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Abstract

The use of drones in structural health monitoring to charge sensors mounted on a bridge and download their data has gained an increasing interest over recent years. In contrast to traditional approaches relying on long records to assess the condition of a structure, the scenario envisioned here may only have access to short amounts of data. The treatment of undesired edge effects, which become more significant as the signal duration decreases, is a key aspect in the analysis of short data bursts. Hence, this paper tests the suitability of the synchrosqueezed wavelet transform to extract the frequency from the acceleration response of a simply supported beam with a very good road profile due to the crossing of a quarter-car model. A relatively short signal of 1 s in forced vibration and 1 s in free vibration, both noise-free and corrupted with noise, is considered. Focus is placed upon the effectiveness of several padding techniques in mitigating edge effects.

Keywords: Short Data Burst; Synchrosqueezed Wavelet Transform; Edge Effect; Signal Padding; Structural Health Monitoring; Bridge Dynamic; Vehicle-Bridge Interaction.

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The use of drones in structural health monitoring to charge sensors mounted on a bridge and download their data has gained an increasing interest over recent years. In contrast to traditional approaches relying on long records to assess the condition of a structure, the scenario envisioned here may only have access to short amounts of data. The treatment of undesired edge effects, which become more significant as the signal duration decreases, is a key aspect in the analysis of short data bursts. Hence, this paper tests the suitability of the synchrosqueezed wavelet transform to extract the frequency from the acceleration response of a simply supported beam with a very good road profile due to the crossing of a quarter-car model. Relatively short signals of 1 s in forced vibration and 1 s in free vibration are considered without and with noise. The focus is placed upon the effectiveness of several padding techniques in mitigating edge effects.

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1. Introduction

The use of Unmanned Aerial Vehicles (UAVs) technology is becoming very popular due to its low cost, energy efficiency and portability. According to a survey by Chen et al., the top three applications in UAVs industry are construction, infrastructure and agriculture. Another potential application area would be Structural Health Monitoring (SHM) [1]. In particular, this approach presents the advantage of avoiding the need for long cables running over the bridge or for permanent access to electric power on site. Bridge SHM aims to derive structural parameters (i.e., frequencies) that will be used as a reference to detect damage. For example,

Nagarajaiah and Yang apply the Wavelet Transform (WT) to obtain bridge frequency and damage information from a 200 s acceleration signal corresponding to the ambient vibration response of the Canton Tower [2]. Similarly, Slavic and Boltezar successfully apply the Continuous Wavelet Transform (CWT) to a 120 s acceleration response for damping identification based on numerical simulations [3]. Nonetheless, long-time series data are not always available. This is the case of UAVs systems, technically limited by factors such as flight duration, sensor battery time and data transmission [4]. Although the WT has proven to be able to extract bridge dynamic features [5-7], there are still drawbacks, including shift sensitivity, poor

directionality and absence of phase information. Therefore, the Synchrosqueezed Wavelet Transform (SWT) has been proposed as an improvement with respect to the WT [8]. SWT also provides time-frequency values in a 2D spectrum, but combining the advantages of empirical mode decomposition and wavelet analysis, it is able to lead to better anti-noise properties and higher mode resolution than an ordinary WT. The latter is of a major relevance to the identification of frequencies from short data bursts. However, edge effects at the beginning and end of the signal remain and they represent a very signification proportion of a short signal [9,10].

This paper employs a number of signal padding techniques for mitigating edge effects and achieving higher accuracy and stability throughout the entire duration of the signal. Section 2 describes the numerical model employed to simulate the acceleration response of a bridge due to a moving vehicle. Section 3 introduces the theory of SWT and various signal padding techniques. Section 4 evaluates the error in estimating frequencies using the SWT applied to both noise-free and noisy short data bursts generated using the simulations of Section 2. Finally, conclusions and recommendations for further research are presented in Section 5.

2. Simulation model

2.1 Vehicle-bridge interaction

The vehicle is modelled as a two degree of freedom quarter-car model and the bridge, as a simply supported discretized beam with a very good road profile (Figure 1).

Figure 1. Vehicle-bridge interaction model

The quarter car is composed of a sprung mass (m_s) and an unsprung mass (m_u). The unsprung mass connects to the road surface, via a spring (K_t), while the sprung mass is connected to the unsprung mass by another spring (K_s) and a viscous damper (C_s).

