Analyze the vibration mode of 1-3-2 Piezoelectric Composite

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ABSTRACT

Based on finite element analysis method, harmonic analyses with infinite and finite boundary conditions have been performed to investigation the vibration mode of 1-3-2 piezoelectric composite. This method has been checked by the experimental data of 1-3-2 PZT5A/Polymer-618 piezoelectric composites. The admittance curves of samples have been calculated under different boundary conditions. The calculation shows that finite element analysis with infinite boundary condition can be used to simulate the thickness mode, and the error is less than 1.5%. But it is incapable of simulation the interferential vibration mode accrued near to the thickness vibration frequency. To avoid non-considering of periodicity and boundary condition in conventional FEA method, limited elements have been used in FEA model to simulate periodicity and boundary condition. Finite element analysis with finite boundary condition is a substitute way to simulate the high order of lamb mode. The 8th order of lamb mode and the thickness mode have been simulated under finite boundary. It shows a good match between the simulation results and the test results by using laser scanning vibrometer while element number equals to 64 or the width/thickness of model is larger than 2.

Keywords: piezoelectric composite; finite element analysis; vibration mode; resonance frequencies

1. INTRODUCTION

1-3 piezoelectric composite has been widely researched and used in medical ultrasound imaging, non-destructive evaluation and underwater transducer for the advantages on their high electromechanical coupling factor, low acoustic impedance, low-density and capability to be shaped on curved surfaces[1-5]. But the mechanical and the temperature characteristics is not good enough[6], because the PZT rods are separated by epoxy resin completely. Meanwhile the PZT rod and the epoxy resin will with the rise of the environment temperature. And these two kinds of components in piezoelectric composite have different thermal dilatability, which can directly change the periodicity of the composite. This is one of the reasons for the frequency shift phenomenon of the composite.

1-3-2 piezoelectric composite[7, 8] composed of piezoelectric ceramic plate and 1-3 composite in structure, is a novel composite. And it increases stability of composite due to the PZT plate, which takes the place of the stiff glass fibers in M. J. Haun's design[9].

Finite-element analysis (FEA) is a very efficient tool to deal with classical 2D or 3D periodic problems[10-12]. A periodic composite structure may be divided into elements, which are distributed symmetrically in composite. The composite may be analyzed using elements. The resonance frequency of composite has been simulated by using different numbers of elements (for n=1, 4, 16, 25, 36, 49, 64) in this paper.

A laser-scanning vibrometer can be used for measuring even the smallest motions of the active area of ultrasonic transducers[13]. By analyzing these motions the vibration mode can be distinguished.

2. STRUCTURE AND FABRICATION OF 1-3-2 COMPOSITE

1-3-2 piezoelectric composite, as shown in Figure 1, is composed of up electrode, 1-3 piezoelectric composite, piezoelectric base and down electrode. The piezoelectric rods array is connected with the base as a whole. Epoxy was filled into grooves of the framework and extracted air-bubble. After the epoxy had cured, roughcasts were formed.

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Shaping the roughcasts and coating electrode, we got the composite. Hard PZT forms support at both transverse and longitudinal directions in 1-3-2 composite, which makes the structure more stable than 1-3 composite[7].

