Improvement of Linear and Rotative Stepping Piezo Actuators Using Design and Control

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Abstract:
Stepping Piezo Actuators (SPA) are inertial piezo motors able to reach long stroke with important resolution. Previous work showed that large benefits in terms of speed and input current are taken from use of Amplified Piezo Actuators (APA®). The aim of this paper is to present new rotative configuration, advancements in maximal actuation force into thermal vacuum conditions and improvements using smart control.

The paper firstly settles the operating principle of the motors in linear but also in rotative way. Then, various configurations are compared and realisations are presented, from low volume rotating solution to high force motor compatible with vacuum and low temperature (down to -180°C). Results obtained by the European Space and Tribology Laboratory (ESTL) are thus exposed. Finally, smart control of SPA, allowing optimisation of performances using Autotune function integrated into dedicated Stepping Piezo Controller SPC45, is detailed.

Keywords: Piezo, Amplified Actuator, Motor, Inertial, Linear, Rotating

Introduction
The stroke offered by piezoelectric actuators is often too short to fit the constraints of some specific designs. A classical solution consists in what is called piezoelectric motors. Possibly ultrasonic, inchworm, or inertial, these motors have the particularity to work on friction and so, to have a holding force without any consumption. One of their main drawbacks concerns the lifetime, because of friction wear. The present work is based on Stepping Piezo Actuator (SPA), which is an inertial piezo motor, a promising type in terms of miniaturization but also facing environment constrains, such as high magnetic fields or thermal vacuum. First prototypes of linear SPA motors have already been presented, especially in Actuator2010 [1]. Improvements and new developments have been identified and implemented on linear as well as on rotating motors.

The concept of inertial piezoelectric motor, introduced in [2], has been used in order to fit extreme precision needed in Tunneling Microscope Scanning [3], compatible with cryogenic environments. A similar concept was proposed by Higuchi in [4], and was adapted to build the Smooth Impact Drive Mechanism [5], used in camera blur reduction mechanism. The aim of this work is to present SPA (see Fig. 1) improvements in terms of configuration, as well as compatibility and command.

Principle
Stepping Piezo Actuators are inertial stepper motors. They are composed of four main elements to make long stroke and high resolution possible: an actuator, a shaft, a mass and a passive clamp. The actuator is an Amplified Piezoelectric Actuator (APA®), widely used in industrial, military and space applications. Its reliability comes from the prestress of the ceramic, and the easiness of integration makes this actuator especially relevant. The principle of such motor is simple and relies on stick-slip effect and dissymmetrical accelerations. Fig. 2 shows the two phases needed to produce one step. First, a slow contraction of the actuator makes the mass moving, without any motion of the shaft, because of clamping friction. Then, a fast actuator expansion gives dynamic forces to mass and shaft and, because of the inertia of the mass, overcomes the friction forces. This moves the shaft into the clamp and one step is completed. By repeating this operation, stroke of several millimetres can be reached. The opposite motion is done by inversing the two sequences. This motion is called “Stepping Mode”.

Fig. 1 Linear SPA30uXS
Another way to use the SPA is called “Deformation Mode”. In this case, the tool is attached to the mass and the actuator deformation is used, without dynamic effect. By the way, the precise motion offered by the APA® allows reaching a high resolution. Fig. 3 presents an example of motor displacement using combination of stepping mode and deformation mode (with PID controller).

The configuration of the SPA offers qualitative arguments in favour of the amplification and especially in favour of the APA®. Firstly, the Deformation Mode is available on a useful stroke (>30 μm), making fine adjustment convenient. Secondly, the long stroke of the APA® makes the design constrains less demanding. The elasticity coming from the shaft and from the contact can be overcome because of this long stroke. Finally, the prestress of the ceramic by the shape of the APA® gives the motor another reliability argument.

Rotating motor
Rotating configuration of the Stepping Piezo Actuator is possible according to the same working principle. Actually, using the Amplified Piezo Actuator APA®, the impact force has to be transmitted to a moving shaft, which is in friction into a cylindrical clamp. The schematic principle is presented on Fig. 4.

