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SIMULATION AND ANALYSIS OF ULTRASONIC GUIDED WAVE NONDESTRUCTIVE TESTING OF COFFERDAM ROD BASED ON DISPERSION CURVES

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ABSTRACT

Nondestructive testing of cofferdam rod bond integrity is a new important subject. Based on dispersion properties, this paper filters out an appropriate guided-wave frequency for cofferdam rod testing and gives the reflected wave which can identify the bottom of cofferdam rod with simulation analysis. The adhesive quality of cofferdam rod can be quantified by calculating the attenuation coefficients, which realizes nondestructive testing.

Keywords: *Ultrasonic Guided Wave, Frequency Dispersion, Adhesive Quality, Simulation And Analysis*

1. FREQUENCY DISPERSION OF ULTRASONIC GUIDED WAVE

The phenomenon that phases velocity is changed with the difference frequency in ultrasonic guided wave known as dispersion. The phenomenon arises from the impact of guided wave's geometry which is a geometric dispersion rather than physical dispersion. The frequency feature of the guided wave is represented in the form of wave packet and wave packed width that usually be used to measure the strength of dispersion. As shown in Figure 1., the time between wave's first edge and second edge reaching the second point can be represented by their speed. After a propagation distance L, the decrement of wave packet' amplitude can be expressed as:

$$\Delta A = C\sqrt{T} = C\sqrt{L\left(\frac{1}{v_{\min}} - \frac{1}{v_{\max}}\right)}$$

$v_{\max}$: the speed of wave packet's first edge， $v_{\min}$: the speed of wave packet's second edge， T_0 : time of initial wave packet， T_1 : time after a propagation distance L， T : increase of wave packet width caused by dispersion.

The expansion of dispersion wave packet is liner in time and space during the propagation. The speed of propagation is different between the two ends of the dispersion wave envelop which causes the increase of wave packet width. For better analysis and process, a single mode and non-dispersive ultrasonic guided wave is expected to be inspired and other mode appearing in the received signal can be regarded as be caused by the defect of waveguide geometry [1-4].

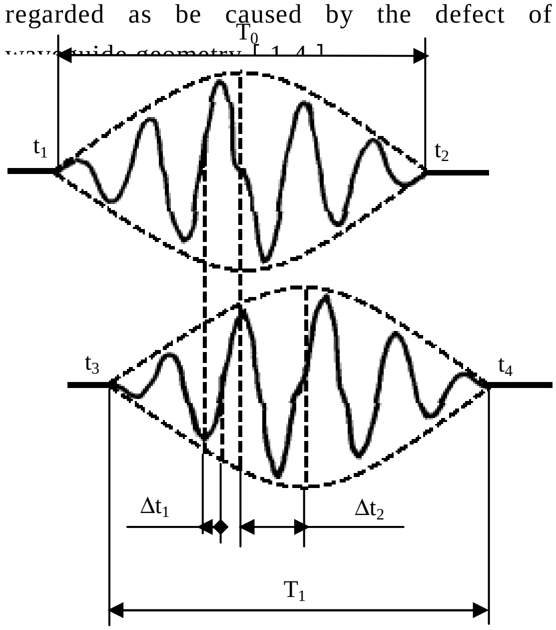

Figure 1. Diagram Of Ultrasonic Guided Wave Time Propagation

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2. FEATURE OF THE ULTRASONIC GUIDED WAVE TESTING OF COFFERDAM METAL-ROD

Cofferdam rod system can be divided into three layer structures as metal rod, adhesives, rock and other media. The drawing of dispersion curve is complicated because of the complex of the boundary condition. The process of analysis will draw on previous work and combine with numerical simulation [5, 6] .

The ultrasonic guided wave testing of cofferdam rod can be divided into low and high frequency. M.D.Beard and others has drawn the low and high frequency energy dispersion curve through experimental as shown in figure 2. and figure 3..

Dispersion curve of low frequency is shown in figure 2. L(0,1) is the minimum power loss mode that it is easy to be distinguished with other modes. And there is a minimum point of attenuation near 70KHZ.As a result, L(0.1) is the best testing mode in low frequency [7, 8] .

