Wavelet Based Damage Assessment and Localization for Bridge Structures

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ABSTRACT

Bridges as a key component of road networks require periodic monitoring to detect structural degradation for early warning. In term of maintaining the bridge safety, it is essential to estimate the damage location and extent. This paper hypothetically investigates employing the wavelet transform to analysis the signal of a vehicle/bridge system to localize and estimate the damage severity. The paper investigated the feasibility of using direct measurements from the bridge system, in compare with using indirect measurements from a crossing inspection vehicle. The study utilizes an implicit Vehicle-Bridge Interaction (VBI) algorithm to simulate the passage of the instrumented vehicle over the bridge to generate the signal; then the signals are processed using Wavelet Transform. The study found that using the indirect vehicle measurements is more sensitive to bridge damage since the vehicle acts as a moving sensor over the bridge. Further, the paper shows promising results for damage detection using the bridge displacement responses, if the static component of the displacement is removed from the recorded displacement history.

Keywords: Structural Health Monitoring, Wavelet Transform, Bridge Damage Detection, Drive-by Bridge Inspection, Non-destructive evaluation, Sensor base Monitoring

1 Introduction

Bridge structures are key components of the transportation network, and their safety is essential to maintain effective and safe operation of the transportation facilities. In order to maintain the structural integrity of the bridge structures, it is essential to estimate the structural damages extent and location through periodic monitoring. Recently, the Structural Health Mentoring (SHM) technologies have been developed drastically, and specifically for bridge structures since their structural systems most of the time are simple (i.e. either simple or continues beam system). The SHM methods can be divided into two broad categories: direct methods and indirect methods regarding the sensor location with respect to the investigated structure.

The direct methods require installing a large number of sensors on the bridge structural elements to collect vibration data for damage assessment [1, 2]. These approaches, in which sensors are installed on the bridges directly may be time-consuming, costly, and even dangerous on-site instrumentation [3]. While the indirect methods are based upon extracting the dynamic properties of the bridge structures from the dynamic response of a passing vehicle over the bridge [4, 5]. Yang, Lin and Yau [4], Yang and Lin [5] recommended using the vehicle measurements instead of using the direct bridge measurement since the vehicle works as a moving sensor crosses all the bridge degrees of freedom. Further, Yang, Li and Chang [6] showed that the indirect measurements from the inspection vehicle, give a better screening for the bridge degrees of freedom than the direct measurements from an installed sensors on the bridge structure. This observation is because the inspection vehicle works as a moving sensor crossing all the bridge degrees of freedom. Contrary to the fixed sensors which are attached to a specific bridge degree of freedom, and thus it has a limited screening range around the sensors spot". This concept has been extended to monitor the change in the bridge dynamic properties using the vehicle responses and it is known by "drive-by bridge health monitoring" [7].

In the drive-by bridge health monitoring system, the vehicle is fitted with sensors, most commonly on its axles. When the instrumented vehicle passes over the bridge, it is effectively used to record VBI dynamic response as a moving sensor. Compared to direct methods, the indirect methods show many advantages in term of equipment need, specialist personnel on-site, economy, simplicity, efficiency, and mobility [3]. The feasibility of such indirect method in practice has been experimentally verified by Lin and Yang [8] via passing a instrumented vehicle over a bridge. In addition, Elhattab, Uddin and OBrien [9, 10] have used the change in the bridge displacement as damage index for the bridge. They used a conventional truck equipped with accelerometers to compute the bridge displacement. The authors demonstrated the idea using a quarter-car model and the results showed to be promising. However, the authors found that the approach is sensitive to the truck transverse location on the bridge, where the change in road roughness masks the change in the bridge displacement.

To both direct method and indirect method for bridge damage assessment, the natural frequency and modal shape are the basic indicators for assessing bridge damage severity [3, 11, 12]. Most natural frequency-based methods and modal shape-based methods could efficiently and accurately assess the existence of bridge structures, but they are not able to identify location of the damage present. In recently years, more and more signal analysis technologies such as wavelet transforms and Hilbert-Huang transform are used for identifying bridge damage and localizing it [13-17].

In this paper, an implicit Vehicle-Bridge Interaction (VBI) algorithm is created on Matlab to simulate the vehicle passing over the bridge based upon the work of Elhattab, Uddin and Obrien [9]. This paper investigates the feasibility of using direct measurements from the bridge system, in compare with using indirect measurements from a crossing inspection vehicle to identify the structural ridge damage utilizing Wavelet Transformation.

2 Vehicle-Bridge Interaction Model

This section describes the Vehicle-Bridge Interaction (VBI) model employed for simulating the bridge structure response under the vehicle. In this paper, the vehicle is modeled as a quarter-car model crossing a 50 m approach distance followed by a 20-m simply supported finite element (FE) bridge (Figure 1). The quarter-car travels with constant speed. The vehicle body mass is represented by a sprung mass, m_s, and unsprung mass, m_a represents the axle components. The two independent DOFs correspond to the sprung mass and the axle mass bouncing, u_s, and u_a, respectively. All the property values of the quarter-car and bridge shown in Figure 1are listed in Table 1 and based upon the work of Cebon [18] and Harris, OBrien and González [19]. The dynamic interaction between the vehicle and the bridge is implemented in MATLAB [9]. The used scanning frequency for all simulations is 1000 Hz.

