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Non-stationary Analysis of Vehicle-Bridge Interaction for Structural Health Monitoring of a Railway Bridge

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Abstract

Structural Health Monitoring for bridges is increasingly used in the asset management of bridges. The dynamic properties are key elements in the structural integrity assessment and the identification of damage. Natural frequencies can provide a relatively simple high-level condition assessment, but suffer from variations in the environmental and operational conditions. Methods considering the transient vibrations and hence the dynamic interaction between the train passing and the bridge itself (Vehicle-Bridge Interaction) are based on non-physical parameters, limiting the understanding of the changes in these parameters.

Here, a damage identification is proposed, based on the change of the instantaneous frequency observed during the traverse phase - the phase in which the train passes the bridge. The damage index relies in the first place on an accurate extraction of the instantaneous frequency which is extracted with the Wavelet Synchro-Squeezed Transformation (WSST). WSST was shown earlier to outperform the Continuous Wavelet Transformation in terms of resolution in the low-frequency range. Secondly, the change of the instantaneous frequency due to damage is distinguished from that due to changes in the environmental and operational conditions by calculating the correlation coefficient.

The results, based on a finite element model with a mass moving over a beam-based bridge, show that the changes in the instantaneous frequency can be positively linked to either damage or a change of vehicle mass, representing a change in the

operational condition. Together with the earlier made observation that the extraction of the instantaneous frequency by WSST is relatively insensitive to noise, compared to CWT, provides a solid ground for more detailed investigations on the capabilities of the method proposed. This research is therefore currently being expanded to include more variations in operational and environmental conditions as well as to include more complex vehicles, such that ultimately a coupling can be made to field data and provide guidelines on how to use this method.

Keywords: Vehicle-Bridge Interaction, Nonstationary Dynamics, Structural Health Monitoring

1 Introduction

Structural Health Monitoring is a growing technology that can be used for condition assessment and an efficient maintenance strategy [1]. The dynamic properties are key elements towards the application of structural health monitoring on the structures such as railway bridges [2]. Among the various dynamic properties, natural frequencies can provide a simple high-level condition assessment of bridges. The free vibration of the bridge forms the base of the extraction of the natural frequencies, which are influenced by the condition of the bridge, be it also by environmental conditions. This latter point forms an important limitation of the free vibration-based methods. The non-stationary part when the train passes the bridge, includes the interaction of the bridge and train dynamics (Vehicle-Bridge Interaction – VBI), leading to a more challenging data analysis. Investigation of the traverse phase response is motivated for two reasons: 1) the changes in the dynamic properties of the bridge structure due to damage are reported to be amplified by the presence of the moving vehicle on the bridge [3]; and 2) combining the resonance frequency of the non-stationary part of the signal with that of the stationary signal allows for the elimination of environmental factors in the signal. However, including the traverse phase in the analysis requires accurate determination of the resonance frequencies in this part of the signal and a way to identify the effect of the damage.

This paper proposes a damage index, based on the analysis of the traverse phase and with the aim to distinguish between changes due to environmental and operational conditions and those due to damage or an increased level of degradation.

2 Methods

The analysis of the VBI time signal calls for a time-frequency analysis, hence to devise a distribution function that describes the energy density of a signal in time and frequency [4]. Feng et al. [5] have recently reviewed many advanced methods for time-frequency analysis. Hilbert-Huang Transform (HHT) and Continuous Wavelet Transform (CWT) have been widely used in literature for the condition assessment of bridges. Despite their proven strengths in analysing non-stationary signals, these methods do show shortcomings when analysing typical VBI signals, such as insufficient frequency resolution for the lower frequencies and mode mixing for closely spaced frequencies.

Daubechies et al. [6] developed the wavelet-based synchro-squeezed transformation (WSST) method as an empirical mode decomposition-like tool that has the potential to overcome limitations such as mode-mixing and blurred time-frequency representations [7,8]. It is shown by Mostafa et al. [9] that the WSST method is a suitable method for extracting the instantaneous frequency of the bridge in healthy condition.

The extracted instantaneous frequency, combined with the resonance frequency extracted from the free-decay phase is then used to define a damage index *D*, which is capable of eliminating environmental and operational conditions, while maintaining changes due to damage:

$$D = \frac{\int_{\Delta t} |\not{f}_H - \not{f}_D| \, \mathrm{d}t}{\int_{\Delta t} (f_H - \not{f}_H) \, \mathrm{d}t} \tag{1}$$