Dispersion curve of high frequency is shown in figure 3. L(0,11) is the minimum power loss mode and other modes will be attenuated quickly in the area. From the figure ,we can see the minimum attenuation frequency band is in the 1.8MHZ between 2.5MHZ.For high frequency of ultrasonic guided wave testing ,it will be helpful to bring out minimum attenuation mode that choose the frequency band between 1.8MHZ and2.5MHZ.

Attenuation will be increased by the increasing of frequency in low-frequency testing. However, there is a difference between the low and high frequency band that energy spread will be concentrated in the center of cofferdam rod with the increasing of frequency in some mode of high-frequency which means the impact of the metal rod and surrounding become reducer and medium energy attenuation become less. In the high-frequency ultrasonic guided wave testing, we can take advantage of high-end mode of high-frequency to make a reasonable choice for test frequency.

3. SIMULATION AND ANALYSIS

Finite element model can be set to rod bonded well (BG) , rod bonded better (MG) , rod bonded general (CC) , rod bonded poor (RE) and rod bonded stick poor (EE) . Time step is 1us. Total time is 2ms. Loading force F=50N.

3.1 The Excitation Mode Of Ultrasonic Guided Wave

The wave group mode is adopted to simulate the excitation mode on-site to generate group wave with different wave packet width and frequencies. Three types of different first wave width of ultrasonic guided wave have been simulated as 50µs,110µs and 240µs The corresponding frequencies are 25KHZ, 40KHZ, 50KHZ, 60KHZ, 75KHZ, 80KHZ, 90KHZ, 1MHZ, 2MHZ and 3MHZ. Some graphs of group wave field is shown in Figure 4.

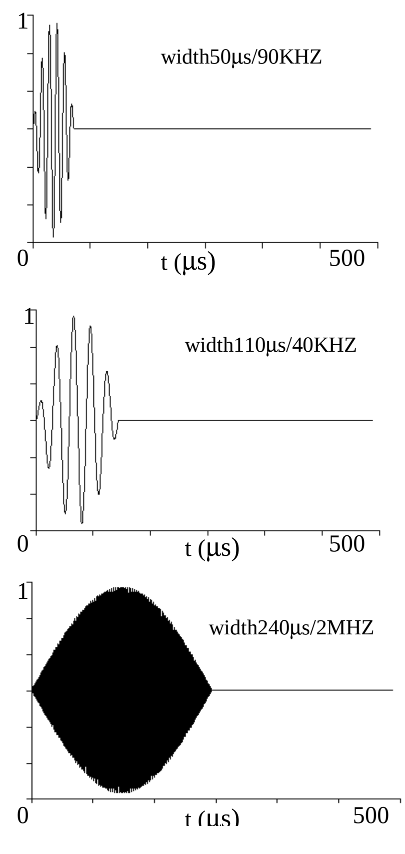

Figure 4. Different First Wave Width Of Excitation Wave

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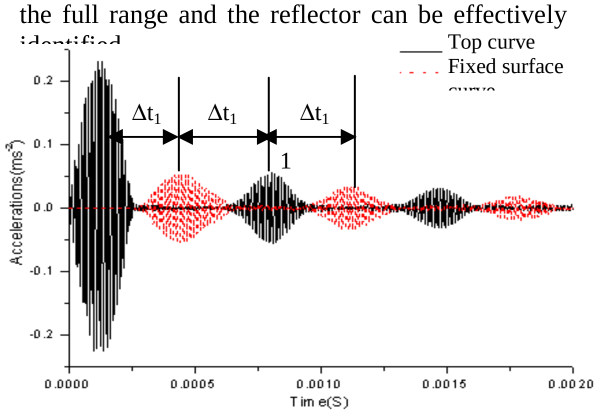
3.2. Identification Of Cofferdam Rod Reflected Wave

It's important to identify the bottom of cofferdam rod reflected wave and distinguish the adhesive quality of the cofferdam rod by using the attenuation and compare the difference between the response curve of top and bottom of cofferdam rod. In order to avoid the confusion with the fixed surface reflected wave, it's necessary to collect response curve on the fixed surface to identify the bottom of cofferdam rod reflected wave. The following is divided into two parts, low and high frequency, to analyze.

