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PVDF interdigitated transducer for generating and detecting Lamb waves in plates

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Abstract. Piezoelectric materials have been widely used in ultrasonic nondestructive testing (NDT). PZT ceramics can be used to receive and generate surface acoustic waves. It is a common application to attach PZT transducers to the surface of structures for detecting cracks in nondestructive testing. However, not until recently have piezoelectric polymers attracted more and more attention to be the material for interdigitated (IDT) surface and guided-wave transducers. In this paper, an interdigitated gold-on-polyvinylidene fluoride (PVDF) transducer for actuating and sensing Lamb waves has been introduced. A specific etching technology is employed for making the surface electrodes into a certain finger pattern, the spacings of which yield different single mode responses of Lamb waves. Experiments have been performed on steel and carbon fiber composite plates. Results from PVDF IDT sensors have been compared with those from PZT transducers for verification.

Keywords: surface acoustic waves; PZT transducer; gold-on-PVDF transducer.

1. Introduction

Since the recognition of the advantages of using Lamb waves in nondestructive testing (NDT), Lamb waves and other guided waves have attracted more and more attention nowadays. As Alleyne and Cawley (1992) have mentioned that conventional ultrasonic inspection of large structures is very time-consuming because the transducer needs to be scanned over each point of the structure that must be tested. Unlike waves used in conventional ultrasonic inspection, such as bulk longitudinal and shear waves, which propagate in the region of structure immediately around the transmitting transducer, Lamb waves can propagate over a long distance. If a receiving transducer is positioned at a remote

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point on the structure, the received signal contains information about the integrity of the line between the transmitting and receiving transducers. The test therefore monitors a line rather than a point and considerable savings in testing time may potentially be obtained. This probably gives rise to those "smart structures", where the implementation of transducers over the entire structure is impossible and sensors are located a certain distance away. However, the received Lamb wave signals are usually complex due to the fact that at least two Lamb wave modes can propagate at a given frequency. As a result, to design a transducer, which is capable of producing a single mode signal has become a thought provoking topic in this field.

The generation and reception of Lamb wave can be realized by matching transducers. Monkhouse, *et al.* (2000) has proposed that the challenge in developing a "smart structure' based inspection system is to design permanently attached sensors which will send a particular Lamb mode or modes along the structure in controlled directions and to receive the resulting signals at the same transducer and/or other receivers. One of the most commonly used ones is angles piezoelectric transducer in which the wavenumber bandwidth is determined by the size of the transducer and its angle to the structure surface. Another widely used one is the electro magnetic acoustic transducer. Unfortunately, these sensors are usually bulky and inappropriate for being integrated into a structure.

Being a competitive alternative, sensors based on the techniques analogous to those employed in surface acoustic wave (SAW) devices in the electronic industry have drawn a lot of people's interest. In these devices, electrodes with comb or finger pattern are mounted on the surface of a piezoelectric material. A common application is to put an interdigital electrode, also called interdigital transducer (IDT), on the surface of PZT. Limited by its bandwidth and the rigidity of the material, PZT materials are not widely applicable; Polyvinylidene fluoride (PVDF) film, however, envisioned itself to be a suitable substrate for surface and guided wave transducers which are required to couple electrical energy into the piezoelectric material and to detect the wave, due to the facts that it has a broad bandwidth, a lower price, and it's thin and flexible, so that it can be bended and attached to almost all kinds of substrates. Besides, the metal coatings of PVDF film can be etched by certain chemicals to be made into many desired electrode patterns. Some researchers have employed PVDF films as substrates attached to a thin copper layer with finger pattern interdigitated electrodes. Monkhouse, *et al*. (1997) have built interdigital PVDF transducers and their experiments have shown that these transducers can be successfully used to excite and receive Lamb waves. Their transducers can be operated over the frequency range 0.5 to 4 MHz, modes being strongly excited when the wavelength at which the transducer is designed to operate and the excitation frequency applied correspond to a point on the dispersion curves. Hey and Rose (2002) have developed a comb PVDF transducer and have conducted experiments on pipes. Results showed that these comb transducers successfully excited and received surface acoustic waves close to their maximum group velocities. However, both Monkhouse and Hey and Rose have used PVDF simply as a substrate of the transducer. There is another layer of electrodes, usually made of copper, either being bonded or being clamped on top of the PVDF substrate. This not only increases the complicity of the transducer structure, but also brings up sensor delamination as a potential problem especially when dealing with civil structures with uneven surfaces. Besides providing the sensor with interdigital electrodes, the metal layer also improves the low frequency performance of the transducer. The increase in the operating frequency leads to more complex wave problems. Therefore, low frequencies are favorable in the scope of this study to keep the received signal as simple as possible. Since gold has larger density and conductivity than copper, better performance at low frequencies is expected from this monolithic gold-on PVDF sensor. Not many experimental results have been reported on these interdigitated transducers, which may partially be due to the difficulty of producing reproducible results with “handmade” transducers, and a lack of research on coupling efficiencies of these gages to different modes at disparate operating points.

In this study, the development and proof-of-principle testing of a monolithic interdigitated PVDF transducer, specifically the design and response of an interdigitated transducer with relatively large finger spacings are reported. The finger spacings yield measurable responses, which may be useful for nondestructive testing of many mechanical and civil structural systems. The results of PVDF as being active and passive IDT transducers are demonstrated. Furthermore, these PVDF sensors are also able to be integrated into wireless systems, which will tremendously lower the overall cost of a large scale monitoring and also make real-time monitoring realizable.