Damage is modeled following Sinha, Friswell and Edwards [20] model, where it assumes that damaged is extended over a region of three times the beam depth. In this damaged area, there is a gradual reduction in stiffness from a minimum at the crack location to the gross element stiffness at the end of the damaged length. The damage level is defined as the ratio of the crack depth and beam depth of intact bridge. For instance, if the damage level is 0.6 or 60%, it means the crack depth equals to 0.48 m since the bridge depth is 0.8 m as mentioned above. In this case, the minimum stiffness at the cracked section is $0.4^3 I_B$, where I_B is the intact bridge stiffness.

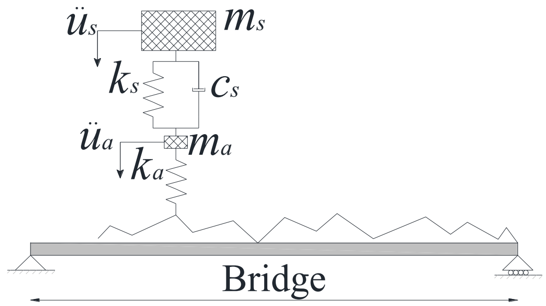


Figure 1: The VBI model with crack

Table 1.Parameters of vehicle and bridge model

Vehicle properties		Bridge properties	
m_s	14000 kg	Span	20m
k_s	20 kN/m	Density	4800kg/m^3
c_s	10 kN s/m	Width	4m
m_a	1000 kg	Depth	0.8m
k_a	250 kN/m	Modulus	2.75×10^{10} N/m^2

3 Identification of Bridge Damage with Wavelet Transform

3.1 Backgrounds

In recent years, wavelet analysis has been used in many signal-processing disciplines. The Wavelet predicts the signal discontinuity that makes it a robust signal-processing tool in the damage detection field [13, 21-23].
Mathematically, the wavelet transform of a function *f(t)* is defined as the integral transform of *f(t)* with a family of wavelet functions, *ψa,b(t)*:

$$WT(a,b) = \int_{-\infty}^{+\infty} f(t)\frac{1}{\sqrt{a}}\Psi\left(\frac{t-b}{a}\right)dt \; a \in R^{+}, b \in R \qquad \textbf{(Eq. 1)}$$

where *WT(a,b)* referrers to the complex wavelet coefficients or wavelet transform; a and b are real scale and translation parameters. $\psi_{a,b}(t)$ denotes the conjugate of the complex mother wavelet function which satisfies the properties of $\int_{-\infty}^{+\infty}|\Psi(t)|dt = 0$ and $\int_{-\infty}^{+\infty}|\Psi(t)|^2 dt < \infty$.

Hence wavelet transform is similar to the Fourier Transform (FT) that uses a series of cosine functions to approximate the objective signal. FT only works as a signal-converting tool from the time domain to the frequency domain. It cannot give the knowledge that when a particular frequency happened. However, performing wavelet transforms, a signal is shown in the frequency domain while the information in the time domain still retained. So wavelet analysis gives better frequency-time information to objective signals. And this is why the wavelet transforms can be used in localizing the damage in bridge structures.

When the wavelet transforms is applied to a signal, it returns a wavelet coefficient for each scale at each point in time. Scales of wavelet transforms correspond to signal frequency. Therefore, we can observe the objective signal in time domain at different frequencies correspond to different scales. A higher scales implies stretched wavelet, so coefficients associated to high scales correspond to low-frequency content. In contrast a low scale implies a high-frequency content [13]. Equation 2 relates the scale of a wavelet to pseudo-frequency:

$$F_S = \frac{F_C}{a\Delta} \qquad \textbf{(Eq. 2)}$$

where F_s is the pseudo-frequency corresponds to scale a in Hz, F_C is the center frequency of the wavelet in Hz (center frequency effectively means the frequency of a periodic signal that most closely resembles the wavelet), a is the scale of the wavelet, and Δ is the sampling period used to record the signal.

3.2 Bridge damage identification from bridge acceleration response

Figure 2 illustrates the mid-span acceleration response for the VBI model mentioned above, where the vehicle velocity is 2.5m/s, damage level is 0.6 and located at 0.35L (L = bridge span). The road surface profile is not considered in this simulation. Wavelet Transform is used to analysis this signal. Hester and González [13] pointed out that Gaussian 2 and Mexican Hat were the most successful at identifying the type of damage investigated in their researches, which adopted the same methods to simulate the bridge damage. Therefore Gaussian 2 will be employed for utilizing wavelet transforms in this paper. When the wavelet transform is applied to this continuous time series acceleration history (Figure 2) at a series of scales, the result is a 3-demensinal surface shown in Figure 3. In this plot, time and scale can be represented by two mutually perpendicular horizontal axes and wavelet coefficient on the vertical axis. Here the value of wavelet coefficients is controlled by the color. The x-axis shows the normalized position of the vehicle axle on the bridge with respect to the bridge length (L) (0 and 1 when the axle is at the start and end of the bridge, respectively). In Figure 3, the horizontal axis gives the normalized position of the load on the bridge. The vertical axis shows the range of scales used in the wavelet transform. The magnitude of the absolute value of the wavelet coefficient at a given scale, a, for a particular location of the load in time is indicated using a lighter color for higher values of *WT(a,b)*.

