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Piezoelectric actuator for machining on macro-to-micro cylindrical components by a precision rotary motion control

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ABSTRACT

A powerful piezoelectric actuator has been developed for precisely controlling the rotational motion of cylindrical components from macroscale to microscale. The actuator is supported at the nodal point and works at an elliptical vibration mode under anti-resonant frequency. The workpiece's rotational speed can be controlled accurately via the contact frictional force and has a linear relationship with the actuator's vibration. An application on machining operation has confirmed the fabricable dimension of the developed actuator. The dimension of to-be-machined workpiece can be smaller than the diameter of a human hair. Compared with the traditional methods, it provides a more effective approach to fabricate macro-to-micro cylindrical components in high-aspect-ratio for micromachining, biomedicine and electrochemistry.

1. Introduction

Generating an accurate and controllable motion at micro/nano-scale has become a big challenge in precision engineering [1,2]. Conventional motors such as servo motor and stepper motor could no longer satisfy the current high requirements [3,4]. To solve this problem, many approaches have been explored by means of force which is converted through strain in materials, such as piezoelectric [5], magnetostrictive [6–8], shape-memory alloy [9,10], inchworm [11,12], surface tension [13,14], and thermal expansion [15,16]. Among them, due to the outstanding advantages of compact size, large output power, high precision, quick response and no magnetic field, piezoelectric components have been widely used [17,18].

Under inverse piezoelectric effect, the piezoelectric element can generate an extremely small displacement which is normally in the form of an elliptic motion by coupling two directional ultrasonic vibrations [19,20]. By adjusting the applied voltage, this motion can be accurately controlled in a range of sub-nanometer to 100 μm, which can be used as an approach to drive a contacted slider into a linear motion via frictional force [21,22]. It has now been introduced into cameras [23,24] and watches [25] for rotational control, and scanning microscopys [26,27] and nanomachining systems [28,29] for micro/nano-scale positioning control, and some other new designs, such as hole-shaped piezoelectric micromotors to drive millimetre-sized spherical rotors in high rotational speed [30]; face-shear mode motors for high driving forces [31]; and stepped piezoelectric motors to obtain nanoscale actuation [2]. It has also been applied in some of micro-machining processes, such as in vibration assisted cutting by using anti-resonant frequency to avoid the unstable vibration caused

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by big electric-mechanical loss and sharp temperature rise in resonant frequency [32–36], and in the design of high-speed machining spindle for precision machining [37,38].

The aim of this paper is to develop a powerful piezoelectric actuator/motor capable of rotating the microscale rotor with high accuracy and efficiency and apply it in precision machining of micro cylindrical components with ultra-high aspect ratio for micromachining, biomedicine and electrochemistry. Finite element modelling will be conducted first to design the actuator and predict its vibration and dynamic response. The designed actuator will be then characterized by measuring its actual vibration performance. After that, grinding operations will be conducted to evaluate the controllability of the designed actuator on workpiece rotation motion. Finally, experimental tests will be also performed to verify the proposed method, following with mechanics modelling for clarifying the workpiece rounding mechanisms.

2. Actuator design

The piezoelectric actuator was designed by bonding a piezoelectric element (4 electrodes, FDK Corporation) onto a stainless steel (SUS304) elastic body and its structure is shown in Fig. 1a. To achieve an elliptical vibration, its dimensions were established using a finite element modelling with software PIEZOplus and Femap (see Fig. 1a). The material properties for the elastic body and piezoelectric elements are listed in Table 1 and Table 2, respectively. To achieve the same boundaries as those in the real working system, the base of actuator (see Fig. 1a) was fixed in the modelling. To get the elliptical vibration, two alternating current (AC) signals, V_{AC} and V_{BD}, were applied to the 4 piezoelectric electrodes (A & C and B & D), separately (see Fig. 1a). Assume their frequencies and amplitudes were set at the same value of f and V_p, then

$$\begin{cases} V_{AC}(t) = V_p \sin(2\pi ft) \\ V_{BD}(t) = V_p \sin(2\pi ft + \psi) \end{cases} \tag{1}$$

where the phase shift between V_{AC} and V_{BD} was ψ [17]. When f was set to be the same as or close to the resonant or anti-resonant frequencies of the bending and longitudinal modes of the assembled actuator, the actuator would vibrate in two modes simultaneously. As a result, the synthesis of vibration displacements in the two directions would create an elliptic motion on the end-face of the metal body as shown in Fig. 1b.

