Crack Length Quantification Based on Planar Eddy-Current Sensor Array and Two-Dimensional Image

Liu Lihui, *Tian Wugang*, *Pan Mengchun* *, *Chen Dixiang*, *Xie Ruifang*, *Ren Yuan*

College of Mechatronics and Automation, National University of Defense Technology, Changsha 410073, P. R. China

(Received 27 September 2017; revised 12 June 2018; accepted 27 June 2018)

Abstract: Eddy-current (EC) testing is an effective electromagnetic non-destructive testing (NDT) technique. Planar eddy-current sensor arrays have several advantages such as good coherence, fast response speed, and high sensitivity, which can be used for micro-damage inspection of crucial parts in mechanical equipments and aerospace aviation. The main purpose of this research is to detect the defect in a metallic material surface and identify the length of a crack using planar eddy-current sensor arrays in different directions. The principle and characteristics of planar eddy-current sensor arrays are introduced, and a crack length quantification algorithm in different directions is investigated. A damage quantitative detection system is established based on a field programmable gate array and ARM processor. The system is utilized to inspect the micro defect in a metallic material, which is carved to micro crack with size of 7 mm (length) × 0.1 mm (width) × 1 mm (depth). The experimental data show that the sensor arrays can be used for the length measurement repeatedly, and that the uncertainty of the length measurement is below ±0.2 mm.

Key words: crack; planar eddy-current sensor array; non-destructive testing (NDT); quantification; 2-D image

CLC number: TP213.13 **Document code**: A **Article ID**: 1005-1120(2018)06-1047-06

0 Introduction

The planar eddy-current (EC) non-destructive testing (NDT) is a new technology developed in recent years, which is an effective to detect defects[1-5] and measure the length of defects[6-7]. On one hand, similar to the conventional eddy-current technique, the planar eddy-current sensor does not require an acoustic couplant in contrast to ultrasonic detection. It is more convenience and less dangerous than radiography. On the other hand, the planar eddy-current testing possesses many advantages against the conventional eddy-current testing, including better coherence, faster response speed, and higher sensitivity. It can be used for detecting crack in high-temperature components in power plants[8] and gap measurements between large smooth metallic and nonmetallic surfaces of arbitrary shapes[9].

Jiao et al.[6] studied the model of crack perturbation and eddy-current sensor and detected the crack with the accuracy of 1 mm. Chen et al.[10] designed an eddy-current probe to inspect the nuclear power plant pipelines with accuracy of several millimeters. Cha et al.[11] designed a high detection sensitivity micro-coil sensor with size of 400 μm × 380 μm × 35 μm using microelectro mechanical system (MEMS) technology. Marchand et al.[12] developed a flexible eddy-current array probe. It was fairly sensitive to small defects, but the quantitative detection results were not reported. Endo et al.[13] used a flexible array eddy-current probe and a 12 dB drop method sizing the crack length with an accuracy of ±3 mm. However, there were some weakness in all these studies, such as insufficient detection accuracy and low detection efficiency. The main purpose of this paper is to detect the defect with high accuracy and in different directions based on the planar ed-

* Corresponding author, E-mail address: nudt_emgroup@163.com.

How to cite this article: Liu Lihui, Tian Wugang, Pan Mengchun, et al. Crack length quantification based on planar eddy-current sensor array and two-dimensional image[J]. Trans. Nanjing Univ. Aero. Astro., 2018,35(6):1047-1052.
http://dx.doi.org/10.16356/j.1005-1120.2018.06.1047

dy-current array sensor and 2-D image.

1 Planar Eddy-Current Sensor Array and Two-Dimensional Image

The planar sensor array is an inductive, eddy-current-based sensor that is designed specifically for the characterization of material properties near surface region. As shown in Fig. 1, the planar eddy-current sensor array consists of a driving winding wires creating the magnetic field and sensing elements located below the driving winding. I_D, λ, H and V_{S1}—V_{S6} of the sensor array in Fig. 1 are the sinusoidal current, the spatial wavelength, the spatially periodic magnetic field the and the inductive voltages at the terminals of the sensing windings, respectively.

