Nanometric Linear Piezo-Actuator with Integrated Strain Gages for High Stability Positioning

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Abstract:
Many applications require a mechanism capable of nanometric resolution position tuning, and with the ability to maintain perfectly this position for a long time (more than several days). For those applications, piezo-actuators are a perfect fit since they easily provide nanometric resolution. However, they require the use of a position sensor to be able to maintain stable position over time. Until now, the long-term stability of strain gages (SG) for position measurement was questionable. Using its extensive know-how of strain gages integration and new instrumentation equipment, Cedrat Technologies has managed to demonstrate the ability of a piezo-mechanism with integrated strain gages sensors to achieve nanometric position stability. This technology opens new possibilities for industrial, aeronautical, and space applications.

Keywords: Piezo, Strain Gages, Nanometer, Stability, Space

Introduction

In most applications, compactness and cost are important issues. This is even truer for space applications. Piezo-mechanisms offer a compact solution, with high resolution, long lifetime, and high reliability. The major drawback is that those actuators suffer non linearities, such as hysteresis and creep effect, requiring closed-loop control with position sensor. Cedrat Technologies has experience with integrated Strain Gages (SG) sensors to linearise the position of its piezo-mechanisms, in order to obtain fine precision and stability. The SG technology has space heritage, since it is already used in Rosetta [2] and selected for other space programs [1]. Contactless sensors such as capacitive or eddy current position sensors are well known as accurate sensors, but their volume and cost are major drawbacks, especially for multi-axis systems.

This paper presents a new space compliant PPA40M-SG-based push-pull mechanism (see Fig. 1), called “NLA” for Nanometric Linear Actuator. This actuator is equipped with strain-gages that allow high precision position sensing and closed loop control. This mechanism has been tested to demonstrate that it is possible to achieve nanometric precision and long term stability.

Space compliant piezo-mechanism with integrated SG sensors

The mechanism is based on PPA40M actuators mounted in a push-pull configuration (Fig. 1). The push-pull configuration consists in two actuators moving simultaneously in opposite directions, when one is pulling, the other one is pushing. The two actuators are integrated in a mechanism whose kinematics takes advantage of this opposite motion. This mechanical topology has the advantage to reduce some parasitic effects and to sum the stroke of both actuators. This mechanism was designed for a space application requiring a high precision and long-term stability. The design was made in compliance with the ECSS. Redundancy of the actuation is achieved by using two independent ceramics per actuator, resulting in a primary and a secondary actuation channel. This means that the mechanism features four ceramics to cope with redundancy. The total stroke of the mechanism with both channels activated is around 80µm, giving 40µm of stroke in cold redundancy. The mechanism was modeled and simulated to justify that it can withstand the environmental constraints (vibrations and shocks), since a space application is targeted.

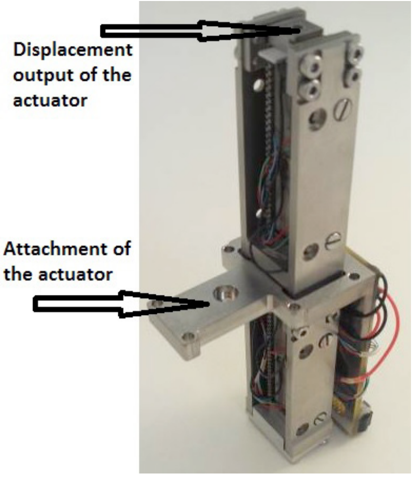

__Fig. 1:__ View of NLA.

From the electrical point of view, the push-pull configuration requires a specific electrical configuration for driving the ceramics. The ceramics are connected in serial, so that there are three electrical leads per channel, as presented on the Fig. 2. There are two electrical rails providing constant regulated voltage at the extremities. Only the voltage of the middle point between the ceramics is modified to create motion of the channel. Thanks to this configuration, the voltage applied on the ceramics in naturally varying in opposition direction, creating motion of the ceramics in opposite directions as required.

