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APPLICATION OF WAVELET SYNCHRO-SQUEEZED TRANSFORM (WSST) METHOD TO RAILWAY BRIDGE HEALTH MONITORING

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Abstract. Typically, the identification of resonant frequencies in railway bridges is carried out from free-decay stationary signals as a train leaves the bridge. The same identification proves very challenging when nonstationary vibrations are measured as a train traverses the bridge. Despite the numerous attempts, nonstationary signals with low modulating frequencies are still difficult to be processed. This paper attempts to evaluate the bridge-vehicle first bending resonance by a method known as Wavelet Synchro-Squeezed Transform (WSST). The significant advantage of this signal processing method is to deal with low-frequency modulations, which are typical of long bridges. This research focusses on a Finite Element Model (FEM) of a bridge simulating the nonstationary vibration responses exerted by a spring-mass model traversing the bridge. The paper sets two objectives, and the first one is to investigate how the WSST analyses nonstationary signals generated by the FE model. The instantaneous frequency trace of the bridge-vehicle system will be compared to a similar frequency trace, that is created by performing several modal analyses at different locations of the bridge. The second objective of the paper is to investigate if the instantaneous frequency obtained from WSST is suitable for damage detection, as the FE model is fitted with damages. Both objectives are met, and the results will be presented. The trace of the first natural frequency matches well the one calculated by the WSST, and the instantaneous frequency shows to be capable of detecting damages included in the model.

1 INTRODUCTION

Understanding the vibration response in Vehicle-Bridge interaction is challenging because the actual instantaneous frequency will depend on the instantaneous location of a moving load. It is therefore understandable that Structural Health Monitoring (SHM) methods, aimed at identifying damage to assess the structural integrity and safety of a structure, have complicated problems to solve. Nevertheless, damage detection techniques have been developed.

In general, the majority of vibration-based damage detection techniques can be grouped into four categories. The first group, the traditional approach, contains the modal-based damage detection techniques [1,2]. These techniques are based on extracting and monitoring the modal properties, which can vary due to the presence of damage. The second group contains structural health monitoring based on Vehicle-Bridge interaction (VBI) response [1-3]. The third one involves model-based techniques which are based on updating the parameters of an analytical or numerical model such that the model matches the real measurements [3,4,5]. The fourth group contains data-driven methods (DDMs). Silva et al. [6,7,8] believe that SHM approaches are in the statistical pattern recognition paradigm.

Most damage detection researches have shown that a singularity appears in the forced vibration signal once damage occurs [9]. Yang et al [10] stated that a discontinuity appears in the acceleration signal when the moving load is in the vicinity of damage. The structure also exhibits non-linear behaviour once the moving load crosses the damage [11]. Therefore, the forced vibration response contains a ‘damage event’ triggered by the moving load making it more sensitive than the free vibration response. For this reason, a large number of research studies has been devoted to the second group, the vehicle-bridge interaction response.

VBI refers to the dynamic coupling between a bridge and a moving vehicle. VBI has been widely studied in the literature for detecting damage in bridges by analyzing the bridge response (direct methods) or the vehicle response (indirect methods). The focus of the current study is on the damage detection techniques of bridges by analyzing the VBI response measured on the bridge (direct methods). Literature [11,12,13] indicates that the target signal for the majority of the techniques is the bridge mid-span time-deflection response. From a practical point of view, there are motivations to study the bridge acceleration rather than the deflection signal. Firstly, it might not be possible to measure the bridge deflection signal at mid-span directly. Secondly, in comparison with the deflection signal, the bridge acceleration signal is more sensitive to damage [14]. However, the acceleration signal also contains more noise making it challenging to analyze. Continuous Wavelet Transform (CWT), Discrete Wavelet Transform (DWT) [1], Hilbert Huang Transform (HHT) [4], Empirical Mode Decomposition (EMD) [5] and Ensemble Empirical Model Decomposition (EEMD) [6] have been mostly applied to identify damage [15,16].