2. Waves in plates

Rose (1999), Viktorov (1967), J. Krautkraemer and H. Krautkraemer (1991) have all studied and introduced the theories of waves in plates. There are two major kinds of waves in solid media – guided waves and bulk waves. Bulk waves travel in the bulk of the material, hence, away from the boundaries. However, often there is interaction with boundaries by way of reflection and refraction, and mode conversion occurs between longitudinal and shear waves. Although bulk and guided waves are fundamentally different, they are actually governed by the same set of partial differential wave equations. Mathematically, the principal difference is that, for bulk waves, there are no boundary conditions that need to be satisfied by the proposed solution. In contrast, the solution to a guided wave problem must satisfy the governing equations as well as some physical boundary conditions.

It is the introduction of boundary conditions that makes the guided wave problem difficult to solve analytically. Additionally, unlike the finite number of modes that might be present in a bulk wave problem, there are generally an infinite number of modes associated with a given guided wave problem. Some examples of guided wave problems that have been solved are Rayleigh, Lamb, and Stonely waves. For plates, the propagation conditions have been described by Lamb (1904) and the waves are known as Lamb waves. They are waves of plane strain that occur in a free plate, and the traction force must vanish on the upper and lower surface of the plate.

The solution of the free plate problem can be derived in the following equations:

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{4k^2pq}{(q^2-k^2)^2}. \quad \text{for symmetric modes} \tag{1}$$

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{(q^2-k^2)^2}{4k^2pq}. \quad \text{for antisymmetric modes} \tag{2}$$

where $p^2 = \frac{\omega^2}{c_L^2} - k^2$ and $q^2 = \frac{\omega^2}{c_T^2} - k^2$

c_L is longitudinal wave velocity, c_T is shear wave velocity, ω is the circular frequency, and k is wave number. Eqs. (1) and (2) are functions of k and ω, where k can be complex numbers. When the imaginary part of k equals zero, waves propagate with no damping. Commonly, it is helpful to consider various regions of the above equations for k compared with ω/c_L or ω/c_T. These regions are $k > \omega/c_T$, $\omega/c_T > k > \omega/c_L$, and $k < \omega/c_L$.

For the symmetric modes, the wave structure across the thickness of the plate is symmetric for displacement u and antisymmetric for angular frequency ω, while for the antisymmetric modes, the wave structure across the thickness is symmetric for ω and hence antisymmetric for u.

Eqs. (1) and (2) are known as the Rayleigh-Lamb frequency relations, and they were first derived at the end of the nineteenth century. These equations can be used to determine the velocity at which a wave of a particular frequency (fh or fd product, where f is frequency, d is the thickness of the plate and h is half the thickness of the plate) will propagate within the plate. Equations of this nature are known as dispersion relations. Although the equations look simple, they can be solved only by numerical methods.

When plotting the dispersion curves, one is only interested in the real solutions of these equations in region $k < \omega/c_L$, which represent the (undamped) propagating modes of the structure. It is therefore useful to rewrite the above two equations so that they take on only real values for real or pure imaginary wavenumbers k. This is achieved by the following set of equations:

$$\frac{\tan(qh)}{q}+\frac{4k^2 p\tan(ph)}{(q^2-k^2)^2} = 0. \quad \text{for symmetric modess} \tag{3}$$

$$q\tan(qh)+\frac{(q^2-k^2)^2\tan(ph)}{4k^2 p} = 0. \quad \text{for antisymmetric modes} \tag{4}$$

Wave number $k = \frac{2\pi}{\lambda} = \frac{\omega}{c_p}$, where $\omega = 2\pi f$ and phase velocity $c_p = f\lambda$. λ is wavelength.

Group velocity is associated with the propagation velocity of a group of waves of similar frequency, also termed as "velocity of wave packets". After phase velocity is solved numerically, group velocity c_g can be found from the phase velocity c_p by using the formula $c_g = \frac{d\varpi}{dk}$. Substituting $k = \omega/c_p$ and using $\omega = 2\pi f$, the equation becomes:

$$c_g = d\omega\left[d\left(\frac{\omega}{c_p}\right)\right]^{-1} = d\omega\left[\frac{d\omega}{c_p}-\omega\frac{dc_p}{c_p^2}\right]^{-1} = c_p^2\left[c_p-\omega\frac{dc_p}{d\omega}\right]^{-1} = c_p^2\left[c_p-(fd)\frac{dc_p}{d(fd)}\right]^{-1} \tag{5}$$

where fd denotes frequency times thickness.

3. PVDF IDTs

Some basic construction and operation about IDTs made from the piezoelectric polymer PVDF have been studied by Wilcox, *et al.* (1998). PVDF has been selected and used due to some advanced features it has such as feasibility, flexibility, and low cost. PVDF has been used in compression wave ultrasonic transducers for some years and has also been used in arrays. Although the amplitude of the acoustic field from an IDT is affected by the materials and the construction of the IDT, which works as a drawback in the case of PVDF since it's relatively a weak piezoelectric material, the shape of the acoustic field is only affected by the IDT geometry. As stated by Monkhouse, *et al.*, there are a few reports of PVDF being used for interdigital transducers. Matiocco, *et al.* (1980) have generated and received Rayleigh waves on a duralumin substrate at a frequency of 7 MHz and Toda and Sawaguchi (1987) have produced a leaky Lamb wave transducer. Nasr, *et al.* (1988) have used polymer transducers

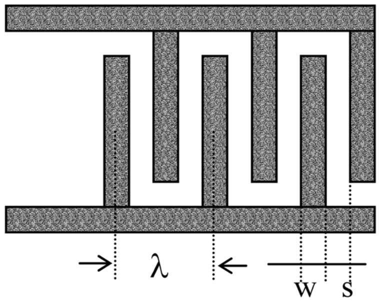

Fig. 1 Sketch of transducer electrodes

to generate and detect Scholte waves at a water-silica interface and Wagers (1979) has used interdigital PVDF transducers to generate a variety of wave modes in a silicon substrate.

