ROTATING STEP BY STEP PIEZOMOTOR FOR NANOPOSITIONING & SPACE APPLICATIONS

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Abstract

Piezomotors are well known in various applications where high precision actuation is required like AFM or handling equipment for semiconductor production. Their specific low speed in direct drive and high torque characteristics combined with high holding torque in off power conditions make them very attractive for any positioning application and especially space mechanisms where low electrical consumption is always sought. A new concept of rotating stepping piezomotor has been developed in the frame of the LISA space project where the mechanism of the telescope orientation was addressed. A full space qualification campaign has been carried out on the piezomotor model. Both thermal behaviour on a [-25, 75]°C range, and a 5.10^5 cycles lifetime have been validated whereas the vibration test was partially successful. The motor characteristics unchanged after the lifetime test display a ±1° rotation angle and a 0.05 rpm speed at 50Hz driving and a positioning resolution measured around 200 nrad. These reliable and high motor performances can answer to demanding positioning requirement including moreover non magnetic specification.

Introduction

Among the three different piezomotors categories, resonant, quasistatic or stepping and inertial, and as far as accuracy is concerned a quasistatic behaviour is far more preferable, because of the infinite resolution of the piezo element driven in static. However, this benefit is then obtained at the expense of the speed which is reduced again typically below 1mm/s. Cedrat has already and successfully developed its own concept of Ultrasonic Piezo Drive which can combines resonant and static driving modes for higher accuracy [1]. But such dual driving modes required a complex control electronics. In stepping motor, the driving sequence is not so far from the human walking and such motors can be designed both for linear or rotation actuation.

The paper introduces a new concept of rotating stepping piezomotor developed in the frame of the LISA space project where the mechanism of the telescope orientation was addressed. The most stringent requirement was the motor angular positioning resolution and precision wished respectively below 50 and 200nrad. Compared to typical electro-magnetic DC and stepper motors, piezo motors offer special characteristics, which still appear very attractive for space applications, such as:

- Non-powered holding torque higher than the maximum driving torque
- High positioning accuracy in direct drive mode
- Feasibility of non-magnetic motor designs

Basic Principle of Operation

The piezomotor concept by CEDRAT Technologies belongs to the category quasistatic step by step motors also called Inchworm [2]. Steppping piezomotors have been mainly developed for linear motion. The initial development has been performed by Burleigh from the 70's. Stepping motor are using quasistatic deformations of basically two sets of piezo elements: one for the driving function and another for the clamping function (Fig. 1). The position accuracy of the motor depends then on the control of the elongation members and on the stiffness of the clamping device.

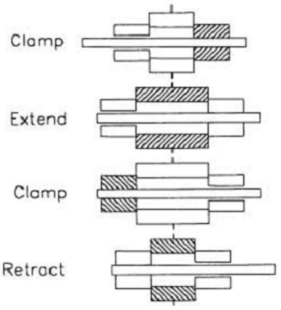


Fig. 1: Operating sequence of a stepping piezomotor

However this basic design suffers from the lack of play recovery mechanism which makes it sensitive to wear and thermo-mechanics effects. Amplify the displacement of the clamping element is a route to push away such limitations but which is nevertheless performed at the expense of the piezomotor stiffness. Amplified Piezo Actuators (APA) from Cedrat Technologies have been already considered in stepping piezomotors development [3,4]. Recent work at Virginia Tech. University lead to the stepping motor displaying the higher force capability ever reported : a blocking force of 170 N and a linear speed of 5mm/s, when operated at 50Hz. Such speed was reached thanks to the use of an APA120ML for the driving function.

The basic working principle of the Cedrat stepping piezomotor concept is illustrated through a simplified linear model based on a pair of APAs (Fig. 2). These displacements and forces produced by the APA are transferred to the slider or the rotor by friction. At least one pair of APAs is used in the following conditions : held by their centre, the APA are actuated opposite in phase.

The motion sequence is in fact not so far from the human walking, each APA working as one leg and whose contact top would be one feet. However, the displacement sequence which produces one step is simplified in the sense that the tops are only actuated with series of pure normal or tangential displacements. During one displacement step, each APA alternatively takes part to drive the slider during a driving stage (a) by friction whereas the other APA returns backward once released from the slider (b).

