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Butterfly-shaped ultra slim piezoelectric ultrasonic linear motor

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ABSTRACT

A new piezoelectric ultrasonic linear motor, shaped ‘Butterfly’ wings, has been developed for use in thin electronic products, such as cellular phones and PDAs. The butterfly piezoelectric transducer with a volume of 9 mm × 8 mm × 1 mm is composed of an elastic plate which includes a tip for energy transfer, two protrusions, and two piezoelectric ceramics. The ultra slim butterfly motor with a thickness of ~1 mm could be achieved by positioning the layered piezoelectric transducer and a linear guide in parallel. The manufactured motor based on FEM analysis was successfully driven at the resonance frequency range that combines the longitudinal and transverse vibration modes. The maximum velocity of 88 mm/s was achieved at a driving frequency close to the pure vibration modes such as the longitudinal or transverse modes. In opposite, the maximum thrust force of 162 g was obtained at a middle frequency between two vibration modes.

1. Introduction

Compared with the conventional electromagnetic motors, piezoelectric ultrasonic motors offer many advantages, such as high retention being very controllable, high torque at low speed, light weight, simple structure and no electromagnetic field induction [1–3]. These advantages have helped to expand the application fields where precise position control and rotational/linear motions can be utilized. Various kinds of the piezoelectric ultrasonic linear motors, using a traveling wave or an impact force, have been proposed [4], and their applications have been intensively studied. Piezoelectric ultrasonic linear motors using the traveling wave, found in the literature [5,6], have been designed based on the combination of two different vibration modes where the transverse and longitudinal modes are combined to achieve an elliptical motion on the surface of the contact point. In recent years, micro industries and consumer devices such as mobile phones, PDAs, and micro-positioners, requiring very thin thickness as well as having very low energy consumption and manufacturing cost, call for linear motors with extremely low profile. Although many of the proposed piezoelectric transducers for the ultrasonic linear motors could achieve large forces and high torques even with a small volume of <1000 mm^3, it was difficult to be installed inside thin electronic devices due to the absence of low profile [7,8]. And also, most of the proposed piezoelectric motors could not achieve the required thin layered structures due to their unique operating principles and structures. To improve the design flexibility for the slim electronic devices, the thickness of piezoelectric transducer should be less than 1 mm. Considering the operating principle of piezoelectric motor, a low profile motor can be designed when the surface of the piezoelectric ceramic and the moving axis become parallel.

In this paper, elliptical trajectory formation for a thin piezoelectric ultrasonic linear motor is introduced and discussed. Structure of the piezoelectric transducer was first simulated by ATILA in order to determine the dimensions and the operating frequency offering an effective elliptical motion for a piezoelectric linear motor. Based on the simulation results, an ultrasonic linear motor has been manufactured and its dynamic properties such as velocity and thrust force have been investigated with respect to driving frequency.

2. Design and analysis

2.1. Structure of butterfly actuator

It is well known that piezoelectric ceramics release traveling waves excited by natural vibrations when two standing waves with a phase difference at resonance frequency are applied. An elliptical motion can be also excited when a couple of vibration modes are effectively combined at a certain frequency range [10]. Based on the elliptical motion, a new piezoelectric actuator named as a ‘Butterfly’ implying the butterfly wings motion has been designed to produce mixed piezoelectric vibration modes, which are the combination of the longitudinal and transverse vibrations. In particular, it was considered that the proposed butterfly piezoelectric

