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Defect detection of pipes using Lyapunov dimension of Duffing oscillator based on ultrasonic guided waves

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ABSTRACT

This study proposes a novel small defect detection approach for steel pipes using the Lyapunov dimension (D) of the Duffing chaotic system based on ultrasonic guided waves. In this paper, inspection model is constructed by inputting the measured guided wave signal into the Duffing equation as the external turbulent driving force term and then$D$is calculated. The properties of the Duffing system's noise immunity are first demonstrated theoretically based on the Lyapunov exponents. By comparing$D$of the Duffing inspection system between the conditions of the inputted pure noise and the guided wave signal, the amplitude of the periodic force (F), the important parameter of the Duffing inspection system, could be determined. The values of other parameters of the Duffing inspection system are subsequently determined according to the numerical investigation. Furthermore, a time-moving window function is constructed to scan along the measured signal to locate the defect. And the small defect echo signal polluted by the noise is illustrated to prove the availability of the proposed method. Both numerical and experimental results show that the proposed approach can be used to improve the sensitivity of small defect detection and locate the small defect in pipes.

1. Introduction

Pipelines have been widely used in the industries, and it is significant to develop the reliable health monitoring methods and technologies for pipelines to reduce the related accidents caused by corrosion, external force or pipe material defects. Ultrasonic guided wave-based nondestructive testing/evaluation (NDT/NDE) is an effective method to inspect the defects in long-distance pipelines, due to its powerful abilities of fast speed and wide range, and so on. However, there are some difficulties in analyzing guided wave signals, because of the mode conversion of guided wave, dispersion, attenuation, and especially the strong noise influence, resulting that the weak guided wave immerged in the noise is difficult to extract defect information directly. In this situation, some novel inspection methods have been proposed, including time-domain, frequency-domain and time–frequency analysis. Time-domain and frequency-domain are based on the assumption that the process generating signals is stationary and linear [1]. Time–frequency analysis is the most popular method for the analysis

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of non-stationary signals, such as wavelet transform [2–5], short Time Fourier Transform(STFT) [6], Hilbert-Huang transform [7], the Wigner-Ville distribution [8,9] and so on. But each of the time–frequency analysis methods has suffered some problems [10]. In recent years, chaos oscillators have been demonstrated to be an effective tool to deal with the weak signals with strong noise, due to its high detection efficiency and strong sensitivity to the initial value [11].

Common chaos oscillator inspecting systems, include Lorenz system [12,13], Duffing system [14–16], Logistic system [17]. The Duffing oscillator, which was first published in 1918 [18] and sensitive to the periodic signals, has been widely studied. The improved Duffing equation can be described as [19]

$$\ddot{x} + c\dot{x} - x^3 + x^5 = F\ \cos(\omega t) \tag{1}$$

where c is the damping ratio, $(-x^3 + x^5)$ is the non-linear term, F is the amplitude of the periodic force, and ω is the circle frequency of the driving force. A periodic signal $s(t) = f\ \sin\ \omega t$ with the same frequency as the driving force is introduced to the Eq. (1), the equation is

$$\ddot{x} + c\dot{x} - x^3 + x^5 = F\ \cos(\omega t) + s(t) \tag{2}$$

Eq. (2) can be rewritten in the form of Eq. (1) by using the triangle transformation formula. It is seen that the input of a periodic signal with the same frequency as the original driving force will only change the amplitude and initial phase of the driving force. The dynamics of the Duffing chaotic oscillator system is easily to be changed obviously (for instance, from the chaotic state into the periodic state, or from the periodic state into the chaotic state), since it is extremely sensitive to the system parameters. These changes can be found by observing the phase, Lyapunov exponents and dimensions of the Duffing system. Meanwhile, the Duffing chaotic oscillator has strong immunity to the various noises or the periodic signal whose frequency is big gap of ω [17]. Thus, the additional signal can be identified by observing these dynamics changes of the Duffing chaotic oscillator [11].

The potential of identifying the weak signal with strong noise using the chaotic system was proposed by Brix [20] in 1992, which has received a great deal of attention in recently years. Wang et al. [21] studied the bifurcation and statistics properties of Duffing equation, and presented a weak signal inspection method. The influence of noise signals on the Duffing equation was also discussed. Hu and Wen [22] deduced the numerical solutions of the Duffing equation and determination method of bifurcation. Further, some authors carried out the weak signal detection by observing the different phase trajectories for periodic signal and noise. Anjali Sharma et al. [23] mainly focused on how the damping exponent affected the global dynamic behavior of the Duffing oscillator. It is found that the introduction of nonlinear damping in the system did not necessarily increase the fractalness of the basin boundaries. Zhao [24] developed a new detection method of weak signals, according to the phase trajectory change of the van der Pol–Duffing oscillator from the chaos to the periodic state. The influences of noise, different frequency signals, and phase shift were also studied in detail. Patel et al. [25] dealt with the detection of local defects, existing on races of deep groove ball bearing in the presence of external vibrations, using envelope analysis and Duffing oscillator. The Duffing oscillator could confirm the presence of defect frequencies by indicating closed phase plane trajectories and negative Lyapunov exponents. In addition, Duffing equation-based weak signal method can also be used to identify the amplitude [26,27], frequency [18,28] and phase [29,30] of the signal. However, most of these studies focus on the identifications of simple periodic signals such as the sine or cosine signals. Shi [31] proposed a method that could effectively detect the weak resonant signals in the background of the strong noise, according to the frequency and phase characteristic of the output vibration signals. Recently, more and more researchers noticed the potential ability of the chaotic system in detecting guided wave signals. Zhang [19] developed the inspection system parameters to detect a simulated guided wave signals using Melnikov's method. And a dichotomy was suggested to locate the arriving time of the guided wave based on the changes of phase trajectory. Yang [32] further studied a method based on the change of phase trajectory of a Duffing–Holmes chaotic system for inspecting the oblique defects in the pipe. The above mentioned studies have demonstrated that the proposed method could be used to inspect weak guided wave signal. However, the state of the Duffing system is hard to judge by observation of the change of the phase trajectory, because the subjectivity of observers and lack of the rigorous reasoning and proof. Lyapunov exponents and fractional dimension are two main quantitative indexes to judge the state of the chaos system [33]. The sign of the maximum Lyapunov Exponent also can be adopted to accurately judge the critical state of the chaos system. Once the maximum Lyapunov exponent keeps positive value, that the motion state is chaos motion with the characteristics of fractional dimension [34].

The main objective of this study is to propose a new method of the defect detection for pipes by developing a relationship between the Lyapunov dimension and ultrasonic guided wave, based on the Duffing oscillator. Actually, to the authors' knowledge, the articles with the idea that using Lyapunov dimension of Duffing oscillator to identify and locate the defect in pipes are relatively rare in nondestructive testing (NDT). The performance of the proposed method is demonstrated by numerical investigation and experiment.

The outline of this paper is as follows. The theory of Lyapunov exponents and Lyapunov dimension of the Duffing equation is presented, and the properties of the immunity of Duffing system to the noise are introduced theoretically by calculating Lyapunov exponents. And then both the theoretical description and solving process of Lyapunov dimension are given in Section 2. The effect of parameters on the motion states of the Duffing equation is studied and the inspection and localization principles are also presented in Section 3. Then, in Section 4, the values of the parameters of both Duffing inspecting system and time-moving function are determined by numerical investigation, and the influence of noise is