Ultrasonic Inner inspection of Crude Oil Pipeline Based on Bispectrum Dimension Reduction Method

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Abstract. The key technology of Ultrasonic inner inspection of crude oil pipeline is to obtain the residual thickness of pipeline wall by the analysis and processing of the ultrasonic echo signal. In order to solve the problem that the second-order statistics are easy to appear errors, bispectrum is proposed to process the echo signal with the least amount of computation in higher order statistics in this paper. Then bispectrum is projected into one-dimensional frequency space by the dimension reduction method, and the one-dimensional diagonal slice of bispectrum is extracted to analyse the characteristics of echo signal, which greatly improves the intuition of data processing. Experimental results show that the bispectrum dimension reduction method has high accuracy in processing ultrasonic echo signal, which is much better than the second-order statistics method. It is suitable for ultrasonic inner inspection of long distance crude oil pipeline.

Keywords: Crude Oil Pipeline, Ultrasonic Inner Inspection, Second-Order Statistics, Higher-Order Statistics, Bispectrum Dimension Reduction

1. INTRODUCTION

Due to long-time operation, crude oil pipelines are prone to corrosion due to internal and external factors[1]. The corrosion would make the pipeline wall rough and many mutational interfaces appear, moreover the acoustic reflectivity of pipeline inside wall is very higher, which caused the ultrasonic echo signal very complex. At the same time, the non-uniform movement of the detector under the oil pressure drive, the trafficability of the detector at the turning or pipe diameter change, the impurities and bubbles in the oil layer, oil temperature, and the data lack of some probe, etc., will cause the distortion of the echo signal, which brings great difficulties to the data processing[2]. Therefore, the core problem of ultrasonic inner inspection of crude oil pipeline is to analyse and process the ultrasonic echo signal to obtain the remaining thickness of the pipe wall, so as to predict the corrosion of the pipe wall, maintain the pipeline in time and reduce unnecessary losses.

At present, the method of second-order statistics (correlation function in time domain, power spectral density in frequency domain) is mostly used in the processing of ultrasonic echo signal, among which the correlation function (Blackman-Tukog) method and the periodogram method[3] of classical spectrum estimation, and Burg algorithm[4-6], Levinson-Durbin recursive algorithm[7] and Marple algorithm[8], etc. of modern spectrum estimation are widely used. However, the second-order statistics method assumes that the echo signal has linear and Gaussian characteristics, based on which the amplitude or second-order statistical information is obtained, but a large amount of higher-order statistical information hidden in the echo is lost.

In fact, the ultrasonic inner inspection signals of crude oil pipeline have nonlinear and non-gaussian characteristics, and the second-order statistics is prone to errors in processing such signals. The higher-order statistics[9] not only has the advantages of second-order statistics, but also contains more abundant information, such as phase, gaussianity and so on [10], so it can be used to analyze the ultrasonic echo signal. In this paper, bispectrum is used to process the echo signal with the least amount of computation in higher order statistics. Then bispectrum is projected into one-dimensional frequency space by the dimension reduction method, and the one-dimensional diagonal slice of bispectrum is extracted to analyse the characteristics of echo signal, which greatly improves the intuition of data processing.

2. BISPECTRUM

2.1. Bispectrum Estimation Algorithm

Bispectrum estimation is divided into nonparametric method and parametric method[11]. The nonparametric method is divided into direct method (FFT method) and indirect method (correlation method). Among them, because of the fast operation speed of FFT, the direct method is adopted here:

- The data to be processed $x(0),\cdots,x(N-1)$ (length is N) is divided into k segments, and each segment contains M samples, namely, $x^{(i)}(0),\ x^{(i)}(1),\ \cdots,\ x^{(i)}(M-1)$, among them, $N=k\bullet M$, $i=1,\cdots,k$.

