NDT&E International 41 (2008) 491–500

Contents lists available at ScienceDirect

NDT&E International

journal homepage: www.elsevier.com/locate/ndteint

Statistical pattern analysis of ultrasonic signals for fatigue damage detection in mechanical structures ☆

Shalabh Gupta, Dheeraj S. Singh, Asok Ray *

Department of Mechanical Engineering, Pennsylvania State University, University Park, PA 16802, USA

ARTICLE INFO

Article history:
Received 13 December 2007
Received in revised form
17 March 2008
Accepted 2 June 2008
Available online 6 June 2008

Keywords:
Fatigue damage monitoring
Ultrasonic sensing nethodology
Pattern identification

ABSTRACT

This paper addresses online monitoring of fatigue damage in polycrystalline alloy structures based on statistical pattern analysis of ultrasonic sensor signals. The real-time data-driven method for fatigue damage monitoring is based on the concepts derived from *statistical mechanics*, *symbolic dynamics* and *statistical pattern identification*. The underlying concept is detection and identification of small changes in statistical patterns of ultrasonic data streams due to gradual evolution of anomalies (i.e., deviations from the nominal behavior) in material structures. The statistical patterns in terms of the escort distributions from statistical mechanics are derived from symbol sequences that, in turn, are generated from ultrasonic sensors installed on the structures under stress cycles. The resulting information of evolving fatigue damage would provide early warnings of forthcoming failures, possibly, due to widespread crack propagation. The damage monitoring method has been validated by laboratory experimentation in real time on a computer-controlled fatigue damage testing apparatus which is equipped with a variety of measuring instruments including an optical travelling microscope and an ultrasonic flaw detector.

1. Introduction

Damage due to fatigue phenomena in polycrystalline alloys is one of the most commonly encountered sources of structural degradation in human-engineered complex electromechanical systems (e.g., aircraft, electric power generation units, and petrochemical plants). Accumulation of fatigue damage may cause catastrophic failures, leading to potential loss of life and expensive equipment. Therefore, it is necessary to develop capabilities for online detection of incipient fatigue damage to ensure safety and reliable operation of human-engineered complex systems as well as for enhancement of their service life. In the current state of the art, direct observation of fatigue damage at an early stage (e.g., crack initiation) is not feasible due to lack of adequate analytical models and sensing devices. Several model-based approaches have been proposed for structural health monitoring and life prediction of mechanical structures [1,2]. Apparently no existing model, solely based on the fundamental principles of material physics, can adequately capture the dynamical behavior of fatigue damage at the grain level. Specifically, random distribution of flaws in the material microstructure leads to different behavioral trend of fatigue damage evolution in identically manufactured structural components. Consequently, both theoretical and experimental analysis of time series data [3,4] from the available sensors is essential for real-time monitoring of fatigue damage evolution in polycrystalline alloys.

A variety of damage detection techniques, based on different sensing devices (e.g., ultrasonics, acoustic emission, and eddy currents), have been proposed in recent literature for fatigue damage monitoring [5,6]. Acoustic emission technique has been investigated by several researchers for its sensitivity to the activities occurring inside the material microstructure for early detection of fatigue and fracture failures [7,8]. However, the major drawback of acoustic emission technique is poor performance in noisy environments where signal-noise separation becomes a difficult task. The eddy current technique is based on the principal of electromagnetic induction. When a source of alternating current is supplied to a conductor, a magnetic field develops which induces eddy currents in the material. The presence of faults in the material affect the eddy current flow patterns, which can be measured for detection of structural damage [6,9]. The advantages of eddy current inspection technique include sensitivity to small defects, portability of sensor equipment, minimum part preparation, and non-contact evaluation. However, the

☆ This work has been supported in part by the US Army Research Laboratory and the US Army Research Office under Grant no. W911NF-07-1-0376 and by NASA under Cooperative Agreement no. NNX07AK49A.

* Corresponding author.
E-mail addresses: szg107@psu.edu (S. Gupta), dss240@psu.edu (D.S. Singh), axr2@psu.edu (A. Ray).

0963-8695/$ - see front matter © 2008 Published by Elsevier Ltd.
doi:10.1016/j.ndteint.2008.06.001

limitations of the eddy current inspection technique are the depth of penetration and it can be used to detect only surface and near surface defects. Furthermore, only conductive materials can be inspected.

Ultrasonic sensing technique functions by emitting high frequency ultrasonic pulses that travel through the specimen and are received by the transducers at the other end. As with the propagation of any wave, it is possible that discontinuities in the propagation media will cause additive and destructive interference. Since material characteristics (e.g., voids, dislocations and short cracks) influence the ultrasonic impedance, a small fault in the specimen is likely to change the signature of the signal at the receiver end [10–13]. Specifically, ultrasonic impedance is very sensitive to small microstructural changes occurring during early stages of fatigue damage evolution. Therefore, it is logical to detect the incipient damage from changes in statistical patterns of ultrasonic data due to gradual evolution of anomalies (i.e., deviations from the nominal behavior) in material microstructures. Ultrasonic sensing is suitable for real-time applications and on site installation of the sensing probes is very simple. Ultrasonic sensing technique is also robust to noisy environments since the externally excited waves are of very high frequency and they do not interfere with small disturbances.

