

Design of Two-Wheeled Ultrasonic Wheel

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Abstract

Design of two-wheeled ultrasonic wheel is proposed for applications in micro-stepping displacement devices. The ultrasonic wheel includes a beam and two displacement members which are respectively pivoted on the beam. Two displacement members are not rotatable. In addition, each displacement member includes a wheel sheet and a piezoelectricity element embedded on its surface. When the piezoelectricity element generates and transmits power to the wheel sheet, the wheel induces vibration and deformation. Therefore, due to the wheel sheets and the touched ground involving their relative motion, the displacement device can move and orient its motion direction in a micro manner. The two-wheeled ultrasonic wheel driven by two piezoelectric elements is direct movement, no rotor requirement. In this research, a 3-D mechanical element with an extra electrical degree of freedom is employed to simulate the dynamic vibration modes of the linear piezoelectric, mechanical and piezoelectric-mechanic behaviours of the two-wheeled ultrasonic wheel.

Keywords: Two-wheeled Ultrasonic Wheel; Micro-stepping; Piezoelectricity

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1. Introduction

Piezoelectric actuators generate large driving torque at low speed and usually introduce low electromagnetic induction and low noise in operation. They are more advantageous than conventional electromagnetic actuators in applications. During the last decade or so, many researchers have been working on piezoelectric actuators development, especially in rotary piezoelectric actuators based on travelling wave. The paper [1] introduced most of recently developed piezoelectric actuators. The author explained in detail various piezoelectric actuators about their driving principles and characteristics, and compared their advantages and disadvantages in terms of speed and thrust. Hirata and Ueha [2] used two vibrations

modes, namely standing and travelling waves, to design their prototype actuator. Bases on this model, they also established the equivalent circuit and estimated its efficiency. Hirata and Ueha [3] also suggested to develop an actuator using travelling wave model and further analyzed this actuator load characteristics such as revolution speed, torque and electro-mechanical conversion efficiency. In [4] a mathematical model for a rotary actuator was established to explain its contact area mechanical behaviour between the rotor and stator. The above research, however, almost all focused on development of the travelling wave propagation on the surface of piezoelectric ceramic stator with the rotor being placed on the surface of stator. For new applications of piezoelectric actuators, it is necessary to consider other wave motion types and to design different piezoelectric actuators. The travelling wave motion is just one of all wave motions excited by piezoelectric ceramics.

This paper describes such a new implementation in the form of two-wheeled ultrasonic wheel driven by two piezoelectric elements (Figure 1). The wheels used are commercially available piezodisc, composed of a nickel-alloy disc on which a piezomembrane [5] is bonded, as shown in Fig. 2. The wheels are in contact with the ground surface, and the driving forces are the friction force between the wheels and ground. To transform the mechanical vibration of the piezodisc into the wheels motion, a travelling wave must be generated on the wheel surface. The locus motion of a particle must be an ellipse, i.e., the mechanical vibration has to have two components. One vibration component, perpendicular to the wheel edge, controls the contacting force between the wheels and ground. The other, tangential to the wheel edge, directs the forward motion. The proposed two-wheeled ultrasonic wheel driven by two piezoelectric elements can be regarded as disc-types, single wavelength mover where a lateral elliptical motion is induced by the standing wave due to the central fixed boundary condition. The main features of the two-wheeled ultrasonic wheel driven by two piezoelectric elements are: simple

structure, good controllability, appreciable torque and high speed; all being obtained with low input power at a low voltage. In addition, the proposed wheel ultrasonic wheel is designed to have broadband frequency responses, including resonant and anti-resonant modes. There are eight driving frequencies near 103Hz, 197Hz, 199Hz, 684Hz, 687Hz, 774Hz, 1106Hz, and 1110Hz.

