ROTATING PIEZOELECTRIC MOTORS FOR HIGH PRECISION POSITIONING & SPACE APPLICATIONS

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Abstract

Piezo-electric motors have been successfully developed for various applications like autofocus drives in camera lenses and handling equipment for semiconductor production. Their high speed and accurate positioning capability, combined with a favourable holding torque in unpowered condition, make piezomotors also very attractive for actuation purposes in spacecraft mechanisms. The paper introduces a new concept of a versatile ultrasonic piezomotor. The testing campaign carried out on the designed rotating piezomotor has validated the vacuum compatibility and the lifetime of the motor in air. This motor has shown a mechanical power of 0.3W under 30mN.m torque, no-load speeds upper than 140 rpm and a positioning accuracy of 10µrad. Its reliable performances over a large temperature range [-15 / +65] °C, has also been demonstrated during a thermal cycling test in vacuum. The developed technology may then find applications in two kinds of outlets, especially in the space field: very accurate positioning of existing guided and fully non magnetic actuation.

Introduction

For more than 20 years, motor concepts relying on the piezo-electric effect have been devised, and a number of industrial applications have reached a remarkable level of maturity within the last decade. More recently, their suitability for utilisation in space has started to be investigated.[1] One of the first in-flight experiments applying small rotary piezo motors is foreseen with the Micro-Imaging Dust Analysis System (MIDAS) onboard ESA's comet exploration mission ROSETTA recently lauched.[2]

The paper introduces a new architecture of piezo motors based on a versatile stator unit called the Ultrasonic Piezo Drive (UPD). Compared to typical electro-magnetic DC and stepper motors, piezo motors offer special characteristics, which might also be very attractive for future space applications, for instance:

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

In the earlier stages of the development, a linear piezo motor has been built by CEDRAT TECHNOLOGIES for a refocusing mechanism in a space-borne telescope.[3,4] Currently, several prototypes of rotary piezo motors are being manufactured and tested.

Basic Principle of Operation

The class of ultrasonic motors utilises harmonic excitation at a resonance frequency in the ultrasonic range. They comprise standing wave and travelling wave motors as well as concepts utilising mode conversion, pure rotation modes or multiple vibration modes.[5] The piezo motor concept by CEDRAT TECHNOLOGIES belongs to the category of multiple-mode ultrasonic motors.[6] It relies on the generation of a vibratory elliptic locus to drive a movable output member as schematically outlined in Figure 1 (not to scale). The UPD or stator unit of such a motor consists of two piezo CMA (Ceramic Multi-layer Actuators), a shell structure, and a central counter mass.

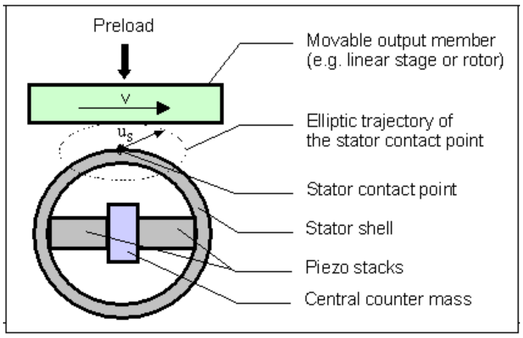

Fig. 1: UPD-based motor concept

The shell is surrounding and preloading the CMA, while the counter mass contributes to the control and tuning of the overall stator dynamics. Such configuration shows two relevant mechanical vibration modes, which occur at resonance frequencies very close to each other:

- a *flexural mode* that produces a displacement normal to the stator contact surface (Figure 2),

- a *translation mode* that produces a displacement tangential to the stator contact surface (Figure 3)