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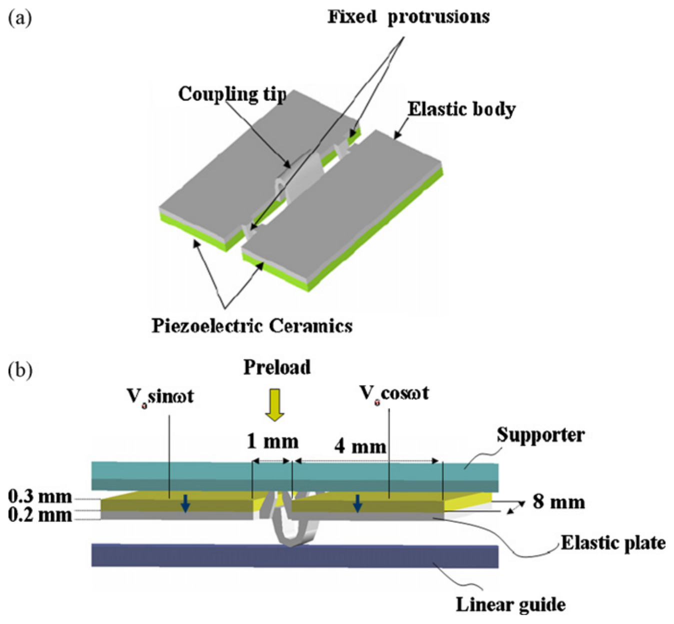

Fig. 1. Configuration of the butterfly piezoelectric ultrasonic linear motor; (a) piezoelectric transducer, (b) stereoscopical view.

linear motor exhibits not only a low profile but also a direct linear motion by a point contact. The configuration of the butterfly piezoelectric ultrasonic linear motor is shown in Fig. 1(a), where the piezoelectric transducer is composed of an elastic plate including two piezoelectric ceramic plates. The center of the elastic plate connecting two wings is bent to play a role of tip for a point contact to a linear guide so that the tip can transfer the mechanical energy formed by the piezoelectric vibration to the linear guide as shown in Fig. 1(b). Two protrusions heading for the opposite direction of the contact point tip are also built to fix the piezoelectric transducer to a supporter using epoxy. The most suitable supporting method should be introduced to minimize the interference against the piezoelectric vibrations and to fix the piezoelectric transducer to a frame through the supporter. To avoid complication of the structure, the tip and two protrusions coexist on the elastic plate. The final dimension of the piezoelectric transducer is 9 mm × 8 mm × 1 mm, and the total height of the butterfly piezoelectric motor including the tip and supporter is ~1 mm, achieving a low profile ultrasonic motor. Finally the supporter may be installed to desired systems such as hinges of a sliding mobile phone or a position control unit. The piezoelectric ceramics are poled in the thickness direction, and then firmly affixed on both the wings of the elastic plate using an epoxy. The vibration of the piezoelectric ceramics is excited by applying two harmonic oscillations with a phase difference of 90°. It is expected that the elliptical trajectory at the tip can be generated by superposing two resonance modes of the piezoelectric ceramics such as the longitudinal and transverse modes as reported elsewhere [9,10].

2.2. FEM analysis

To find a proper driving frequency exciting an elliptical motion, vibration mode analysis of the butterfly piezoelectric transducer has been carried out via the ATILA simulation tool to verify whether the designed structure mentioned in the previous section effectively works. First of all, FEM modeling was employed to create a solid FE model which offers modal frequency and harmonic response analyses. The resonance frequency and coupling coefficient of the piezoelectric transducer can be obtained from the modal frequency analysis. The admittance characteristics as a function of frequency are shown in Fig. 2. Two major resonance frequencies exhibiting considerably higher coupling coefficient are observed at frequencies of 104 and 119 kHz. Utilizing the resonance analysis, the piezoelectric vibration modes can be analyzed through the harmonic response analysis as shown in the inside of Fig. 2, presenting a longitudinal vibration at 104 kHz and a transverse one at 119 kHz, respectively. Although the electric signals with a phase difference of 90° are applied to each piezoelectric element, the vibration of the piezoelectric transducer presents one mode such as the longitudinal or transverse ones for each resonance peak. The motions of two butterfly wings are maintained in in-phase for the longitudinal mode or 180° phase difference for the transverse mode regardless of the phase difference of the driving potential, but these uni-axial motions are unable to give effective dynamic motions for the piezoelectric linear motor. In order to find frequencies offering superposition of two different resonance modes, the harmonic response analysis were carefully carried out in the frequency range of 104–119 kHz. Fig. 3 shows magnitudes and shapes of displacements excited at several points of the examined frequency range. The uni-axial movement presenting the pure longitudinal mode moving along *Z*-axis is changed to elliptical motions in the frequency range of 108–117 kHz, and then the pure transverse mode moving along *X*-axis is detected at 119 kHz. It is obvious, from