For piezoelectric ceramics applied to most piezoelectric transducers, the design of a single-frequency piezoelectric resonator [6,7] is very important. In the case of the resonator, the requirements [8] include: (1) an assurance of the specified mechanical resonance frequency; (2) an absence of spurious resonances close to the working frequency; (3) a high quality factor including minimum energy dissipation in the material and in the attachment. For example, a transducer for most acoustic wave generation applications is required to oscillate at the piston mode. For actuator applications, however, design of a multi-driving frequency piezoelectric element becomes critically important. The multi-driving-frequency design is essentially related to resonance frequency, vibration mode and electromechanical coupling factor which measures how strong the excitation of a specific resonant mode is in the transducer response [9, 10]. Although these characteristic depend on many factors, the topology/shape [11, 12, 13] and material property are the most important. In general, the resonance frequency and electromechanical coupling factor are dependent upon the size and shape of piezoelectric actuator. Thus, optimizing the dimension or boundary condition is one crucial problem in piezoelectric engineering. In our study, by making the boundary condition of the wheel in a centrally fixed configuration, we can make the proposed wheel system an adaptive micro-stepping displacement device.

The two-wheeled ultrasonic wheel driven by two piezoelectric elements introduced in this paper moves in a lateral elliptical motion. It is very different from the travelling-wave type actuators [2, 3, 14], or hybrid type actuator [15], or rotary type actuator [16, 17, 18]. The rotating wave is generated by the combination of two standing natural flexural waves whose phases differ by 90°, both spatially and temporally. They raise the driving frequency of rotary type actuator up into ultrasonic frequency range by using axle vibration. The main advantage of two-wheeled ultrasonic wheel driven by two piezoelectric elements is that its contact region is a single point and remains unchanged, that makes it easy to control. In addition, its mechanism of wheel as well as the driving circuit is

also simple. It should be, however, pointed out the energy transfer in this wheel system is not high. Above all, the key successful point is its fixed support condition with a fixed point at its central point, which produces optimal output to move its wheels.

In order for the proposed wheel system to be widely used, it is necessary that the required characteristics of the proposed two-wheeled ultrasonic wheel driven by two piezoelectric elements are realized. Hence, the main purpose of this paper is to establish a design method for the wheel system. This paper is organized in the following way. First we derive lateral elliptical motion equation by wave motion equation in an elastic circular plate and define its boundary condition. Then, based on the mathematical model, we develop the two-wheeled ultrasonic wheel driven by two piezoelectric elements, including predicting its driving frequencies. Finally we prove the characteristics of the wheel system by experimental method and 3-D finite element mode pattern to make sure the validity of the design prototype.

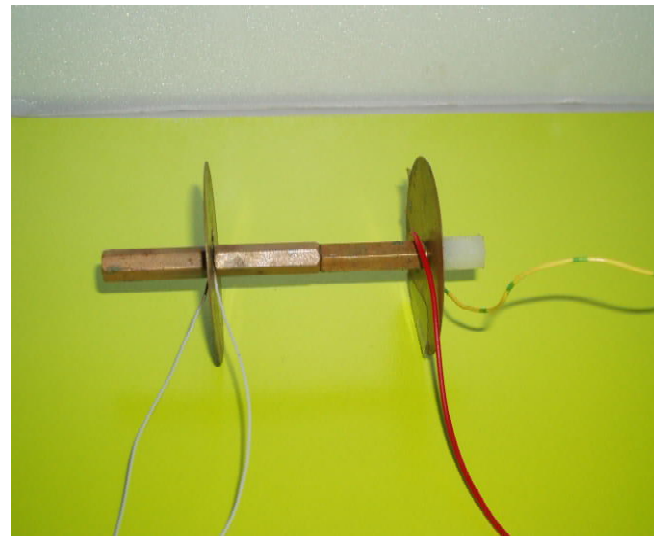
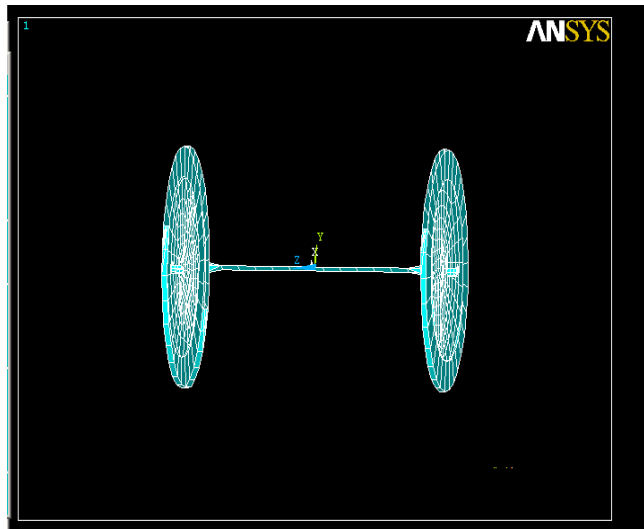
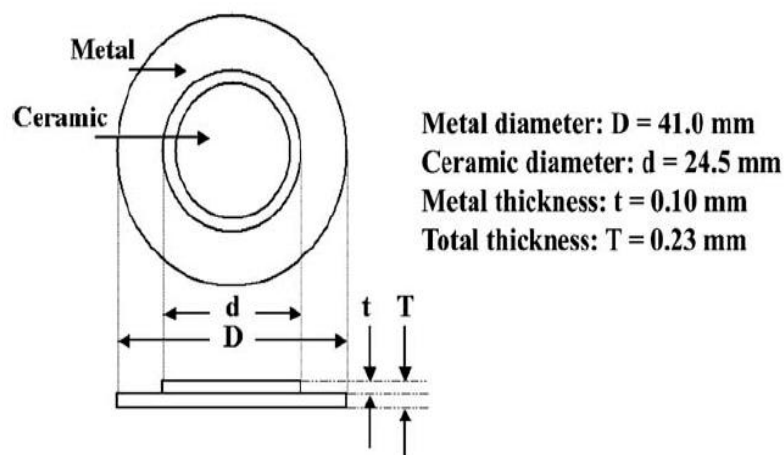
2. The Structure of the Wheel System

