Front. Mech. Eng. 2015, 10(1): 89–94
DOI 10.1007/s11465-015-0323-4

RESEARCH ARTICLE

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A Stoneley wave method to detect interlaminar damage of metal layer composite pipe

Abstract The interlaminar defect is a major form of damage in metal layer composite pipes which are widely used in petroleum and chemical industry. In this paper, a Stoneley wave method is presented to detect interlaminar damage in laminated pipe structure. Stoneley wave possesses some good characteristics, such as high energy and large displacement at the interface and non-dispersive in the high-frequency, so the sensitivity of detecting interlaminar damage can be improved and the higher frequency can be used in damage detection compared with Lamb waves. Additionally, as the frequency increases, the wavelength of the Stoneley wave reduces. Thus, its ability to detect small defects at the interface is enhanced. Finite element model of metal layer composite pipe with interlaminar damage is used to simulate wave propagation of Lamb waves and Stoneley wave, respectively. The damage location is calculated by using the Stoneley wave signal obtained from finite element model, and then the results are compared with the actual damage locations. The simulation examples demonstrate that the Stoneley wave method can better identify the interlaminar damage in laminated pipe structure compared with Lamb waves.

Keywords Stoneley wave, interlaminar damage, metal laminated pipe

1 Introduction

Laminated metal composite pipe is widely used in petrochemical pipelines, which possess the excellent characteristics of each metal component (light, corrosion resistance, cheap, and so on.). Explosion pressure welding is an efficient way of producing metal composite pipe, but blast also has some influences on the structure health [1]. The interlaminar defect is a major form of damage in metal layer composite pipes. It can be divided into two main forms. When a substrate medium used in the composite pipe is defective, impact and pressure pulsation of pipeline fluid would cause crack growth. This is the transverse crack whose direction is perpendicular to the symmetry axis of pipe. When the two media of composite pipe are poorly adhesive in local, these cracks would cause delamination damage due to high interlaminar stresses at the ply interface. Therefore, rapid and online detection and assessment of the defect states are important. Traditional ultrasonic nondestructive testing techniques, which are based on the bulk waves, are very time consuming, since they need an overall inspection of the structure point-by-point. Ultrasonic guided wave is potentially a very attractive solution since it can detect different kinds of damages in large structure within a short time [2–4]. Lamb waves are a kind of the most commonly used ultrasonic guided wave [5–7], but they have some shortcomings for the explosive composite pipe. Lamb waves which have dispersion and energy diffusion characteristic in thick composite pipe are not sensitive to the interlaminar damage [8,9].

Stoneley wave found in 1924 by Stoneley is an ultrasonic guided wave which is guided by the interface, an ideal candidate for inspecting interfacial defects [10]. Stoneley wave possesses some good characteristics, such as high energy and large displacement at the interface and non-dispersive in the high-frequency, so the sensitivity of detecting interlaminar damage can be improved and the higher frequency can be used in damage detection compared with Lamb waves [11–13]. Additionally, as the frequency increases, the wavelength of Stoneley wave is reduced, its ability to detect small defects at the interface is enhanced.

In this paper, a Stoneley wave method is presented to detect two different defects. The echo time of reflected wave is used to locate transverse cracks; the energy reflectivity versus wavelength curve is used to achieve the

Received November 6, 2014; accepted December 23, 2014

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quantitative estimation of the crack size. The velocity change is used to quantitatively estimate the delamination damage length. Finite element models with different size of transverse cracks and different length of delamination damage are established and simulated respectively. In the end, Stoneley wave and Lamb waves propagation in the structure which contains transverse crack are compared.

2 Establishment of the model

A composite pipe is an axially symmetric structure in which the propagation mode (longitudinal mode) of Stoneley wave is also axially symmetric. Therefore, as shown in Fig. 1, an axisymmetric longitudinal section of composite pipe is taken for the study to simplify the model. The total length of Composite pipe is 500 mm and inner radius r_1 is 100 mm. With the 10 mm thickness aluminum tube as inner tube, ordinary cheap carbon steel is wrapped on the outside of aluminum tube as base, whose thickness is 20 mm. The inner and outer surfaces of the left end of the composite pipe are wrapped by 150 mm length infinite element and the piezoelectric ceramic element is bonded at the left end surface to realize the wave excitation. Material parameters of the two materials are shown in Table 1.

