

Benefits from Amplification of Piezo Actuation in Inertial Stepping Motors and application for High-performance Linear Micro Motors

Christian Belly, Frank Claeysen, Ronan Le Letty, Thomas Porchez
Cedrat Technologies S.A. 15 chemin de Malacher, Inovallée, 38246 Meylan Cedex, France

Abstract:

Stepping Piezo Actuators (SPA) are long stroke linear piezoelectric actuators capable to reach long stroke (typ. >10mm) with an important resolution (typ. <1nm). It has been proposed to use Amplified Piezo Actuator into inertial stepper motor to build the SPA. This piezo motor showed good behaviour, with relatively high speed (up to 70mm/s), force (from 0.2N to 20N) and low consumption (down to 700mW). The paper proposes experimental results obtained with a new miniature version of the SPA, so called SPA30uXS. Speed aspects, force and consumption are considered as well as non-magnetic compatibility for medical MRI applications. A comparison with other tiny piezo motors is also proposed, in order to give the reader the opportunity to settle the proposed actuator within the realm of possibility. The Squiggle SQL-RV-1.8, from Newscale Technology and the P563, from Physik Instruments are considered.

Keywords: linear, micro, piezoelectric, motor, actuator, stepping, MRI, APA™

Introduction

The stroke offered by piezoelectric actuator is often too short to fit the constraints of some specific designs. A proposed solution consists in what is called piezoelectric motor. 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 miniaturisation. The concept of inertial piezoelectric motor, introduced in [1], has been used in order to fit extreme precision needed in Tunneling Microscope Scanning [2], compatible with cryogenic environments. A similar concept was proposed by Higuchi in [3], and was adapted to build the Smooth Impact Drive Mechanism [4], used in camera blur reduction mechanism. The aim of this work is to present the new SPA30uXS, miniature inertial piezo motor, taking advantage from mechanical amplification from the APA™.

Motor principle

Stepping Piezo Actuators are inertial stepper motors. They are composed of four main elements, enough 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 got from the prestress of the ceramic, and the easiness of integration makes

this actuator particularly relevant. We will see further that the benefits taken from this kind of actuator are wider than these two points.

The principle of such motor is simple and relies on stick-slip effect and dissymmetrical accelerations. *Fig. 1* 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 inverting the two sequences. This motion is called “Stepping Mode”.

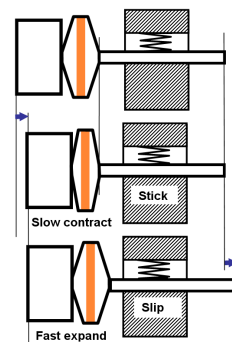


Fig. 1: Concept of Stepping Mode

Another way to use the SPA is called “Deformation Mode”. In this case, the tool is attached to the mass

and it is the actuator deformation which is used, without dynamic effect. By the way, the precise motion offered by the APA allows reaching a high resolution.

Design

In order to fit extreme volume constraints, a new micro APA has been designed: the APA30uXS. Able to reach 40 μm of stroke and to produce 3,3N force, its stiffness is 0,108N/ μm . In the SPA, the APA shell, the shaft and the mass are made in one single part, so the reliability of this kinematics group is strongly improved. Moreover, the manufacturing cost and assembling cost are also reduced, by reducing the number of parts to only two. Fig. 2 presents the realised motor. Its weight is less than 2 grams, for a 15x5x9mm³ outer volume.

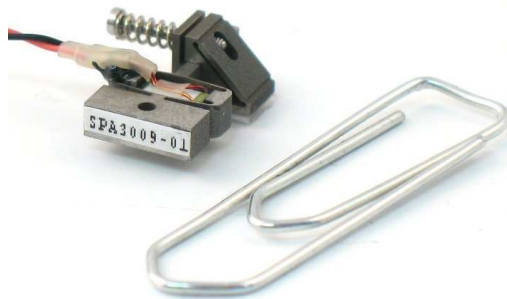


Fig. 2: SPA30uXS

The configuration of the SPA also 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 constraints less demanding. The elasticity of the shaft and the contact can be overcome because of that. Finally, the prestress of the ceramic by the shape of the APA gives the motor another reliability argument.

Results

Step size, speed

The SPA being built around an APA, it has been shown that amplification allows reducing current requirement compared to direct actuators [5] in inertial stepper motors. The amplification offered by APA is also interesting in terms of step size and speed. In fact, analytical approach of step size, already investigated by Higushi, Breguet and others [6], shows that step size is directly linked to the stroke of the actuator, whatever the input signal is. This point explains that the biggest the stroke is, the

bigger can be the step size. Support of Lumped model presented in [8] allows confirming this influence.

