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Detection of Arbitrary Frequency Ultrasonic Guided Wave Signals Based on the Time-Shift Duffing Oscillator

JING WU[1], JINGHUA CAI[2], YAN WANG[1], HAORAN LIANG[1], ZHONGMING LIU[3], AND HONGWEI MA[1]

[1]School of Mechanical Engineering, Dongguan University of Technology, Dongguan 523808, China
[2]State Grid Shandong Electric Power Company Qufu Power Supply Company, Jining 272000, China
[3]Dongguan Rail Transit Limit Corporation, Dongguan 523808, China

Corresponding author: Hongwei Ma (mahongwei@dgut.edu.cn)

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ABSTRACT Low detection accuracy and narrow detection range are observed when detecting weak guided wave signals with the Duffing oscillator as a result of a limited frequency band. In order to solve these problems, we proposed a detection method for detecting weak ultrasonic guided waves of arbitrary frequency based on a defect detection method using the Duffing oscillator scanned by a moving window and combined with variable scale and resampling. In this paper, the proposed method by examining the defect echo signals collected on steel pipe samples and detecting ultrasonic guided wave signals excited by arbitrary frequency was effectively validated. Experiment results show that the proposed approach can be used to detect guided wave signals of arbitrary frequency and arbitrary sampling step size with the fixed system. It is very important for expanding the range of defect detection in pipes with guided ultrasonic waves and improving the sensitivity for detecting small defects in engineering applications.

INDEX TERMS Duffing oscillator, ultrasonic guided waves, pipe detection, variable scale and resampling.

I. INTRODUCTION

In recent years, pipelines have been widely used, becoming the fifth-largest way to transport certain materials after railways, highways, aviation, and navigation [1]–[3]. It is of great significance to monitor long-distance pipeline health, especially to detect defects in pipes, so as to ensure the safe application of such pipes and reduce the occurrence of major accidents. Ultrasonic guided-wave technology is a new non-destructive defect-detection method based on the propagative characteristics of stress wave in solids, the main detection principle of which is that ultrasonic guided wave signals with specific modes and frequencies are transmitted and spread in pipes, causing reflection, transmission, and modal conversion. At the same time, the echo signals of reflection with some defect information will be generated by the ultrasonic guided wave. The defect information, including the location and size of defects in pipes, can be identified and extracted by detecting the features of the echo signals of reflection with defect information [4].

However, the defect echo signal is difficult to identify with weak signal characteristics under strong noise because the ultrasonic guided wave will render some complicated features while spreading in the pipes, such as dispersion, attenuation, and multi-modal features, which will seriously affect the efficiency of the ultrasonic guided wave in testing. With the development of non-linear science, some methods of detecting weak signals based on non-linearity are constantly emerging, e.g., chaotic theory [5]–[7] and stochastic resonance [8]–[10]. In recent years, both Li and Yang [11] and Hongwei [12]–[17] have carried out several studies on the detection capabilities of ultrasonic guided waves based on the Duffing system. Zhang and Ma [12], Zhang *et al.* [13] discussed the parameter settings of ultrasonic guided waves

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known as the Duffing system, identifying the normalized guided-wave signals by their phase trajectory, showing that it was efficient to use a Duffing oscillator in testing using guided waves. Wu *et al.* [17] proposed the method of ultrasonic guided-wave identification based on chaotic quantitative indexes with a Lyapunov exponent and considering the sensitivity of a Duffing system to periodic signals.

However, direct calculation of the Lyapunov exponent of the Duffing oscillator and the fractal dimension method can only detect the initial phase and describe signals within the measurement range. Signals with an initial phase beyond this range cannot be detected. To solve this problem, Wu *et al.* [17] proposed a time-shifted Duffing system detection method based on fractal dimension; that is, they constructed a time-shifted window function to scan a signal to be measured in segments for entry into the Duffing system. They are equivalent to sinusoidal signals with different initial phases; that is, when superimposed with an external driving force, they can lead to different results. Using the changes of the Lyapunov exponent and fractal dimension, one can identify the characteristic signals of the arbitrary phase. Furthermore, the time of occurrence of the weak guided wave signal in the defect echo can be determined by computing the curve of the fractal dimension of the system relative to the center time of the signal to be measured and by observing the range of the sudden change on the curve. Combining this time with the propagation speed of the guided wave, one can determine the location of the defect.

However, some problems remain with this method for pipeline inspection. For example, inspection using a Duffing system is constrained by the frequency and the sampling step size. To identify guided waves of arbitrary frequency and arbitrary sampling step size, the inspection parameters of the system must be reset. This can lower the detection efficiency and prevent broad industrial application.

The goal of our study was to resolve the restrictions on frequency and on sampling step size, carry out a scale transformation on the test signal, and detect guided wave signals of arbitrary frequency and arbitrary sampling step size.