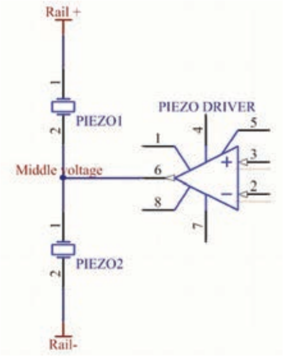

***Fig. 2:** Electrical configuration for push-pull mechanisms.*

The mechanism is equipped with high-stability SG sensors, which take benefit of the mechanical push-pull configuration. The SG are glued on the ceramics as presented on Fig. 3, and there are two SG per ceramic. SG elements are integrated on all ceramics to monitor the displacement of all active elements of the mechanism. The SG bridge is thus composed of 8 SG elements, instead of 4 usually.

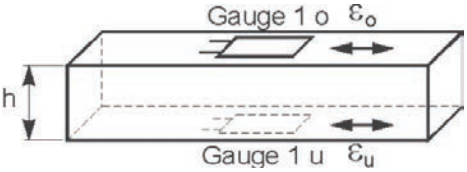

***Fig. 3:** SG mounting on the ceramics.*

The SG elements are connected in full Wheatstone bridge configuration to obtain best performance. A full bridge configuration (Fig. 4) was selected to improve the sensitivity while limiting the thermal impact and non linearity errors on its performance.

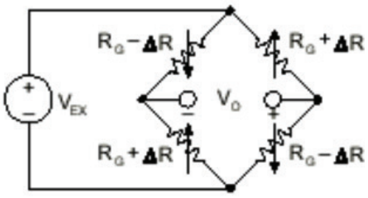

***Fig. 4**: Bridge electrical configuration.*

On Fig. 4, only 4 SG elements are shown for simplicity, but the theory is the same with 8 elements. With 8 elements, the SG elements are paired in serial to form an equivalent single SG element of the bridge. The SG sensitivity depending on strain and temperature is given in Eq.1.

$$\frac{\Delta R}{R} = GF_x \times (\varepsilon_{strain} + \varepsilon_{thermal}) \tag{1}$$

The output voltage from the bridge is given in Eq. 2, with $R_{1,3} = R_0 - \Delta R$, $R_{2,4} = R_0 + \Delta R$

$$Vout = Excitation \times \left(\frac{R4}{R3+R4} - \frac{R2}{R2+R1}\right) \tag{2}$$

The thermal impact has the same sign for all SG; they are all subjected to the same change in temperature. Based on Eq. 1 and Eq. 2, the final bridge output voltage can be expressed in Eq. 3:

$$Vout = Excitation \times \frac{SG}{4} \times 4\varepsilon_{strain} \tag{3}$$

Eq. 3 shows that the full bridge configuration is theoretically insensitive to temperature effect thanks to the symmetry of the bridge. This theory is valid as long as no thermal gradient appears between the bridge components. The degree of the compensation depends on the uniformity of the temperature at the strain gage level. The thermal stability of such sensors was investigated in more details in [1].

Compared to competing position sensing technologies, such as capacitive sensors, or eddy current sensors, the main advantages of the SG sensors are the compactness and low-cost. SG sensors are often considered as low-performance solution. In practice, SG sensors offer a fine linearity, a fine bandwidth, and a fine SNR. The main unknown is the long-term stability of those sensors in piezo-actuator applications. This aspect is investigated during the tests, to show that with proper integration and proper use, a nanometric long-term stability is obtained.

The breadboard model of this actuator is presented on Fig. 1. This breadboard model is representative of the space definition, only it was not integrated in a clean room. The strain gages were integrated using a dedicated space compliant process from Cedrat Technologies. This breadboard model is used for the testing.

Test bench

A dedicated test equipment has been designed and set-up in order to perform high precision measurements on the new device. The bench is presented on the Fig. 5.

