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Analysis of the annual variations in the dynamic behavior of a ballasted railway bridge using Hilbert transform

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ABSTRACT

In this paper the variations in dynamic properties (eigenfrequency and damping) due to seasonal effects of a single span, ballasted railway bridge are studied. It is demonstrated that both the eigenfrequency and characteristic damping vary importantly with environmental conditions and amplitude of vibration. For this, acceleration signals corresponding to roughly a year of monitoring are analyzed with the Hilbert transform and the instantaneous frequency and equivalent viscous damping ratio are calculated during the free vibrations. Over 1000 trains passages were analyzed, with temperatures ranging from −30 to +30 °C and amplitudes of vibration varying from 0.5 m/s^2 to 0. The location of the accelerometers allowed for separation of the signals into their bending and torsional components. It was found that during the cold season, with months of temperatures below 0 °C, the dynamic properties varied the most. Not only did the frequencies (for small vibrations) differ more than 9% even for a given temperature, but the non-linearity present in the structure did also change in a matter of hours. These findings are important in the context of Structural Health Monitoring. Any system that aims at warning early in the onset of damage by analyzing changes in the dynamic characteristic of a structure needs to first fully understand and account for the natural variability of these parameters, often much larger than what could be expected from reasonable levels of damage.

1. Background

Dynamic simulations of bridges are needed to predict the bridge behavior at the design stage or when the loads and/or speeds allowed are increased. Also, an increasing number of bridges around the world are being monitored in order to obtain real time feedback and detect damage. For both cases, dynamic simulations and Structural Health Monitoring, it is important to understand the natural variability of the dynamic characteristic of a bridge. Damage detection systems need to be able to discriminate whether an observed structural change is the result of damage or of a normal environmental change. Also, the simulations performed to predict the acceleration levels in a bridge need to take into account the possible changes in dynamical characteristic, such as eigenfrequencies and damping, in order to correctly assess the safety of a bridge. Thus, a detailed characterization of the bridges dynamic response and its variations with environmental variables becomes very important. It is common for the design and assessment of railway and highway bridges to study the dynamics of the structure, especially when high-speed rail traffic is envisioned. In the case of design of railway bridges, there are regulations limiting the maximum allowed vertical acceleration to ensure ballast stability and passenger comfort [1]. There is also a constant pressure from railway owners to increase both the maximum allowed speed and axle load to provide a better service for freight and passenger traffic [2]. This leads to a necessity of assessing existing structures to ensure that they meet the safety and comfort regulations under the new loading conditions. In both design and assessment these criteria are often verified by performing dynamic simulations using a Finite Element (FE) model of the bridge loaded by moving vehicles. Especially critical for the validity of such analyses are the eigenfrequencies, eigenmodes and characteristic damping of the structure. The bridge's eigenfrequencies together with the train speed and axle spacing dictate if resonance will occur or not and, if resonance occurs, the damping governs the acceleration levels reached [3]. The eigenfrequencies depend primarily on the geometry and material properties, that can be easily estimated from the drawings and project specifications. The real eigenfrequencies often differ significantly from estimates due to mainly (but not only) uncertainties in the boundary conditions. Damping, on the other hand, is very difficult to estimate from drawing only [4–6]. It is a very complex phenomenon that requires many assumptions to be characterized in a simple and practical way. Typically, when the damping of a structure is estimated, it is assumed that the damping is viscous in nature and modal. That means that the

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damping matrix is diagonal in the modal coordinates (and independent of the amplitude of vibration). This is done for simplicity but it has important consequences. Many other mechanisms that introduce damping at larger amplitudes are left aside. This under-estimation of the damping for larger amplitudes can easily result in the unnecessary replacement or strengthening of existing structures. Better tools for the estimation of damping and eigenfrequencies can thus result in an improved assessment of existing structures. In this study the Hilbert Transform is introduced as such a tool. It is applied to acceleration signals gathered at a case study bridge. The variations in eigenfrequencies and characteristic damping, often assumed to be uniquely defined, are studied. Their dependence on temperature, season and amplitude, are quantified. It is hoped that this will also shed light in the difficult but promising field of Structural Health Monitoring, which has a very large potential as a tool for a more efficient infrastructure management. Structural Health Monitoring still has a large distance to travel to reach its full potential, and one critical step is the characterization of the natural variations of structures with the environmental and load conditions attempted in this study.

