DESIGN, PROTOTYPING, AND CHARACTERIZATION OF AN INNOVATIVE PIEZOELECTRIC ROTARY ACTUATOR

S-W. Ricky Lee and H. L. Li
Department of Mechanical Engineering
Hong Kong University of Science and Technology
Hong Kong Special Administration Region, P. R. China

Abstract

An innovative actuation principle is introduced in this paper to drive a rotary motor using an anisotropic piezoelectric composite laminate. The driving element is a three layer laminated beam with piezoceramics sandwiched between two anti-symmetric composite laminae. By taking advantage of material anisotropy, torsional motion can be induced from in-plane strain actuation. With such structural coupling, a rotary motor can be implemented. In addition to conceptual design, a prototype has been fabricated. Actual motion was observed in the laboratory to verify the proposed actuation principle. The performance of this newly developed piezoelectric motor is characterized and discussed.

1. Introduction

Smart materials and structures has become a very active research area in science and engineering since 1980s. The major feature of smart materials is adaptability. Typical examples are shape memory alloy (SMA), piezoelectric ceramics (PZT) and magneto-strictive (MS) materials. In particular, PZT has relatively good performance in both sensing and actuation. In the past, piezoelectric materials were widely adopted in acoustics related applications. Recently, PZT has been successfully used to actuate mechanical motors [1]. Such devices are termed “ultrasonic motors” because the driving frequency is in the ultrasonic range (>20 kHz). The advantages of ultrasonic motors include magnetic field immunity, low-speed/high-torque performance, compact size, and low noise [2]. Typical applications of ultrasonic motors are the mechanism of auto-focused zoom lenses in video equipment and the driver in watches [3]. Many other applications are under development in the industry.

In the present study, a new actuation principle was developed to drive a rotary motor using anisotropic piezoelectric composite laminate. By taking advantage of material anisotropy, a piezoelectric laminated beam can induce torsional motion from in-plane strain actuation [4]. With this structural coupling, a rotary actuator can be implemented. The driving element is a three layer laminated beam as shown in Figure 1. A piezoceramic layer is sandwiched between two composite laminae with anti-symmetric configuration. Once the piezo-layer is subjected to an electric field, the whole beam will extend and twist resembling the motion of a screw driver. This motion can be utilized to drive a rotor at one end of the laminate via mechanical friction. In addition to conceptual design, a prototype has been fabricated. Actual
motion was observed in the laboratory to verify the proposed actuation principle. The performance of developed prototype was characterized and discussed in this paper.

2. Actuation Principle and Conceptual Design

Based on the analysis and results of [4, 5], a rotary actuator can be implemented by taking advantage of the twisting-extension coupling. In Figure 2, the stator is an anisotropic piezoelectric composite laminate with anti-symmetric configuration (see Figure 1, termed as “piezo-beam” hereafter). One end of this piezo-beam is fixed to a rigid foundation while the other end is originally in loose contact with a rotor disk (Figure 2a). Once the piezo-layer is subjected to an uprising electric field, the whole beam will extend and twist resembling the motion of a screw driver. Similar to a clutch mechanism, the extension of the piezo-beam will bring one end into firm contact with the rotor. Due to mechanical friction, the rotor will turn with the end of the piezo-beam (Figure 2b). When the electric field decreases from the peak, the piezo-beam will contract and twist backward. However, due to the rotary inertia, the rotor will continue to rotate in the same direction although there is a deceleration from the sliding contact (Figure 2c). Eventually the piezo-beam will separate from the rotor disk (Figure 2d) and the latter will continue to turn by rotary inertia (Figure 2e). In such kind of cycle, the rotor has rotated by a small angle. With this pattern, a continuous rotary motion can be achieved by applying a high frequency cyclic voltage to the piezoelectric laminate.
3. Prototyping

