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The Review of New NDT Methods of Metal Material Fatigue Monitoring

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Abstract

Non-destructive testing (NDT) techniques have been employed in all kinds of fields successfully for many years. Newly developed and applied NDT methods of detecting and monitoring fatigue crack in metal material are reviewed in this paper. Some methods based on machine vision technique and image recognition techniques are introduced for at or near surface visible crack testing. As a newborn offspring of acoustic emission technique, electromagnetically induced acoustic emission methods also introduced for both visible and invisible fatigue cracks on metal structure. Nonlinear ultrasonic method and some other NDT methods presently available are mentioned, too. The principles, applied testing fields, data processing algorithms, advantages and disadvantages of these methods are discussed.

Keywords: *Non-destructive testing, fatigue, metal material, machine vision, electromagnetically induced acoustic emission*

1. Introduction

Fatigue is the most important reason of crack initiation and propagation. Research results show, in modern industry, most of the mechanical structures failures caused by fatigue cracks. So the perfect solution is monitoring hot spots on structural part, detecting the initiation of fatigue cracks, testing the growth of them and giving alarm before structural parts damages. An electron microscope is probably the most positive means of measuring the fatigue cracks size. But microscopic examination interrupts the structure operation process, so it can be used as a research tool during the course of a fatigue experiment only. Researchers have been interested in finding a method which can be successfully applied in the field for a long time.

Non-destructive testing is defined to evaluating the continuity, integrity, security or some physical properties of materials, components or structures via a variety of physical principles without compromising performance of object to be tested. Purpose is to detect whether material or structure is flawed, or tests the defectives' shape, orientation, size, distribution, etc., and judges the contents of materials [1]. Non-destructive testing process has become an important part of materials and structures in static or dynamic monitoring and quality management.

Nowadays, widely used non-destructive testing methods of metal fatigue detection include ray inspection, ultrasonic and acoustic emission detection, electrical and electromagnetic detection, *etc* [2, 3]. Modern NDT techniques also include computer data and image processing, image recognition and synthesis, *etc*. Some presently available NDT techniques are introduced in this paper.

2. Machine Vision Method

The machine vision technique is computer simulates human visual function to provide information for detection, measurement and recognition of objects [4]. A camera captures images under the control of a computer, special software on the computer process the data contained in the image based on digital image processing algorithms, then make correct calculation and judgment of the objective world of three-dimensional scenes. As a NDT method, machine vision technique has been employed in metal material surface visible fatigue crack measurement [5].

2.1. Principle

Machine vision system for fatigue crack detection is a high-precision, non-contact monitoring program, which combines electronic, mechanical, measurement, machine vision, and many other techniques [6]. The structural diagram of a typical fatigue crack detection system based on machine vision technique is shown in Figure 1.

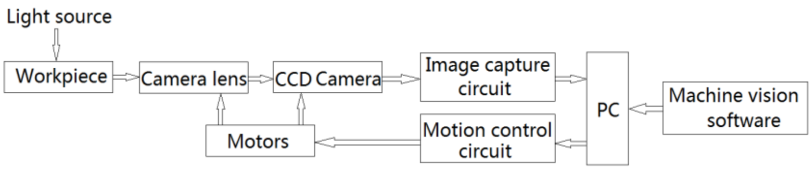

Figure 1. Structural Diagram of Machine Vision Fatigue Testing System

Light source emits appropriate intensity of light at a suitable angle and position to the work piece tested. Reflected light is captured by CCD camera via the lens, then the image capture circuit transfers the image data to the PC. In order to put lens and CCD camera in a suitable angle and position, the PC controls motors via a motion control circuit to move lens and the camera. These devices are also called image capture system of a machine vision system.

The soul of machine vision system is the machine vision software. In metal material fatigue crack testing, the software flowchart is shown in Figure 2.

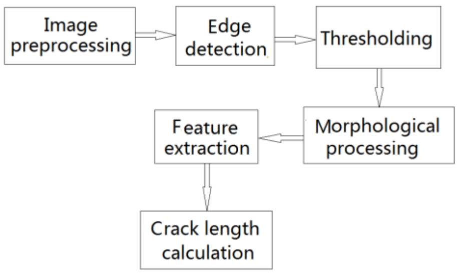

Figure 2. Flowchart of Fatigue Crack Testing Software

2.2. Advantages and Disadvantages

In 1983, Honeywell company supported by the US Department of Energy developed the automatically equipment of detecting surface defects on hot steel slabs based on camera and image processing technique [7]. From then on, machine vision technique has been applied successfully on metal surface defects and fatigue cracks. The most significant advantage of machine vision method in fatigue monitoring is the operation of structure tested need not be interrupted. It is a real-time non-contact measurement with history data recorded automatically [8].