Fig. 1 shows the schematic of a PVDF IDT with straight finger patterns. The electrode printed on the surface of PVDF consists of two sets of parallel strips. The spacing between the centers of adjacent fingers is made equal to half the wavelength of the Lamb wave mode. When the two sets of fingers are excited in anti-phase, a spatially harmonic stress distribution is set up on the surface of the plate beneath the transducer, the wavelength of which determines which Lamb wave mode is excited. A well-designed straight-finger IDT will generate a straight collimate beam of Lamb waves that exhibits minimal divergence and can therefore propagate reasonably long distances in a free plate. The width of each finger pattern is represented by "w" and in a likely manner, "s" represents the spacing between adjacent two finger patterns. A simple relationship between w, s and wavelength λ is: $\lambda = 2\ (w + s)$. For different requirements, different modes of waves can be activated by changing the finger pattern.

The monolithic interdigitated gage is fabricated by a gold-on-PVDF process. The finger pattern has been mounted on the gold electrode by using the photolithography technology. The rest of the electrodes have then been dissolved in the etchant.

4. Design and manufacturing process for PVDF transducer

PVDF transducers with different exciting wavelength have been designed. The computer software DISPERSE is employed for simulating the wave propagation in the sample steel plates. The plate has a length of 914.4 mm, width of 50.8 mm and a thickness of 6.35 mm. With all these parameters, the software solved for the numerical answers for Eqs. (3), (4) and (5). The simulation results are presented in Fig. 2 and Fig. 3.

Modes A_0, S_0, A_1, S_1, A_2, S_2, …… are depicted in the figures. "S" means the modes are symmetric and "A" means the modes are antisymmetric. The two fundamental modes, A_0 and S_0, propagate from zero frequency. The higher order modes are the modes that do not propagate at zero frequency. The numerical index that follows the S or A notation indicates the order of the modes in increasing frequency of their "cut-off" frequencies. The cut-off frequency of a mode is its low-frequency limit where the phase velocity tends to infinity; this relates to through-thickness resonance of the plate.

Those linear lines in the figures are design lines for transducer electrodes, also called activation lines. They hit the desired exiting mode and provide with essential design parameters. For example, to design a transducer to excite the A_0 mode at maximum group velocity to simplify experimental verification, the

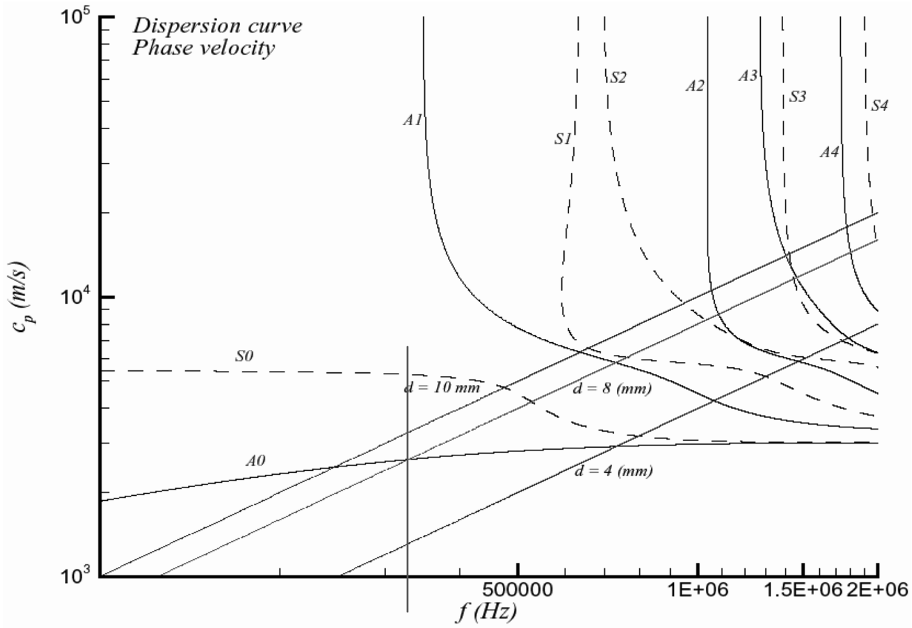

Fig. 2 Dispersion curve for steel plate (Phase velocity) (simulated by DISPERSE, Imperial College, UK)

