

# Envelope Phase Shift Feature Extraction of Underwater Target Echo

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**Abstract.** Aiming at the problem of target classification with different physical property parameters, the phase characteristics of echo envelope associated with different physical property parameters are studied, and the feature extraction method of the phase shift characteristics of the target echo envelope is established. The extraction method and the feature resolution performance of the phase shift characteristics of echo envelope are verified by the water-tank test of cylindrical targets with different materials and finite length. The experimental results of the underwater cylindrical target echo show that the feature of target echo envelope phase shift has significant difference with the change of target material, structure and radial scale. The phase shift feature of underwater target echo envelope has good performance for targets with different physical property parameters.

## 1. Introduction

Active sonar is one of the most important means of detecting and perceiving underwater objects or targets. The source of information for target recognition comes from target feature information, which is carried by the acoustic scattering wave. Among them, the essential physical information of target, such as target material type, structure composition and geometric scale are very important feature information for active sonar target recognition. Furthermore, characterization and extraction of target acoustic scattering feature which is associated with target physical properties have always been the focus of discrimination and recognition of the underwater target scattering signals.

From the view point of communication theory, it can be considered that the acoustic pulse signal emitted by active sonar produces echoes after being reflected by the target. In the process of interaction with the incident acoustic wave and the target, the target makes a linear transformation of the incident acoustic pulse, i.e. the transformation of the amplitude and waveform of the incident acoustic wave [1], which results in the fluctuation of the envelope of the target echo. The study of acoustic scattering mechanism of underwater elastic target reveals the causality between the fluctuation of target echo pulse envelope and the intrinsic physical properties, such as material, structure and scale [2-6]. The amplitude fluctuation of scattered acoustic pulse envelope is caused by the superposition of target geometric scattering wave and elastic scattering wave. Therefore, the fluctuation structure of target echo envelope contains the information of target physical properties. Previous studies have shown that there exists periodicity in the time domain of the circumferential acoustic wave of a simple solid cylindrical target in water [2], which shows periodic fluctuation of the echo envelope of the target, thus proving that the fluctuation frequency of the echo envelope is related to the material and radial diameter of the cylindrical target. The periodic distribution structure of internal baffles in periodically spaced cylindrical shells with finite length can form obvious geometric



acoustic scattering [7], which results in periodic enhancement of the envelope of echo signal, it indicates that there is an intrinsic relationship between the fluctuation of the envelope amplitude of echo pulse and the structural parameters of the target. The research based on Benchmark scaling model shows that the change rate of echo envelope amplitude of complex target not only changes with the angle of ship, but also increases with the increase of carrier frequency [8]. At present, the related research mostly focus on the absolute phase information in acoustic wave [9-15], and the amplitude fluctuation rate characteristics of target echo envelope and its resolution performance [16].

Aiming at the problem of target classification with different physical property parameters, this paper focuses on the echo envelope phase shift characteristics associated with the physical properties information of the target, establishes a method to extract the envelope phase characteristics of the target echo, and validates the echo resolution effect of the envelope phase shift characteristics of the target echo on simple cylindrical targets with different physical property parameters through the anechoic water-tank experiments.

## 2. Theoretical background of echo envelope phase and target physical properties

The echo of underwater target is composed of geometric scattering wave and elastic scattering wave. For elastic underwater target, geometric reflection wave hardly has important relationship with the material of the target, but the circumferential wave is surface wave, the propagation path and velocity of circumferential wave is related to the frequency of incident acoustic wave and the physical properties of the target, such as material, structure, shape and scale. According to geometric diffraction theory, surface circumferential wave propagates along the surface of a cylinder and radiates continuously with the circumference circles. With the increasing of the number, the amplitude of surface wave decreases gradually. As an example, the plane acoustic wave incident vertically to an infinite elastic cylinder is presented, we can get the following formula,

$$\theta_c = \arcsin(c_0/c_{ph}) \quad (1)$$

In formula,  $c_0$  is the velocity of sound in water,  $c_{ph}$  is the phase velocity of a certain type of surface wave on an elastic cylinder, which is mainly determined by the material of the target. The time difference between the geometric reflection signal and the circumferential wave around the cylindrical surface can be expressed as,

$$\tau = 2a\left(\frac{1-\cos\theta_c}{c_0} + \frac{m\pi-\theta_c}{c_{ph}}\right) \quad (2)$$

In the above formula,  $m$  is the number of circles that the circular wave travel around, it can be seen that in the time domain, the circumferential wave is a wave with equal intervals, in which the time of circumferential wave around a cylinder is,

$$\Delta\tau = 2\pi a/c_{ph} \quad (3)$$

The periodicity of the circumferential wave in time domain will cause periodic modulation of the scattering signal envelope, which is determined by the material and scale attribute parameters of the target. It is a feature that can characterize the physical property information of the target.