The values of the parameters involved in the Vehicle-Bridge Interaction (VBI) system are adopted from Cantero et al. [11]. Tables 1 and Table 2 provide properties of the bridge and vehicle respectively.

Table 1. Properties of the bridge

Parameter	Symbol	Value	Unit
Length	L	20	m
Mass per unit	m	37500	kg/m
Second moment of area	I	1.2593	m^4
Modulus of elasticity	E	3.5×10^{10}	MPa
Damping ratio	ζ	0.03	
Approach at both ends	L_{app}	100	m
1 st Frequency	f_1	4.26	Hz

Table 2. Properties of the vehicle

Parameter	Symbol	Value	Unit
Sprung mass	m_s	9250	kg
Unsprung mass	m_u	750	kg

Suspension stiffness	K_s	7.5×10^5	N/m
Suspension damping	C_s	10×10^3	Ns/m
Tyre stiffness	K_t	3.5×10^6	N/m
Velocity	v	20	m/s
1 st Frequency	f_{v1}	1.30	Hz
2 nd Frequency	f_{v2}	12.00	Hz

The natural frequency corresponding to the first mode of vibration of the bridge, f_1 , is defined by Equation (1).

$$f_1 = \frac{\pi}{2L^2} \sqrt{\frac{EI}{m}} \quad (1)$$

Using the values in Table 1, f_1 is equal to 4.26 Hz. It should be noted that there may be differences between the measured (damped) and natural frequencies of a structure. However, damping in bridges is typically low, and for the bridge under investigation ($\zeta = 0.03$), the damped frequency is still 4.26 Hz when rounded to two decimal places.

Figure 2 shows the acceleration response that is obtained at the mid-span section using the values of Tables 1 and 2. The response has been generated simulating 1000 acceleration measurements per second.

Figure 2. Acceleration response for mid-span

From Figure 2, 2.044 s are selected starting at the time the vehicle enters the bridge (at 5 s). Padding techniques have been found to work best when a

signal starting by a zero value also ends in a value close to zero. For this reason, free vibration has been slightly extended (i.e., by 0.044 s) with respect to the 1 s in forced vibration. This portion of the signal, shown in Figure 3, will be the short data burst subjected to analysis in further sections.

Figure 3. Short data burst

2.2 Corruption of data with noise

The short data burst is contaminated with random noise to simulate real measurements. The noise is generated using a normal distribution with zero mean and standard deviation σ_N . The latter is related to the standard deviation of the short data burst (σ_s) through the Signal to Noise Ratio (SNR). Here, SNR is defined as the ratio of σ_s to σ_N . Therefore, a small SNR value implies a significant amount of noise added to the signal whereas a large SNR value represents low levels of noise. Figure 4 shows the noisy signal for the three SNRs considered in the analysis: 5, 20 and 50, which correspond to relative noise percentages of 20%, 5% and 2% respectively. A Fast Fourier Transform (FFT) of the noise-free response or any of the three noisy responses yield a first frequency of vibration of 4.10 Hz, i.e., 3.76% (0.16 Hz) smaller than the true value.

Figure 4. Short data burst with added noise

3. Signal processing technique

3.1 Synchrosqueezed wavelet transform

The SWT reallocates the wavelet energy coefficients, based on the CWT theory, to obtain a sharper representation of frequency information in the time-frequency domain. Signals are decomposed into constituent components with time-varying oscillatory properties. A time series signal $x(t)$ is expressed as [12]:

$$x(t) = \sum_{i=1}^n A_i(t) \cos(\omega_i t) + e(t) \quad (2)$$

where i is the number of auto terms, A_i is the time-varying amplitude, ω_i is the instantaneous phase of the i^{th} term, and $e(t)$ is the measurement error or noise. The goal is to reconstruct the amplitude $A_i(t)$ at the instantaneous frequency $\omega_i(t)$ for each i . The instantaneous frequency of the i^{th} term is estimated on the basis of the instantaneous phase derivation as:

$$f_i(t) = \frac{1}{2\pi} \frac{d}{dt} \omega_i(t) \quad (3)$$

The simulation results from SWT are sensitive to the correct choice of the wavelet basis due to its wavelet-based features. Some wavelet bases can be more suited to short duration VBI events, such as Mexican Hat, Morlet and Complex Morlet [13]. This paper uses the Morlet wavelet to compute the SWT. The CWT is defined as:

$$W(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} x(t) \psi^* \left(\frac{t-b}{a} \right) dt \quad (4)$$

where ψ is the mother wavelet, ψ^* represents the complex conjugate, a (>0) is the scale parameter and b is the position parameter [14]. By Plancherel's theorem, Equation (4) can be expressed as:

$$W(a,b) = \frac{1}{2\pi\sqrt{a}} \int_{-\infty}^{+\infty} \hat{x}(\xi) \hat{\psi}^*(a\xi) e^{ib\xi} d\xi \quad (5)$$