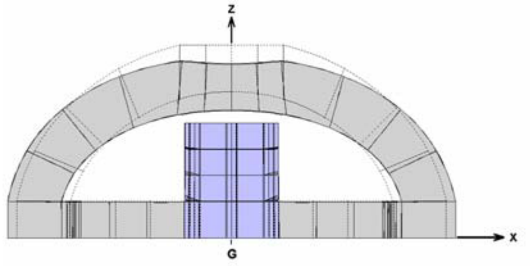

Fig. 2: FEM simulation of the flexural mode

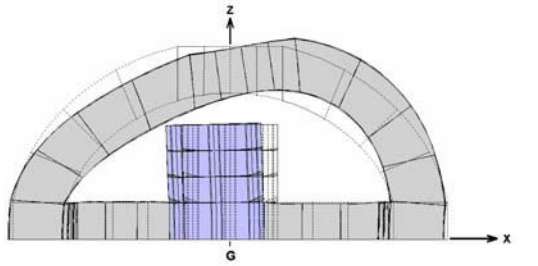

Fig. 3: FEM simulation of the translation mode

By superimposing the two vibration modes, a vibratory elliptic locus of the stator contact point can be obtained (Figure 4).

The stator will be brought in contact with a movable output member, which can feature a flat contact surface for a linear translation as shown in Fig. 1 or a cylindrical surface for a rotation. A play recovery mechanism is used to press the stator against the movable member in order to make sure that the contact preload remains unaffected by wear or thermo-mechanical strains. Under the presence of this preload, the non-powered motor is hold in position by a static friction force or torque, respectively. When the stator is electrically excited at the working frequency, the resulting vibrations induce a movement on the output member relative to the stator.

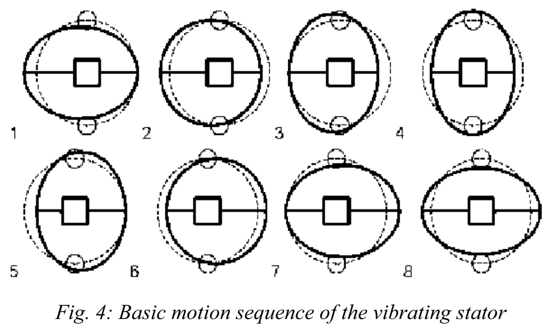

Fig. 4: Basic motion sequence of the vibrating stator

In addition to the application of a defined preload, the stator has to be properly guided in order to avoid any undesired stator displacement. The play recovery and stator guiding functions are embedded in the stator housing design, which furthermore isolates the ultrasonic vibrations of the stator from the external interfaces of the motor.

Motor Concept Options

Two basic sizes of vibrating stator units have been developed so far. They are designated UPD20 and UPD60, where the number indicates the approximate drive frequency in kHz. Starting with the stator design as a technology core, different motor configurations can be conceived:

- Linear Motor

The stator can directly drive a linear stage (Figure 5) which must require special attention with respect to space-compatible lubrication.[7] An actuation force in the order of 1N and a linear speed of 70mm/s have been achieved.

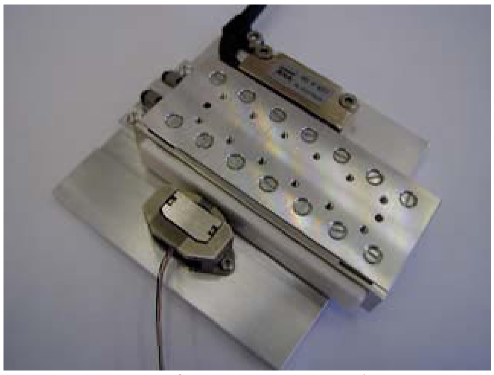

Fig. 5: UPD60 drive unit actuating a linear stage

- Small Rotary Motor

The stator can also drive a small roller (Figure 6) leading to high-speed and low-torque characteristics. The roller is mounted with the output shaft on top of the stator unit. A motor with 20mm diameter can produce a torque of 7mN.m and reach a no-load speed of 1000 rpm. A prototype motor of this kind has successfully passed a random vibration test at the French Space Agency CNES.

Fig. 6: Small rotary motor – type RPM60

- Large Rotary Motor

Alternatively, the stator can drive an annular or cup-type output member with larger diameter, while it is accommodated either inside or outside the overall assembly. The configuration in Figure 7 has been studied in more detail, aiming at a space compatible design with an extended operational temperature range.

Fig. 7: Rotary motor configuration with visible internal UPD unit (top cover not shown)

Above-listed concept options underline the versatility of the overall motor/actuator design utilising the same UPD stator assembly. By changing the diameter of the output element in a rotary motor configuration, the torque-speed characteristics can be tailored to the application over a wide range. Furthermore, the motor function can be closely integrated with the target application. For instance, the UPD stator can directly interface with a contact ring at the outer surface of the item to be moved.