Generally, oblique incidence is a more common phenomenon, in the case of oblique incidence, the cylindrical surface may excite a surface wave, that propagating obliquely at an angle to the axis, and when the cylindrical surface is long enough, it may propagate helical surround waves, which propagate along the inner surface of a cylinder at a phase velocity  $c_{ph}$ , and  $c_{ph}$  decreases with the increase of  $ka$ .

There is the same time interval between adjacent echoes reflecting on the cylindrical surface through one end, but with different number of circles, that is,

$$\tau = \frac{2\pi a(\frac{1}{c_{sg}} - \cos\alpha\cos\beta/c_0)}{\sin\alpha} \quad (4)$$

In the formula,  $a$  is the radius of the cylinder, and  $c_{sg}$  is the group velocity of the surface wave.

There have obvious periodicity in the propagation of cylindrical wave, which will lead to periodic modulation of target echo envelope, and make the echo envelope phase of target with different physical property parameters have certain regularity and differences. Therefore, the envelope phase shift of the target echo contains important information about the formation of the target elastic scattering signal, and correspondingly carries the characteristic information of the target physical property parameters.

### 3. Phase feature extraction method of target echo envelope

Sub-echoes from different parts of the target with extended surface have different time to reach the receiving point. Once, the time interval between some sub-echoes is less than the pulse width of the signal, which makes it impossible to distinguish. The echo observed in the experiment is actually the result of the superposition of a series of sub-echoes. The superposition of the sub-echoes with different arrival time results in the change of the echo waveform, the envelope of echo changes accordingly. The phase is the measure to describe the change of signal waveform, the advance or delay of phase corresponds to the left or right shift of waveform, the more dense the sub-echoes near a certain time, the time of arrival of the sub-echos will be closer. The more sub-echoes arrived near a certain time, the more obvious the superposition effect is, and the larger the amplitude of the synthetic wave will be, that is, the degree of phase shift of the envelope at that time is relatively high, and vice versa. Due to the different shape, structure, material and other physical property information, the echo waveform of targets with different physical property parameters are different, and the corresponding echo envelopes will show differences. How to effectively characterize and extract the different characteristics of the physical property information of these targets is crucial for the detection and classification of underwater targets.

For the problem of target classification with different physical property parameters, this article established a method of target echo envelope phase feature extraction, which is based on the study and analysis of the physical mechanism of target echo envelope formation. Usually, the phase obtained directly from the target echo envelope signal is the wrapped phase with zigzag waveform which varies dramatically with time. To characterize or extract the phase characteristics of the target echo envelope, it is necessary to unwrap the original wrapped envelope phase to obtain the relatively monotonous absolute phase of the target echo envelope. The original phase obtained from the target echo envelope is marked as  $p_o(t)$ , and the absolute phase of target echo envelope after unwrapping is  $p(t)$ , there we have,

$$p(t) = UW(p_o(t)) \quad (5)$$

In the formula, the operator " $UW$ " is the unwrapping operator.