If $\hat{\psi}(\xi)$ is concentrated around $\xi = \omega_0$, then $W(a,b)$ will be concentrated around $a = \omega_0/\omega$. For any (a,b) for which $W(a,b) \neq 0$, a candidate instantaneous frequency $\omega_s(a,b)$ for the signal $x(t)$ is given by:

$$\omega_s(a,b) = \frac{-i}{W(a,b)} \frac{\partial}{\partial b} W(a,b) \quad (6)$$

For a simple case where n and $e(t)$ in Equation (2) are assumed to be 1 and 0 respectively,

$$x(t) = A(t) \cos(\omega t) \quad (7)$$

then, Equation (6) becomes $\omega_s(a,b) = \omega$. If the dependence on $x(t)$ and $\omega_s(a,b)$ is suppressed, the information from the time-scale plane is transferred to the time-frequency plane, according to the map (a,b) to $(b, \omega_s(a,b))$ in an operation referred to as synchrosqueezing. The frequency variable ω and the scale variable a are "binned", i.e., $W(a,b)$ is computed only at discrete values a_j , with $a_j - a_{j-1} = (\Delta a)_j$, and its synchrosqueezed transform $SWT(\omega, b)$ is likewise determined only at the centres ω_l of the successive bin $[\omega_l - \frac{1}{2}\Delta\omega, \omega_l + \frac{1}{2}\Delta\omega]$, with $\Delta\omega = \omega_l - \omega_{l-1}$, by summing different contributions [12]:

$$SWT(\omega_l, b) = \frac{1}{\Delta\omega} \sum_{a_j} W(a_j, b) a_j^{-\frac{3}{2}} (\Delta a)_j \quad (8)$$

3.2 Signal padding

Following the work by Černá et al. [15], six padding techniques are tested: zero, periodic, symmetry, anti-symmetry, smooth of order 0 and smooth of order 1. Figure 5 shows how these techniques are applied to extend the signal in Figure 3.

Figure 5. Six forms of padding the signal

Zero Padding (zpd) assumes that the signal is zero outside the original boundaries. The limitation of zero-padding is that discontinuities are artificially created at the boundary.

Symmetry Padding (sym) assumes that signals can be extended outside their original support by symmetric boundary value replication. Symmetrisation has the drawback of artificially creating discontinuities of the first derivative at the border.

Anti-Symmetry Padding (asym) extends signals beyond their original boundaries by antisymmetric boundary value replication.

Periodic Padding (ppd) assumes that signals can be recovered outside their original support by periodic extension. In this case, discontinuities are also artificially created at the border.

Smooth Padding of Order 0 (sp0) assumes that signals can be recovered outside their original support by a simple constant extrapolation. For a signal extension, this implies the repetition of the first value on the left and last value on the right.

Smooth Padding of Order 1 (sp1) reconstructs signals outside their original boundaries by a simple first-order derivative extrapolation: padding using a

linear extension fit to the first two and last two values.

4. Analysis of results

4.1 Impact of the padding technique

Figure 6 shows the results of applying SWT to the signal in Figure 3. Frequencies of 4.22 Hz and 4.29 Hz can be estimated from the mid-point of forced (i.e., at 5.5 s) and free (i.e., at 6.5 s) vibration respectively. However, huge edge effects are noticeable at each boundary, i.e. from 5.0 s to 5.4 s (left) and from 6.6 s to 7.0 s (right). The transition from forced to free vibration at 6 s also leads to a poor frequency resolution in a time period going from 5.6 s to 6.4 s. Thus, the information that this short data burst can provide is severely limited by its boundaries.

Figure 6. SWT for short data burst

Figure 7 shows the result of applying the SWT to the short data burst extended by a 5% at both ends (0.05 s added at each end) as per Figure 5. Overall, all padding techniques appear to outperform the lack of padding of Figure 6 in mitigating the edge effect. However, symmetry padding and periodic padding are not as effective as the others, and they will not be illustrated in the subsequent sections due to space limitations.