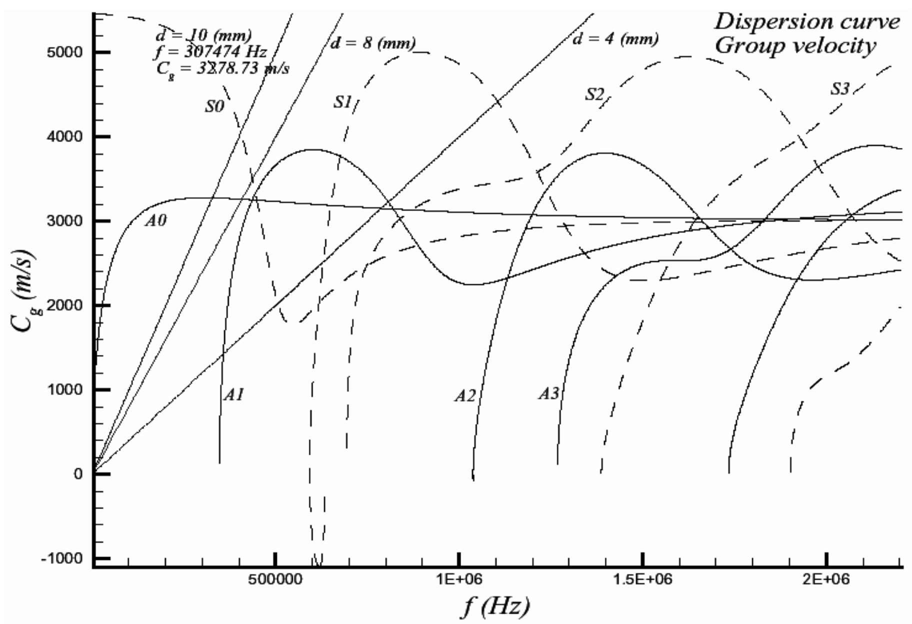

Fig. 3 Dispersion curve for steel plate (Group velocity) (simulated by DISPERSE, Imperial College, UK)

procedures are as follows. The dispersion curve shows the group velocity of A_0 reaches its maximum value at 3278.73 m/s. The corresponding frequency is 304249 Hz; On phase velocity diagram, a vertical line is drawn at frequency 304249 Hz, which intersects the line representing $A0$ mode at a point with a phase velocity of 2592.46 m/s. The slope of the line connecting this point and the original point gives

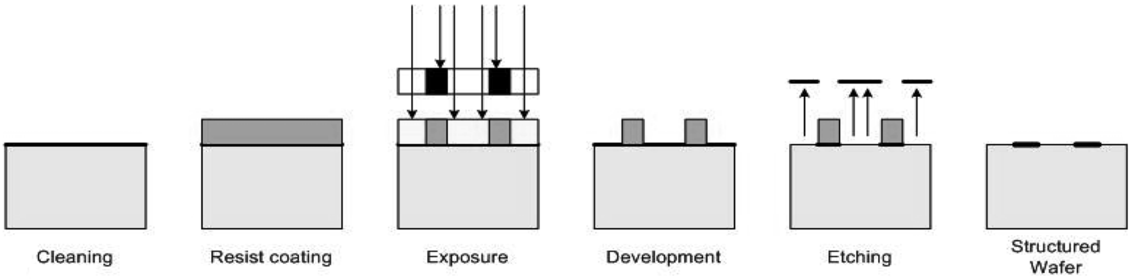

Fig. 4 Photolithography technology for building PVDF IDTs

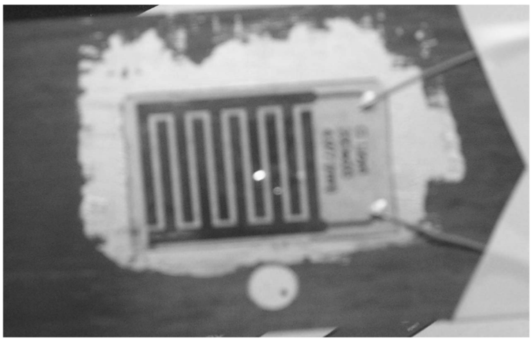

Fig. 5 Gold-on-PVDF IDT transducer

the wavelength λ, which can be calculated by equation $\lambda = \frac{v_{ph}}{f} = 8.52$ mm.

The fabrication of PVDF IDTs is realized by using the photolithography technology as indicated in Fig. 4. PVDF films with gold coating on one of the surfaces are acquired from manufacturer. After the surface is cleaned, a thin layer of photo resist is evenly spun on top of the gold coating. The finger pattern design is carefully printed out on transparencies and transferred to the photo resist layer through exposing under the strong light. After being developed, the pattern then stays on the film. The structured film is finalized by etching out the rest of the gold. A PVDF IDT transducer product is demonstrated in Fig. 5.

5. Experimental setup

Two sets of experiments have been conducted on two different materials. Set 1 was performed on plates of cold rolled 1018/A108 steel ($C = 0.158\%$, $Cr = 0.034\%$, $Ni = 0.22\%$, $Mn = 0.785\%$, $Al = 0.014\%$, $Mo = 0.003\%$, $P = 0.008\%$, $S = 0.003\%$, $Cu = 0.07\%$), with a Rockwell hardness of B84. The density is $\rho = 7.932$ (g/cm^3). The total length of the plates is 914.4 mm; the width and thickness are 50.8 mm and 6.35 mm, respectively. Two PVDF IDT gages with $\lambda = 4.977$ mm were attached to the steel plate surface by epoxy and were spaced $L = 825.5$ mm. Two PZT buttons (Navy II, thickness 0.40 mm, diameter 6.40 mm, $f_0 \sim 5$ MHz) were mounted at the same locations. The active transducer was driven by a tone burst sinusoidal signal (rectangular window). The response of the passive and active transducers was acquired by an oscilloscope. Set 2 was performed on plates of carbon fiber composite material with