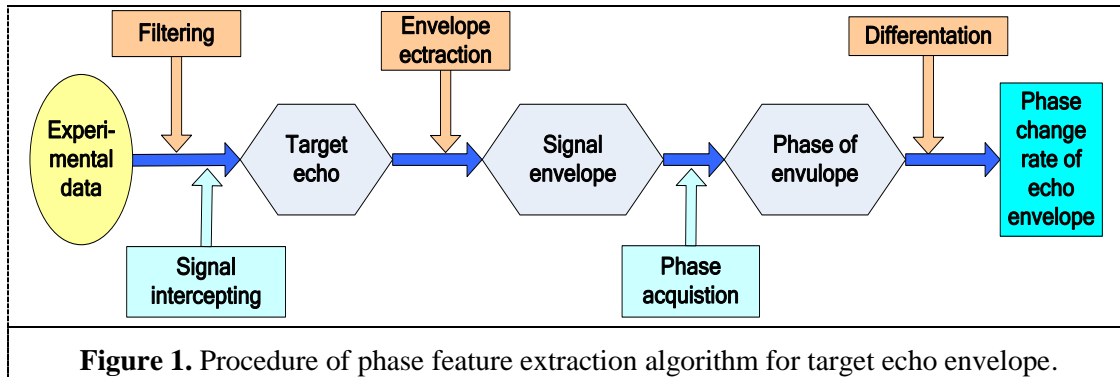
For our purposes, the absolute phase of the envelope is recorded as  $angle(S_{envelope}(t))$ , then, the specific formula of the envelope phase shift rate of echo obtained from the absolute phase of target echo envelope is as follows,

$$RCP = \frac{diff[angle(S_{envelope}(t))]}{diff(t)} \quad (6)$$

In the upper formula,  $RCP$  is the phase shift rate of envelope in time domain, the unit is in radian per second.  $S_{envelope}(t)$  is the envelope of the echo,  $angle(S_{envelope}(t))$  is the phase of the envelope, its unit is in radian.

It is noteworthy that the dimension of  $RCP$  given by formula (6) is radian/second. The larger value is not easy for comparative analysis. In practice, the dimension of  $RCP$  is converted into radian/microsecond, so that the value is in a cell which is convenient for comparative analysis. Therefore, the dimensions of the  $RCP$  in the result graph given in this paper are all radian/microsecond.

The signal processing flow of target echo envelope phase feature extraction is shown in figure 1. In the process of signal processing, the phase shift rate of the echo envelope is analysed, and two feature parameters are obtained for target discrimination, namely, the mean square deviation of the shift rate representing the change rate of the parameter value and the dispersion degree of the parameter value.



#### 4. Water-tank experiment of simple cylindrical target

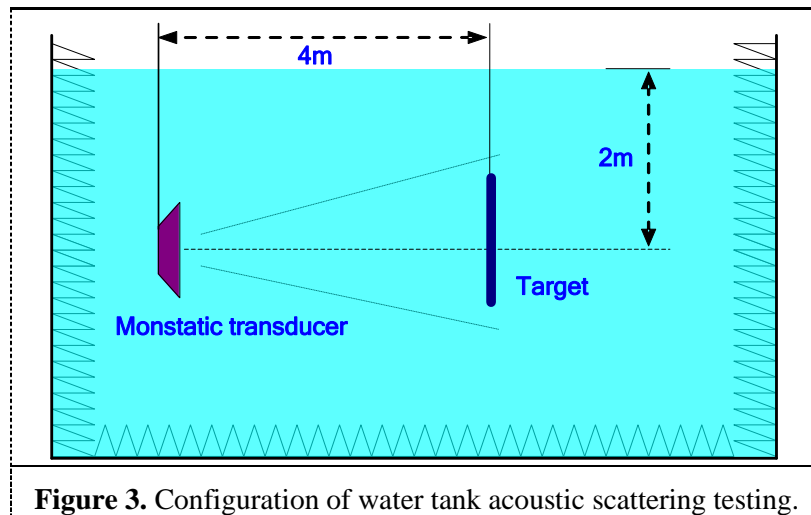
The echo characteristics of simple cylindrical targets were tested in the anechoic water-tank, and six different types of cylindrical targets were tested. Table 1 shows the specific physical properties of each target, and the photo of tested targets is shown in Figure 2.



