FINITE ELEMENT ANALYSIS ON PIEZOELECTRIC RING TRANSFORMER

Hing Leung Li * Ψ, Jun Hui Hu * and Helen Lai Wah Chan*
*Department of Applied Physics and Materials Research Center,
* The Hong Kong Polytechnic University, Hunghom, Kowloon, Hong Kong, China;
† ΨASM Assembly Automation Ltd.
4/F Watson Center, 16 Kung Yip Street, Kwai Chung, Hong Kong, China

Abstract - By using concentric electrode patterns, a ring-shaped transformer can be designed to operate at its high order radial extensional modes. In our previous study, a piezoelectric transformer (PT) using the third symmetric radial extensional mode was studied and characterized. A maximum efficiency, transformation ratio and power density of 92.3%, 1.9 and 14.3 W/cm^3 could be achieved. In this paper, three-dimensional (3D) finite element models were built to study and analyze the vibration characteristics of the PTs using higher order modes (>3). The resonance frequencies, mean electromechanical coupling effect, and other open-circuit characteristics are simulated and compared with experimental measurements. The dimensions for the PTs using higher order radial extensional modes are optimized by FEM. The ring PT offers advantages of simple structure and small size. It has good potential in making low cost PT for low voltage applications.

I. INTRODUCTION

The idea of piezoelectric transformer (PT) was first implemented by C. A. Rosen in 1956 [1]. PT offers many advantages over the conventional electromagnetic transformer such as high power-to-volume ratio, electromagnetic field immunity and non-flammable. Due to the demand on miniaturization of power supplies in electrical equipment, the study of PTs has become a very active research area in engineering. In the literature, many PTs have been proposed and a few of them found practical applications [2,3]. Recently, PTs of ring or disk shapes have been suggested and investigated [4,5]. The main advantages are their simple structure and small size.

In our previous study, a ring transformer operated at the third symmetric extensional mode was proposed and developed [6]. Different from all the conventional PTs, the proposed ring PT only required a single poling process and a properly designed electrode pattern. The PT was fabricated by a PZT ring by dividing one of the electrodes into two concentric circular regions. The third symmetric extensional mode was used as the operation mode. Prototypes were fabricated and a maximum efficiency and power density of 92.3% and 14.3 W/m^3 could be achieved. With similar approach, PTs using higher order mode (m) could also be designed using a suitable electrode pattern. Owing to the mode coupling effect and the complexity of vibration modes at high frequency, the conventional lumped equivalent circuit method may not accurately predict the dynamic behaviors of the PTs. In this study, a commercial finite element code (ANSYS) was used as a computational tool to analyze and study the ring piezoelectric transformer. Different electrode patterns were designed to excite the higher order extensional mode of a PZT ring. Three-dimensional (3D) finite element models were built to study the dynamic behaviours at its resonance. The performance of the PTs was evaluated by the mean coupling factor of the input and output sections (k_m). The dimensions of the ring were optimized to achieve maximum efficiency.

II. CHARACTERISTICS OF PZT RINGS

For a fully-electroded PZT ring, several main resonances would be identified in the frequency domain. It includes the radial, wall-thickness, thickness and other complex modes [7]. The radial and wall-thickness modes are also referred to as the 1st and 2nd order radial extensional mode of a ring, respectively. However, extensional modes with higher m are often very weak or even vanished in the frequency spectrum. In order to excite higher order extensional modes of a PZT ring, it is necessary to decouple the compressive and tensile stress regions by splitting the electrode according to the stress distribution. As an example, the 3rd radial extensional mode could be excited by splitting the electrode at its nodal line of the radial stress as shown in Figure 1. By driving the PZT ring at either the positive or negative stress region, the mode for m=3 could be excited. Similarly, higher order modes could also be excited by using more concentric electrodes.