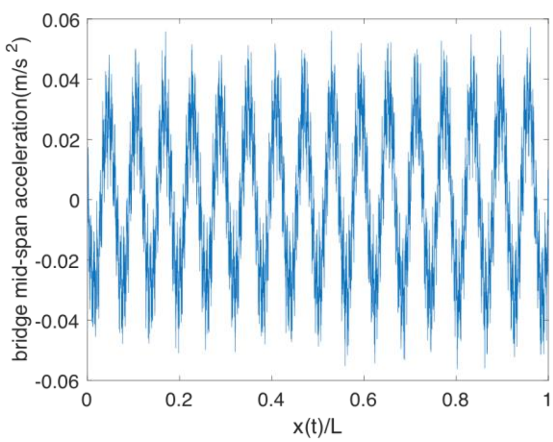


Figure 2: The mid-span acceleration response

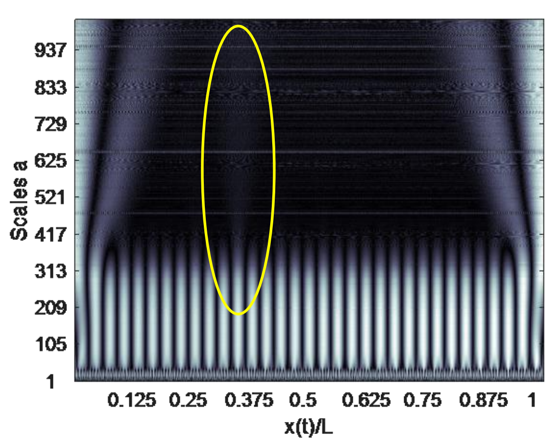


Figure 3: Wavelet transform of the damaged acceleration response shown in Figure 2

From Figure 3, expect the edge effect of wavelet transforms, there is a local increase in the absolute value of the wavelet coefficients at the location of 0.35L as the axle passes over the crack, even though it is not so obvious. In addition, it found that this visible change emerges when the scale is greater than around 400. For the Gaussian 2 wavelet, Fc=0.30 Hz, and Δ=0.001s. Based on the equation2, the scale 400 corresponds to pseudo-frequency of 0.75 Hz. While the damaged bridge 1st nature frequency is 2.06Hz. To achieve more precise results for bridge damage identification, Figure 4 shows the wavelet coefficient line plot at a specific scale (a=450 or its pseudo-frequency of 0.67Hz) for the damaged signal shown in Figure 2. This plot shows an apparent peak at the location at 0.35L, indicating that a change in the structural integrity is located at this place.

It has presented that the bridge mid-span acceleration signal can be used to identify the damage location through applying the wavelet transform with suitable wavelet mother function and proper scale. The wavelet coefficient plot shows a good estimation of the damage location. The following section will discusses the application of the Wavelet Transform to the bridge displacement response instead of the acceleration response.

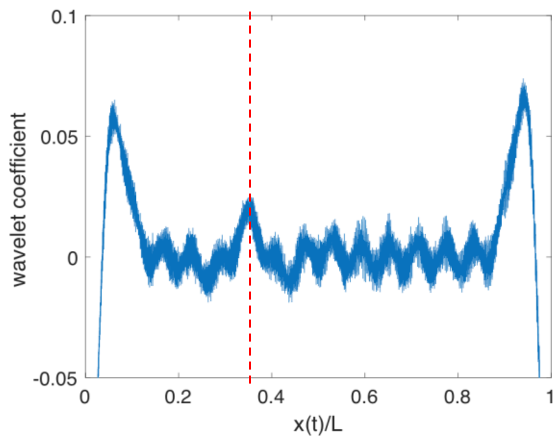


Figure 4: Coefficient line plot for the damaged signal shown in Figure 2

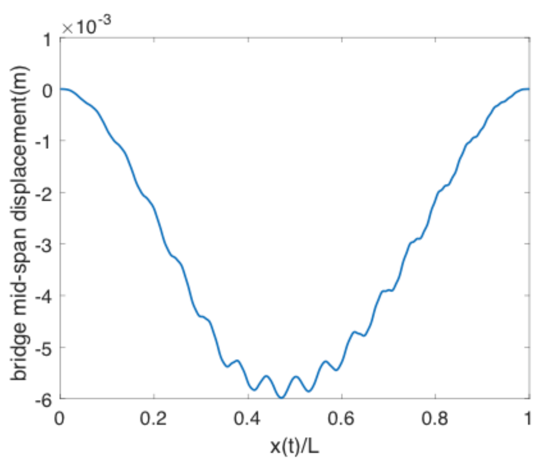


Figure 5: The mid-span displacement response

3.3 Bridge damage identification from bridge displacement response

Using the same VBI model utilized in the previous section, the bridge mid-span displacement history is extracted and illustrated in Figure 5. As shown, the displacement history does not demonstrate any visible discontinuity due to the structural damage. Similarly, wavelet transform is applied to analysis this signal and the outcome is illustrated in Figure 6. This wavelet coefficients line plot at a scale of 450 (pseudo-frequency of 0.67Hz) demonstrates a clear, distinctive change at the damage location as addressed in the figure. It is worth to mention that there is a slight error in identifying damage location here. In Figure 6, the damage localized at 0.36L while the real damage located in 0.35L. This observation reveals the successful identification of the damage through processing the displacement signal utilizing the wavelet transform.

