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AN ULTRASONIC GUIDED WAVE TOMOGRAPHIC IMAGING APPROACH FOR CHARACTERIZING BALLISTIC DAMAGE IN COMPOSITE STRUCTURES

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ABSTRACT

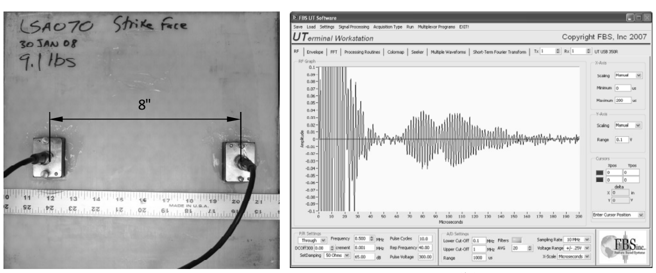
Through Small Business Innovative Research (SBIR) support from the U.S. Army, an industry partner has explored the possibility of using an ultrasonic guided wave computed tomography (CT) imaging approach to detect and characterize ballistic damage to composite armor panels that are commonly used in ground vehicles. Laboratory tests have been conducted and shows that the guided wave CT approach can indeed be applied to these complex structures to provide accurate damage mapping potential. Analytical analysis and finite element method (FEM) modeling has been used to aide in understanding guided wave propagation behavior in these anisotropic structures. The work presented herein clearly shows great potential for using a guided wave sensing approach to locate and image ballistic damage in composite armor panels as well as the ability to predict wave propagation and scattering in these complex structures that could be used in the future to predict optimal sensor geometry, configuration, defect type, and detection sensitivity.

INTRODUCTION

There currently exists a need to develop new technologies for real time health monitoring of composite armor panels on ground vehicles in order to inform decision makers on board or at remote locations as to the severity of damage that may occur. Ultrasonic guided waves offer an attractive solution for embedded structural health monitoring (SHM) of such structures because of their ability to travel long distances and to inspect inaccessible and hidden areas from locations where access is achievable. The guided wave sensors can be used during field deployment to detect an impact event and then determine the location and size of the resulting damage. The guided wave sensors can be embedded in the composite panels during manufacture. Key to the development and optimization of the monitoring system is the development of sensors based on a theoretical understanding of the guided wave mode selection possibilities in these complex structures. Analytical and FEM modeling work has been used to study the complex wave propagation phenomenon. Comparisons with experiment have shown promising correlation. Guided wave tomography experiments have been carried out on an actual armor panel with surface mounted sensors and accurate mapping the location of simulated damage was observed. Further, a representative composite panel with embedded piezoelectric ceramic sensors has been fabricated. Experiments to date show great promise for mapping ballistic damage with the embedded sensing approach.

EXPERIMENTS ON AN ACTUAL COMPOSITE PANEL

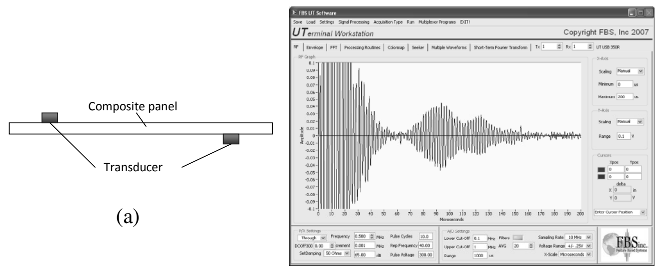
Tests were carried out on a composite specimen. Specific details of the make-up of the panel are not known but in general the panel is ~1 ft. x 1 ft., ~0.59” thick, and it is assumed that is comprised of glass fiber reinforced polymer (FRP) layers, ceramic cylinders, and epoxy resins as reported in the literature for composite armor panels [1]. Initial testing on this panel were conducted to show that guided wave energy could propagate well in all directions and through the entire thickness of the panel. Both normal beam incidence and angle beam incidence tests were conducted in a through transmission approach. The transducer setup for normal incidence tests is shown in Figure 1a. Two 500 kHz center frequency transducers were used in through-transmission (pitch-catch) mode. The transducers were 8” apart. In this case, the wave propagation direction was defined as the 0^{o} direction. The transmission signal obtained in the experiment using a 10 cycle 500 kHz tone-burst as the input is shown in Figure 1b. As can be observed, two clear wave packages were received by the receiving transducer. To determine whether the received wave packages were guided waves, the receiver was moved to the opposite surface of the plate, as illustrated in Figure 2a. The corresponding received signal is shown in Figure 2b. It was demonstrated that ultrasonic wave energy can still be well-received with the transmitter and receiver transducers on different surfaces of the composite panel. The received wave packages look similar to what was received when the two transducers were on the same surface, which proved that the received ultrasonic waves were ultrasonic guided waves whose energy floods the entire thickness of the composite panel. Ideally, since the panel is symmetric with respect to the center plane of the panel, guided waves in the panel should be either symmetric or antisymmetric modes, which should yield either the same waveform or out-of-phase but with the same amplitude waveforms for the two cases shown in Figures 1 and 2. The discrepancy in waveforms shown here was mainly due to the misalignment of the transducers and variances in transducer coupling conditions.



