NANOMETRIC POSITIONNING WITH PIEZOELECTRIC ACTUATOR & HIGH STABILITY STRAIN-GAGES

F. BARILLOT[(1)], T. PORCHEZ[(1)], C. BELLY[(1)]

(1) Cedrat Technologies, 59 chemin du Vieux Chêne, 38246 Meylan, France, Email: actuator@cedrat-tec.com

ABSTRACT

Many applications require long-term position stability, which relates to the notion of absolute precision 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 nanometric position stability of a closed-loop piezo-mechanism with integrated strain gages sensors. This technology opens a wide range of new possibilities for industrial, aeronautical, and space applications.

1. INTRODUCTION

Space, military, and industrial applications require stable and precise actuating solutions. In most of the applications, the compactness of the solution is also an important issue. Piezo-mechanisms offer a compact solution, together with wide bandwidth, long lifetime, and high reliability. However, those actuators suffer non linearities, such as hysteresis and creep effect, requiring closed-loop control with position sensor to linearise their behavior. 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]. Though contactless sensors like capacitive or eddy current position sensors are well known as accurate sensors, their volume and cost are major drawbacks, especially for multi-axis systems.

In this paper, a new space compliant PPA40M-SG-based push-pull mechanism is presented and tested. This actuator is equipped with strain-gages that allow high precision position sensing and closed loop control. The objective of the tests is to demonstrate that is possible to achieve nanometric precision and long term stability on such a mechanism. For the purpose of those tests, a specific test bench has been designed, to be able to perform long-term nanometric measurements.

2. 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.

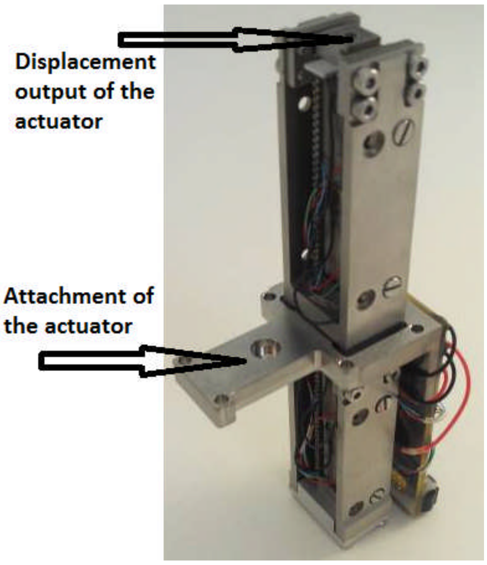

Figure 1. PPA40M-SG-based push-pull space-compliant mechanism.

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.

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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.

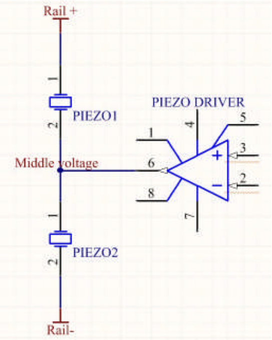

Figure 2. Electrical configuration for push-pull mechanisms.

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.

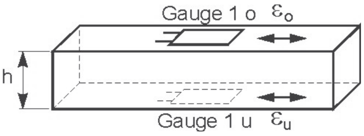

Figure 3. SG mounting on the ceramics.

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.

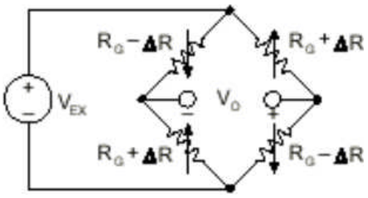

Figure 4. Bridge electrical configuration.

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.

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

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

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

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:

$$Vout = Excitation \times \frac{SG}{4} \times 4\varepsilon_{strain} \qquad (3)$$

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.

3. SETUP FOR NANOMETRIC MEASUREMENTS

A measurement in the nanometric range requires a very specific instrumentation setup. In the nanometric range, contributions that are usually considered neglectable become main contributors. A dedicated test equipment has been proposed and set-up in order to perform high precision instrumentation of systems.