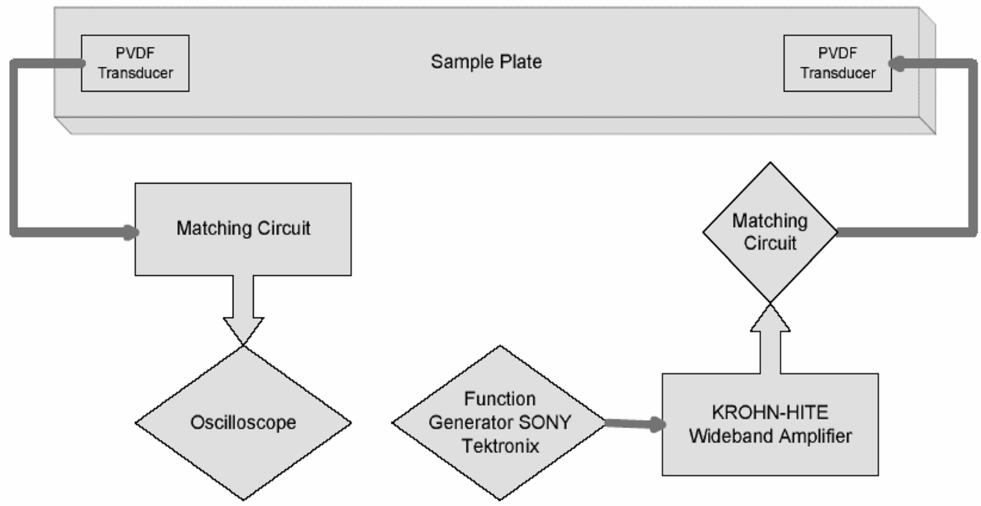

Fig. 6 Block diagram of the experimental setup

epoxy as matrix. Each of the sample plates is composed of 3 layers of the same carbon fiber composite plate with a thickness of 1.35 mm bounded by 2 layers of epoxy in between with a thickness of 0.085 mm. Each sample plate is of 914.4 mm long, 50.8 mm wide and 4.22 mm thick.

Fig. 6 illustrates the block diagram of the experiments. PVDF transducers are used as both exciter and receiver. Falling in the same category of piezoelectric materials, piezo ceramic material PZT is widely used in the application of surface acoustic waves and interdigitated PZT transducer technology is very well developed. Therefore, PZT buttons are also attached to the steel plate at a location right next to the PVDF transducers, so that results from PVDF sensors can be compared to results from PZT transducers. Signals with similar wave information, such as modes propagated and time-of-arrival of some modes, are expected to be acquired from both PZT transducers and PVDF IDTs.

6. Results and discussion

The capability of the PVDF IDT transducers as being both an active sensor and a passive sensor has been tested and results are discussed.

6.1. Experiments on steel plates

Tests have been done by using PVDF IDT as an active sensor. Lamb waves are generated by PVDF IDT transducer and received by PZT button. The results were compared with PZT gage and demonstrated in Fig. 7.

Fig. 7 shows that as an active sensor, PVDF IDT transducer can successfully generate Lamb waves. The results are similar to those from PZT gages.

Responses from PVDF IDT transducer as a passive transducer on steel plate at different frequencies have been observed. Fig. 8 illustrates the signals received by a PVDF transducer with $\lambda = 4.977$ mm at some selected frequencies.