Space-Compatible Design

The present development is focussing on a multi-purpose rotary motor for use in space mechanisms. A view of the realised motor model is shown in Figure 8. The motor has an external diameter of approximately 70mm and a height of about 30mm.

Special attention is given to the suspension of the output member or rotor. A duplex angular-contact ball bearing in O-configuration has been selected to support external loads, e.g. due to launch vibrations, as well as the internal radial preload between rotor and stator.

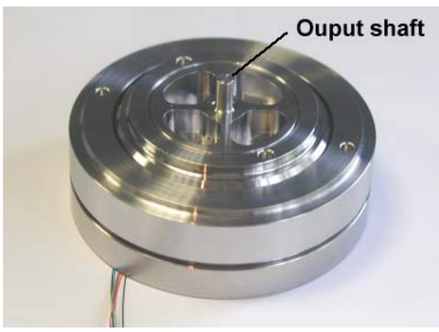

Fig. 8: Rotary motor prototype (RPA)

The motor can operate in air and in vacuum, which is assured by the appropriate choice of bearing lubricants, insulation materials, etc. Furthermore, in view of the large target temperature range, material combinations with suitable coefficients of thermal expansion and thermo-optical properties have been selected. The motor design also allows to include 3 UPD drive units in parallel which then could significantly increase its performances.

The friction contact between the stator and the rotor represents a critical function for correct operation of the motor. It should behave similarly in air and in vacuum. In general, a high friction coefficient and a low wear rate should be maintained throughout the lifetime of the motor. Dedicated sample tests were performed on a pin-on-disc tribometer in order to compare the behaviour of different friction layer materials at several temperatures in air and in vacuum. However, the first motor tests with the selected ceramic couple based interface led to short lifetime results. Finally a polymer/steel friction couple based solution was preferred although the operational temperature range was then limited by the thermo-mechanical properties of the polymer.

Functional Tests Results

After an usual no-load running-in period where the motor speed slightly increased, the motor performance vs. external load was characterised in air (Figure 9). A good symmetrical behaviour was measured in both rotation directions and the mechanical power approached 0.25W under a 35mN.m loading.

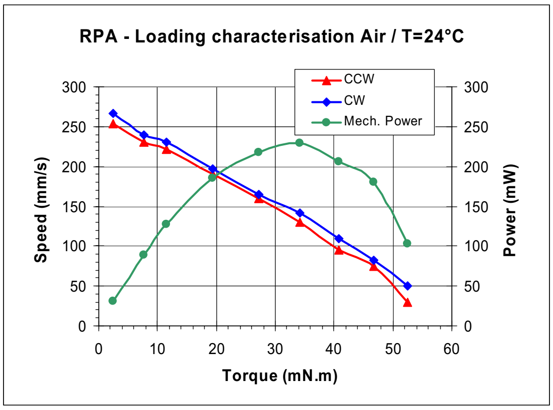

Fig. 9: Initial loading characterisation of the motor

A typical thermal vacuum test is then performed including a storage thermal cycling, 2 cycles in the range of [-25...+75°C], before a functional thermal cycling: 8 cycles up to the range of [-15...+65°C]. The pressure level in the chamber varied during the test between 9.10^{-7} and 9.10^{-6} Torr versus the temperature. The motor instrumented with several thermocouples was mounted on a test bench including a displacement sensor and an hysteresis brake (Figure 10). The motor excitation and behaviour through the sensor response was fully monitored with a dedicated Labview program: thus average motor speed and position were calculated and recorded at each excitation pulse. A digital scanner was used for the temperature acquisition and at each new thermal plateau a complete motor loading characterisation was performed. The excitation frequency of the motor was adjusted versus the temperature from the signals of 2 piezo-sensors integrated in the UPD unit.

