Stepping Piezoelectric Actuators Based on APAs

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Abstract:
Stepping Piezoelectric Actuators (SPA) are new small long-stroke linear piezoelectric motors for micro/nano positioning applications benefiting of the advantages and the heritage of the APA. SPA is formed of only 4 parts: the well-established Amplified Piezoelectric Actuators (APA), a front mass, a clamp and a rod. SPA operates by accumulation of small steps, using inertial mode, impact forces and stick-slip effects, allowing performing long strokes (> 10mm). Main advantages induced by the choice of the APA above a usual inertial drive mechanism (IDM) are high reliability, low peak current (<0.1A), relatively high speed (> 20mm/s), useful forces (from 1N for XS to 30N for SM type) and nano positioning mode. Other advantages are that only one channel per SPA is required and that virtually all standard APAs can be operated. The paper presents the design of a SPA based on APA35XS and provides numerous experimental data, as regard step size, speed, current requirement, lifetime close loop control and nano-positioning capabilities.

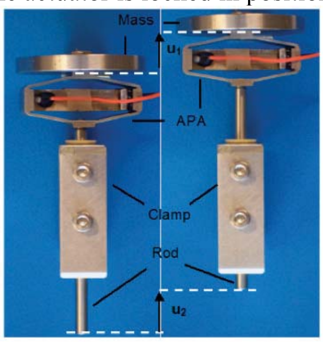
Keywords: Impact Drive Mechanism ; Inertial Stepping Motor ; Piezoelectric Actuator ; Nano Positioning ; SPA

Introduction

Stepping Piezoelectric Actuators (SPA) are new long-stroke linear inertial piezoelectric motors for micro/nano positioning applications benefiting of the advantages and the heritage of the APA [1,2] and based on an IDM [3].
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) [1,2]. 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 and they are selected in many EU and US space missions [4]. 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, piezo generators [5]…
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 [3].
As will be shown in this paper, the SPA provides significant improvement over standard IDM and other Inertial Stepping Motors (ISM) : Much less current, useful fine mode, good reliability … The presents the design of these actuators especially the SPA XS based on the APA35XS, and provide numerous experimental data, as regard step size, speed, current requirement, micro positioning capabilities, etc …

Stepping Piezoelectric Actuators concept

Stepping Piezoelectric Actuators (SPA) are formed of only 4 parts (Fig 1): the well-established Amplified Piezoelectric Actuators (APA), a front mass, a clamp and a rod. SPA operates by accumulation of small steps, using inertial mode, impact forces and stick-slip effects as introduced in [5] and analysed in [6]: Typically, a slow APA actuation generate 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 (M1). Between each step the actuator is locked in position.



(a) (b)

Fig 1 *SPA SM-S based on the APA60SM before (a) and after (b) a 10mm stroke with the mode M1*

The load may be fixed on different positions leading to 2 different motor capabilities thanks to different modes. In a first configuration offering nano positioning, the load can replace the mass or can be fixed to the mass. So when the long stroke (M1) is performed, the motor can be also operated in a deformation mode (M2) for a fine adjustment. In this case, the stroke is proportional to the applied voltage, which leads to a nanometer resolution and a high bandwidth. In a second configuration, the load is fixed on the moving rod. In this case, the advantage is a high stiffness.

The long stroke stepping mode (M1) is produced by step accumulation with an appropriate 0-150V voltage pattern. The short stroke deformation mode (M2) is produced by deformation of the APA, which is simply proportional to the excitation voltage between –20 to +150V. Only one amplifier channel per SPA is required.

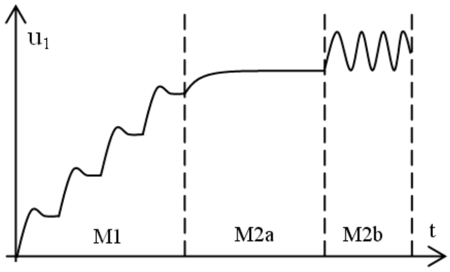


Fig 2 *Displacement u1 of the Mass*
M1 : Long stroke stepping mode
M2 : Short stroke deformation mode
(M2a : quasi-static ; M2b : dynamic)

Because of the use of the APA instead of usual piezoelectric ceramics, the required current is strongly reduced compared to usual Inertial Stepping Motors (ISMs).

