Fatigue Crack Width Detection Based on the Active Sensing Method: A Feasibility Study

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Abstract—**Across multiple industries, metal fatigue damage is one of the most common failure types, and it will induce great loss if the fatigue damage cannot be detected in a timely manner. To predict the fatigue life of metal structures under practical service status, the fatigue test of metal materials is necessary. Current fatigue tests only focus on the total number of cycles before fatigue failure; however, the occurrence and expansion speed of cracks have not been studied before. Therefore, in this paper, based on the active sensing method, a feasibility study is developed to make crack growth detection of standard metal specimen during the fatigue testing. Two PZT patches are bonded on both sides of the crack on a specimen, which is caused by cyclic tension-compression loads. One patch works as the actuator, and the other one is used as the sensor. Based on the wavelet packet signal energy, a damage index is proposed to quantify the received signals and then represent the degree of crack width. The experimental results demonstrate that the received signal wavelet package energy decreases monotonically with enlarging crack width, and thus the effectiveness of the proposed method is verified.**

Keywords—piezoelectric transducer, active sensing method, fatigue crack, structural health monitoring

I. INTRODUCTION

For engineering equipment, the loss caused by metal fatigue failure is huge. For instance, fatigue leads to more than half of mechanical failure cases [1], including bolted fracture, bridge collapse, broken shaft in railway and aircraft disintegration. Most metal constructions suffer repeated loads during service process, and fatigue is the phenomenon that structures crack locally and fracture completely under repeated loads (i.e., alternating stress and strain [2]). To predict the fatigue lifetime of metal constructions under practical use, the fatigue tests of metal materials are essential, since we can determine the fatigue curve and fatigue limit of metal materials through the tests.

Current approach for metal fatigue testing is the stress up-and-down method, which is mainly used to detect the random behavior of fatigue strength of materials and structures in the medium/long life period [3]. Under the set cyclic stress, the testing will last to the specified number of cycles (10^7) or until failure of specimen. However, the stress up-and-down method only focuses on the total number of cycles before failure, rather than the time of occurrence or expansion speed of cracks. When the metal specimens suffer high-cycle fatigue stage, most time of fatigue life is spent at the inception stage. On the contrary, the growth stage of cracks remains dominant over the whole fatigue life [4]. Therefore, we can have better understanding the damage law of metal materials and thus prevent structural failure efficiently, if the relationship between crack width and cycle numbers can be determined. At present, proper selection of transducers and damage index for crack detection is the main problem that we face to conduct abovementioned investigations.

Lead Zirconate Titanate (PZT) is a common piezoelectric ceramic material, has been used as transducers. PZT have some attractive features, such as actuation [5] and sensing, wide bandwidth, energy harvesting [6-9], communication [10, 11], and generate guided waves [12, 13]. In recent years, with rapid development of damage detection of metal structures, the active sensing method [14, 15] based on piezoelectric transducers has been used to monitor cracks in various structures, such as the pipe [16] and the concrete [17, 18]. By measuring the change of the wave propagation characteristics (e.g., the signal energy attenuation), the active sensing method can be applied to identify structural damage. For instance, the detection of rock bolt [19-21], timber structures [22] and metal plate structures [23] have been reported. However, the potential of the active sensing method on fatigue crack detection was overlooked, particularly, no investigation on detection of cracks caused by repeated tension-compression tests was reported before.

In this paper, a feasibility study is conducted to detect fatigue crack width through the active sensing method. By bonding two PZT patches, which worked as actuator and sensor, on both sides of a surface crack on the specimen, we verify that the micro-crack caused by fatigue testing can cause signal energy attenuation. Additionally, considering the micro size of the fatigue crack, we apply a surface profiler to measure different crack widths. Then, based on the wavelet package signal energy, a damage index is proposed to quantify the received signal energy and then express corresponding crack width. The experimental results demonstrated the effectiveness of the active sensing method on fatigue crack width detection quantitatively.

The rest of this paper is organized as follows. Section II introduces the active sensing method and wavelet package for stress wave energy calculation. Fatigue testing experiment is described in Section III. Experiment data are shown and discussed in Section IV. Concluding remarks are drawn in Section V.