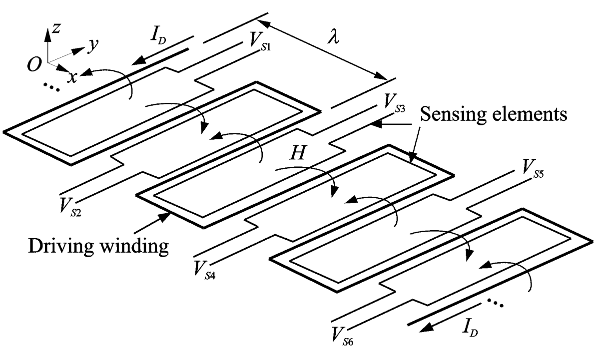

Fig. 1 Basic structure of the planar eddy-current sensor array

The driving and sensing windings are typically mounted on a thin and flexible substrate. Micro-fabrication techniques are used to produce highly reliable and highly repeatable sensors. The individual sense elements in x-direction shown in Fig. 1 can create property images when scanned in the y-direction. The driving winding is designed to produce a spatially periodic magnetic field. The periodic winding pattern permits the sensor array response to be accurately modeled with rapid computational methods. The design dramatically reduced calibration requirements. The response of sensor array is converted into material properties using pre-computed database[14-15].

The image of response of sensor array is implemented with LibGDX architecture, which is a kind of cross platform 2-D/3-D game development engine[16]. The LibGDX architecture based on protocol of Apache License, including OpenGL ES and Box2D, is programmed by Java/C/C++ language and employed free for commercial or non-commercial. OpenGL ES and Box2D are used as graphics engine and physical engine, respectively. The 2-D image should employ a significant Mesh class, which is responsible for graphic processing. Mesh class which extends object class is popularly used in game development. The color change of 2-D image, representing cracks or not, is accomplished by mesh class. On account of widespread use and easy development, android is selected as target platform for LibGDX.

2 Crack Quantification in Different Directions

Eddy-current testing for crack length quantification contains two steps: Crack detection and length measurement of crack. Crack detection is the first stage where a feature threshold is set to figure out which of the three works should be conducted: The part of the specimen being scanned has a discontinuity (crack) or not. If discontinuity is predicted, the second stage of crack quantification is carried out. The information of the length of crack can be used to evaluate the severity of the detected crack of the component or material. It can help judge which of the three works should be conducted: The component or material under test can still be used safely, maintenance work must be scheduled, or a replacement must be needed.

The spatial resolution in length and the sensitivity is considered in the design of array sensor. In order to obtain a high spatial resolution, the wavelength λ of driving winding is as small as possible. But a small wavelength value will lead to a very small induced voltage in sensing elements that will reduce the sensitivity of sensors. Therefore, the half-wavelength of 0.8 mm is employed in view point of the spatial resolution and the sensitivity based on the flexible printed circuit board.

The transimpedance[17] of the planar eddy-current sensor array are given by

$$Z_i = V_{Si} / I_D \tag{1}$$

where Z_i is the transimpedance of sensing element i, I_D the current of the driving winding, and V_{Si} the inductive voltages of the sensing elements. When a crack appears in the material under test (MUT), the inductive voltages V_{Si} will change, corresponding to result in the change of transimpedance Z_i. Thus the crack in the MUT can be inspected through measuring the transimpedance Z_i.