3.1. Presentation of the setup

The setup is based on a high precision laser interferometer that is used as a reference position sensor. This sensor features 3 channels, so that it is possible to monitor the actuator motion, and also parasitic displacements. The sensor technology is sensitive to pressure. Ambient pressure variations create measurement errors of more than few nanometers. In order to make a fine measurement, it is thus mandatory to stabilize the pressure.

A specific vacuum chamber (see Fig. 5) has been manufactured to be able to perform the testing in an environment with stable pressure. By analysis, the target is to obtain pressure stability of 10mTorr, so that the measurement error due to pressure variations can be considered neglectable. Based on the requirement, a primary vacuum chamber is sufficient for the application. The pressure inside the vacuum chamber is monitored, but not controlled. The vacuum pump runs continuously to bring the pressure as low as possible.

Figure 5. Primary vacuum chamber.

In addition to pressure stability, a fine thermal stability is also required. When temperature is not stable, thermal expansion of the bench will create parasitic displacements. The bench parasitic displacements have to be minimized, since they are seen by the reference sensor, itself attached to the bench. Temperature control is thus implemented inside the vacuum chamber. The temperature regulation is realized by means of Peltier effect devices.

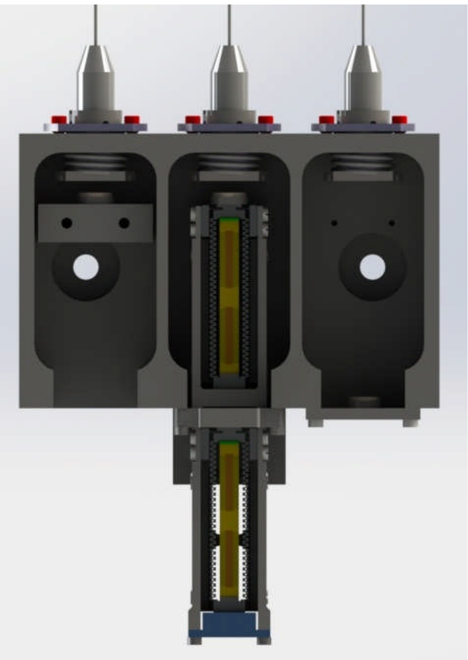

Figure 6. CAD view of the mechanical bench.

A mechanical bench was designed to hold the piezo-mechanism and the sensors. This mechanical bench is attached to the thermally regulated plate inside the vacuum chamber. The bench is made of INVAR, to minimize the parasitic displacements due to thermal expansion, since the thermal regulation is not perfect and cannot compensate all perturbations. The bench features three identical sensing areas, one for each position sensor channel (see Fig. 6). The mechanism is attached in the middle area, and its position is measured by one of the sensor channels. The two other channels measure fixed reference points on the two other sensing areas. With the reference measurements, the objective is to monitor the parasitic displacements of the bench itself. Those reference measurements can be used in post-processing to remove the parasitic influences of the bench in the measurement of the mechanism position. The mechanism integrated on the setup before testing is shown on the Fig. 7.

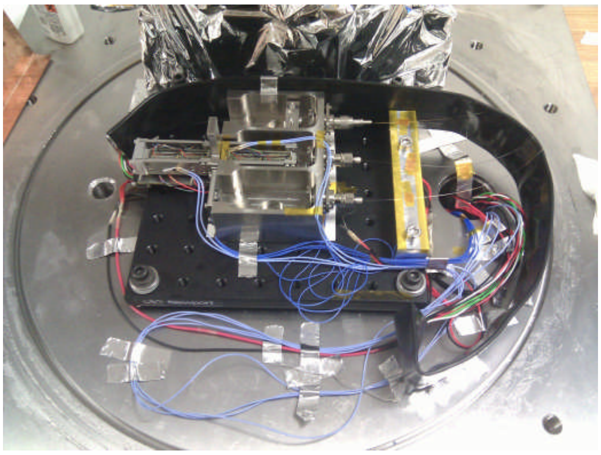

Figure 7. Mechanism integrated on the specific test bench.

The vacuum chamber features a pressure sensor, so that the pressure can be monitored and recorded during the tests. A number of temperature sensors are placed on the bench and mechanism to have thermal map of the setup during the tests.

3.2. Functionality of the setup

The performance of the bench was tested during long-term measurements performed on the mechanism. Fig. 8 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.