(a) (b)

Figure 1. (a) Transducer setup for a normal incidence guided wave test. (b) Through-transmission signal received by a receiver placed at the same surface with the transmitter transducer.

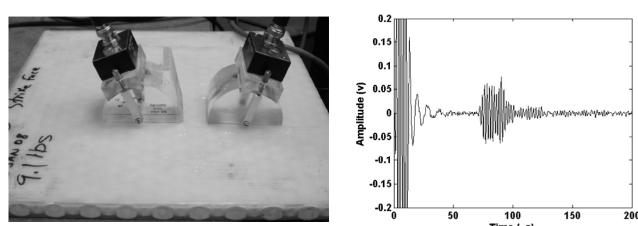
Guided wave through-transmission tests were also performed for different wave propagation directions in the composite panel. The signal for the 90^{o} direction was quite similar to the one for the 0^{o} direction. However, the 45^{o} signal was quite different. This is expected as the fiberglass plates are anisotropic materials with material symmetry for both 0^{o} and 90^{o}. Also, the ceramic pellets inside the composite panel are not in a square distribution pattern. Instead, the lines of the ceramic cylinders are at a 60^{o} angle with respect to the panel edges. This should cause differences to the wave propagation characteristics for the 0^{o} vs. 45^{o} directions.



(a) (b)

Figure 2. (a) Transducer setup for a normal incidence guided wave test with the transmitter transducer and the receiver transducer placed at different surfaces of the composite panel. (b) Through-transmission signal received by a receiver placed at the opposite surface as that of the transmitter (result similar to that shown in Figure 1).

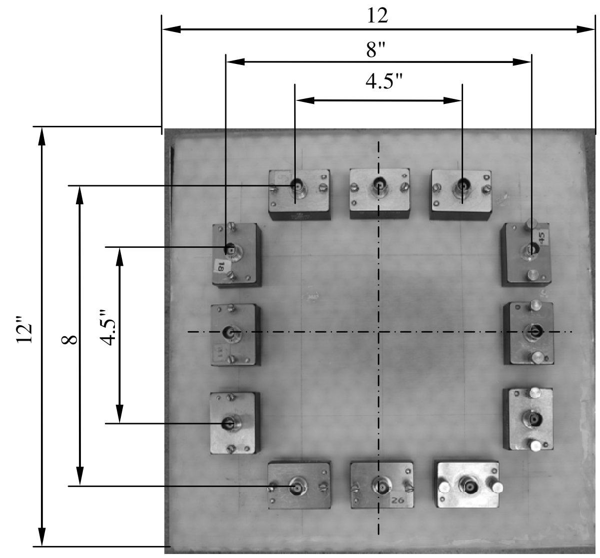
Angle beam transducers were also used in the experiments to send and receive guided waves in the composite panel. Angle beam transducers can provide phase velocity selection based on the incident angle [2]. The through-transmission setup of two angle beam transducers is shown in Figure 3a. The incident angle was close to 40^{o}. The corresponding signal for a 10 cycle 500 kHz input is shown in Figure 3b. As shown, a nice guided wave packet was received. The receiver was also placed to the other surface of the panel to receive the guided wave signal. A very similar signal was observed for that case as well.