In this research, we propose a two-wheeled ultrasonic wheel driven by two piezoelectric elements used in the system described above. The configuration of the wheel system is shown in Fig. 1(a)-(b). It consists of a beam and two displacement members which are respectively pivoted on the beam. The wheel system is powered by two piezodiscs at the same time. In addition, the beam with the installed wheels must be able to move forward-backward and laterally in order to transfer a stable and optimal output to the wheel system. The motion transfer from the piezodisc to the wheel is from two vibration modes, standing and travelling waves, excited by an input voltage propagating on an elastic stator. The waves will create a lateral elliptical motion at its edge. It will generate a relative motion to move the wheels. As for boundary condition, a fixed support condition with a fixed point at its central point is used for mechanism design of the two-wheeled ultrasonic wheel driven by two piezoelectric elements.

Figure 1: The two-wheeled ultrasonic wheel driven by two piezoelectric elements configuration

(a) 3-D cad mesh figure

(b) the real system picture

**Figure 2:** The structure of piezoelectric membrane.

where

$$\{\bar{U}_r\} = \left\{ A \frac{\partial J_n(lr)}{\partial r} + nB \frac{J_n(kr)}{r} \right\}$$

$$\{\bar{U}_\theta\} = -\left\{ nA \frac{J_n(lr)}{r} + B \frac{\partial J_n(kr)}{\partial r} \right\}$$

Where u_r and u_θ are radial and tangential motion of the wheel, respectively. The more detail derivation about calculating (1), (3) and (4) are shown in the books [19-21]. We can confirm that a lateral elliptical motion occurs at the wheel edge and the maximal displacement around edge occurs in contacted area, it is the optimal output location for moving the wheels.

Friction Driving Force

The friction between the wheels and ground is assumed to be coulomb friction. According to the wave equation derivation of an elastic circular plate, the transverse displacement motion can first be obtained, and then the transverse forces per unit length near the wheel edge can be estimated under the standard elastic plate assumption. Finally the friction driving force of the two-wheeled ultrasonic wheel driven by two piezoelectric elements is determined as follows:

$$F_d = V_\theta + \mu(V_r + VP),$$

where V_θ , V_r , μ and VP are transverse tangential force per unit length, transverse radial force per unit length, kinetic friction coefficient and pre-stress, respectively. As usual, $0 < VP < \text{buckling}$ is required.