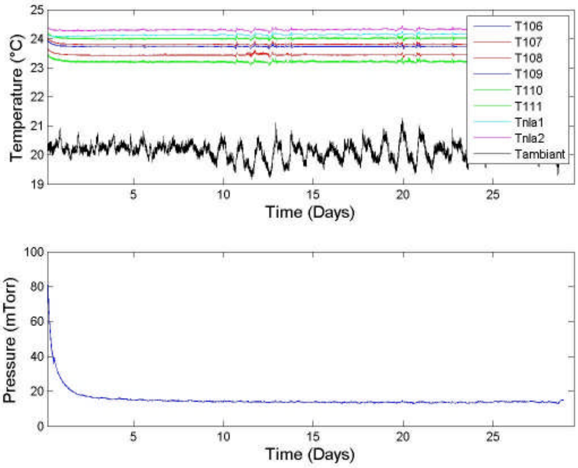

Figure 8. Temperature and pressure stability inside the chamber during the tests.

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.

The temperature of the setup is not perfectly homogeneous, and there is more than 1°C difference between the coldest and warmest locations. The main reason is that the SG elements are producing around 37mW of heat, which have to be dissipated by conduction in the setup, creating temperature gradients. This explains that the piezo-mechanism is the warmest area of the setup. In addition, some electrical connections are creating locally thermal bridges between the thermally regulated side and the non-regulated side, which also create temperature gradients.

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.

4. PERFORMANCE OF THE PIEZO-MECHANISM

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 a capability to realize a stable motion in the nanometric range. For driving the mechanism in closed-loop, the electronics are placed outside the vacuum chamber, in a non regulated laboratory environment. A SG75 conditioner is used to read the SG position signals. A LA75A power amplifier is used to drive the piezo-mechanism. Both the conditioner and driver have been modified to reduce their bandwidth to 100Hz, since the application is quasi-static. A 16bits acquisition platform is used to sample the SG position and to generate the command to the power amplifier. This platform is controlled by a computer user interface, which performs the closed-loop control. The position setpoint is set by software and can be adjusted manually during the tests. Since the application does not require large dynamics, a slow integral controller is implemented to close the loop.

Three major tests are presented in this paper to demonstrate the nanometric precision of the piezo-mechanism. The tests presented are performed in a cold redundancy configuration, meaning that only one actuation channel is used. The second actuation channel is passivated.

4.1. Resolution

The first test is the resolution testing, which corresponds to the short-term stability. In this test, the aim is to verify that the mechanism is capable of producing displacement steps in the nanometric range. During the test, the position setpoint of the controller is adjusted several times consecutively to command the small displacement steps. After each change of command, a minimum 10min period with constant command is kept to verify the stability of the position.

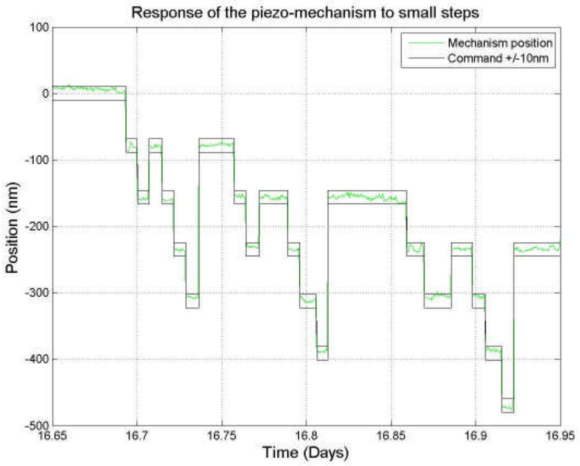

Figure 9. Comparison between the command and position of the mechanism.

Fig. 9 presents the result of this test, the actual position of the mechanism is shown in green, and the command with ±10nm margin is shown in black. As can be seen on the results, the piezo-mechanism is able to generate displacements in the nanometric range, and the short-term stability is within ±10nm of the command. Some fast variations of the position can be observed on the graph. Those fast variations are mainly due to the remaining temperature variations on the bench, leading to measurement errors.

The test results also show a fine short-term repeatability of the position, since some positions are repeated successfully several times.