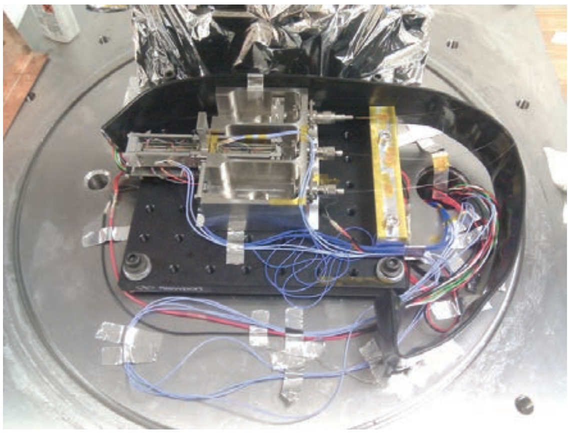

Fig. 5: Dedicated test bench.

The setup is based on a high precision laser interferometer that is used as a reference position sensor. In the nanometric range, the sensitivity of the laser to pressure variations cannot be neglected. The bench is thus integrated inside a primary vacuum chamber to provide sufficient pressure stability. Since temperature variations also create parasitic displacements due to thermal expansion, the bench is temperature controlled.

The performance of the bench was tested during long-term measurements performed on the mechanism. Fig. 6 presents the pressure (bottom plot in blue) and temperature measurements (top plot) during a four week test. The pressure stabilizes close to 20mTorr two days after the beginning of the test. The measured pressure variations after two days are of few mTorr, which is better than the expected stability. This means that the pressure is sufficiently stable to consider that its impact on the reference position sensor is neglectable.

During the test, the temperature setpoint for the regulation is 25°C. On the temperature plot, the black trace (average value of 20°C) corresponds to the ambient temperature outside the climate chamber. The other traces correspond to the temperatures of the bench and mechanism at different locations. The regulation setpoint is 25°C, but in practice the average temperature of the setup is 24°C. The regulation is not very precise, but this is not problematic since the objective is to achieve fine stability, and not fine precision. The ambient temperature exhibits variations of ±1°C during the test. Thanks to the temperature regulation inside the chamber, the outer perturbations are mostly rejected. The temperature variations observed on the bench or piezo-mechanism do not exceed ±0.15°C.

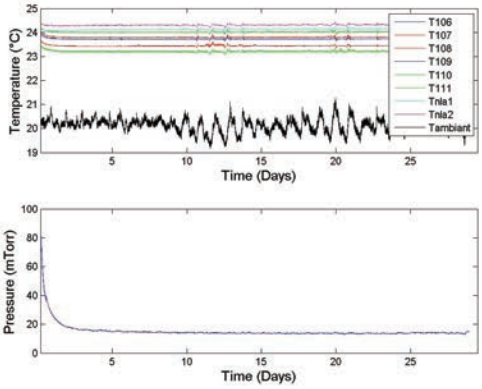

Fig. 6: Temperature and pressure stability inside the chamber during the tests.

The obtained thermal stability is sufficient for the tests performed, but there is still an impact of few nanometers of the temperature variations on the position measurements. This means that the thermal stability could be enhanced further, to improve the performance of the setup.

Results

For the tests, the piezo-mechanism is controlled in position closed-loop based on the integrated SG sensor feedback. The objective is to verify that the mechanism has the capability to realize a stable motion in the nanometric range.

Several tests are performed to demonstrate the nanometric precision of the piezo-mechanism. In particular, a test has been performed to assess the long-term position stability of the NLA. For that test, the system has a fixed command, and it is verified that the actual position of the mechanism remains stable over a 2 weeks time. The result of the test is shown on the Fig. 7:

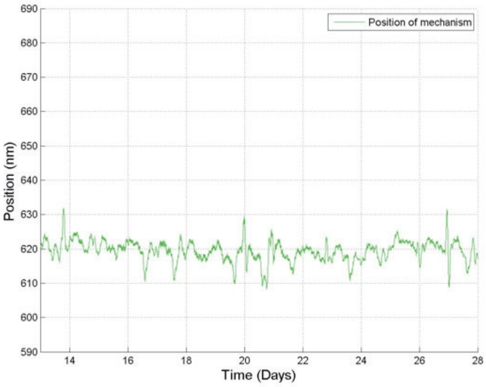

Fig. 7: Stability of the position for a 2 weeks time.