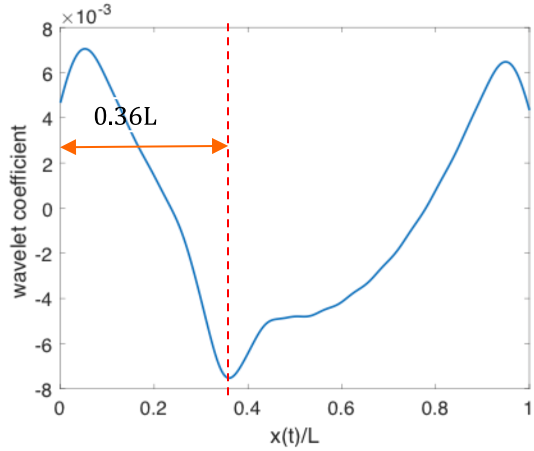


Figure 6: Coefficient line plot for the displacement signal

3.4 Bridge damage identification using indirect method

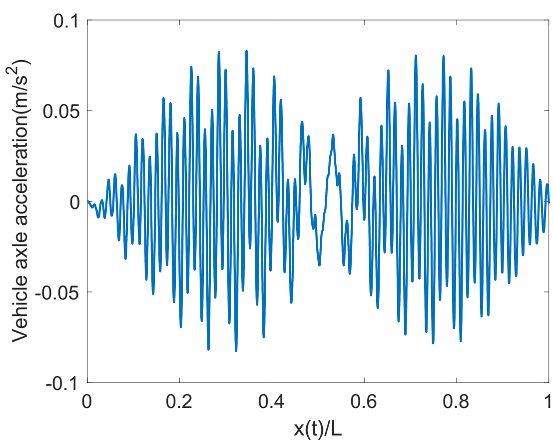


Figure 7: The vehicle axle acceleration response

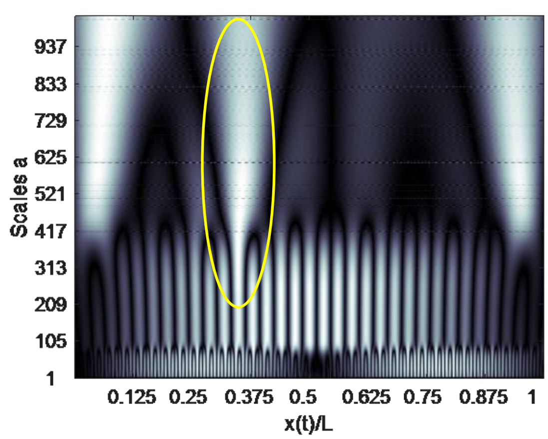


Figure 8: Wavelet transform of the damaged acceleration signal shown in Figure 7

Recently, the concept of using indirect measurements from a crossing vehicle took the authors attention, since it has more advantages in compare with direct measurements approach. In the drive-by method, the vehicle is fitted with accelerometers (mostly installed on its axles) recording the vehicle responses while it is passing over the bridge. This makes the vehicle works as a “moving sensor” crosses all the bridge DOFs. Figure 7 lists the vehicle axle acceleration signal of VBI model for the previous bridge and vehicle conditions. Similarly, the signal has been processed using wavelet transform with Gaussian 2 at a series of scales, and the contour plot is illustrated in Figure 8. From Figure 8, it is astonished that there is also a local increase in the absolute value of the wavelet coefficients as the axle passes over the crack, besides the edge effect of wavelet transforms. Compared to Figure 4, Figure 8 has a more clear result of identifying bridge structure damage location.

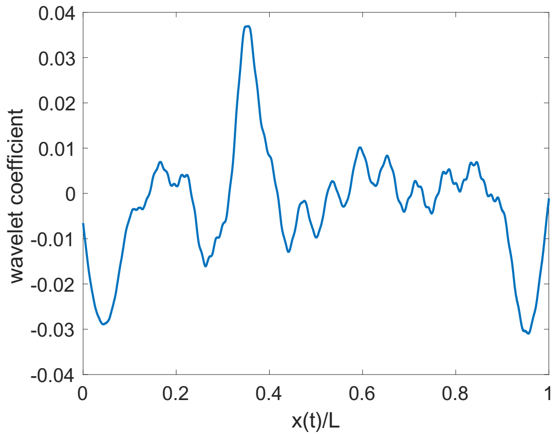
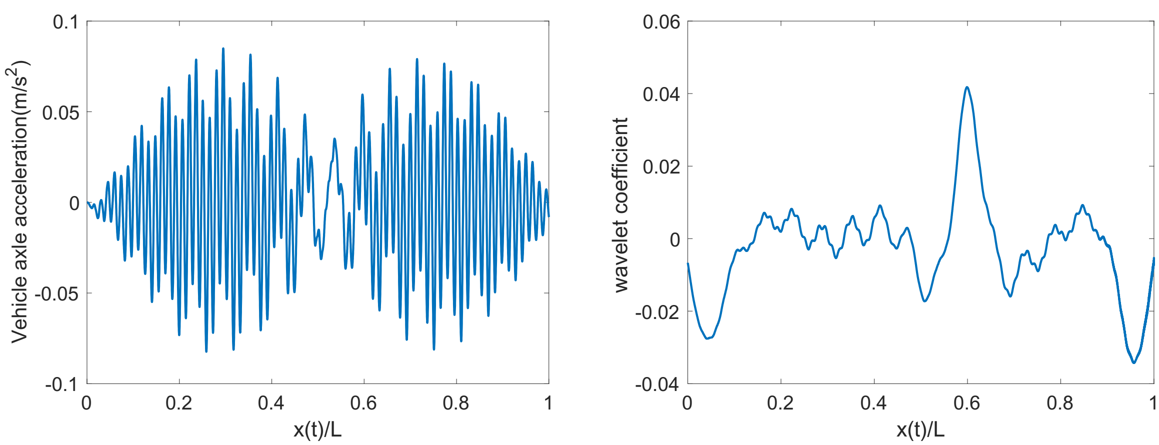