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- Calculation of DFT coefficient

$$X^{(i)}(m)=\frac{1}{M}\sum_{n=0}^{M-1}x^{(i)}(n)e^{-j2\pi mn/M}, m=0,\cdots,M/2; i=1,\cdots,k \tag{1}$$

Among them, $x^{(i)}(n)$ is the segment i data.

- Triple correlation Calculation of DFT coefficients

$$\hat{b}_i(m_1,m_2)=\frac{1}{\Delta\omega^2}\sum_{p_1=-L_1}^{L_1}\sum_{p_2=-L_1}^{L_1}X^{(i)}(m_1+p_1)X^{(i)}(m_2+p_2)X^{(i)}(-m_1-p_1-m_2-p_2) \tag{2}$$

Among them, $\Delta\omega=f_s/N_0$, $0\le m_2\le m_1$, $m_1+m_2\le f_s/2$, and N_0 and L_1 must satisfy $M=(2L_1+1)\bullet N_0$.

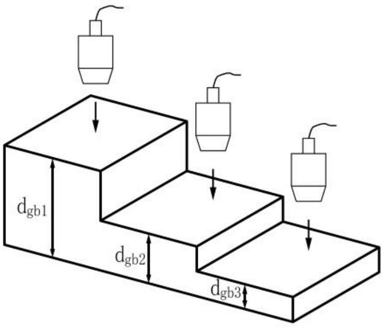
- The bispectrum estimation of the data to be processed is given by the average value of K segment bispectrum estimation, namely,

$$B_x(\omega_1,\omega_2)=\frac{1}{k}\sum_{i=1}^{k}\hat{b}_i(\omega_1,\omega_2) \tag{3}$$

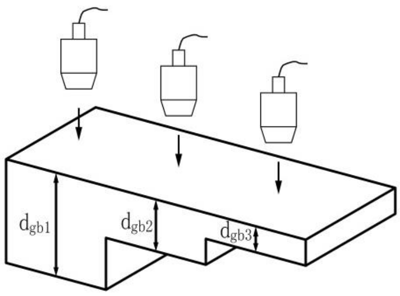
Among them, $\omega_1=m_1\bullet\frac{f_s}{N_0}, \omega_2=m_2\bullet\frac{f_s}{N_0}$.

2.2. Simulation Experiment

A ladderlike steel sample whose material is close to the actual pipeline is used to simulate the residual wall thickness of crude oil pipeline in the experiment, as shown in **Fig.1**. The sample is detected with single point on the different thickness location using single ultrasonic probe (center frequency is 5 MHz) and sampling frequency of 100 MHz.



(a) Simulation of inner wall corrosion detection



(b) Simulation of outer wall corrosion detection

Fig. 1 Simulation of corrosion detection for inner and outer wall of pipeline

Among them, the case of pipeline inner wall corrosion detected single-point by the single probe is simulated in **Fig.1**(a), and the case of pipeline outer wall corrosion detected single-point by the single probe is simulated in **Fig.1**(b). d_{gb1} is the normal wall thickness of pipeline, 25.4mm; d_{gb2} and d_{gb3} is the residual wall thickness at corrosion site, 12.8mm and 6.4mm respectively.

In **Fig.1**, when the probe scans and detects a point at d_{gb3} (the pipe wall thickness of 6.4mm), the time domain diagram of the original A-scan waveform data with 7029 sampling points is obtained, as shown in **Fig.2**.

