# NUMERICAL SIMULATION OF ULTRASONIC WAVE PROPAGATION IN FIBER-ENHANCED DIELECTRIC NANOCOMPOSITES FOR QUALITY INSPECTION

J. Wu[1*], Y. Lin[2], B. Tseng[1]
[1] Department of Industrial, Manufacturing and Systems Engineering, University of Texas at El Paso, El Paso, TX 79968, USA;
[2] Department of Mechanical Engineering, University of Texas at El Paso, TX 79968, USA;
* Corresponding author (jwu2@utep.edu)

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## ABSTRACT

The dielectric nanocomposites where ceramic fibers are mixed in polymer matrix could achieve significantly higher energy density when used in dielectric capacitors. The alignment of these fibers in the polymer matrix have significant influence on the final dielectric properties. This paper investigates the feasibility of utilizing ultrasonic testing to inspect the aligning quality of ceramic fibers through microstructure modeling and wave propagation simulation. The results indicate that the ultrasonic testing has great potential as an NDE tool to inspect the quality of dielectric nanocomposites.

## 1 Introduction

With an increasing demand on energy storing capabilities, more and more research scientists are focusing on the development of capacitors of high energy density [1]. Dielectric capacitors are most commonly used for their excellent dielectric properties, easy accessibility and low cost. The traditional dielectric materials include polymer and ceramics. Compared with polymer-based capacitors, ceramic-based capacitors have higher relative dielectric permittivity. However, their high dielectric permittivity is at the cost of lower break-down strength, which limits their energy density and performance. To mitigate this issue, many researchers are developing nanocomposites where ceramic fiber materials with higher relative dielectric permittivity are dispersed into polymer matrix that have higher breakdown strength [2, 3]. These nanocomposites could improve both the dielectric permittivity and break-down strength of capacitors, thus achieving a higher energy density.

It is found that the alignment of ceramic fibers could significantly influence the dielectric properties [4]. Well-aligned high aspect ratio fibers with the same orientation could increase both permittivity and breakdown strength. The alignment of fibers in polymer matrix has been achieved by many methods, such as extrusion methods [5], and uniaxial stretching assembly [2]. To facilitate a scale-up production, a fast-yet-effective quality inspection technique is critically important to ensure the quality of fiber alignment. The standard method is through microscopic images, which are time-consuming and costly to obtain. Ultrasonic testing is one of the most popular nondestructive evaluation techniques and has been widely used in thickness measurement, flaw detection and microstructure characterization [6, 7]. This paper investigates the feasibility of using ultrasonic nondestructive testing method to inspect the alignment of lead zirconate titanate (PZT) in polyvinylindene fluoride (PVDF) matrix through microstructure modelling and ultrasonic wave propagation approach. The rest of this paper is organized as follows. Section 2 introduces the microstructure modeling and wave propagation approach. Section 3 presents the simulation results and conclusion.

## 2 Microstructure Modeling and Wave Propagation Simulation

### 2.1 Microstructure Modeling

The microstructures of size $0.8\text{mm} \times 0.8\text{mm}$ are generated for wave simulation. In the microstructure modeling, the fiber alignment is evaluated by the variance $\sigma^2$ of its orientation angle $\theta$, the angle between the wave propagation direction and the fibers. For example, for the perfect alignment, $\theta = 90°$ or $\theta \sim N(90, \sigma^2 = 0)$; for well-alignment, $\theta \sim N(90, \sigma^2)$ where $\sigma^2$ is a small value; if there is no specific orientation, the $\theta$ of all fibers are totally random with $\theta \sim \text{Uniform}(0°, 360°)$. The PZT fiber length and width are set to be 50 $\mu m$ and 4 $\mu m$ respectively. The PZT fiber are uniformly distributed in the PVDF matrix following complete spatial randomness (CSR). Each pixel of the generated microstructural image is set to be $\Delta x = 1\ \mu m$, which is the spatial step size in wave propagation simulation. The volume fraction of the fibers is set to be about 5%. Three simulated nanocomposites are illustrated in Fig. 1.

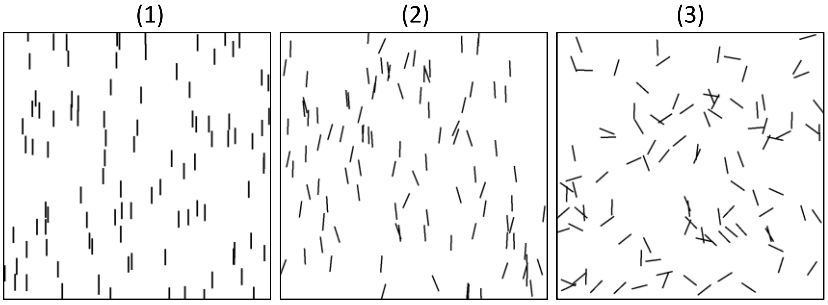

Fig. 1. Three generated nanocomposites of different fiber alignment: (1) perfect alignment; (2) $\theta \sim N(90, 10^2)$; (3) totally random.

