# Development of Piezoelectric Motor Using Momentum Generated by bimorph


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## Abstract

*Piezoelectric motors have been used in many applications where excellent controllability and fine position resolution are required or magnetic field noise should be eliminated. However, the piezoelectric motor has two major drawbacks. One is difficulty in maintaining vibration amplitude constantly with temperature rise and wear, and the other is heat generation induced by dielectric and mechanical loss. In this study, a piezoelectric motor that can overcome these problems is proposed. The proposed piezoelectric motor is operated using momentum exchange between a bimorph and a rotor. To maximize steady state velocity and static torque of the proposed motor, a guideline is established using two bimorph models. The guideline is then partially validated by comparison between simulation and experiment results. There was no heat generation in several hours of testing.*



## Keywords

Bimorph, Piezoelectric motor, Momentum


## INTRODUCTION

A miniaturized motor that can generate high torque or fine resolution is required in various areas such as medical instruments, micromachining, and the electronics industry. Though different specifications are required for various applications, two important parameters are efficiency of the motor and design of the gear box when the motor is miniaturized. To this end, electromagnetic motors have been widely employed. While these motors are still dominant in (what?) industry, drastic improvement cannot be expected unless significant developments are made in magnetic or superconducting materials. Regarding conventional electromagnetic motors, tiny motors smaller than $1cm^3$ are rather difficult to produce with sufficient energy efficiency. Furthermore, they are at a disaventageous in terms of miniaturation [1].

An alternative to electrostatics is piezoelectricity. Though piezoelectric motors have various advantages such as rapid response time, ability of direct drive, high position resolution, simple structure, etc, they were of limited practical use at that time at the time of their induction, because of difficulty in maintaining constant vibration amplitude with temperature rise, wear, heat generation, and tearing [2].

In the present paper a new piezoelectric motor that can overcome excessive heat generation and wear induced by friction is proposed. The proposed motor is operated by momentum exchange between a bimorph and a rotor.

## DESIGN OF PIEZOELECTRIC MOTOR

### Proposed piezoelectric motor

Figure 1 shows an overview of the developed motor. The rotor is basically disk-shaped with an added shaft. Ac voltage is applied to the four bimorphs attached to the inclined side of the stator such that they vibrate in resonant frequency.

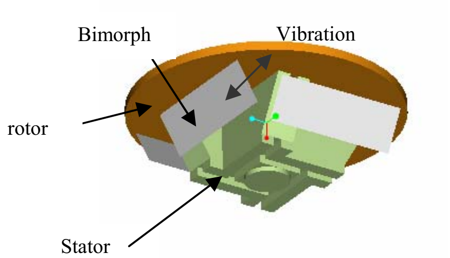


**Figure 1. Overview of the proposed piezoelectric motor**

The driving principle of the motor is as follows. Large momentum is generated to rotate the rotor. This is achieved by the bimorph making a large deflection relative to the stacked piezoelectric materials. Using this momentum, rotary motion occurs when the vibrating ends of the bimorphs impact against the edge of the rotor. In other words, the motor is operated by momentum exchange induced by vibration of the bimorph's end. Based on this principle, we reasoned that the proposed motor could overcome some problems that were unavoidable in previous piezoelectric motors, as impact results in less wear and heat generation than friction. Furthermore, as the length of the bimorph decreases with constant thickness, the blocked force, which means the force measured when the deflection is zero, increases. This feature could allow the motor to maintain high efficiency and torque even when it is fabricated in a few mm scale.

### Modeling

Modeling is carried out to estimate the characteristics of steady state velocity and torque of the proposed motor. As

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illustrated in Figure 2, $\vec{v}_b$ is a vector describing the velocity of bimorph's end $\vec{v}_{bt}$ and is a vector describing a tangential component of $\vec{v}_b$ to the outer circle of rotor. We anticipated the parameters that would have a dominant effect on the maximum angular velocity and static torque of the proposed motor, which in general are the major performance indices of a motor.

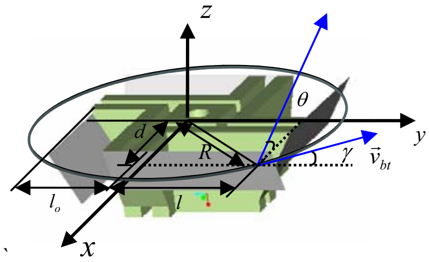



**Figure 2. Velocity of bimorph's end**

To establish design guidelines, it was assumed that angular velocity is proportional to the tangential velocity of the bimorph's end and static torque is proportional to the tangential component of momentum generated by the bimorph. This assumption is reasonable considering that rotation of the rotor is induced by impact and large momentum can be converted to high force with finite time.

