THERMAL VACUUM BEHAVIOUR OF A STEPPING PIEZO ACTUATOR

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ABSTRACT

The presented work illustrates the design of a new high force Stepping Piezoelectric Actuator (SPA) and describes its Thermal Vacuum testing as performed by ESTL, in order to investigate SPA compatibility with vacuum environment within a wide temperatures range; from +60°C down to -180°C. A dedicated test bench was designed, in order to check motor force and speed for all performed tests. Instrumentation, testing and observations about tribological behaviour of friction interface have been realized by ESTL, showing interesting perspectives.

1. Background

Fast and precise positioning in space environments implies various constrains, including vacuum and thermal compliances. When long strokes are needed, electric motors coupled to gearbox are usually chosen, allowing holding position without consumption. However, the embedded mass for such a solution may start to be too high when numerous components are required. However, simple direct drive solution may be interesting, when low volumes and masses are needed. Such applications are targeted by the presented Stepping Piezo Actuator.

The present paper firstly details the working principle of such actuator, highlighting its inherent advantages and drawbacks, especially when facing space environment constrains. Secondly, a thermal vacuum compatible test bench is presented, allowing vacuum and low temperature testing. Then tests results are compiled and assumptions are made about thermal vacuum capacities of SPA actuator.

2. Description

Stepping Piezoelectric Actuators (SPA) are long-stroke linear inertial piezoelectric motors for micro/nano positioning applications benefiting of the advantages and the heritage of the APA® [1] and based on an Impact Drive Mechanism (IDM) [2].

Amplified Piezoelectric Actuators (APA®) are solid-state linear actuators offering large deformations (from 1 to 10% depending on the type) and medium strokes (up to 1mm). 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 launching). 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 consequences, they are extremely reliable (life time is larger than 10^{10}cycles), they have passed many aerospace qualifications [3] and they are selected in many EU and US space missions. Using the ability of APA for dynamic motions, various mechanisms have been built: fast piezo shutters (FPS), fast tool servo (FTS) circuit-breakers, micro scanners, anti-vibration, sound & vibration generators, proportional piezo valves (PPV) and piezo generators amongst others.

The Stepping Piezoelectric Actuator (SPA) is a new application of APAs using their capability and reliability for both fast transient motion and nano-positioning. It can be considered as a way to expand the limited stroke of the APA®, to centimetre strokes. This feature is achieved using the IDM principle.

SPAs are formed of only four parts: the well-established Amplified Piezoelectric Actuators (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 [4]. 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 (M_1). Between each step the actuator is locked in position [5].

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 (shown in Figure 1 below), the load can replace the mass or can be fixed to the mass. So when the long stroke (M_1) is performed, the motor can be also operated in a deformation mode (M_2) for a fine adjustment. In this case, the stroke is proportional to

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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 no more available.

The long stroke stepping mode (M_1) is produced by step accumulation with an appropriate 0-150V voltage pattern. The short stroke deformation mode (M_2) 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.

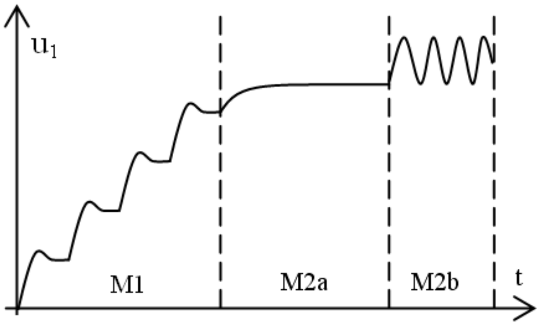

Figure 1. SPA stepping mode (M_1) and deformation mode (M_2)

Compared to a piezo stack of the same size, an APA® presents a typically 20 to 100 times larger compliance and a 4 to 10 times larger stroke. The larger compliance of the APA® leads to a 5 to 10 lower resonance frequency (at constant mass) and so a 5 to 10 times smaller current demand than the same piezo capacitance in a stack.

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 a lower step frequency. Benefits from amplification in Impact Drive Mechanism have been demonstrated in [6].

