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Piezoelectric Ultrasonic Mirror Tip/Tilt Stage

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Abstract

This paper proposes a 2-degrees-of-freedom (2-DoF) miniature beam steering stage (16 × 16 × 16 mm³) driven by a single piezoelectric ceramic excited at resonant ultrasonic frequency. First, the module's components and structure are described. Second, finite element method (FEM) simulations, including modal analysis of the piezoelectric ultrasonic motor and direction-changing driving methods are presented. Finally, experimental results of a functional prototype under open-loop motion control are shown. Its angular motion range was measured using an autocollimator, demonstrating range limitations with a maximal angular motion of about ±10 mrad. Additionally, a laser vibrometer was used to measure oscillation amplitudes of the piezoelectric stator tips under resonant excitation, validating the simulation results.

Tip/Tilt Mirror, Piezoelectric Motor, Ultrasonic Drive, Resonant Drive, Open-Loop Functional Sample, Beam Steering

1. Motivation

Lasers are used in many areas of technology, including metrology, medical technology, military, metal working, communications, and many more. The laser beams in such industries are usually precisely directed, or guided, via tip/tilt mirrors. The necessary precision in the guidance of the laser beam may be manually achieved via micrometer screws, e.g., in experimental setups on optical tables. However, industrial applications depend on automated solutions, with a growing demand for miniaturization. Piezoelectric drives are commonly used, e.g., for positioning tip/tilt mirrors.

Physik Instrumente (PI) offers a wide range of stages and positioners, including tip/tilt mirrors based on piezoelectric actuators with a parallel kinematic design, which exhibit high stiffness, high control bandwidth, position stability, and resolution [1]. Due to fundamental principles, further miniaturization of such devices comes with a significant loss in motion range and/or stiffness.

Complementary to such directly driven actuator stages, positioning stages based on piezoelectric motors are provided. In these systems, the motion of the rotor or runner element is generated by the piezoelectric ceramic via a frictional tip. The deformation or oscillation of the actuator, excited by an electrical signal, is transmitted to the driven element through this friction interface. In this way, a wide range of motion is achievable while maintaining a compact design and high stiffness.

A well-established approach involves screw designs driven by piezoelectric inertia motors for the movement of mirrors [2-5]. Here, the stator is threaded into a nut and maintains frictional contact with it. This nut is directly or indirectly connected to a piezoelectric actuator, which drives the screw via stick-slip motion based on the inertia principle.

The primary limitation of inertia-driven systems is the restricted speed of the moving or rotating components. This arises from the motor's inertia-based operating principle: the piezoelectric actuator cannot drive the screw at frequencies exceeding 10 kHz, as the static friction between the actuator and screw cannot transition to sliding friction beyond this threshold.
Additionally, inertia-driven systems with two piezoelectric actuators for 2-DoF movements and parts like screws or spindles require relatively large installation space.
Furthermore, the excitation frequency range of piezoelectric inertia drives is within the audible spectrum, which can be noisome during operation. In most closed-loop motion control systems, the impact

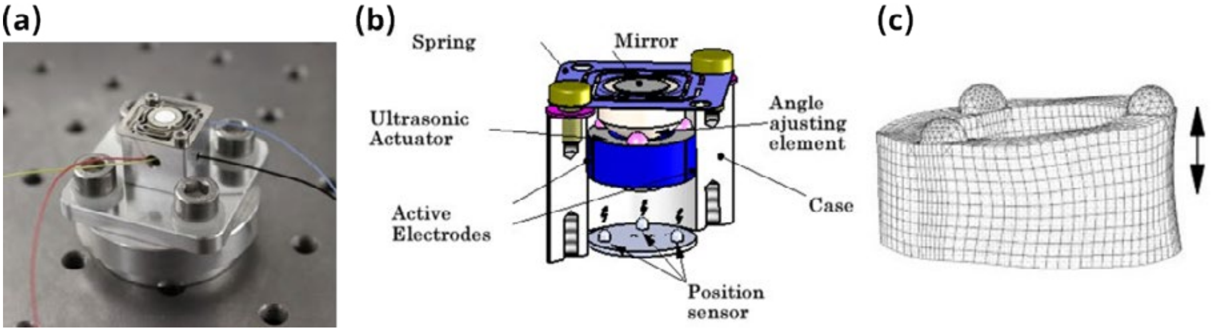

Figure 1. Proposed tip/tilt mirror drive a) functional sample b) CAD model of its interior c) FEM modal analysis when only one electrode is excited.

forces of piezoelectric actuators occur within a frequency bandwidth in the order of 1 to 10 kHz [6].