3. Operation Principles of the Wheel System

3.1. Laterally Elliptical Motion

To design the two-wheeled ultrasonic wheel driven by two piezoelectric elements, it is necessary to establish models of the system and the friction drive between the wheels and ground. In this research, a lateral elliptical motion equation first is used for the motion transfer from the piezodisc to the wheel. The friction driving force can be acquired by involving iterative force into lateral elliptical motion model. In this model, the wave equation of an elastic circular plate is initial step for lateral elliptical motion equation. From this derivation, the lateral elliptical motion equation is express as follows:

$$\left(\frac{u_r}{\{\bar{U}_r\}} \right)^2 + \left(\frac{u_\theta}{\{\bar{U}_\theta\}} \right)^2 = 1,$$

Driving Frequency

The driving frequency for the wheel system can be obtained through solving the eigenvalue of equation (1). And it is expressed by

$$f_d = \left(\frac{Q}{2\pi\rho}\right)^{1/2} \beta^2, \quad (4)$$

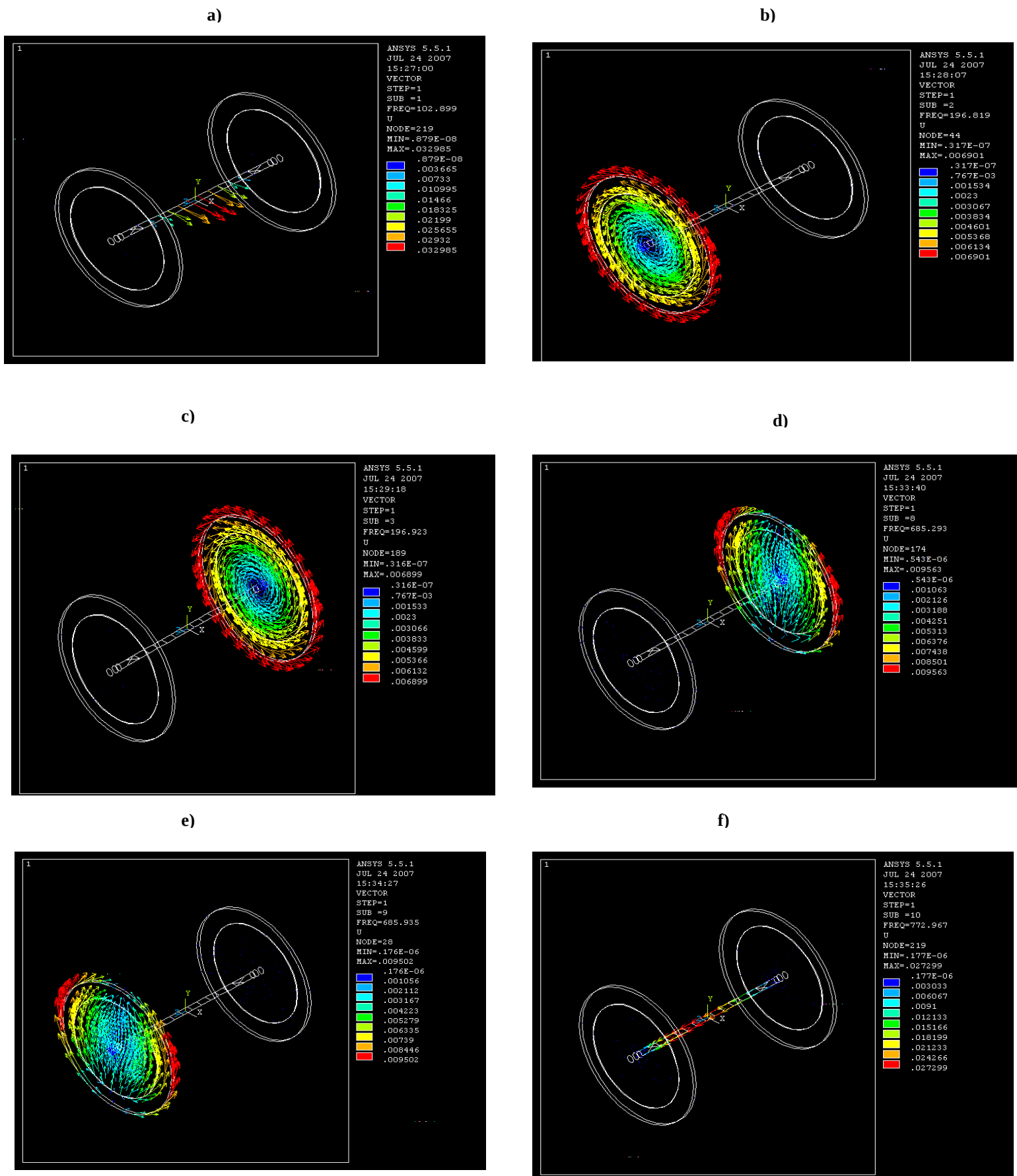
where β is the eigenvalue of the two-wheeled ultrasonic wheel driven by two piezoelectric elements, its relative value is also derived in the books [19-21]. In fact, the driving frequencies are equivalent to the resonance and anti-resonance of the two-wheeled ultrasonic wheel driven by two piezoelectric elements. They can be confirmed by analyzing the two-wheeled ultrasonic wheel driven by two piezoelectric elements mode patterns.

