Development of a 3-D Finite-element Solver for Piezoelectric Transformer Analysis

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ABSTRACT

In this work, we develop a 3-D finite-element-method (FEM) solver, NTUPZE, for piezoelectric transformer (PT) analyses. The solver employs the 8-node brick element, and applies the harmonic analysis to study the voltage gains and the phase difference at different frequencies for PTs. Using the NTUPZE, we analyze two different types of piezoelectric transformers: the modal-type and the unipoled-disk-type. In the simulation of modal-type piezoelectric transformers, the voltage gain increases as the impedance increases when the phase increases with frequencies for each loading condition. In the simulation of the unipoled-disk-type, similar phenomenon is also observed. In addition, higher input/output area ratio will lead higher voltage gain and higher resonance frequency.

Keywords: finite element method (FEM), piezoelectric transformer (PT), and modal-type piezoelectric transformer

1 INTRODUCTION

Piezoelectric transformers, which were proposed in 1954 [1] (the Rosen type, as shown in Fig. 1), step up or step down input voltages by electrical/mechanical/ electrical conversion. Piezoelectric transformers have been proved to be promising alternatives for magnetic transformers, because of the advantages such as (1) low profile, (2) high efficiency (low loss), (3) no electromagnetic radiation, (4) nonflammable, (5) low harmonic current noise (6) low temperature rise, and so on. Recently, the rapid growth in liquid crystal display (LCD) indicates a possibly huge demand of piezoelectric transformers because each LCD panel requires a few transformers to ignite cold cathode fluorescent lamps (CCFL) for backlighting. Furthermore, since the fabrication technology of thin-film piezoelectric materials becomes mature, piezoelectric transformers are particularly useful for integrating with the MEMS devices that require high input voltages, such as comb drives or electrostatic switches.

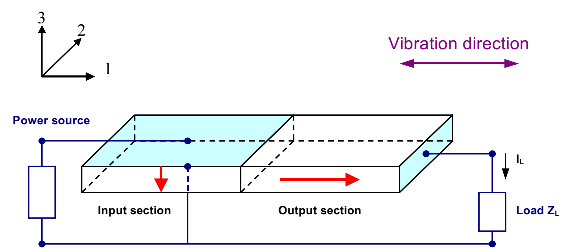

Fig. 1 A typical schematic view of a PT (Rosen-type) with a electric loading imposed at the output electrodes.

In order to design and optimize the MEMS piezoelectric transformer, a 3-D finite element method (FEM) piezoelectric solver is needed [2-4]. Typical commercial finite element packages, such as ANSYS and ABAQUS, are capable of to analyzing piezoelectric material [5,6]. However, they cannot take into consideration the electric loading (the loading effect) connected on the output port of piezoelectric transformers. Since the loading effect is one of the most important factors for power devices, we develop a 3-D FEM piezoelectric solver NTUPZE, which employs a new finite-element piezoelectric formulation, and is capable of accounting for various types of electric loading conditions.

2 THEORETICAL FORMULATION

Under a sinusoidally steady-state condition, the governing equation for piezoelectric material is shown in Equation (1):

$$\begin{bmatrix} -\omega^2[M]+[K_{dd}] & [K_{d\varphi}] \\ [K_{d\varphi}]^T & [K_{\varphi\varphi}] \end{bmatrix} \begin{Bmatrix} \{d\} \\ \{\varphi\} \end{Bmatrix} = \begin{Bmatrix} \{F\} \\ \{Q\} \end{Bmatrix} \qquad (1)$$

where ω represents the frequency, $[K_{dd}]$ the stiffness matrix, $[K_{d\varphi}]$ is the piezoelectric matrix, $[K_{\varphi\varphi}]$ the dielectric matrix, $\{d\}$ the displacement, $\{\varphi\}$ the voltage, $\{Q\}$ the charge.