From Figure 2, Eq.1 and Eq.2 can be derived via geometric relation. These are performance indices that indicate the qualitative characteristics of velocity and torque.

$$f_v = \left|\overrightarrow{v_{bt}}\right|_{\max} = \delta\omega \sin\gamma \cos\theta \tag{1}$$

$$f_m = m_{eff}\left|\overrightarrow{v_{bt}}\right|_{\max} = m_{eff}\delta\omega \sin\gamma \cos\theta \tag{2}$$

where $\delta$, $\omega$, and $m_{eff}$ are the deflection, driving frequency, and effective mass, respectively. $\gamma$ is calculated from geometry, as given by Eq.3.

$$\sin\gamma = \frac{\sqrt{R^2 - d^2}}{R} \tag{3}$$

and modeling of bimorph are required to determine the effects of $\delta$, $\omega$, and $m_{eff}$ on $f_v$ and $f_m$ .

When the bimorph is driven by AC voltage, voltage across the piezoelectric elements cause one of them to contract and the other to expand; this bends the bimorph periodically. We must now address an important question: "How do we represent the internal force that bends the bimorph?" Jan. G. Smits answered this question by noting that the forced strain in each of the elements is equal to $\pm d_{31}E_3$, where $E_3$ is the electric field in each of the elements. This means that, if we restrain the bimorph from bending for instance by an externally applied moment, the forced stress is also uniform throughout both elements, and equal to $\pm d_{31}E_3/s_{11}^E$. In conclusion, we have a uniform and internally generated moment inside the bimorph, and we now bring that outside as an externally applied moment. This has the same effect; i.e., it results in a uniform internal moment [7]. The total moment in the bimorph is

$$M = 2\int_0^{\frac{h}{2}} z\frac{d_{31}E_3}{s_{11}^E} w dz = \frac{d_{31}Vwh}{4s_{11}^E} \tag{4}$$

To derive the governing equation and boundary condition, we extended Hamilton's equation to the bimorph, which has added mass in the tip. From the expansion theorem, the beam displacement response can be assumed as given by Eq.5. Here, we can calculate the steady state response that satisfies the boundary conditions as shown Eq.6. [7][8].

$$w(x,t) = \sum_{n=0}^{\infty} W_n(w)q_n(t) = W(x)q(t) \tag{5}$$

$$w(x,t) = (C_1(\cos\beta x - \cosh\beta x) + C_2(\sin\beta x - \sinh\beta x))\sin(\Omega t) \tag{6}$$

$$C_1 = \frac{M\beta^3(-\cos\beta l - \cosh\beta l) + \frac{Mm_{add}\Omega^2}{EI}(\sin\beta l - \sinh\beta l)}{2EI\beta^5(1+\cos\beta l\cosh\beta l) + 2m_{add}\Omega^2\beta^2(\cos\beta l\sinh\beta l - \sin\beta l\cosh\beta l)}$$

$$C_2 = \frac{-M\beta^3(\sin\beta l - \sinh\beta l) - \frac{Mm_{add}\Omega^2}{EI}(\cos\beta l - \cosh\beta l)}{2EI\beta^5(1+\cos\beta l\cosh\beta l) + 2m_{add}\Omega^2\beta^2(\cos\beta l\sinh\beta l - \sin\beta l\cosh\beta l)}$$

where *l, E,* and $\Omega$ are bimorph length, Young's modulus, and operation frequency.

While we can estimate the deflection of the tip, which is a function of dimension, voltage, piezoelectric materials and frequency, the derived response has infinite deflection in resonant frequency; this cannot be so in reality. Thus, dissipation of internal energy should be addressed in order to predict the velocity and torque of the proposed motor correctly.

To take energy dissipation into consideration, we established a simple 1 DOF model based on the considerations that the bimorph is operated in first resonance and energy dissipation can be considered as a damper. A deflection curve with moment M applied at the tip of the bimorph is described in Eq.7.

$$\delta(x) = \frac{M}{2EI}x^2 \tag{7}$$

Effective stiffness can be derived from Eq.8, which means the equivalence of the potential energy between a continuous model and the simple 1 DOF model.

$$V(t)_{\max} = \frac{1}{2}\int_0^l \left(EI\left(\frac{\partial^2 w}{\partial x^2}\right)_{\max}^2\right)dx = \frac{1}{2}\left(\frac{4EI}{l^3}\right)\delta(l)^2 \tag{8}$$

$$K_{eff} = \frac{4EI}{l^3}$$

Effective mass can be derived from Eq.10, which means the equivalence of kinetic energy.