As other machine vision measuring system, the metal fatigue crack measuring system based on machine vision technique has a significant disadvantage, which is the CCD digital camera must be calibrated before measuring the crack size. And the camera calibration is the decisive factor of measurement accuracy of fatigue crack [9].

Direct Liner Transformation (DLT) calibration method was put forward by Abdel-Aziz and Karara. Because of the simplicity of linear calibration method, it is most widely used. In this calibration method, parameters of the camera model can be obtained by solving linear equations. Since the actual lens perspective model is not ideal, but with varying degrees of distortion, the image obtained from space points is not on the ideal position described by linear model. So the calibration accuracy of DLT method is not high [10]. Nonlinear method uses a large amount of non-linear optimization and a wide range of unknowns. The more accurate of nonlinear models, the more calculation is required. Levenberg-Marquadt algorithm is often employed to realize the nonlinear optimization. Although nonlinear methods compensate for lens distortion, the iterative nature of the algorithm makes the algorithm sensitive to initial values and easy to fall into local optimum [11].

Camera calibration using nonlinear optimization requires accurate design of camera model, and the result of solving nonlinear equations depends on the setting of initial value. In order to take the advantages of the two methods, the combination of them, a two-step method, was developed. At the first, linear transformation method is used to solve the camera parameters. And then these parameters are used as initial values, considering the distortion factor, nonlinear optimization methods are employed to further optimization to improve the calibration accuracy. One of the most typical two-step methods is the radial alignment constraint (RAC) two-step method proposed by Tsai [12]. This method has a high accuracy, and a lot of improvements of camera calibration algorithms are based on Tsai two-step method. Besides, some camera dynamic calibration methods and self-calibrating methods are developed by researchers [13-15].

3. Electromagnetically Induced Acoustic Emission (EMAE)

Acoustic emission (AE) is a well developed NDT technique which has been used in many industry fields successfully [16, 17]. Traditional AE testing required mechanically loaded on the entire structure or material, and then additional damage caused. Besides, it is quite difficult to put mechanical load on a large structure overall. EMAE technique is a new NDT technique which is the result of AE technique developing and electromagnetic technique developing.

3.1. Principle

EMAE is a method of giving electromagnetic load on conductive materials, generating Lorentz force, thus stimulating the acoustic emission effects, and using this effect for non-destructive testing. Therefore, EMAE technique has the advantage of electromagnetically load and AE testing. In the defect spot, there is a current concentration phenomenon when current flowing through the metal conductor. So the current density around the defective spot is significantly greater than that on the other areas. On the tip of a crack, the current density is one order of magnitude compare to that on the other parts. Under the electromagnetic field, Lorentz force makes crack expand further and produce acoustic emission signals [18]. An EMAE testing system for fatigue crack of a joint on thin metal plate is illustrated in Figure 3.

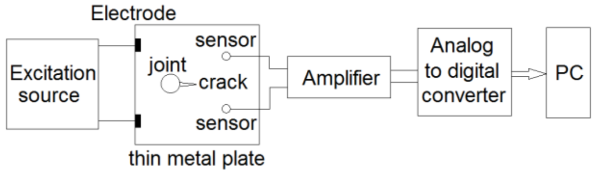

Figure 3. Diagram of EMAE Testing System

3.2. Advantages and Disadvantages

As an offspring of AE NDT method, EMAE has the same advantages as AE as follows:

(1) It is a dynamic detection method by detecting the energy from the test object itself, rather than NDT instruments as ultrasound or radiographic inspection.

(2) It can provide continuous real-time information when defect grows with the dynamic loads, time, temperature, etc. So it is suitable for on-line monitoring of industrial processes, or real-time evaluation for early damage forecasts.

(3) It is more sensitive to the extended defect. It can detect the activity of these defects under applied stress in the structure. Because of Kaiser effect, the stable defect does not generate acoustic emission signals.