3.2.1 identification of reflected wave in low frequency

Figure 5,6,7,8 are the comparison chart between the top and fixed surface which are good, fair, poor and very poor adhesive quality. Measurement shows $\Delta t_1 = 332\mu s$、$\Delta t_2 = 331\mu s$、$\Delta t_3 = 332\mu s$、$\Delta t_4 = 335\mu s$ that fixed surface reflected wave(1,2,3,4) can be indentified clearly which means Center frequency 75KHZ is sensitive to the adhesive quality of cofferdam rod fixed surface of the full range and the reflector can be effectively identified.



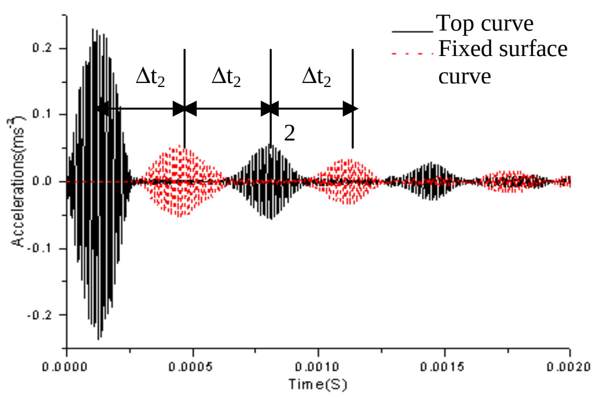


Figure 6. Time Domain Curve Of General Adhesive Quality (75KHZ)

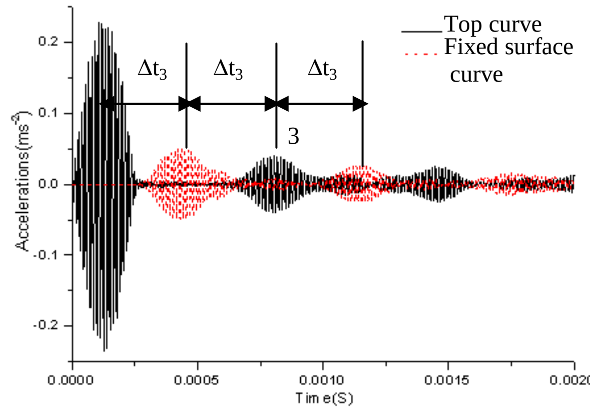


Figure 7. Time Domain Curve Of Poor Adhesive Quality (75KHZ)

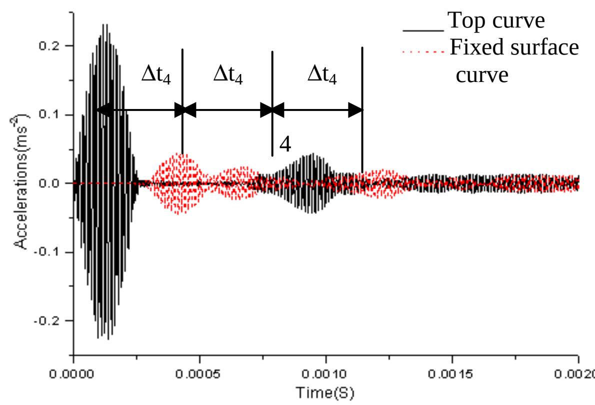


Figure 8. Time Domain Curve Of Worse Adhesive Quality (75KHZ)

3.2.2 the identification of reflected wave in high-frequency

As shown in the figure 9,10,11,12 , the adhesive quality of the response curve is different, but the first reflected wave 1 is the same in time (as shown in table 1) , roughly in the 888us place which is the same as reflected wave of the bottom of cofferdam rod with good adhesive quality. So it's the bottom of cofferdam rod reflected wave. Sometimes it's difficult to identify the bottom of cofferdam rod reflected wave at second time because of attenuation and the increasing mode of ultrasonic guided wave, which is determined by the dispersion feature of high-frequency ultrasonic guided wave. Hence it's not difficult to conclude that center frequency 2MHZ can identify the bottom of cofferdam rod reflected wave clearly of the full range adhesive quality.