$$T(t)_{\max} = \frac{1}{2}\int_0^l \left(\frac{\partial w}{\partial t}\right)_{\max}^2 \rho A dx = \frac{1}{2}\left(\frac{\rho A l}{5}\right)\delta(l)^2\omega^2 \tag{10}$$

$$m_{eff} = \frac{\rho A l}{5} \tag{11}$$

Finally based on deflection of the bimorph tip, effective force mass can be calculated as given by Eq.12. If we consider energy dissipation as a damping coefficient, which is obtained from the Q-factor in experiments, the maximum deflection is derived as

$$\delta(l) = \frac{l^2 M}{2EI} = \frac{1}{k_{eff}}\left(\frac{2M}{l}\right) \tag{12}$$

$$F_{eff} = \frac{2M}{l} \tag{13}$$

$$\delta(l) = \frac{F_{eff}}{\sqrt{(k_{eff} - m_{eff}\omega^2)^2 + c^2\omega^2}} \quad .$$

(14)

Figure 2 shows the frequency responses of the continuous model and the 1 DOF model, where the effective mass is adjusted to describe the deflection correctly. From the 1 DOF model, we confirmed that resonant frequency and amplitude can be estimated accurately in comparison with experiments.

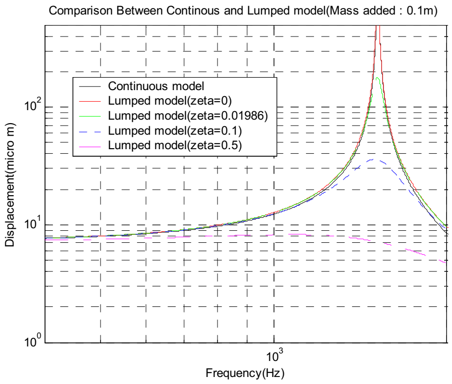


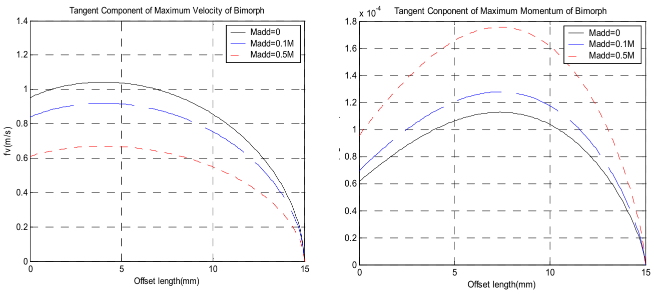

**Figure 3. Comparison between continuous model and lumped model** $(m_{eff} = 0.355\rho Al)$

## Guideline of design

As shown in Eq.15 and Eq.16, the performance index can be established by substituting Eq.14 into Eq.1 and Eq.2.

$$f_v = \left|\overrightarrow{v_{bt}}\right|_{\max} = \frac{F_{eff}}{\sqrt{(k_{eff} - m_{eff}\omega^2)^2 + c^2\omega^2}}\,\omega\frac{\sqrt{R^2 - d^2}}{R}\cos\theta \tag{15}$$

$$f_m = m_{eff}\left|\overrightarrow{v_{bt}}\right|_{\max} = m_{eff}\frac{F_{eff}}{\sqrt{(k_{eff} - m_{eff}\omega^2)^2 + c^2\omega^2}}\,\omega\frac{\sqrt{R^2 - d^2}}{R}\cos\theta \tag{16}$$




(a) $f_v$ vs. added mass and offset distance (b) $f_m$ vs. added mass and offset distance

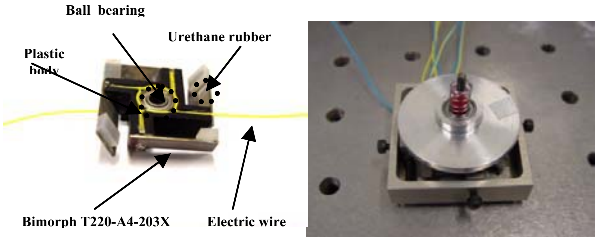
**Figure 4. Effect of offset distance and added mass on $f_v$ and $f_m$**

Figure 4 shows the effect of offsetting the distance of the bimorph and added mass on $f_v$ and $f_m$, which are tangential components of the velocity and momentum of the bimorph when $\theta=20^o$, $R=15mm$, and the applied voltage is $50V$.

As the added mass increases, $f_v$ decreases and $f_m$ increases. $f_v$ and $f_m$ maintain maximum values at $d=4mm$ and $d=7mm$, respectively. Here we can establish guidelines for designing the proposed motor. While the offset distance should be determined in the range between *7mm* and *4mm* to maximize the velocity and torque of the bimorph, a compromise of added mass is required since characteristics of the proposed motor are in conflict with each other, namely, velocity and momentum.