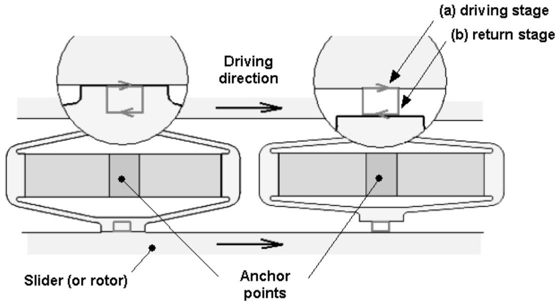


Fig. 2: Step by step principle based on a pair of APAs

Both the required normal and tangential displacement can be easily obtained at the tops of the APA with the appropriated voltage supply of its pair of piezo-ceramics (MLA) :

- the same additional voltage supply produces a normal displacement (Fig. 3),
- an opposite additional voltage supply produces a tangential displacement (Fig. 4).

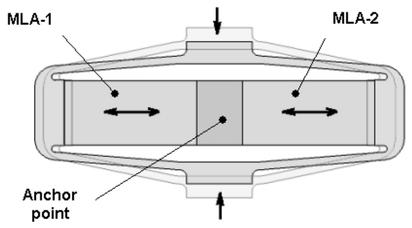


Fig. 3: Pure normal displacement of the APA tops

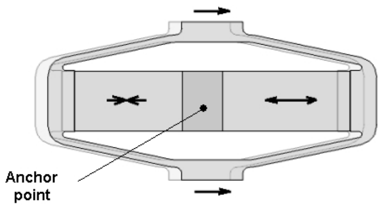


Fig. 4: Pure tangential displacement of the APA tops

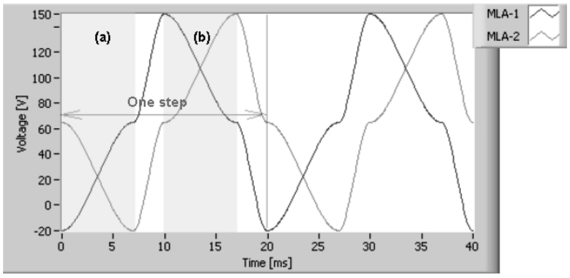
Using the APA symmetry, both its tops can be exploited to produce the driving and then optimise the energy conversion as shown in Fig. 2. Another advantage of using APAs is the amplified displacement in the normal direction to reduce the potential losses induced by friction during the return stage (b). Compared to the basic Inchworm design, both the functions of clamping and driving are here mixed through the same APA.

Running Modes

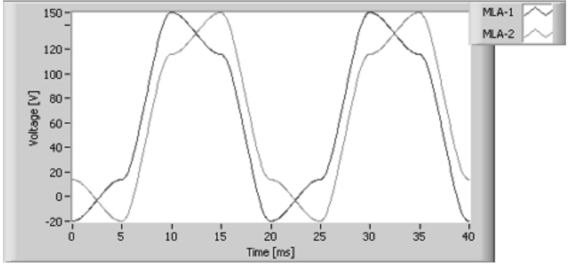
This piezomotor concept displays two distinct modes of running which are easily combined successively to reach the targeted position:

- a coarse mode through the above described stepping principle. In this driving mode the stroke is not limited and one linear displacement step can vary from 1 to 10µm lenght versus the voltage level applied.
- a fine mode to increase the precision positioning after a coarse approach. In this mode, the pair of APA is driven in phase and actuated so that a tangential displacement is produced. The total stroke centred around the non powered state is in this case limited to about the equivalent of one coarse step.

In coarse mode, the excitation pattern for one APA of the pair can be modified depending on both the time and voltage ratios λ and ρ respectively, which give the distribution in time and in amplitude between the APA tangential and normal displacements during one step. The following graphs show two typical examples of excitation schemes with different ratios values. Especially, the step length can be easily modified (shorter step with the second pattern). A pre-shaper is included to smooth the command on the MLA at the end of tangential or normal motion sequences.



a) λ =70% and ρ=50%



b) λ =50% and ρ=20%

Fig. 5: Voltage command for one APA at 50Hz

Close to the targeted position, the fine mode allows to reach it thanks to a better precision as far as the coarse mode can be subjected to backlash effect due to alternation of contact from one APA to another during one step. Moreover, in fine mode, the output motion is directly proportional to the voltage to be applied on the APA apart from the hysteresis effect of the MLA itself.