Simulation and Test

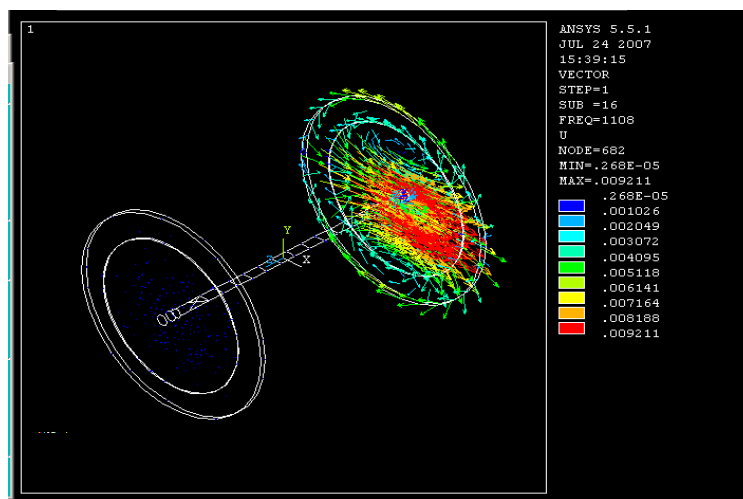
To check if the previous derivation model and design method fit in with an actual design of the two-wheeled ultrasonic wheel driven by two piezoelectric elements, it is necessary to make some modal analyses. The ANSYS simulation is employed to investigate the dynamically piezoelectric, mechanical and piezoelectric-mechanic vibration behavior of the two-wheeled actuator with the parameters listed in Table 1. The analysis results show that there are some responses at 102.899Hz, 196.819Hz, 196.923Hz, 685.293Hz, 685.935Hz, 772.967Hz, 1108Hz, and 1109Hz, which are the first, second, third, eighth, ninth, tenth, sixteenth, and seventeenth resonant modes for the two-wheeled ultrasonic wheel driven by two piezoelectric elements. These are the driving frequencies for the wheel system since the system can only be moved near these frequencies. We can also identify that changing the exciting frequency, amplitude and phase would yield a better performance. The whole wheel system can be forward movement by 102.899Hz. The left wheel of the wheel system can be driven into forward movement by 196.819Hz, and the right wheel is by 196.923Hz which are a pair of resonant frequencies. The right wheel of the wheel system can be driven into right movement by 685.293Hz, and the left wheel is by 685.935Hz which are also a pair of resonant frequencies. The whole wheel system can be left movement by 772.967Hz. The right wheel of the wheel system can be driven into oblique-angle movement by 1108Hz, and the left wheel is by 1109Hz which are also a pair of resonant frequencies.