The results show that the mechanism has the ability to maintain its position stable in the nanometric range. The average measurement of the position remains within less than ±5nm of the original position. “Fast” variations of the measurement are due to temperature changes outside the vacuum chamber, which are not totally rejected by the temperature control.

The Fig. 7 does not present the results of the first week of stability testing, but only the performance in stability once the system is properly settled. During the first week of the stability testing, a residual drift of approximately 40nm appears, before the system settles completely. This effect is shown on the Fig. 8.

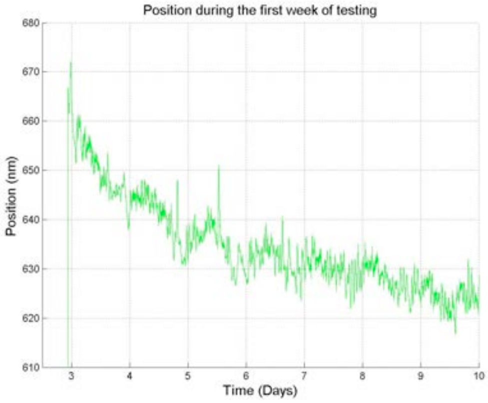

Fig. 8: *Position during the first week of testing.*

This result means that there is a residual drift of the mechanism, which is not sensed by the SG bridge. The Fig. 9 presents the evolution of the controller output during the first week of the testing. The controller output is not constant, and it compensates a mechanical drift of around 620nm.

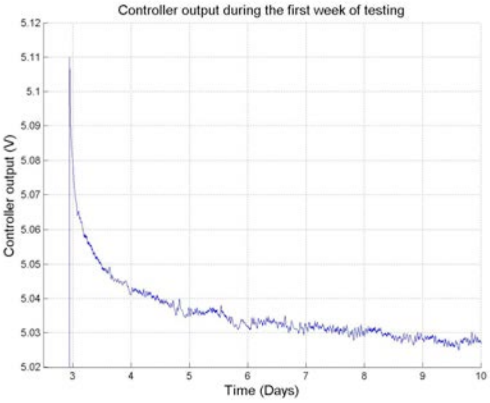

Fig. 9: *Control output during the first week of testing.*

The mechanical drift is expected and corresponds to the ceramics drift. This drift was assumed to be fully measured by the SG sensors, but the results show that it is only compensated to 94%. 6% of the ceramics drift thus remain uncompensated by the closed-loop and appear on the system position. This partial insensitivity to drift comes from the gain difference between SG elements. Gain dispersion of 5-10% is observed between the SG elements composing the bridge. This implies that their sensitivity to drift is also different, explaining that part of the drift is not read by the sensors, and thus not compensated by the closed-loop. This effect can be corrected by optimizing the SG gain repeatability before and during integration. An alternative solution would be to match SG gains after integration on the ceramics, before integration on the mechanism.

Conclusion

A new space compliant piezo-mechanism was designed and tested especially with respect to long-term stability aspects. The mechanism features high quality SG elements to perform fine closed-loop control. The results show that the mechanism exhibits nanometric resolution and long-term stability as desired.

The tests results also show that the prototype exhibits some residual drift of around 40nm during the first week of stability testing. The origin of this residual drift is understood, and it corresponds to a non-compensated second order effect which was not expected originally. This remaining drift can be reduced by optimizing the SG topology and integration.

A more general conclusion is that the SG sensors appear very simple and easy to use for performing a rough measurement. However, it requires an extended know-how in using such devices to take benefit of high precision and high stability.

Acknowledgements

This work has been funded by the French Space Agency (CNES).

References

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