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A discussion on the merits and limitations of using drive-by monitoring to detect localised damage in a bridge

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ABSTRACT

Given the large number of bridges that currently have no instrumentation, there are obvious advantages in monitoring the condition of a bridge by analysing the response of a vehicle crossing it. As a result, the last two decades have seen a rise in the research attempting to solve the problem of identifying damage in a bridge from vehicle measurements. This paper examines the theoretical feasibility and practical limitations of a drive-by system in identifying damage associated to localised stiffness losses. First, the nature of the damage feature that is sought within the vehicle response needs to be characterized. For this purpose, the total vehicle response is considered to be made of 'static' and 'dynamic' components, and where the bridge has experienced a localised loss in stiffness, an additional 'damage' component. Understanding the nature of this 'damage' component is crucial to have an informed discussion on how damage can be identified and localised. Leveraging this new understanding, the authors propose a wavelet-based drive-by algorithm. By comparing the effect of the 'damage' component to other key effects defining the measurements such as 'vehicle speed', the 'road profile' and 'noise' on a wavelet contour plot, it is possible to establish if there is a frequency range where drive-by can be successful. The algorithm uses then specific frequency bands to improve the sensitivity to damage with respect to limitations imposed by Vehicle-Bridge vibrations. Recommendations on the selection of the mother wavelet and frequency band are provided. Finally, the paper discusses the impact of noise and road profile on the ability of the approach to identify damage and how periodic measurements can be effective at monitoring localised stiffness changes.

1. Introduction

With the increasing interest in drive-by monitoring to identify damage in a bridge, this paper presents a timely theoretical examination of the merits and potential limitations of the approach. Here, drive-by monitoring refers to recording vehicle acceleration signals as the vehicle passes over a bridge and then analysing these signals to identify damage in the bridge. To set the context of the study this introduction is broken in three sub-sections. Section 1.1 gives a brief overview of the area of bridge Structural Health Monitoring (SHM), Section 1.2 looks specifically at the area of drive-by inspections and finally Section 1.3 describes the objectives of this paper.

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1.1. Bridge SHM

Mufti et al. [1] argue that SHM can reduce the cost of maintenance of existing bridges by providing owners with information that will enable them to carry out the most effective repair. Vibration-based condition monitoring techniques, typically used in SHM to discern information about the bridge, have been discussed in several reviews [2,3]. Essentially these approaches work by tracking changes in the modal parameters of the structure (e.g., frequencies and mode shapes). The latter are determined by the physical properties of the structure such as stiffness and mass, therefore any change in the physical properties (e.g., a localised or global loss of stiffness) will cause detectable changes in the modal properties [4].

Damage can be identified by tracking changes in the natural frequency [5,6]. However, Salawu [7] points out that while resonant frequencies have the advantage of being easy to measure, the disadvantage is that changes in frequency can be due to environmental conditions as well as damage. Damage can also be identified by analysing the mode shape directly [8,9] or by tracking changes in the mode shapes of the structure [10,11]. Broadly speaking mode shapes are significantly less affected by environmental effects than natural frequencies. However, a disadvantage of mode shape based approaches lies in the requirement of many sensors for an accurate definition of their shape. Other authors have identified damage in bridge/beam structures using Finite Element Model (FEM) updating [12,13]. While FEM updating techniques have been shown to provide high levels of accuracy, they rely on accurate and sufficient experimental data for model calibration which sometimes can prove to be difficult or expensive to undertake. Finally, a number of authors have placed emphasis upon identifying localised damage in a beam from its response to a moving force. For example, while Zhu & Law [14] and Roveri & Carcaterra [15] apply wavelet analysis and Hilbert-Huang transform respectively to the mid-span displacement response, Hester & González [16] apply wavelet analysis to the acceleration response, for identifying the location of damage in a beam.

The aforementioned methods are based on analysis of measurements by sensors installed on the structure. The difficulty/cost of installing instrumentation (on a signification proportion of the bridge stock) has led to increased research on drive-by inspection systems. Algorithms using indirect (vehicle) measurements are based on similar principles as those designed for direct measurements taken on the bridge. In addition to noise, difficulties associated with monitoring structures using drive-by systems are mainly twofold: (1) the sensitivity to damage decreases as the measurement location (i.e., the moving load) moves away from the damaged location, and (2) the separation of the content related to the bridge from content purely due to vehicle dynamics or road profile can be troublesome.

1.2. Drive-by inspections

The increasing amount of research on the use of vehicle vibrations to discern information about the bridge is motivated by the large number of bridges that are not instrumented, and therefore the need for some alternative cost-efficient monitoring method [17]. Previous investigations have focused on the extraction of bridge frequencies from vehicle measurements [17]. The vehicle operates as an exciter of bridge frequencies and the vehicle also receives the bridge vibrations. Theoretical investigations show that, when tracked over a long period, this information could act as a useful reference for determining the degradation in stiffness or strength in the structure [18]. Experimental work by the same research group using a cart fitted with accelerometers towed behind a light commercial truck corroborates the findings of their earlier theoretical study [19]. A follow up theoretical study by the same authors examines the relative influence of the various dynamic parameters of the system on correctly identifying the bridge frequencies of concern [20], and a subsequent study looked at the effectiveness of different filtering methods to identify bridge frequencies [21]. Other authors have validated their drive-by algorithms via scaled laboratory experiments [22–26]. It must be noted that the level of resolution of the spectrum is related to the time that the vehicle is on the bridge, i.e., frequencies cannot be predicted accurately at high traffic speeds, and sufficient level of bridge excitation is needed [27]. Rather than using only changes in bridge frequency as a potential damage indicator, vehicle measurements are used by Kim et al. [25,28], Gonzalez et al. [29] and Keenahan et al. [30] to track changes in structural damping and by Yang et al. [31] and Oshima et al. [32] to extract mode shapes, which can be subsequently employed for damage detection similarly to bridge SHM. In addition to dynamic characteristics of the bridge, McGetrick et al. [26] and OBrien et al. [33] demonstrate that a static mechanical property such as global stiffness can also be obtained from the vehicle response and used for damage detection purposes.

Using numerical simulations, Nguyen and Tran [34] are some of the first researchers to show that in principle drive-by systems can not only be used for identifying global damages (by tracking parameters such as frequencies or damping), but also localised damage. In particular, they analyse the body displacement experienced by a 2-axle vehicle crossing a beam using wavelets and they observe that small peaks in the wavelet coefficients occur as each axle crosses the damaged section of the beam [34]. In more recent work, Zhang et al. [35] use the acceleration response of a vehicle (as it crosses the beam) to identify the location of damage in the beam. The method they use to identify damage is based on using operational deflected shape curvature and they demonstrate the effectiveness of the approach using both numerical simulations and experimental testing. Both authors [34,35] report deterioration in their results as the speed of the vehicle increases. In spite of all advances in indirect bridge monitoring using passing vehicles, a recent review by Malekjafarian et al. [36] concludes that further investigations on the impact of vehicle speeds, noise and rough road profiles are needed before drive-by systems can be successfully implemented in practise. The sections below represent a step forward towards addressing these issues.