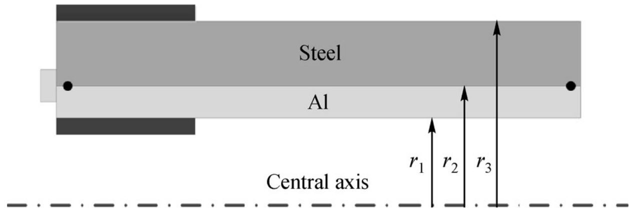

Fig. 1 An axisymmetric longitudinal section of composite pipe and the overall of the detection system

The explicit dynamic finite element method of ABAQUS/Explicit is used in the simulation, which is an effective method to simulate short and transient dynamic events. It doesn't need iteration and convergence criteria. Thus it makes a low cost of calculation.

Two analysis steps are set for the simulation. The first analysis step is used to apply load which excites the structure and generates Stoneley wave at the interface. In the second analysis step, the load is canceled to simulate the free propagation of Stoneley wave after exciting in the structure. The time of first analysis step is very short, which is as long as the duration of the instantaneous excitation signal. The time of second analysis step should be long enough so that the wave can propagate throughout the whole structure. It is set as 2×10^{-4} s.

In order to accurately simulate wave propagation, it is necessary to guarantee that there are at least six elements in each wavelength [14]. Considering the accuracy and computation time consumption, each wavelength is divided into ten elements.

The explicit dynamic finite element method is based on the start time and the increment time to calculate the current state. The increment time should be smaller than the ratio of the smallest element size and the wave propagation velocity in the structure [14]. If the increment is larger than the limit, the calculation may be unstable and the correctness of the analysis results cannot be guaranteed. Considering the accuracy and computation time consumption, time increment should be approximate as much as possible but not exceed the stability limit.

The element CAX4R, an axisymmetric solid element in ABAQUS, is chosen to simulate the finite element model of longitudinal section of the composite pipe, which greatly reduces the occupancy rate of computer memory and storage.

The infinite element which wrapped on the inner and outer surfaces of the left end is used to absorb body wave that spreads to inside and outside surface. It eliminates the interference of reflected body waves to Stoneley wave at the interface. After propagating a certain distance, the propagation of Stoneley wave becomes steady, so it is only needed to set the infinite element at the left ends with 150 mm length which was determined by a simulation test. Twelve rectangular piezoelectric ceramics are circumferentially arranged at the left end face, which generate evenly distributed radial force. In an axisymmetric longitudinal section of structure, the excitation force is equivalent to a radial concentration load. The excitation signal is a five-cycle sine wave with Hanning window. Two detection points are respectively arranged at the distance 20 mm away from both ends at the interface as shown in Fig. 1.

3 Damage identification method

There are two main injury forms in explosion composite pipe. When a substrate used in the composite pipe is defective, impact and pressure pulsation of pipeline fluid would cause crack growth. These are the transverse cracks whose directions are perpendicular to the symmetry axis of

Table 1 Material parameters of the two materials

Material	Density/(kg·m^{-3})	Young's modulus/GPa	Poisson's ratio	Longitudinal speed of sound/(m·s^{-1})	Transverse speed of sound/(m·s^{-1})
Al	2700	79	0.33	6584	3316
Steel	7850	210	0.30	6001	3208

pipe. When the two media of composite pipe have local poorly adhesive, these cracks cause delamination damage due to high interlaminar stresses at the ply interface. For two kinds of defects, different Stoneley wave methods are used to detect them respectively.

1) Transverse cracks

As shown in Fig. 2, at a distance of 200 mm from the excitation face, two different sets ((1×6) and (1×8) mm) of elongated slot in the base steel material are established to simulate the transverse cracks. When the piezoelectric ceramic excites ultrasonic guided waves in the structure, the waveform signals propagating at the interface are obtained by the detection points at the left and right ends. The signals obtained are Hilbert transformed to get the envelope curve of the waveform. The peaks of the envelope curve are extracted to get echo time of transverse crack damage. Then the echo time combins with Stoneley wave velocity to get the distance between the excitation end face and the injury. Stoneley wave velocity can be obtained by theoretical wave speed formula or experiment [11]. It can realize the damage location of transverse crack. Detection waveform of detection Points 1 (near to the left end) and 2 (near to the right end) in the excitation frequency 500 kHz and its envelope are shown in Fig. 3. The legend 500k1 presents detection waveform of detection Point 1; and 500k2 presents detection waveform of detection Point 2.