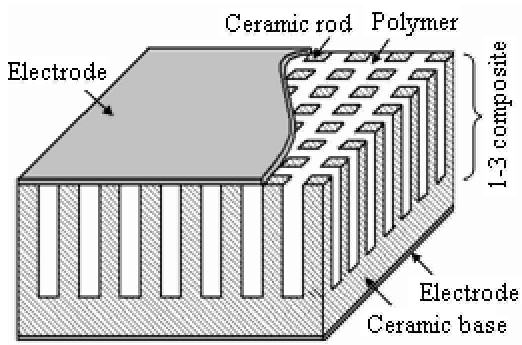

Fig. 1. 1-3-2 piezoelectric composite configuration

3. FEA MODELING

The commercial FEA package ANSYS® is used to model 1-3-2 structure. It is a very efficient tool to deal with classical 2D or 3D periodic problems. A periodic composite structure shown as Fig. 2 may be divided into units. These units are distributed symmetrically in composite. So the composite can be analyzed using these units. The 3D models are built by SOLID5 and SOLID45 elements, which described the PZT and the epoxy resin, respectively. Different voltages are applied on the nodes of the bottom and top planes to simulate the open circuit electrical boundary. Composite with a symmetry structure is modeled by one quarter of a unit. The model of 1-3-2 piezoelectric composite consists of 1/4 PZT rods and the surrounding polymer matrix as shown in Fig. 3. By defining all the four sides of these 1/4 units as symmetric areas, the whole composite with infinite units is simulated. This is a widely used method which didn't take into account the influence of the neighbor units and the influence of the position of unit. Considering this condition, a simple approach that increasing the number of finite units has been present. By defining two intersecting sides of these 1/4 units as symmetric areas, the whole of a unit is simulated. The rest may be deduced by analogy that models with 4/4, 9/4, 16/4, 25/4, 36/4, 49/4, 64/4 units can be used to simplify the simulation of samples with 4, 9, 16, 25, 36, 49, 64 units. The model with 36/4 units has been shown in Fig. 4, it can be used to simulated sample with 36 units by defining two intersecting sides as symmetric areas. This kind of model has limited units, so units can be divided into inside units, side units and corner units by their positions.

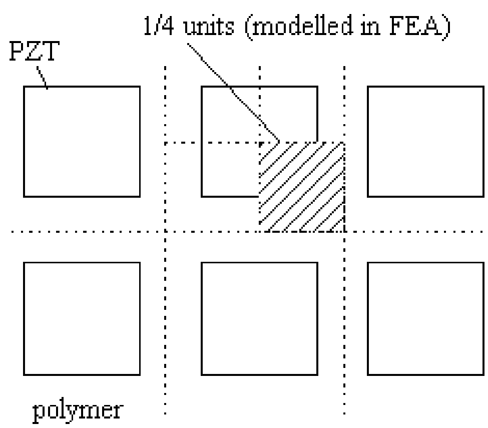

Fig. 2. Units of 1-3-2 piezoelectric composite

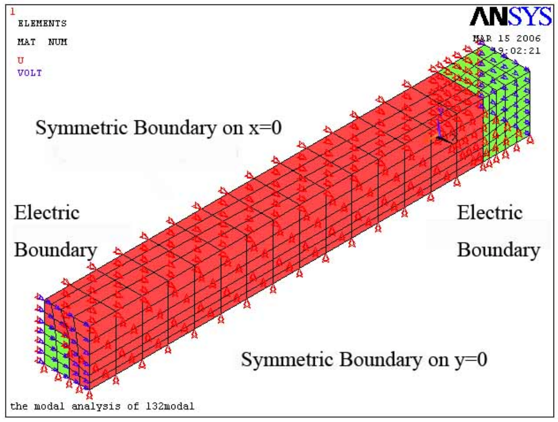

Fig. 3. Mesh model of 1-3-2 piezoelectric composite for n=1

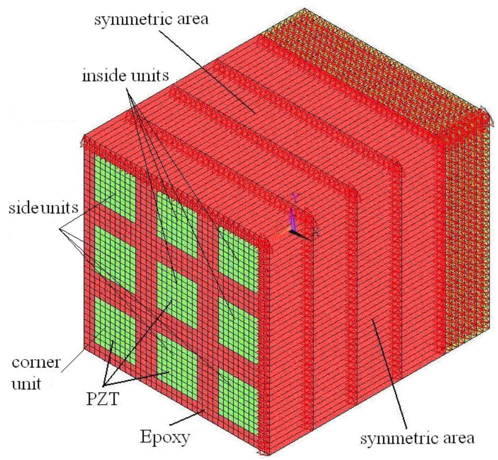

Fig. 4. Mesh model of 1-3-2 piezoelectric composite for n=36

Modal analysis is widely used to find the resonance frequencies of sample out, but it is not easy to identify the thickness mode when the model of sample is complicated, because there are lots of vibration modes. Resonance frequencies can be found out by analyzing the peaks appeared in admittance curve.