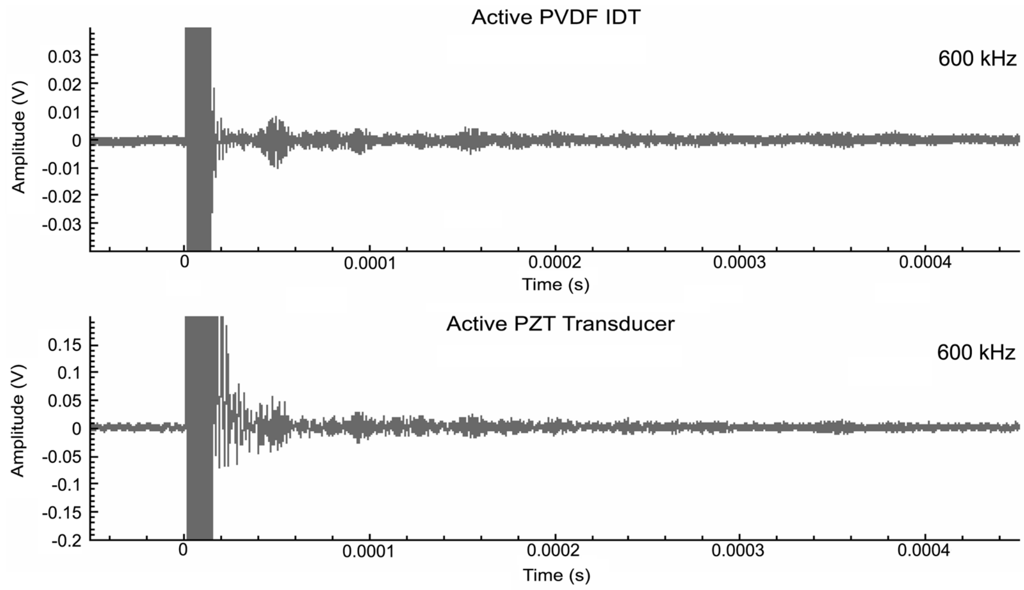

Fig. 7 Active PVDF IDT transducer

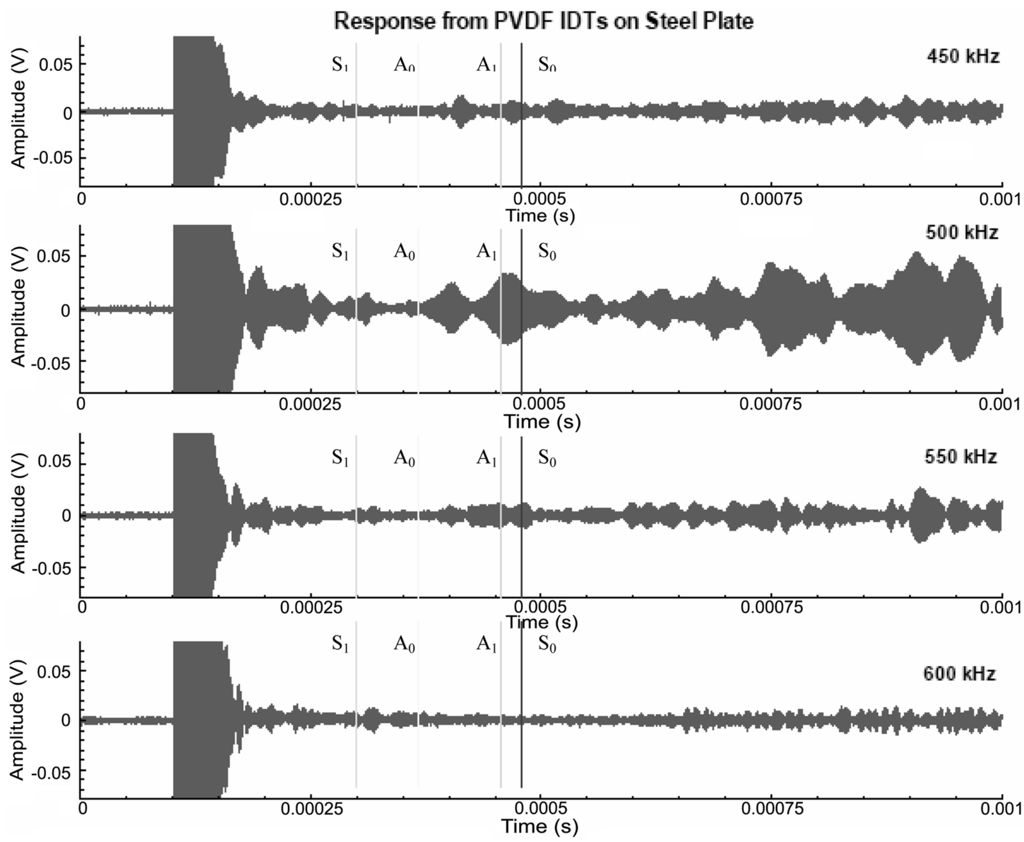

Fig. 8 Response from PVDF IDTs at different frequencies

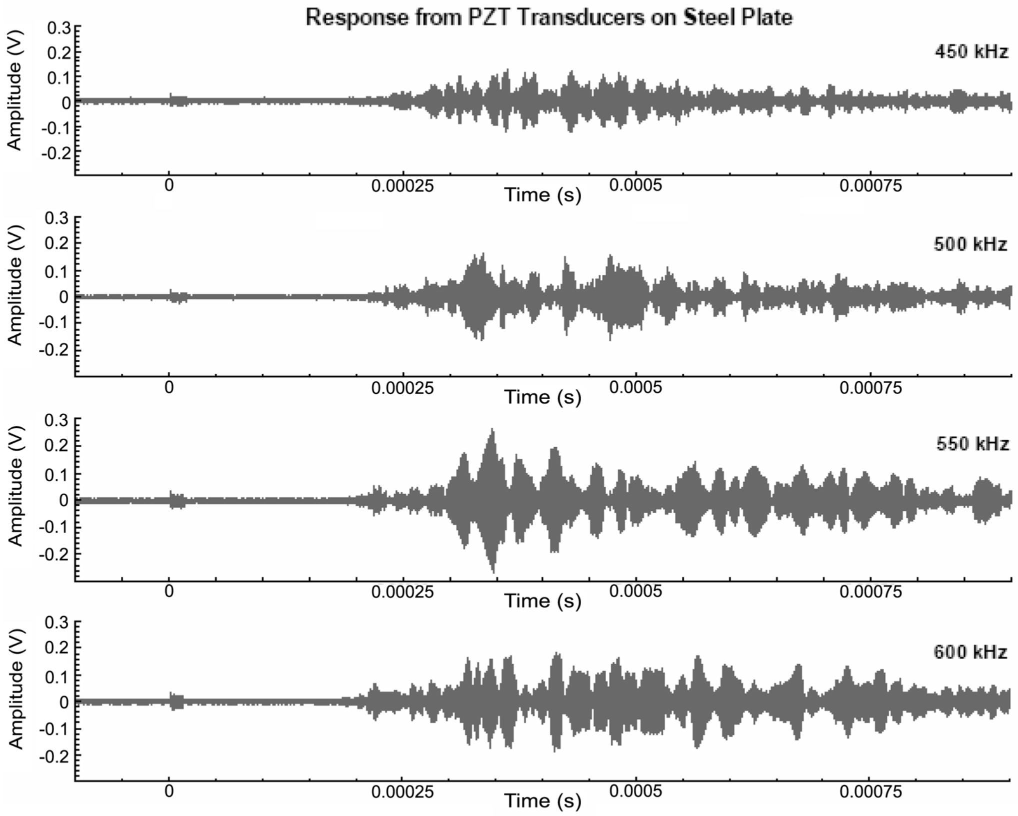

Fig. 9 Response from PZT transducers on steel plate

Likewise, responses from PZT buttons at the same locations were also obtained and plotted as below:

Fig. 8 and Fig. 9 show that compared to PZT transducers, PVDF IDTs are less sensitive, but the received signal is smooth. The immediate saturation response in Fig. 8 is RF breakthrough. The interpretation of the response is complicated, because the diagrams include information of forward waves, backward waves, reflections from the bar ends, and higher order harmonics generated by the rectangular window. Based on the simulation results, the predicted direct first times of arrivals of several modes were calculated and illustrated in Fig. 8. S_0 and S_1 modes were relatively easy to identify in the figure.