An electric loading is usually connected at the output electrode of a piezoelectric transformer in practical applications (as shown in Fig. 1). Therefore, the loading effect must be considered. To take the loading effect into consideration, Equation (1) should be modified as the following equation:

$$\begin{bmatrix} -\omega^2[M]+[K_{dd}] & [K_{d\varphi}]_i & [K_{d\varphi}]_k \\ [K_{d\varphi}]_i^T & [K_{\varphi\varphi}]_{ii} & [K_{\varphi\varphi}]_{ik} \\ [K_{d\varphi}]_k^T & [K_{\varphi\varphi}]_{ki} & [K_{\varphi\varphi}]_{kk}-\frac{1}{j\omega}[Y]_{kk} \end{bmatrix} \begin{Bmatrix} \{d\} \\ \{\varphi\}_i \\ \{\varphi\}_k \end{Bmatrix} = \begin{Bmatrix} \{0\} \\ -\{Q\}_i \\ \{0\}_k \end{Bmatrix} \quad (2)$$

where the subscript i refers to the nodes associated with the region without the output electrode, and the subscript k refers to the nodes associated with output electrode. The term $[Y]_{kk}$ is associated with the loading and the effective area A_k of node k and defined as following Equation (3).

$$[Y]_{kk} = \begin{bmatrix} \frac{A_1}{Z_L\sum_m A_k} & 0 & \cdots & 0 \\ 0 & \frac{A_2}{Z_L\sum_m A_k} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \frac{A_m}{Z_L\sum_m A_k} \end{bmatrix} \quad (3)$$

3 SIMULATION OF PIEZOELECTRIC TRANSFORMER

We will use the NTUPZT to simulate two types of piezoelectric transformers: the modal-type piezoelectric transformer and the unipoled-disk-type piezoelectric transformers.

3.1 Modal-Type Piezoelectric Transformers

Figure 2 shows a modal-type piezoelectric transformer [7] that we model and measure in this work. The major difference between the Rosen-type and the modal-type device is the shape of the electrode. A modal-type transformer has an input electrode with sinusoidal shape, while the electrode of a Rose-type transformer is in a uniform shape. The sinusoidal shape of electrodes is capable of taking into consideration the spacial weighting of the most important coefficient e_{31} in piezoelectric matrix [e], and thus can effectively reduce the unwanted frequency responses. Therefore, the modal-type piezoelectric transformer has better output waveforms, which potentially increases the lifetime of the device.

The input section of the simulated modal-type PT is 22.3mm in length, , and the output section is 21.7mm in length. The width of the structure is 6.5mm, and thickness, 2.2mm. The meshed model has 1107 nodes and 640 elements and the material properties are list in Table 1.

Fig. 3 shows the simulated and the measured voltage gains vs. frequency for different loadings. The maximum voltage gain and its frequency increase as the impedance increases (the loading increases). The phase plot is shown in Fig. 4. The phase increases with frequencies for each loading condition. There is no significant difference in phase while the loading varies. However, in the frequency range between 73kHz and 76kHz, the case of 100k Ohm has the largest phase difference. Finally, the simulated deformed shape and the voltage distribution of the modal-type piezoelectric for loading impedance 250k Ohm is as shown in Fig. 5.

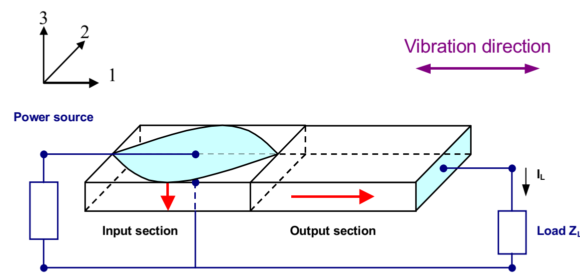

Fig. 2 The schematic of a modal-type PT.

Material Property	**Parameter**
Density ρ (kg/m^3)	7500
Stiffness matrix [c] (N/m^2)	$\begin{bmatrix} 15.6 & 8.8 & 8.4 & 0 & 0 & 0 \\ 8.8 & 15.6 & 8.4 & 0 & 0 & 0 \\ 8.4 & 8.4 & 13.0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2.8 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2.8 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2.8 \end{bmatrix} \times 10^{10}$
Piezoelectric matrix [e] (C/m^2)	$\begin{bmatrix} 0 & 0 & 0 & 0 & 11.4 & 0 \\ 0 & 0 & 0 & 11.4 & 0 & 0 \\ -7.3 & -7.3 & 12.6 & 0 & 0 & 0 \end{bmatrix}$
Dielectric matrix [ε] (F/m)	$\begin{bmatrix} 14.7 & 0 & 0 \\ 0 & 14.7 & 0 \\ 0 & 0 & 13.842 \end{bmatrix} \times 10^{-9}$

Table 1 The material property of the modal-type PT.