Theoretical electrical input admittance Y vs. frequency pattern of a sample has been performed. Electrical input admittance Y was also been calculated as I/V, where I is the current and V is the applied potential. The current I is related to the accumulated charge on the electrode surface as $I = j\omega\Sigma Q_i$, where ω is the operating frequency, ΣQ_i is the summed nodal charge. A series of calculations are made between 200 kHz and 350 kHz in post processing, which span the resonance frequency.

One sample with 46% volume fraction of PZT5 has been chose for both infinite and finite calculation.

4. RESULTS OF FEA SIMULATION

4.1 Harmonic Analysis with infinite boundary condition

Harmonic Analysis with infinite boundary was performed. Electrical input admittance Y of a sample which has a 46% volume fraction of PZT-5 was calculated and shown in Fig. 5. The piezoelectric composite's height is 5mm, and the composite is a square having sides of 25mm×25mm. The width of PZT rod is 0.96mm and the width of Epoxy between two PZT rods is 0.44mm. There are 18×18 units in the composite. The calculation results show only one peak in each curve between 200 kHz and 350 kHz. And all these peaks appeared near to 260 kHz which matched the experimental result 264 kHz very well. The error is 1.5%. The experimental data shows three peaks in this frequency range, and the second one is thickness mode, which can be simulated by harmonic analysis with infinite boundary conditions. But the other two vibration mode can not be presented in this simulation. So analysis with finite boundary is necessary.

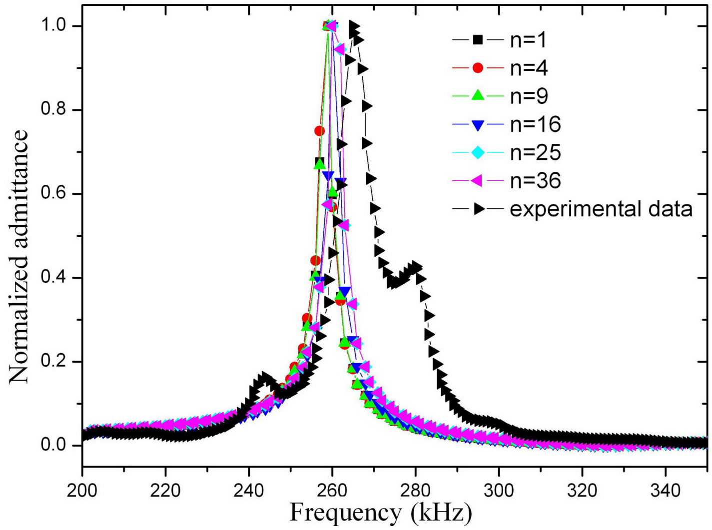

Fig. 5. Admittance curves with different units under infinite boundary condition

All those FEA calculation results with infinite boundary conditions figure only one mode out. This mode can be identified as thickness mode by analyzing the strain of sample as shown in Fig. 6. In the figure, black solid lines represent the undeformed shape of sample model. The PZT rods shown as darkish zone deform in thickness direction, and the epoxy shown as fuscous zone are forced to deform in the thickness direction. It is the characteristic of thickness vibration mode.

