Measurement of Acoustic Basic Parameters of Polyethylene Pipe

Guoquan Qi¹, Yuke Li², Nan Ding¹

¹CNPC Tubular Goods Research Institute, State Key Laboratory for Performance and Structure Safety of Petroleum Tubular Goods and Equipment Materials, Xi’an, Shaanxi, 710077, China.
²Wuhan ZhongKe Innovation Technology Company, Wuhan 430075, China.

Abstract. The acoustic characteristics testing, research and analysis on steel reinforced polyethylene composite pipes is conducted in this paper to provide strong basis for design of suitable phased array ultrasonic probe. The acoustic characteristic parameters are tested first, and the sound velocity is measured through twice reflected echo from the bottom surface. At the same time, the variation of the longitudinal wave velocity of the PE100 material under different temperature conditions is measured. The values of critical angle and acoustic impedance of the PE100 material are calculated by measuring the sound velocity. Then, the attenuation coefficient of the probes with different frequencies in the PE100 material is measured by the simulation calculation method and the actual measurement method, and the measurement attenuation coefficient of each frequency is further calculated. The results show that: (1) the sound velocity of PE100 material is 2,340m/s and the attenuation coefficient is 0.3dB/mm; (2) phased array ultrasonic inspection method can be used to make vertical incidence of longitudinal wave and avoid non-existence of the second critical angle; (3) 2MHz is the best frequency to inspect the body of steel reinforced polyethylene (PE) pipe.

Key words: Polyethylene material; attenuation coefficient; basic acoustic parameters; steel reinforced plastic composite pipe.

1. Introduction
The steel reinforced polyethylene composite pipes is a new type of double-sided anti-corrosive pressure pipe produced by specific production process, and has both the strength of steel pipe and the corrosion resistance of plastic pipe[1]. It is widely used in petroleum, chemical industry, public facilities, water supply and drainage, gas, mining, power plant, coking and other fields [2-3]. The steel reinforced polyethylene composite pipe is a new industry of engineering application pipes and the welded joints have more complicated structure than those of ordinary polyethylene pipes, making it difficult to apply the conventional non-destructive testing (NDT) technology and for the ordinary probe to accurately detect it. Hence, it is easier to have more quality defects [4].

The acoustic characteristics testing, research and analysis on the steel reinforced polyethylene composite pipes and comparative analysis with actual measurement and simulation calculation methods are carried out in this paper to provide strong basis for design of suitable phased array ultrasonic probe.
2. Acoustic parameters testing on the materials

2.1. Sound velocity

There are many methods to measure the sound velocity, such as measurement by ultrasonic test instrument, measurement by thickness gauge and measurement by oscilloscope. The basic principle of these methods is based on that the sound velocity is the distance divided by the time.

In order to achieve accurate measurement results, the interference caused by the initial pulse wave is eliminated and the sound velocity is measured through twice reflected echo from the bottom surface. A standard test piece with a thickness of 30mm is used as the sound path for sound velocity measurement, and the more accurate sound velocity of such test piece at the current temperature after measurement with a HS620 instrument is 2,340m/s.

Of course, sound velocity is affected by many external factors, such as temperature, elastic modulus, Poisson ratio and etc. Among them, temperature is the largest variable affected by the environment. As can be seen from Figure 2, like other common solid materials, the sound velocity of polyethylene materials decreases as the temperature rises.

2.2. Critical angle

By measuring the sound velocity, the first critical angle and the second critical angle between the plexiglass (probe protection layer) and the polyethylene material can be calculated, so as to better distinguish the structural echo from the flaw echo.

Formula for calculation of critical angle:

$$\alpha_i = \sin^{-1} \frac{C_{L_1}}{C_{L_2}}$$  \hspace{1cm} (1)
\[
\alpha = \sin^{-1} \frac{C_{L1}}{C_{s2}}
\]  

(2)

According to the sound velocity of the material measured in the preceding paragraphs and the sound velocity (2,337m/s) of the polystyrene cross-linked resin material which forms the probe protection layer found from relevant data, the first critical angle of the polyethylene material is 76.84°, close to 90°, while the second critical angle does not exist. This is because the refraction angle is smaller than the incidence angle when the longitudinal wave is obliquely incident on the second medium from the first medium and when the sound velocity of the first medium is higher than that of the second medium, and the first critical angle is usually larger while the second critical angle does not exist when the sound velocity of the first medium is slightly lower than that of the second medium. Therefore, phased array ultrasonic inspection method can be used to make the longitudinal wave be vertically incident and the wave angle deflect after the sound waves are incident on the inside of the workpiece, thus avoiding the above situation.