Figure 9: Coefficient line plot for the axle acceleration signal

Figure 9 shows the wavelet coefficients line plot at specific scale of 450 (pseudo-frequency of 0.67 Hz) and it presents that it owns a dominant peak at the bridge damage location. Therefore, the vehicle axle acceleration response from VBI model also can be used to identify the bridge damage location. When it is applied on wavelet transform with suitable wavelet mother function at proper scale, the wavelet coefficient plot will show a distinct peak at the damage. Comparing with Figure 4, Figure 9 shows a higher signal peak where the damage location exists. It means that the vehicle axle acceleration response is more sensitive to the bridge damage than the bridge mid-span acceleration response. In this way, when it is essential to consider the signal noisy in the VBI model or detect the small damage level, the vehicle axle acceleration signal owns the advantage of localizing the bridge damage.

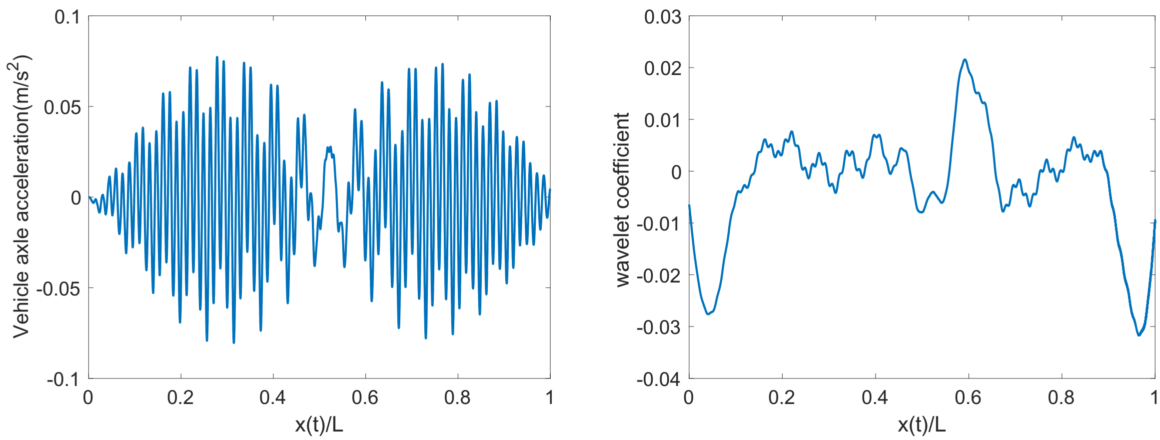


(a) **(b)**

Figure 10: Case 1. (a) The vehicle axle acceleration signal. (b) Its corresponding wavelet coefficient plot.

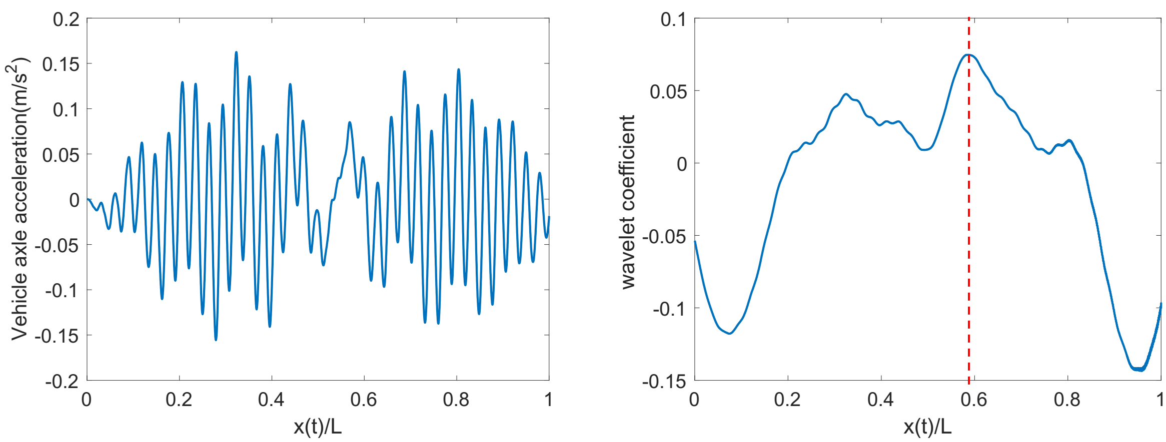
To investigate the approach feasibility, different cases have been investigated.

- Case 1: the damage is located at 0.6L with velocity of 2.5m/s and the damage level is 0.6.
- Case 2: the damage is located at 0.6L with velocity of 2.5m/s and the damage level is 0.3.
- Case 3: the damage is located at 0.6L with velocity of 5m/s and the damage level is 0.6.



(a) **(b)**

Figure 11: Case 2. (a) The vehicle axle acceleration signal. (b) Its corresponding wavelet coefficient plot.