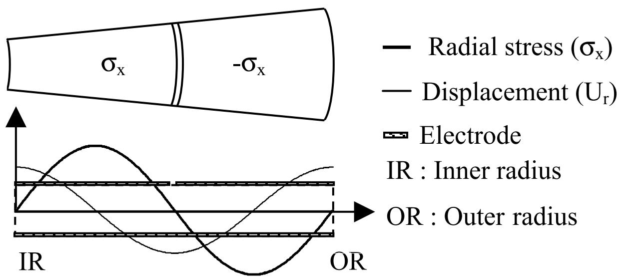

Figure 1. Electrode pattern for high order radial extensional modes (m=3)

A commercial PZT ring, from Fuji Ceramics Ltd. (Fuji 213), with an outer diameter of 12.7 mm, inner diameter of 5.1 mm and a thickness of 1.2 mm is used to demonstrate this idea. With reference to Figure 1, two rings were designed to excited mode with m equal to 3 and 4. One of the electrodes of the PZT ring is splitted into two concentric regions for the excitation of m =3. Other PZT ring has three concentric electrodes to excite the 4th order mode. All the allowable modes of the two rings together with one full electrode sample were measured by a HP 4149A Impedance/Gain Phase Analyzer. The measurement was also compared with the FEM predication in Figure 2.

The shaded area represented the driving electrode(s) of the ring. For figure 2(a), the fully-electroded ring could excite two strong modes at 120kHz (m=1) and 453kHz (m=2). With splitting the driving electrode into two concentric rings, the strongest mode occurred at 818kHz (m=3). By splitting the electrode into 3 circular sections, the main resonance was shifted to 1073kHz (m=4).

III. CONSTRUCTION AND PRINCIPLE

The construction of the PT using higher order extensional modes of a ring is to divide the top electrode into concentric regions. According to the radial stresses distribution, the compressive regions are connected together as the input section. Similarly, the tensile stress areas are connected as the output section. The bottom electrode served as a common ground for both the input and output. To minimize the disturbance on the resonance characteristics of the ring, the solder joints are applied at the displacement nodal points. Prototype of a PT using 3rd and 4th extensional mode are shown in Figure 3.