2.3. Acoustic impedance

The acoustic impedance \( Z \) is defined in mechanics as the product of the medium density and the velocity of acoustic wave (elastic wave). It shows the reflection and transmission efficiency of the acoustic wave between different mediums. The reflection and transmission degree of ultrasonic wave on the interface and the reflection and transmission characteristics of the defects with different properties are all related to the acoustic impedance \( Z \) of the materials on both sides of the interface. The acoustic impedance value under the existing conditions is obtained by calculating the mass on the basis of obtaining the weight with a weighing instrument, the density of a square polyethylene material with side length of 15mm and according to the sound velocity measured in Figure 1. As shown in Table 1.

| Table 1. Acoustic impedance value of PE100 materials |
| Acoustic impedance (106kg/m²s) | Radial | Axial | At an angle of 45° |
| PE100 | 2.24 | 2.14 | 2.15 |

2.3. Acoustic impedance

The acoustic impedance \( Z \) is defined in mechanics as the product of the medium density and the velocity of acoustic wave (elastic wave). It shows the reflection and transmission efficiency of the acoustic wave between different mediums. The reflection and transmission degree of ultrasonic wave on the interface and the reflection and transmission characteristics of the defects with different properties are all related to the acoustic impedance \( Z \) of the materials on both sides of the interface. The acoustic impedance value under the existing conditions is obtained by calculating the mass on the basis of obtaining the weight with a weighing instrument, the density of a square polyethylene material with side length of 15mm and according to the sound velocity measured in Figure 1. As shown in Table 1.

Table 2. Probe parameters

| No. | Frequency (MHz) | Wafer diameter (Ds) | PE wavelength (\( \lambda \)) | Near field length (N) |
|-----|----------------|---------------------|-----------------------------|----------------------|
| 1   | 1              | 12                  | 2.36                        | 15.254               |
| 2   | 1.5            | 9.8                 | 1.573                       | 15.263               |
| 3   | 2              | 8.5                 | 1.18                        | 15.307               |
| 4   | 3              | 6.9                 | 0.787                       | 15.124               |
| 5   | 4              | 6                   | 0.59                        | 15.254               |

3. Experimental plan

The phenomenon that the ultrasonic energy gradually weakens with the increase of the propagation distance when the ultrasonic wave propagates in the medium is called ultrasonic attenuation. Medium attenuation and diffusion attenuation are the main causes of ultrasonic attenuation. The frequency of the ultrasonic probe is proportional to the degree of attenuation. The higher the frequency, the greater the attenuation. Therefore, for steel reinforced polyethylene pipes, the probe with appropriate frequency should be selected to ensure that the sound energy attenuation produced by the probe in the actual inspection process has no effect on the defect detection and quantitative analysis. Meanwhile, the bottom wave method is usually used to measure the attenuation coefficient of workpieces with small thickness, parallel upper and lower bottom surfaces and smooth surface.

In this experiment, the probes with five different frequencies are prepared in the acoustic test of the base materials. The frequencies are 1MHz, 1.5MHz, 2MHz, 3MHz and 4MHz. The relevant parameters of the above five probes are shown in Table 2. The PE100 material is processed into stepped test pieces with different thicknesses. Figure 4 shows the processed test pieces with the step heights of 10mm, 15mm, 20mm, 25mm, 30mm, 35mm, 40mm, 45mm and 50mm in sequence. Five kinds of straight
probes with different specifications are used to detect different thick bottoms. The current gain is recorded after the bottom reflected echo gain reaches 80%.

(a). Stepped test pieces
(b). The size of one of the test pieces

Figure 4. Stepped test pieces

Then the sound field attenuation of the probe in the ideal state is simulated by C language to measure the attenuation coefficient in large plane echo amplitude and distance measurement. Finally, the measure data is compared with the simulated data.

