Highway bridge damage detection from operating vehicle response

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This paper presents the new method for detecting and localizing damages of highway bridges using responses induced by operating vehicle load. Since vehicle induced response data can be contaminated by measurement noise, it is de-noised by filtering out the wavelet transform (wt) coefficients of small energy. A damage index is calculated from the deviations in signal energy from the reference signal energy. From a set of these damage indices from signals measured at various sensor locations along the structure, a spatial wavelet transform based curvature shape is constructed from which location of damage is identified. Thus this technique has the potential of detecting damages using vehicular response of highway bridges with small number of sensors and without interrupting traffic flow.

Key Words: damage detection, highway bridge, operating vehicle load, wavelet analysis

1. Introduction

The ability to continuously monitor the integrity of structures in real-time can provide for increased safety to the public, particularly for the aging structures in widespread use today. The ability to detect damage at an early stage can reduce the costs and downtime associated with repair of critical damage. Thus assessing damage is one of the main components of structural maintenance. Damages of civil engineering structures, such as highway bridges, including the degradation of columns, joints and beams, the breakage of braces, cumulative crack growth, impact by foreign object, fatigue etc., result in a sudden change of the stiffness and hence natural frequencies of the structures. Various approaches have been proposed in the literatures for detecting the damage in different types of structures[1)-3)]. In these studies, damages have been detected by a comparison of the system properties of damaged and undamaged structures. A comparative study of damage identification algorithms applied to a test bridge was conducted by David et al.[4)]. In this study experimental modal data from a bridge were used. Damage index method, obtained from changes in mode shape curvature, performed best in detecting and localizing damages than other methods.

Recently, methods based on signal decomposition have been proposed by the researchers to identify linear structures quite successfully[5)]. They have used the vibration data in their signal processing. When the damage event occurs during the recording period of the health monitoring system, the recorded signal in the vicinity of the damaged location will have a discontinuity at that time or space instant. Such discontinuity can be detected through the data analysis techniques.

In case of structural health monitoring of a bridge structure, in order to have vibration response data, it requires to close the lanes to apply any external forced vibration. Hence, It is necessary to direct the research of using bridge response induced by traffic operation by using ordinary vehicle instead of any external forced vibration and loading. Responses can be obtained induced by vehicles at crawling speed or by driving speed. It is better if responses induced by operating vehicles (at driving speed) passing over the bridge can be used. In that case there will be no limitations on traffic closings. Responses induced by vehicles at crawling speed can also be used in which case there will be some limitations on continuous traffic flow. However, operating vehicle response data is necessarily contaminated by measurement noise and dynamic effects of both from vehicle and structure related to wheel suspension, vehicle speed etc.[6)]. Road surface roughness will also significantly contribute to the noise. Thus makes it difficult to use this response data for damage detection of bridge structure.

As a promising tool for data analysis, wavelet transformation may be viewed as an extension of the traditional Short Term Fourier Transform (STFT) with adjustable window location and time. Advantages of wavelet analysis lie in its ability to examine local data with a zoom lens having an adjustable focus to provide multiple levels of details and approximations of the original signal. Therefore, the transient nature of the data can be retained.

Recent developments in the mathematical theory of wavelets and their applications may be found in Lokenath Debnath[7]. Application of wavelet analysis on ASCE benchmark studies is given by Adriana and Hou[8]. A statistical wavelet transform based method for structural health monitoring has been proposed by Sun and Chang[9]. All of the researchers have used global response (vibration signal) of the structure in their analysis. Though one basic premise of using vibration data is that the information of any structural change is hidden its dynamic response, it requires expensive and sophisticated techniques.

In this paper a new method has been proposed to extract damage information from the measured time history of displacement data of a bridge structure induced by operating vehicles. Time history of displacement response of the bridge structure due to moving vehicle at regular speed can be extracted by displacement sensors installed at few locations only. First this method de-noises the extracted signal by wavelet transform (wt) and then reconstructs a fresh signal. From the reconstructed de-noised signal, signal-energy is calculated and compared to the reference signal. It has been found that wt coefficients energy is a good condition index that is sensitive to changes of structural rigidity yet almost insensitive to measurement noises[10]. Hence a damage index is calculated from the deviations in signal energy from the reference signal energy. Increase in damage tends to increase this damage index. When damage indices exceed a preset threshold value, the presence of damage is indicated. From a set of these damage indices from a set of signal energy measured at various sensor locations, a spatial wavelet transform based curvature shape is constructed. This spatial curvature has good sensitivity to localize damages. Thus this technique has the potential of detecting damages using vehicular response of highway bridges without having any undamaged information apriority and with small number of sensors. The time displacement vehicular response will be measured without applying any forced vibration and closing the traffic lanes. This technique can also be integrated with the online bridge monitoring system such that any damage index above the threshold value will give an alarming signal about existing or occurring damages in its service life.