The instantaneous frequencies of the baseline (healthy) and damaged response, $\not{f}_H$ and $\not{f}_D$, are subtracted and integrated over the timespan of the traverse phase Δt in the numerator, while the instantaneous frequency is subtracted from the free-decay resonance frequency f_H in the denominator. The Pearson correlation coefficient ρ is used to quantify the difference between the two instantaneous resonance frequencies:

$$\rho(\not{f}_H, \not{f}_D) = \frac{\sum_{i=1}^{N} (\not{f}_H - \bar{\not{f}}_H)(\not{f}_D - \bar{\not{f}}_D)}{\sqrt{\sum_{i=1}^{N} (\not{f}_H - \bar{\not{f}}_H)^2} \sqrt{\sum_{i=1}^{N} (\not{f}_D - \bar{\not{f}}_D)^2}} = \frac{\mathrm{cov}(\not{f}_H, \not{f}_D)}{\sigma(\not{f}_H)\sigma(\not{f}_D)} \tag{2}$$

3 Results

As a first step, the WSST is tested on a basic numerical model comprising of a beam with a moving mass. The added mass will vary the frequency of the coupled system depending on the location of the mass. This leads to a first resonance frequency that is expected to be lowered until the mass is halfway, after which it is expected to increase to the resonance frequency of the bridge without mass. The way the resonance frequency changes, is different in case of the presence of damage, compared to a change due to a different loading condition, as shown in Figure 1. This figure shows the change due to a variation of the mass of the vehicle passing the bridge (left) and that due to the presence of damage. Note that the stiffness reduction is relatively large, but only one element has a lowered stiffness, hence it is a very localized damage.

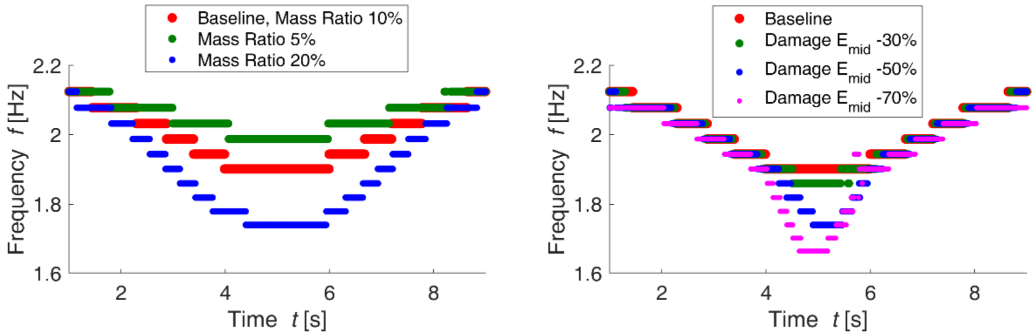

Figure 1: The instantaneous resonance frequency, extracted with WSST for varying vehicle mass (left) and damaged bridge (right).

The difference in the shape of the instantaneous frequency for the damaged cases is reflected in a lower correlation coefficient, while the correlation coefficient remains high in case only the mass varies. The amount of change is then found by applying the defined damage coefficient. The damage index and correlation coefficient as defined in Equations (1) and (2), are collected in Table 2. The values for the damage indices of the changed operation conditions (variation in mass ratio) cannot be compared directly to those of the damage case: the change of mass results in a larger overall effect. The importance of this comparison is that the correlation coefficient remains high for the mass ratio variation, while it reduces for the stiffness reduction – clearly indicating a different shape of the instantaneous frequency. This shows that the concept of the damage identification method as proposed here has the potential to distinguish between operational conditions and damage. Further steps include a variation in the parameters, such as the number of elements that are affected by the damage and more variation in the operational conditions, and more complexity in the vehicle passing the bridge by including spring-damper systems such as present in train vehicles. The effect of noise on the signal will also be investigated, but the work of Mostafa et al. [9] already showed that the extraction of the instantaneous frequency using WSST is less sensitive to noise compared to using CWT.

Operational Condition			Damage		
Mass Ratio	D	ρ	Stiffness change	D	ρ
5%	-0.74	0.95	-30%	0.06	0.98
20%	0.43	0.98	-50%	0.20	0.92
			-70%	0.39	0.88

Table 1. Damage indices and correlation coefficients for a change in the operational conditions and for a change of stiffness of one element, representing damage.

4 Conclusions and Contributions

The extraction of the time-varying resonance frequency from the dynamic response of a vehicle-bridge system is a crucial element for the damage identification using the non-stationary of the time series response of a passing train for the condition assessment of railways bridges. These first results show that the difference in the response to a change in the operational conditions can be distinguished from that due to the presence of damage. This is an important step in extending the capabilities of SHM of (train)bridges based on the resonance frequencies of the system.

The main contribution is the increased understanding that the application of a damage index based on the WSST provides. The non-stationary part of the dynamic signal of a train passage over a bridge has been subject of other researches, in which a link could successfully be established between non-physical parameters of the non-stationary signal processing methods and the loading of the bridge. However, linking physical properties, such as the resonance frequencies, will allow the extraction of more detailed information on the condition of the bridge. This can either be based on measurements, on models, or a combination of both. The latter connects with the development of digital twins for this type of assets, with the objective to translate state identifications by field measurements to prognostics of the remaining useful life of the bridge.

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