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Finite element analysis on 1-3 piezocomposite rings for ultrasonic transducer applications

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Abstract

In this study, a commercial finite element code (FEM), ANSYS, is used to study the behaviors of 1-3 lead zirconate titante (PZT)/epoxy composite rings. The composite rings are fabricated by a dice-and-fill technique with an epoxy width of 80 μm. By using different number of cuts per direction (cpd), the composites with PZT volume fraction (ϕ) from 0.88 to 0.93 could be obtained. It is found that the lateral characteristics (radial modes) of a PZT ring can be reduced significantly by using a 1-3 composite ring. Three-dimensional finite element models are built to understand and study the vibration characteristics of the composite rings. Good agreements are found between experimental results and FEM simulations. Results from this study can be used to optimize the number of cpd of the composite rings for practical transducer applications.

Keywords: Lead zirconate titnate; 1-3 Composite; Finite element method; Ultrasonic transducers

1. Introduction

The 1-3 composites of active piezoceramic pillars embedded in a passive polymer phase have been widely used in ultrasonic medical transducers and hydrophones. They offer superior properties such as high electromechanical coupling, low mechanical quality factor (Q_m), low acoustic impedance and reduction of planar or lateral mode coupling. The material properties of the 1-3 composites has also been tailored to specific device requirements by choosing suitable PZT, polymer and their volume fractions. A recent application of 1-3 composite was found in replacing the conventional piezoceramics by composite rings for an ultrasonic wire-bonding transducer [1–4]. It gains the benefit of suppressing unwanted spurious vibration and reducing mode coupling. Together with other advantages such as higher electromechanical coupling and broader bandwidth, the composite transducer has a good potential to be used in fine-pitch and high-speed bonding for future wirebonder machines.

Several analytical models have been proposed to predict and simulate the behaviors of 1-3 composites [5–7]. Each of them has either not consider full set of moduli or has made certain assumptions that limit the application of the theories to general applications. To overcome that, finite element method (FEM) was employed and it is useful to analyze complex problems such as piezoelectric pillar geometries [8–10]. However, the previous FEM studies were mainly based on the assumption that the 1-3 composite has an infinite size when compared with the PZT pillars. Therefore, a unit cell could be accurate enough to represent the whole composite panel. For the 1-3 composite rings in the wire-bonding transducers, it was fabricated by the dice-and-till technique [11]. The number of cuts per direction (cpd) has to be limited in order to retain a high PZT volume fraction (>90%) for good transducer properties and reduce the manufacturing costs. However, the cpd has to be adequate such that the 1-3 composite ring can be treated as a homogenous media. In this study, a commercial FEM code, ANSYS, was employed to study the effect of the cpd on the properties of a 1-3 composite ring. Unlike the previous studies, the whole composite ring was modeled with three-dimensional FEM from 5 to 9 cpd. For composite ring with small cpd, the high PZT element aspect ratio (width to height, L/T) makes the

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Table 1
Material properties for PZT and epoxy

Properties	PZT-8	Epoxy
Young's modulus (GPa)	67.4	4.0
Density (kgm^{-3})	7517	1150
Poisson's ratio	0.3	0.37
d_{33} (pC/N)	278	–

previous analytical models no longer accurate enough. With the use of FEM, the dynamic behaviors of such composite rings can be predicted.

2. Samples preparation

The 1-3 composite rings were prepared by the dic-and-fill technique. Commercial available PZT-8 materials supplied by ASM were used as the active phase. The passive polymer phase was the Araldite LY5138/HY5138 epoxy (Ciba-Geigy). The materials properties of the PZT-8 and epoxy are listed in Table 1. Parallel grooves were cut in the two perpendicular directions on the PZT rings (12.7 mm outer diameter, 5.1 mm inner diameter and 2.3 mm thickness) by using a Disco DAD321 automatic dicing saw. Eighty micrometer grooves could be made on the PZT rings by a thin diamond saw blade. Epoxy was filled into grooves under the action of vacuum. After the curving of the passive epoxy phase, the composite was lapped and polished to remove excess polymer. Finally, a conductive paint was applied on the major surface to serve as the electrodes. By varying the numbers of cuts per direction from 5 to 9, the composite rings with ceramic volume fraction ϕ from 0.93 to 0.88 could be obtained. The photos of a 5, 7 and 9 cpd composite rings are shown in Fig. 1.