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II. THEORETICAL BACKGROUND

A. Active sensing method

In this paper, the active sensing method is employed to detect the fatigue crack width caused by repeated tension-compression testing, and the schematic diagram is depicted in Figure 1. Due to the piezoelectric effect and inverse piezoelectric effect, the PZT patch can work as actuator and sensor. As shown in Figure 1, two PZT patches are bonded on both sides of a surface fatigue crack: PZT 1 works as actuator to emit swept sine wave, and PZT 2 works as sensor to receive stress wave signal. Ultrasonic wave has the reflection property on the interface of different materials when propagating in the medium. If a defect is encountered and the size of the defect is equal to or greater than the wavelength of the ultrasonic wave, the ultrasonic wave will reflect back on the defect. For fatigue specimen, when there is a crack, the energy of received signal decreases, since the stress wave reflects and interferes at the crack, which attenuates signal energy. Moreover, with the increase of the crack width, the received signal energy reduces more severely.

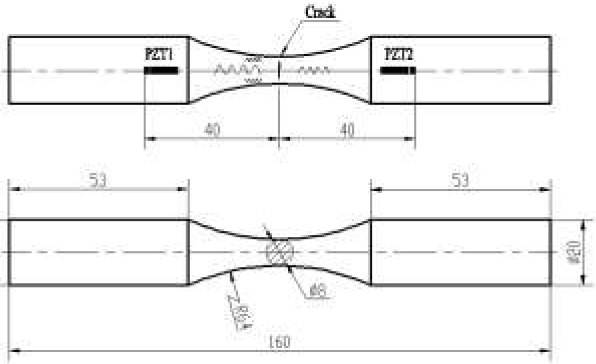


Fig.1. Schematic diagram of the active sensing method for fatigue crack width detection

B. Wavelet package signal energy

To quantify the received signal energy, the wavelet package method is employed in this paper, and thus a damage index is developed. The wavelet package consists of linear combination of typical wavelet functions, and it has abilities such as orthogonality and time-frequent localizing. Therefore, the wavelet package method has been widely used in engineering analysis. Based on the wavelet package analysis, the stress wave energy can be calculated as follows.

Conducting the wavelet package decomposition of the received stress wave signal $x(t)$ with j level, we can obtain 2^j wavelet package coefficients,

$$c_{j,k}^{i}(t)=\int_{-\infty}^{\infty}x(t)\psi_{j,k}^{i}(t)dt \tag{1}$$

where $\psi_{j,k}^{i}(t)$ is the wavelet package function, t is the time, i is the modulation parameter, j is the scale factor, k is the translation parameter.

Subsequently, through reconstructing each wavelet package coefficient, the corresponding wavelet package components of original signal $x(t)$ can be expressed as,

$$x_j^i(t)=\sum_{-\infty}^{\infty}c_{j,k}^{i}(t)\psi_{j,k}^{i}(t) \tag{2}$$

Finally, the stress wave energy can be calculated as the sum of energy of each wavelet package component,

$$E=\sum_{i=1}^{2^j}\int_{-\infty}^{\infty}x_j^i(t)^2\,dt \tag{3}$$

III. EPERIMENTAL SETUP

In this paper, the repeated tension-compression testing is conducted on a fatigue testing machine, and the testing continued until visible crack appeared. As shown in Figure 2, the specimen is designed and fabricated as a waist drum structure according to standard ISO 1099:2006 and GB/T 3075-2008, and the crack generally appeared in the middle of the specimen with minimum diameter. After clamping the specimen on the fatigue testing machine, the axial sine load is applied with 2 Hz, and the maximum tension and compression are both 25 KN. When number of loading reached 119, 380, we can find visible surface crack occurred at the smallest cross-section with a direction perpendicular to the axis of specimen. At this time, the length of crack is 3.5mm in the circumferential direction, and we stop the testing.

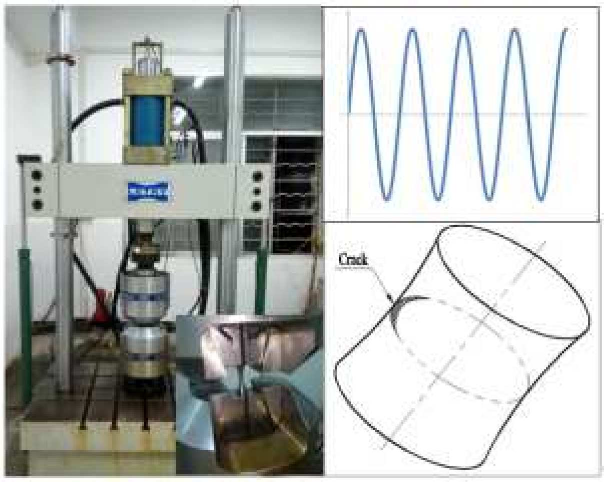


Fig.2. Fatigue testing machine and applied load.