6.2. Experiments on carbon fiber composite plates

The similar experiments have been conducted on carbon fiber composite plates. First of all, the dispersion curve of the experimental sample plates has been set up and illustrated in Fig. 10 and Fig. 11.

The group velocity of carbon fiber composite shows that waves propagate in this material are less dispersive than those propagate in steel. This is so, perhaps due to the fact that carbon fiber composite material used in this experiment is anisotropic, which enhances the wave propagation along the longitudinal direction of fiber. As a result, waves with larger amplitude are expected.

PVDF IDT has been tested on its performance of both being an exciter and a receiver. The schematic

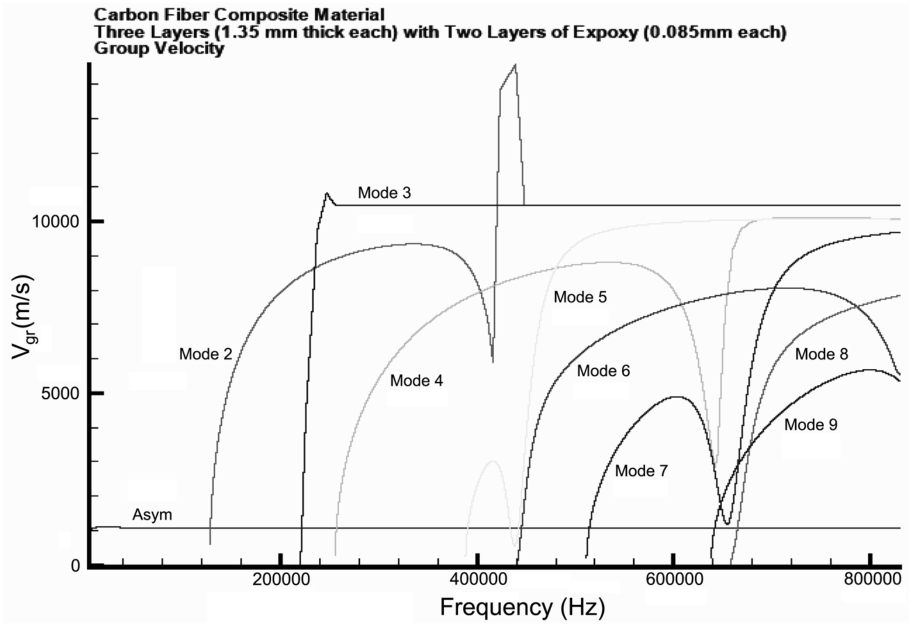

Fig. 10 Dispersion curve for carbon fiber composite plate (Group velocity) (simulated by DISPERSE, Imperial College, UK)

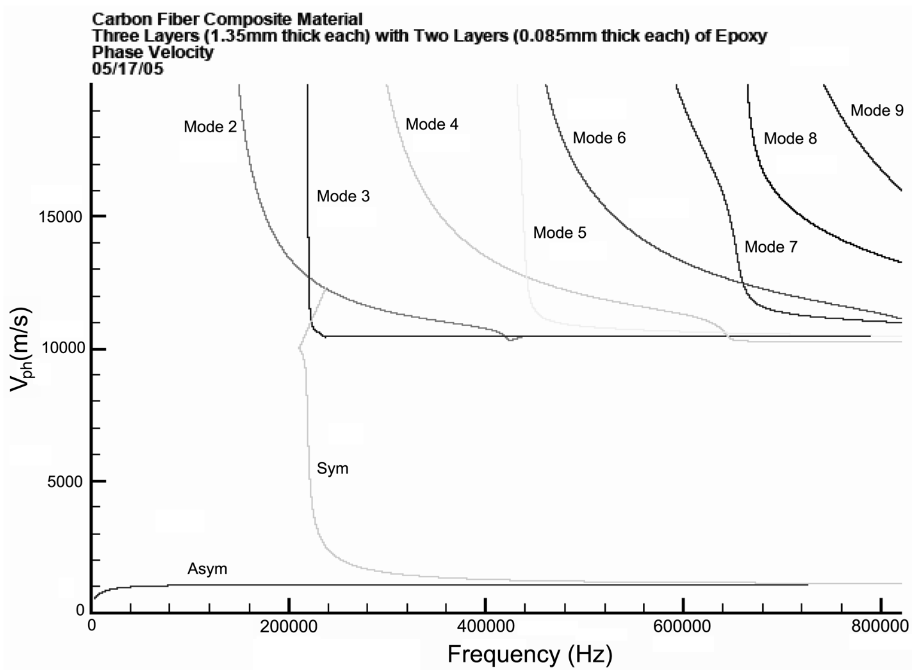

Fig. 11 Dispersion curve for carbon fiber composite plate (Phase velocity)(simulated by DISPERSE, Imperial College, UK)

of the experimental plan is demonstrated in Fig. 12.

