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Identification of sudden stiffness changes in the acceleration response of a bridge to moving loads using ensemble empirical mode decomposition

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ABSTRACT

The growth of heavy traffic together with aggressive environmental loads poses a threat to the safety of an aging bridge stock. Often, damage is only detected via visual inspection at a point when repairing costs can be quite significant. Ideally, bridge managers would want to identify a stiffness change as soon as possible, i.e., as it is occurring, to plan for prompt measures before reaching a prohibitive cost. Recent developments in signal processing techniques such as wavelet analysis and empirical mode decomposition (EMD) have aimed to address this need by identifying a stiffness change from a localised feature in the structural response to traffic. However, the effectiveness of these techniques is limited by the roughness of the road profile, the vehicle speed and the noise level. In this paper, ensemble empirical mode decomposition (EEMD) is applied by the first time to the acceleration response of a bridge model to a moving load with the purpose of capturing sudden stiffness changes. EEMD is more adaptive and appears to be better suited to non-linear signals than wavelets, and it reduces the mode mixing problem present in EMD. EEMD is tested in a variety of theoretical 3D vehicle–bridge interaction scenarios. Stiffness changes are successfully identified, even for small affected regions, relatively poor profiles, high vehicle speeds and significant noise. The latter is due to the ability of EEMD to separate high frequency components associated to sudden stiffness changes from other frequency components associated to the vehicle–bridge interaction system.

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1. Introduction

Bridges are subjected to continuous structural deterioration caused by repeated traffic loading, aging and environmental conditions. The degree of deterioration needs to be monitored periodically in order to ensure structural safety. If damage is prevented at an early stage, maintenance works will be carried out as required and before the bridge can become damaged beyond repair. For this purpose, accelerations due to bridge vibrations induced by everyday traffic and environmental loading are commonly collected by structural health monitoring systems to capture dynamic characteristics of the bridge (i.e., frequencies and mode shapes). The latter is a popular way to identify, locate and quantify deterioration based on the principle that damage affecting the mechanical properties of the structure will change the dynamic properties of the structure and it will allow the bridge operator

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to take adequate action. These vibration-based methods typically require many sensors and long records to distinguish between true damage and deviations from the expected 'healthy' results that do not necessarily imply damage (i.e., due to forced vibration and environmental conditions) [1–3].

Still another approach (complementary, but not exclusive) to damage detection is the identification of an anomaly in the time history of the total structural response in forced vibration (i.e., static+dynamic) to the passage of traffic. Using signal processing techniques, which often combine frequency and time domains (such as wavelet analysis), a number of researchers have been able to locate an anomaly in the processed signal that can be related to damage and located in the bridge with respect to the position of the moving load. These approaches aim to identify and locate damage using less testing requirements in number of sensors and test duration than other level II damage detection methods such as those based on mode shape curvature. In the development of these approaches, difficulties in gathering data from a real bridge in both healthy and damaged states (or after and before repair) have motivated the use of numerical models for theoretical testing based on assumptions that sometimes can be unrealistic, i.e., assuming a linear response even for significant stiffness losses. While these numerical models are valid to illustrate a concept, they appear to be insufficient to challenge and validate a technique able to capture the initiation of damage before stiffness losses become unrealistically large (i.e., leading to section failure). For example, damage modelled as a sudden or gradual loss of stiffness in a portion of a bridge assumed to be permanent and respond in the linear elastic range for the test duration can be easier to capture (i.e., via a frequency change) than a non-linearity only revealed when the yielding point is exceeded at a specific section. The latter takes place within a narrow time window while the structural response remains unaltered outside this period. However, it would be obviously beneficial to identify the first signs of non-linearity before critical damage in the form of significant losses of inertia or cracking (leading to catastrophic failure in prestressed concrete sections) could take place.

Therefore, this paper focuses on developing an approach that will capture a non-linear behaviour (modelled as a brief stiffness change) from the acceleration response of a structure traversed by a moving load. The first question that arises is how to characterise a non-linear response. This has been addressed in a wide range of mechanical and civil engineering applications via methods such as the continuous wavelet transform (CWT) [4,5], Unscented Kalman filter (UKF) [6,7], Hilbert–Huang transform (HHT) [2,8–10] and others. The HHT utilises empirical mode decomposition (EMD) to estimate the instantaneous frequency (IF) and the instantaneous phase (IP). EMD is used to separate the signal (e.g., acceleration) into intrinsic mode functions (IMFs) that separate the frequency content of the signal. The lowest IMFs contain the part of the signal corresponding to the highest frequencies. Applications of the EMD method to nonlinear and non-stationary signals for wide range of signals from speech characterisation to ocean wave data have shown its versatility and robustness in detecting inconsistencies. Several authors have attempted to identify nonlinearity by applying EMD and HT to a nonlinear damaged structures [2,11–13]. However, detractors of EMD argue its lack of physical meaning due to mode mixing in the IMFs. First introduced by Wu and Huang [14], ensemble empirical mode decomposition (EEMD) has been found to eliminate the mode mixing problem of EMD [15]. EEMD has only been recently applied to damage detection in a number of applications. For example, An et al. [16] applies the EEMD with Hilbert transform to analyse the non-linear and non-stationary signal produced by faulty wind turbines. Zhang and Xie [17] test concrete samples using impact echo data for defects by applying the EEMD and find that the white noise amplitude needs to be significantly higher compared to other investigations due to the implications of strong surface waves. Zheng et al. [15] are able to successfully implement a new method called partly empirical mode decomposition (PEEMD) to detect faulty signals with high frequency and non-linear and non-stationary components. Even though the method proves successful in decomposing the signal by eliminating mode mixing, it does not show significant improvements compared to EEMD.

By the first time, EEMD is applied here to the acceleration response of a structure to a moving load to detect a sudden stiffness change. Accelerations are the subject of investigation as they are relatively easy to measure on the field and commonly used for monitoring purposes. Acceleration is a global load effect, as opposed to strain, where the measurement location needs to be at or nearby the damaged location to be able to perceive the damage. In this paper, the stiffness change is introduced using a bi-linear moment–curvature relationship in two types of finite element models (FEMs): a 1-D beam and a 2-D plate. For clarity, the advantages and drawbacks of employing EEMD are discussed first using the simulations of the response of the beam FEM to a moving load and compared to other techniques such as wavelet analysis [4,5] and EMD [18] which have been used in a similar context in the literature. Second, EEMD is tested using the accelerations of a plate FEM traversed by a sprung vehicle with different damage extent, road roughness, vehicle speed and noise.

2. Application of EEMD to damage detection using the acceleration response of a beam to a moving load

This section uses a relatively simple discretised beam FEM traversed by a moving constant load to illustrate the feature in the total acceleration response that denotes non-linearity and how it is captured by a signal processing technique. A more sophisticated vehicle–bridge interaction (VBI) simulation model is employed in further sections, but it is avoided here as it may hinder characteristics of the damage feature to be highlighted. Damage can be detected once it has occurred or as it is occurring, i.e., cracking that causes a stiffness loss will remain with the structure as long as repairs (or further deterioration) do not take place. A far more challenging task is to detect damage before a deterioration sign such as cracking is visible, namely, when the yielding point is exceeded. The duration of the time window where the section enters a plastic range may be very short and it needs to be captured as it is occurring. (Outside this window, a linear elastic stress-strain curve will apply again.) Unless the section was very brittle, an element will exceed the elastic range before approaching failure [19,20], and in this window, the affected element will respond in the elasto-plastic range [21]. In the case of composite structures, the yielding of steel gives a non-linear nature to the

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