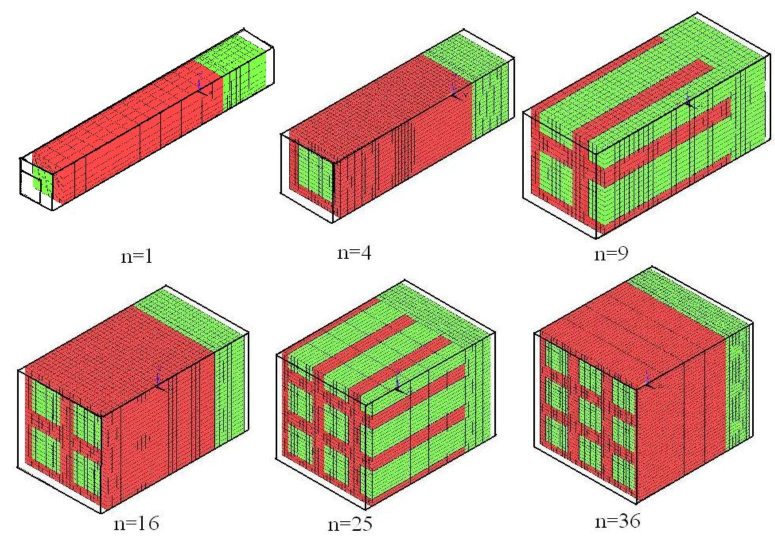

Fig. 6. Vibration modes with different units under infinite boundary condition

4.2 Harmonic Analysis with finite boundary condition

Harmonic Analysis with finite boundary condition was performed to study the influence of neighboring units and the influence of boundary effect. The dimensions of sample are the same as using in infinite calculation. In Fig. 7(a), a comparison between n=1, 4 has been performed. Only one peak appears in the curve n=1. That is because when n=1, sample has only one unit. It can be seen as a long rod, whose vibration mode is quiet pure. Comparing with Fig. 5, it is notable that the frequency is much lower than the thickness vibration frequency under infinite boundary. This kind of vibration can be seen as length extension vibration mode. There are two peaks appeared in curve n=4. One is the same as appeared in cure n=1, the other one is the first-order vibration in width direction as the width of model is 1.4mm. The admittance curves shown in Fig. 7(b) and (c), are much complicated than the situations in Fig. 7(a). The resonance frequency where the maximum peak appeared gets lower while increasing the number of units from 9 to 36. In this case, the ratio of width /thickness is between 0.84 and 1.68, which indicates the model has a figure of cube. There are much more complicated vibration modes than long rod and laminate plate. Most vibration modes calculated in these conditions are caused by the width of model. These modes wouldn't happen in the real sample in these frequencies at all. So models with number of units fewer than 36 can not be used to simulate the vibration of sample with 324 units. Admittance curves with 36 and 64 units have stronger vibration peaks approaching to the experimental results 264 kHz. Evidently, the curve with 64 units matches the experimental data very well in the range near to the thickness vibration. The thickness vibration frequency calculated by FEA is 269 kHz, and the error is less than 1.5%. The ratio of width /thickness is up to 2.24 while n=64, in which the model can be seen as a plate. The more width /thickness are closing to the real one, the more accurate the simulation has.