In this paper, sensor array scanning over the MUT in y-direction is shown in Fig. 2. The sensor array is parallel to the x-axis as well as the crack, and scan direction is parallel to the y-axis but perpendicular to the crack. When the sensor array move over a crack in the MUT, the transimpedance magnitude jumps to a higher level due to the crack as shown in Fig. 3. It is seen from Fig. 3 that the transimpedances of the eleventh to the twenty-second sensing element (channel) is greater than the one of the other channels. This curve shown that there is a crack in MUT. We can find that the sensor array has a spatial resolution because of its space periodic structure, and the width of driving winding element is $\lambda/2$, with 0. 8 mm. In addition, the transimpedances of Channel 11 and Channel 22 at the two end of crack is lower than the value of Channel 12 to Channel 21 within the area of cracks, as shown in Fig. 3. This is resulted from the end of the crack covering a portion of Channel 11 and Channel 22. A reasonable transimpedance threshold value 5. 7 Ω is set. And if the transimpedance of the sensing element is greater or equal to 5. 7 Ω of threshold value, the crack can be judged as completely covering the driving element, and 0. 8 mm is accumulated to the length of crack. When the transimpedance of the sensing element is less than the 5. 7 Ω of threshold value, the crack partly goes through. Then the length of crack within the sensing element is calculated by the normalized crack signal fitting (NCSF) algorithm[18]. Its primarily principle is based on the fact that transimpedances of the array unit is different when the crack edge is at different positions of the array elements. And the relation between the transimpedances value and position is monotonous. Therefore, the position of crack edge corresponding to the transimpdances can be calculated by linear interpolation with the known measured point.

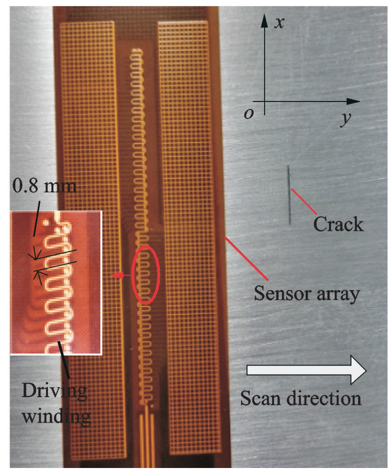

Fig. 2 Photograph of the sensor array (Driving winding in Fig. 1 at the top layer of actual sensor in Fig. 2) and the crack

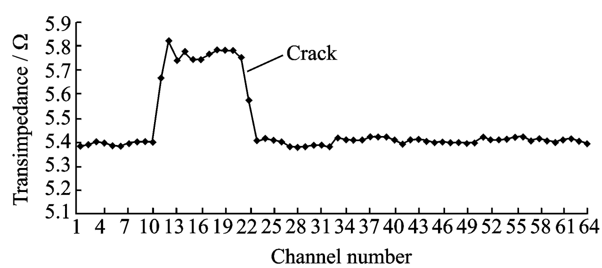

Fig. 3 Transimpedances curve of the sensor array (including 64 sensing elements) through a crack

The above length quantification of the crack is used when the orientation of sensor array is parallel to the crack. If an angle θ exists between the sensor array and the crack, as shown in Fig. 4, the quantification method should be modified.

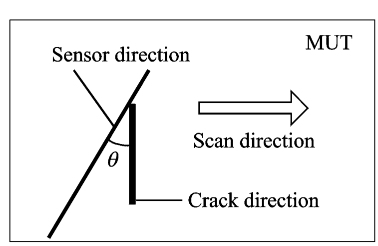

Fig. 4 Angle between the sensor and crack

A viable improvement of quantification algorithm is how to obtain the information of θ, then the actual length of the crack is given by

$$L = L_P \times \cos\theta \tag{2}$$

where L is the actual length of crack and L_P the length of the sensor sensing crack. Fortunately, θ can be obtained from image of sensor array scanning crack in Fig. 5. Therefore, we can see that the image is useful for the quantification of the defects.

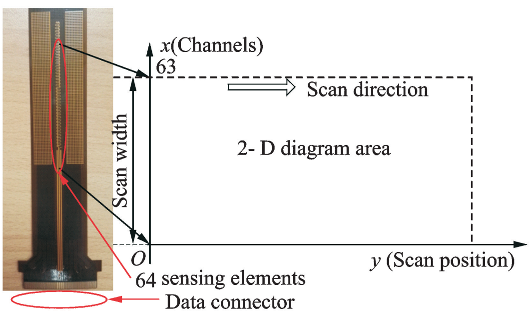

Fig. 5 2-D diagram of sensor array for scanning crack

3 System Design and Experiment

3.1 Experimental set-up

The experimental set-up we developed is embedded system, consisting of a probe and an impedance measurement systems. The data are collected by synchronous data acquisition chip AD9272, which are processed with a digital lock-in amplifier (DLIA) based on the field programmable gate array (FPGA). The processed data are then transmitted to an ARM processor via RS232 interface, in which the image is accomplished and the possible crack is detected and quantified. A voltage control current source (VCCS) circuit is designed to supply a constant current flowing through the driving winding of the planar eddy-current sensor array. The inductive voltage are first amplified with a preamplifier and then collected by AD9272 after switched with multiplexer. The schematic diagram of the experimental set-up is shown in Fig. 6.