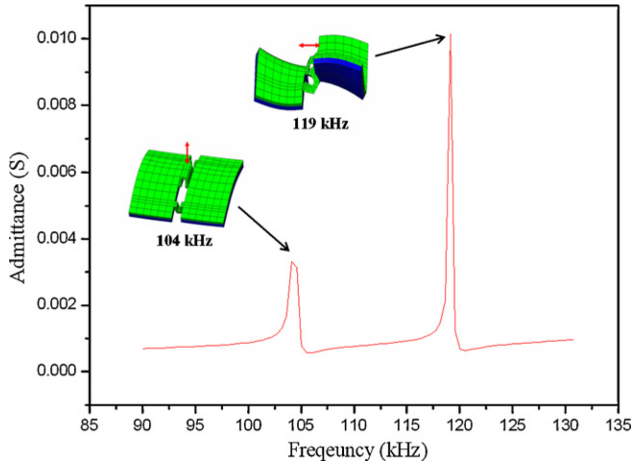

Fig. 2. Admittance plot and displacement shape as a function of frequency for the Butterfly piezoelectric transducer.

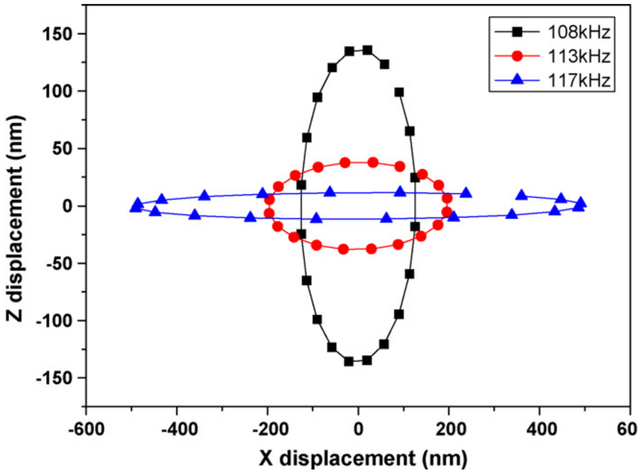

Fig. 3. Magnitudes and shapes of displacement for the butterfly piezoelectric transducer between two different resonance frequencies. Magnitudes and shapes of the displacement for the butterfly piezoelectric transducer fixed with two supporters at different resonance frequencies.