This step size conclusion can be extended to the motor speed, taking into consideration that step recurrence (input signal frequency) has to be limited by the natural frequency of the motor. Indeed, if the input signal frequency comes too close or behind the natural frequency, the behaviour of the motor may become erratic, creating big speed variation, or even motion direction reversing. Investigations about use of dynamic strain of APA, especially in SPA, are currently in progress [7].

The speed of a SPA30uXS can reach 70mm/s, and 0,3N actuation force under optimal conditions (shaft preload and signal).

Voltage characteristic and power

SPA is driven using a kind of sawtooth signal. This signal reaches a maximum voltage, which characterises the amplitude of the deformation of the actuator. This deformation induces the step size and so, it is possible to present the relation between maximum voltage of the input signal and the step size. This curve allows determining the minimum voltage needed to move the motor: the threshold voltage [8]. The second information available is the gain [$\mu\text{m}/\text{V}$], which determines the capability of the motor to convert voltage into motion.

Experimentation has been led with three different actuators from Cedrat Technologies: PPA20M APA40SM and APA60SM. Each of them presents a different stroke, respectively 20, 40 and 60 μm . The three characteristics are plot in Fig. 3. It can be seen that, for the three cases, the threshold voltage is quite similar. However, the gain is totally different and it is clear that the bigger is the stroke, the bigger is the gain, making the motor more efficient, in terms of motion and speed.

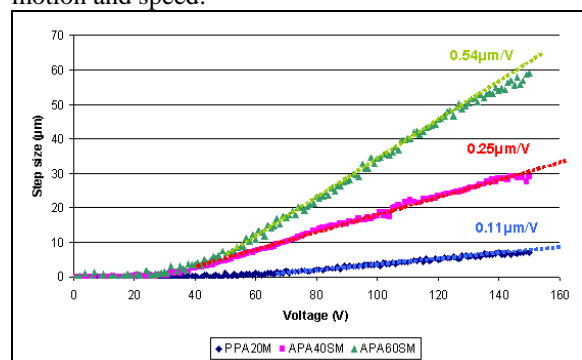


Fig. 3: SPA voltage characteristic

The standard sawtooth-like input signal imposes a quasistatic behaviour to the motor and so the associated power. The amplification reducing current

requirement compared to other inertial piezo motor, it does not avoid to use of high voltage (typically 150V for standard piezo ceramics), rising the driving power. However, other control methods (signals...) and ceramics definition can be investigated in order to decrease the voltage need and power consumption.

Load characteristic

Every motor owns a load characteristic, showing the influence of the loading on its speed. The SPA is no exception to rule. The example presented on *Fig. 4* presents the load characteristic of the SPA30uXS, mobile clamp, for a holding force of 1,3N. This kind of curve allows outlining important points of the motor, among which maximum speed and maximum force.

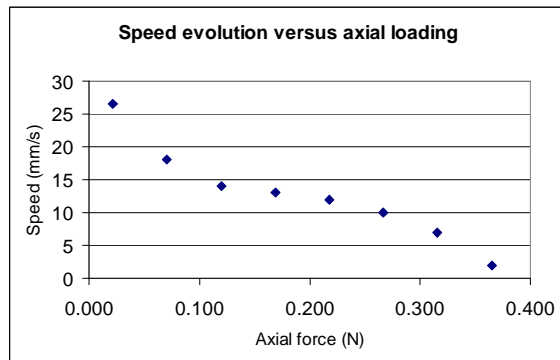


Fig. 4: SPA load characteristic example

Life time test

Lifetime of such device may be an issue for many applications. Friction based motors, like SPA, are often subject to reliability problems, not easy to solve. The solution relies on a combination of materials and contact geometry choice. In the SPA case, lifetime tests have been achieved using a Labview acquisition board and UC45 controller board from Cedrat Technologies. The sensor used is an incremental magnetic sensor, with a resolution of 61nm. Tests have been performed during more than 10^6 cycles showing a slow speed decreasing, but with continuous working, without any motor failure.