Additionally, to achieve and keep various fatigue crack width in a stable state during the active sensing process, we designed an assistant apparatus, as shown in Figure 3. After fixing two ends of the specimen, we can rotate the bolt to apply a bending moment on the specimen, and the crack will open correspondingly. Thus, we can have different crack widths. Additionally, the viscous-elastic material is placed between the specimen and the assistant apparatus, to avoid influence caused by wave propagation across the apparatus.

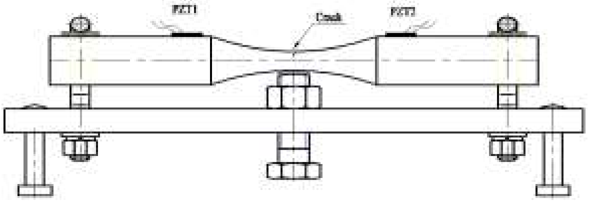


Fig.3. Assistant apparatus for crack extension.

In this paper, five levels of crack width are selected. Under each crack level, we first measure the crack width through the surface profiler (Zegage Plus, Zygo, USA), as depicted in Figure 4. Then, the experimental procedure followed the active sensing method: (1) a swept sine wave (from 1 kHz to 100 kHz) with duration 1s and amplitude 1V is generated by a NI multifunction DAQ device (USB-6363); (2) after amplifying the wave signal fiftyfold (Trek Model 2100HF) to ensure sufficient power, we excite PZT 1 through the amplified signal; (3) the received signal is captured by PZT 2 after the stress wave propagated across the crack. Finally, the received signal energy can be calculated based on the wavelet package method introduced in Section II.B.

Fig.4. Experimental apparatus.

IV. RESULT AND DISCUSSION

As shown in Figure 5, the crack width was measured through the Zygo surface profiler, and thus crack widths under five levels are measured as 0.034mm, 0.05mm, 0.055mm, 0.06mm, and 0.064mm, respectively.

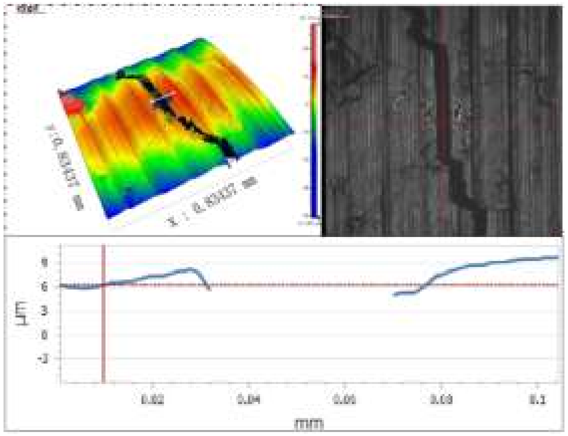
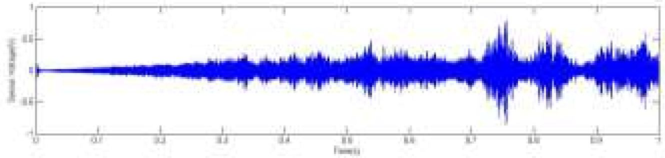
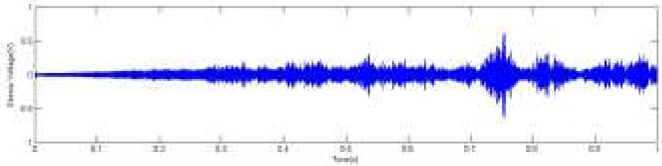


Fig.5. Measured crack width.

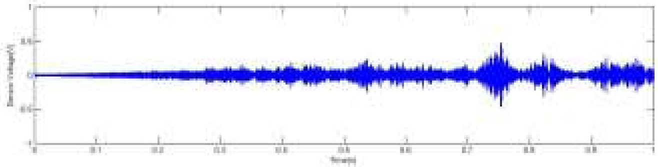
Then, the received signal under each crack width is given in Figure 6 (a)-(e), and we can find that the amplitude of received signal decreases with the increase of crack width.