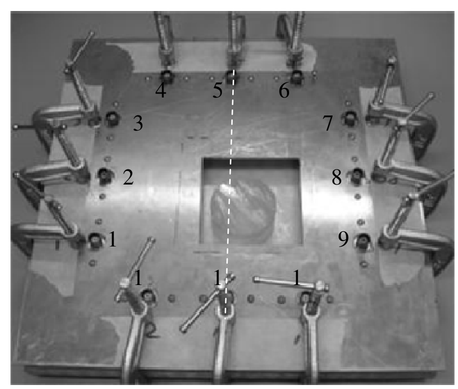
(a) (b)

Figure 3. (a) Angle beam transducer setup. (b) Guided wave signal received in the angle beam transducer test showing a simplified single packet of energy achieved by a special angle-frequency combination.

Upon proving that guided wave energy can indeed propagate well in the composite panel, work efforts were concentrated on setting up test to show that damage mapping is possible using a guided wave CT approach. As shown in Figure 4, twelve of the 500 kHz transducers were placed on the surface of the panel. The transducers were gel-coupled to the sample and clamped in place with an aluminum fixture as shown. Reference data was acquired by sending and receiving guided wave signals with every possible transducer combination in the sensing array. For this experiment, a 300 kHz, 10 cycle toneburst signal was used to drive the transducers. A sample received waveform is shown in Figure 5. Damage was then simulated by gluing a 2" diameter plexiglass cylinder onto the plate. The data was then reacquired and a computed tomography image was constructed by comparing the reference data set to the damage data set. The CT image, shown in Figure 6, clearly shows the position and approximate size of the simulated damage. This is a powerful result that shows it is clearly possible to detect and image damage in these complex structures. Further, since earlier work showed that it is possible to propagate guided wave energy throughout the entire thickness of the panel, it should be possible to detect and image damage at any depth inside the panel.



(a)



(b)

Figure 4. Tomography experiment setup on a 12" x 12" ceramic composite panel. (a) Sensor array configuration; (b) sensor array fixture on test specimen with a 2" diameter Plexiglas cylinder glued on as an artificial defect.

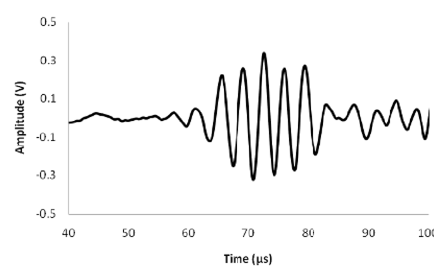


Figure 5. Typical waveform recorded at 300 kHz by the sensor pair 5-11 (lined up in dash line as shown in Figure 1b, showing a defect sensitive mode with an average group velocity of 3200 m/s.

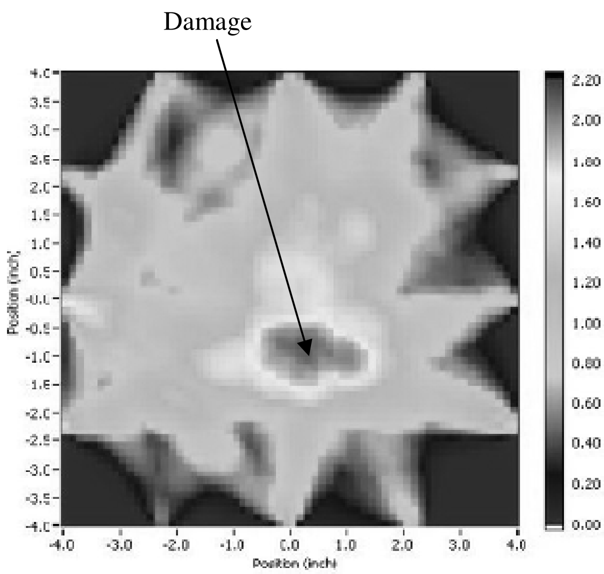


Figure 6. Reconstructed tomographic image based on the selected mode shown in Figure 5 with an average group velocity of 3200 m/s, demonstrating a very good defect detecting capability and potential for the ceramic composite type panel.

EXPERIMENTAL PHASE VELOCITY DISPERSION CURVE DEVELOPMENT

Phase velocity dispersion curves are essential for guided wave applications as they describe all possible guided wave mode and frequency combinations that can propagate in the wave guide. By using a 2D FFT approach, we have experimentally measured the phase velocity dispersion curves of the composite panel. Figure 7 illustrates the data collection of a 2D FFT test. As shown, in a 2D FFT test, guided wave signals are collected from a series of equally spaced positions along the wave propagation direction.

