Journal of Sound and Vibration 375 (2016) 254–274

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Vibration characteristics and damage detection in a suspension bridge

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ARTICLE INFO

Article history:
Received 27 February 2016
Received in revised form
4 April 2016
Accepted 21 April 2016
Handling Editor: L. G. Tham
Available online 6 May 2016

Keywords:
Suspension bridges,
Cables,
Vibration based damage detection,
Component specific damage index,
Noise

ABSTRACT

Suspension bridges are flexible and vibration sensitive structures that exhibit complex and multi-modal vibration. Due to this, the usual vibration based methods could face a challenge when used for damage detection in these structures. This paper develops and applies a mode shape component specific damage index (DI) to detect and locate damage in a suspension bridge with pre-tensioned cables. This is important as suspension bridges are large structures and damage in them during their long service lives could easily go unnoticed. The capability of the proposed vibration based DI is demonstrated through its application to detect and locate single and multiple damages with varied locations and severity in the cables of the suspension bridge. The outcome of this research will enhance the safety and performance of these bridges which play an important role in the transport network.

1. Introduction

As transport infrastructure systems, particularly bridges, in many countries are rapidly aging, structural deterioration can set in. Environmental influences, changes in load characteristics and random actions [1] accelerate the structural deterioration and can cause damage leading to expensive retrofitting or bridge failure. The importance of detecting damage in these bridges at an early stage and carrying out the necessary retrofitting to prevent bridge failure is therefore obvious.

Structural Health Monitoring (SHM) has emerged as an approach that can address this need. Current SHM systems are integrated with a variety of damage detection methods, which are global and local in nature. Limitations in local methods necessitate the non-destructive and global techniques for damage diagnosis. This has led to continuous development in vibration based damage detection (VBDD) methods in SHM systems. The basic principle of vibration based SHM is that the damage in a structure changes its structural properties which in turn results in changes in its vibration characteristics. A change in the vibration characteristics can hence be used to detect damage in a structure. In the context of VBDD technology, methods that use Damage Indices (DIs) are effective, inexpensive and have the ability to automate the damage assessment process [2,3]. Many researchers have used Damage Index (DI) methods to successfully detect and locate damage in structures constructed with different material such as steel [4,5], composites [6] reinforced concrete [3] and timber [7]. In the literature, different vibration characteristics such as natural frequencies [8,9], damping ratios [10,11], mode shapes [12,13], derivatives of mode shapes [4,14,15], modal flexibility [7,16–23] and modal strain energy values [3,24–26] have been

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http://dx.doi.org/10.1016/j.jsv.2016.04.025
0022-460X/

used to developed the DIs for damage detection in various structures. A special DI based on Poincare´ maps (which contain data for the displacements and the velocities of the structure) was proposed by Manoach and Trendafilova [27] to identify damage in rectangular plates.

Suspension bridges are increasingly used in today's infrastructure system to span large distances and are rich in architectural features and aesthetical aspects. They are large structures and their main cables may be subjected to severe corrosion and fatigue damage, which can go unnoticed. These bridges are flexible structures with low stiffness and low mass. They are vibration sensitive and exhibit complex vibration characteristics. Such vibration is multi-modal and coupled and hence it is difficult to identify the damage sensitive modes for use with the normal vibration based methods for detecting damage. Due to this reason the use of vibration based DI to assess damage in suspension bridge cables has been limited.

Among different VBDD techniques the traditional modal flexibility (MF) method is a promising method which incorporates the natural frequencies and mass normalised mode shapes. It usually requires a few of the lower order modes for detecting damage in structures and has been used by a number of researchers for locating damage in beam and plate like structures [16–18,26,28]. Wang et al. [19] identified that MF was a sensitive damage indicator compared with other modal indices in detecting damage in the bearings, decks and hangers of the Tsing Ma Bridge. Choi et al. [7] also used the changes in flexibility to develop a new hybrid algorithm to estimate damage severity in timber structures. Relative flexibility change (RFC) between intact and damaged states of the cable stayed bridge was studied by Ni et al. [20], whose RFC index was successful in locating damage in single damage scenarios in the absence of ambient effects. However difficulties were encountered in detecting and locating damage in cross girders. Moragaspitiya et al. [21] predicted the axial shortening of vertical load bearing elements of reinforced concrete buildings using the MF method. Montazer and Seyedpoor [22] developed a new damage index named as strain change based on flexibility index (SCBFI) which was used for locating multiple damage cases in truss systems and demonstrated its capability. Recently, Sung et al. [23] developed a method based on MF to detect damage in cantilever beam type structures. It was successfully applied to identify damage in a ten story building by both numerically and experimentally for single and multiple damage cases. The literature confirms that the MF method has a wide variety of applications in damage diagnosis studies but not in detecting and locating damage in the main cables of suspension bridges.

This paper develops and applies a mode shape component specific damage index (DI) that can successfully detect and locate damage in the main cables of a suspension bridge with pre-tensioned cables. These are very important components of a suspension bridge. This special VBDD method is a modified form of the traditional MF method and incorporates only a few lower order modes and their components. It is able to overcome the issues associated with the complex vibration exhibited by suspension bridges and is easy to calculate and apply. The effectiveness of the proposed DI is demonstrated under a range of damage scenarios.

To illustrate the proposed method a laboratory model of a suspension bridge with three sets of cables namely; top supporting cables (TSC), pre-tensioned reverse profiled (bottom) cables (RPC) in the vertical plane and pre-tensioned bi-concave side cables (BCSC) in the horizontal plane is considered. These cables serve different structural actions in the bridge. A FE model of this bridge was developed and validated using vibration data from the laboratory performed experiments. This was then used to examine the competency of the component specific DI under different damage scenarios involving single and multiple damages and varying damage intensities in the different cables of this rather complex bridge structure. It is shown that the proposed DI provides better and more reliable results compared to those from the traditional MF method. This paper illustrates the application of the proposed DI to a three dimensional suspension bridge model which exhibits complex vibration characteristics. Other case studies related to real suspension bridges are presented in reference [29]. The research outcomes will enable the timely retrofitting of cables to ensure the safe operation of suspension bridges in the infrastructure and optimal allocation of public resources for retrofitting and maintenance.

2. Vibration based component specific damage indices

The MF method is a widely accepted technique in damage detection which associates vibration characteristics of a structure that include natural frequencies and mass normalised mode shapes. MF of a structure converges rapidly with increasing frequency and can be therefore computed using only a few lower order modes [16]. It does not require any analytical model of a structure to evaluate the flexibility and can be used with only the experimental data collected from the structure (data from experimental modal analysis (EMA) can be used directly in computing MF). However, online monitoring systems instrumented in large scale structures can only measure ambient vibration response which means mass normalised mode shape data is not available. In order to apply the MF method in large scale structures, many researchers [30–33] developed various methods to calculate the MF with ambient vibration measurements with and without use of FEM. The MF method is widely used in SHM application due to its accuracy, convenient computation and ease of application [21]. The MF, F_x at a location x of a structure can be written as;

$$F_x = \sum_{i=1}^{m} \frac{1}{\omega_i^2} \phi_{xi} \phi_{xi}^T \tag{1}$$