**Table 1.** List of Target Attribute Parameters under Test

Target	Material	Shape	Diameter(mm)	Wall thickness(mm)	Length(mm)
1	Aluminum	Solid cylinder	30	-	1500
2	Stainless steel	Solid cylinder	30	-	1500
3	Rubber	Solid cylinder	30	-	1000
4	Aluminum	Hollow circular tube	30	3	1500
5	Aluminum	Hollow circular tube	50	5	1500
6	Stainless steel	Hollow circular tube	30	3	1500

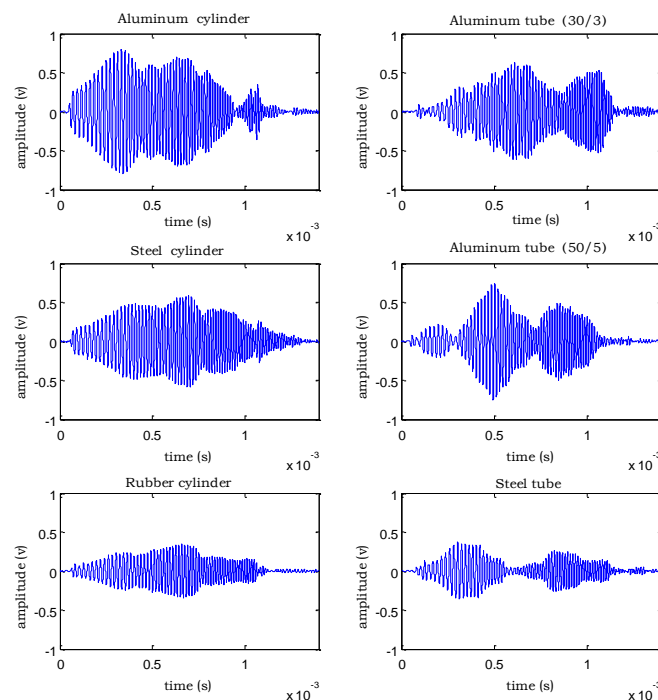
The configuration of water-tank acoustic scattering testing is shown in figure 3. The monostatic underwater acoustic transducer was placed at 2.0m underwater position through suspender. Cylindrical targets were hung at 2.0m below water surface by thin rope. The geometric centre of the target is 4.0m away from centre of transducer, which was located in the beam center of directional monostatic transducer. The test signal is broadband linear frequency modulation signal, with frequency range from 40 kHz to 80 kHz, and the pulse width of the signal is 1ms.



**Figure 3.** Configuration of water tank acoustic scattering testing.

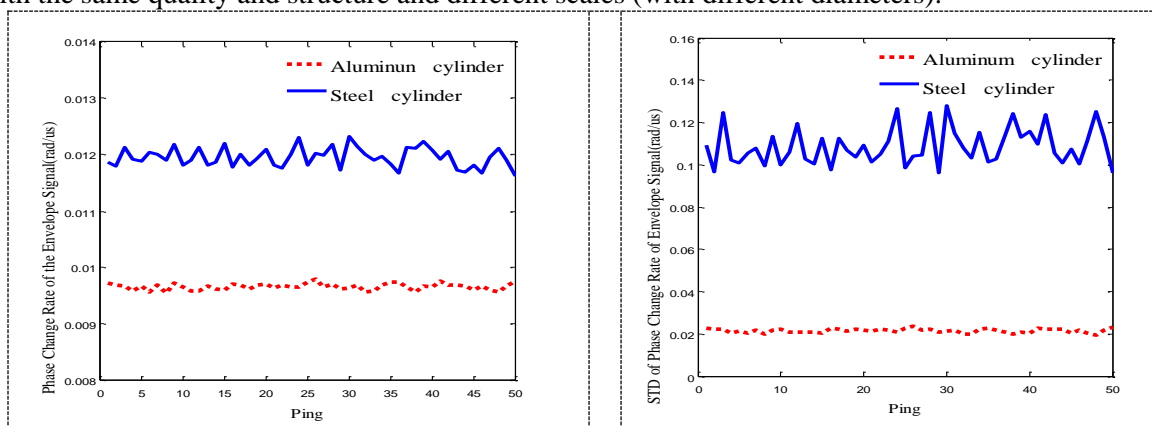
## 5. Experimental result and discussion

Based on the analysis of formation mechanism of echo envelope phase of underwater targets, the experimental data of cylindrical targets with different materials, structures and scales are processed and analysed. The echo signals of simple targets are processed according to the data processing flow shown in figure 1. Echoes of simple cylindrical targets and the corresponding echo envelope phase characteristics within 50 consecutive pings are given in the follow-up figures.