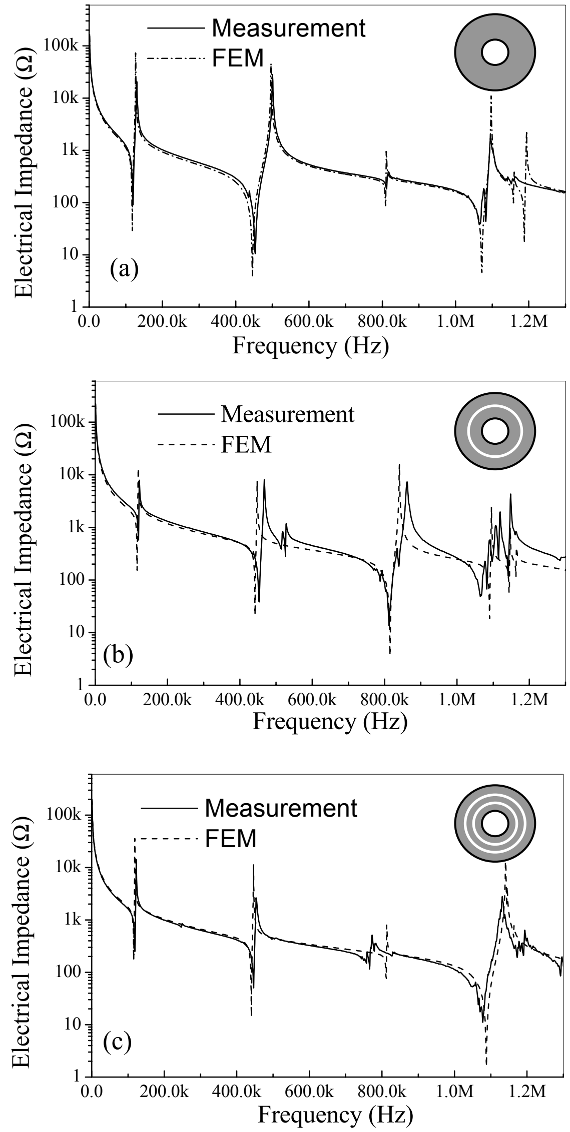

Figure 2. Electrical spectrum of a PZT ring for (a) m=1 and 2, (b) m=3, (c) m=4

IV. FEM ANALYSIS

To study the characteristics of PTs using higher order modes, a commercial finite element code, ANSYS, was used. The 3D FEM was constructed by 8-nodes brick couple field elements. The element can take into account both the direct and inverse piezoelectric effects at the same time in one model. As the loading condition cannot be implemented into the present FEM, the open circuit characteristics of PT will be investigated.

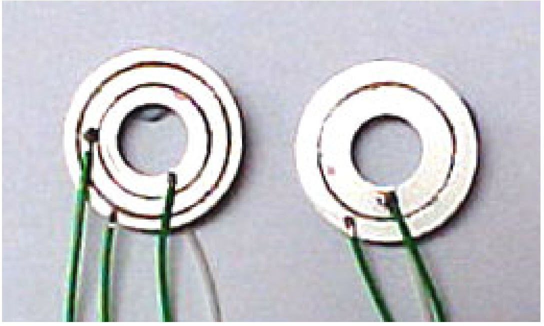

Figure 3. Prototypes of PTs using 3rd and 4th radial extensional modes

A PT utilizes the direct piezoelectric effect at the driver section to excite the whole structure in resonance. Electrical charges will be built up at the output section by the inverse piezoelectric effect. Hence, the performance of a PT will be determined by effective electromechanical coupling factors at both the input and output sections, represented by k_{in} and k_{out} hereafter. In evaluate the performance of a PT, the mean effective coupling factor will be used and it is given by

$$k_m = \sqrt{k_{in} \times k_{out}} \quad \text{, and} \quad k_i = \sqrt{(F_a^{\,2} - F_r^{\,2}) / F_a^{\,2}} \quad (1)$$

where F_r and F_a are the resonance and anti-resonance frequency which could be determined by a modal analysis. In a harmonic analysis, the open circuit characteristics and transformation ratio (R) could also be predicted. The actual transformation ratio value was determined by the damping ratio (ζ) of the PT. The ζ was found by best fitting the experimental results with FEM simulation in Figure 4. A damping ratio of 1.5% of the critical damping will be used by

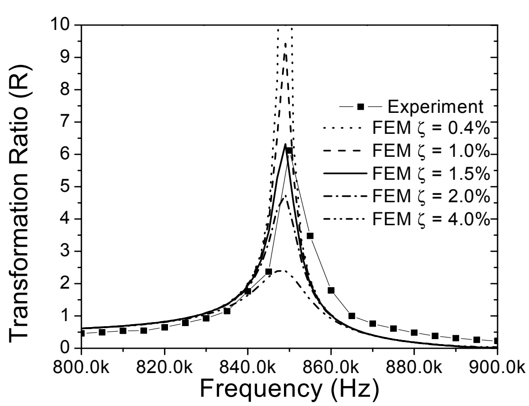

Figure 4. Frequency response of PT (m=3)

assuming the loss factor to be constant from 1MHz to 2 MHz.

The FEM prediction on the characteristics of PT using higher mode order (up to mode order 7) extensional mode of a ring is shown in Figure 5. The resonance frequencies of the PT increases as the mode order increases. It is also noticed that both k_m