4.2. Repeatability

An important aspect of the precision of the system is its capability to repeat the same position for the same command. In this test, the repeatability of the system is tested after power off. When the system is turned off, the mechanism will go to its rest position, and it will cool down. The objective is to verify that the mechanism returns to the same position as it was before power off.

At the beginning of the test sequence, the system receives a constant command, which corresponds to around +14µm compared to the rest position. The system is then turned off for few hours, which is sufficient to cool down, and reaching the rest position. The system is then turned on again with the +14µm command. The test result is shown on Fig. 10, the actual mechanism position is in green, and the ±10nm margin in black.

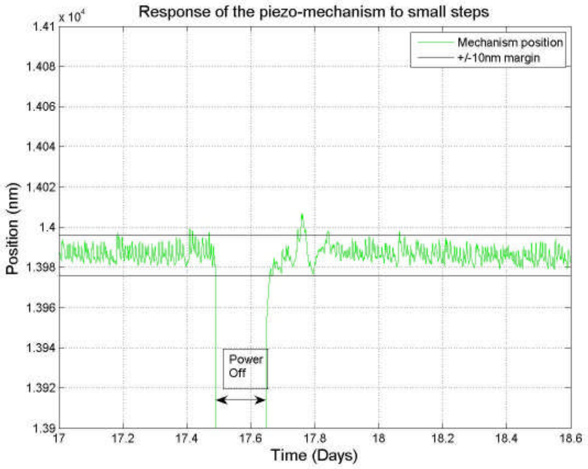

Figure 10. Repeatability of the position after power off.

The test results show that the system returns in position with a repeatability of only few nanometers after power off. After the system is turned on again, it takes approximately 1h30 to settle with the nanometric repeatability.

4.3. Long-term stability

The final test consists in assessing the long-term stability of the position of the piezo-mechanism operated in closed-loop based on the SG sensor feedback. The aim is to verify that the system has the capability to maintain a constant position with minimum drift. Thus, the position order of the control loop is kept constant during the test.

Fig. 11 presents the position of the mechanism after two weeks of testing. The average position of the mechanism exhibits almost no drift, thus long-term nanometric stability is achieved. As for the previous test results, there are still fast position variations, which are assumed to be measurement errors due to the temperature variations.

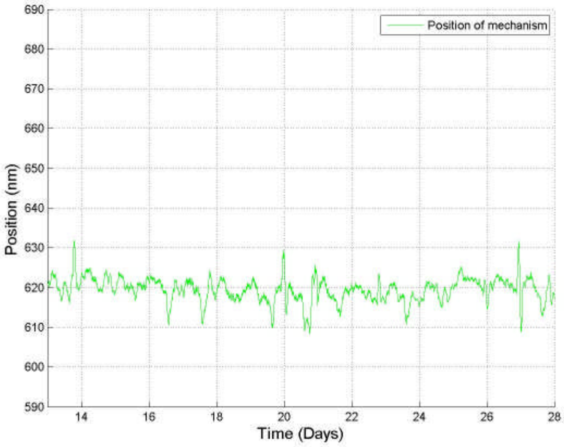

Figure 11. Stability of the position of the piezo-mechanism for a two-weeks duration.

5. CONCLUSION

A new space compliant PPA40M-SG-based Push-Pull mechanism has been designed to answer high precision and high stability requirements in space applications. It is has been shown in practice that it is possible to achieve a nanometric positioning and long-term stability with this piezo-mechanism. This performance is achieved thanks to the integrated SG sensors which are used to control the mechanism in closed-loop. Several test results have been presented to demonstrate the nanometric performance. In particular, a final test shows that after two weeks of testing, the position of the mechanism exhibits no drift: the stability approximates 1nm/week. When properly used, the SG sensors become a fine low-cost alternative to popular capacitive or eddy-current sensing solutions.

For the testing of the mechanism, a specific test bench was designed and used. Thanks to this test equipment, it was possible to demonstrate the functionality of the mechanism in the nanometric range. The main auxiliary result is that the test equipment has the capability to make long-term nanometric measurements. Some improvements to this equipment could be made in order to achieve even better thermal stability inside the chamber.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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