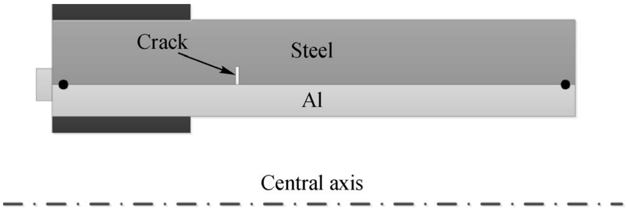

Fig. 2 Schematic of transverse crack damage

Because Stoneley wave velocity is non-dispersion, different excitation frequencies can produce different certain excitation wavelengths of Stoneley waves at the interface. As the excitation frequency increases, the wavelength of the Stoneley wave is reduced. When Stoneley waves with different wavelengths interact with the certain size of the transverse crack, there are three different situations. Firstly, Stoneley wave is almost entirely reflected when its wavelength is less than the size of injury. The reflectivity is close to constant and the diffraction energy reaching detection Point 2 is very small. Secondly, reflection energy begins to decrease when the wavelength of Stoneley wave approximates the size of injury. The reflectivity begins to decrease with a low speed. Finally, reflection energy decreases rapidly when the wavelength of Stoneley wave is greater than the size of injury. The reflectivity decreases rapidly. In conclusion, with the increase of wavelength, the reflectivity value varies through three phases in which it maintains constant in the first phase, decreases slowly in the second phase and decreases rapidly in the third phase. Therefore, the reflectivity can be used as an index to quantitatively estimate the size of damage. The wavelength of Stoneley wave which corresponding to the initial decrease area of the reflectivity curve is the estimated value of transverse crack size.

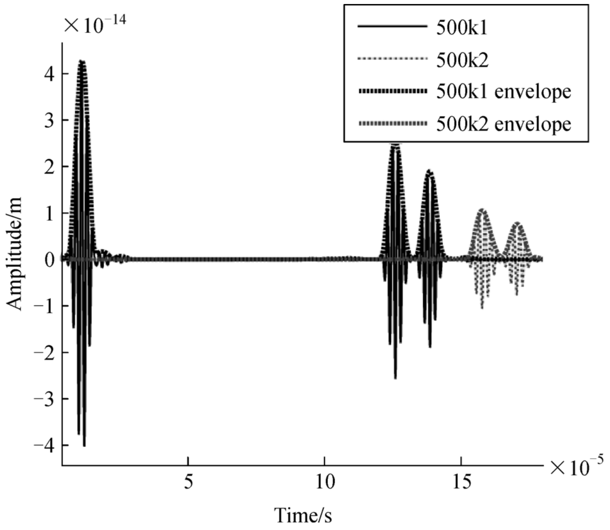

Fig. 3 Waveform signal and its envelope of detection Points 1 and 2

Two transverse cracks with different size ((1×6) and (1×8) mm) are simulated by ABAQUS/explicit software. Eight groups of signal with different wavelength varying from 3 to 10 mm are simulated in the 6 mm depth crack case. Seven groups of signal with different wavelength varying from 5 to 11 mm are simulated in the 8 mm depth crack case. The identification results of damage location are shown in Fig. 4. Figure 4(a) is the location results of the 6 mm depth crack case. And Fig. 4(b) is the location results of the 8 mm depth crack case. The distance between detection Point 1 and excitation end face is 20 mm, so the theoretical value of distance between the detection Point 1 and the injury is 180 mm. Simulation result is consistent with the theoretical value in the figure, and the effect of damage location is stable at different excitation frequencies. For the transverse cracks with different size, the good location results can be got as long as we use the appropriate excitation frequency.

Figure 5 shows the reflected wave curves of Stoneley wave at different excitation frequencies in structure with a 6 mm transverse crack. The peak of different reflected waves for 3, 4, 5, and 6 mm Stoneley wavelength are proximate. For the 7, 8, 9 and 10 mm Stoneley wave wavelength, as the wavelength increases, the reflected wave peak decreases. Reflected energy is normalized by taking the incident energy of waves with different wavelength as the reference, respectively.