## FABRICATION

Figure 5 shows the basic structure of the fabricated piezoelectric motor. The stator is made from engineering plastic by machining and glued to four bimorphs. The bimorphs are T220-A4-203X (Piezo System,Inc). Urethane rubbers are attached to the tip of the bimorph to control the contact conditions between the rotor and stator by selecting the contact area and thickness. This allows the bimorph to transmit momentum to the rotor effectively. Weight and inertia of the proposed motor is 2.905g and 3.6gcm$^2$, respectively. Each urethane rubber has a weight of 0.034g and a radial bearing is placed in the center of the stator to stabilize rotation of the rotor. Preload can be adjusted by controlling the displacement of the contracted spring, which is set at the top of the rotor.




**(a) Component** **(b) Fabricated motor**

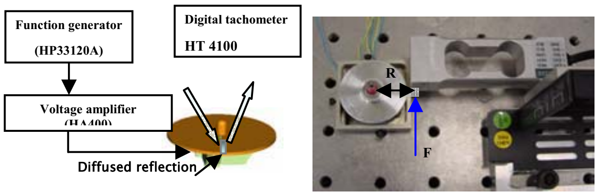
**Figure 5. Overview of proposed piezoelectric motor**

## EXPERIMENT

The experimental set up for velocity measurement is presented in Figure 6 (a). It consists of a function generator, a voltage amplifier, and a digital tachometer. A sinusoidal signal generated by the function generator is amplified 10 times, which causes the bimorph to vibrate in resonant frequency. Rotation velocity is measured using the digital tachometer via a non-contact procedure.The experimental set up for static torque measurement is presented in Figure 6 (b). Here we measured tangential force and estimated static torque.

In order to compare the experiment results with the theoretical guidelines, various types of motors were fabricated.

The offset distance of the bimorphs was varied as shown in Table 1 and each type of bimorph is operated at its own resonant frequency.




(a) Set up for velocity measurement (b) Set up for static torque measurement

**Figure 5. Experimental setup for motor evaluation**

**Table 1. Parameters of fabricated piezoelectric motor**

| | Type1 | Type2 | Type3 |
|---|---|---|---|
| Diameter of rotor | *30mm* | *30mm* | *30mm* |
| Offset Length of Bimorph | 10mm | 9mm | 6mm |
| Inclined Angle of Bimorph | 30º | 20º | 20º |

Figure 6 provides a comparison between the theoretical guideline and the experimental results. Comparing type2 with type3, the velocity characteristics of the fabricated motor are analogous to performance index $f_v$, which makes $f_v$ reliable. The fabricated motor was operated for more than 1 hour without heat generation or any drastic change in velocity or torque.

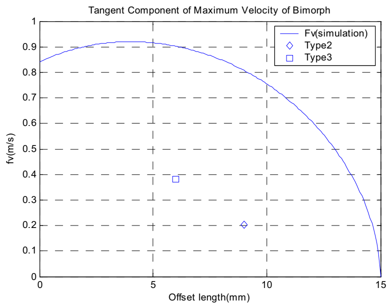
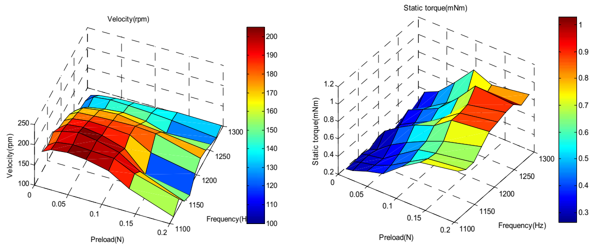



**Figure 6. Comparison between experiments and simulation**

Figure 7 (a) shows the steady-state velocity of the piezoelectric motor when the applied voltage is *100V*. Maximum velocity, *200 RPM*, is obtained at a resonant frequency of *1140 Hz* and *0.05N* preload. As the operation frequency become far from resonant frequency, the velocity decreases. In addition, the velocity gradually decreases with higher preload.

Figure 7 (b) shows the static torque of the piezoelectric motor with the same conditions as those employed for the velocity measurement. While there is a specific value of preload that maximizes the velocity of motor, the static torque is proportional to the preload up to *0.14N*. Maximum torque is 1.1mNm at a resonant frequency of *1280 Hz* and *0.14N* preload. In contrast to the velocity measurement, the output torque is not sensitive to change of frequency.




(a) Set up for velocity measurement (b) Set up for static torque measurement

**Figure 7. Velocity and torque vs. preload and frequency**

## CONCLUSIONS

Figure 1 shows an overview of the developed motor. The rotor is basically disk-shaped with an added shaft. Ac voltage is applied to four bimorphs attached to the inclined side of the stator to vibrate at resonant frequency.

In order to maximize the performance of the proposed motor, we established design guidelines with the assumption that angular velocity is proportional to the tangential velocity of the bimorph's end and static torque is proportional to the tangential component of momentum generated by the bimorph.

The reliability of $f_v$ is partially validated by a comparison between the guideline and velocity of various motor fabricated with different offset distance.

The fabricated motor didn't generate heat during 1 hour of operation and the effects of frequency and preload on the motor were experimentally determined.

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