II. THE RESEARCH OF THEORY

A. LYAPUNOV EXPONENT AND FRACTAL DIMENSION

The improved Duffing equation can be described as [18]

$$\ddot{x} + c\dot{x} - x^3 + x^5 = F\cos\omega t \tag{2.1}$$

where c is the damping ratio; $-x^3 + x^5$ is the non-linear term; F is the amplitude of the periodic force; ω is the circle frequency of the driving force.

The Lyapunov exponent can be used to characterize the average exponential rate of convergence or divergence of the adjacent orbits in the phase space over time, which is one of quantitative indexes used to describe the sensitivity of a chaotic system, approaching quantitative identification of the state of the chaotic system. In this study, as the main criteria of the Duffing system, the Lyapunov exponent, and fractal dimension are used to judge the dynamic changes of the system between after inputting the guided wave and before, which can finally achieve the objective of locating the destruction in defective pipes. The Lyapunov exponential spectrum is that the three-dimensional Duffing equation corresponds to three Lyapunov exponents, sorted by their size [16], the relation of which is expressed as

$$\begin{cases} L_1 = \lim\limits_{N\to\infty} \dfrac{1}{NT} \sum\limits_{k=1}^{N} \ln \left\| V_1^k \right\| \\ L_2 = \lim\limits_{N\to\infty} \dfrac{1}{NT} \sum\limits_{k=1}^{N} \ln \left\| V_2^k \right\| \\ L_3 = \lim\limits_{N\to\infty} \dfrac{1}{NT} \sum\limits_{k=1}^{N} \ln \left\| V_3^k \right\| \end{cases} \tag{2.2}$$

The entire state of the dissipative system (a Duffing system is a dissipative system) can be described by attractors. The strange attractor is known as "chaotic attractor," which is a set of infinitely many points in the phase space. These points correspond to the chaotic state of the system, and one of its characteristics is that the final state value is closely related to the initial value. (These points are extremely sensitive to the initial value.) Thus, the chaotic state of a system can be researched by studying the state of the strange attractor. Moreover, the strange attractor is a typical fractal structure with fractal dimension. The fractal dimension is another effective index used to measure chaotic characteristics, which can include Hausdorff, correlation, self-similar, box, Lyapunov, and information dimensions. The Lyapunov dimension of the chaotic attractor is defined as [17].

$$D = j + \frac{\sum\limits_{i=1}^{j} L_i}{\left|L_{j+1}\right|} \tag{2.3}$$

Then,

$$\sum_{i=1}^{j} L_i > 0, \quad \sum_{i=1}^{j+1} L_i < 0 \tag{2.4}$$

It is effective to characterize the chaotic attractor based on the fractal dimension, which indicates that the chaotic state of the system can be judged by calculating the fractal dimension. Only when the system is in chaotic state do the positive Lyapunov exponent and fractal dimension appear. When the system is in periodic and quasi-periodic motion, it corresponds to the integer dimension. To compare the integer dimension with the fractal dimension of the chaotic state, in this paper the dimension of the system in the periodic state is defined as integer 2, the maximum of the Lyapunov exponent as L_1, and the Lyapunov dimension as D. Fractal dimension D is mainly used for detection in the work described in this paper.

B. THE RELATIONSHIP BETWEEN THE LYAPUNOV EXPONENT AND DIMENSION

Suppose a closed surface is taken in the three-di A closed surface is taken in the three-dimensional phase space of x,y,z, and the change of the volume V enclosed by the surface with time has the following relationship with the motion of the representative points [19]:

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \int_V \mathrm{d}V(\frac{\mathrm{d}}{\mathrm{d}x}\dot{x} + \frac{\mathrm{d}}{\mathrm{d}y}\dot{y} + \frac{\mathrm{d}}{\mathrm{d}z}\dot{z}) \tag{2.5}$$

in which $\dot{x}, \dot{y}, \dot{z}$ represent the velocities of the points in the corresponding direction of the phase space. Apply this formula to the above Duffing equation [19]:

$$\frac{\mathrm{d}}{\mathrm{d}x}\dot{x} = 0, \quad \frac{\mathrm{d}}{\mathrm{d}y}\dot{y} = -c, \quad \frac{\mathrm{d}}{\mathrm{d}z}\dot{z} = 0 \tag{2.6}$$

