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A method based on SVD for detecting the defect using the magnetostrictive guided wave technique

Mingxi Tang, Xinjun Wu*, Ming Cong, Kai Guo

School of Mechanical Science & Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

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ABSTRACT

Magnetostrictive guided wave testing is a useful non-contact nondestructive testing method. However the signal to noise ratio (SNR) of its testing signal is low due to the lift-off. In this paper, a novel index called singular decreasing index (SDI) is proposed to distinguish the defect signal, which is based on a new matrix form improved from the Hankel matrix and the singular value decomposition (SVD). Further, an SDI spectrum is proposed to locate defects. Simulation signals with different SNR are employed to evaluate the performance of this method, and results show that the SDI spectrum can locate the defect at a very low SNR. Experimental results also show the excellent performance of the SDI spectrum in defect location. Hence, it is believed that this method can effectively detect defects at low SNR.

1. Introduction

In recent years, many researches on the guided wave inspection technique have been conducted in petro-chemical [1], aviation [2], nuclear industry [3], bridge [4], rail [5] inspection, and so on. The guided wave propagates along the tested component and is reflected by the defect. The defect can thus be detected according to the echo signal corresponding to the defect which is received by the transducer. When compared with other non-destructive testing techniques, guided waves have advantages such as: long traveling distance without substantial attenuation, ability of examining entire cross section, capability of inspecting coated structure. The technique can be realized by many methods, such as the Lorentz force [6], the magnetostrictive effect [7], the piezoelectric effect [8] and the laser [9]. Among these methods, the magnetostrictive method has received a great deal of attention due mainly to its features of non-contact and large lift-off distance. However, the energy conversion efficiency of this method is lower than other contact methods due to the lift-off, leading to a lower signal to noise ratio (SNR) of testing signals, masking defect signals and remaining undetected [10]. For this reason, there is a more urgent need to interpret magnetostrictive guided wave signals.

To interpret testing signals of the guided wave inspection better, many signal processing methods have been proposed. Siqueira [11] used the band-pass filter and the wavelet de-noising to reduce the noise of the guided wave signal of the pipe and results showed that the wavelet analysis has better performance. Rizzo [12–15] conducted a series of studies on the application of wavelet analysis in guided wave signals and made a detailed analysis of the method when different kinds of

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* Correspondence to: School of Mechanical Science & Engineering, Huazhong University of Science and Technology, Room B503, East of Advanced Manufacture Building, 1037 Luoyu Road, Wuhan 430074, Hubei Province, China. Tel./fax: +86 27 8755 9332.

E-mail addresses: 15527783964@163.com (M. Tang), xinjunwu@mail.hust.edu.cn (X. Wu), mingcm2013@163.com (M. Cong), guokaikuan@163.com (K. Guo).

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inspected objects were tested. Grabowska et al [16] employed wavelets to detect different kinds of damage using the Lamb wave. Liu et al [17] used the Gabor wavelet to detect the radial crack in annular structures. It has been proved that the wavelet transform is powerful in processing the guided wave signal, whereas, of which the selection of the wavelet basis, the decomposition level and the threshold value have a strong effect on results and it is difficult to select optimum parameters in different conditions, making the method complex.

Singular value decomposition (SVD) has been widely used in many applications, such as the fault diagnosis [18–19], the structure health monitor [20–21], the biomedical signal processing [22–23] and the image processing [24]. The SVD is usually employed to process specific form matrix constructed from testing signals to reveal the intrinsic nature of observed objects. Xuezhi et al [25] have proved the SVD has similar mechanism of signal processing with the wavelet transform. Having in mind that the wavelet transform is a powerful method to process guided wave signals, the SVD may also offer a powerful but simpler method to interpret guided wave signals. However, few researches have employed this method. In this paper, a method based on the SVD is proposed to detect defects while the testing signal is with a very low SNR. With the consideration of defect signal characteristics, a novel defect index which is called SDI (singular decreasing index) is proposed based on a new matrix form which is improved from the Hankel matrix. The SDI is extracted as the feature of the defect from the singular spectrum, which will dramatically increase if the processed time series contains information of the defect. Then, the SDI spectrum is proposed to locate the defect and it is confirmed that this method can effectively detect defects even at a very low SNR.

The paper is organized as follows: In Section 2, a novel matrix form is proposed based on the Hankel matrix. Principles of the SDI are also described in this section. The algorithm of SDI spectrum is proposed in Section 3. To evaluate the performance of the SDI spectrum, simulation signals with different SNR are processed by this method in Section 4. In Section 5, experimental signals have been processed for further verifying the SDI spectrum and some discussions are also shown. Section 6 contains our conclusion of this paper.

2. A novel defect index based on SVD

In the magnetostrictive guided wave testing, a sinusoidal signal of several cycles is usually employed as the excitation signal. In essence, the origin of the defect signal is the ultrasonic echo from the defect. Thus, the defect signal has the same length and a similar structure with the excitation signal. Usually, it is considered as a sinusoidal signal of several cycles windowed by a Hanning window in the structure [26], which is symmetric about its center. To distinguish the defect signal, the Hankel matrix should be firstly improved with the consideration of characters of the defect signal in the structure.

Consider a time series as $\{x\}=\{x(1), x(2), \ldots x(\mathrm{N})\}$. The Hankel matrix can be constructed as follows:

$$H=\begin{bmatrix} \boldsymbol{x}_1^h \\ \boldsymbol{x}_2^h \\ \vdots \\ \boldsymbol{x}_m^h \end{bmatrix}=\begin{bmatrix} x(1) & x(2) & \cdots & x(n) \\ x(2) & x(3) & \cdots & x(n+1) \\ \vdots & \vdots & \ddots & \vdots \\ x(m) & x(m+1) & \cdots & x(m+n-1) \end{bmatrix} \tag{1}$$

Where $m=\mathrm{N}-n+1$. In practice, the m and n are chosen as large as possible for revealing hidden information of the signal and here we define $n=\lceil \mathrm{N}/2 \rceil$ [27], where the symbol $\lceil\,\rceil$ means getting the minimum integer not less than the operated data. With the consideration of the centrosymmetric structure of the defect signal as mentioned above, the Hankel matrix should be improved and more suitable to identify a centrosymmetric structure. Here, the improved Hankel matrix can be expressed as follows:

$$P=\begin{bmatrix} \boldsymbol{x}_1^p \\ \vdots \\ \boldsymbol{x}_k^p \\ \boldsymbol{x}_{k+1}^p \\ \vdots \\ \boldsymbol{x}_m^p \end{bmatrix}=\begin{bmatrix} x(1) & x(2) & \cdots & x(n) \\ \vdots & \vdots & \ddots & \vdots \\ x(k) & x(k+1) & \cdots & x(k+n-1) \\ x(k+n) & x(k+n-1) & \cdots & x(k+1) \\ \vdots & \vdots & \ddots & \vdots \\ x(m+n-1) & x(m+\mathrm{n}-2) & \cdots & x(m) \end{bmatrix} \tag{2}$$

Where $k=\lceil m/2 \rceil$. The matrix P is transformed from the matrix H by rearranging $\boldsymbol{x}_i^p$ in a reverse order while $i>k$. If the $\{x\}$ is a defect signal, the $\{x\}$ will be similar to a structure which is symmetric about its center, which means $x(i)=-x(\mathrm{N}-i+1)$.