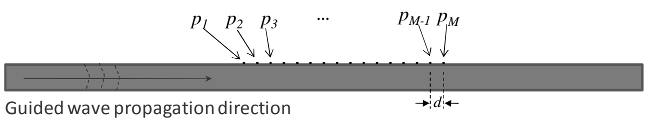


Figure 7. Illustration of the data collection of a 2D FFT test. Guided wave signals are collected from M equally spaced positions along the guided wave propagation direction. The spacing between two adjacent data collection positions is *d*.

After digitization, the collected signals can be arranged into a data matrix with each row being the time domain sampled guided wave signal for one data collection position. Column wise, the signals taken from different positions are arranged in a descending order of the position number. We all know that FFT of a time domain sampled signal yields a frequency series of the signal. If we conduct FFT of one column of the data matrix, the input to the FFT is a spatial domain sampled signal. Since the phase variation of a harmonic guided wave propagation can be described by $e^{i[kx-\omega t]}$, the spatial domain FFT, similar to the time domain FFT that reveals frequency information, will lead to a wave number domain representation of the guided wave signal. Therefore, a 2D wave number-frequency domain representation of the received guided wave signals can be obtained by performing a 2D FFT (FFT of each row and then FFT of each column, for example) of the data matrix. The resulting wave number-frequency 2D FFT results can be easily mapped into a phase velocity dispersion curve space using the relation *Cp=w/k*.

To obtain more information in the experimental dispersion curves, it is desired to excite more guided wave modes at a broad frequency range in a 2D FFT test. In our experiments, we used two broad band transducers with both normal incident and angle beam incident setups to perform the 2D FFT tests at different frequencies. The results from all different tests were then combined together to produce a final experimental study of the phase velocity dispersion curves. Figure 8 presents the experimental phase velocity dispersion curves of the composite panel sample from TARDEC. As can be seen, several highlighted areas with high image intensity (red and yellow areas) were generated in the phase velocity dispersion curve space. Such areas demonstrate the guided wave modes and frequencies that were efficiently generated in the 2D FFT tests. Therefore, with the experimental dispersion curves, we can decide which transducer settings may be applied to effectively excite certain guided waves in the panel, and also the dispersion characteristics of the excited guided waves.

Based on Snell's Law, normal incident transducers excite guided waves with high phase velocities, while angle beam transducers excite guided waves with phase velocities determined by the incident angles. The experimental dispersion curves obtained by normal incident transducers and angle beam excitations are marked in Figure 8. It is interesting to notice that for the frequency range from 200 kHz – 600 kHz, the normal incident setup only excited two guided wave modes. As a result, when we design any normal incident transducers/sensors for guided wave damage detection in this frequency range, we will need to focus on these two modes and use the frequencies of them as the operating frequencies of the transducers/sensors.

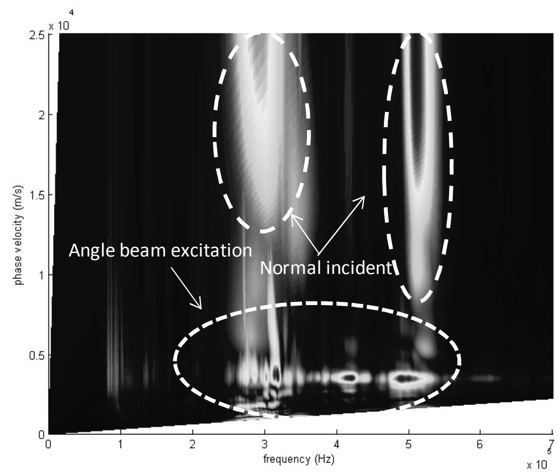


Figure 8. Experimental phase velocity dispersion curves of the composite panel. The results were obtained using 2D FFT tests.

REPRESENTATIVE PANEL FABRICATION AND TESTING

To study wave propagation using embedded sensors, a representative panel was fabricated. The panel has dimensions of 4" x 4" and is comprised of two 0.030" thick fiberglass plates sandwiched around aluminum oxide cylinders (0.53" diameter, 0.46" height). Two PZT ceramic sensing elements (0.50" diameter, 0.25" height) were embedded as shown in Figure 9. Clear Epoxy and Potting

Compound was used to pot the cylinders and attach the fiberglass plates.