The applied voltage (AC power 20V) is fixed for all of the desired frequency ranges. The finite element theoretical derivation was carried out by commercially available Finite Element (FEM) ANSYS 9.0/ Multiphysics software, which provides structure analysis with piezoelectric effect. The simulating model consists of eight-node SOLID5 structure element to model the elastic-metal-back plate and coupling element for a piezoelectric membrane. In ANSYS software, the SOLID5 structure element with four degree of freedom at each node is solved for the nodal displacement in X, Y, and Z axes plus electrical potential (see Introduction to ANSYS for Revision 9.0 and Dynamics User's Guide for Revision 9.0). Under fitting mechanical and electrical boundary conditions, ANSYS FEM code to get the relative simulation graphs of displacement, stress and electrical potential for the elastic-metal-back plate and piezoelectric membrane. Fig. 3(a)-(h) shows the displacement vector flow (y dir. view) at 102.899Hz, 196.819Hz, 196.923Hz, 685.293Hz, 685.935Hz, 772.967Hz, 1108Hz, and 1109Hz. The exciting frequencies are at 103Hz, 197Hz, 199Hz, 684Hz, 687Hz, 774Hz, 1106Hz, and 1110Hz under a AC power 20 V_{p-p} input signal to match the real driving condition. The results reveal that the wheel system has standing wave that exists, especially significant at these driving frequencies. As we know, the standing wave transfers most driving energy into the wheel system. The results show why the wheel system can be driven into forward, right, left, and oblique-angle movement. The wheel system can be oriented its motion by tuning driving frequency. Basically, motion speed increases as current gain increases at a constant driving frequency before saturation. The reason is that the friction driving force becomes more as the lateral displacement gets amplifying because of gain increase. In addition, relative motion also increases as motion speed before saturation because it is proportion to current. The test results show that these driving frequencies will have an optimal motion speed, about 6cm/s, when a constant gain is applied to two piezoelectric elements. Due to using AC power driving under open loop with nonlinear friction contact ground, the measured motion speed-applied voltage characteristic is much fluctuated. In addition, because the wheels are not rotationable and they are direct movement, no rotor requirement, there are no revolution speed-load torque and efficiency-load torque measured characteristics.

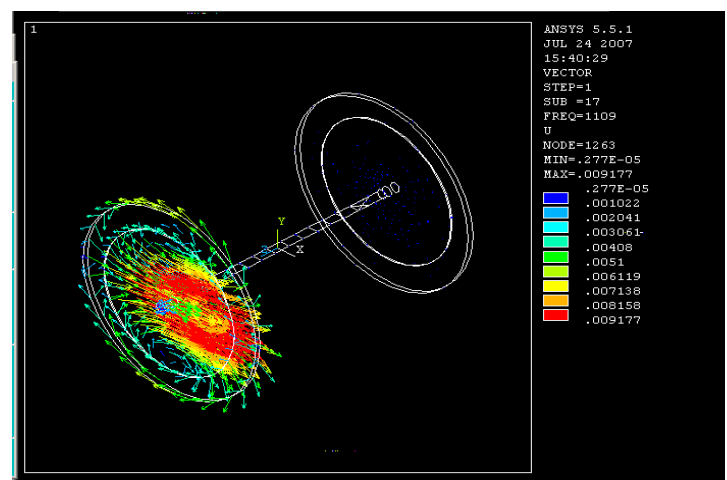
Figure 3: The displacement vector flow (y dir. view) at (a) 102.899Hz, (b) 196.819Hz, (c) 196.923Hz, (d) 685.293Hz, (e) 685.935Hz, (f) 772.967Hz, (g) 1108Hz, and (h) 1109Hz by finite element modal simulation.



g)