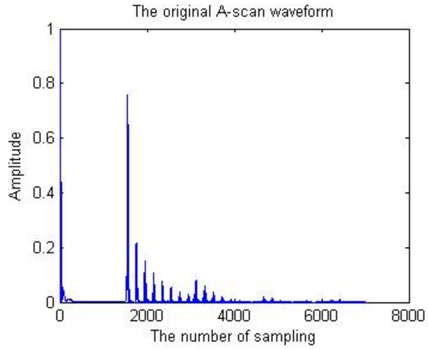
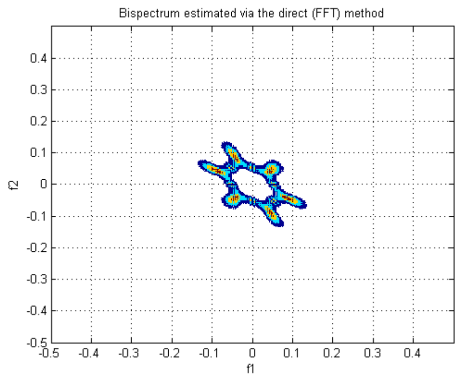
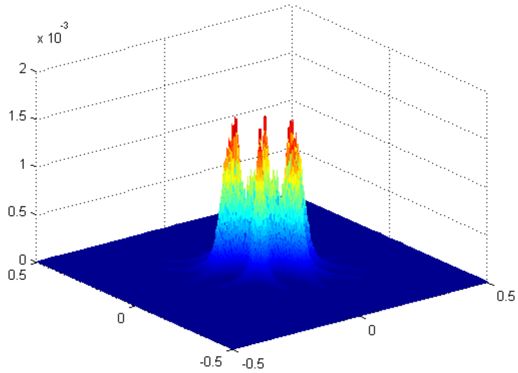


Fig. 2 Time-domain diagram of original A-scan waveform data

The original A-scan waveform shown in **Fig.2** is processed by using direct bispectrum estimation, and it is divided into segments, the FFT length of each segment, the number of data overlaps, and the Rao-Gabr ideal window is added when the sampling sequence is segmented to obtain the bispectrum amplitude contour map and three-dimensional graph shown in **Fig.3**.



(a) Contour map



(b) Three-dimensional graph

Fig. 3 Bispectrum estimation

It can be seen in **Fig. 3** that the obvious peak appears at the frequency pair (0.05, 0.05), which not only gives the position of the secondary phase coupling phenomenon (and the position of the other 11 peaks can be obtained by the symmetry of the bispectrum), but also shows that the bispectrum has a certain inhibition effect on Gaussian noise. But bispectrum is a two-dimensional function, and the image describing its amplitude is three-dimensional, so the analysis is not as easy as power spectrum. Therefore, if the "dimension reduction" method is adopted, the bispectrum is projected into one-dimensional frequency space, and the one-dimensional diagonal slice of bispectrum is extracted to analyze the characteristics of echo signal, the intuitiveness of data processing can be greatly improved.

3. ULTRASONIC ECHO SIGNAL PROCESSING BASED ON BISPECTRUM DIMENSION REDUCTION METHOD

3.1. Bispectrum Dimension Reduction Method

Considering that three-order cumulant and three-order moment of stationary random process $x(n)$ with zero mean are equal, the three-order cumulant is defined as:

$$C_{3x}(\tau_1,\tau_2)=E[x(n)x(n+\tau_1)x(n+\tau_2)] \tag{4}$$

Taking $\tau_1=\tau_2$, we obtain the main diagonal slice of three-order cumulants[12]:

$$C(\tau)=C_{3x}(\tau,\tau)=E[x(n)x(n+\tau)x(n+\tau)] \tag{5}$$

The results of bispectrum dimension reduction can be obtained by one-dimensional Fourier transform for $C(\tau)$, namely:

$$SB(\omega)=\sum_{\tau=-\infty}^{\infty}C(\tau)e^{-j2\pi\omega t} \tag{6}$$

3.2. Algorithm Steps

- Intercepting the data between the primary and secondary interface waves in the ultrasonic echo signal.
- Bispectrum dimension reduction analysis is performed on the intercepted echo data.
- According to the symmetry of the spectrum diagram, only to reserve the left half, namely, low frequencies, and find out the maximum points of amplitude.
- To extract the max value of the maximum points, the corresponding frequency of this value is the frequency of wall thickness.
- According to the corresponding relationship between the transit time t of wall thickness, the frequency f_{gb} of wall thickness and the wall thickness d

$$d=\frac{v\cdot t}{2}=\frac{v}{2f_{gb}} \tag{7}$$

The wall thickness d of pipeline can be calculated.