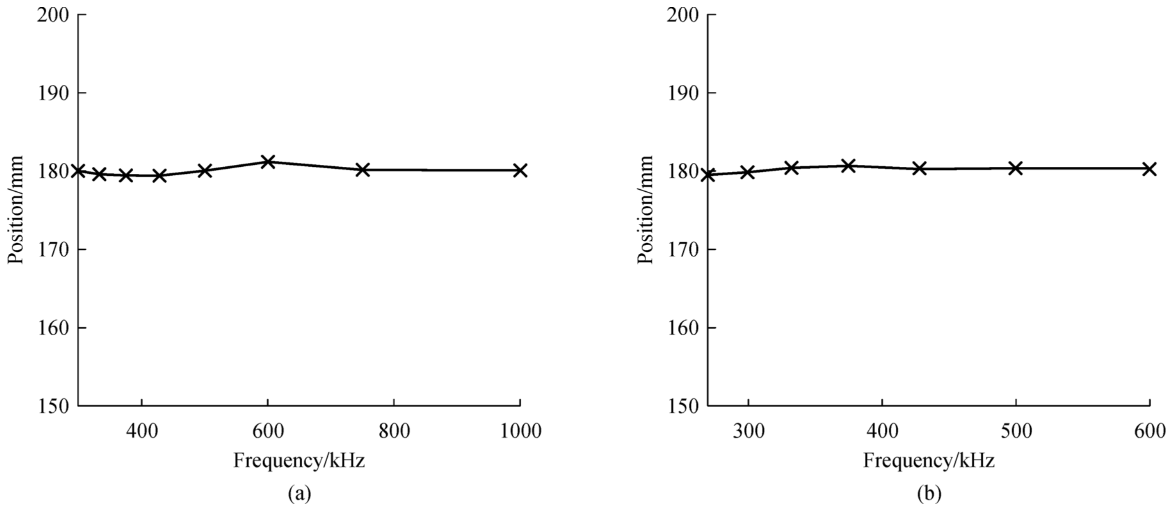

Fig. 4 Results of damage location. (a) Location of the 6 mm depth crack case; (b) location of the 8 mm depth crack case

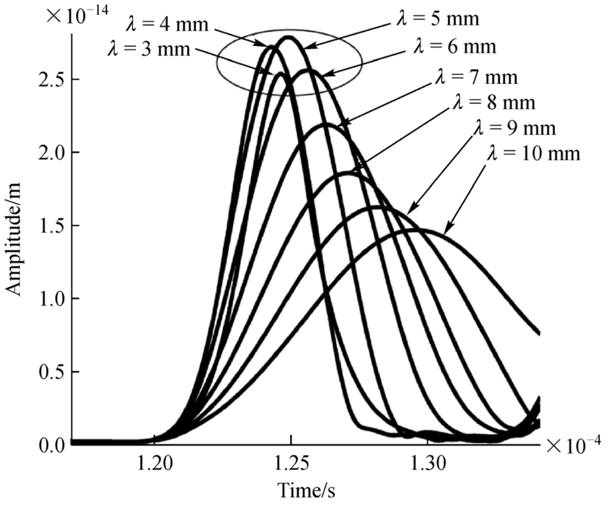

Fig. 5 Comparison of the reflected wave of different sizes wavelength

Then the reflectivity versus wavelength curve shown in Fig. 6 is obtained. Figure 6(a) is the change curve of the reflectivity for 6 mm crack. The region where wavelength varies from 3 to 5 mm is a stability region; the region where wavelength varies from 5 to 6 mm is a region in which reflectivity starts to decline; and in the region where wavelength varies from 6 to 10 mm, the reflectivity rapidly declines. Therefore, the detection result of the crack size is 6 mm. Figure 6(b) is the curve of the reflectivity changes for 8 mm crack. The region where wavelength varies from 5 to 7 mm is a region in which reflectivity remain stable; the region where wavelength varies from 7 to 8 mm is a region in which reflectivity starts to decline; and in the region where wavelength varies from 8 to 11 mm, the reflectivity rapidly declines. So the detected crack size is 8 mm.

2) Delamination damage

As shown in Fig. 7, at a distance of 200 mm away from the excitation end face, nine groups of elongated slot with different size (from (10 × 1) to (50 × 1) mm) in the base steel material are established to simulate the different lengths of delamination damage, respectively. Excitation signal is produced by the piezoelectric ceramic element at the left end of the structure. The waveform signals of Stoneley wave are obtained at detection Points 1 and 2, respectively. As described above, the time that Stoneley wave arrives at detection Points 1 and 2 are extracted by enveloping the two waveform signals. Then the average velocity of wave propagating in the structure can be calculated by dividing the distance between two detection points by the Stoneley wave propagation time between the two detection points.