3. Finite element analysis

The FEM package, ANSYS, was used for modeling the composite dynamic behaviors. Unlike the previous study, the composite was modeled as a complete ring rather a unit cell or using lumped material parameters. It could help to relax the assumption of composite for being a homogenous media that may not be true for high L/T ratio. As the composite is symmetric with the two perpendicular planes, a quarter

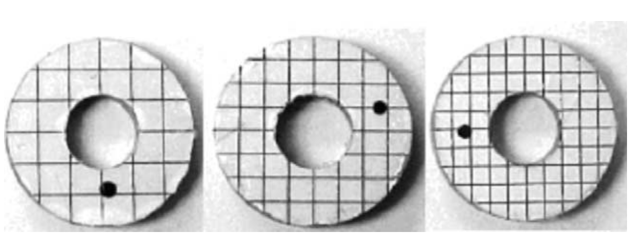

Fig. 1. 1-3 Composite rings with 5, 7 and 9 cpd.

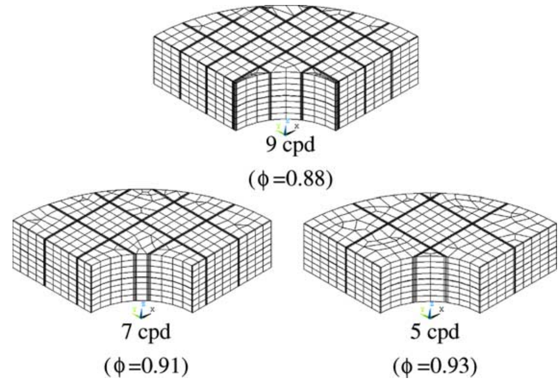

Fig. 2. FEM models of 1-3 composite rings.

was modeled to represent the whole ring. Three-dimensional coupled-field elements (Solid5), which include both mechanical and electrical degree of freedom (DOF), were used to build the active PZT materials. The epoxy width of the composite was set at 80 mm. The thin electrodes were neglected in the FEM. However, the equipotential boundary condition was applied to the two major surfaces to simulate the physical conductive behaviors of the electrodes. Fig. 2 shows three-dimensional FEM models for a 5, 7 and 9 cpd 1-3 composite rings. As the composite has been splitted into a number of PZT pillars, a modal analysis would give all the possible resonance modes and hence result in numerous unwanted modes to be simulated. However, most of the resonance modes from a modal analysis may not be excited electrically. In view of that, a harmonic analysis was used instead. The composite models were driven by a voltage signal and the electrical impedance responses were simulated in the frequency domain. The simulated results were compared with the measurement by an HP4194A impedance analyzer in Fig. 3. Theoretically, for an ideal 1-3 composite ring, all the PZT pillars will vibrate in their thickness direction. A single and clean resonance peak can be observed in the frequency domain. From the experimental results, the composite ring with 5 cpd has many spurious modes. It indicated that the L/T ratio of 5 cpd composite ring is too large and cannot be treated as a homogenous media. For 7 or higher cpd composite rings, a single resonance was identified at around 700 kHz which was the thickness mode resonance frequency of its PZT pillars. Other planar or radial resonances were greatly suppressed. Similar phenomena can also be found from the FEM analysis. Many spurious modes have been excited in the electrical impedance spectrum of a 5 cpd composite ring. For higher cpd, a single resonance mode could be detected. The minimum number of cuts for making a homogenous 1-3 composite ring for above-mentioned dimensions was found to be 7. To minimize the manufacturing costs and maximize the PZT volume fraction, the desirable composite should has 7 cpd and a PZT volume fraction of 0.91.