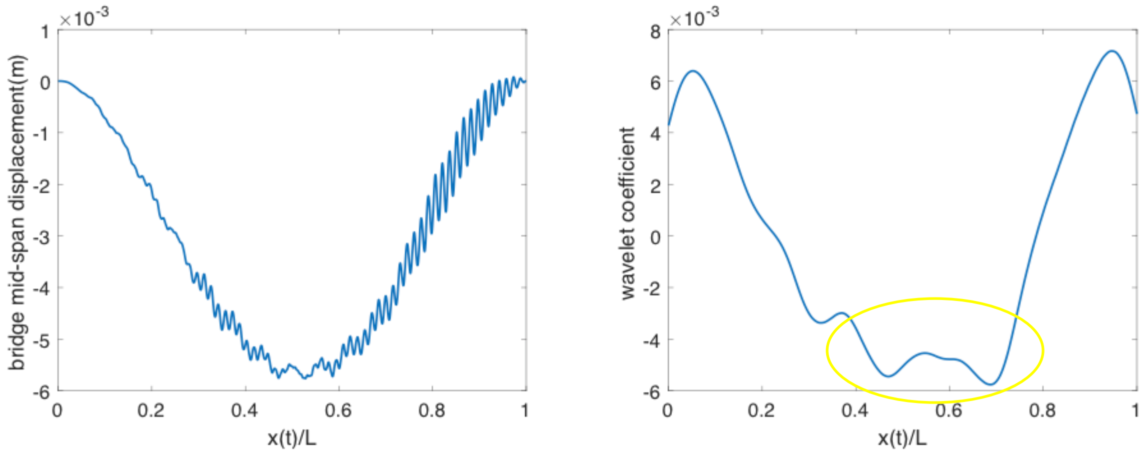
(a) **(b)**

Figure 12: Case3. (a) The vehicle axle acceleration signal. (b) Its corresponding wavelet coefficient plot.

These three cases are adopted the previous wavelet transforms methods to identify the bridge damage location. The results are illustrated in Figure 10, Figure 11 and Figure 12, respectively. The results show a good attribute of identifying the damage location for the three cases. Even for small damage extents, the wavelet transform could recognize the damage location, which has been proofed by the result of case 2. From case 3, for the velocity of 5m/s, wavelet transforms still be able to identify the damage extent and localize it. However, it has shown that the result of damage identification is worse than the lower speed of 2.5m/s. It concludes that lower speeds benefit localizing the damage location through providing more scanning points. Studies found that wavelet transforms would lose the ability to identify damage when the axle velocity is more than 10m/s at this situation.

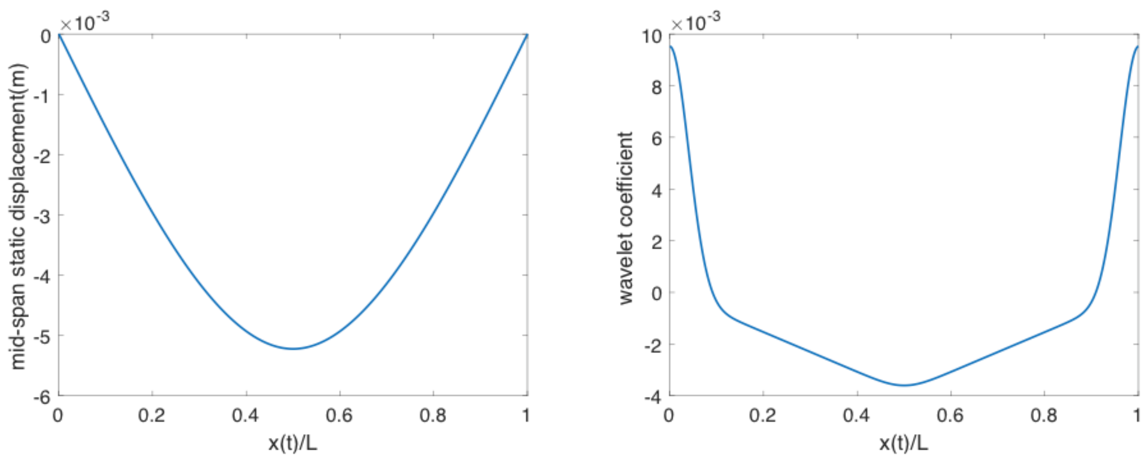
3.5 Identify damage location considering the bridge road roughness

The road roughness is one of the most challenging issues in the drive by bridge monitoring [24-26].



(a) **(b)**

Figure 13: Considering the bridge road roughness. (a) The mid-span displacement response. (b) Its corresponding wavelet coefficient plot.