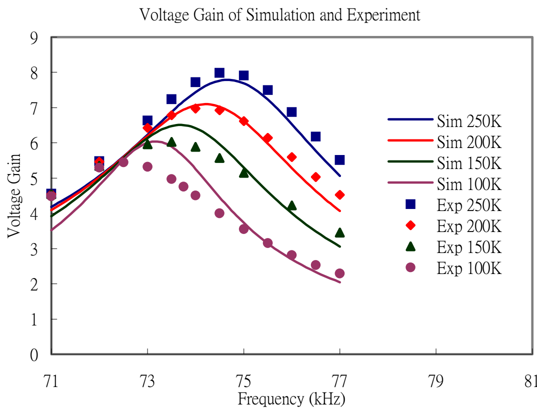

Fig. 3 The simulated and measured voltage gain vs. frequency for the modal-type PT with different loading.

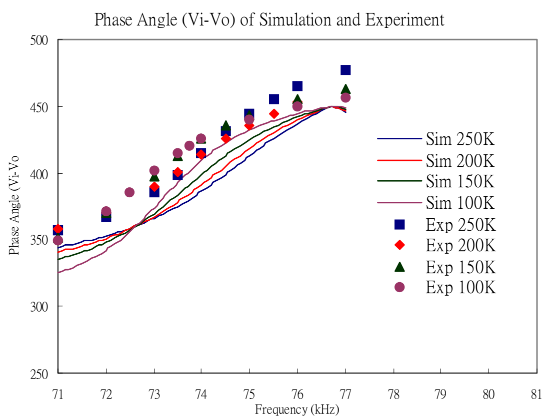

Fig. 4 The simulated and measured phase difference vs. frequency of a modal-type PT for different loadings.

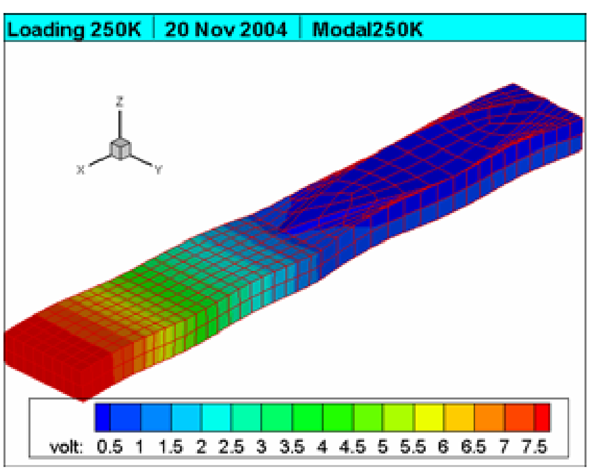

Fig. 5 The deformed shape and voltage distribution at the max voltage gain with different loading.

3.2 Unipoled-Disk-Type Piezoelectric Transformers

Unipoled-disk-type piezoelectric transformers was first proposed by Berlincourt in 1973. The fact that the input and output terminals have the same polarization is the most attractive property of this design, because it simplifies the fabrication process effectively. The schematic of the simulated unipoled-disk-type PT is shown in Fig. 6. The input and output electrodes are concentrically placed on the top surface of the device structure. The input electrode is the external ring and the output electrode is on the center. The bottom electrode, which serves as the ground electrode, is connected to both the input and the output sections. The arrows in the figure indicate the poling direction of the input and the output sections. By driving the input part (external ring) with an AC voltage, a vibration in radial direction is generated. The device operates at its first radial vibration mode. The strain energy propagates to the output electrode through vibration, and then is converted into an electrical voltage drop across the output electrode and the ground electrode.

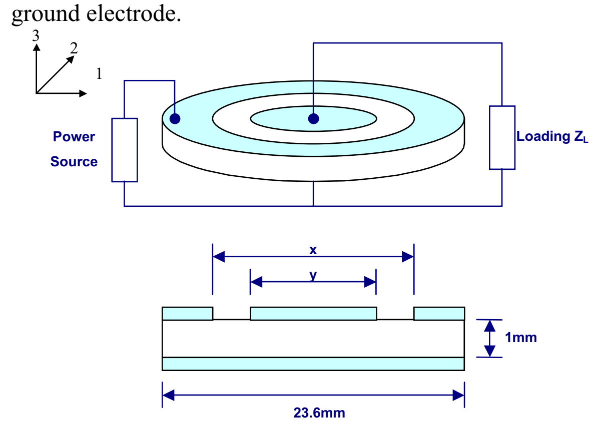

Fig. 6 The schematic and the dimensions of a unipoled-disk-type PT.