2. Highway Bridge Response due to Vehicle Load

In order to evaluate the vehicular responses of highway bridges, Public Works Research Institute (PWRI), Japan conducted a number of tests on a real bridge inside its facility[11]. The test bridge was a 30m simply supported steel girder bridge with reinforced concrete deck. The data were measured at girders at various locations. Two types of vehicles were used: 20ton air suspension two-axle vehicle and 20ton leaf suspension two-axle vehicle. It has been found that for crawl vehicle loading (3km/h) the response pattern is almost like static loading response both for air suspension and leaf suspension as shown in the Fig.1. However it should be noted that deflection of the bridge is due to influence of two axles of the vehicle. That is why the responses at both ends are comparatively small, which can be explained by Fig.2.

The response of the bridge due to operating vehicle loading (at regular speed) includes dynamic effects of vehicle and bridge interaction, arises from bump of the wheels, vehicle speed and surface roughness. Measurement noise also significantly contaminates the response. The displacement response of the PWRI test bridge for 40km/h vehicle speed is shown in Fig.3. Vehicle with air suspension system significantly reduces the bumping effect of the bridge response.

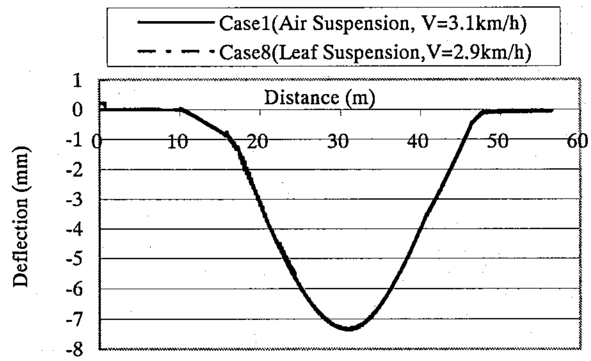

Fig.1 Deflection of G1of PWRI test bridge for 20ton crawl vehicle loading

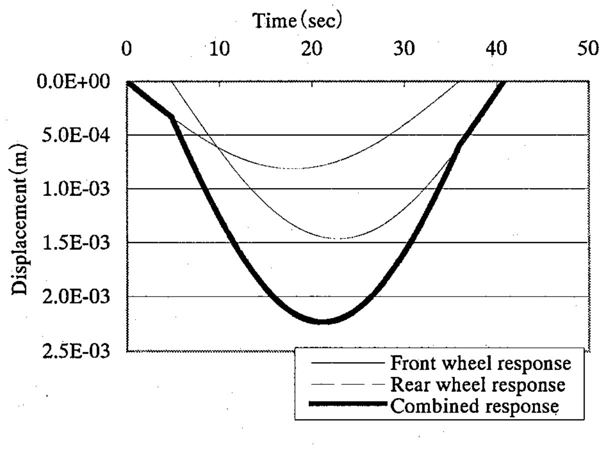

Fig.2 Two axle vehicle response of a bridge at 3km/h crawling speed

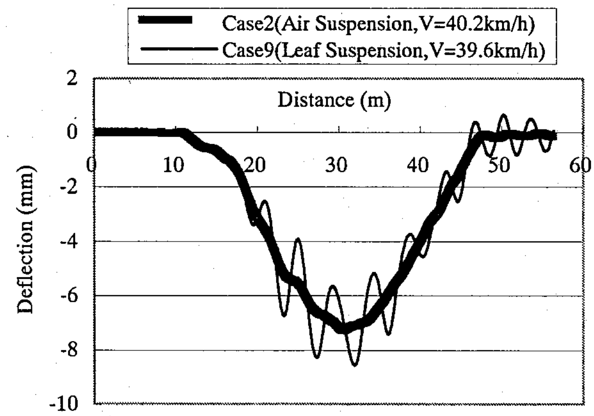

Fig.3 Deflecion of G1 for ordinary vehicle speed

3. Simulation of Vehicle Response

In the absence of bridge response field data due to vehicle load, a set of simulation were performed with various damage cases using a typical short span bridge similar to the PWRI test bridge. This bridge structure as shown in Fig.4 is 30m long with a cross sectional area of $6m^2$ and moment of inertia about X-axis is $2m^4$ and about Z-axis is $0.1m^4$. Stiffness, E is 3.04e10 Nt/m^2. A two axles simulated standard vehicle with total axle loads 20ton at a speed of 3km/h (crawl speed) and 60km/hr (operating speed) moves from one end to other end of the structure. Nonstationary random response of highway bridges due to moving vehicle load is used for simulation program. Governing equations can be found in many research papers as Tung et al.[12)] and Kawatani et al.[13)].