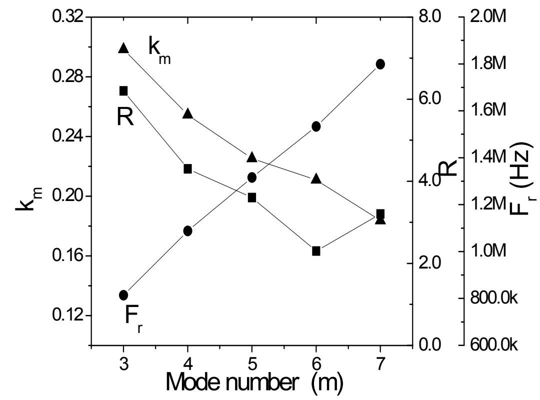

Figure 5. Characteristics of PT at higher mode order

and R decrease in the higher order mode. The wavelength also decreases as the resonant frequency increases. The wavelength propagate in the radial direction is comparable to the ring thickness. Hence, other complex modes in the thickness direction could also be excited simultaneously. Mode coupling will occur and reduce the k_m and R of the PT and also the efficiency of the transformer. From the FEM results in Figure 5, k_m of the PT reduces from 0.26 to 0.14 as m increases from 3 to 7. In addition, R also reduces from 6.2 to 3.2. To demonstrate the mode coupling in higher order modes, the resonance frequencies of the radial extensional modes and thickness mode are plotted against the ring thickness in Figure 6 (a). When the ring thickness from 0.8 mm to 1.2 mm, the thickness mode falls into the operation frequency range of PT with mode order of 5 to 7. The mode coupling between thickness and radial modes could happen. When the ring thickness is less than 0.6 mm, mode coupling with thickness mode no longer exists. k_m of the PT in the higher order modes are shown in Figure 6(b). In general, k_m decreases as the ring thickness increases. However, for a ring with 0.8 mm to 1.2 mm thickness, k_m drops significantly. Coupling with the thickness mode will reduce k_m of the PT. As the thickness approaches to zero, the value of k_m will be similar in modes. Therefore, when the ring thickness becomes very small, the performance of the PT will be independent of the mode order.

V. CONCLUSION

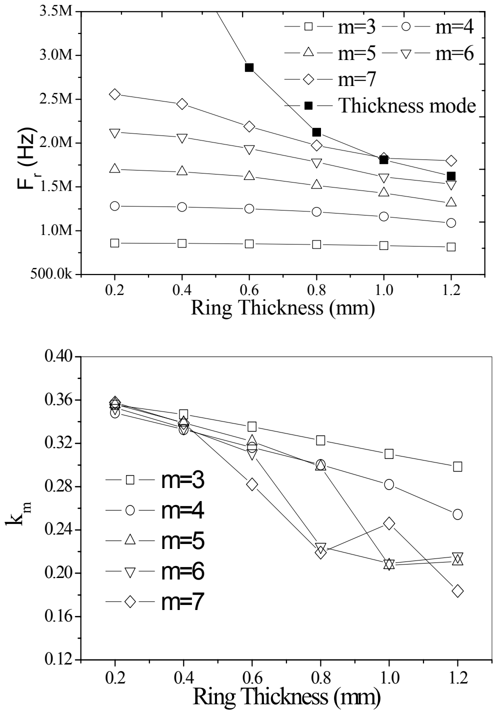

Figure 6 (a) F_r and (b) k_m against the ring thickness

The PT using higher order extensional modes of a PZT ring was studied by FEM. With properly designed concentric electrodes, the higher order extensional modes could be excited and a PT using higher order mode could be fabricated. Prototypes of PT of mode number 3 and 4 were fabricated to prove the proposed idea. Three dimensional finite element models were used to predict the characteristics such as resonance frequencies, transformation ratio and mean electromechanical coupling factor of PT using higher order mode. It was found that, a PZT ring with outer and inner diameter of 13.5 mm and 5.1 mm, the ring thickness has to be less than or equal to 0.6 mm to avoid coupling with the thickness mode. It was also found that when the ring thickness become very small, the mean coupling factor will no longer depend on the mode number. Hence, the proposed PT will be ideal for a very thin structure, such that the operating frequency can be tuned using the mode order without affecting the performance.

VI. ACKNOWLEDGMENTS

The authors would like to acknowledge the supports by the Center for Smart Materials of the Hong Kong Polytechnic University and the Innovation and Technology Fund (ITF UIM/29) of the HKSAR Government.

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