An aluminum specimens whose conductivity is 18.9 MS/m and thickness is 10 mm is designed to verify the performance of the system. A defect with size of 7 mm in length, 0.2 mm in width and 1 mm in depth is carved on the surface of the aluminum. A probe with the array sensor scanning the aluminum could lead to a 2-D image of crack in different angle in Fig. 6. And the excitation frequency of probe is 3 MHz. The flexible material can keep the array sensor good contact with the aluminum. The probe and material are shown in Fig. 7.

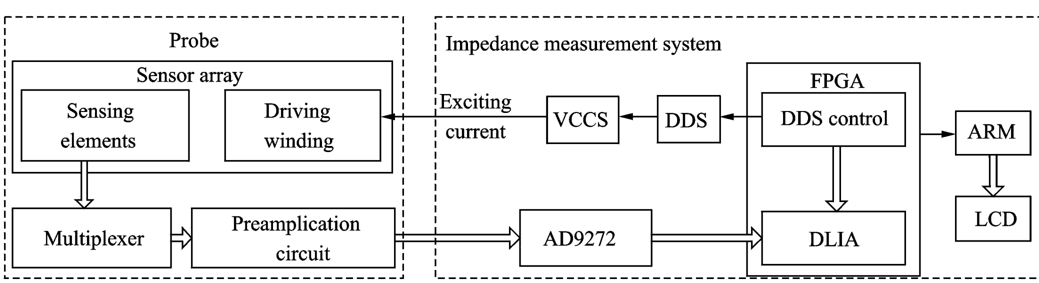

Fig. 6 Schematic diagram of the experimental set-up (DDS: Direct digital synthesizer; LCD: Liquid crystal display)

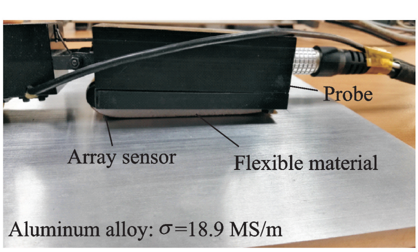

Fig. 7 The material (Aluminum alloy) and probe

The difference between before and after probe responses to the crack is shown in Fig. 8. The output signal of probe is smooth, and the value of transimpedance of array sensor is about 5.4 Ω when the crack cannot appear in the aluminum alloy. If there is a crack in the material, the output signal occurs, as shown in Fig. 8.

3.2 Experimental result and discussion

The main purpose of this section is to verify the quantification accuracy of the system based on