4. Experimental results

Integral formula of large flat-bottomed echo signal simulation:

$$P_1 = 2\sqrt{\pi} \int_0^a r \int_0^{\sqrt{a^2-x^2}} P_0 \left( \frac{t-d}{c} \right) dydxdr$$

(3)

Where: $d = \sqrt{\left(2z\right)^2 + \left(x-r\right)^2 + y^2}$

(4)

The corresponding measured data are shown in Table 3:

Table 3. Simulated data in large plane echo amplitude and distance measurement

| Frequency | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 |
|-----------|----|----|----|----|----|----|----|----|----|
| 1         | -.34| .03| .49| 1.20| 2.05| 2.91| 3.74| 4.58| 5.35|
| 1.5       | -.12| .28| .71| 1.37| 2.19| 3.04| 3.88| 5.69| 5.47|
| 2         | 0   | .37| .74| 1.38| 2.17| 3.01| 3.81| 4.67| 5.43|
| 3         | 0   | .34| .81| 1.51| 2.33| 3.17| 4.04| 4.79| 5.55|
| 4         | 0   | .37| .85| 1.49| 2.24| 3.14| 3.93| 4.73| 5.45|

It can be seen from Table 3 that the attenuation data obtained by simulation is basically the same at each distance. This is because the size of probe of each frequency is designed to be the same near field length, and the distance amplitude rule is basically the same.

Table 4. 80%dB value of bottom wave of PE100 materials

| Frequency | 50 | 45 | 40 | 35 | 30 | 25 | 20 | 15 | 10 |
|-----------|----|----|----|----|----|----|----|----|----|
| 1         | 38 | 34.7| 32.3| 30 | 27.3| 25.8| 23.7| 21.2| 19.3|
| 1.5       | 43.8| 40.6| 37 | 33.5| 30.1| 27.3| 24.3| 19.8| 15.7|
| 2         | 48.2| 44.7| 41 | 37.1| 32.6| 29.3| 25.2| 20.2| 15.9|
| 3         | 58.5| 55.9| 52.5| 47.5| 44 | 38.5| 32.9| 26.9| 21 |
| 4         | 81.7| 77.7| 65.3| 65.3| 58.9| 45.8| 37.7| 30.1| 22.8|
Table 4 is a data form formed on the basis of using five kinds of straight probes with different frequencies to detect different thick bottoms and recording the current gain after the bottom reflected echo gain reaches 80%. The above data are presented in the form of curves as shown in Figure 5.

It can be concluded from Figure 5 that: 1) for the probes with the same frequency, the gain value of adjusting the bottom wave to 80% of the full screen increases continuously with increase of the inspection thickness, which verifies that the attenuation described in preceding paragraphs increases constantly with increase of the inspection distance.

![Figure 5. Parameter curve](image)

2) For the probes with the same thickness but different frequencies, except the thickness less than 15mm, the higher the probe frequency, the greater the attenuation. 3) For the probes with the same thickness but different frequencies, it can be observed from the data on the probes with thickness of less than 15mm that the attenuation law of the three probes with frequencies of 1MHz, 1.5MHz and 2MHz does not fully conform to the concept of ultrasonic attenuation. This is because the current inspection thickness is located in the near-field region of the probe, and there is a maximum and minimum value of sound pressure in the near-field region, which will seriously affect the acquisition of attenuation data of the probe. So the 80% bottom wave gain value of the high-frequency probe may sometimes be slightly lower than that of the low-frequency probe in this inspection thickness range.
Table 5. Comparative data of large plane echo amplitude and distance measurement