Motor Design and Electronics

The architecture of the Cedrat Rotary Piezo Motor (RPM) is fully symmetric : the stator composed of three pairs of APA is pressed between two rotors. Six APA60SM are distributed on a 100mm diameter circle and offer a good compromise in terms of motor performances and steadiness, and general size, while avoiding contact hyperstatism problem.

The rotors include a polymer friction layer selected for the given tribological conditions including the vacuum and thermal space requirements. A preloading device has been integrated in the rotor part design in order to initially adjust precisely and easily the preload and then optimise the motor performances. This device was also necessary to limit the preload variation regarding the specified thermal range and the given thermo-mechanics behaviour of the APA, and to compensate the wear at the friction interface regarding the lifetime requirements. The rotor stiffness ratios have been also carefully examined to reduce the elastic losses and homogenise the contact pressure on the APA tops.

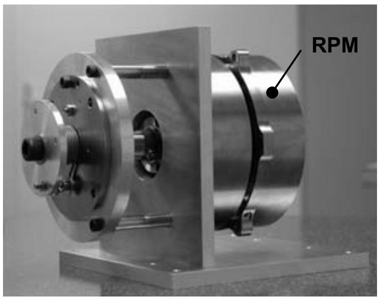


Fig. 6: RPM mounted on its loading bench

The through output shaft of the motor is rigidly guided by a pair of compact elastic pivot mounted at each side. The pivot design is based on three crossed flexural blades at 120° which displays very high stiffness ratios to withstand the vibration stress. In this configuration, the angular range of rotation is then limited to about +/-7°. However, an additional pair of Eddy current sensor integrated in the motor guiding device reduce this angle down to +/-2° rotation. The motor overall dimensions are detailed in the table 1.

The RPM electronics rack is based on standard Cedrat linear amplifiers LA75-B2 boards [5]. Four output channels are used to feed the RPM and are controlled through the micro-controller UC75 board connected to the sensor electronics of the RPM.

Achieved Performances

The motor has followed a full test campaign for space qualification. The environmental tests have shown that the motor behaviour in air and vacuum at ambient temperature was unchanged. A vacuum thermal test including a storage cycling in the range [-200...+150]°C and a functional cycling in the range [-25...+75]°C was successfully performed (Fig. 7).

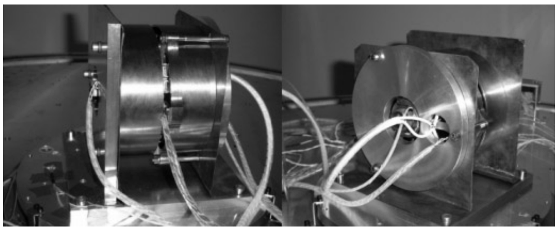


Fig. 7: Thermal vacuum cycling test conditions

The RPM characteristics (step lenght) display a regular decrease with a temperature reduction. The maximal driving torque is about 0.5Nm whereas a 0.05 rpm rotation speed can be reached in no-load conditions with a 50Hz step frequency. On the angular tested range +/-1°, the behaviour in coarse mode is very steady with repeatable steps up to 140µrad at full voltage level (Fig. 8).

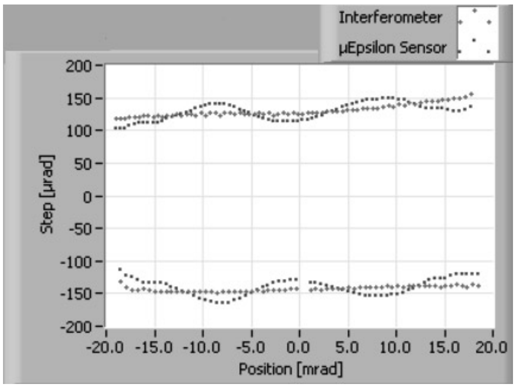


Fig. 8: No-load characterisation in coarse mode at 20°C

The RPM vibration tests and a shock tests performed with a 0.3kg payload up to a 20g_{RMS} random level were almost conclusive (Fig. 9) : The rotor/stator contact interface appeared as the most critical point on the RPM ability to withstand such a requirement.