Thus,

$$\frac{\mathrm{d}V}{\mathrm{d}t} = -cV \tag{2.7}$$

From the Eq. (2.7)

$$V(t) = V_0 e^{-ct} \tag{2.8}$$

where V_0 is volume of the initial phase space. Because $c > 0$, the volume of the phase space of the Duffing equation shrinks with time and finally shrinks to a point. This shows that the Duffing system is a dissipative system. The Lyapunov exponent describes the development of phase space and Eq. (4) determines the contraction of the Duffing system. According to the definition of Lyapunov exponent, could be written as the following Eq. (2.9)

$$L_1 + L_2 + L_3 = \frac{1}{V}\frac{dV}{dt} = -c \tag{2.9}$$

Therefore, Therefore, when the strange attractor appears, the maximum of the Lyapunov exponent is greater than 0 ($L_1 > 0$). In the Duffing system, $L_2 = 0$ is always satisfied. From this, the Lyapunov exponent is satisfied as

$$L_3 = -c - L_1 \tag{2.10}$$

The definition of Lyapunov dimension can be transformed as:

$$D = 2 + \frac{L_1}{c + L_1} \tag{2.11}$$

The core of determining the dimension is calculating the maximum of the Lyapunov exponent, and the order of magnitude is larger than the effect of directly calculating the Lyapunov exponent because of the definition of the fractal dimension, which is more efficient in detection. Combined with the previous analysis and the change of the internal driving force F, not only has the state of system changed, but the Lyapunov exponent and fractal dimension have changed as well. A different state of the system can be judged by using the Lyapunov exponent and fractal dimension; the results are shown in Table. 1.

TABLE 1. System of the relationship between the state and the Lyapunov exponents, dimension.

Lyapunov exponent	Value	fractal dimension	State of motion	Phase diagram
L_1, L_2, L_3	-, -, -	2	Fixed point	Fixed point
L_1, L_2, L_3	-, 0, -	2	periodic motion	Limit cycle
L_1, L_2, L_3	0, 0, -	2	Quasi-periodic motion	Two-Torus
L_1, L_2, L_3	+, 0, -	>2	chaos	Strange attractor

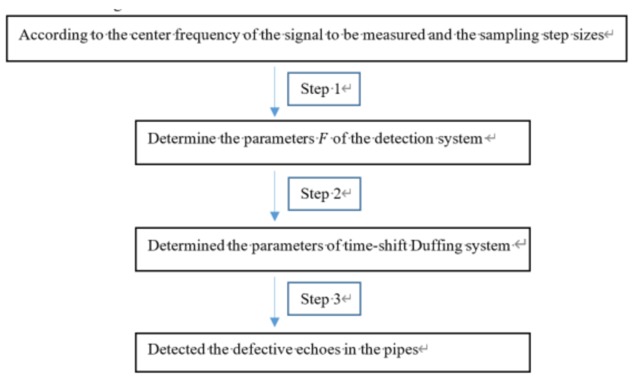

FIGURE 1. Principle of detecting pipeline defects by duffing system.

C. DETECT PIPELINE DEFECTS USING THE CHAOS SYSTEM

Using the Lyapunov exponent and fractal dimension to determine the parameters of the detection system. The method as shown in Figure 1.

Step 1: Determine the angular frequency ω of the driving force of the detection system according to the center frequency of the signal to be measured. By comparing the change in the maximum Lyapunov exponent of the Duffing oscillator with the amplitude F of the driving force before and after no signal input, weak guided wave signal input, and pure noise signal input, the F value for identifying the guided wave signal may be determined. Then, the identification of the weak guided wave signal in the presence of strong noise can be accomplished using the change in the state of the Duffing oscillator.

Step 2: Determine the width and moving speed of the rectangular window by combining the method proposed previously [17] for detecting the signal under test using the time-shifted Duffing detection system.

Step 3: Detect the defect echo received in the defective pipeline using the above-mentioned time-shifted Duffing system. The way to use this method is to scan the defect echo signal by shifting the scanning window, input each segment of the signal into the Duffing system, calculate the corresponding fractal dimension number of the signal, and then plot the D-t curve of the dimension number versus the center time of the signal. By observing the time when the sudden change occurs on the D-t curve, one can find the time of occurrence of the weak guided wave in the defect echo. Further, the actual location of the defect in the pipeline may be determined using the ultrasonic propagation velocity of the guided wave or the proportional relationship between the incident wave, the defect echo, and the end-face echo.

It follows from the above-described detection process that the excitation frequency of the signal to be measured and the sampling step size both have an important influence on the determination of the parameter F of the detection system. In the traditional detection method, one needs to combine the center frequency of the signal to be measured in determining the driving force amplitude F, and each frequency will correspond to a complicated calculation process.

III. DETECTION OF GUIDED WAVE SIGNALS OF ARBITRARY FREQUENCY AND ARBITRARY STEP SIZE

A. PRINCIPLE OF DETECTING GUIDED WAVE SIGNAL OF ARBITRARY FREQUENCY

The basic principle of the Duffing system used to identify weak ultrasonic guided wave signals is that the center frequency of the guided wave signal to be measured coincides with the frequency of the internal driving force term of the Duffing system. Thus, the frequency of the internal driving force term of the Duffing system is set to be the same as the center frequency of the guided wave signal to be measured. When the center frequency of the signal to be measured changes, the frequency of the internal force term of the Duffing system changes accordingly, and so does the F value of the Duffing detection system. Then, it is necessary to re-determine the F value of the detection system according to Step 1 of the above-described procedure so that different center frequencies correspond to different detection systems.