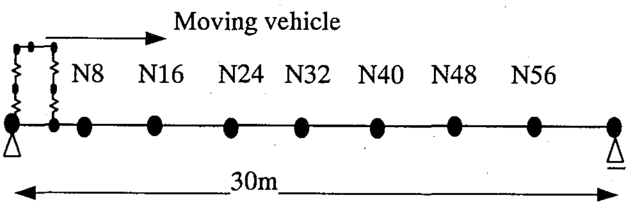

Fig.4 Bridge model with simulated vehicle and sensor locations

Displacement response includes the dynamic interaction of vehicle wheels and bridge structure, suspension system and roughness effect of the deck surface. The measurement noise is included in the surface roughness. Here random surface roughness has been assumed in every measurement. Roughness has been calculated from power spectrum of surface roughness as:

$$Z(X) = \sum_{k=1}^{N} a_k . \cos(2\pi\Omega_k . X + \phi_k) \qquad (1)$$

Surface roughness power spectrum as shown in Fig.5 is as:

$S_z(\Omega)=\alpha.\Omega^{-N}$, where
α= Roughness parameter
N= Number of division in frequency range
Ω= Spatial frequency
$a_k^2=4S_z(\Omega_k)\Delta\Omega$
$\Delta\Omega=(\Omega_U-\Omega_L)/N$
$\Omega_k=\Omega_L+(k-1/2)\Delta\Omega$
$\phi_k= 0\sim2\pi$

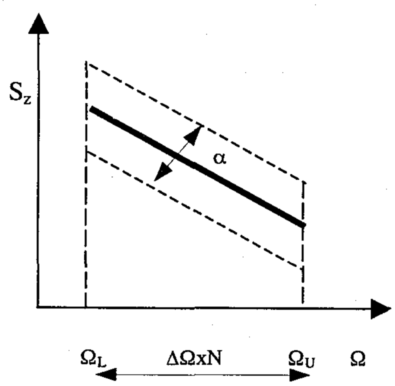

Fig.5 Power spectrum of road surface roughness

Fig.6 shows the simulated time history displacement response, measured at mid span of the bridge, induced by a two-axle vehicle of load 20ton moving at a speed of 60km/hr from one end to other end of the bridge. Fig.7 shows a particular random roughness used for simulating the vehicle response shown in Fig.6.

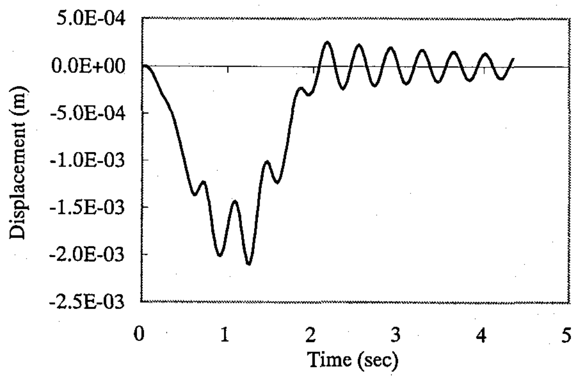

Fig.6 Time history of displacement at mid span of the bridge (20ton, 60km/h)

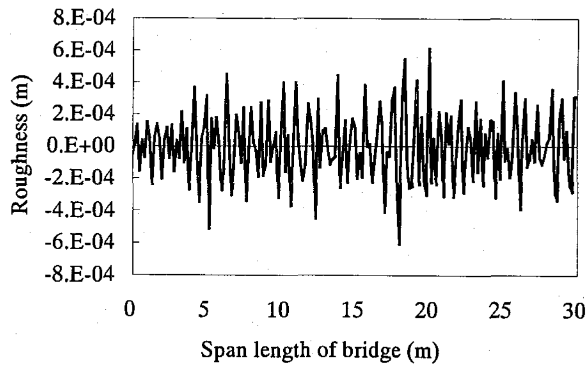

Fig.7 Road surface roughness profile

4. Damage Detection Tool

4.1 Ordinary curvature method

(1) Damage detection

There are several structural identification methods for damage detection using static response. One of the methods is direct application of curvature method. The deflection of the beam structure can be obtained from the moving vehicle response of the bridge using the reciprocal theorem, which states that a load P, placed at point A, produces at point C the same deflection as the load P, placed at C, produces at point A as shown in Fig.8.