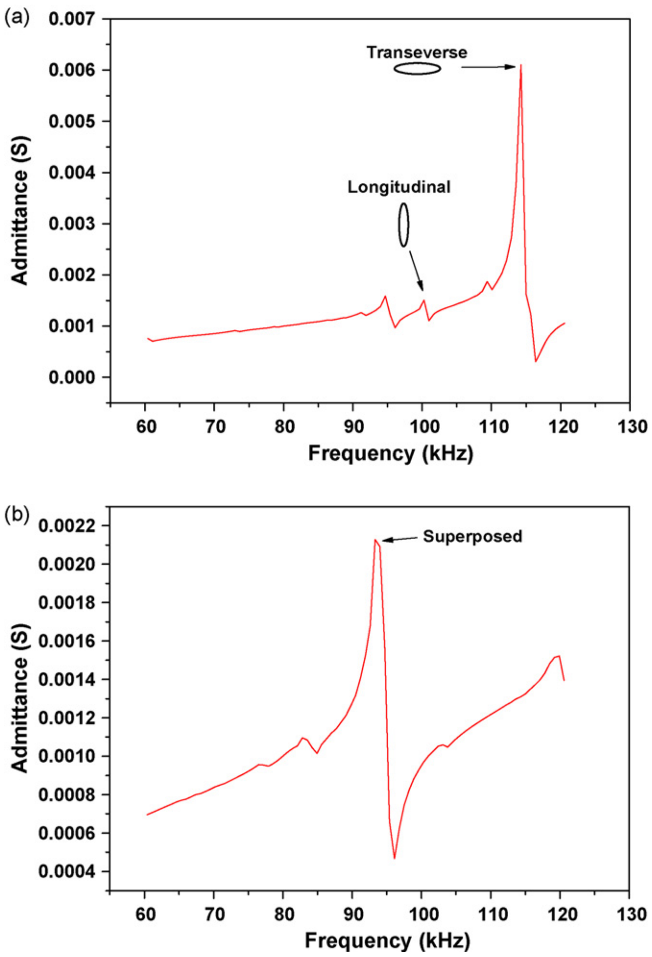

Fig. 4. Admittance plots as a function of frequency for the butterfly piezoelectric linear motor; (a) under no preload, (b) under preload.

the displacement shapes, that the vibrations induced at the intermediate resonance frequencies show mixed modes by means of superposition between the longitudinal and transverse modes. In general, a combination of two different vibration modes need to be considered to obtain an elliptical trajectory motion and consequently an optimal driving frequency can be determined between the two resonance frequencies corresponding to the different vibration modes [7]. It is therefore expected that a driving frequency for an actual motor can be determined using the resonance frequency creating an effective elliptical motion.

3. Results and discussion

Based on the simulation results, an actual piezoelectric transducer as shown in Fig. 1(a) has been manufactured. To find an ideal working frequency, admittance vs. frequency for the piezoelectric transducer has been first measured using an impedance analyzer (HP4192A) as shown in Fig. 4 (a). Fig. 4(a) shows the impedance characteristics of the transducer without a preload in order to compare with the simulation results. The resonant frequencies presenting the longitudinal and transverse modes are observed at around 100 and 114 kHz, respectively. This configuration is very close to the simulated results although slight discrepancy for the resonance frequencies between the simulated and experimental results is observed because of the different conditions such as mechanical defects in the fixed area and adhesive strength between the piezoelectric layer and the elastic plate. To prepare a final butterfly piezoelectric linear motor, a linear guide is placed on the tip of the piezoelectric transducer and then a proper preload should be applied to generate a frictional force between the tip and linear guide. Another admittance plot for the butterfly piezoelectric linear motor under a preload is shown in Fig. 4(b). As the applied preload increases, the resonant frequency of the transducer shifts lower. The highest resonance peak is lowered to 93 kHz compared to that of the piezoelectric transducer under no preload. At this time, it should be verified that what mode exists in this peak. If a single mode exists, the linear motion cannot be excited due to no elliptical motions. However, if a superposition between two modes is introduced under a certain preload, the linear guide is starting to move by means of induced elliptical motions. The elliptical motion introduced by the superposition between the longitudinal and transverse modes can be verified using the characterization of dynamic properties. A signal generator (WF1943A by NF) and a high frequency amplifier (NF4010) were used as a driving power source. Electrical and mechanical behavior of the motor was measured using a digital power gauge (WT1600 by Yokogawa). The dynamic properties of the manufactured motor at a preload of 200 g as a function of driving frequency are presented in Fig. 5. The velocity of the motor was measured with a laser doppler vibrometer (VDD-Z-011 and OFV-551, by Polytec PI). Actuating force of the motor was measured by a digital force gauge (DSP-5 by IMADA). The motor is efficiently operated at a frequency just below or above the highest frequency as shown in Fig. 4(b). It means that the resonance peak as shown in Fig. 4(b) is not a pure transverse vibration mode but a mixed mode by the superposition. The manufactured butterfly motor can be therefore operated in the frequency range of 89–95 kHz to obtain the elliptical motion by the superposition of two different modes as shown in Fig. 5. It should be also noted that the resonance peak shows wider bandwidth and broader peak compared to that appeared in Fig. 4(a). Although two modes are apparently superposed as a peak, the longitudinal and transverse vibrations are clearly existed with very close clearance. The piezoelectric motor working with a driving frequency close to the longitudinal or transverse resonance ones results in higher velocity because of strong tendency moving along one direction as shown in Fig. 3. In opposite to this behavior, the thrust force is getting greater as the driving frequency lies on the intermediate frequency of two different resonance modes. Therefore, the driving frequency can be easily selected according to the purpose of use. The butterfly piezoelectric ultrasonic linear motor exhibits considerably high dynamic performance, such as a maximum velocity of ~88 mm/s and a maximum thrust force of 162 g at the frequency range of 89–95 kHz. Compared with commercialized motors [9] having a volume of 53 mm^3 and velocity of 100 mm/s, it is obvious that the