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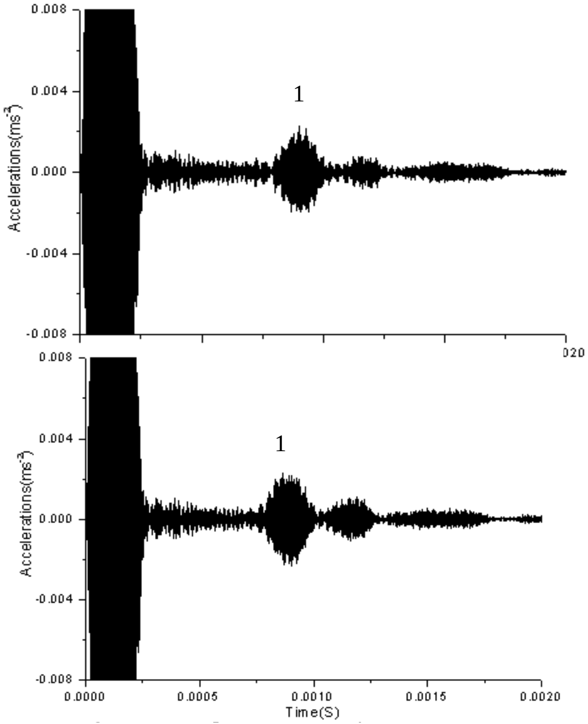
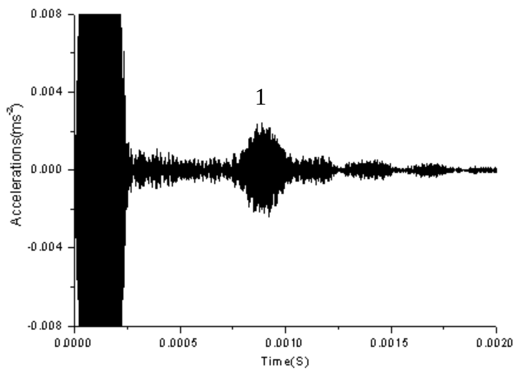


Quality (2MHZ)



lity (2MHZ)

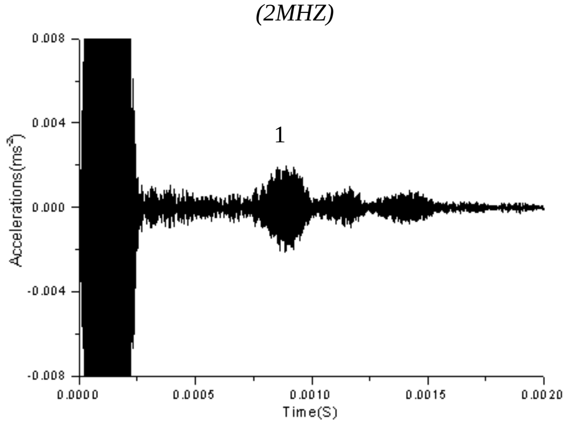


Figure 12. Response Curve Of Worse Adhesive Quality (2MHZ)

4. THE QUANTITATIVE PARAMETER FOR JUDGING COFFERDAM METAL ROD BONDING QUALITY

Judgment of cofferdam rod bonding quality depends on bonding situation between Metal rod and the surrounding media. In this paper, the differences of bonded area which is a concept used to measure the bonding quality lead to the differences of reflection amplitude. Making use of response curve measured on the spot, we can learn the amplitude of each reflection wave and distinguish bonding quality of cofferdam metal rod quantitatively［9-12］.