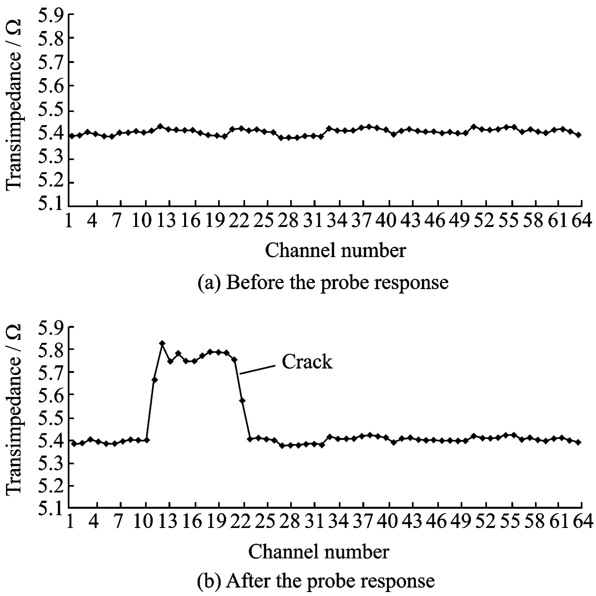

Fig. 8 The before and after probe responses to the crack

planar eddy-current sensor array in different directions and 2-D image. Fig. 9 depicts the image of the crack (7 mm in length) measured at different angles between the scan direction and the sensor array orientation. In this image, the scanning direction of the sensor array is always along the horizontal orientation. As shown in Fig. 9, the smaller the absolute angle between the sensor and the scan direction, the longer the image of crack. However, the quantification accuracy of crack keeps unchanged with different angle, and the corresponding quantification length of the crack image are measured and listed in Table 1. For the special case that the angle is zero, a false quantification length 0.8 mm is measured. The real length of the crack can be measured by repetitive measurements with different angles. It can be seen that the length quantification of the crack can be implemented based on the sensor array and 2-D image in different orientation, and the quantification accuracy is below ± 0.2 mm. The above

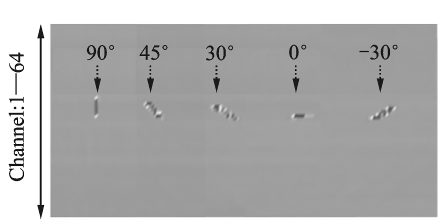

Fig. 9 2-D image of the crack with 7 mm length in different angle

results show that the planar sensor technique and 2-D image technique are useful to detect and quantify the crack.

Table 1 Quantification of the crack in different scan angles

Parameter	Value				
Angel/(°)	90	45	30	0	−30
Crack length/mm	7.10	7.18	7.02	0.80	7.09

4 Conclusions

The length quantification technique of cracks based on planar eddy-current sensor array and 2-D image is studied. Crack detection technique, as the first step of quantification, is also achieved by the change of transimpedance of sensor array. The experimental result shows that the crack length can be measured in multi-direction, and the accuracy of length is less ± 0.2 mm except that the angle equals to zero or the crack is curve. However, the conclusion should be useful for the quantification of cracks and future work. Therefore, our future research will include scanning method and length quantification of abnormity cracks by image processing, which may contain more information of cracks.

Acknowledgements

The work was supported by the National Natural Science Foundation of China (No. 61171460). The authors would like to acknowledge the following people for their assistance: Mr. Zhou Weihong, Mr. Dai Shouqiang.

References:

[1] GOLDFINE N, ZILBERSTEIN V, CARGILL J S, et al. MWM-array eddy current sensors for detection of cracks in regions with fretting damage[J]. ASNT Materials Evaluation, 2002, 60(27):1-14.

[2] ZILBERSTEIN V, KAREN W, DAVE G, et al. MWM eddy-current arrays for crack initiation and growth monitoring[J]. International Journal of Fatigue, 2003, 25(9):1147-1155.

[3] MARCHAND B, DECITRE J M, CASULA O. Innovative flexible eddy current probes for the inspection of complex parts[C]//18th World Conference on Nondestructive Testing. Durban, South Africa:[s. n.],2012.

[4] FUKUTOMI H, OGATA T. Eddy-current inspection of cracking in land-based gas turbine blades[J]. Review of Quantitative Nondestructive Evaluation,

2004, 23(5):368-373.

[5] HOU Bo, HE Yuting, GAO Chao, et al. Film sensor design for metallic structure crack monitoring [J]. Journal of Nanjing University of Aeronautics & Astronautics, 2014, 46(3):419-424. (in Chinese)

[6] JIAO S, CHENG L, LI X, et al. Construction of crack perturbation model and forward semi-analytical model of attached eddy current sensor[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2015, 32(3):279-288.

[7] XIE R, ZHOU W, CHEN D, et al. A novel flexible eddy-current probe with high sensitivity for NDT [C]//11th IEEE Far East Forum on Nondestructive Evaluation/Testing—New Technology and Application(FENDT). Chengdu China:IEEE, 2014.

[8] SHEIRETOV Y, GRUNDY D, ZILBERSTEIN V, et al. MWM-array sensors for in situ monitoring of high-temperature components in power plants[J]. IEEE Sensor Journal, 2009, 9(1):1527-1536.