Therefore, if the center frequency of the guided wave signal to be measured is not 70 kHz, the above-mentioned detection system cannot be used for detection. In order to realize the detection of signals of any frequency and any step size, a method of variable scale transformation and linear interpolation of experimental data and resampling are introduced. There are mainly two scenarios in detecting signals of any frequency and any step size.

For the experimental data of any frequency, scale transformation is used to stretch or shrink the step size to change the frequency into the same frequency as that of the detection system. At this time, the actual measurement data have not changed, but the sampling step size and the frequency have changed.

After obtaining the same frequency, if the sampling step size is different from the integration step size of the detection system, proceed to re-sample the signal using the integration step size of the detection system by interpolation or under-sampling.

After these two steps, a signal of arbitrary frequency and arbitrary sampling step size may be transformed to have the same frequency and the same step size as the fixed detection system.

The so-called scale transformation [20] refers to changing the frequency/time scale of the signal under test, that is, compressing or stretching the scale of the signal under test without changing the discrete value. For example, the sampling time interval may be Δt.

For a guided wave signal under test with a center frequency of fc ($f_c > f$), we introduced a variable scale factor f_c/f If the time scale of the signal is enlarged by f_c/f times, the time interval is also magnified by f_c/f times, i.e.,

$$\Delta t' = \left(f_c/f\right) \Delta t \tag{3.1}$$

This is equivalent to compressing the frequency scale of the periodic signal by f_c/f times or compressing the guided wave signal by a factor of f_c/f so that it becomes f. Hence, through scaling, the signal with a center frequency of f_c is converted to be the same as the center frequency of the fixed detection system. In short, the relation between center frequency and the step size of changing scales and before is

$$f_c \cdot \Delta t = f \cdot h \tag{3.2}$$

where f and h are center frequency and the sampling time interval, which are as same as the fixed detection system.

The transformation of signals of different frequencies through variable scale coefficients is an equivalent linear mapping transformation. This time scale transformation does not change the values of the data involved in the calculation; it only reorders them on the time or frequency axis.

With scale transformation, signals of any frequency can be converted into the center frequency of the fixed detection system under different sampling steps. In the following sections, we focus on the detection of signals with different sampling step sizes as the detection system.

B. EFFECT ON SAMPLING STEP

Generally, the step size of the detection has a greater impact. For an ultrasonic guided wave signal with an excitation center frequency of 70 kHz, when the sampling step size is 0.04 μs, a suitably chosen detection system would have $F = 0.28$ according to the above-described method of selecting a detection system [21]. The detection results would be better if this system were used on the signal under test.

However, such a system would be considerably different from the detection system used in this article. In fact, the sampling step sizes of the signals acquired in actual experiments would all be different. If a different detection system is chosen for each sampling step size, the detection efficiency would be quite low, which is not conducive to the promotion of broad application of this method. We therefore proposed that the acquired test signals be re-sampled to be consistent with the integration step size of the fixed Duffing system. Then, guided wave signals of any step size could be detected under the fixed detection system.

When the sampling step size is different, it is greater than the integration step size of the fixed detection system, and is

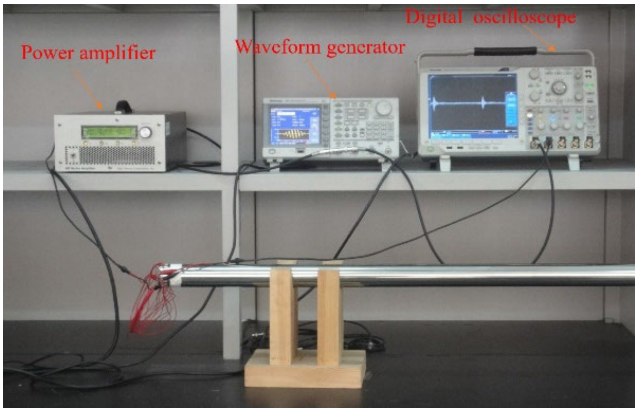

FIGURE 2. Experimental instruments.

an integer multiple of that of the fixed detection system so that the signal under test can be re-sampled using segmented linear interpolation.

When the sampling step size is greater than the integration step size of the fixed detection system but is not an integer multiple of that of the fixed detection system, one could use either segmented linear interpolation or some other interpolation method, such as spline interpolation. Then, the re-sampling would be an up-sampling.

When the sampling step is smaller than the fixed step, only a down-sampling is required.

The specific procedure for the up-sampling is as follows:

1. First, perform a linear interpolation between every 2 data points of the test signal.

2. Re-sample the interpolated function using a step size of 0.02 μs.

IV. EXPERIMENTAL VERIFICATION

A. EXPERIMENTAL DEVICE

In order to validate the performance of proposed method, the experiment is carried out in this section. In this experiment [16], steel pipes 3-m and 6-m long with inner radius of 50.75 mm and wall thicknesses of 2.32 mm were chosen as separate detecting objects to verify the proposed method. The main instruments include an arbitrary signal generator, low-frequency power amplifier, and digital oscilloscope, which are shown in Figure.2. The piezoelectric ring and piezoelectric sheet are made of PZT5, which were used as an exciting sensor and receiving sensor shown in Figure.3, respectively.