3. Test bench definition

In order to assess the behaviour of the Stepping Piezo Actuator in a thermal vacuum environment, a dedicated test bench has been designed integrating a SPA40SM.

The expected maximum drive force of such a motor is approximately 20N, which represents a tenth of the piezo actuator blocked force. The details of each component are given further.

3.1. Hardware

The APAs offer a large range of stroke and force. In our case, the use of an APA40SM is preferred. The stroke of such actuator is 52µm and blocked force is 194N. A photograph is this amplified actuator is presented in Figure 2.

Figure 2 APA40SM

The clamp system has been designed in order to fit normal and tangential forces and stress. Play recovery system is included and material is chosen to offer good thermo-mechanical behavior. Contact geometry is defined in order to minimize contact pressure between clamp and shaft, allowing lifetime improvement.

The contact is made between a metal on a friction polymer material. This material couple has been already used in space applications, and showed good results in miniature Stepping Piezo Actuators. The contact interface is longer than the stroke used during functional tests in order to get easy comparison between worn out and virgin contact area.

In order to assess the performance of the motor, a thermal vacuum compatible sensor is needed. For displacement an LVDT sensor was used to give sufficient resolution. This kind of sensor doesn't need any additional bearing. A Sensorex SX20MR005 was used for this test.

3.2. Complete motor and bench

The whole motor is thus composed with its four main elements, and is completed by the LVDT sensor, and a loading system, acting on the shaft. The loading system is composed of a spring which will give the loading characteristics of the motor (see 3.3). The loading spring is calibrated using spring mass resonance frequency measurement.

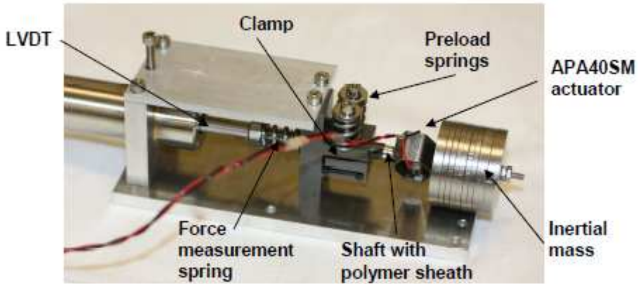

Figure 3. SPA40SM test bench

For testing the entire bench was mounted horizontally onto heat exchanger, which could be heated or cooled using electric heaters or by circulating fluid through drilled channels. Temperature control was performed using a series of thermistors and PT100s.

The motor was controlled using a Labview user interface, coupled to a National Instruments Labview acquisition/generation board. The command signal was amplified using LA75C linear amplifier from Cedrat Technologies. This amplifier allows amplifying input signal from 0-7.5V to 0-150V, with a 2.4Amp current limitation.

3.3. Protocol

The functional test allows assessment of the motor's behavior during motion, acting both against and with loading. The LVDT sensor is used in order to determine step size and speed of the motor. Each test is composed of 10 back-and-forth, between lower and upper limit stop, as demonstrated in Figure 4. At (1), the motor is in lower limit stop and moves upward, until the spring starts to be compressed (2). The motor keeps moving in the same way until the step size becomes null (3). At this moment, the maximal force of the motor can be deducted from the reach position. Then, the backward motion starts (4), the motor is helped by the spring which is compressed until the point (5). After that, the speed should remain constant until the motor reaches the lower stop limit (6). The speed and force are deduced from the step size and the position of the motor, using spring stiffness.