In well bonded interface, the wave propagates in the form of Stoneley wave and its propagation velocity is Stoneley wave velocity v_S. When the delamination damage occurs at the interface of the structure, the wave converts into Rayleigh surface wave form at the delamination damage and its propagation velocity is Rayleigh wave velocity v_R. Because the velocity of Stoneley wave is greater than the velocity of Rayleigh wave [15], the average velocity calculated by detection Points 1 and 2 will be less than the velocity of Stoneley wave when delamination damage occurs. And with the length of delamination damage increases, the average velocity will also gradually reduce.

Assuming the length of delamination damage is x. The average velocity v of the wave in structure is defined in Eq. (1):

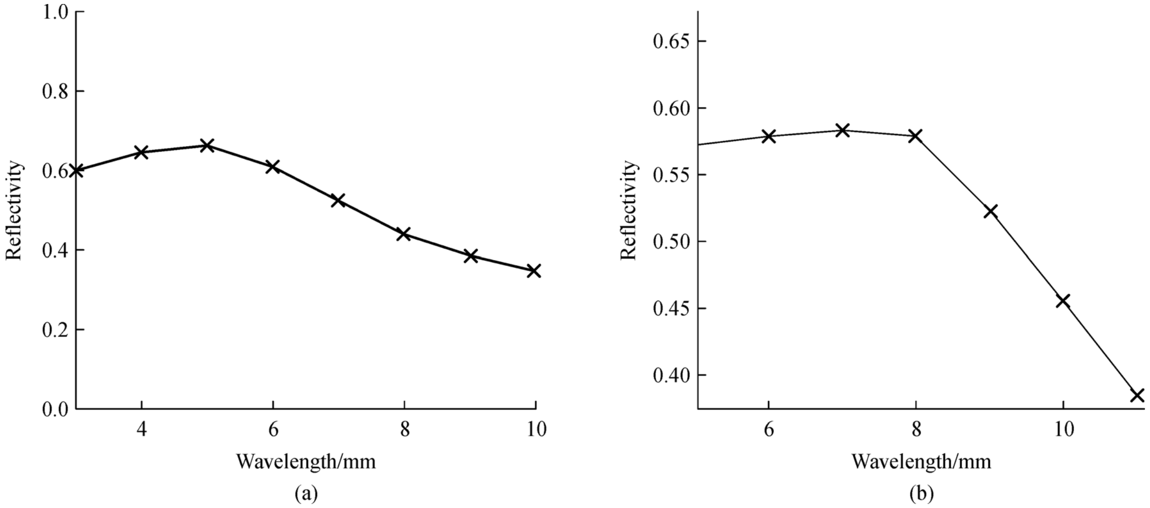

Fig. 6 Reflectivity versus wavelength curve of (a) 6 mm depth crack and (b) 8 mm depth crack

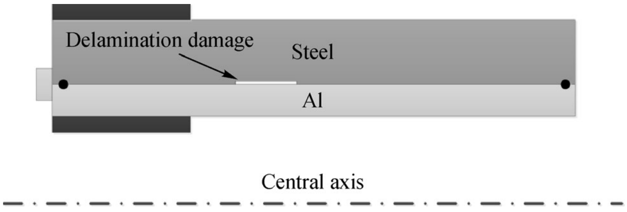

Fig. 7 Schematic of delamination damage

$$v = \frac{0.46}{\dfrac{x}{v_R} + \dfrac{0.46 - x}{v_S}} \tag{1}$$

where v_S and v_R are constants as long as material parameters of the medium remain unchanged [16,17]. So the relationship between average velocity and delamination damage length x is inversely proportional. The relation curve of them is inversely proportional curve. And the velocity range corresponding to small delamination damage length is in the large gradient region of the inversely proportional curve. Therefore, the velocity has good sensitivity on the identification of delamination damage length. The curve in this local large gradient region is approximate linear decrease.

The comparison between the simulation results and the theoretical values for nine groups of different delamination damage lengths (from (10 × 1) to (50 × 1) mm) is shown in Fig. 8. The simulation result and the theoretical calculated curve are in good agreement, which verifies that the velocity can be used as a quantitative estimate indicator of delamination damage length. For each different measured velocity in practice, we can obtain the corresponding value of different delamination damage length in the curve.