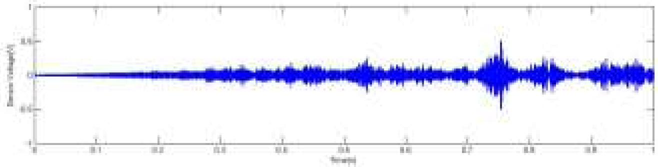
(a) Crack width 0.034mm



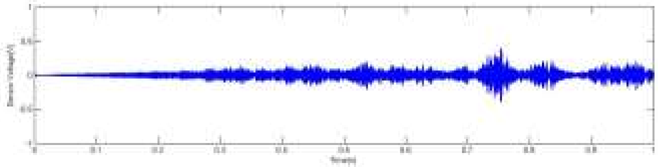
(b) Crack width 0.05mm



(c) Crack width 0.055mm



(d) Crack width 0.06mm



(e) Crack width 0.064mm

Fig.6. Received signal.

Then, the signal energy is computed by using the wavelet package method, and the result is shown in Figure 7.

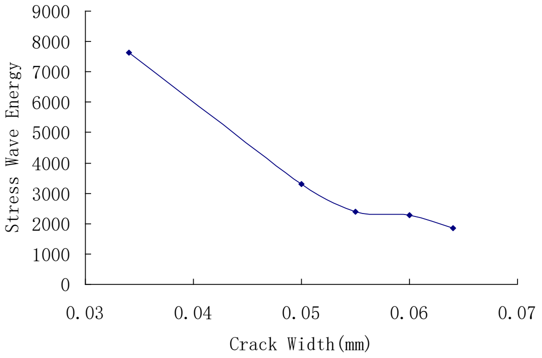


Fig.7. Received signal energy versus crack width.

We find that the energy decreases significantly as crack width increase. This phenomenon can be attributed to the change of contact area at the crack. As crack width increases, the contact area at the cross-section decreases, which hampers the wave propagation and thus attenuates more energy. Therefore, the effectiveness of the proposed method is verified.

V. CONCLUSIONS

In this paper, the active sensing method was employed to detect crack width of specimen after fatigue testing for the first time. In addition, the wavelet package method was used to quantify the energy of received signal. The results demonstrated that the received signal energy decreased with the increase of crack width. Therefore, we verified that the active sensing method is capable of detecting fatigue crack, and on-line monitoring of fatigue crack will be conducted in future investigations. In addition, the effect of ultrasonic wavelength on crack width and signal energy can be considered and investigated in future studies.

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REFERENCES

[1] M. Kamal, and M. M. Rahman, "Advances in fatigue life modeling: A review," *Renew. Sust. Energ. Rev.,* vol. 82, pp. 940-949, Feb, 2018.

[2] M. D. Sangid, "The physics of fatigue crack initiation," *Int. J. Fatigue,* vol. 57, pp. 58-72, Dec, 2013.

[3] R. I. Stephens, A. Fatemi, R. R. Stephens, and H. O. Fuchs, *Metal fatigue in engineering*: John Wiley & Sons, 2000.

[4] Y.-L. Lee, J. Pan, R. Hathaway, and M. Barkey, *Fatigue testing and analysis: theory and practice*: Butterworth-Heinemann, 2005.

[5] F. R. Wang, S. C. M. Ho, L. S. Huo, and G. B. Song, "A Novel Fractal Contact-Electromechanical Impedance Model for Quantitative Monitoring of Bolted Joint Looseness," *IEEE Access,* vol. 6, pp. 40212-40220, 2018.

[6] H. S. Kim, J.-H. Kim, and J. Kim, "A review of piezoelectric energy harvesting based on vibration," *Int. J. Precis. Eng. Manuf.,* vol. 12, no. 6, pp. 1129-1141, 2011.

[7] J. Liang, and W.-H. Liao, "Improved design and analysis of self-powered synchronized switch interface circuit for piezoelectric energy harvesting systems," *IEEE Trans. Ind. Electron. ,* vol. 59, no. 4, pp. 1950-1960, 2012.