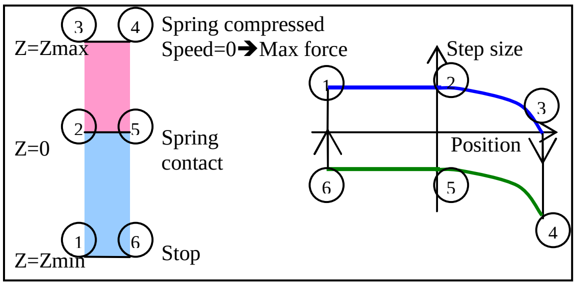

Figure 4. Functional test description

3.4. Test plan

Testing comprised of five separate stages

- Ambient assessment – assessment of the actuator in air, at room temperature
- Storage tests – assessment of the position stability of the actuator under vacuum through cycling at +60°C and -40°C
- Functionality tests – assessment of the performance of the actuator under vacuum within the temperature range +60°C to -180°C
- Dwell tests – assessment of the actuator after subjection to 12-days dwell under vacuum at room temperature
- Vaccum cycling – returning the test bench to ambient conditions, and investigating the effect of vacuum cycling on the unit

Figure 5 shows the test plan for the storage and functionality tests. Between each temperature test there is a 'control' test performed at room temperature.
During the storage tests (green marks in Figure 5) the temperature was held until steady for each cycle. Temperature was then returned to 20°C, and this cycle repeated three times.
Note, due to limitations of the test rig the final test was carried out at -180°C, not -196°C.

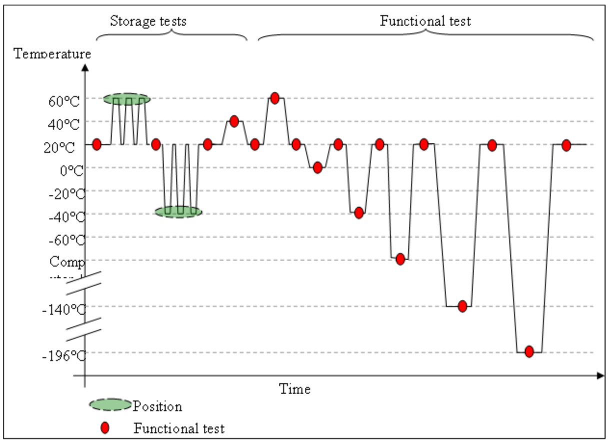

Figure 5. Storage and functional test planning

4. Results

4.1. Displacement overview

According to the motor's actuation profile (Figure 4), the measured motor displacement is naturally dissymmetrical. The positive motion (Figure 6) plays the role of spring loading. By the way, the motion looks like a capacitance loading curve, loading energy into spring. In the opposite direction (Figure 7), the motor speed is not exactly as expected. Indeed, at the beginning of the motion, the motor is pushed by the force measurement spring, so higher speed was expected. As a contrary, lower speed is measured. This shows that motor speed is mainly ruled by the motor itself and not by external forces. At the end of the negative motion, a constant speed is reached.

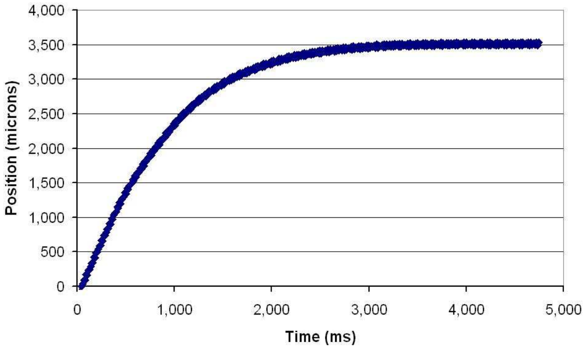

Figure 6: Positive motion

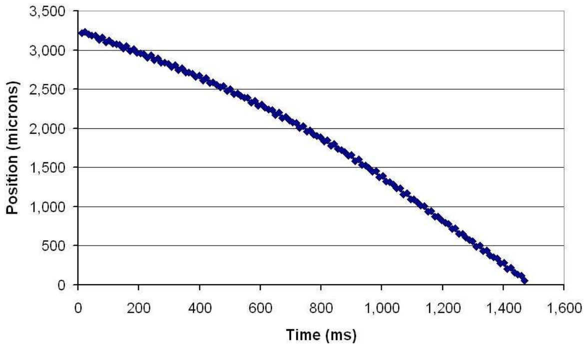

Figure 7: Negative motion

These two motions examples are used to get the SPA40SM performances for all the thermal vacuum testing.