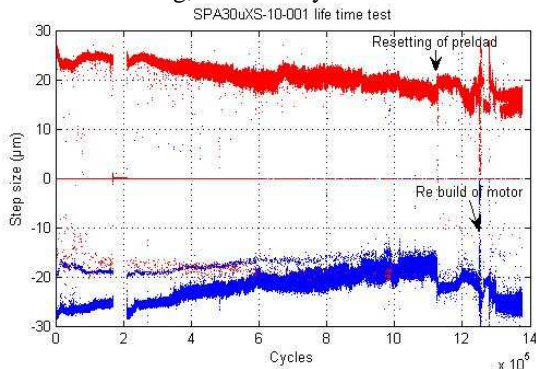


Fig. 5: Lifetime test results over 10^6 cycles

Compatibilities

The SPA30uXS has been designed with totally non-magnetic materials and components in its standard version. Foreseen to be part of biomedical devices or surgical robotics apparatus, the SPA30uXS has been widely tested to check its compliance with Magnetic Resonance Imaging (MRI). Tests have been performed into a 4.7 Tesla magnet, at the Small Animal Facility, INSERM Grenoble, and the three MRI compatibility rules have been proved. The first point is the safety issue: the motor is not attracted by the magnet, so it can be placed into a MRI scanner room and even into the scanner. The second point is the “invisibility issue”: the motor does not disturb the MR images. Tests have been done putting the motor within the field of view of the scanner and no impact on the Signal / Noise Ratio (SNR) has been observed. Other tests have been done with rat brain observation, reinforcing these results. The third point concerns the insensitivity: the motor is not disturbed by the MRI magnetic fields. This point is harder to observe because of the leak of adapted sensor. So, MR Images have been used to see the motor position into the scanner, using an adapted test bench (see *Fig. 6*).

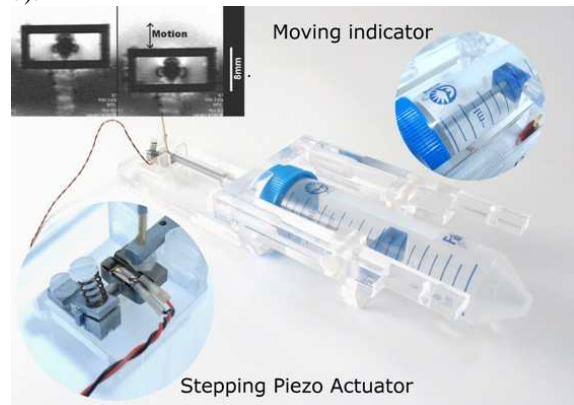


Fig. 6: SPA MRI test bench and results

Comparison with other tiny motors

Micro systems need small actuators, capable to perform high performances in a very little space. The SPA30uXS targets this kind of application, and proposes an alternative choice to other resonant piezo motors. In this part, we want to compare two other comparable tiny motors to the SPA30uXS. The first motor is the Squiggle SQL-RV-1.8, from New Scale Technologies. The second one is PILine P-653, from Physik Instruments.

The comparative study is focussed on performances in terms of speed, holding force and pushing force, but also lifetime and resolution. Main information is taken from [9] and [10].

The speed of resonant piezo motors is typically larger than inertial motor speed. Indeed the fact to use a non resonant excitation makes the signal repetition relatively slow. However, because of the introduction of amplification, the step size that can be reached is much larger than for other inertial motor. That is why the speed of the SPA30uXS is totally comparable with the speed of the other motors and why the SPA can go faster than the SQL. The resolution of the motor is a significant point for lots of applications. A particularity of the SPA is to combine both motion modes (described in Motor principle) to offer a high resolution. This aspect is a major differencing point facing other motors and it is especially visible on Table 1. Considering the length of each motor, a ratio stroke/resolution is also proposed (number of million positions available all along the motor stroke).

Piezo motors are characterized by two types of force capability: The actuation blocked force is the maximal force the motor is able to produce on load when supplied. The holding force at rest represents the maximum force the motor can support without losing its locking position and without electric power. This aspect is very important for applications where position as to be kept without power. Both of these forces from the SPA are comparable to those of the other motors

Conclusion

This paper presents the SPA30uXS, current smallest prototype of the Stepping Piezo Actuator, an APA based piezo motor. The interest to use amplified actuator is shown regarding qualitative arguments and performances aspects. These points are compared to other available tiny motors and it shows that SPA30uXS is a totally coherent solution for

micro systems, especially when strong magnetic fields are involved, due to its MRI compatibility.

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Nom	Units	SQL-RV-1.8	P-653	SPA30uXS
Manufacturer		New Scale Tech	Physik Instruments	Cedrat Technologies
Stroke	mm	6	2	4
Max speed unloaded	mm/s		90	70
Max speed loaded	mm/s	10	55	30
Resolution	nm	500	100	1
Holding force (OFF)	N		0.3	0.8
Max blocked force	N	0.5	0.15	0.3
Lifetime	cycles	1 000 000	2 000 000	1 000 000
External Volume	mm ³	94	220	675
Weight	gr	0.16	1	2
Comparison ratios				
Stroke/Length	mm/mm	0.50	0.18	0.27
Stroke/resolution	nm/mm	0.01	0.02	4.00

Table 1: Comparative study between several tiny motors