[8] S.-C. Lin, and W.-J. Wu, "Piezoelectric micro energy harvesters based on stainless-steel substrates," *Smart Mater. Struct.,* vol. 22, no. 4, pp. 045016, 2013.

[9] M. H. Malakooti, and H. A. Sodano, "Piezoelectric energy harvesting through shear mode operation," *Smart Mater. Struct.,* vol. 24, no. 5, pp. 055005, 2015.

[10] S. Siu, Q. Ji, W. Wu, G. Song, and Z. Ding, "Stress wave communication in concrete: I. Characterization of a smart aggregate based concrete channel," *Smart Mater. Struct.,* vol. 23, no. 12, pp. 125030, 2014.

[11] S. Siu, J. Qing, K. Wang, G. Song, and Z. Ding, "Stress wave communication in concrete: II. Evaluation of low voltage concrete stress wave communications utilizing spectrally efficient modulation schemes with PZT transducers," *Smart Mater. Struct.,* vol. 23, no. 12, pp. 125031, 2014.

[12] G. Song, C. Wang, and B. Wang, "Structural health monitoring (SHM) of civil structures," Multidisciplinary Digital Publishing Institute, 2017.

[13] B. Xu, G. Song, and Y. Mo, "Embedded piezoelectric lead-zirconate-titanate-based dynamic internal normal stress sensor for concrete under impact," *Journal of Intelligent Material Systems and Structures,* vol. 28, no. 19, pp. 2659-2674, 2017.

[14] F. R. Wang, L. S. Huo, and G. B. Song, "A piezoelectric active sensing method for quantitative monitoring of bolt loosening using energy dissipation caused by tangential damping based on the fractal contact theory," *Smart Mater. Struct.,* vol. 27, no. 1, pp. 9, Jan, 2018.

[15] L. Huo, F. Wang, H. Li, and G. Song, "A fractal contact theory based model for bolted connection looseness monitoring using piezoceramic transducers," *Smart Mater. Struct.,* vol. 26, no. 10, pp. 104010, 2017.

[16] G. Du, Q. Kong, H. Zhou, and H. Gu, "Multiple Cracks Detection in Pipeline Using Damage Index Matrix Based on Piezoceramic Transducer-Enabled Stress Wave Propagation," *Sensors (Basel, Switzerland),* vol. 17, no. 8, 2017 Aug, 2017.

[17] Q. Z. Kong, R. H. Robert, P. Silva, and Y. L. Mo, "Cyclic Crack Monitoring of a Reinforced Concrete Column under Simulated Pseudo-Dynamic Loading Using Piezoceramic-Based Smart Aggregates," *Appl. Sci.-Basel,* vol. 6, no. 11, pp. 14, Nov, 2016.

[18] Q. Feng, Q. Z. Kong, L. S. Huo, and G. B. Song, "Crack detection and leakage monitoring on reinforced concrete pipe," *Smart Mater. Struct.,* vol. 24, no. 11, pp. 8, Nov, 2015.

[19] B. Wang, L. S. Huo, D. D. Chen, W. J. Li, and G. B. Song, "Impedance-Based Pre-Stress Monitoring of Rock Bolts Using a Piezoceramic-Based Smart Washer-A Feasibility Study," *Sensors,* vol. 17, no. 2, pp. 10, Feb, 2017.

[20] G. B. Song, W. J. Li, B. Wang, and S. C. M. Ho, "A Review of Rock Bolt Monitoring Using Smart Sensors," *Sensors,* vol. 17, no. 4, pp. 24, Apr, 2017.

[21] L. S. Huo, B. Wang, D. D. Chen, and G. B. Song, "Monitoring of Pre-Load on Rock Bolt Using Piezoceramic-Transducer Enabled Time Reversal Method," *Sensors,* vol. 17, no. 11, pp. 12, Nov, 2017.

[22] T. Jiang, Y. Li, and G. Song, "Detection of High-Strength Bolts Looseness Using Lead Zirconate Titanate Due to Wavelet Packet Analysis," *Earth and Space*, pp. 1069, 2018.

[23] G. Lu, Y. Li, M. Zhou, Q. Feng, and G. Song, "Detecting Damage Size and Shape in a Plate Structure Using PZT Transducer Array," *Journal of Aerospace Engineering,* vol. 31, no. 5, pp. 04018075, 2018.