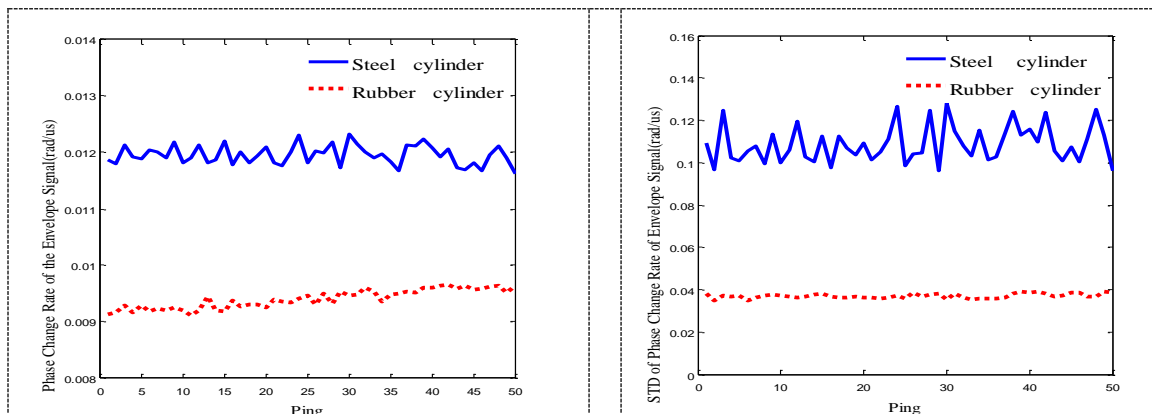


**Figure 4.** Time domain echo structures of each simple target under test.

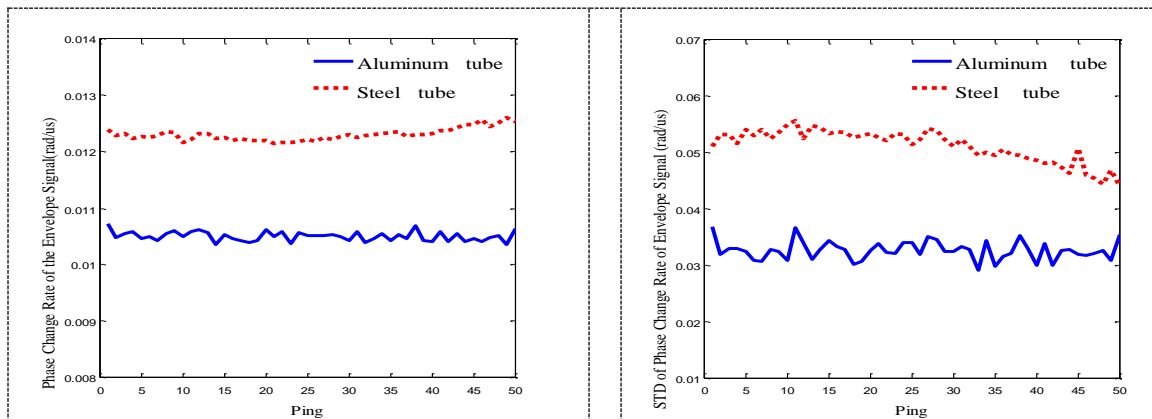
Figure 4 is the time domain echo structure of the simple cylindrical targets. The echo waveform of targets with different physical property parameters are different. The experimental results are consistent with the theoretical analysis. Figure 5 to figure 10 are the comparison of echo envelope phase characteristics of various simple targets according to the corresponding relationship of physical attribute parameters. Figure 5 and figure 6 are the comparison of echo envelope phase characteristics of solid cylindrical targets with the same scale, structure and different materials; figure 7 is the comparison of echo envelope phase characteristics of hollow cylindrical targets with the same scale, same structure and different materials; figure 8 and figure 9 are the comparison of echo envelope phase characteristics of targets with the same scale, material and different structures (solid cylinder and hollow cylinder); figure 10 is the comparison of echo envelope phase characteristics of hollow cylindrical targets. Comparisons of echo envelope phase characteristics of hollow cylindrical targets with the same quality and structure and different scales (with different diameters).