At the mechanical resonance of the devices, the vibration amplitude is amplified by a factor of Q_m (mechanical quality factor). Compared with typical Rosen-type PT, higher energy conversion efficiency and output power can be achieved because the electro-mechanical coupling coefficient (k_p) for the unipoled-disk type PT is higher than the coupling coefficient, (k_{31}) used in the Rosen-type PTs.

The diameter of the transformers is 23.6mm and the thickness is 1mm. The detailed dimensions are listed Table 2 [9] and the material property is listed in Table 3. Fig. 7 shows the voltage gains vs. frequency for these three designs. The maximum voltage gains are obtained at the driving frequencies of 97.7 kHz and 103.5 kHz for the PTA and PTB. The experimental data shown in Fig. 7 are from [9].

	PTA	PTB
X (mm)	12	16
Y (mm)	8	12
Input/Output Area Ratio	6.47	2.10

Table 2 The dimensions of unipoled-disk-type PT.

Material Property	Parameter
Density ρ (kg/m^3)	6600
Stiffness matrix $[c]$ (N/m^2)	$\begin{bmatrix} 13.2 & 7.1 & 7.3 & 0 & 0 & 0 \\ 7.1 & 13.2 & 7.3 & 0 & 0 & 0 \\ 7.3 & 7.3 & 11.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2.6 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2.6 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3.0 \end{bmatrix} \times 10^{10}$
Piezoelectric matrix $[e]$ (C/m^2)	$\begin{bmatrix} 0 & 0 & 0 & 0 & 10.5 & 0 \\ 0 & 0 & 0 & 10.5 & 0 & 0 \\ -4.1 & -4.1 & 14.1 & 0 & 0 & 0 \end{bmatrix}$
Dielectric matrix $[\varepsilon]$ (F/m)	$\begin{bmatrix} 11.1 & 0 & 0 \\ 0 & 11.1 & 0 \\ 0 & 0 & 9.8 \end{bmatrix} \times 10^{-9}$

Table 3 The material property of unipoled-disk-type PT.

4 CONCLUSION

In this work, we develop a FEM piezoelectric solver, the NTUPZE, to analyze various types of piezoelectric transformers. We also focus on the implementation of the boundary conditions with electric loading that are connected on the output electrodes. The derivation of the system equation for a piezoelectric 8-node-brick finite element is demonstrated. The loading effect at the output edge is regarded as a Neumann boundary condition and can be imposed by modifying the global system matrices. The results simulated by the NTUPZE for various types of piezoelectric transformers, such as the modal-type, and the unipoled-disk-type, are presented and discussed.

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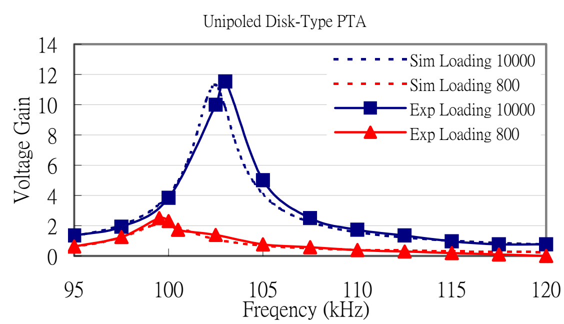

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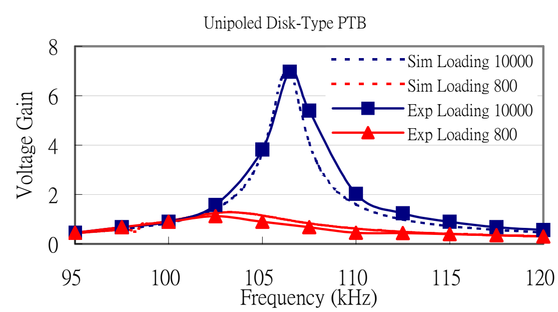

(b)

Fig. 7 The voltage gains vs. frequency for unipoled-disk-type PTs PTA and PTB. The measured data are from [9].