The possibility to keep the amplified actuator linked to the ground allows offering an infinite rotation. In many cases, this option seems to be the more promising. However, sometimes it can be advantageous to make the actuator move. The case where miniature driving electronics is rotating with the motor can be presented as an example into a wireless embedded application. In this case, power is coming from external coil, collected by an embedded planar coil, regulator and capacitance. A photograph of this type of motor is visible on Fig. 5. For the smallest RSPA developed so far, the holding torque without consumption is around 3 mNm and actuating torque is 1 mNm. The maximal speed reaches 90 rpm.

Bigger RSPA are expected to get higher holding torque up to 20 mNm for 8 mNm of actuating torque.

High force thermal vacuum motor
The inherent advantages of the APA® coupled to the possibility to hold the position without any consumption make the SPA technology relevant in terms of thermal vacuum application. By the way, with support of the European Space Tribology Lab. (UK), a specific design has been defined 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.

The whole test bench (Fig. 6) is composed of the four main motor elements (including APA40SM), and is completed by a LVDT sensor, and a loading system, acting on the shaft. The loading system is composed of a spring which will give the loading
The loading spring is calibrated using spring mass resonance frequency measurement.

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. 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.

The functional test allows assessment of the motor’s behavior during motion, acting both against and with loading. Each test is composed of 10 back-and-forth, between lower and upper limit stop, as demonstrated in Fig. 7. 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 reached 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.

According to the motor’s actuation profile (Fig. 7), the measured motor displacement is naturally dissymmetrical. The positive motion 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, the measured 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.

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.

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 on Fig. 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.

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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.)

**Autotune function**

Stepping Piezo Actuators have the particularity to get an optimal working frequency which can change with working conditions, such as loading, temperature... In a first approach, a standard
frequency can be used as input signal of the motor, efficient for a certain range of conditions. However, this option can face limitation if working frequency becomes too far from nominal value. By the way, an Autonomous Tunability function (AutoTune) is programmed. The look-up protocol is based on a frequency sweep, and position acquisition. In both direction, the frequency is changed and step size is acquired. The optimal frequency is defined as the very best absolute velocity coupled to the best symmetry. This goal, called $J$, has to be maximised. It is described in (1).

$$J = \frac{\max \text{speed}_{\text{pos}}^2 \cdot \max \text{speed}_{\text{neg}}^2}{\max \text{speed}_{\text{pos}} - \max \text{speed}_{\text{neg}}} \quad (1)$$

The Autotune procedure has been developed and integrated into dedicated driver SPC45. This Stepping Piezo Controller is able to control Stepping Piezo Actuators from tiny to micro sizes (SPA30uXS up to SPA35XS). It is an autonomous driver capable to read encoder (magnetic, inductive, or optical) and to close the loop into stepping mode. The SPC45 is visible on Fig. 9.

The Autotune function has been applied to an 8 motors batch in order to get a quantitative feedback of the global efficiency of the procedure. The results of this study are visible on Fig. 10. Setting of the optimal frequencies dedicated to each motor allows limiting dispersion in speed between every motor. On the selected batch, only the motor 10-007 still has a speed below 30mm/s. For others, frequency evaluation seems relevant.

**Fig. 9 SPC45 driver**

**Fig. 10 LSPA30uXS performances be fore and after Autotune**

**Conclusions & Future Work**

Improvements presented here, such as thermal vacuum compatibility and rotating configuration, are already involved into industrial developments on biomedical field, as well as into air & space and defence applications. Stepping Piezo Actuator can be Linear or Rotating, and can be implemented as single motor or even into guided stage, with or without sensor. In this case, the dedicated name is Stepping Piezo Stage (SPS). This flexibility allows the SPA technology to be compatible with various application fields.

Future work will concern friction interface materials to enlarge the maximal enabled temperature. Control developments are still ongoing to minimize the motor resolution into stepping mode, giving strong advantage facing classical electrical stepper motor coupled to gear box, larger and heavier.

**References**