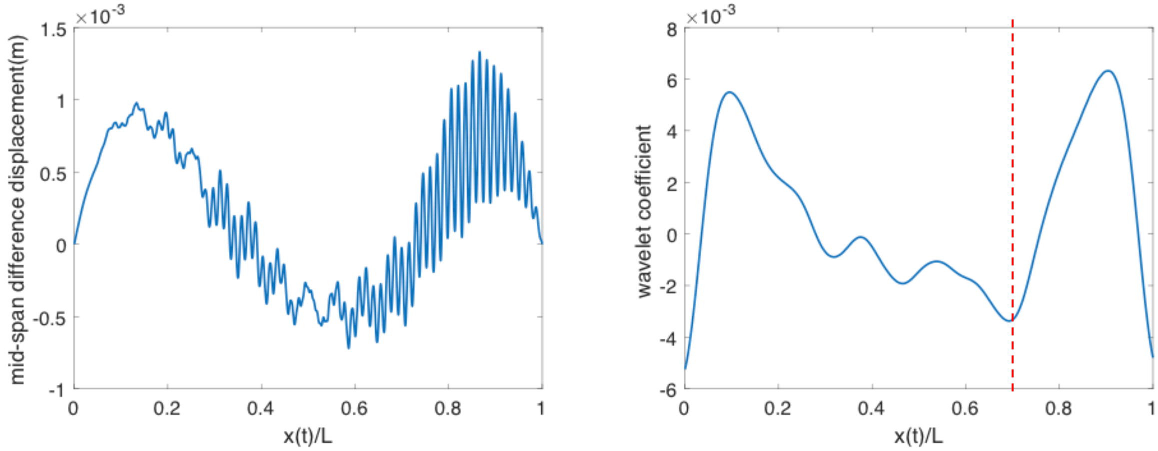


(a) **(b)**

Figure 14: (a) The bridge mid-span static displacement response. (b) Its corresponding wavelet coefficient plots.

As mentioned above, the bridge mid-span displacement history has the potential to recognize the damage location. Figure 13(a) illustrates the mid-span displacement signal considering the bridge road roughness in the condition of damage location at 0.7L with velocity of 2.5m/s and damage level of 0.6. Its corresponding wavelet coefficient plot is shown in Figure 13(b). However, it shows two clear troughs located at mid-span and position of 0.7L respectively, leading to masking the exact damage location. The troughs at mid-span are created by the bridge mid-span static displacement response. Figure 14 (a) shows the bridge mid-span static displacement response and its wavelet coefficients plot are showed in Figure 14 (b). As it has shown, there is a clear trough at mid-span. Therefore, to obtain a better result of damage identification, it is essential to decrease or delete the bridge static displacement response effect.

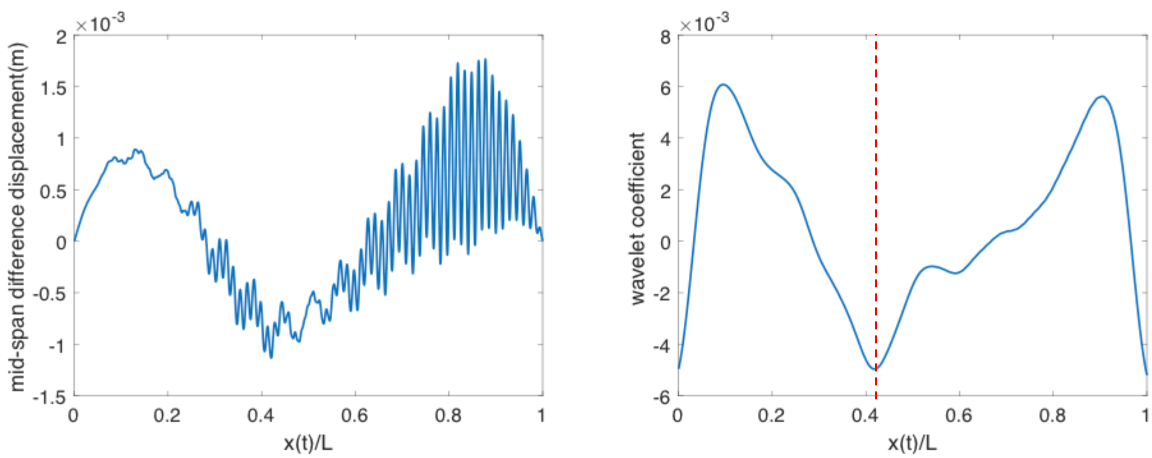
The difference between bridge mid-span dynamic displacement response (Figure 13 (a)) and static displacement response Figure 14 (a) is illustrated in Figure 15 (a). Then the subtracted displacement signal is applied with wavelet transforms and its result is showed in Figure 15(b). In this way, the trough created by damage is clearer than before. It is worth to notice that there is a little error using the mid-span displacement signal to identify the damage location. In fact, the identification damages location in case of Figure 15 is 0.68L, while the real damage location is 0.7L.



(a) **(b)**

Figure 15: (a) The mid-span difference displacement signal with damage location at 0.7L, (b) its corresponding wavelet coefficient plots.

For the purpose of further proof on this method, Figure 16 gives another example about identifying the damage location at the condition of road roughness with the damage location at 0.4L. From Figure 16(b), it shows only an apparent trough around 0.4L where the vehicle passed over the bridge damage. In summary, removing static component of the displacement from dynamic displacement response is an effective method to localize the bridge damage considering the road roughness profile.



(a) **(b)**

Figure 16: (a) The mid-span difference displacement signal with damage location at 0.4L. (b) Its corresponding wavelet coefficient plots.

4 Conclusions

(1). This paper presented wavelet transform as a robust signal process could be applied on bridge health monitoring to identify the damage location using direct measurements and indirect measurements.

(2). In the VBI model with damaged bridge, all of the signals of mid-span acceleration response, mid-span displacement response and vehicle axle acceleration response conceal the bridge damage information, and wavelet transform is an effectively and accurately method to make them localize the bridge damage.

(3). Compared to direct measurement with mid-span acceleration response, the indirect measurement with vehicle axle acceleration response is more sensitive to the bridge damage. It owns advantages of detecting of slight damage and detection in practice with working noise.