The above discussions evince the fact that time series analysis of ultrasonic data is essential for real-time detection and monitoring of fatigue damage. However, appropriate signal processing and pattern identification methods must be incorporated for extraction of relevant information from the ultrasonic time series data. Although there exist diverse techniques of pattern identification [14], only very few of these tools (e.g., artificial neural networks, and principal component analysis) have been applied for online damage detection. Moreover, such applications are largely restricted to the crack propagation regime after a substantial part of the useful service life has already been expended.

This paper presents a novel multidisciplinary approach of pattern identification through integration of the concepts derived from *statistical mechanics* and *symbolic dynamics*. The statistical patterns are identified from observed time series data of sensors for detection of small changes in the underlying process characteristics. The algorithms based on the proposed concept are applied to ultrasonic data for real-time fatigue damage monitoring in polycrystalline alloys. The ultrasonic signals are converted from the time domain to quasi-stationary symbolic sequences by symbolic dynamic encoding [15] using a recently reported statistical pattern identification tool, called symbolic dynamic filtering (SDF) [16]. This procedure enables noise suppression due to symbolization by coarse graining [17], extraction of relevant information by *maximum entropy partitioning* and information compression into low-dimensional probability vectors. Subsequently, behavioral patterns are derived from these probability vectors using escort distributions [18] that are also known as generalized canonical distributions in the statistical physics literature [19].

The escort distributions have the advantage that they are capable of scanning the original probability distribution for increasing the sensitivity of anomaly detection without any significant increase in the computational requirement. Fault signatures are usually hidden in a few elements of the original probability vector (i.e., information is carried by a few symbols) and therefore, the use of escort distribution provides the capability of zooming into certain regions of the partition that reveal more information about the microscopic anomaly progression. As anomalies gradually progress in cyclically stressed structures, the escort distributions evolve relative to the nominal condition and thereby facilitate early detection of small changes in the material microstructure.

The pattern identification algorithms are executable on commercially available inexpensive platforms, thereby allowing real-time implementation. A combination of time series data symbolization and low-dimensional escort pattern generation enables information compression and robust anomaly detection in real time with enhanced sensitivity, especially at early stages of fatigue damage. From the above perspectives, the major contributions of this paper are delineated below:

(1) Development of a data-driven pattern identification algorithm for real-time fatigue damage monitoring based on the statistical mechanical concept of escort distributions and symbolic dynamic filtering (SDF) of ultrasonic sensor signals.
(2) Application of the above damage monitoring method for detection of small changes in the material microstructures, especially at early stages of fatigue damage evolution (e.g., crack initiation).
(3) Experimental validation of the proposed concept on a special-purpose computer-controlled fatigue damage testing apparatus that is equipped with a variety of measuring instruments including an optical traveling microscope and arrays of ultrasonic flaw detectors.

The paper is organized in five sections including the present one. Section 2 outlines the concept of statistical pattern identification using tools of symbolic dynamics and statistical mechanics. Section 3 describes the experimental apparatus on which the proposed concept is validated for early detection of fatigue damage. Section 4 presents the results and discussion and the paper is concluded in Section 5 along with recommendations for future research.

2. Problem formulation for behavioral pattern identification

This section presents the behavioral pattern identification problem for anomaly detection in complex dynamical systems. Specifically, the theory of SDF is presented and the concept of escort distributions in statistical mechanics is described for pattern identification and detection of fatigue damage evolution in polycrystalline alloys.

The study of dynamical systems using the tools of statistical mechanics has been a subject of immense interest over the last few decades and is known as *thermodynamic formalism* of complex systems [17,18]. As discussed earlier, detailed models of complex physical processes often prove to be mathematically untractable and computationally intensive especially in the high dimensional phase space. In statistical mechanics, similar issues are dealt with by estimating the macroscopic properties (e.g., pressure, temperature, and chemical potential) of the entire system from the distribution of the elementary particles in various microstates [19]. Following this concept, the behavior of a dynamical system is investigated from both *microscopic* and *macroscopic* perspectives. From the point of view of statistical mechanics, a dynamical system is conceptually visualized to be analogous to a thermodynamic system, where each data point in a sequence of time series data can be treated as a particle in the statistical mechanical sense. The macroscopic behavior of the dynamical system is estimated from the time series data sequences by describing statistical distributions of the (so-called) data particles at different energy levels that are defined by partitioning the time series data sequence as explained in Section 2.1.

Pattern identification of a quasi-stationary process is recognized as a two-time-scale problem. The *fast-time scale* refers to the local behavior of the dynamical system and is defined as the time scale over which the behavior of system dynamics is assumed to