Comparison between PVDF IDTs and PZT transducers has been made. Lamb wave signals have been

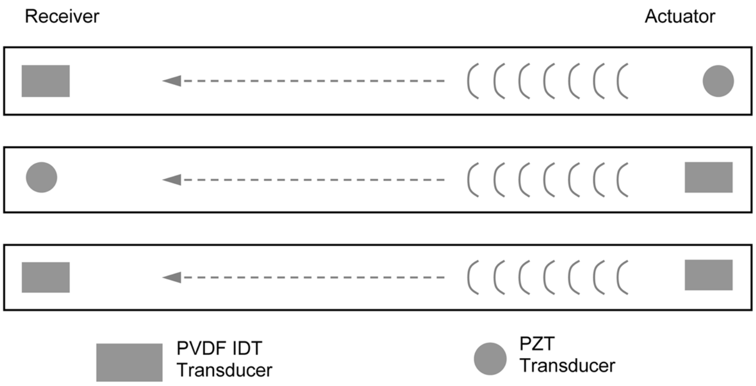

Fig. 12 Schematic of experimental plan

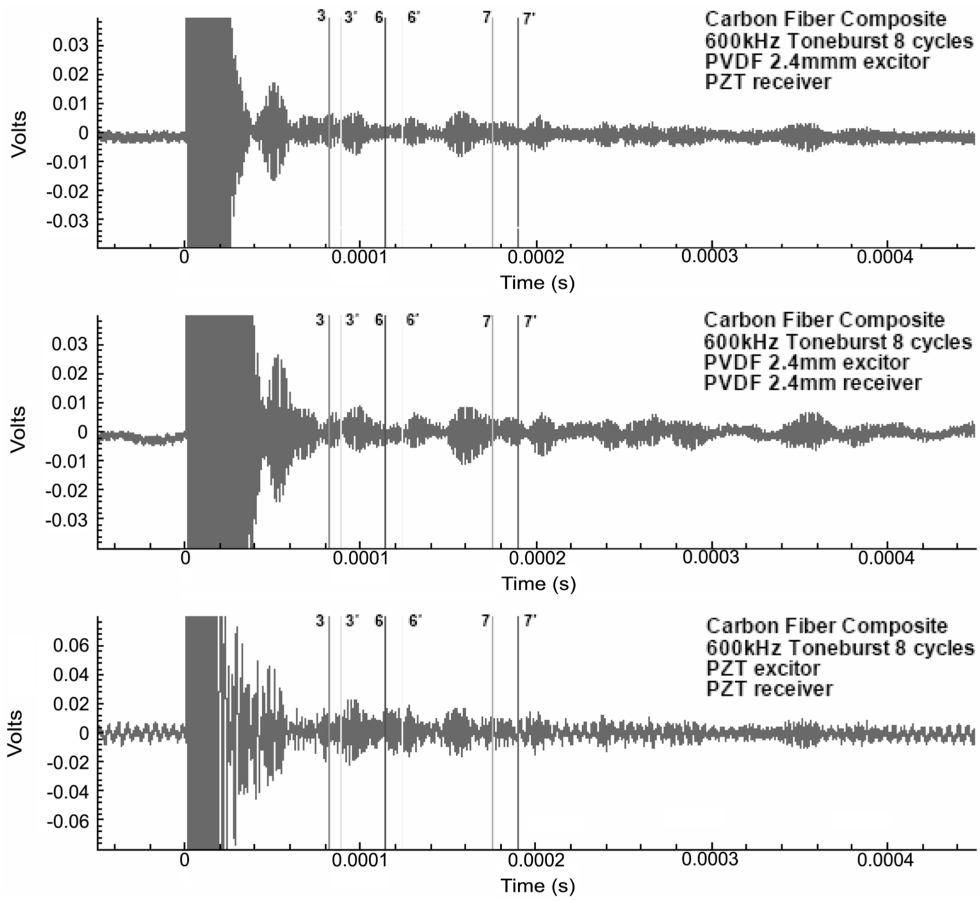

Fig. 13 Comparison between PVDF IDTs and PZT transducers on carbon fiber composite plates at 600 kHz

generated and received on carbon fiber composite plates by both PVDF IDTs and PZT transducers. Results at 600 kHz is demonstrated in Fig. 13 as an example. It shows that PVDF IDTs work both as an exciter and a receiver on carbon fiber composite material. The signal generated and received by PVDF

IDTs contains the same information as that from PZT transducers. Referring to dispersion curves, the arrival time of each mode is calculated and some of them are illustrated in Fig. 13 by vertical lines. The number in the figure denotes the mode number. Signal travels both forward and backward in the plate. A prime sign was added to represent the signal travels backwards and bounces back at the boundary of the plate before being received by a receiver.

7. Conclusions

This paper reports the results of experiments conducted to compare the performance of PVDF interdigitated sensors with PZT sensors. A flexible monolithic PVDF IDT transducer has been constructed for generating and receiving Lamb waves in nondestructive testing by using the photolithography technology. While guided waves can be generated by point or line piezo-ceramic devices, such sources suffer from wideband, uncollimated operation, and are typically very brittle and expensive. Two key advantages of using PVDF for guided wave monitoring are that it is very flexible, which makes possible the attachment of sensors to “smart structures” with different surface shapes, and it is relatively inexpensive, which facilitates the monitoring of structures in large scale.

The integration of these sensors into wireless systems can also be envisioned. Preliminary results confirmed that a monolithic transducer, based on a gold-on-PVDF technology, yields promising results both as an exciter and a receiver.

Further research needs to be done to optimize the design and operation of these sensors, so that even less modes will appear in the received signal, which will simplify mode identification and make it possible for PVDF IDTs to be employed for defect detection in a structure based on the changes of a certain mode. Research on coupling efficiencies of these gages to different modes at disparate operating points is also needed.

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