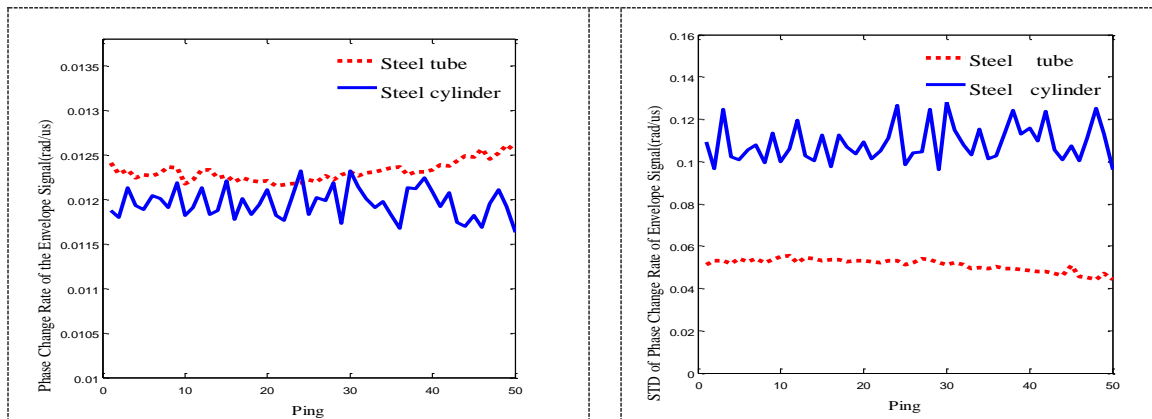
**Figure 5.** Echo envelope phase characteristics of aluminum cylinder and steel cylinder at the same scale.(Left) Phase shift rate, (Right) Standard deviation of phase shift rate.



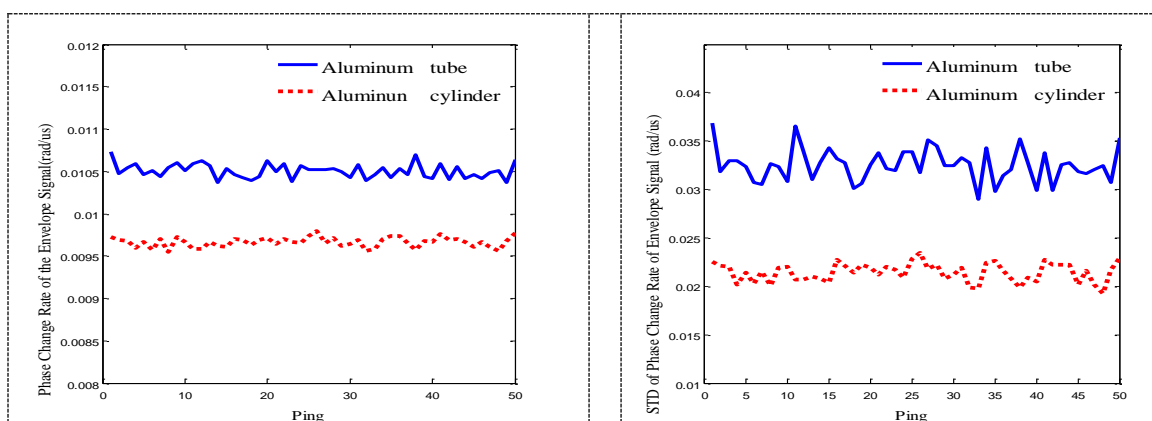
**Figure 6.** Echo envelope phase characteristics of steel cylinder and rubber cylinder with the same scale.(Left) Phase shift rate, (Right) Standard deviation of phase shift rate.