4.2. Vacuum and storage tests

The motor was firstly tested in air and vacuum at room temperature. Comparison between these two environments shows no detrimental influence of vacuum on the SPA40SM motor's speed and force.

Storage cycling has been realized between +60°C and -40°C under vacuum, demonstrating motor operability, without any observable detrimental effect of storage cycling at these temperatures under vacuum.

4.3. High and low temperature results

The maximum motor working temperature is limited by the friction material's maximum allowed temperature. For this reason, functional tests were limited to +60°C. Tests under vacuum demonstrated that the actuator keeps its performance up to this temperature.

Low temperature tests were performed on the SPA40SM from 0°C down to -180°C, the lowest temperature allowed by the test rig. The results are shown in Figure 8. It can be seen that a drive force reduction is observed at lower temperatures, but not lower than 75% of nominal force achieve at ambient temperatures. Speed is also affected, but in a coherent way, with a linear speed reduction with temperature. However, after every temperature step, the performance is recovered upon returning to room temperature, showing no continued reduction in performance after periods of exposure to low temperatures under vacuum.

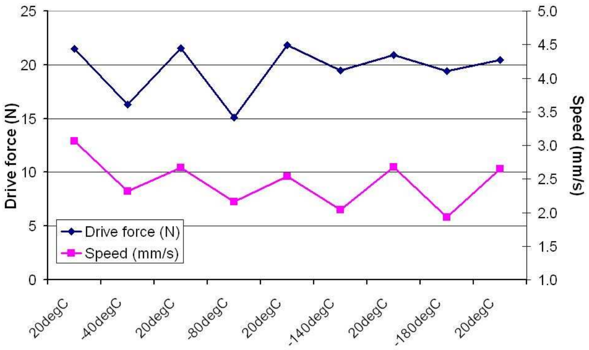

Figure 8. Low temperature performances

4.4. Dwell test and ambient return

A dwell test of 12 days under vacuum was subjected to the SPA40SM, during which no problem with the motor was observed. However, a first functional test showed unexpected behaviour. In this case, the very first motion occurs as if the sensor position feedback was wrong, or as if the motor moved (which seems improbable). The reason for this is not clear between hardware, sensor or software origin.

When returning to air following completion of the vacuum test the performance of the actuator was reduced (speed down to 1.7mm/s). However the root cause of this is not clear, due to the nature of an un-anticipated return to atmosphere following a vacuum pump failure, and the fact that the actuator had seen a large number of in-vacuum cycles by this point.

4.5. Tribological observations

Following testing, tribological observations were made on the friction interfaces, namely the clamp and the friction polymer material. No wear or debris was observed on clamp, and on the polymer shaft some indentations are seen on the extremities. This may be due to impacts during assembly or against fixed component of the test bench. Moreover, no debris was observed. A close-up of the shaft is shown in Figure 9. It can be seen that friction polymer wear appeared but without debris generation. The dark uniform areas are identified as third body.

Figure 9. Friction interface close up

5. Lessons learned

The SPA40SM actuator has been demonstrated as operable in air and vacuum at room temperature (+20°C). No detrimental effect was observed following thermal cycling under vacuum at -40°C / +60°C. The actuator is able to operate without issue up to +60deg.C in vacuum Actuation was demonstrated down to -180°C (lowest attainable temperature using the set-up used in this study.)

Operation in vacuum below -40deg.C caused a reduction in the performance of the actuator, but no less than 75% of the initial drive force. Performance was recovered upon returning to 20deg.C. Performance of the actuator was reduced when returning to air.

6. Future work

The SPA is especially relevant for precision positioning purposes (optics, valves…), when holding force without consumption is needed. Active shape control of structures can also be addressed using such motor, due to the good stroke/resolution ratio.

Recommendations made for future testing include longer duration assessments performed under vacuum. During this program all tests were performed as 10 cycle actuations. Longer duty actuations would be useful to assess if drive force drops off with continued operation (as has been observed for previous actuators tested at ESTL [7]).

More investigations are still needed according to the friction material's temperature range. Limiting forces may also be increased using higher contact pressures, but requires correct material and geometry choices.

7. REFERENCES

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