Experimental principle is shown in Figure. 4. Specifically, the piezoelectric ring with the same size as the detected pipeis used to generate the guided wave signal. Simultaneously, sixteen piezoelectric patches are used to receive the guided wave signal. Piezoelectric patches can receive L(0,2) mode guided wave and restrict the flexural mode as soon as possible. The arbitrary signal generator used to output signal, low frequency power amplifier with the capability of signal amplification, and oscilloscope used to record tested signal.

The artificial defects of 3-m-long steel pipe were made 1.5 m from the sensor by a saw, adding three varieties of

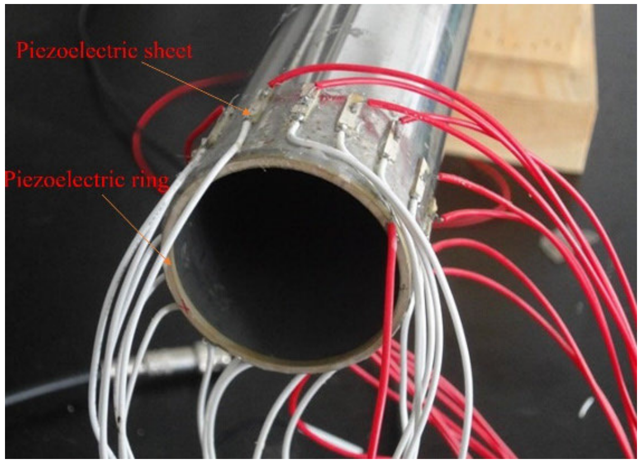

FIGURE 3. Piezoelectric ring and piezoelectric sheet.

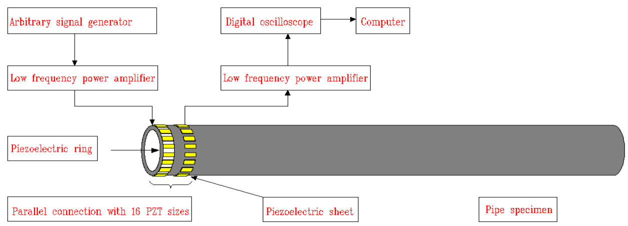

FIGURE 4. Experimental principle.

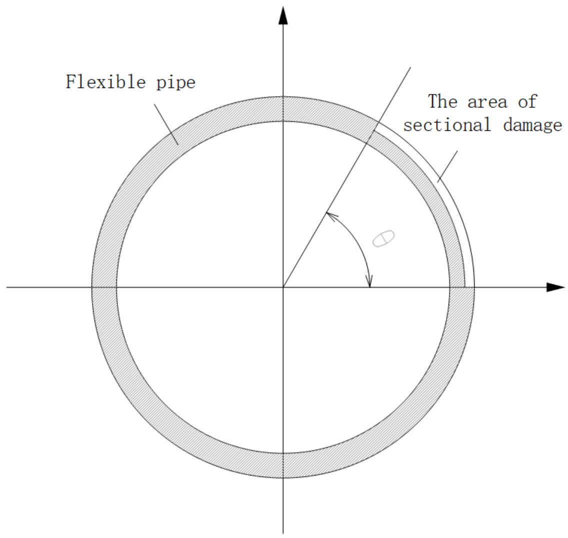

FIGURE 5. Defects setting.

cross-sectional reduction ratios [16] in turn, and radial depth and circle angle can be used to calculated section reduction ratio (%), and the results are 3.8%, 9%, 17% in turn. Similarly, it can be calculated that the defect sizes at 2m and 4m in 6m pipeline are 21% and 15% respectively. Defects setting are shown in Figure.5.

B. DETECTION SYSTEM AND EXPERIMENT RESULTS

During ultrasonic inspection of pipelines, 10-cycle Hanning-window modulated guided wave signals with a center frequency of 70 kHz are often used to excite the L(0,2) mode of guided wave in the pipeline [7]. In this work, we used signal with a center frequency of 70 kHz as the characteristic signal. The expression of the normalized guided wave signal was [17]:

$$\bar{s}(t) = \frac{1}{2}(1 - \cos\frac{2\pi f_c t}{n})\sin(2\pi f_c t) \tag{4.1}$$

where n is the number of selected single audio; f_c is center frequency.

Following Step 1, the detection system parameter $F = 0.569$ and $2\sigma = T$ for the moving window can be used to detect signals with the usual center frequency of 70 kHz and sampling step size of 0.02 μs from the reference [17]. 2σ is the window width, and T is the cycle of the guided wave signal.