In the equation, v is the propagation velocity of ultrasonic wave in the detected pipeline wall; f_{gb} is calculated by the abscissa serial number $peak\_pos(b)$ corresponding to the maximum amplitude except DC component in the bispectrum dimension reduction diagram:

$$f_{gb}=peak\_pos(b)\cdot\Delta f \tag{8}$$

In the equation, Δf is the unit length of abscissa.

And $$\Delta f=\frac{f_s}{num\_1d} \tag{9}$$

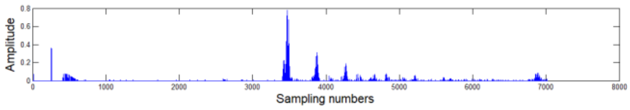
where f_s is the sampling frequency, num_1d is the echo data points of participating in bispectrum dimension reduction analysis.

Substituting equations (8) and (9) into equation (7) to obtain the wall thickness:

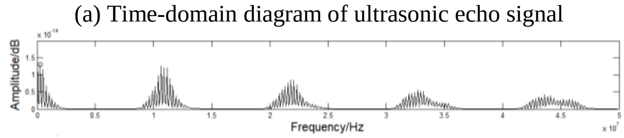
$$d=\frac{v\cdot num\_1d}{2\cdot peak\_pos(b)\cdot f_s} \tag{10}$$

3.3. Simulation Experiment

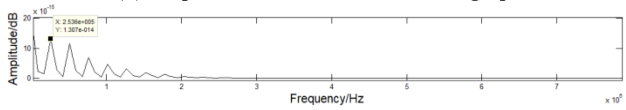
For the steel test block simulating the corrosion of the inner and outer wall of the pipeline in **Fig. 1**, take a detection point at d_{gb2} (the wall thickness is 12.8mm) to analyze, and the time domain waveform of the ultrasonic echo signal is shown in **Fig. 4** (a). The data between the primary and secondary interface waves are intercepted for bispectrum dimension reduction analysis, and the results are shown in **Fig. 4**(b). The frequency corresponding to the maximum value marked by the circle is the wall thickness frequency. After local amplification, as shown in **Fig. 4** (c), it can be seen that the wall thickness frequency is 2.536×10^5 Hz, and according to equation (10), the wall thickness is 12.6187 mm. At the same time, the ultrasonic echo signal shown in **Fig. 4**(a) is intercepted and FFT (Fast Fourier Transform, basic method of second-order statistics) is performed, and the result is shown in **Fig. 4**(d). The frequency corresponding to the maximum value marked by the circle is the wall thickness frequency. After local amplification, as shown in **Fig. 4** (e), it can be seen that the wall thickness frequency is 5.072×10^5 Hz, and according to equation (10), the wall thickness is 6.3093mm.



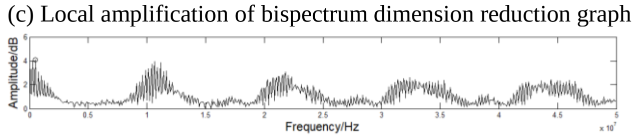
(a) Time-domain diagram of ultrasonic echo signal



(b) Bispectrum dimension reduction graph



(c) Local amplification of bispectrum dimension reduction graph



(d) FFT spectrum

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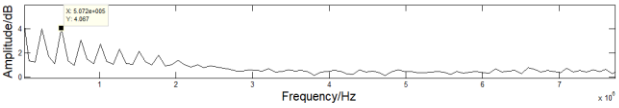

(e) Local amplification of FFT spectrum

Fig. 4 Time domain, bispectrum dimension reduction and FFT spectrum of ultrasonic echo from tube wall

Then, single point detection is carried out at different thickness of the steel test block simulating the corrosion of the inner and outer wall of the pipeline in **Fig. 1**, and the echo signal is analyzed by bispectrum dimension reduction and FFT. The results are shown in **Table. 1**.