To examine the vibration mode shape of the 1-3 composite rings, the thickness vibration contour have been plotted

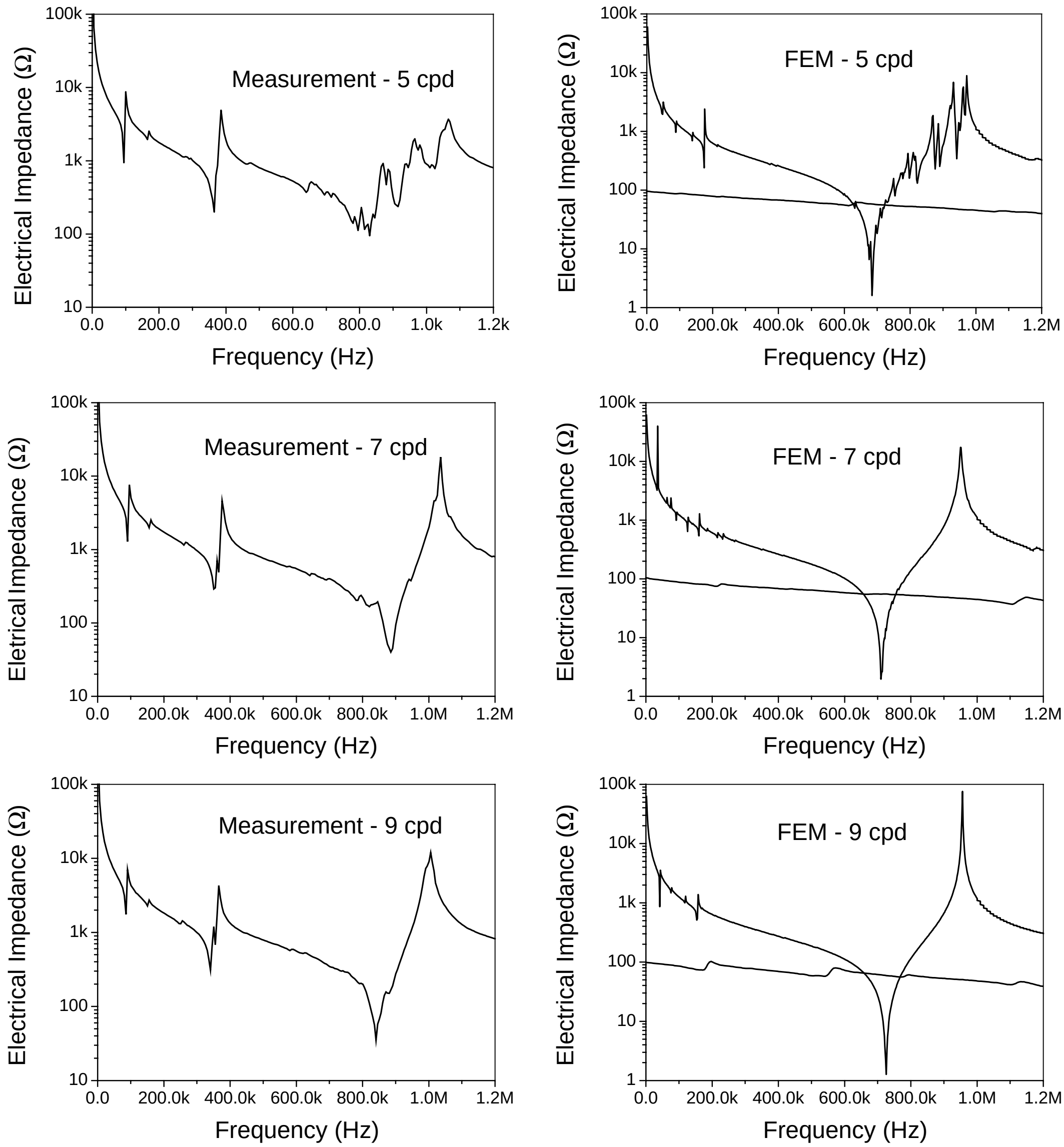

Fig. 3. Impedance vs. frequency spectrum for composite rings with 5 cpd ($\phi = 0.93$), 7 cpd ($\phi = 0.91$) and 9 cpd ($\phi = 0.88$).

in Fig. 4. For the 5 cpd composite ring shown in Fig. 4a, due to the large L/T ratio (0.99), each PZT pillars has its own vibration characteristics. Hence, the whole ring was not purely vibrating in its thickness direction. Other planar and radial modes have been coupled together. When the composite rings were used in devices such as a Langevin transducer for wirebonding, those planar and radial modes will excite other unwanted resonances as bending and torsional modes. For 7 cpd composite rings (Fig. 4b), all the PZT pillars were moving in the thickness direction. Due the difference in pillars geometry and boundary conditions, each pillar may have different vibration amplitude. However, the vibration amplitude within individual pillar was found to be quite uniform. Furthermore, each pillar was moving in the same direction with negligible planar or radial activities. These properties were essential for the composite to reduce and suppress undesirable resonances in devices such as a wirebonding transducer. For composite ring with even higher cpd as shown in Fig. 4c, the PZT pillars is moving uniformly in the same direction despite some with different amplitude. It is due to the fact that those PZT pillars on the periphery have different boundary conditions and pillar geometries.