(4). Considering the road roughness, only could the signal of mid-span displacement response still be able to identify the bridge damage location. However, in order to achieve more intuitive and obvious result, it is essential to decrease the static displacement response effect.

Acknowledgment

This research is sponsored by National Science of Foundation (NSF-CNS-1645863). Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the view of the sponsors.

REFERENCES

[1] Carden, E. P. and Fanning, P. Vibration based condition monitoring: a review. *Structural health monitoring*, 3, 4 2004), 355-377.
[2] Rytter, A. Vibrational based inspection of civil engineering structures1993).
[3] Malekjafarian, A., McGetrick, P. J. and Obrien, E. J. A Review of Indirect Bridge Monitoring Using Passing Vehicles. *Shock and Vibration*, 20152015), 1-16.
[4] Yang, Y. B., Lin, C. W. and Yau, J. D. Extracting bridge frequencies from the dynamic response of a passing vehicle. *Journal of Sound and Vibration*, 272, 3-5 2004), 471-493.
[5] Yang, Y. B. and Lin, C. W. Vehicle–bridge interaction dynamics and potential applications. *Journal of sound and vibration*, 284, 1 2005), 205-226.
[6] Yang, Y. B., Li, Y. C. and Chang, K. C. Constructing the mode shapes of a bridge from a passing vehicle: a theoretical study. *Smart Structures and Systems*, 13, 5 2014), 797-819.
[7] Kim, C. W. and Kawatani, M. Challenge for a drive-by bridge inspection. *International Conference; 10th, Structural Safety and Reliability; Safety, Reliability and Risk of Structures, Infrastructures and Engineering Systems; ICOSSAR2009; Osaka, Japan*2009).
[8] Lin, C. W. and Yang, Y. B. Use of a passing vehicle to scan the fundamental bridge frequencies: An experimental verification. *Engineering Structures*, 27, 13 2005), 1865-1878.
[9] Elhattab, A., Uddin, N. and Obrien, E. Drive-by bridge damage monitoring using Bridge Displacement Profile Difference. *Journal of Civil Structural Health Monitoring*, 6, 5 2016), 839-850.
[10] El-Hattab, A., Uddin, N. and Obrien, E. Drive-by Bridge Damage Detection using Apparent Profile.
[11] Fan, W. and Qiao, P. Vibration-based damage identification methods: a review and comparative study. *Structural Health Monitoring*, 10, 1 2011), 83-111.
[12] Obrien, E. J. and Malekjafarian, A. A mode shape-based damage detection approach using laser measurement from a vehicle crossing a simply supported bridge. *Structural Control and Health Monitoring*, 23, 10 2016), 1273-1286.
[13] Hester, D. and González, A. A wavelet-based damage detection algorithm based on bridge acceleration response to a vehicle. *Mechanical Systems and Signal Processing*, 282012), 145-166.
[14] Li, H., Deng, X. and Dai, H. Structural damage detection using the combination method of EMD and wavelet analysis. *Mechanical Systems and Signal Processing*, 21, 1 2007), 298-306.
[15] Poudel, U. P., Fu, G. and Ye, J. Wavelet transformation of mode shape difference function for structural damage location identification. *Earthquake Engineering & Structural Dynamics*, 36, 8 2007), 1089-1107.
[16] Roveri, N. and Carcaterra, A. Damage detection in structures under traveling loads by Hilbert–Huang transform. *Mechanical Systems and Signal Processing*, 282012), 128-144.
[17] Yan, R. and Gao, R. X. Hilbert–Huang transform-based vibration signal analysis for machine health monitoring. *IEEE Transactions on instrumentation and measurement*, 55, 6 2006), 2320-2329.
[18] Cebon, D. *Handbook of vehicle-road interaction*. ALWAYS 1999.

[19] Harris, N. K., OBrien, E. J. and González, A. Reduction of bridge dynamic amplification through adjustment of vehicle suspension damping. *Journal of Sound and Vibration*, 302, 3 2007), 471-485.
[20] Sinha, J. K., Friswell, M. I. and Edwards, S. Simplified Models for the Location of Cracks in Beam Structures Using Measured Vibration Data. *Journal of Sound and Vibration*, 251, 1 2002), 13-38.
[21] Grabowska, J., Palacz, M. and Krawczuk, M. Damage identification by wavelet analysis. *Mechanical systems and signal processing*, 22, 7 2008), 1623-1635.
[22] Ren, W.-X. and Sun, Z.-S. Structural damage identification by using wavelet entropy. *Engineering Structures*, 30, 10 2008), 2840-2849.
[23] Bayissa, W. L., Haritos, N. and Thelandersson, S. Vibration-based structural damage identification using wavelet transform. *Mechanical Systems and Signal Processing*, 22, 5 2008), 1194-1215.
[24] McGetrick, P. J., González, A. and Obrien, E. J. Theoretical investigation of the use of a moving vehicle to identify bridge dynamic parameters. *Insight - Non-Destructive Testing and Condition Monitoring*, 51, 8 2009), 433-438.
[25] Keenahan, J., Obrien, E. J., McGetrick, P. J. and Gonzalez, A. The use of a dynamic truck-trailer drive-by system to monitor bridge damping. *Structural Health Monitoring*, 13, 2 2013), 143-157.
[26] McGetrick, P., González, A. and O'Brien, E. J. *Monitoring bridge dynamic behaviour using an instrumented two axle vehicle*. BCRI, City, 2010.