Table. 1 Comparison of bispectrum dimension reduction and FFT

Corrosion Location	**Actual Thickness (mm)**	**Detected thickness (mm)**		**relative error (%)**	
		bispectrum dimension reduction	***FFT***	***bispectrum dimension reduction***	***FFT***
Inside Wall	25.4	25.6427	25.1307	0.9555	1.0602
	12.8	12.6187	6.3093	1.4164	50.7086
	6.4	6.2827	0.2856	1.8328	95.5375
Outside Wall	25.4	25.6427	25.1307	0.9555	1.0602
	12.8	12.7467	12.7467	0.4164	0.4164
	6.4	6.5013	6.5013	1.5828	1.5828

It can be seen that when detecting the inner and outer wall corrosion at 25.4mm and the outer wall corrosion at 12.8mm and 6.4mm, the residual thickness of pipe wall can be obtained more accurately whether using bispectrum dimension reduction analysis or FFT, but sometimes the error is slightly larger using FFT algorithm. When detecting the inner wall corrosion at 12.8mm and 6.4mm, the thickness error generated by FFT algorithm is very large. While the wall thickness accuracy obtained by bispectrum dimension reduction method is higher, and the relative error is less than 2%.

4. MULTIPOINT CONTINUOUS INSPECTION EXPERIMENT

A single ultrasonic probe is used for spiral guided (i.e. reciprocating) scanning to simulate the situation of multi-channel ultrasonic inner inspection system in detecting the actual pipeline. The working frequency of ultrasonic probe used is 5 MHz, the sampling frequency of A/D is 100 MHz, and the ultrasonic echo gathered is full-wave detection mode.

The cuboid steel test block used in the experiment is shown in **Fig. 5**. The test block is engraved artificially with two rectangular corrosions on the upper surface, which is used to simulate the uniform corrosion of the inner wall of pipeline. The thickness of steel test block is 14.8mm, the depth of corrosion is 3.2mm, and the residual thickness after being eroded is 11.6mm. Among them, the length of the rectangular corrosion Ⅰ is 10.2mm, and the width is 10.3mm. The length of the rectangular corrosion Ⅱ is 31.4mm, and the width is 10.5mm.

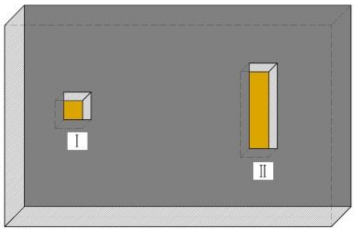

Fig. 5 Stereo schematic diagram of rectangular steel test block

The scan settings are as follows:

(1) Scanning axis: 0; Scan length: 110.465mm; Scanning resolution: 1.500mm.

(2) Step axis: 1; Step length: 78.105mm; Step resolution: 1.500mm.

(3) A-scan Wave length: 9454 (points).

The collected echo data is processed by bispectrum dimension reduction method, and the B-scan diagram shown in **Fig. 6** is obtained.