4. Experimental verification

To verify the simulated mode shape experimentally, a Polytec laser vibrometer was used to scan the out-plane displacement of the major surface alone the radial direction of a PZT ring and a 7 cpd composite ring. Both samples were driven at the same input electrical power of 1 W. The scanning results were plotted in Fig. 5. The vibration profile of both the PZT ring and 7 cpd composite were similar. However, the vibration amplitude in the PZT ring was highly

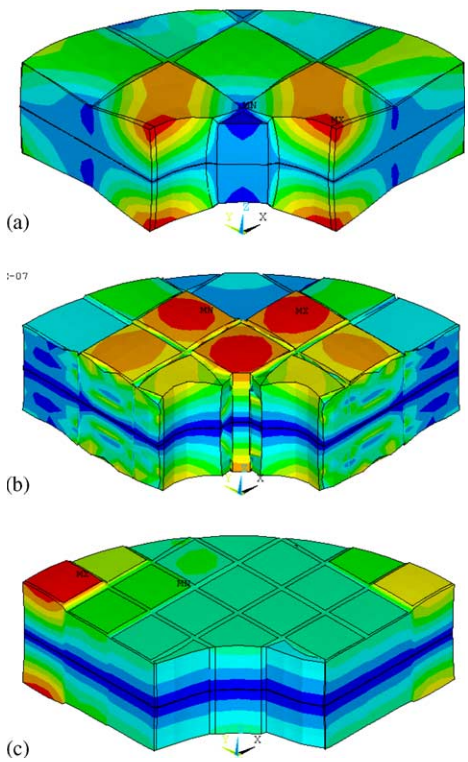

Fig. 4. FEM displacement contour in the thickness direction for a (a) 5 cpd, (b) 7 cpd and (c) 9 cpd composite rings.

non-uniform. Maximum peaks and nodal points co-existed along the scanning path. On the contrary, for a 7 cpd composite, the vibration profile was much flatter and uniform. No sharp nodal point was found on the scanning path. The maximum difference in vibration amplitude was found to be around 10 nm. It is approximately three times less than that of a PZT ring. Hence, the major surface of the composite was moving in a more uniform way. The uniformity of the thickness vibration causes the composite ring to reduce and suppress lateral and radial modes of a device. It also helps to reduce the mode coupling effect on the thickness mode for composite devices. In the case of a wirebonding transducer, the use of composite rings can reduce others unwanted lateral vibrations and retain a purer one direction axial resonance mode. It will promote the application of fine-pitch and high-speed bonding in the wirebonding process.

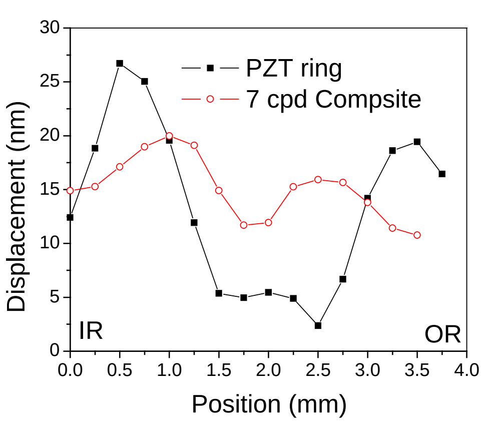

Fig. 5. Laser scanning profile of PZT and 7 cpd composite ring (IR: inner radius; OR: outer radius of the ring).

5. Conclusion

FEM analysis on PZT/epoxy 1-3 composite rings fabricated by the dic-and-fill technique has been reported. The 7 cpd ($\phi = 0.91$) composite ring was found to behavior as a homogenous media. With 7 cpd, we can maximize the PZT volume fraction and minimize the manufacturing cost. Both FEM and experimental results show that the 1-3 composite rings give uniform thickness vibration mode. It help to reduce mode coupling effect and suppress unwanted lateral vibration modes for devices such as wirebonding transducer.

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