In the usual ISM, a strong current is demanded at each cycle to produce the fast motion: This is needed to fast charge the piezo capacitance. Fast means in a short time t_1 compared to the eigen period T, the inverse of the resonant frequency. An example based on a standard ISM [3] gives:

Resonant frequency = 10kHz, meaning an eigen frequency period : T=100µs. So t_1= T/2 = 50µs.

As the piezo ceramic capacitance = 5µF, under 150V, the required current is :

$$I = C.V/t_1 \qquad (1)$$

giving I = 15A. This high current is typical of usual ISMs. It is a strong limitation of the ISM as it is constraining for the electronics, the reliability, etc…

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 fine short stroke mode (M2). It also contributes in getting good speed in long stroke mode (M1): Larger steps per cycle compensate a lower step frequency.

These expected advantages provided by the APA into an IDM stepping piezoelectric motor have been experimented in several prototypes.

SPA-XS prototype based on APA35XS

The APA35XS was selected to assess a SPA-XS IDM motor concept and the expected advantages.

The AP35XS is an eXtra Small standard Amplified Piezoelectric Actuator manufactured by Cedrat [1]. It is based on a Multilayer piezoelectric ceramic with a capacitance up to C=0.37µF. The shell provides a pre-stress of the ceramic to avoid tensile stress in the ceramic. This is useful as IDM are based on fast transient motions generating high internal stresses.

Fig 3 *Set of standard APA35XS*

The total stroke is 57µm for V=-20V to 150V. It corresponds to a 1% max. free strain. Max. blocked force is 27N and stiffness is 0.5N/µm. With a 50 grams mass, T=2ms. By applying t_1= T/2 with (1), the required charge current is I = 55.5mA. This is much weaker than in other IDM [3] and is easy to provide with standard electronics.

With a step frequency of 250Hz (initial idea), so a step cycle time of 4ms, and assuming each step is equal to one full stroke of the actuator (50µm for 150V), the speed of the motor would be 12,5mm/s. About the forces, the expectation was to get a fraction of the actuator blocked force.

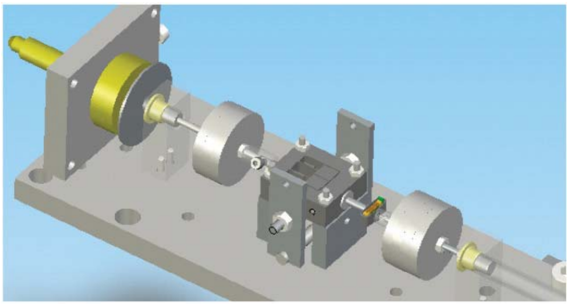


Fig 4 *Test bench of the SPA concept based on APA35XS (CAD view)*

The test bench to check the IDM motor concept is shown in Fig 4. The APA35XS is fixed on one side on a guided back mass. On the other side, it is fixed to a rod. The rod goes through a clamp, the normal force of which can be adjusted by either external springs (as Fig 5) or internal springs. Back to the clamp, the rod is loaded by an optional front mass and also supports the target of a capacitive sensor. This target is located in front of the probe of a MMC30 capacitive sensor from FOGALE. This sensor is used to measure the motor stroke and speed. The blocked force of the motor is measured using additional masses and vertical gravity loading. Both front and back masses can be easily changed.
Fig 5 represents a typical interesting test case, where the back mass is 40gr and the front mass is null (except the rod mass). The clamp is made of steel. Two rods have been realised: One in steel without surface treatment, one in steel covered by polymer. By this way, two friction interfaces can be compared.