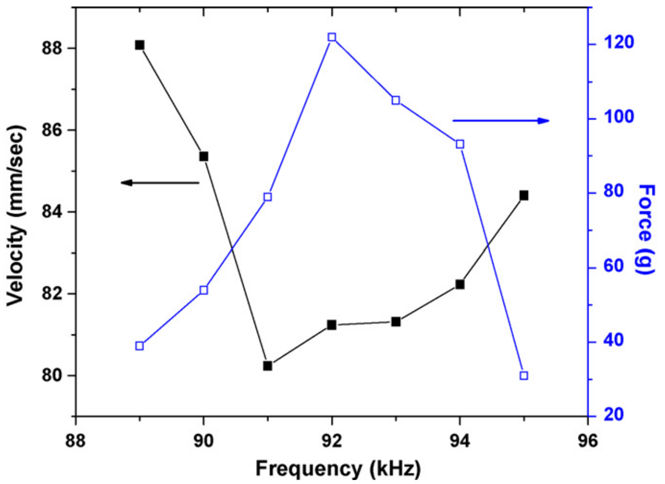

Fig. 5. Velocity and thrust force of the butterfly piezoelectric ultrasonic linear motor.

new motor presented in this paper can be a promising candidate for future slim electronic devices.

4. Conclusions

A novel butterfly-shaped piezoelectric ultrasonic linear motor with a traveling wave has been developed in order to present ultra slim profile as well as a fast speed and a large force. Since a linear guide as a moving element and a piezoelectric transducer consisted of a thin elastic plate including two piezoelectric ceramics are positioned in parallel, the ultra slim type motor could be achieved. The elliptical motions on the tip of piezoelectric transducer for the linear movement of butterfly motor could be achieved under a certain preload using the superposition of the longitudinal and transverse vibration modes. The manufactured butterfly motor with a very low profile of ~1 mm has been successfully driven, presenting the following dynamic properties; a maximum velocity of 88 mm/s and a thrust force of 162 g at the intermediate frequency range between two different resonance frequencies. The dynamic characteristics of the motor vary depending upon the driving frequency, i.e. the closer to the pure resonance frequency the higher velocity and the closer to the medium frequency the larger thrust force.

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Biographies

Won-Hee Lee received his MS degree from the Department of Electrical Engineering, Korea University, Seoul, Korea, in 2008, respectively. From 2008 to the present, he has been a PhD student at the School of Electrical engineering in Korea University. He also works at Korea Institute of Science and Technology (KIST) as co-op student, since 2008. His research interests include design of the piezoelectric actuators, microcomputer technology and ultrasonic systems.

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Seok-Jin Yoon received the PhD degree in electrical engineering from Yonsei University, Seoul, Korea, in 1992. From 1988 to the present, he has been a principal scientific researcher at the Electronic Materials Center, KIST. His current research activities are in the areas of piezoelectric materials and actuators, ultrasonic linear motors and rotary motors and tiny ultrasonic linear actuators.