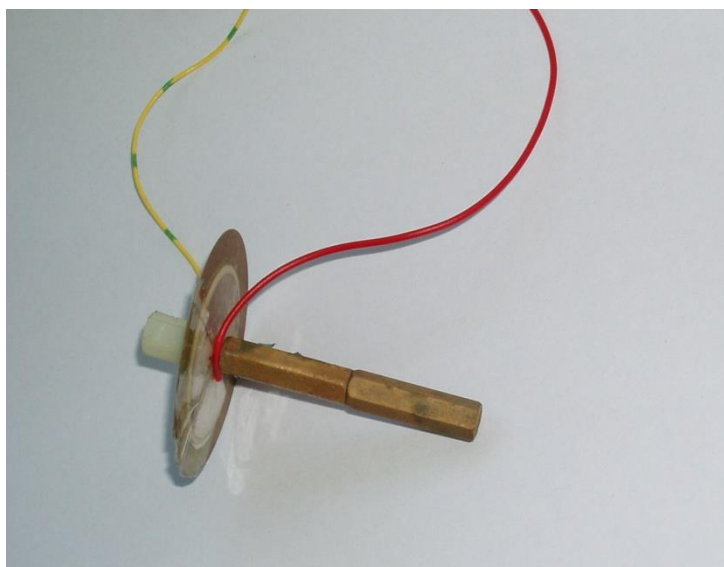
h)



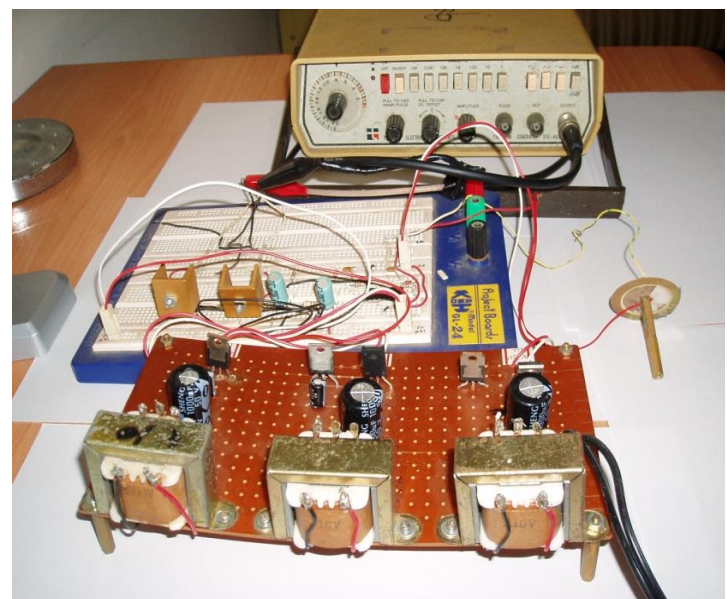
The similar theoretic model and a real test have been also verified by “characterization of one-wheeled actuator had driven by one piezoelectric element” in the accepted paper [22]. Fig. 4(a)-(b) shows the configuration of the wheel actuator with an open-loop circuit driver. Fig. 5(a)-(b) shows the displacement vector flows (y dir. view) at the driving frequencies of 24.12Hz and 42.753Hz. The whole wheel actuator is found to have Clockwise rotation (CW) at 24.12Hz and Counter-Clockwise rotation (CCW) at 42.753Hz. As depicted in Fig. 6(a)-(b), the experimental results confirm that the one-wheeled actuator can be driven into Clockwise (CW) rotation at 24 Hz and Counter-Clockwise (CCW) rotation at 42 Hz.

Figure 4: The one-wheeled actuator driven by one piezoelectric element configuration

(a) A recent actuator



(b) With an open-loop circuit driver



Conclusion

The model derivation of a design method for the two-wheeled ultrasonic wheel driven by two piezoelectric elements based on the lateral elliptical motion has been proposed for prototyping the wheel system. Its driving frequencies can be precisely predicted by this finite element mode pattern. The mechanical response under constant voltage excitation is also obtained by finite element analysis. It has been shown that the theoretical model can exactly examine the piezoelectric influence on a two-wheeled ultrasonic wheel driven by two piezoelectric elements. It has great potential to serve as a design guideline for possible use in practical design, especially in the wheel system using its lateral motion. Boundary condition design is the successful key because it induces a standing wave but lets a traveling wave be partly reflected and mixed. It is useful in moving the wheel system. The proposed two-wheeled ultrasonic wheel driven by two piezoelectric elements can be driven into forward, right, left, and oblique-angle movement by tuning driving frequency and its motion speed can be adjusted by current gain change. Due to no rotor requirement, the two-two-wheeled ultrasonic wheel driven by two piezoelectric elements found that it is very adaptive for a micro-stepping displacement device.

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