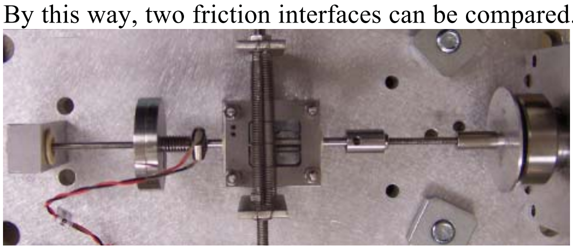


Fig 5 *Test bench of the SPA concept based on APA35XS (Typical configuration)*

For speed operation, the most interesting excitation was found a double-quarter of sinus of 1ms up and 1ms down with voltage amplitude of 150V. Thus the step cycle is 2ms and the step frequency is 500Hz. This signal can be provided with standard Cedrat low power LA75A linear amplifier limited to 90mA. The speed reaches more than 20mm/s when the back mass is larger than 30gr. It is larger than initially expected. In this condition, the step size is 55µm. It is a bit larger than the actuator stroke at 150V. It is concluded that due to inertia some kinetic energy is stored in the motor. Transient displacement measurements show that steady state step is got after 2 steps. The speed of the steel interface motor is larger than the polymer interface motor because the contact stiffness is higher. Applied clamping force was set to get similar actuation for in both cases:
With a 7N clamping force, the steel interface motor presents a 3.5N holding force at rest and a 0.8N actuator force.
With a 11.2N clamping force, the polymer interface motor presents a 6.3N holding force at rest and a 0.8N actuator force. (resp. 23% and 3% of the APA blocked force).

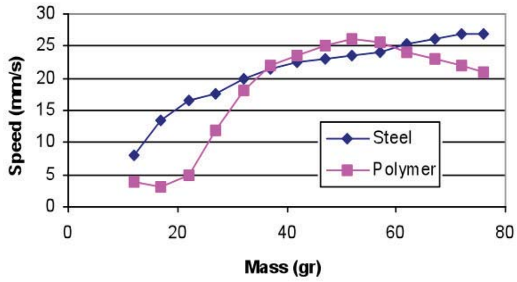


Fig 6 *Speed vs Mass for 2 different interfaces*

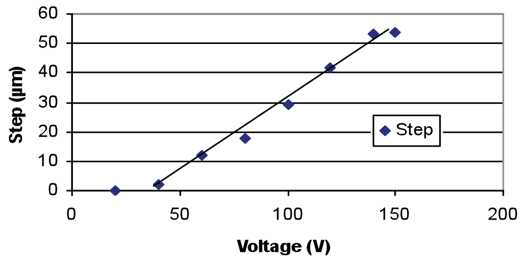


Fig 7 *Step size vs voltage (Steel int., 45gr mass)*

The step size can be controlled by the applied voltage (Fig 7). Above a threshold of 40V needed to generate slip, the step and the speed are proportional to the applied voltage. This is an advantage for micro and even nano positioning: By reducing the step size, the final position can be achieved to the micron range with Mode M1. Then for final nano positioning, the moving mass can be adjusted with M2 mode of the APA35XS from –50µm to +7µm.
Lifetime tests have been performed on both interface types. Steel interface shows unreliability after 5,000 return strokes. At the opposite, the polymer interface motor has succeeded tests of 10,000 back and forth strokes without significant speed variations (*Fig 8*). The speed forward is slightly larger than the speed backward, but both converge progressively.

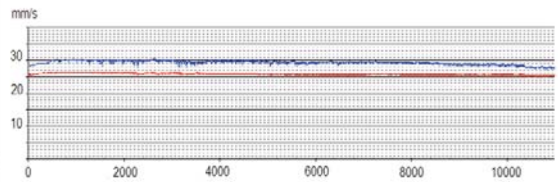


Fig 8 *Speed vs cycles (Polymer int.- 45gr mass)*

For force operation, the most interesting excitation was found double-quarter of sinus of 2ms up and 2ms down with voltage amplitude of 150V. The polymer interface motor presents a 6.3N holding force at rest and a 2.0N actuator force (resp. 25% and 7.5% of the APA blocked force). In this case, the max speed is reduced to 15mm/s.