AE signals generated from material defects sudden release of energy. So signal processing technique of AE is also facing the diversity of problems, such as separating acoustic emission sources, capturing the weak and sudden signal, and eliminating noise. With the discovery of new materials, improvement of sensitivity and band characteristics of sensors and successful use of wavelet transform technique in AT testing, faint AE signal from micro-cracks and fatigue damage can be captured and separated from the noise [91-21].

EMAE method is different from traditional AE testing in the behalf of locally electromagnetic force, which has a big advantage of non-contact load. On EMAE method, sensors only receive signals from loading area, local signal processing resolves the problem which traditional AE method is difficult to overcome.

A problem of EMAE technique is the AE signal changes with the electromagnet loading mode, such as loading time, exciting frequency, current amplitude, etc. Generally speaking, EMAE need a short time high amplitude exciting energy to stimulate the crack vibrating and emitting mechanical waves. The finite element analysis is effective tools to research how the exciting conditions decide the current, the Lorentz force and the deformation of EMAE. A finite element model of EMAE must be built based on the detecting principle. Now the EMAE technique is still in experimental stage, and different electromagnetic exciting load methods are researched, such as eddy current induced AE technique [22].

4. Nonlinear Ultrasonic Method

The basic principle of the nonlinear ultrasonic testing is that the waveform is distorted and higher-order harmonics generate by nonlinear stress-displacement relationship when the ultrasonic wave reaches the interface of different materials. Nonlinear acoustics is sensitive to various mechanical defects in materials. Researchers in the fields of nondestructive evaluation have studied and exploited nonlinear acoustic phenomena for a long period. With the value of the nonlinear acoustic information constantly being discovered, material defect detection technology based on nonlinear acoustic got increasingly applications.

Second harmonic motivating efficiency was used as the feature parameter of quantitatively identifying fatigue micro-crack defect of metal component, and the deduction of theory formula was obtained [23]. Contact acoustic nonlinearity was study experimentally by Korea researchers using the measurement system constructed in the pitch-catch method that permits the transducers to access the only single side of a test structure. Results showed that the magnitude of the second-order harmonic wave represented the existence of the closed area clearly and that the crack sizing performance was greatly improved by the combination of the linear and nonlinear ultrasonic techniques [24, 25].

In order to enhance the sensitivity of nonlinear acoustic methods further, higher-order non-linear effects is taken into account. When the third or higher order nonlinearity is considered, the testing system needs to be more accurate. Because usually the nonlinear effect of higher orders is much smaller than the second order, as shown in Figure 4 [26, 27].

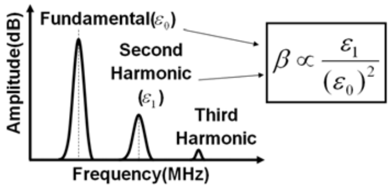

Figure 4. Higher Harmonic Generation

Nonlinear Elastic Wave Spectroscopy (NEWS) is a new offspring of nonlinear acoustic techniques. There are two methods of NEWS. The one is single mode nonlinear resonant acoustic spectroscopy (SIMOBRAS), another is nonlinear wave modulation spectroscopy (NWMS). On the SIMOBRAS, nonlinear response of a single resonance mode is studied, changing of the resonant frequency, harmonics and damping are functions of harmonic resonance peak acceleration or stress amplitude [28].

5. Other NDT Methods for Fatigue Crack Monitoring

With the NDT technique developed, more testing method can be used in metal fatigue monitoring.

Electrical resistance testing method has applied in the metallic materials damage detection and life prediction. Based on the resistance change before and after crack appearance, this method was used to detect the fatigue crack on steel deck [29].

Metal magnetic memory (MMM) defect detection method is widely used in early diagnosis and life prediction of ferromagnetic materials. MMM technique for crane rails inspection was simulated, and effects of crack size, tensile load, lift-off height and applied magnetic field on crack MMM signals were studied quantitatively [30].

With continuously improve of computer simulation software and numerical simulation methods, numerical simulation, which can effectively prevent a large number of repeat purchase equipment for the experiment on different parameters, has been widely used in NDT studies by more and more researchers.

6. Conclusion

With varieties of most presently developed NDT techniques suitable for testing metal material fatigue cracks, constructing structural health monitoring systems based on different principles is the next goal of researchers. In order to monitor the fatigue process, predict the structure life and even predict the generation of fatigue cracks, the following task would be applying the methods obtained by experimental research in fields of industry, aviation and aerospace.

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