[9] DING T, CHEN X, HUANG Y. Ultra-thin flexible eddy current sensor array for gap measurements[J]. Tsinghua Science and Technology, 2004, 9(6):667-671.

[10] CHEN Z, JANOUSEK L, YUSA N, et al. A nondestructive strategy for the distinction of natural fatigue and stress corrosion cracks based on signals from eddy current testing[J]. Journal of Pressure Vessel Technology, 2007, 129(5):719-728.

[11] CHA Y J, NAM B, KIM J, et al. Evaluation of the planar inductive magnetic field sensors for metallic crack detections[J]. Sensors and Actuators A:Physical, 2010, 162(15):13-19.

[12] MARCHAND B, DECITRE J M, SERGEEVA-CHOLLET N, et al. Development of flexible array eddy current probes for complex geometries and inspection of magnetic parts using magnetic sensors [C]//Proceedings of the 39th Annual Review of Progress in Quantitative Nondestructive Evaluation. Denver, CO, USA:[s. n.], 2012:488-493.

[13] ENDO H, NISHIMIZU A, TOOMA M, et al. Signal evaluation system of flexible array ECT probes for inspecting complexly shaped surfaces[C]//Proceedings of the Review of Progress in Quantitative Nondestructive Evaluation. San Diego, CA, USA: [s. n.], 2010:597-603.

[14] GRUNDY D, WASHABAUGH A, SCHLICKER D, et al. Health monitoring using MWM®-array and IDED®-array sensor networks [C]//Nondestructive Evaluation for Health Monitoring and Diagnostics. San Diego, CA, USA:[s. n.], 2005.

[15] GOLDFINE N, SHEIRETOV Y, SCHLICKER D, et al. Rapid, nonlinear "system" identification for NDT, using sensor response databases[J]. Materials Evaluation, 2008, 66(7):1-12.

[16] OEHLKE A. Learning libgdx game development [M]. 2nd ed. Birmingham, UK:Packt Publishing Ltd, 2015:11-13.

[17] CHEN D, XIE R, ZHOU W, et al. Multi-channel transimpedance measurement of a planar electromagnetic sensor array[J]. Measurement Science and Technology, 2015, 26(2):1-7.

[18] XIE R, CHEN D, PAN M, et al. Fatigue crack length sizing using a novel flexible eddy current sensor array[J]. Sensors, 2015, 15(12):32138-32151.

Mr. **Liu Lihui** is a Ph. D. candidate in College of Mechatronics Engineering and Automation, National University of Defense Technology, Changsha, China. He received his M. S. degree from National University of Defense Technology in 2013. His research interests are focused on electromagnetic non-destructive testing, digital signal process, and instrumental science and technology.

Prof. **Tian Wugang** currently works in College of Mechatronics Engineering and Automation, National University of Defense Technology, China. His present research interests are focused on electromagnetic non-destructive testing, and instrumental science and technology.

Prof. **Pan Mengchun** received the M. S. and Ph. D. degrees from the National University of Defense Technology, China. He currently works in College of Mechatronics Engineering and Automation, National University of Defense Technology. He is the Director of the Department University of Defense Technology. He has published more than 100 scientific papers. His main research interests include sensors, intelligent instruments, and non-destructive testing.

Prof. **Chen Dixiang** received the B. S., M. S. and Ph. D. degrees from the National University of Defense Technology, China, in 1992, 1995, and 2005, respectively. Currently, he works in National University of Defense Technology. He has published more than 70 scientific papers. His main research interests include sensors, intelligent instruments, and non-destructive testing.

Mr. **Xie Ruifang** is a Ph. D. candidate in College of Mechatronics Engineering and Automation, National University of Defense Technology, Changsha, China. His research interests are focused on electromagnetic non-destructive testing, digital signal process, and instrumental science and technology.

Mr. **Ren Yuan** is a Ph. D. candidate in College of Mechatronics Engineering and Automation, National University of Defense Technology, Changsha, China. His research interests are focused on electromagnetic non-destructive testing, digital signal process, and instrumental science and technology.

(Production Editor:Xu Chengting)