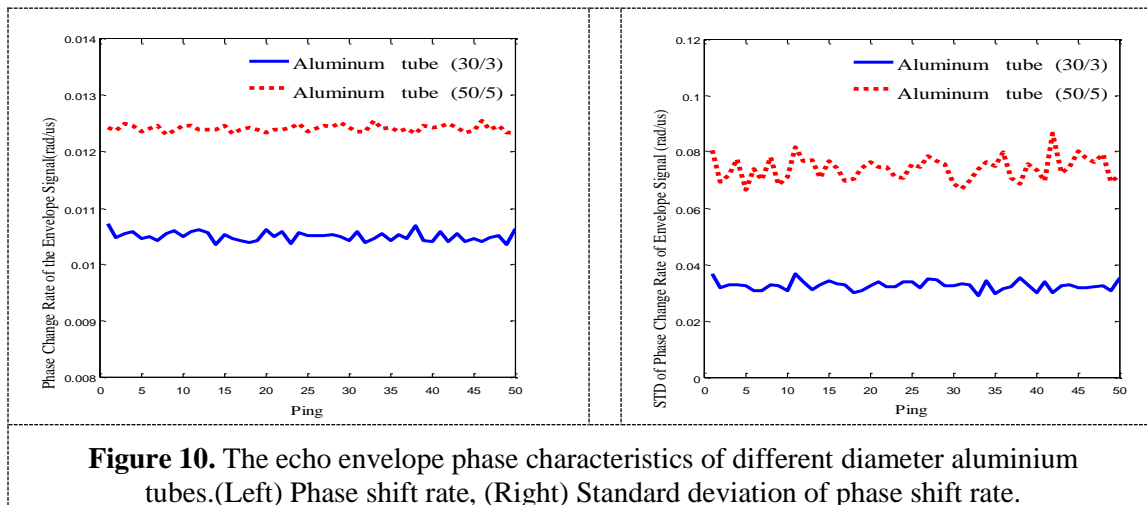
**Figure 7.** The phase characteristics of echo envelope of aluminium tube and steel tube with the same scale. (Left) Phase shift rate, (Right) Standard deviation of phase shift rate.



**Figure 8.** The echo envelope phase characteristics of steel tube and steel cylinder with the same scale. (Left) Phase shift rate, (Right) Standard deviation of phase shift rate.



**Figure 9.** The echo envelope phase characteristics of aluminium cylinder and aluminium tube at the same scale. (Left) Phase shift rate, (Right) Standard deviation of phase shift rate.



From figure 5 to figure 10, we can draw some conclusions as follows. Firstly, under the same scale and structure, the phase shift rate of echo envelope of steel cylinder is larger than that of aluminium cylinder, while that of rubber cylinder is the smallest of the three. The phase shift rate of echo envelope of the three cylinders is in the range of 0.009 rad/us and 0.013 rad/us. Secondly, under the same scale and structure, the change rate of echo envelope phase of hollow steel tube is larger than that of hollow aluminium tube, and the values of both are in the range of 0.01 rad/us and 0.013 rad/us. Thirdly, under the same scale and different structure conditions, the echo envelope phase shift rate of hollow steel tube is larger than that of solid steel column, the echo envelope phase shift rate of hollow aluminium tube is larger than that of solid aluminium column. Fourthly, under the same length, the echo envelope phase shift rate of hollow aluminium tube with diameter of 50 mm and wall thickness of 5 mm is larger than that of hollow aluminium tube with diameter of 30 mm and wall thickness of 3 mm. The last but the most special one is that the phase shift rate of echo envelope is relatively large, and the corresponding fluctuation rate of single Ping echo envelope phase shift is relatively large; however, it is noteworthy that the phase shift rate of echo envelope of hollow steel tube with the same scale is larger than that of solid steel column, and the fluctuation degree of phase shift rate of echo envelope of solid steel column is sharper than that of hollow steel tube.

By comparing the echo envelope phase characteristics of simple cylindrical targets with different physical property parameters, it can be seen that the echo envelope phase shift rates of cylindrical targets with different physical property parameters, that is, their mean square deviation, are obviously different.

## 6. Conclusion

Based on the formation mechanism of target echo envelope, the correlation between echo envelope phase shift and target physical property parameters is analysed in this article. The phase characteristics of echo envelope associated with target physical properties are studied according to the classification problem of target with different physical property parameters. A feature extraction method based on the phase characteristics of echo envelope is established. The extraction method and feature classification performance are verified in an anechoic water-tank experiment. The results show that the difference of target physical property parameters will lead to the difference of target echo envelope phase characteristics. Especially, when the material and structure of the target change, the target echo envelope phase characteristics have a good ability to classify and distinguish the target. Therefore, the envelope phase feature of target echo is an important feature reflecting the physical properties of target, and it is a potential feature for target classification.



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