In this paper, the above-described system with $F = 0.569$, $2\sigma = T$ was used for detecting defects in 3-meters and 6-meter pipes, respectively. Test signals with a center frequency of 70 kHz and sampling step size of 0.04 μs were acquired for defects of different sizes from the 3-meter steel pipe, which section reduction ratio are 3.8%, 9%, 17% in turn. These signals were first linearly interpolated, re-sampled, and with their sampling step size were converted to 0.02 μs. The signals were then input into the detection system, and the corresponding fractal dimension were calculated. The results are shown in Figure. 6. In Figure. 6, the blue line represents the experimental time-history curve with 0.04 μs time interval, which shows that there are defect echoes at the corresponding times 1.5 m are reached. The red line in Figure.6 represents the fractal dimension, calculated from the time-shift Duffing system, which shows that there are three peaks are greater than 2. These peaks correspond to the incident wave, defect echo and end echo. This was consistent with the results obtained by using the proposed method, which also illustrated the feasibility of the method.

In order to illustrate the advantage of the method, a band-pass filter method was used for the comparison, and the results are shown in Figure. 7 blue line. Figure 7 shows that, relative to the amplitude of the incident wave and the back-wall echo, the defect echoes after filtered were too small to be observed directly. However, the sudden change in the calculated fractal dimension was very prominent; they enhanced the defects and made the defective echoes directly visible in the time-history curve. Then the method of the fractal dimension is better than band-pass filter.

The same method was used to detect the artificial defects 2 and 4 m from the sensor in the 6-m-long steel pipe, and the results obtained are shown in Figure. 8. In Figure.8, the blue line represents the experimental time-history curve with a center frequency of 70 kHz and sampling step size of 0.1 μs, which shows that there are defective echoes at the corresponding times that 2 and 4 m are reached. The red line in Figure.8 represents the fractal dimension, calculated from the time-shift Duffing system, which shows that there are the fractal dimensions at the corresponding time that 2 and

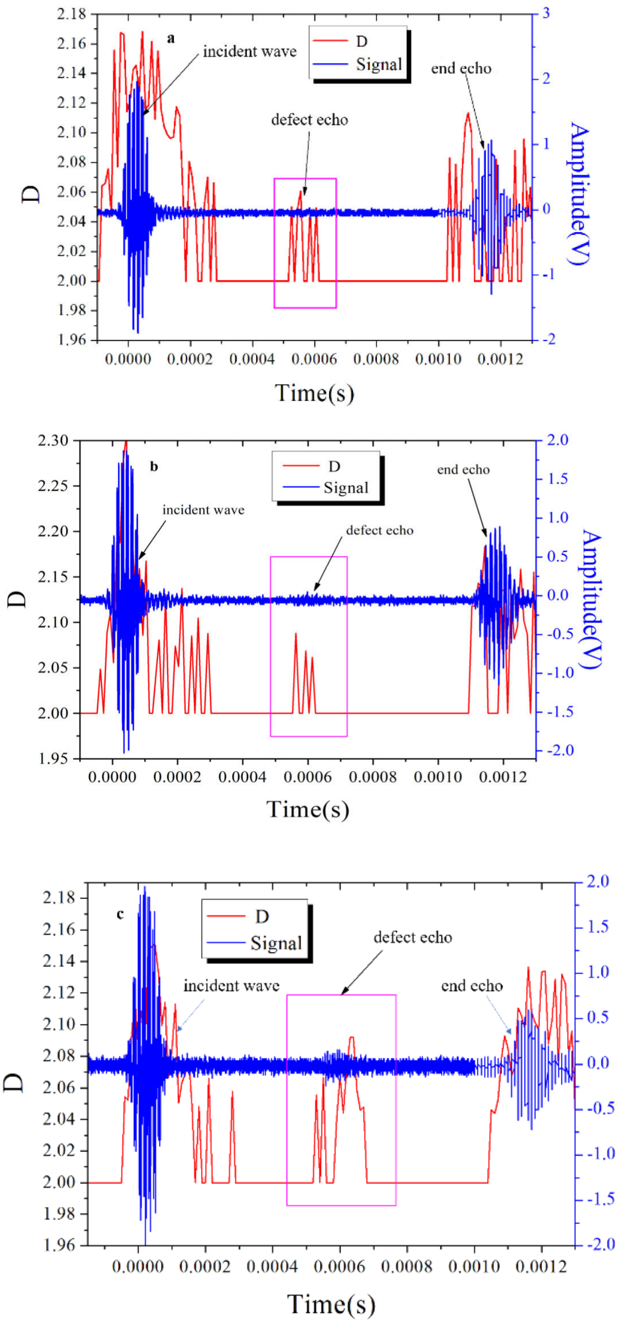

FIGURE 6. Comparison between fractal dimension and signal in different cases.