Figure 9. Picture of the 4” x 4” panel. Two PZT ceramic sensors were embedded inside the panel as shown.

A series of experiments were carried out on the newly fabricated panel and each of the individual components that comprise the panel. To determine the elastic properties of the individual materials, we performed ultrasonic bulk wave tests on the epoxy and ceramics (Aluminum oxide) that were used for the sample fabrication. The density and the measured bulk wave velocities the two materials are given in Tables 1 and 2.

Table 1. Density and measured bulk wave velocities of the ceramic and epoxy

	Longitudinal velocity	Shear velocity	Density ρ
Ceramic (aluminum oxide)	10.359 km/s	6.1398 km/s	3866.9 kg/m^3
Epoxy	2.3934 km/s	0.9943 km/s	1116.6 kg/m^3

Table 2. Calculated elastic constants of the ceramic and epoxy

	Young’s modulus	Poisson’s ratio
Ceramic (aluminum oxide)	358.3732 GPa	0.2292
Epoxy	3.0815 GPa	0.3957

Guided wave tests were then carried out on the sample plate. The through transmission signal between the two embedded PZT cylinders is shown in Figure 10. The driving signal applied to the transmitter cylinder was a 5 cycle 125 kHz tone-burst signal. Notice that 125 kHz is the radial resonant frequency of the PZT cylinder. As can be seen, a very clear guided wave reception was obtained by the receiver PZT cylinder. Since guided waves are sensitive to changes in the wave path, it is expected that the guided wave signal shown here can be used for detecting damage between the embedded cylinders.

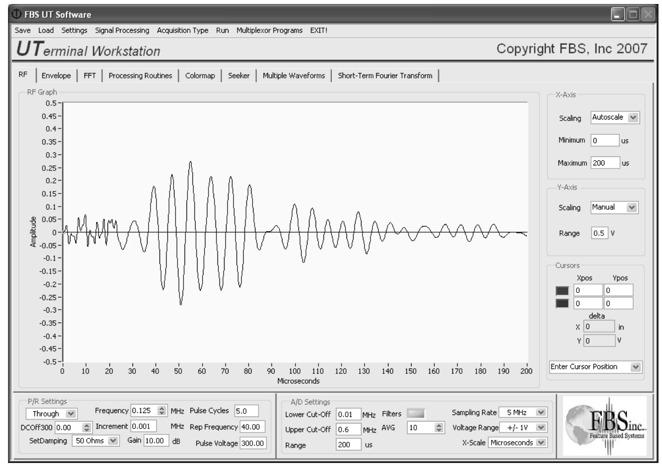


Figure 10. Through transmission guided wave signal between two embedded PZT cylinders inside the FBS composite sample.

In addition, a broadband acoustic emission sensor was used as a receiver to receive guided waves generated by one embedded cylinder at different locations. Good guided wave reception was obtained for different locations that covered both surfaces of the sample. The acoustic emission sensor was also used to measure the group velocity of the guided wave excited by the embedded cylinder. Two signals collected from two positions that were 1 inch apart and both on the line between two embedded PZT cylinders are shown in Figure 11.

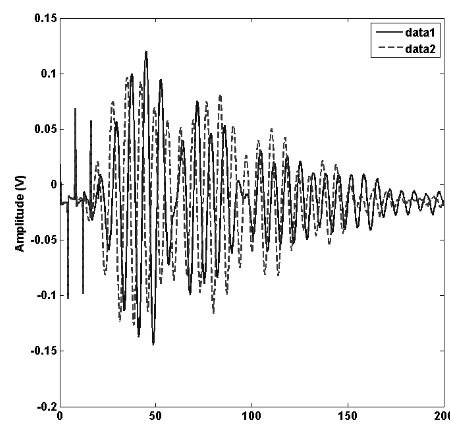


Figure 11. Two guided wave signals collected by placing an acoustic emission sensor at two positions that were placed 1” apart.