To obtain the dimensions of the actuator, except the length of elastic body l_e (see Fig. 1a), all the other dimensions were fixed as listed in Table 3. Firstly, to get actuator's initial dimension, the modal analysis was performed for the actuator with length l_e = 97.45 mm and l_e = 96.45 mm, respectively. After that, finite-difference method was introduced to narrow down the range of actuator's length [44], and finally, when the length of actuator reached 96.60 mm, as shown in Fig. 2, both anti-resonant frequency of 4th bending and 1st longitudinal vibration modes change to 16.9 kHz, *i.e.*, elliptic vibration motion occured (as the trace of ellipse shown in Fig. 1b).

Considering that the actual values of 4th bending and 1st longitudinal vibration modes would not agree well with the predicted ones, due to the dimensional errors of the elastic body and PZT element manufactured, three actuators with different values of l_e = 97.45 mm, l_e = 96.95 mm and l_e = 96.60 mm were constructed. An impedance analyser (4294A by Agilent Co. Ltd.) was then used to investigate the impedance characteristics of the actuators and the results are shown in Fig. 3. Obviously, the simulation results agree well with the experimental measurement. As the actuator's length was l_e = 96.60 mm, the minimum (resonant frequency) and maximum (anti-resonant frequency) impedance for both 4th bending and 1st longitudinal vibration modes were stimulated at frequency of 16.68 kHz and 16.90 kHz (see Fig. 3c), respectively.

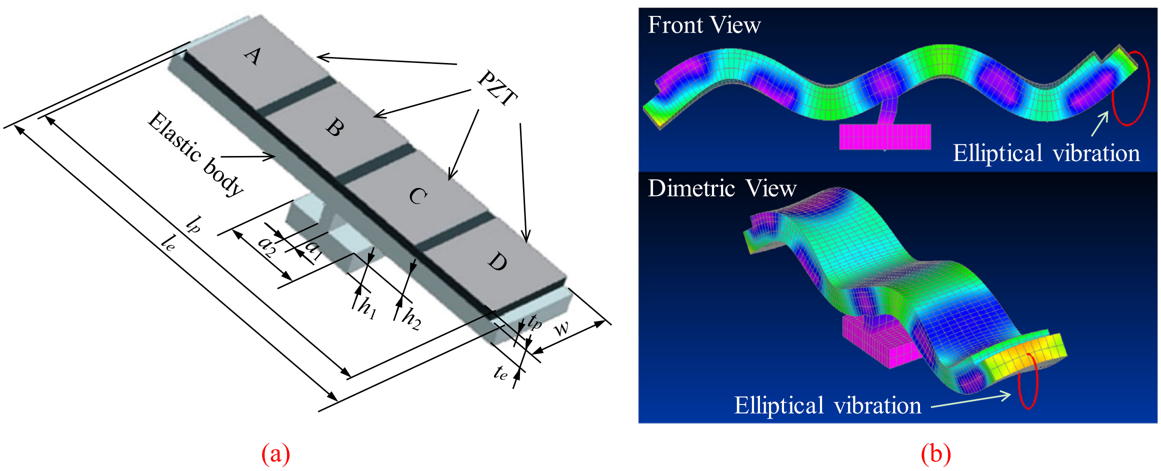

Fig. 1. An illustration of the piezoelectric actuator: (a) actuator's structure and (b) a simulation result of actuator's vibration (4th bending vibration and 1st longitudinal vibration at V_{AC} = V_{BD} = 50 V and ψ = 90°) using finite element modelling.