Regardless of the applied method, the damage indicators are associated with a singularity. This one does not exist in the healthy bridge and appears in the response of the damaged structures [9]. Furthermore, the singularities are caused by a stiffness change and, therefore, the time-dependent stiffness should be visible in time-dependent resonances (the Instantaneous Frequency: IF). However, IF has only been investigated for the bridge mid-span displacement signal. Roveri et al [11] applied HHT on the mid-span deflection of a modelled bridge. In the first IF of the system, a crest appeared at the instant of damage occurrence. The current paper proposes an approach by applying Synchrosqueezed Wavelet Transform (WSST) on the VBI acceleration response to extract the Instantaneous Frequency (IF) of the system to detect a localized stiffness change. The research work is based on numerical simulations obtained from a Finite Element Model of a real bridge (Boyne Viaduct) located in Ireland. The bridge was refurbished and instrumented with a vibration response monitoring system, which provides many

test data. Considering the healthy conditions of the bridge, the authors decided to investigate the matter numerically and evaluate the WSST technique, as provided in the MATLAB function toolbox.

2 NUMERICAL MODEL AND MODAL SIMULATIONS

Although a large amount of vibration data is available for the Boyne bridge, the measurements are not applicable for the validation of the proposed damage detection approach, because of the recent refurbishments. Hence, to verify the proposed approach, a bridge is modelled numerically.

Figure 1: The schematic of the numerical model

All finite element simulations are conducted in a two-dimensional space in ABAQUS where the analysis scheme is chosen to be the implicit time integration. A beam with 50 m of length, 1 m of thickness and 0.5 m of width with Young's modulus of $E = 210$ GPa and density of $\rho = 7860$ kg/m³ is implemented as a bridge model. The same geometry has been already used in [17,18] for damage detection. However, the model is modified for the current study due to the moving mass. The forced response of the bridge corresponds to the period during which the mass is moving on the bridge. Achieving free vibrations from the bridge requires the mass should be removed from the bridge. However, the moving mass generates kinetic energy during the forced response analysis, which cannot be removed instantaneously to simulate the free vibration. Hence, approaching and leaving length are added before and after the bridge to properly locate the mass during the forced and free vibrations (see Figure 1).

Three dynamic analysis steps are implemented to calculate the bridge acceleration, corresponding to the mass approaching, crossing and leaving the bridge, as shown in Figure 1. Both approach and leave phases are modelled with beam elements that are clamped in all their nodes. The approaching part is not strictly necessary but is used to provide symmetry to the structure. The bridge model (the centre part of 50 m) has 200 elements, and the benchmark simulation corresponds to a point mass equal to 10% of the bridge mass which slides with a speed of 5 m/s over the bridge. The contact of the mass with the bridge is modelled using a hard node to surface interaction [19]. In the FEM model, the vehicle is considered to be a moving point mass (M) (i) to induce a non-stationarity to the simulated signal [20] and (ii) to investigate the time-varying resonance of the system due to the moving mass.

To implement the damage in the model, the stiffness (or equivalently the elastic modulus E) of a single element at the damage location (mid-span) is reduced [21] to simulate pitting- corrosion or a loose connection. In addition to the benchmark simulation, four groups of simulations are executed to verify the proposed approach for various operational conditions and health states. In the first group, moving masses equal to 5% and 20% of the bridge mass are simulated, and the bridge is considered healthy.

Modal analysis solutions were initially carried out with the mass positioned at specific locations of the bridge. Figure 2 shows the first and second resonances of the bridge as a collection of all the natural frequencies calculated at several locations. Interestingly, the location of the mass on the bridge has a relevant effect on the natural frequencies, which for the first resonance

is very marginal at the extreme locations but more relevant as it is moved towards the mid-span of the bridge. Similarly to the first one, the second shows an equivalent behaviour. The second resonance frequency is unaffected when the mass is positioned mid-span, which as expected as this is a nodal point of the second resonance. This basic modal analysis approach provides a useful insight on what one should expect from the IF recovered by the WSST method, in particular regarding the first bending resonant mode.

Figure 2: First and Second modal frequencies of the bridge with the mass moved at various locations

3 TIME RESPONSE SIMULATIONS AND RESULTS

A time response simulation of the moving load is carried out in Abaqus with the model earlier introduced. This paper will not focus on any uncertainty deriving from the non-uniform stiffness distribution of the bridge or the non-uniform crossing velocity or the Signal-to-Noise Ratio of typical real acquisitions.