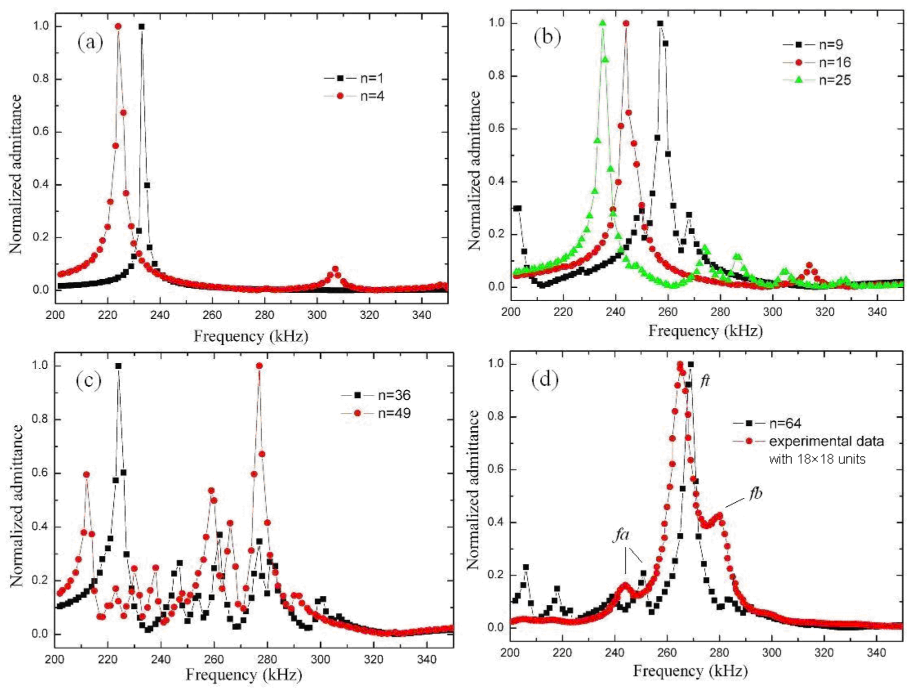

Fig. 7. Admittance curves with different units under finite boundary. (a), (b), (c) and (d) respectively, patterned the real part of admittance which has been normalized, when n=1, 4, 9, 16, 25, 36, 49, 64 and the experimental results of a sample which has 18×18 units.

The first vibration mode named as f_a in Fig. 7(d), has been checked by laser scanning vibrometer. Fig. 8(a) shows the surface vibration velocity distribution measured by laser scanning vibrometer at 245 kHz. These two views show the maximum and minimum velocity phases which can be used to confirm the vibration mode of sample. Sample has a 25mm×25mm surface and 18×18 units. In each side, there are four wave lengths. It is the 8^{th} order of width vibration mode. For the simulated results shown in Fig. 8(b), this model has a 5.6 mm side which is near to a quarter of 25 mm. In each side of this surface, there is one wave length. The simulation results and experimental data match very well both at the vibration frequency and the surface transmutation.

The second vibration mode named as f_t in Fig. 7(d), has also been checked by laser scanning vibrometer. The surface transmutations of the 1-3-2 composite and the model used to simulate composite at ft mode shown in Fig. 9. The surface vibration velocity distribution shown that surface points vibrating at the same phase. It can be distinguished as thickness mode. Vibration mode with n=64 under finite boundary condition shown in Fig.9(b) is a traditional thickness mode, as all the points in the upper surface vibrating in z direction and the thickness of mode flex in z direction.

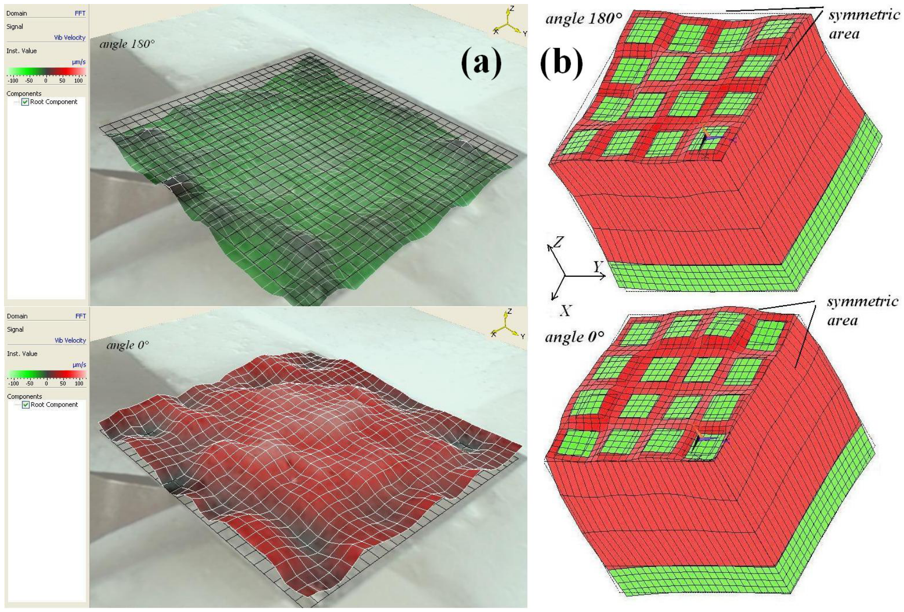

Fig. 8. Calculated and measured surface transmutation of the 1-3-2 composite at *f*a mode. (a) Surface vibration velocity distribution measured by laser scanning vibrometer at 245 kHz; (b) Vibration mode with n=64 under finite boundary at 251 kHz.