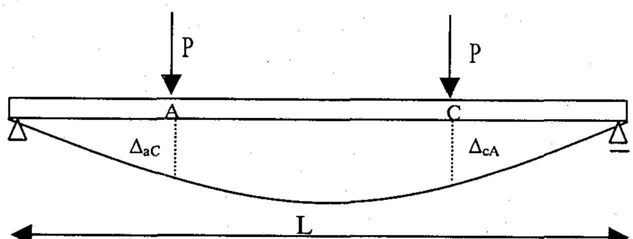

Fig. 8. Simple beam with moving load

Structural property EI of a deflected beam due to a load can be obtained by

$$EI_j = \frac{M_{aj}}{v_j''} \qquad (2)$$

Here j stands for j-th node location, M_a stands for section moment and v'' stands for instantaneous curvature. Curvature can be estimated from central difference operator[14] as

$$v_j'' = \frac{\delta_{(j-1)} - 2\delta_j + \delta_{(j+1)}}{h^2} \qquad (3)$$

where h is the average distance between measurement points. v_j'' is the curvature at point j and δ_j is the displacement at point j. Influence line of moment diagram of the bridge due to vehicle loading can be obtained by the combination two axles response as shown in Fig.9.

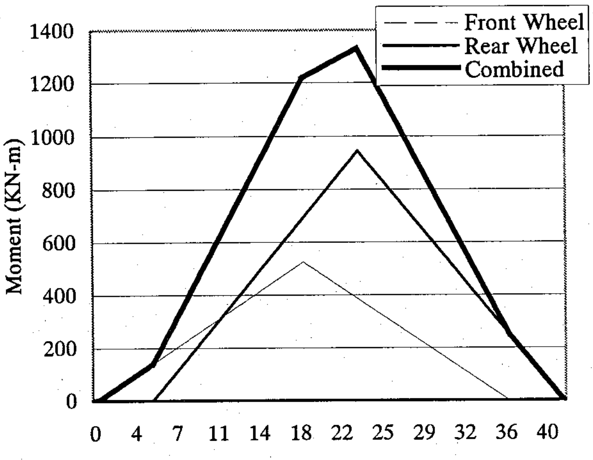

Fig.9 Bending moment due to vehicle load at speed, V=3km/h

From Eq.(2) it is evident that curvature is directly proportional to the inverse of the bending stiffness, EI. If there is damage anywhere in the structure, bending stiffness say EI_j^* will be reduced and accordingly curvature will be changed. Thus using the curvature method we can identify and localize damage as,

$$(EI_j) - (EI_j^*) = 0 \ \text{(Nodamage)}$$

$$(EI_j) - (EI_j^*) \neq 0 \ \text{(Damage)}$$

(2) Simulation results

A set of bridge response was obtained by simulation having different damage scenarios (locations, size, severity and number) due to vehicle speed at 3km/h and 60km/h. Damage cases are shown in Table1. Due to various dynamic effects and inclusion of noises, the measured response has been filtered by using Hanning window as:

$$X_i = \frac{1}{4}x_{i-1} + \frac{1}{2}x_i + \frac{1}{4}x_{i+1} \qquad (4)$$

It can be mentioned here that by using FFT filtering method, we got almost identical filtered data as filtered with Hanning window.

Table1: Damage cases

	Span Length 30m		
Damage Cases	Damage Location (m)	Damage Length (m)	Change in EI %
Case1			No Damage
Case2	12	1.5	50
Case3	12	0.5	50
Case4	7.5	0.5	50
Case5	7.5	0.5	20
Case6	5	0.5	20
Case7	7.5 & 20	0.5 & 0.5	20 & 20

Table.2 shows the natural frequency of the test bridge measured by PWRI and by simulation respectively.

Table2: Natural freq.(Hz) obtained by PWRI and simulation

Mode No	PWRI (A)	Simulation (B)	A/B
Mode:1	2.7210	2.7218	0.99970
Mode:2	10.8820	10.8873	0.99952
Mode:3	22.4720	22.5087	0.99837
Mode:4	24.4720	24.4964	0.99901
Mode:5	43.4270	43.5491	0.99720
Mode:6	67.5510	67.5120	1.00058

However, it is not easy to get natural frequencies (modes) of the bridge from response induced by moving vehicle due to interaction of vehicle frequency with bridge frequency. Moreover, since, 1st mode of bridge natural frequency is dominant, it is also difficult to obtain natural frequencies of several modes as shown in Fig.10. It is necessary to have several natural frequencies to detect damages in frequency domain because certain modes may be less sensitive to the damage or may include higher noise leading to false diagnosis.