During the course of this study, a prototype was fabricated to verify the proposed actuation principle. The top and the bottom plies of driving laminate were unidirectional AS4/3501-6 Graphite/Epoxy composites from Hercules. The fiber direction was oriented in $45^\circ$ and $-45^\circ$, respectively. The middle piezo-layer was PZT-5H from Morgan Matroc. The thickness of each layer was 1 mm. The dimensions of the laminated beam were 25 mm x 115 mm. The schematic diagram for prototyping is given in Figures 3. One end of the piezo-beam was engaged in a circular rotor disk. The other end was clamped by a rigid fixture. The clamping area was 25 mm x 25 mm. Two leads were soldered to the top and the bottom electrode surfaces of the PZT layer and connected to a high voltage power supply. The power supply was modulated by a function generator at the kilo-Hz range and could output voltage up to 1000 volts. A typical case was actuated at 1.3 kHz with 150 V amplitude. Figure 4 shows the actual rotary motion of prototype. Therefore, the proposed actuation principle is verified.
4. Performance Characterization

After fabricating the prototype, efforts were made to characterize the system performance. The objective is to identify the performance of prototype in terms of rotating speed, torque, and power output. The testing results are presented in Figure 5. It is observed that the torque declines as the angular velocity increases and the output power grows rather linearly with respect to the torque. In addition to the above characteristics, the stability is also a major concern for the performance of a rotary motor. The prototype was subjected to a heavy loading for a continuous operation of three hours and could maintain a stable rotating speed. Therefore, the stability of this new motor is satisfactory to a certain extent.

5. Discussion

The rotary motor developed in this study adopted a new actuation principle which is different from other types of piezoelectric motors. On the other hand, they can be considered as the same category of actuators because the fundamental mechanisms are mechanical vibration and friction. Since the current driving frequency is at 1.3 kHz, the present device is not yet a real “ultrasonic motor” which is usually driven at a frequency higher than 20 kHz. However, the resonant frequency can be increased if a piezo-beam with smaller dimensions is used. Another alternative is to use composite materials with higher stiffness. It is believed that this motor can be operated at the ultrasonic range with certain modifications in design.

From the design configuration and the results of system characterization, several advantages of the developed motor can be identified. Among them are magnetic field immunity, simple structure for easy maintenance and low cost, and good low-speed performance. Besides, this motor can be easily programmed to perform intermittent motion. Nevertheless, it was found that the system efficiency of the present device is relatively low. This could be attributed to the nature of actuators driven by mechanical vibration and friction. Further design and prototyping are required to improve this deficiency. Besides, the detailed contact behavior
between the piezo-beam and the rotor disk has not yet been investigated in the present study. With further analysis in tribology, the system efficiency may be improved by choosing the appropriate contact geometry and media.

6. Summary and Conclusions

A rotary motor driven by an anisotropic piezoelectric composite laminate was developed and characterized in this study. The actuation was due to the structural coupling and mechanical friction. The driving element is a three layer laminated beam with piezoceramics sandwiched between two anti-symmetric composite laminae. By taking advantage of material anisotropy, torsional motion can be induced from in-plane strain actuation. With this structural coupling, a rotary motor can be implemented. In addition to conceptual design, a prototype was fabricated during the course of this study. Actual motion was observed in the laboratory. The proposed actuation principle has been completely verified.

The prototype was characterized for angular velocity, torque, power output, and stability. The system performance was discussed. It was found that the torque and power output increase while the angular velocity decreases. The advantages of this newly developed piezoelectric motor include magnetic field immunity, simple structure for easy maintenance and low cost, and good low-speed performance. In addition, this motor can be easily programmed to perform intermittent motion. However, the system efficiency is relatively low for the moment. Some suggestions were made for improvement. Further efforts are required to resolve related issues. In conclusion, the present research has demonstrated a live model of using piezoelectric composite laminates for actual mechanical device. Although the proposed actuator is still in its infancy, it may lead to many inspiring activities in engineering research.

Acknowledgments

This study is sponsored by the Chiang’s Industrial Charity Foundation through a grant RH97107 to the Hong Kong University of Science and Technology.

References