Coupled with dedicated driver (CA45), a specific controller (UC45 or UC75) and an incremental magnetic sensor, a response similar to fig2 been obtained experimentally. Coupling long stroke mode (M1) and short stroke mode (M2a) offers very high stroke / precision ratio and stroke / resolution ratio. Precision achieved in the test was 60nm being limited by the magnetic sensor. The motor resolution is limited to 0.5nm in M1 mode due to the amplifier.

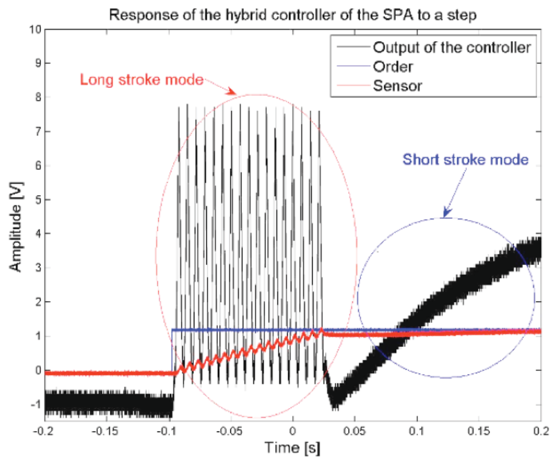


***Fig 9:** Stroke measured on sensor in response to a square order (piezo voltage is amplified by 20)*

Using SPA concept, virtually all standard APAs can be operated as a SPA with appropriate add parts. However smaller APAs (series µXS, XXS, S, SM) are of higher interest, because they lead to flat tiny piezo motors. Tests with SPA SM (Fig 1) also shown that its holding and actuation forces represent good shares of the blocked force of the APA60SM (resp 25-30% and 7-10%) as for the SPA-XS. Therefore the SPA concept can be considered as a way to expand the limited stroke of the APA. A range of products with preliminary data is defined in Table 1.

Non magnetic actuators APAs (NM option) can also be selected for non magnetic motors. Temperature range is typically –40°C to +80°C, but it can be extended to cryogenic (77K) or warm (140°C) temperatures.

Conclusion

SPAs are APA-based IDMs providing a new solution for making small non-magnetic motors offering blocking force at rest. Compared to usual IDM they require much less current. They also offer significant speed (up to 25mm/s) as well as high holding and blocked forces. They appear quite robust: The motor can run with various mass loads without changing the command. The speed is stable with the number of cycles. Coupling long and short stroke modes has been tested with numerical controller. It offers very high stroke / precision and stroke / resolution ratios.
Future applications are identified in instruments for medical, space and optic domains.

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References	Unit	SPA µXS	SPA XS-S	SPA XS-F	SPA SM-S	SPA SM-F
Notes		Preliminary	Preliminary	Preliminary	Preliminary	Preliminary
Base		APA µXS	APA35XS	APA35XS	APA60SM	APA60SM
Blocking force at rest (M1, M2)	N	0,3	3	6	15	30
Long stroke (M1)	mm	5	10	10	20	20
Actuation force (M1)	N	0,1	1	2	5	10
Max speed (M1)	mm/s	20	20	5	20	5
Short high resolution stroke (M2)	µm	60	55	55	80	80
Bandwidth (M2)	kH	7	5	5	4	4
Resolution (M2)	nm	< 6	< 5,5	< 5,5	< 8	< 8
Capacitance (M1, M2)	µF	0,02	0,25	0,25	1,55	1,55
Height along active axis	mm	13	20	20	40	40
Base size	mm2	3 x 13	9 x 13	9 x 13	12 x 27	12 x 27
LA75 types compatibility		A - B - C	A - B - C	A - B - C	B - C	B - C
CA45 compatibiliy		yes	yes (adapted)	yes (adapted)	no	no

***Table 1:** Performance of different SPA motors and according to Speed operation (-S) or Force operation (-F)*