Using the signal envelopes calculated by a Hilbert transform, the group velocity of the guided wave signal was calculated at 2.49 km/s. An effective moduli approach [2] was used to calculate dispersion curves of the sample using the material properties in Tables 1 and 2. The calculated group velocity dispersion curves are shown in Figure 12. As can be seen, at a frequency of 125 kHz, which is the center frequency of the PZT cylinder driving signal, there are three modes: A0, S0, and A1 modes. The group velocities of the three modes are 2.32 km/s, 4.66 km/s, and 3.01 km/s. Compared to the calculated group velocities, it appears that the excited guided wave is the A0 mode. It should be pointed out here that the material properties of the glass FRP face plates were from literature. The inaccuracy of the properties may contribute to the small discrepancy between the calculated velocity and the measured one. The approximation nature of the effective moduli approach may also affect the accuracy of the velocity calculation. In the future, FE models can be used to compare with the experiments.

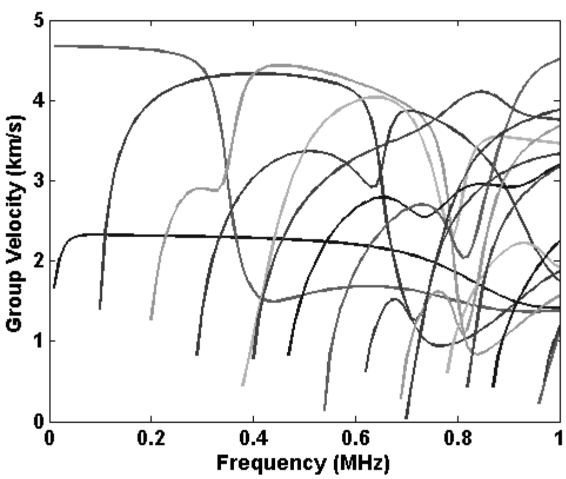


Figure 12. Group velocity dispersion curves of the sample that were calculated using the effective moduli approach.

FEM MODELING – MODEL SETUP AND INITIAL SIMULATION

An initial FEM model of a representative composite panel was created and an initial simulation was carried out using a normal loading source.

A FEM software package was used here. An example finite element simulation result is shown in Figure 13 in Mises stresses. The stress distribution shown here was calculated for the time of 112 μs following the application of the point source. It was demonstrated that guided waves can be generated well by the point source, although there were also local ultrasonic resonances among the ceramic cylinders. It is possible that the local ultrasonic resonances were actually associated with frequency band gaps as usually can be observed for photonic type structures [3-5]. Further investigations are needed to look at the frequency contents of the propagating guided waves as well as their phase and group velocities. Nevertheless, the FE simulation result validated the feasibility of exciting ultrasonic guided waves in the composite panel. As ultrasonic guided waves are sensitive to perturbations on their wave propagation paths, there is a great potential of using them for damage detection in composite structures. The analytical and FEM analysis presented in this paper are key in moving forward with a guided wave SHM system for composite structures in order to:

- Validate theoretical calculations and experiments,
- Provide direct visualization of wave propagation and scattering phenomenon,
- Study frequency band gaps associated with the composite panels,
- Serve as guidelines for transducer design and selection, and
- Study the interactions between the guided waves and different defect types.

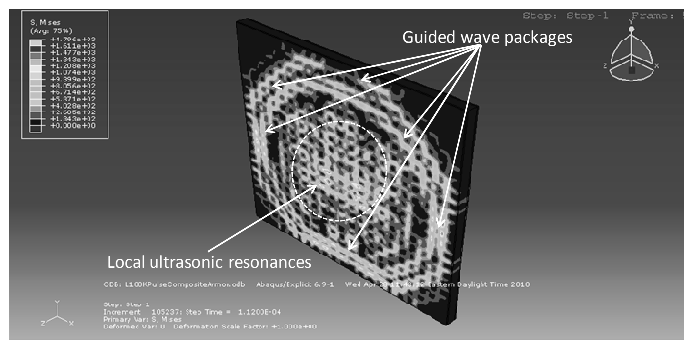


Figure 13. FE simulation result of wave propagations in the composite panel. As can be seen, clear guided wave packages were generated by the input point source. Local ultrasonic energy resonances among the ceramic cylinders can be observed as well.

CONCLUSIONS

Work has been carried out and shows great potential for using guided waves to detect and map damage occurring to composite panels. Guided wave energy was shown to propagate well in panels with sufficient signal to noise ratio to allow mode isolation and feature extraction. Theoretical work has also been carried out and matches well with the experimental observations.

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