4 m are reached. Therefore, it is known that these defective echoes could be detected by calculating the fractal dimension. Figure.9 represents the result of calculating the cross-correlation, which shows that there are defective echoes at the corresponding times that 2 and 4 m are reached. Through comparison with Figure.8 and Figure.9, it is feasible and better to use fractal dimensions to identify defects.

At last, test signal with a center frequency of 60 kHz and sampling step size of 0.04 μs was acquired for defect from the 3-meter steel pipe. The signal was first scale transformation, linearly interpolated, re-sampled, and with their sampling

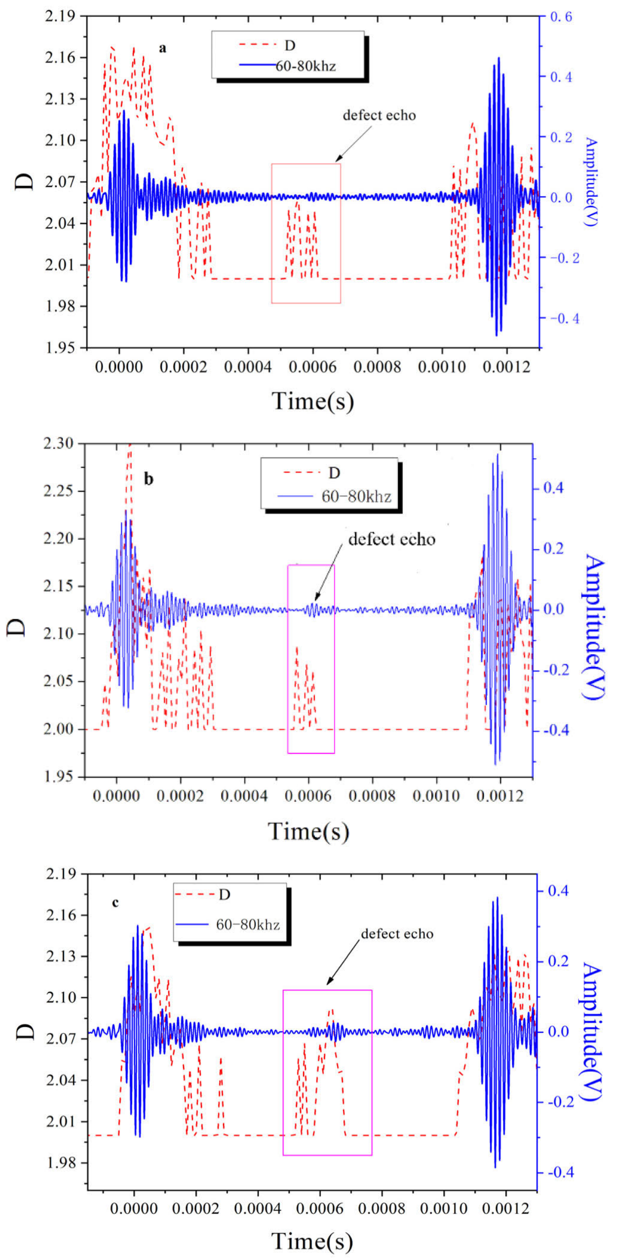

FIGURE 7. Comparison between fractal dimension and filtered signal in different cases.

step size were converted to 70 kHz and 0.02 μs. The signal was then input into the detection system, and the corresponding fractal dimension and cross-correlation were calculated respectively. The results are shown in Figure. 10, which fractal dimension was still better than cross-correlation.

In summary, the two steps of the procedure above may be used on signals of any arbitrary frequency and any arbitrary step size to achieve signal pre-processing and ultimately obtain a parameter consistent with the fixed detection system.

The first step is to use a variable scale transformation to convert the signals of different frequencies to a fixed

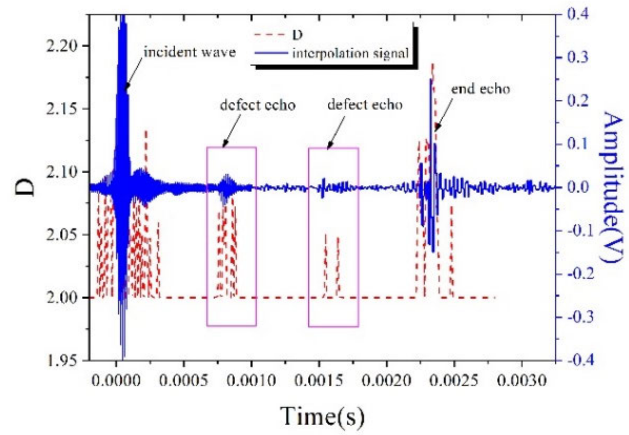

FIGURE 8. Compared with the fractal dimension and filter.