These drawbacks of low traversing velocity, noisy actuation, and bulky spindle drive dimensions inherent to inertia-based systems can be mitigated by replacing the inertia drive with a piezoelectric ultrasonic motor for mirror adjustment. At the same time, general advantages of piezo motors are maintained, like e.g., wide range of motion and self-locking property, meaning the position is retained when electrical voltage is removed.

2. Approach

For the reasons mentioned above, we propose a tip/tilt mirror stage driven by an ultrasonic piezoelectric motor.
Figure 1 illustrates a functional sample (a) and a CAD model of its interior structure (b). The entire assembly has compact dimensions of about 16 × 16 × 16 mm³. The motor features an ultrasonic actuation element, i.e., a hollow cylindrical resonator fabricated from PIC 181 hard piezoelectric ceramic (PI Ceramic GmbH, Germany) [7]. The mirror is mounted inside a hemispherical ceramic element (rotor), which is driven via three 120°-spaced tip elements bonded onto the piezoelectric resonator. The rotor is spring-loaded to ensure sufficient friction force at the tip contacts.
The resonator features one common inner electrode and three outer electrodes, which divide it into three 120° segments. It exhibits certain vibrational modes, which can be excited by application of a sinusoidal voltage signal at one of the segments. Figure 1 (c) shows the FEM modal analysis of such a vibrational mode, with a resonance frequency of 406 kHz. Due to the high oscillation amplitude of the active segment, the rotor rotates out of plane. By driving the three electrodes sequentially, the mirror can be adjusted to any tip/tilt angle.

A key advantage of this design is its ability to achieve two-degree-of freedom (2-DoF) angular motion using only a single piezoelectric stator, enabling a very compact size. Additionally, the operation is silent due to the high operating frequency, which lies in the non-audible range.

A functional sample of this tip/tilt mirror stage was prepared for further testing. The piezoelectric tip/tilt actuator is designed to exert an actuation force on the order of 1 N at the contact surface between the spherical tips and the rotor. During operation, the flat spring applies a restoring force to the rotor that depends its angular position, thereby altering the effective actuation force. As the restoring force increases with the angular displacement, the achievable range of motion is limited. At the maximal tilting angle, the restoring force equalizes the driving force.

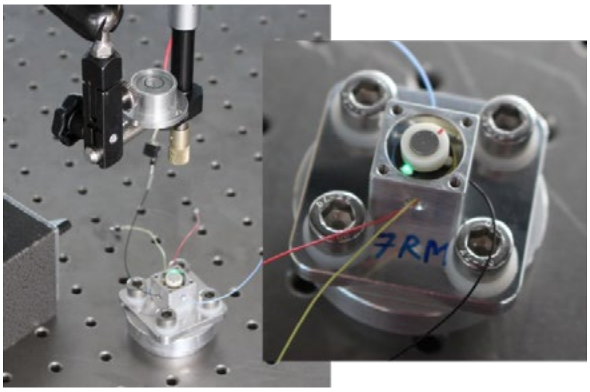

Figure 2. Test setup for the Vibrometer measurement of resonance frequency and oscillation amplitude of the functional sample.

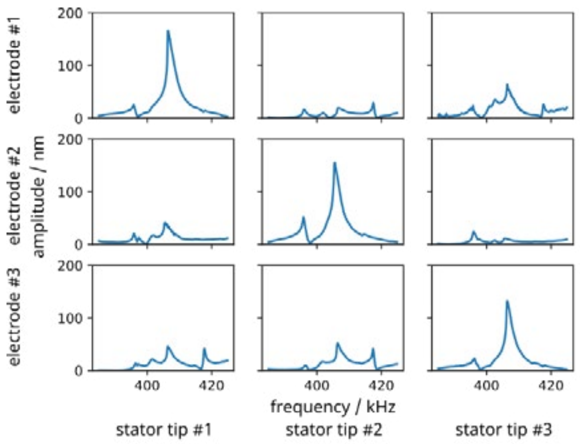

Figure 3. Actuation amplitudes of the stator tips upon single electrode driving at *Vrms* = 15 V, measured at various frequencies with a Vibrometer.