Attenuation extent of ultrasonic Guided wave spreading in a medium is different because of the difference impedance surface energy. As we know from this, relations between Wave attenuation extent and stand or fall of metal rod bonding quality are close. We can obtain through analysis that consonant Law wave can be expressed equally as follows when guided wave spread in a medium.

$$A = A_0 e^{-ax} e^{j(\omega t - kx)} \qquad (1)$$

In this formula, $A_0 e^{-ax}$ is envelope function. From $A_0 e^{-ax}$, Attenuation coefficient which reflect wave attenuation extent is expressed as follows：

$$a = \frac{1}{x}\ln\frac{A_0}{A} = \frac{2.3026}{x}\lg\frac{A_0}{A} \qquad (2)$$

In this formula, A_0 is high amplitude of first wave. A is Transmission distance and highest point amplitude of reflection wave from x. Corresponding amplitudes is A_1, A_2 for two different positions $x_1, x_2 (x_2 > x_1)$. So according to formula (2) attenuation coefficient may be expressed approximately as follows:

$$a = \frac{1}{(x_2 - x_1)}\ln\frac{A_1}{A_2} \qquad (3)$$

Therefore, finding the key reflection wave is the key of quality detection to cofferdam metal rod bonding. Table 1 is time and amplitude data of each highest point of reflection wave. Using the data in table 1, we can calculate attenuation coefficient shown in table 2.

Figure 13. is corresponding relation curve fitted out from the table 2. data which

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expresses the relation between bonded area overall length and attenuation coefficient. We can know , the attenuation coefficient increases gradually with the increase of bonding area. The corresponding energy attenuation increases either. The physical trend that energy attenuation increased with the increase of bonding area can be reflected correctly. So we can judge the binding quality of cofferdam metal rod and solve the major puzzled problem which plagued nondestructive testing world of cofferdam metal rod in the long time.

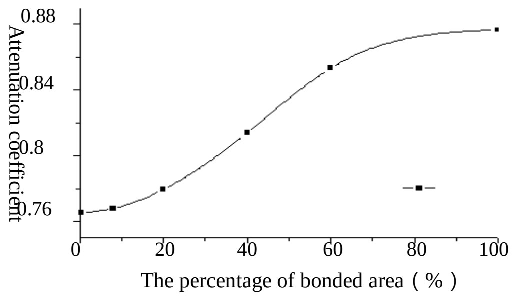

Figure 13. Corresponding Relation Curve Between Attenuation Coefficient And Bond Area

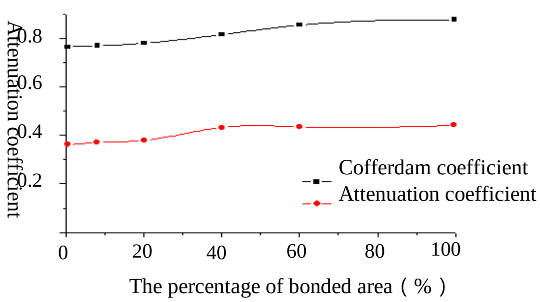

Figure 14. Corresponding Relation Curve Of Attenuation Between Coefficient And Cofferdam

Figure 14. is the contrast curve for overall length and attenuation in cofferdam period. It can be seen attenuation coefficient in cofferdam period is a half of the attenuation coefficient overall length approximately. In other words, half of ultrasonic guided wave energy decays in the internal of metal rod. This proves further the conclusion is correct that high frequency part exist the spreading of certain mode energy which focus on the internal of metal rod. The attenuation coefficient of cofferdam section also increases with the increase of bond area, which shows the stand or fall of bond quality affects the size of the attenuation coefficient really and directly.

5. CONCLUSIONS

1) To make sure first wave and bottom reflected wave are not overlapped with each other, the larger first wave width of ultrasonic guided wave should be selected for any tested object which will reduce dispersion and be identified critical reflected wave.

2) The multi-mode of ultrasonic guided wave should be considered when select the size of exited area. The less modes the larger exited area and the more modes the smaller area. It can inhibit the effect generated by the unnecessary mode.

3) fixed surface reflected wave can be identified clearly as the present of 75KHZ in low-frequency and effective bond length can be calculated. The bottom of rod reflected wave can be identified clearly as the present of 2MHZ in high-frequency and attenuation coefficient can be calculated. According to the coefficient adhesive quality can be quantified.