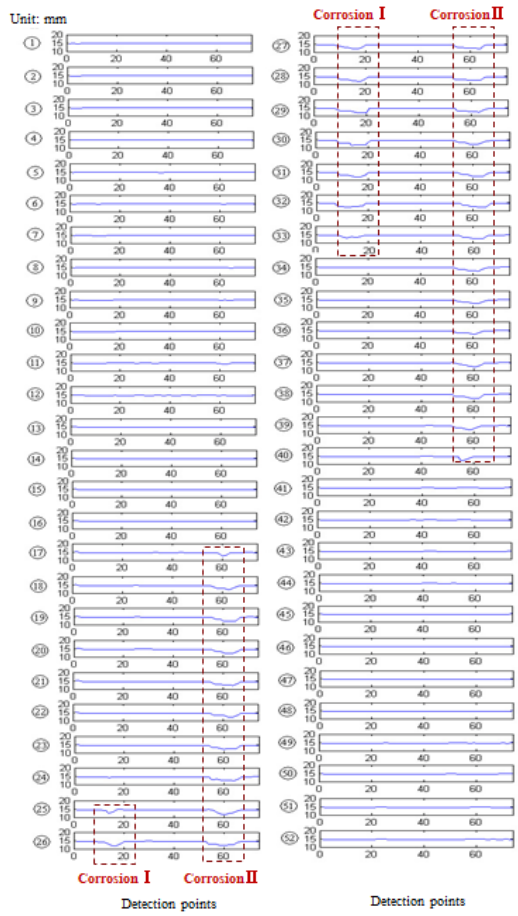

Fig.6 B-scan of rectangular steel test block

The abscissa in **Fig. 6** is the number of the detected points, and the ordinate is the test block thickness calculated automatically by program. From ① to ㊿② is the number of rows scanned by the probe with spiral guide, which is equivalent to parallel forward scanning using 52 probes.

The residual thickness of the test block at any test point scanned by any probe can be clearly seen in **Fig. 6**. The thickness between the test points 10~20 and 55~65 is obviously reduced to about 12mm, which is indicated by "corrosion I" and "corrosion II" respectively. It is consistent with the two rectangular corrosion of the steel test block in **Fig. 5**.

The B-scan thickness data of each detected point is denoted by the different colors, and C-scan images can be obtained, as shown in **Fig.7**.

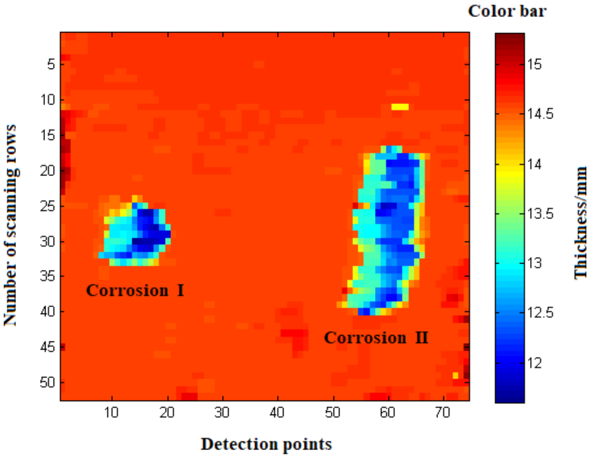

Fig. 7 C-scan of rectangular steel test block

Two rectangular corrosions can be seen clearly in the above figure. Through the instructions of the color bar, the residual thickness on the location of corrosion(shown by navy blue, about 12mm, very close to the actual value), the size of corrosion(The length of rectangle Ⅰ is about seven detected points, so 7*1.5mm=10.5mm; The width is about six detected points, so 6*1.5mm=9mm. The length of rectangle Ⅱ is about twenty-first detected points, so 21*1.5mm = 31.5mm; The width is about seven detected points, so 7*1.5mm=10.5mm. They are very close to the actual values.) and the area thickness without corrosion(shown by orange, about 14.8mm, consistent with the actual value) can be seen intuitively.

5. CONCLUSION

The analysis and interpretation of ultrasonic echo signal is the key and difficult point in ultrasonic inner detection of crude oil pipeline. Based on the non-linear and non-Gaussian characteristics of ultrasonic inner inspection signal of crude oil pipeline, bispectrum is proposed to process the echo signal with the least amount of computation in higher order statistics in this paper. Then the dimension reduction analysis is carried out, and the echo signal processing results are compared with FFT---the basic method of second-order statistics. It can be seen that the precision of bispectrum dimension reduction method for ultrasonic echo signal processing is very high, and the relative error is less than 2%, which is much better than the second-order statistics method. Through multi-point continuous detection experiments for the steel test block, it is verified that both B-scan waveforms and C-scan images obtained by bispectrum dimension reduction method can clearly and intuitively show the corrosion position, size and depth, and so on, which can meet the requirements of signal processing in the ultrasonic inner inspection of long-distance crude oil pipeline.

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