3) Contrast of Lamb waves and Stoneley wave

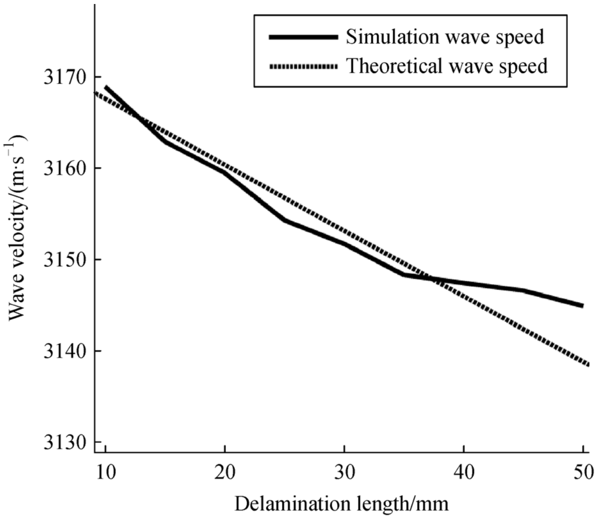

Fig. 8 Comparison of theoretical and simulation result about wave velocity versus delamination damage length

The propagation of Stoneley wave and Lamb waves in the structure with a transverse crack are compared. The simulation model is consistent with the model shown in Fig. 2. In Fig. 9, the black line in the middle represents the interface between steel and Al medium. The medium on the left side is aluminum, and the other is steel. As shown in Fig. 9, Figs. 9(a) and 9(b) demonstrate three propagation states when Lamb waves and Stoneley wave propagate in the structure with crack, respectively. The three propagation states include the state of approaching the crack, the state of interacting with the crack and the state of passing through the crack. Lamb waves are disperse and its width of the wave packet expands with the increase of propagation distance, which causes almost no effect on the crack identification. Stoneley wave has non-dispersion

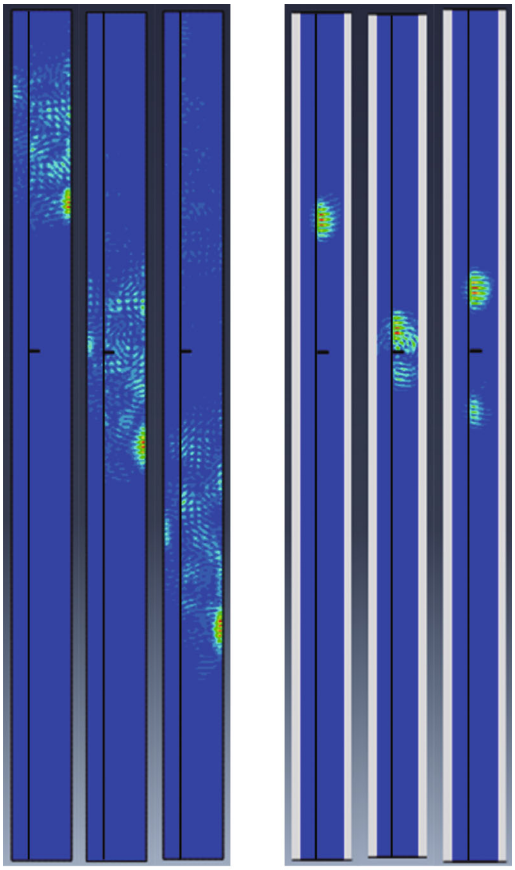

Fig. 9 Comparison of the damage identification effect for (a) Lamb waves; (b) Stoneley wave

with the propagation distance increasing and is sensitive to crack. Its energy is concentrated at the interface, which makes it has a good detection effect.

4 Conclusions

In this paper, the location and quantitative identification of transverse cracks and delamination damage in the steel and aluminum metal composite pipe are studied by Stoneley wave method. The finite element model of the structure with different size of transverse cracks and different length of delamination damage are established and simulated respectively. The echo time of reflected wave is used for transverse crack location, and the energy reflectivity versus wavelength curve is used to achieve the quantitative estimation of the crack size. The theoretical and simulated velocity curve with respect to the delamination damage length are obtained, which verifies that the average velocity could be an indicator as the quantitative estimate of the delamination damage length. In the end, Stoneley wave and Lamb waves propagation in the structure which contains transverse crack are compared, the results of which demonstrate the superiority of the Stoneley wave in transverse crack identification of metal composite pipe.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant No. 51475356).

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