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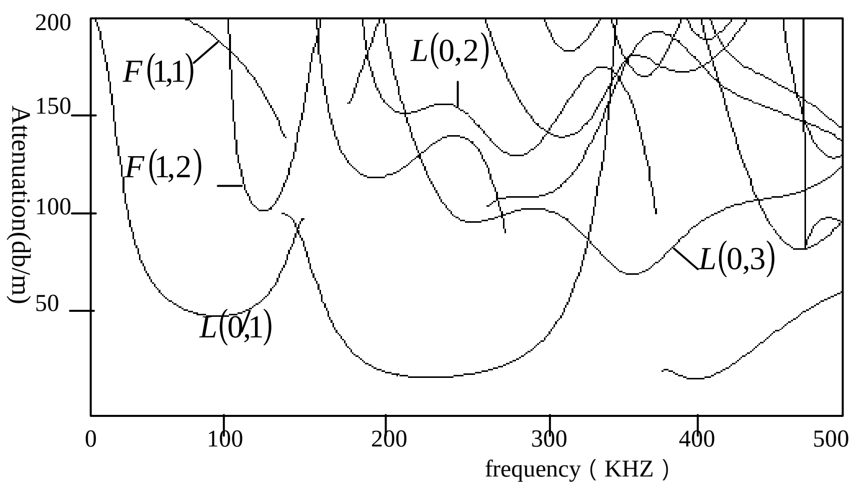

Figure 2. Dispersion Curve Of Low Frequency Propagation

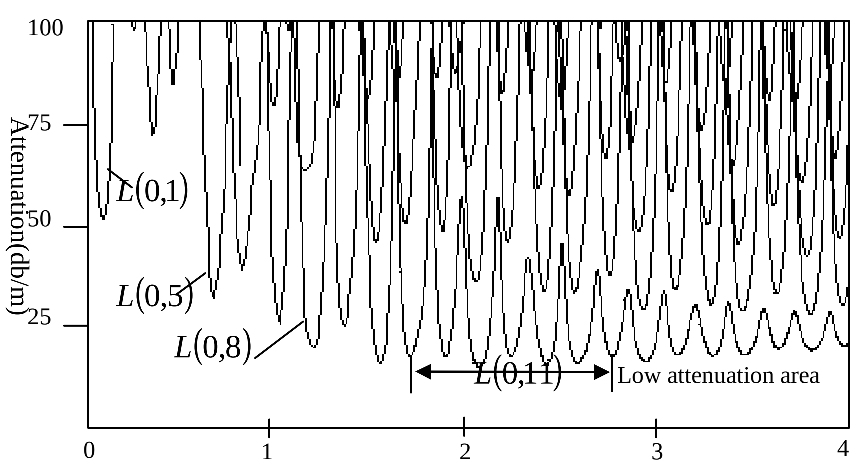

Figure 3. Dispersion Curve Of High Frequency Propagation

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Table 1. The Highest Point Of Each Reflected Wave

data		better	good	general	poor	Stick poor	Metal rod
Top first wave	time(μs)	140	140	140	140	140	140
	amplitude (ms^{-2})	0.029270	0.029280	0.029280	0.029280	0.029280	0.029280
Bottom reflected wave	time (μs)	887	889	886	887	886	889
	amplitude (ms^{-2})	0.0017720	0.0019100	0.00216100	0.00241841	0.0025052	0.0025290
Surface first wave	time (μs)	383	375	375	375	375	396
	amplitude (ms^{-2})	0.003400	0.003310	0.003300	0.0031590	0.003008	0.0032291
Bottom first wave	time (μs)	515	513	512	512	513	514
	amplitude (ms^{-2})	0.00275	0.002687	0.0026528	0.002620	0.0025000	0.0026901

Table 2. Attenuation Coefficient Of Each Band

attenuation coefficient	better (100%area)	Good (80%area)	General (60%area)	Poor (30%area)	Stick poor (10%area)	Metal rod (0%area)
Full length	0.87660	0.85306	0.81262	0.77543	0.76595	0.7649
Cofferdam rod	0.44041	0.43361	0.43137	0.37857	0.36047	0.35277