Figure 3 shows the simulated acceleration signal for the undamaged bridge, at the bridge mid-span, where both the forced and the free decay vibration can be appreciated. Despite the simple approach, it was immediately noticed that the very first sample of the vibration vector contained high spikes, as the mass slide from an infinitely rigid surface to a flexible one. Those were removed and not taken into account since most of the vibration energy of those spikes would affect high-frequency modes, not relevant in this paper. Therefore, the signal for the Entrance Phase is a horizontal line at zero acceleration which is not plotted and not used for this study. The Traverse Phase and the Leaving Phase will be analyzed in two steps, such as (i) time series separation and (ii) application of the WSST to each of the time series.

Figure 3: Acceleration simulated during the traversing and leaving phase.

Given the velocity of the moving mass 5 m/s and the length of the bridge, 50 m, the mass leaves the bridge at $t = 10$ s. The second step is to extract the bridge frequencies by applying WSST to the signal of the Leaving Phase. Figure 4 a&b presents the Instantaneous Frequency of the traversing and leaving (bridge free vibration signal) phases. It can be seen that the Leaving Phase signal only contains the bridge first frequency (2.1 Hz) which is constant in time as expected for a stationary signal. Then, this frequency component should be tracked in the Traverse Phase by again applying WSST. The result is the Synchrosqueezed transform (SST) matrix with the rows and columns corresponding to frequency and time, respectively. The 2D density plot of the SST matrix is shown in Figure 4a in which the IF is displayed as a frequency ridge. This ridge can be extracted as a time-frequency vector by finding the corresponding frequency of the local maxima at each time instant. It is straightforward to observe the similarity between the frequency traces described by the modal solution for the first natural frequency and the one retrieved by processing the time series with the WSST method. Furthermore, Figure 4 shows how the resonance conditions are time-dependent because of the instantaneous location of the moving load.

Figure 4: Ifs of the first resonance frequency in the traversing and leaving phase.

3.1 Simulation results

A set of time response simulations were carried out to observe how the IF changes when the mass ratio is changed, to simulate different operating conditions as different train weight traversing the bridge. Figure 4 displays the bridge first resonance frequency, which varies in time depending on the magnitude and the location of the moving mass. For the benchmark simulation, the bridge frequency reduces to 1.9 Hz due to the added mass of the vehicle when it is located at mid-span ($t = 5$ s). As expected, IF depends on the different mass ratio, the highest the lowest the resonant frequency. Several papers investigated the dynamic behaviour of a bridge subjected to damage, some of those are referenced in here [22-27].

Figure 5: Change of IF caused by various Mass Ratios

The simulations were carried out by changing the mid-span element Young's modulus by 30%, 50% and 70%, respectively, by using the baseline model with mass ratio 10%. Both 50% and 70% are somewhat unrealistic damage conditions for a bridge. However, the purpose is to investigate the sensitivity of the IF to the appearance of damage. Figure 6 shows how the instantaneous resonant frequencies change as the moving load traverses the region where the damaged element was setup. This statement is not difficult to comprehend because the WSST resolves for the highest vibration energy at every point and frequency and, therefore, the instantaneous resonant frequency becomes even lower as the load is near to the weak spot.

Figure 6: Change of IF caused by element stiffness reduction at the mid-span

As a closing remark of this section, one can appreciate that potential of the WSST as provided by the function toolbox of Matlab. Hence, a much thorough investigation of the system parameters governing the signal processing of the WSST method may increase its capacity beyond this simple simulated case study.

4 CONCLUSIONS

This paper presents for the first time a novel application of the WSST signal processing to the calculation of the instantaneous first resonant frequency of a bridge traversed by a moving mass. The WSST can be potentially exploited in health monitoring where the vibration signals could be processed in a *quasi* real-time as the train has crossed a bridge. It was demonstrated

that the WSST identifies the instantaneous resonant frequency, and which was verified against modal analysis results. Furthermore, it was showed that the IF is sensitive to the presence of damage. This behaviour was demonstrated by fitting the model with damages at the mid-span of the bridge. The IF presented a sudden discontinuity where the damage was set up for all three severity selected for these attempts.

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