3. Results

The resonance frequency and oscillation amplitude of the functional sample were measured using a laser vibrometer (Polytec, Germany). The measurement setup is shown in Figure 2. An open-loop sinusoidal frequency sweep signal was applied, with a bandwidth of 380 to 430 kHz and a mean operating voltage of 15 Vrms. Figure 3 illustrates the oscillation amplitudes of all three stator tips upon activation of each individual electrode. All three diagonal measurements, where the measured stator tip corresponds to the active electrode, show oscillation amplitudes of about 150 nm at the resonance. These diagonal measurements confirm a consistent resonance frequency of approximately 406 kHz, aligning with the FEM simulation results. Measurements outside the diagonal cases, i.e., when non-corresponding electrodes are excited, reveal that tip movements are negligible compared to those observed during direct electrode excitation.

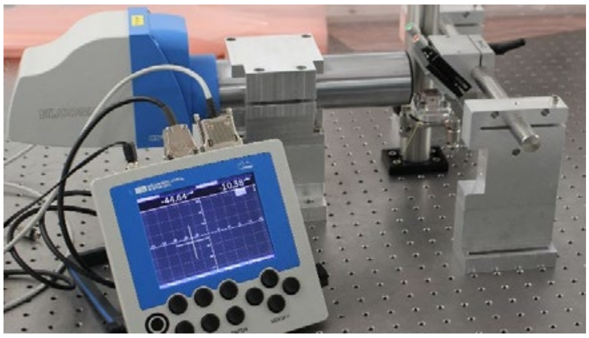

Figure 4. Test setup with autocollimator for the measurement of the angular movement range of the functional sample.

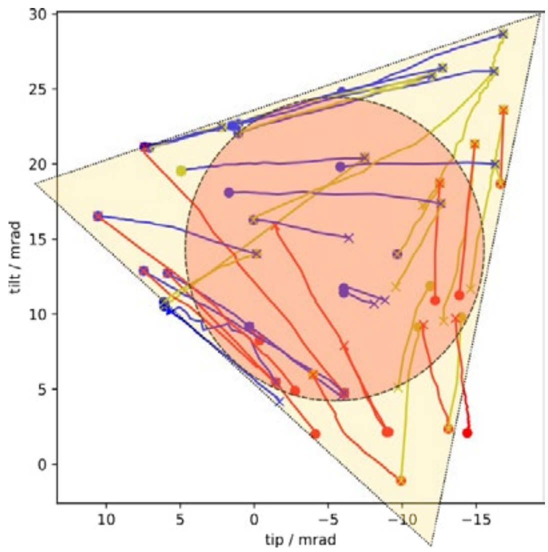

Figure 5. 2-DoF autocollimator measurement of the range of motion. The trajectories of 55 individual steps are shown. Each start (end) position is marked with an 'x' (full circle). Steps of axis 1, 2, 3 are depicted in blue, red, yellow, respectively. The circular motion range of ±10 mrad is marked in red.

The 2-D tip/tilt angular movements of the functional sample were measured using an autocollimator, as shown in Figure 4. A set of 55 individual steps in alternating directions is presented in Figure 5. Due to the motor design constraints and the restoring force of the flat spring in particular, the attainable angle of rotation is restricted to a triangular area (yellow area in Fig. 5). To quantify the controllable angular range, we defined a circle enclosing the largest possible area within this triangular boundary (red area in Fig. 5). Within this definition, the functional sample achieved an angular motion range of ±10 mrad.

4. Conclusion

A 2-DoF miniature tip/tilt mirror, driven by an ultrasonic piezoelectric motor using only a single piezoelectric ceramic, is presented. Experimental measurements from a laser vibrometer show close agreement with FEM modal analysis results. The functional sample demonstrates rotational motion of up to ±10 mrad in all directions. Future work will focus on integrated sensor development and closed-loop motion control strategies to enhance the performance of this compact tip/tilt mirror.

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