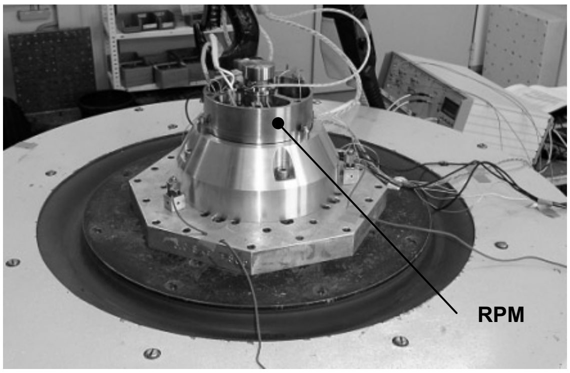


Fig. 9: Vibration test conditions

A vacuum lifetime test under 0.3Nm loading was also performed on the RPM. The target of 5.10^5 cycles were achieved on the ±1° angular range, at the average speed of 2.5mrad/s. The test parameters fully monitored with a dedicated Labview program indicated a great steadiness of the motor characteristics during the whole test. The low wear volume observed at the friction interface is stayed well confined in the contact area avoiding any other pollution.

Finally, the fine positioning capabilities of the motor have been measured and checked through additional calibration sensor with two different autocollimators from Moëller-Wedell (Fig. 10). The positioning resolution is currently about 200nrad but could be yet improved at the sensor level.

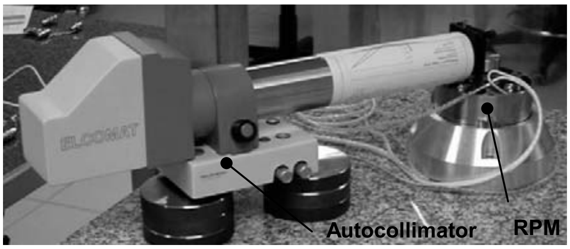
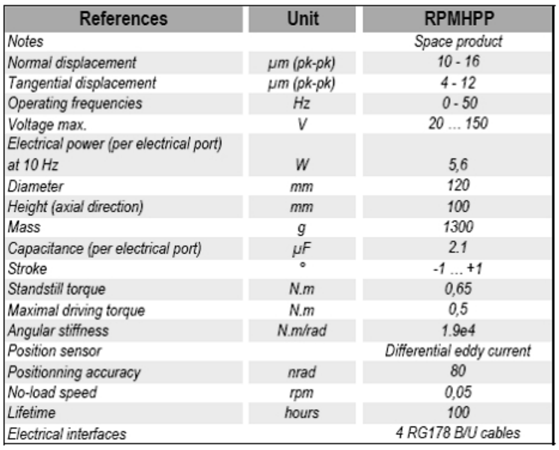


Fig. 10: RPM Positioning capability characterisation

The following Table sums-up the main characteristics of the current RPM motor.



References	Unit	RPMHPP
Notes		Space product
Normal displacement	µm (pk-pk)	10 - 16
Tangential displacement	µm (pk-pk)	4 - 12
Operating frequencies	Hz	0 - 50
Voltage max.	V	20 … 150
Electrical power (per electrical port) at 10 Hz	W	5,6
Diameter	mm	120
Height (axial direction)	mm	100
Mass	g	1300
Capacitance (per electrical port)	µF	2.1
Stroke	°	-1 … +1
Standstill torque	N.m	0,65
Maximal driving torque	N.m	0,5
Angular stiffness	N.m/rad	1.9e4
Position sensor		Differential eddy current
Positionning accuracy	nrad	80
No-load speed	rpm	0,05
Lifetime	hours	100
Electrical interfaces		4 RG178 B/U cables

Table 1: RPM main characteristics

Conclusion

The presented stepping piezomotor technology has the potential to provide very high accuracy positioning for spacecraft instruments and mechanisms. The performances and lifetime of this new stepping rotary motor has been demonstrated on a large range of environmental conditions. Future work should focus on new improvements of both the RPM positioning precision and its driving torque.

References

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