Available online at www.sciencedirect.com

ScienceDirect

Computers and Structures 85 (2007) 476–485

Computers & Structures

www.elsevier.com/locate/compstruc

Statistical damage identification for bridges using ambient vibration data

Q.W. Zhang *

Department of Bridge Engineering, Tongji University, 1239 Siping Rd., Shanghai 200092, China

Received 19 April 2004; accepted 13 August 2006
Available online 17 November 2006

Abstract

The inherent uncertainties in experimental data have been recognized as one of the main barriers against the application of vibration-based damage identification techniques on real-life bridges. A statistical damage identification procedure for bridge health monitoring is presented in this paper. It is assumed that the structure, in both healthy and unknown conditions, is monitored and the dynamic responses under ambient excitations are available. The damage identification procedure runs following a 4-step scheme including (1) data sample formation, (2) data normalization, (3) damage feature extraction, and (4) statistical damage evaluation. A hierarchical sequence matching scheme is suggested for data normalization to account for the effects of various environmental and operational conditions on the structural dynamics. The damage feature extraction technique based on time series analysis combining auto-regressive and auto-regressive with eXogenous inputs prediction models is adopted. A statistical index based on the damage features that are derived from a large number of data samples is proposed for novelty detection and damage localization. The effectiveness and robustness of the proposed procedure is demonstrated by numerical simulations performed on a three-span continuous girder bridge with reasonable damage severity.

Keywords: Damage identification; Parametric modeling; Feature extraction; Sequence matching; Ambient vibration; Bridge health monitoring

1. Introduction

Structural damage detection and integrity assessment is one of the fundamental objectives for bridge health monitoring. In such application, it is desired that the early stage damage in a bridge be detected by examining changes in its measured responses. Structural vibrational responses such as accelerations are the most commonly used measurements, in part due to the hypothesis that damage changes the physical properties of a structure, which in turn will cause changes to the vibrational characteristics of the structure. Vibration-based damage detection is a rapidly developing technology and a considerable amount of methods has been proposed [1–4]. Comprehensive reviews about the vibration-based damage detection methods for nuclear, aerospace, mechanical, offshore and civil engineering structures can be found in Refs. [5,6]. Most of the existing damage identification methods can be classified into two groups: model-based and feature based. The model-based methods are basically a model updating procedure, in which the mathematic model, or strictly say, the physical parameters of a structure is calibrated or updated using vibration measurements [7,8]. A fundamental difficulty, however, lies in the fact that the physical parameters obtained from the updating procedure may be unrelated to the actual damage scenarios, though they can be consistent with the measured modal data. The feature based approaches detect structural changes by using some damage features, without the need of a detailed model of the structure. Damage features are extracted from measured responses and ideally, should be sensitive to structural changes. Features for damage identification have used to

* Tel.: +86 21 65981352; fax: +86 21 65983427.
E-mail address: zhangqw@mail.tongji.edu.cn

0045-7949/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compstruc.2006.08.071

be based on natural frequencies, mode shapes, mode shape derivatives, stiffness matrix and flexibility matrix, etc. [9–12]. The sensitivity of some vibration-based features to various levels of damage was evaluated by Farrar and Jauregui [13,14], based on the data collected from the I-40 Bridge in New Mexico by introducing controlled damage to a girder. It was demonstrated that the modal property based features were not good indicators of damage. Recently, feature based methods that operate in the time-frequency domain by using techniques, such as wavelet transform and wavelet packet transform, have been explored [15,16].

Usually four levels of damage identification are categorized according to a logical sequence [17]: level 1, identification of the occurrence of damage; level 2, localization of damage; level 3, quantification of the severity of damage; and level 4, prediction of the remaining service life of the structure. In practical applications, however, it seems that the existing vibration-based methods are not effective to achieve the four levels of damage detection. Actually, it is not easy even if to give an unambiguous judgement on the occurrence and location of structural damage when the damage is at an early stage. From the viewpoint of bridge health monitoring, the hindrances against the use of vibration-based damage identification techniques include: (1) bridges, in routine operational and environmental conditions, typically vibrate with lower frequency global modes, which are not significantly influenced by local damage; (2) bridges generally behave in a nonlinear (or weak nonlinear) and time-varying way, which may invalidate the approaches that are based on linear system modeling [18]; (3) dynamic characteristics of a bridge can be significantly affected by changing environment temperatures [19], and may be amplitude-dependent, especially for long-span cable-supported bridges [20]; and (4) data measured from an actual bridge are inevitably contaminated with noise. The two latter issues make it difficult to discriminate the changes in structural responses caused by damage from those caused by changing environmental and operational conditions or those due to noise. To address these issues, Farrar et al. [18] posed the damage detection problem in the context of a statistical pattern recognition paradigm and described the paradigm as a four-part process: (1) operational evaluation; (2) data acquisition and cleansing; (3) feature selection and data compression; and (4) statistical model development. In the frame of this paradigm, Sohn and Farrar [3] developed an attractive procedure for damage diagnosis of mechanical systems. They introduced the concept of data normalization to account for environmental and operational variability and proposed a damage-sensitive feature based on the time series analysis of vibration signals. The procedure had the ability to perform the damage identification in an unsupervised learning mode, which is very important for the development of structural health monitoring system because data from damaged structures are typically not available for most real-world structures.

In this study, a statistical damage identification procedure for continuous bridge health monitoring is presented. The ambient vibration responses measured from a bridge, in both healthy (known) and unknown structural conditions, are utilized. Attention is mainly focused on the effects of the inherent uncertainties in experimental data on damage assessment for real-life bridges. The procedure is carried out following a 4-step diagnosis scheme, which includes (1) data sample formation, (2) data normalization, (3) damage feature extraction, and (4) statistical damage assessment. A hierarchical sequence matching scheme is suggested for data normalization in an effort to account for the effects of the varying environmental and operational conditions on the structural vibration indirectly. The strategy for damage feature extraction suggested in Ref. [3] is adopted, in which a two-stage time series analysis combining auto-regressive (AR) and auto-regressive with eXogenous inputs (ARX) prediction models is involved. A statistical measure based on the damage features derived from all data samples are proposed for structural novelty detection and damage localization. The improvement of the proposed approach compared with that presented in Ref. [3] is in the use of a hierarchical sequence matching scheme for data normalization and a probability-based measure for damage assessment. The hierarchical sequence matching scheme can avoid the mismatching problem that are liable to occur when simply using the Euclidean distance for similarity searching. The proposed probability-based measure of damage is explicit in form and quite straightforward to calculate. The effectiveness and robustness of the proposed procedure is investigated through numerical simulations performed on a 3-span continuous girder bridge with reasonable damage severity and realistic noise levels.

2. Diagnosis scheme and formulation

2.1. Proposed diagnosis scheme

In general, the structural vibration responses under ambient excitations such as wind and traffic loading are measured and employed in the application of long-term bridge health monitoring. The damage diagnosis scheme proposed here takes two assumptions: (1) the structural vibration response time histories are obtained from a bridge both when it is in undamaged condition (known) and when it is in unknown condition; (2) the vibration measurements obtained when the bridge is undamaged cover the various environmental and operational conditions, which mainly includes climatic, seasonal and daily cycles of environmental and ambient conditions as well as changing traffic loadings. Note that the second assumption does not mean that measures of the environmental or operational conditions should be available. The diagnosis scheme, as illustrated in Fig. 1, consists of the following 4-steps: