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Impact of Road Profile when Detecting a Localised Damage from Bridge Acceleration Response to a Moving Vehicle

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Abstract. Previous work by the authors have shown that the acceleration response of a damaged beam subject to a constant moving load can be assumed to be made up of three components: 'dynamic', 'static' and 'damage'. Therefore, appropriate filtering of the acceleration signal can be used to highlight the 'damage' component and quantify its severity. This paper builds on these findings to examine if the same approach can be used to identify damage in the more realistic case of a bridge loaded by a sprung vehicle travelling on a road profile. The consideration of a road profile has the effect of exciting the vehicle modes of vibration which will corrupt the spectrum of bridge accelerations with road/vehicle frequencies. Some of these vehicle frequencies may be lower than the first frequency of the bridge and close to the frequency of the 'damage' component. In the latter, the vehicle frequencies are difficult to remove without also filtering part of the 'damage' component out. As a result, the approach is shown to perform best for low vehicle speeds.

Introduction

Past research has shown the potential of using a signal processing technique (i.e., wavelets) to detect damage in a beam by analysing its displacement response to a moving constant load [1]. The difficulty with using displacement signals as the input to a damage detection algorithm is that they may not be easy to record to the required level of accuracy and scanning rate on a bridge site. Therefore, other authors have investigated the possibility of using accelerations as the input signal [2,3]. The latter are model-free damage detection methods with no need for baseline data from the healthy structure. They are based on the fact that for some types of bridge damage, the acceleration signal contains a feature that is not present in the acceleration signal of a healthy bridge. In order to visualize the damage feature, Gonzalez and Hester [4] suggest to consider the total displacement response (at a given measurement point) versus time (as the load travels on the bridge) made of 'dynamic' (i.e., derived from the deflection due to the vibration induced by the inertial forces of the bridge), 'static' (i.e., derived from the static deflection of the healthy bridge) and 'damage' (i.e., derived from the extra displacement that occurs at the measuring point due to the damage). These components as illustrated in Fig. 1(a) for the mid-span displacement of a 40 m beam model with damage of $\delta = 0.2$ at $0.33L$ to a moving constant force (5 tonnes) travelling at 6 m/s. Here, δ is used to define the severity of damage, and it is given by the ratio of the crack height to the beam depth (i.e., $\delta = 0.1$ represents a loss of inertia at a damaged section of 29% with respect to the healthy section). Modulus of elasticity of 3.5×10^{10} N/m² and inertia of 6.02 m⁴ are used for the beam. In this figure, the legend "dynamic", "static", and "damage" stands for 'dynamic', 'static' and 'damage' components respectively as defined above. The term "D static" refers to the total static displacement of the damaged bridge (The 'damage' component is the result of subtracting 'static' from "D static"). The x-axis in the figure represents the normalised position of the load on the bridge, i.e., 0 and 1 when the load is over the left and right hand supports respectively.

Fig. 1(a) shows the theoretical components of displacement, however, this paper uses acceleration as the input signal for damage detection. The corresponding components of the

acceleration signal (i.e., obtained by twice differentiating each of the displacement components shown in Fig. 1(a) with respect to time) are shown in Fig. 1(b). The ‘dynamic’ component of acceleration is plotted on the left y-axis of the figure, while the ‘static’ and ‘damage’ components are plotted on the right y-axis of the figure. It can be seen from the scale on the axes that the amplitude of the ‘dynamic’ component is an order of magnitude larger than the amplitude of the ‘static’ or ‘damaged’ components (Note, if the components in Fig. 1(b) are summed, the total mid-span acceleration signal is obtained, which will be clearly dominated by the ‘dynamic’ component).

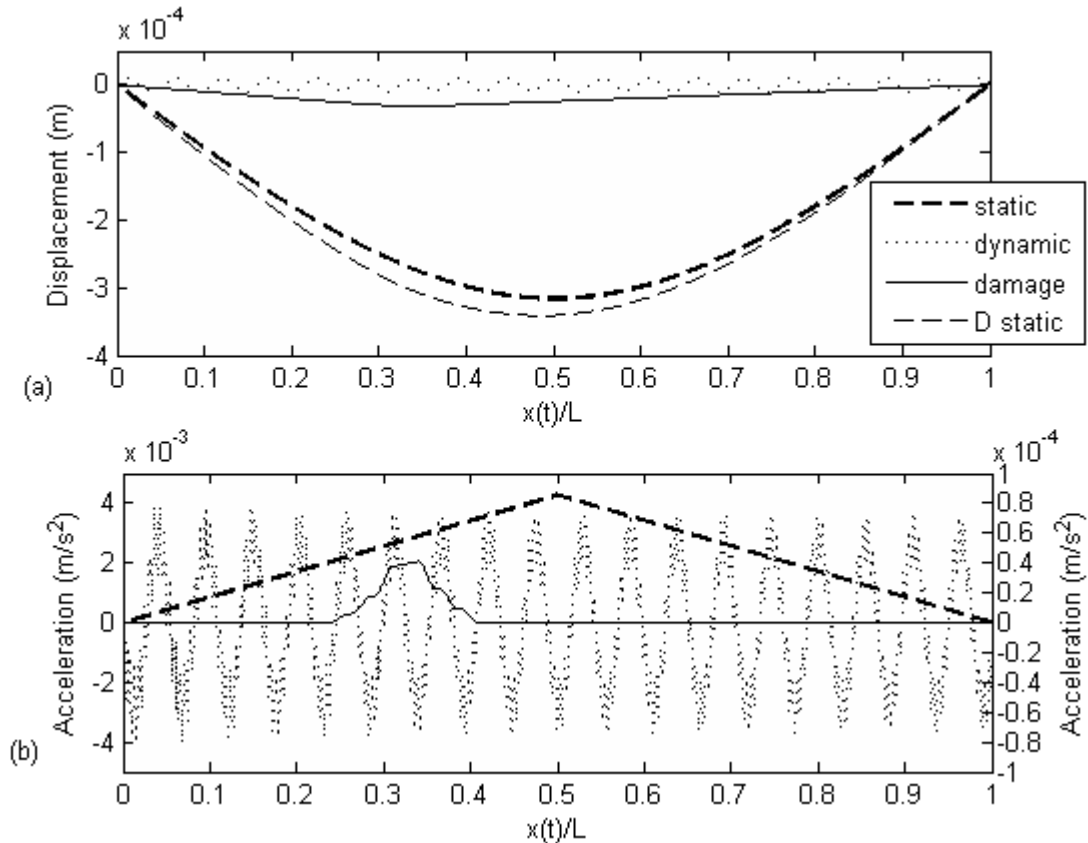


Fig. 1 - Response of a damaged structure to a moving load: (a) displacement, (b) acceleration.

The fact that the amplitude of the ‘damage’ component is much smaller than the amplitude of the ‘dynamic’ component makes difficult to extract the ‘damage’ component from the total acceleration. In order to successfully separate the total acceleration signal into its component parts, it becomes necessary to know the frequency content of the ‘damage’, ‘static’ and ‘dynamic’ components.

Frequency Content of Acceleration Components

Fig. 2(a) shows the continuous wavelet transform (CWT) of the ‘static’ component of acceleration shown in Fig. 1(b) (note the wavelet used in this analysis is the mexican hat wavelet). In the figure, a lighter colour indicates high values of wavelet coefficient. The y-axes on the left and right of the figures show the wavelet scale being used and the corresponding value of pseudo frequency respectively (sampling period is 0.0005 seconds). The figure shows that the largest values of wavelet coefficients for the ‘static’ component occur in the range of scales 9000-5000, which corresponds to a pseudo frequency range of 0.1 - 0.05 Hz. Fig. 2(b) shows the CWT of the ‘damage’ component shown in Fig. 1(b). This time the largest wavelet coefficients occur at a scale of 1400-600 (pseudo frequency range 0.35 - 0.83 Hz) when the load is at 0.33L, i.e., load being located over the damaged section. Fig. 2(c) shows the CWT of the total acceleration. This time the highest value of wavelet coefficient occur at wavelet scales between 170 and 180, which correspond to a pseudo frequency of about 2.89 Hz, i.e. the first natural frequency of the bridge. The reader may be surprised that there are not lighter colours in the area marked by the ellipse in Fig. 1(c), as

from Fig. 2(b) it is known that damage will cause an increase in the wavelet coefficients in this area. The reason for the absence of a distinct light coloured area inside the ellipse is simply that the wavelet coefficients due to the ‘dynamic’ component (i.e., oscillations at the main frequency of the bridge) are far larger than those resulting from the ‘damage’ component. However, the increased wavelet coefficients due to damage (at $x(t)/L=0.33$) are still present and can be visualized if a section is taken through the wavelet surface plot at a scale of 600 (Fig. 2(d)).

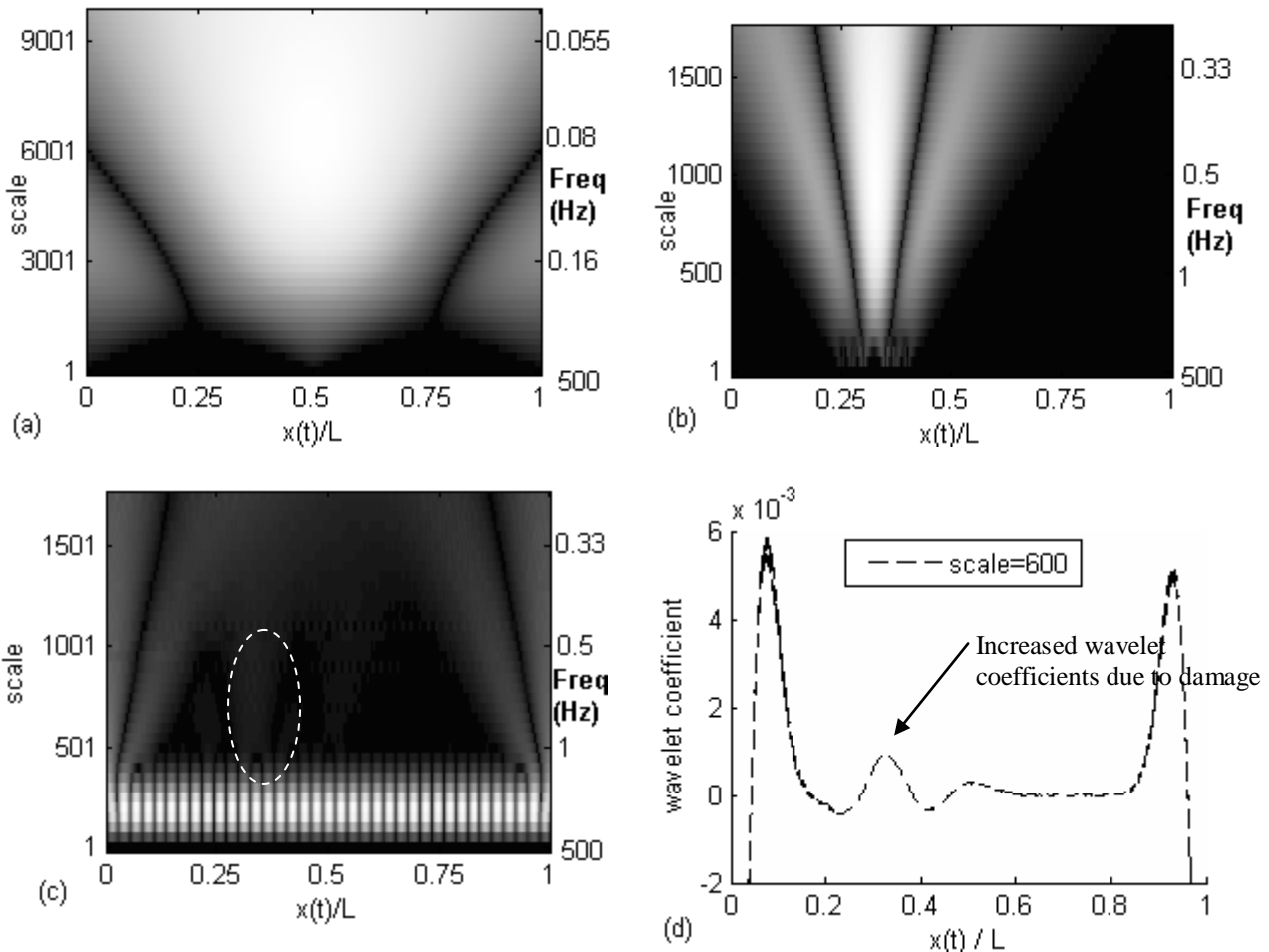


Fig. 2 - CWT of acceleration when the load is travelling at 6 m/s: (a) ‘static’ component, (b) ‘damage’ component, (c) total mid-span acceleration, (d) wavelet coefficients for a scale of 600

Figs. 3(a) and (b) show the CWT of the ‘static’ and ‘damage’ components respectively when the speed of the load is 24 m/s. In both figures the largest wavelet coefficients occur at lower scales (higher pseudo frequencies) than in Figs. 2(a) and (b) when the speed of the load was 6 m/s. Higher speed has the effect of shortening the input signal in the time domain, and as a result, increasing the frequency of the ‘static’ and ‘damage’ components. The fact of having the component defined within a higher frequency range as load speed increases, is important for damage detection. The latter means that for certain load speeds the frequency of the ‘damage’ component may actually match the frequency of the ‘dynamic’ component and therefore, the ‘damage’ component will not be identified. Fig. 3(c) shows the wavelet transform of the total acceleration signal when the speed of the load is 24 m/s. Similar to the situation at 6 m/s, the largest wavelet coefficient occur in the range of scales 170-180. However, this time when a section is taken at a scale of 600 (figure 3(d)) there is no distinct peak at $x(t)/L = 0.33$. This is simply because the ‘damage’ component principally exists at scales of less than 500. However it cannot be detected at scales of less than 500 because these scales are dominated by the first natural frequency of the beam.

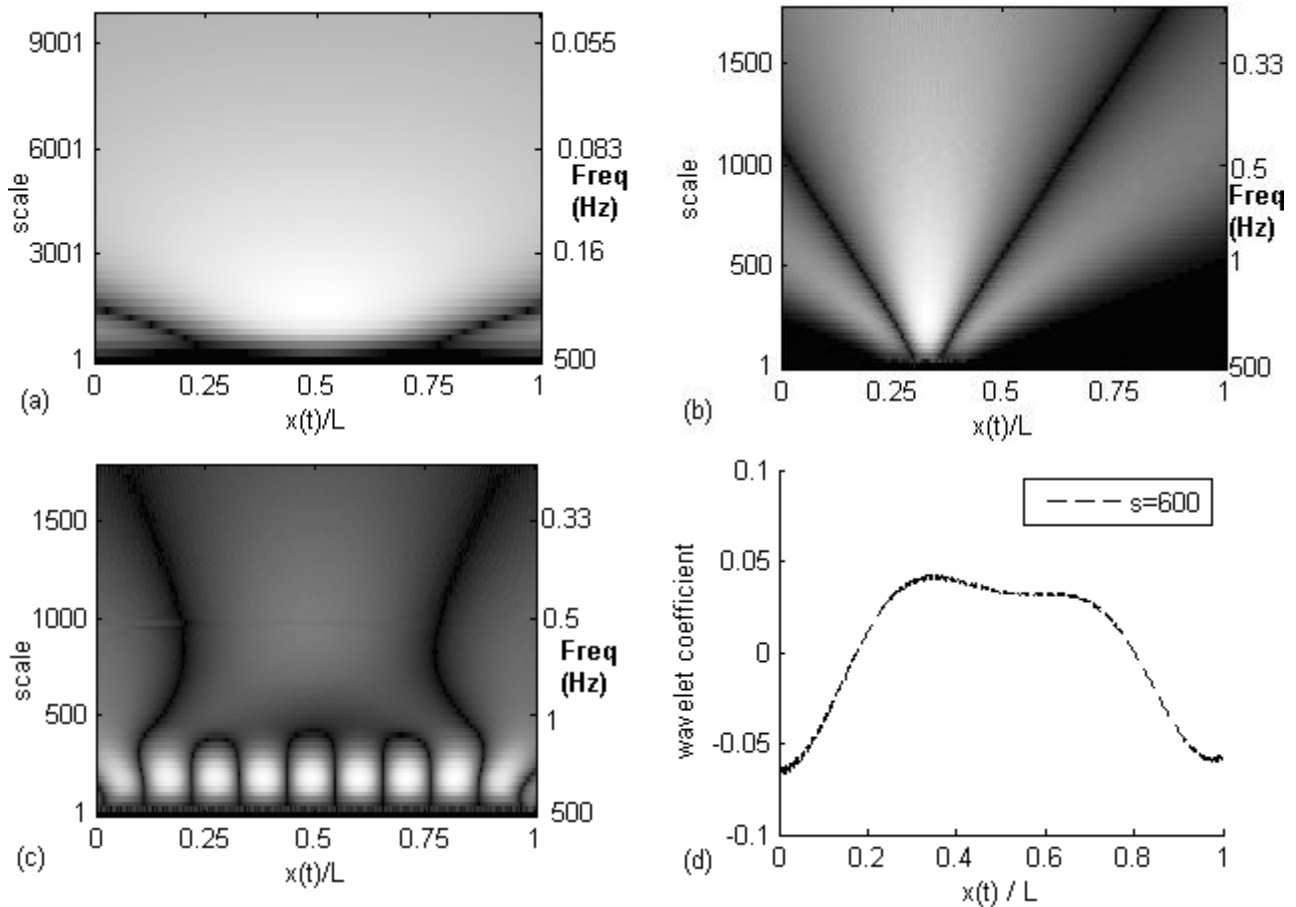


Fig. 3 - CWT of acceleration when the load is travelling at 24 m/s, (a) 'static' component, (b) 'damage' component, (c) total mid-span acceleration, (d) wavelet coefficients for a scale of 600

Theoretical results based on constant load models have revealed that for lower speeds of the moving load, the frequency content of the 'static' and 'damage' component is found sufficiently below the first frequency of the bridge as to safely filter the 'dynamic' component out of the recorded acceleration signal using a Moving Average Filter (MAF). The span of the MAF is typically made equal to the period of the first bridge frequency and as a result the positive and negative parts of the 'dynamic' component cancel each other out, thereby exposing the 'static' and 'damage' component. After exposing the 'damage' component, previous research by the authors shows that it becomes possible to locate and quantify the severity of the damage based on the ratio of the area under the 'damage' component to the area under the 'static' component. However, theoretical investigations in [4] are limited to numerical models of vehicles traversing bridges over smooth road surfaces. The challenges of dealing with acceleration signals generated by a 2-axle vehicle driving on a bridge with a rough profile and subject to noise are addressed in this paper.

Use of Area Ratios for Locating and Quantifying Damage

A planar vehicle-bridge interaction simulation model is implemented using the iterative approach described in [2,5,6]. The vehicle represents a 2-axle rigid truck with four degrees of freedom: the pitch and vertical displacement of the sprung mass and the displacement of the two unsprung masses. The properties of the vehicle are typical of a 15 tonne 2-axle truck: the approximate weight distribution between the axles is 5 and 10 tonne in front and rear axle respectively. The natural frequencies of the vehicle for bounce, pitch, and front and rear axle hops are 1.43 Hz, 2.07 Hz, 8.60 Hz and 10.22 Hz respectively. For comparative purposes, the authors employ the same bridge models as in [4]. Spans of lengths 10, 20 and 40 m with inertias of 0.28, 1.36 and 6 m⁴ respectively

are tested. Modulus of elasticity is 3.5×10^{10} N/m² and the assumed section width is 15 m for all bridge spans being investigated. First natural frequencies of 10.40, 6.24 and 2.89 Hz are associated to 10, 20 and 40 m bridge spans respectively. Damage severities of $\delta = 0.1$ and $\delta = 0.2$ are introduced at $0.33L$ of each span L under investigation.

A road profile can be generated for a specified ISO roughness/classification [7] as described by [8]. Fig. 4(a) shows an ISO class 'A' (very good) profile, typical of well-maintained highways. Fig. 4(b) shows the mid-span acceleration response that results when the vehicle model traverses a 40 m bridge at 6 m/s with a $\delta = 0.2$ at the $0.33L$ and the profile in Fig. 4(a). The consideration of a road profile in a sprung vehicle model renders a significantly rougher mid-span acceleration than found with constant loads.

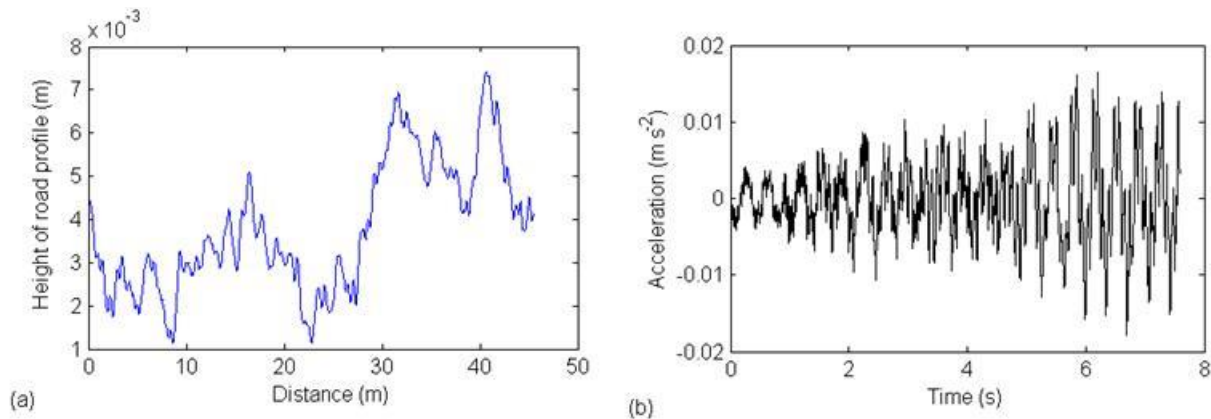


Fig. 4. (a) road profile on bridge, (b) mid-span acceleration resulting from vehicle on road profile

Similar to the approach in [4], the first step toward trying to expose the 'static' and 'damage' components is to use a MAF to remove the main frequency of vibration of the bridge from the signal shown in Fig. 4(b). The value of the governing frequency is established through a Fourier transform of the total response. Then, the span of the MAF is set equal to the number of data points corresponding to one period of vibration. For example, the first natural frequency of the bridge when there is a $\delta = 0.3$ crack at $0.33L$ is 2.76 Hz, therefore the period of vibration is 0.362 seconds, which for a scanning frequency of 2000 Hz, leads to a span of 725 points. The result of applying a MAF of span 725 points to Fig. 4(b) is shown in the 'filt 1' plot of Fig. 5.

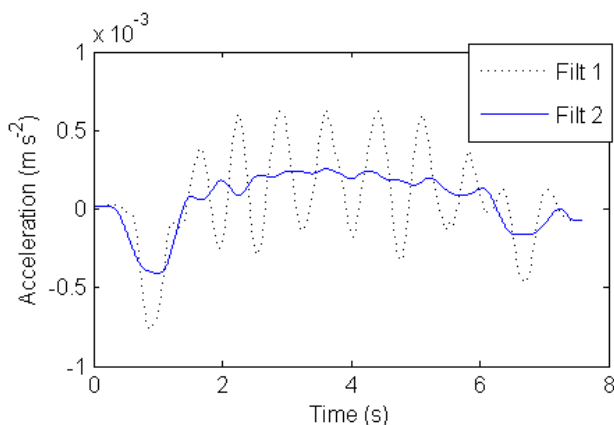


Fig. 5 - Filtering of unwanted bridge and vehicle frequencies from bridge acceleration signal

When the vehicle was travelling on a smooth profile [4], once the main bridge frequency was removed, typically all that remained were the 'static' and 'damage' components, but this time, there is a periodic vibration left that obscures any damage features that may be present. If a Fourier transform is carried out on the 'filt 1' signal, the dominant frequency is found to be 1.4 Hz, which corresponds to the bounce frequency of the vehicle. It appears that the road profile has caused a considerable excitation of one of the modes of vibration of the vehicle that has been subsequently transmitted to the bridge acceleration due to the interaction between both models. To remove these

vibrations it is necessary to apply a second MAF with a span corresponding to 1.4 Hz. The result is 'filt 2' plot of Fig. 5 where vehicle vibrations have been damped out.

Once the vehicle frequencies have been removed, the equivalent acceleration curve due to a single force (as opposed to two forces) is calculated based on the principle of linearity and superposition [9] to be able to compare results in a common framework regardless the vehicle configuration. Having removed the bridge and vehicle frequencies from the bridge acceleration, there is left a residue mostly comprised of the 'static' and 'damage' components shown in Fig. 1(b) (the accuracy of this removal will depend on a number of factors such as load speed, road roughness, bridge span and damage severity, amongst others). To be able to quantify the severity of damage, the 'static' component is estimated by fitting a triangle (which is the theoretical shape of the healthy static response according to Fig. 1(b)) to the residue. Once the triangle has been fitted, it is subtracted from the residue, and what remains is in effect the 'damage' component.

Finally, the ratio of the area under the 'damage' component to the area under the 'static' component is calculated and used to quantify damage. These area ratios are only approximated and inaccuracies derived from the filtering process explained above are unavoidable. In some cases, some of the 'damage' component may be removed to a extent that locating damage was unfeasible. The exact areas under 'damage' and 'static' components (i.e., shown in Fig. 1(b)) and their ratios have been analysed in a previous work by the authors [4]. They found that for a given measurement location, damage location and delta, the ratio of the exact area under the 'damage' component to the exact area under the 'static' component is approximately equal regardless the load magnitude, velocity and the bridge span. As expected, these exact area ratios will increase the closer the location of damage is to the measurement point. If the area ratios corresponding to a fixed measurement location (i.e., mid-span) are calculated for every possible location of the damage along the span, those area ratios with the same damage severity (i.e., $\delta = 0.1$ data or $\delta = 0.2$ data) follow a linear trend as shown by the straight lines in Fig. 6 (exact area ratios of a given delta increase linearly from the first support up to the measurement point and then, decrease linearly from the measurement point down to the second support). Finally, if the exercise is repeated for the three spans and exact area ratios for a given measurement point and delta are all plotted together with respect to the location of the damage, they all fall on the same damage contour line. Therefore, damage contours defining the level of damage ($\delta = 0.1$ contour, $\delta = 0.2$ contour, etc.), can be constructed a priori and these contours make possible to estimate the damage severity by merely calculating the ratio of 'damage' to 'static' areas and locating this point with respect to the damage contours for each delta. In Fig. 6, area ratios (represented by symbols and estimated through a filtering process of the total response) and damage $\delta = 0.1$ and $\delta = 0.2$ contours (represented by straight dashed and dotted lines and calculated based on the exact damage' to 'static' areas) are illustrated for damage located at $0.33L$, different random class 'A' profiles (i.e., Fig. 4(a)), two vehicle speeds (6 and 24 m/s), two deltas (0.1 and 0.2) and three bridge spans (10, 20 and 40 m).

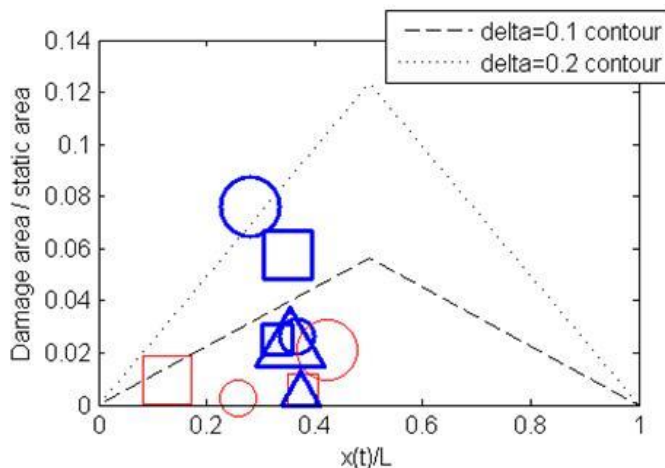


Fig. 6 - Location and quantification of damage based on ratio 'damage' to 'static' area obtained from mid-span accelerations due to a two-axle sprung vehicle model on class 'A' road profiles for different damage scenarios. Span (m): O 40, □ 20 and Δ 10; velocity (m/s): 6 (thick marker border) and 24 (thin marker border); damage severity: $\delta = 0.2$ (large marker size) and $\delta = 0.1$ (small marker size).

Only damage in simulations involving the 40 and 20 m spans and a load velocity of 6 m/s are identified with some degree of accuracy, but the predictions of area ratios for the 10 m bridge and results associated to a load velocity of 24 m/s are incorrect and very sensitive to the random road profile employed in the simulations.

For the load travelling at 6 m/s on a 40 m bridge, even after removing the vehicle frequency, a significant portion of the ‘damage’ component remains unaltered and therefore identifiable. However, for higher velocities and shorter spans the application of a MAF to remove the 1.4 Hz vehicle frequency will likely smooth the ‘damage’ component. The MAF maintains the area of the ‘damage’ component but the removal of such a low frequency will spread the area widely over the length of the signal instead of concentrating it close to the damage location. The lack of success in detecting damage in some scenarios is mainly related to two factors: the portions at the ends of the response corrupted by axles entering and leaving the bridge, and the difficulty in safely removing frequencies interfering with the ‘true’ frequencies that define the ‘damage’ component. Provided that the frequency content of the ‘damage’ component remains below the frequency of the filters used to remove bridge and vehicle frequencies, the approach appears to be robust with respect to the randomness of the road profile as shown by Fig. 7. In Fig. 7, the ratios of ‘damage’ to ‘static’ area are given for the accelerations of a 40 m bridge due to a two-axle vehicle travelling at 6 m/s. Fifty scenarios with different class ‘A’ road profiles are modelled: twenty-five corresponding to a healthy bridge ($\delta = 0$) and twenty-five to a damaged bridge ($\delta = 0.2$ at $0.33L$). While the healthy accelerations do not give a value of zero every time, they are identified as having damage close to zero. Similarly, the severity of the crack in the damage scenario is not predicted exactly every time, but it is identified in all cases as being in the vicinity of $0.33L$ with severity levels between $\delta = 0.15$ and $\delta = 0.25$.

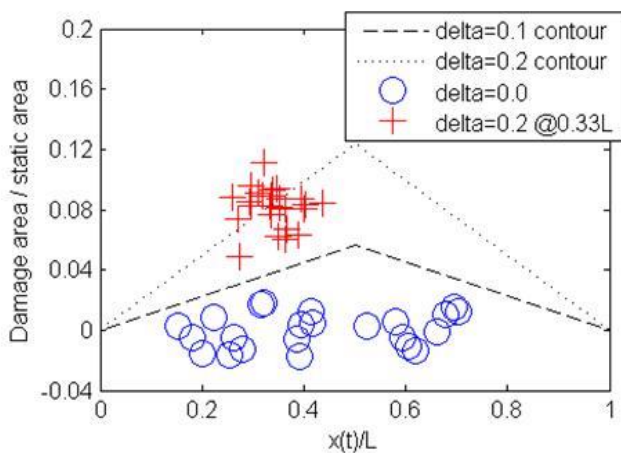


Fig. 7 - Influence of randomness of the road profile on the location and quantification of damage based on the ratio ‘damage’ to ‘static’ area

Conclusions

A damage detection algorithm based on filtering the ‘dynamic’ component from within the total acceleration and using the remaining ‘damage’ to ‘static’ area ratio as a mean to locate and quantify damage has been proposed. Once the total acceleration has been filtered, the remaining signal will contain the ‘static’ component (‘static’ here meaning the static response to the moving load if the structure was healthy) and an additional distinctive feature due to a localised loss of stiffness (here named ‘damage’, representing the difference between the static response of the damaged structure and the static response of the healthy structure). If the filtering of the ‘dynamic’ component has been successful, then a local ‘damage’ component will be easily visualized. Then, this damage will be located and quantified based on the ratio of the area under the ‘damage’ component to the area under the ‘static’ component. Using a MAF as filtering technique to remove unwanted frequencies has been found to be effective in the presence of a smooth road profile because it preserves the area under the ‘damage’ and ‘static’ components (and obviously their ratios) while removing the ‘dynamic’ component. However, the filtering of the acceleration signal to remove the ‘dynamic’

components in order to visualize the ‘damage’ component, has had the negative effect of spreading the ‘damage’ component over the length of the filtered signal (i.e., it is not as narrowly located as in the original signal).

The algorithm has been tested using beam accelerations from a planar vehicle-beam interaction simulation model that included a localised loss of stiffness. It has been found that including a sprung vehicle and a road profile substantially increases the difficulty of identifying the damage. This is principally because other oscillatory vibrations may still be present after filtering out the bridge’s ‘dynamic’ component. As vehicle speed increases, the beam acceleration response becomes shorter leading to a ‘damage’ component defined by higher frequencies (i.e., closer to the bridge frequency and possibly other vehicle/road frequencies). Therefore, removing the ‘dynamic’ component without compromising the ‘damage’ component has sometimes been unfeasible for higher speeds and as a result, damage has been predicted more inaccurately. Nonetheless, the technique has been found to be relatively reliable across a range of road profiles when the vehicle travelled at low speed on a long span beam.

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