was developed to measure the thermo-mechanical drift occurred during four thermal cycles from ambient temperature to cryogenic temperature (i.e. 30K) between CFSM attached points and the CFSM mirror attached points reaching values of 45μ m (linear at the centre of CFSM mirror).

An accelerated Life Test at 800Hz is currently being carried out under cryogenic temperature at the moment of this paper, in order to verify the 5.5 years continuously working requirement for space and cryo environments.

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