2. Bridge and instrumentation

In this section, the bridge (shown in Fig. 1) and its instrumentation (depicted in Fig. 2) are presented. The studied bridge is situated in the northern part of Sweden and has its longitudinal axis in the north–south direction. It has a horizontal skew of 30°, a span length of 36 m and carries one ballasted track. The thickness of the reinforced concrete deck varies between 320 and 350 mm and its total width is 6.7 m. The cross-section of the two main steel beams varies along the bridge and has an average height of approximately 1.8 m. The main beams are connected with transverse braces at 4 sections along the deck as well as at the deck ends. One of the supports is fixed, but free to rotate over the transversal axis. The other end is supported on roller bearings to relieve constraints essentially caused by temperature variations.

The bridge rests on shallow foundations on an approximately 5 m thick layer of silty moraine. The geotechnical survey estimated the modulus of elasticity of the subsoil to be approximately 30 MPa and its density was determined as 1700 and 2000 kg/m^3 for the drained and undrained state, respectively. This estimate of the elastic modulus of the subsoil is intended for calculations of long-term settlements and is therefore a lower bound, characteristic value. The foundation plates have the width 9.2 m and the length 5.8 m and are placed with a skew of 30° with respect to the bridge center line. The instrumentation used in the current study consisted of three accelerometers and a temperature gauge.

Fig. 1. Picture of the Skidträsk bridge.

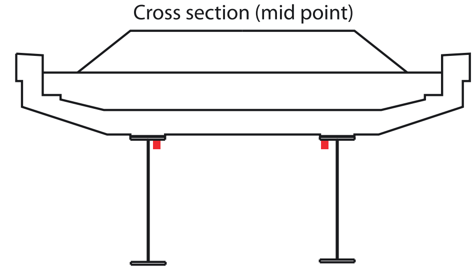

Fig. 2. Schematic cross section and plan view of the bridge with the location of the sensors highlighted.

The data acquisition system consisted of a Spider8 data logger from HBM and a laptop PC. The accelerometers are of the MEMS-type, manufactured by Colibrys and encased by the laboratory personnel at KTH, Department of Structural Engineering and Bridges. These were placed under the top flanges inside the bridge, two at mid span (one on each main beam) and one to the quarter point of one of the main beams. The temperature gauge was placed so as to measure the outdoor air temperature.

3. The Hilbert transform

The Hilbert transform is a linear operator that can be used to obtain an analytical representation of a signal. The Hilbert transform of a signal $u(t)$ can be defined as [7]

$$H_u(t) = \frac{1}{\pi}\text{p.v.}\int_{-\infty}^{\infty}\frac{u(t)}{t-\tau}d\tau \tag{1}$$

where p.v. denotes Cauchy's principal value. The analytical expression of the signal $u(t)$ is then given by $u_a(t) = u(t) + H_u(t)$. An analytic signal is a complex-valued function that has no negative frequency components, as will be explained later. The major advantage of this analytical representation is that, under certain conditions, it possesses a well-defined instantaneous frequency and amplitude. In the Fourier sense only stationary signals possess well-defined frequency-spectrum. The Fourier frequency content is a property of the whole signal, not of any given point in time, making it impossible to see how the energy distribution changes with time. This limitation has been circumvented by different techniques. One of them is the short-time Fourier transform [8], but this introduces new difficulties such as poor frequency resolution and a certain degree of arbitrariness in the choice of windowing method. A more powerful method is the Wavelet transform [9,5], but it is not without shortcomings. The choice of mother wavelet is far from trivial, the continuous transform is computationally expensive and the discrete transform suffers from poor time resolution for the lower frequencies.

The Hilbert transform can be used to overcome these problem, as it gives a rigorously defined instantaneous frequency. Provided that the signal is narrow-band (a sufficient but not necessary condition) its Hilbert transform represents its quadrature. Thus, if the signal is written as an amplitude and frequency modulated real-valued function with a carrier frequency ω in the from

$$u(t) = A(t)\cos(\omega t + \phi(t)) \tag{2}$$

then its Hilbert transform will be its quadrature:

$$H_u(t) = A(t)\sin(\omega t + \phi(t)) \tag{3}$$

with $A(t)$ amplitude modulation and $\phi(t)$ frequency modulation both varying in a time-scale larger than ω. Thus the analytical representation of u can be re-written in complex polar coordinates as

$$u_a(t) = A(t)\exp(i(\omega t + \phi(t))) \tag{4}$$