Figure 7. SWT for 5% extended short data burst

4.2 Influence of the padding percentage

The signal in Figure 3 is padded adding 2.5%, 5%, 7.5%, and 10% of the duration of the original signal at both ends. Figure 8 shows that the best results by all techniques are achieved with a 5% extension of the original signal. Padding the signal by 2.5% and 10% of the original duration does not mitigate the edge effect to the same extent. In this figure, the solid horizontal line represents the first natural frequency of the bridge.

Figure 8. SWT for different percentage extension

4.3 Error using the noise-free response

Equation (9) is used to calculate the error in predicting the first modal frequency.

$$error_1 (\%) = \left| \frac{f_1^e - f_1}{f_1} \right| \times 100 \quad (9)$$

where f_1^e is the frequency extracted from the short data burst with various signal padding techniques, and f_1 is 4.26 Hz.

Figure 9 shows instantaneous errors calculated according to Equation (9) for a 5% extended short data burst without noise. The error obtained by signal padding at the edge is nearly eight times smaller than the one from the original short data burst. Thus, there is a significant improvement in accuracy due to signal padding. If the entire duration of the signal is considered, the technique leading to a smaller Root Mean Square Error (RMSE) of 0.1680 Hz is smooth padding of order 1, and the technique with the largest RMSE of 0.1692 Hz is anti-symmetry padding. It is worth to note that RMSE is 0.4365 HZ in the case of using the original noise-free signal without any padding.

Figure 9. Errors using 5% extended data burst without noise

4.4 Error using the noisy response

Figure 10 illustrates the errors for a 5% extended short data burst with Gaussian noise (SNR = 50, 20 and 5 as per Figure 4). Comparing these three graphics with Figure 9, the strong anti-noise property of the SWT technique becomes evident, i.e., Gaussian noise has only a small impact on the results, although the improvement achieved by signal padding at the edges is generally reduced.

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Figure 10. Errors using 5% extended data burst with SNR = 50, 20, and 5 (from top to bottom)

Table 3 summarises the RMSE of the estimated frequency for the six padding techniques and three noise levels being considered. The RMSE of the original signal, without any padding, is also included as a reference to show the general improvement achieved through padding. In the case of noisy data, zero padding, smooth padding of order 0, and anti-symmetry padding yield the best results, and their increment in error as SNR decreases is almost negligible. Although instantaneous frequencies are very accurate when predicted far from discontinuities, the RMSE using the entire signal is larger than the error of 0.16 Hz using FFT despite the improvements achieved by SWT combined with padding. The latter is mainly due to the inaccuracies remaining around the instant where the bridge response shifts from forced to free vibration.

Table 3. RMSE (Hz) for different padding techniques and noise levels

PADDING TECHNIQUE	Noise- free	SNR		
		50	20	5
original	0.4365	0.4360	0.4383	0.4373
zpd	0.1682	0.1683	0.1664	0.1693
sym	0.3008	0.3058	0.3058	0.3058
asym	0.1692	0.1697	0.1689	0.1711
ppd	0.3904	0.3904	0.3904	0.3904
sp0	0.1682	0.1683	0.1668	0.1694
sp1	0.1680	0.1693	0.1845	0.1857

5. Conclusions

Edge effects due to the discontinuities at the boundaries corrupt the instantaneous frequencies estimated by a SWT. As a result, the underlying true frequencies are masked at both ends of a signal and at intermedium discontinuities. The shorter the duration of the signal, the more challenging the determination of frequencies becomes. This paper has assessed the performance of a number of padding techniques in ameliorating edge effects.

The results have highlighted that all padding techniques under investigation have rendered better estimation of frequencies than not applying padding at all. In the case of a noise-free signal, symmetry padding and periodic padding perform worse than the others. Best results have been obtained when padding the input data by 5% of its duration, compared with 2.5%, 7.5%, and 10%. Based on the RMSE, smooth padding of order 1 and 0, zero padding, and anti-symmetry padding have clearly outperformed symmetry and periodic types of padding. Finally, in the case of a signal with SNR = 5, the best padding techniques have been zero padding, smooth padding of order 0 and anti-symmetry padding. Further research aims to propose an efficient technique able to deal with the discontinuity at the transition period between forced and free vibration.

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