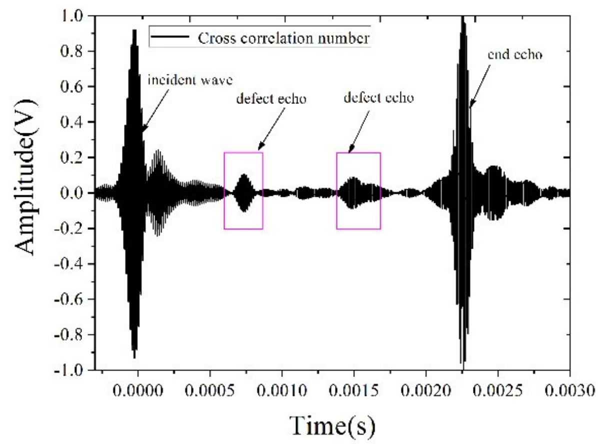

FIGURE 9. The result of the cross-correlation.

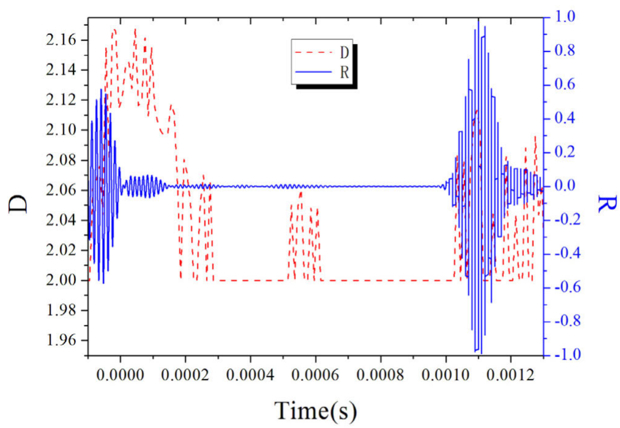

FIGURE 10. Compared with the fractal dimension and cross-correlation.

frequency. In this work, we took the 70 kHz often used in pipeline inspection as an example, but under normal circumstances, 10 kHz may be used for the universal fixed detection system.

A second step is to up-sample the data by linear interpolation in segments.

As all the pre-processing steps such as linear interpolation are linear operations, they are not expected to have a big effect on the system.

Therefore, the detection system can theoretically be used in the detection of signals of any arbitrary frequency and of any arbitrary step size. However, actually sampled signals with a large step size may be severely distortion when up-sampled by linear interpolation. In such cases, it is preferable to use the detection system selection method described above to choose a new detection system.

V. CONCLUSION

The basic principle of using the Duffing system to identify weak ultrasonic guided wave signals is that the center frequency of the guided wave signal to be measured is the same as the frequency of the internal driving force term of the Duffing system, and that different center frequencies correspond to different detection system parameters. In order to achieve the detection of signals of any frequency and any step size, a method of variable scale transformation and linear interpolation of experimental data was introduced. This method effectively resolved the problem, in actual inspection, of different defect types on different pipes corresponding to different detection frequencies and different sampling step sizes, confirming the need for changing the chaos detection system. Through scale transformation, re-sampling, and changing the step size, signals of any frequency and any step size can be converted into ones of the same frequency and integration step size as the fixed detection system so that the detection may be carried out using a fixed detection system. Through calculating the fractal dimensions of defect echos of 3m and 6m crack pipeline with different center frequencies and time intervals, relative to the amplitude of the incident wave and the end echo, the defect echoes after filtered or cross-correlation were too small to be observed directly. However, the sudden change in the calculated fractal dimension number was very prominent; they enhanced the defects and made the defective echoes directly visible in the time-history curve. Then the method of the fractal dimension is better than band-pass filter and cross-correlation.

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JING WU received the Ph.D. degree in mechanical engineering from Jinan University, Guangzhou, China, in 2017. She is currently a Lecturer with the School of Mechanical Engineering, Dongguan University of Technology, Dongguan, China. Her research interest includes signal processing.

JINGHUA CAI was born in Shandong, China, in 1990. She received the master's degree, in 2014. She currently works with State Grid Shandong Electric Power Company Qufu Power Supply Company, Jining, China. Her research interest includes data analysis.

YAN WANG received the Ph.D. degree in mechatronic engineering from Xi'an Jiaotong University, Shanxi, China, in 2018. He is currently a Lecturer with the Dongguan University of Technology, Dongguan, China. His research interest includes signal processing.

HAORAN LIANG was born in Shantou, China, in 1998. He received the B.S. degree from the School of Mechanical Engineering, Dongguan University of Technology, Dongguan, China, in 2018. He is currently pursuing the M.S. degree with the School of Electromechanical Engineering, Guangdong University of Technology, Guangzhou, China. His research interests include machine learning and data analysis.

ZHONGMING LIU received the master's degree in commercial management major from Jinan University, Guangzhou, China, in 2016.

His research interests include railway vehicle and metro operation management.

HONGWEI MA received the Ph.D. degree in mechanical engineering from the Taiyuan University of Science and Technology, Taiyuan, China, in 1995. He is currently a Professor with the Dongguan University of Technology, Dongguan, China. His research interests include nondestructive testing and nonlinear dynamics.