### 2.2 Wave Propagation Simulation

Table 1. Acoustic parameters of PZT and PVDF used in the simulation [8].

| | Density (g/mm3) | Normal velocity(m/s) | Shear velocity(m/s) |
|---|---|---|---|
| PZT | 0.0076 | 4410 | 2630 |
| PVDF | 0.00178 | 2200 | 775 |

The elastodynamic finite integration technique [9] is used to simulate the wave propagation process. The transducer with size of 0.6 mm and central frequency of 20MHz is attached to the left side of the nanocomposites to generate ultrasonic pulses. The boundary condition is set to be absorptive on the left, top and bottom side, and reflective on the right side. The time step is set to be $\Delta t = 1.6 \times 10^{-4} \mu s$. The acoustic parameters of PZT and PVDF is shown in Table **1**. The snapshots of the wave propagation process for $\theta = 90°$ are illustrated in Fig. 2.

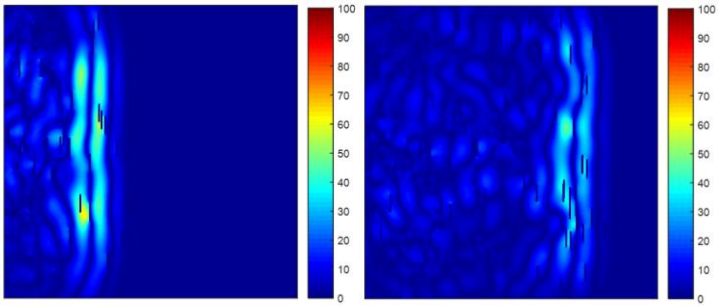

Fig. 2. Snapshots of wave propagation process at $t = 0.16\ \mu s$ (left) and $t = 0.32\ \mu s$ (right)

### 2.3 Ultrasonic Attenuation Calculation

Ultrasonic attenuation is one of the most commonly used ultrasonic parameters for material characterization. It refers to the decaying rate of the acoustic wave as it propagates through materials. It contains rich information about the microstructures and can be used to infer the fill alignment. The ultrasonic attenuation (dB/mm) is calculated using the spectral ratio analysis technique [6] as:

$$A(f) = \frac{1}{2d} \ln \left| \frac{S_1(f)}{S_2(f)} \right| \tag{1}$$

where $A$ is the attenuation, $d$ is the thickness of the specimen, $s_1$ and $s_2$ are the frequency spectrum of the initial pulse and the first echo respectively. For each type of microstructures, simulation is repeated 40 times to account for the randomness.

## 3 Results and Conclusion

Fig. 3 shows the ultrasonic attenuation as a function frequency under four fiber orientation conditions. For the fourth case, $\theta = 0°$, which means the ultrasonic wave propagates along the direction parallel to the perfect aligned fibers. From the attenuation curves we can see that when the ultrasonic wave propagates along the path perpendicular to perfectly aligned fibers, the ultrasonic energy has the lowest loss. In contrast, when the wave path is parallel to these perfectly aligned fibers, the wave energy reach the highest level. The energy losses of the other two cases are between these two mentioned ones. The energy loss for the uniform case is higher than that when $\theta \sim N(90, 10^2)$. Based on these curves, we found that the more fibers perpendicular to the wave path, the lower the energy scattering loss. The more fibers parallel to the wave path, the higher the energy scattering loss. This finding could be used to develop ultrasonic testing based quality evaluation techniques to evaluate the fiber aligning quality in dielectric nanocomposites manufacturing. In our future work, experimental study will be conducted to evaluate the ultrasonic testing method.

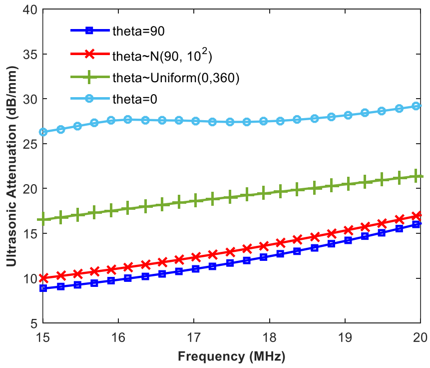

Fig. 3. Ultrasonic attenuation as a function of frequency under four fiber orientation conditions.

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