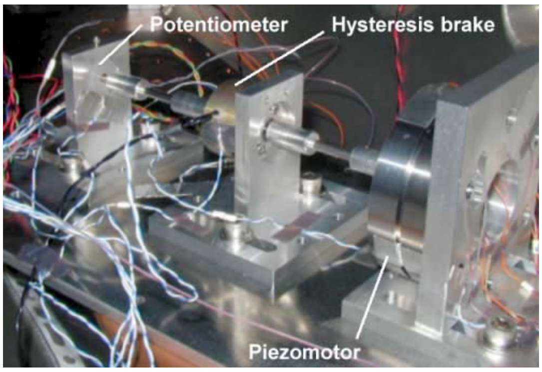

Fig. 10: Instrumented test rig inside the vacuum chamber

At ambient temperature, no significant change of motor performance was noticed in vacuum environment compared to the reference one in air. Moreover, the cycling test has shown a stable and predictable (frequency variation) motor behaviour over the temperature range (Figure 11).

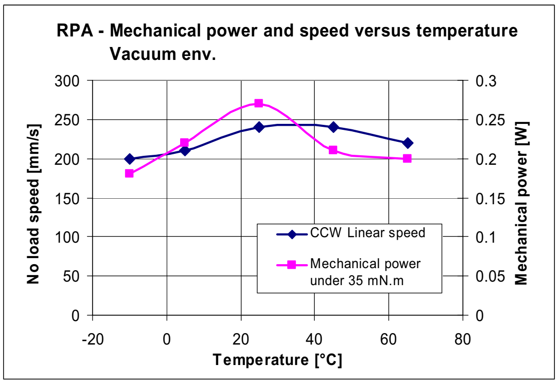

Fig. 11: Motor performances in vacuum (thermal cycling)

Then, a no-load lifetime test was performed in air: the motor was driven on a reciprocating 90° stroke (90° per excitation pulse). 91 hours of effective motor running, equivalent to 78 km linear travel, were cumulated before the failure of the stator guiding device which ended the test. The slight motor performance improvement and the steady excitation parameters throughout this test have shown a larger "tribological potential" which was confirmed by the final tribological investigation. However, despite the low wear rate of the polymer layer, the dispersion of fine wear dust should require a specific care in the debris management, especially for space applications.

The fine positioning capability of the motor has also been demonstrated: step sizes as small as 10µrad were obtained, whereas no electrical power is needed to maintain the target position at zero speed. Moreover, no measurable backlash was observed when rotation direction was reversed. The following Table 1 sums-up the main characteristics of the RPA rotary piezomotor.

Parameter	Value
Excitation frequency	53.4 kHz
Blocked torque	55 mN.m
Static holding torque	≈ 0.1 N.m
No load angular speed	140 rpm
Operational temp. range	–15 … +65 °C
Duty cycle	up to 35%

Table 1: RPA motor key characteristics

Conclusion

The presented piezomotor technology has the potential to provide high-accuracy positioning for spacecraft instruments and mechanisms [8] in a way complementary to existing electro-magnetic motors. The vacuum compatibility and lifetime of the new rotary motor has been demonstrated. Further work shall concentrate on the drive electronics and on the implementation of advanced commanding schemes for closed-loop positioning control.

References

1. Bar Cohen, Y., X. Bao, and W. Grandia, "Rotary Ultrasonic Motors actuated by Travelling Waves", SPIE vol. 3329, pp. 794-800, 1998.
2. Arends, H. et al., "The MIDAS Experiment for the ROSETTA Mission", Proc. of the 9th European Space Mechanisms and Tribology Symposium, ESA SP-480, pp. 67-74, September 2001.
3. Six, M.F. et al., "Original Piezomotor for Space Applications", Proc. of the 33rd Aerospace Mechanisms Symposium, Pasadena, CA, May 1999.
4. Pochard M. et al., "Smart Mechanisms for Optical Space Equipment", 48th IAF Congress, Torino, 1997.
5. Ueha, S. et al., “Ultrasonic Motors: Theory and Applications”, Clarendon Press, Oxford, 1993.
6. CEDRAT Homepage: http://www.cedrat.com
7. Lewis, S.W., "Building and Testing of MIDAS Instrument Sub–assemblies", Proc. of the 9th European Space Mechanisms and Tribology Symposium, ESA SP-480, pp. 355-359, Sept. 2001.
8. Seiler, R. et al., "The Ultrasonic Piezo-Drive: An Innovative Solution for High-Accuracy Positioning", Proc. of the 16th Small Satelite Conference, Logan, Utah, Aug. 2002.