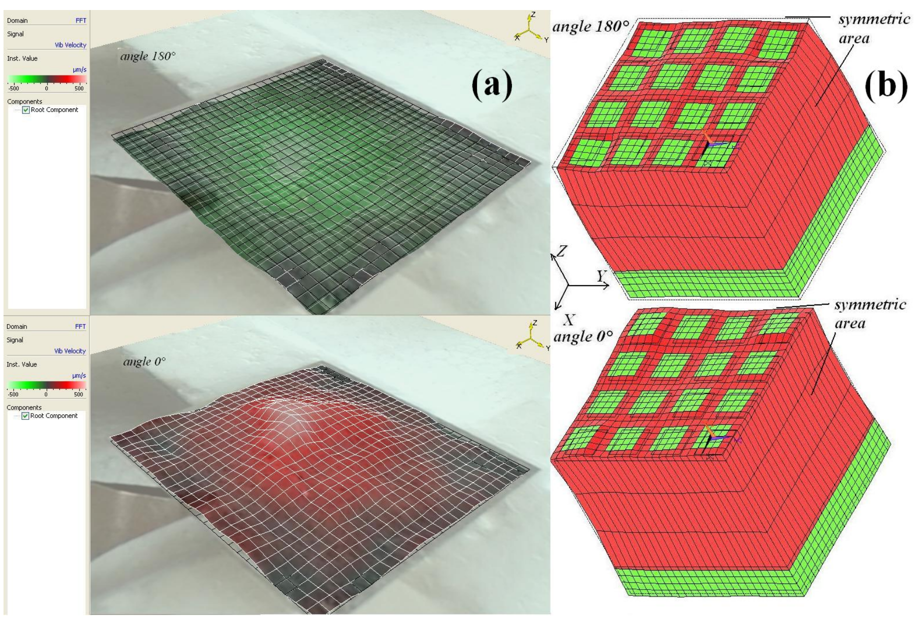

Fig. 9. Calculated and measured surface transmutation of the 1-3-2 composite at *f*t mode. (a) Surface vibration velocity distribution measured by laser scanning vibrometer at 264 kHz; (b) Vibration mode with n=64 under finite boundary at 269 kHz.

The third vibration mode f_b appeared in Fig. 7(d) can not be simulated by this model for now. This vibration mode always couple with the thickness mode, which can be used to broaden the bandwidth of piezoelectric composite. So authors will investigate this kind of vibration mode in the next work.

5. CONCLUSION

Based on finite element analysis method, harmonic analyses with infinite boundary conditions and finite boundary conditions have been performed to simulate the vibration of 1-3-2 piezoelectric composite. And the admittance curves have been calculated under different boundary conditions. The calculation shows that finite element analysis with infinite boundary condition can be used to simulate the thickness mode, and the error is less than 1.5%. But it is useless to simulate the interferential vibration mode accrued near to the thickness vibration frequency. Finite element analysis with finite boundary condition is a substitute way to simulate the high order of width vibration. The 8^{th} order of width vibration mode and the thickness mode have been simulated under finite boundary condition. The comparison shows that the calculations agree with the experimental measurements while n=64 or the width/thickness of model is more than 2. This method is useful to optimize the properties of the composite, especially in designing bandwidth piezoelectric transducer. It also can be used to study the crosstalk phenomena and the influence of position of unit on the vibration form. These will be the next works.

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