| Probe | Distance | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | Average |
|-------|----------|----|----|----|----|----|----|----|----|----|---------|
| 1MHz  | Simulated| -0.34 | 0.03 | 0.49 | 1.20 | 2.05 | 2.91 | 3.74 | 4.58 | 5.35 |
|       | Measured | 19.3 | 21.2 | 23.7 | 25.8 | 27.3 | 30 | 32.3 | 34.7 | 38 |
|       | Difference | 19.6 | 21.1 | 23.2 | 24.5 | 25.2 | 27.0 | 28.5 | 30.1 | 32.6 |
|       | Attenuation coefficient | 0.16 | 0.15 | 0.2 | 0.14 | 0.07 | 0.18 | 0.15 | 0.16 | 0.25 | 0.16 |
| 1.5MHz| Simulated | -12 | 0.28 | 0.71 | 1.37 | 2.19 | 3.04 | 3.88 | 4.69 | 5.47 |
|       | Measured | 15.7 | 19.8 | 24.3 | 27.3 | 30.1 | 33.5 | 37 | 40.6 | 43.8 |
|       | Difference | 15.8 | 19.5 | 23.6 | 25.9 | 27.9 | 30.5 | 33.1 | 35.9 | 38.3 |
|       | Attenuation coefficient | 0.28 | 0.37 | 0.41 | 0.23 | 0.20 | 0.26 | 0.27 | 0.28 | 0.24 | 0.25 |
| 2MHz  | Simulated | 0 | 0.37 | 0.74 | 1.38 | 2.17 | 3.01 | 3.81 | 4.67 | 5.43 |
|       | Measured | 15.9 | 20.2 | 25.2 | 29.3 | 32.6 | 37.1 | 41 | 44.7 | 48.2 |
|       | Difference | 15.9 | 19.8 | 24.5 | 27.9 | 30.4 | 34.1 | 37.2 | 40.0 | 42.8 |
|       | Attenuation coefficient | 0.34 | 0.39 | 0.46 | 0.35 | 0.25 | 0.37 | 0.31 | 0.28 | 0.27 | 0.30 |
| 3MHz  | Simulated | 0 | 0.34 | 0.81 | 1.51 | 2.33 | 3.17 | 4.04 | 4.79 | 5.55 |
|       | Measured | 21 | 26.9 | 32.9 | 38.5 | 44 | 47.5 | 52.5 | 55.9 | 58.5 |
|       | Difference | 21 | 26.6 | 32.1 | 37 | 41.7 | 44.3 | 48.5 | 51.1 | 53 |
|       | Attenuation coefficient | 0.4 | 0.56 | 0.55 | 0.49 | 0.47 | 0.27 | 0.41 | 0.26 | 0.19 | 0.35 |
| 4MHz  | Simulated | 0 | 0.37 | 0.85 | 1.49 | 2.24 | 3.14 | 3.93 | 4.73 | 5.45 |
|       | Measured | 22.8 | 30.1 | 37.7 | 45.8 | 58.9 | 65.3 | 65.3 | 77.7 | 81.7 |
|       | Difference | 22.8 | 29.7 | 36.9 | 44.3 | 56.7 | 62.2 | 61.4 | 73 | 76.3 |
|       | Attenuation coefficient | 0.67 | 0.69 | 0.71 | 0.75 | 1.24 | 0.55 | -0.8 | 1.12 | 0.33 | 0.66 |

Table 5 is obtained by comparing the simulated data in Table 3 with the actually measured data in Table 4.

It can be concluded from Table 5 that the amplitude rule at different frequencies and different distances is not consistent and different material attenuations exist at different frequencies. The difference in Table 5 is obtained by subtracting the measured data from the simulated data. The simulated values measure the diffusion attenuation of the probe in the ideal state, while the gain values in the measured data include diffusion attenuation and material attenuation. So the subtraction of the two can result in a more pure material attenuation. The attenuation data is obtained by subtracting the difference of the latter distance from the difference of the previous distance. The measured attenuation coefficient at each frequency is calculated by comparing it with the simulated distance-amplitude curve. That is the average values obtained in Table 5. The X value in Table 5 refers to the probe wafer diameter.

5. Conclusion

In this paper, the basic acoustic characteristics of the steel reinforced polyethylene composite pipe is tested and studied and the acoustic characteristic parameters of PE100 material are tested. Then, the attenuation coefficient of the probes with different frequencies in the PE100 material is measured by the simulation calculation method and the actual measurement method, and the measurement attenuation coefficient at each frequency is calculated. The results show that:

1) The sound velocity of PE100 material is 2,340m/s and the attenuation coefficient is 0.3dB/mm;
2) Phased array ultrasonic inspection method can be used to make vertical incidence of longitudinal wave and avoid non-existence of the second critical angle;
3) 2MHz is the best frequency to inspect the body of steel reinforced polyethylene (PE) pipe with phased array probe.
6. References

[1] Steel Reinforced Polyethylene Plastic Pipes for Water Supply (CJ/T123-2004)[S].
[2] Liu Wentao. Application of Steel Reinforced Plastic Composite Pipes[J]. Sci-Tech Information Development & Economy, 2007, 17(32):246-247.
[3] Tian Zhong, Zhao Yuan & Zhang Fenyan et al. Performance and Application of Steel Reinforced Plastic Composite Pipe [J]. Petrochemical Industry Application, 2008 (5): 1-3.
[4] Chen Bin, Yang Hong & Hu Xuwen. Discussion on Steel Reinforced Polyethylene Plastic Pipes Used under High Temperature [J]. Process Equipment and Piping, 2010 (2): 50-52.