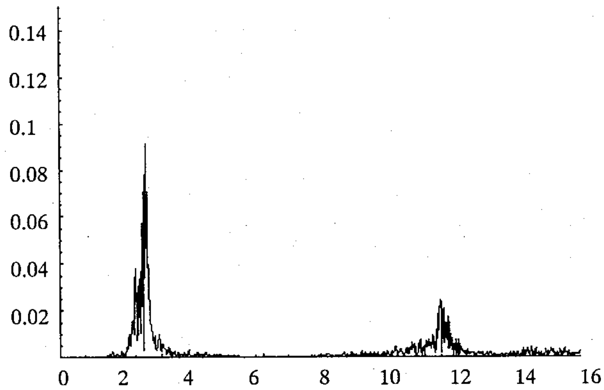

Fig.10 Frequency spectrum of undamaged response induced by crawling vehicle load

Fig.11 to Fig.14 shows the change in structural stiffness EI at various damage cases due to crawling load (3km/h) over the bridge structure. For damage case 2, 3 and 4 where damage is relatively large as shown in Fig.11 and Fig.12, damage location can be identified from the distinguished peak. But in case of small damages (damage case5, 6 &7) it is cumbersome to localize damage as shown in Fig.13 and Fig.14. One reason of this inaccuracy is that damage information is being lost when filtering the response. Damage near bridge end would be difficult to identify as it gives false damage location at those regions without having any damages as shown in Fig.11 to Fig.13. The reason is that relatively small deflection response at bridge ends becomes severely contaminated by measurement noise than that of responses at mid span.

The responses induced by operating vehicle loading (60km/h) are more dynamic and noisy. Fig.15 shows the change in EI of the bridge from responses induced by operating vehicle speed with single and relatively large (50% reduction in EI) damage at 12m (case2). From the plot it is difficult to identify any distinguished peak other than at ends and hence to localize the damage.

Fig.16 plots the change in EI of the bridge with multiple

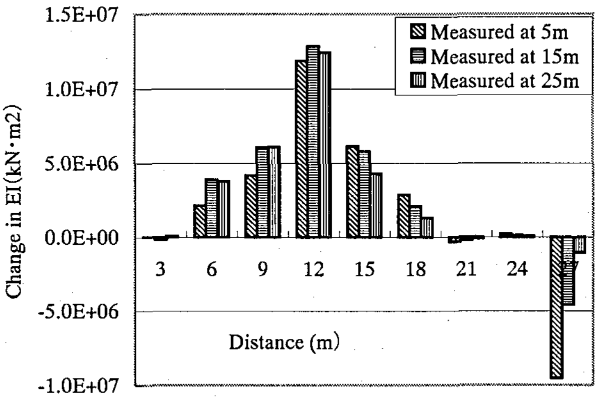

Fig.11 Change in EI for case2, damage at 12m (V=3km/h)

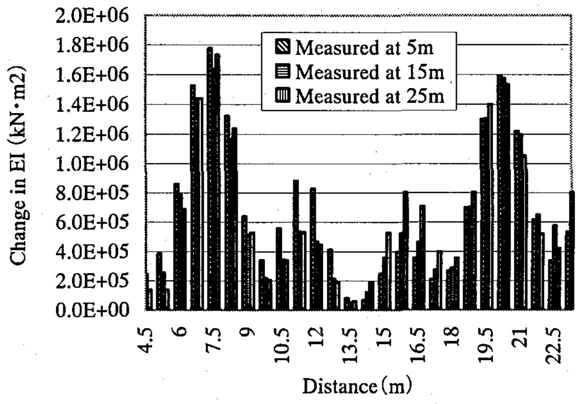

Fig.14 Change in EI for case7, damage at 7.5m & 20m (V=3km/h)

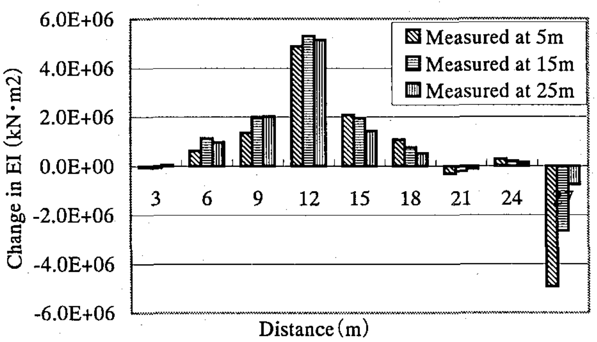

Fig.12 Change in EI for case3, damage at 12m (V=3km/h)

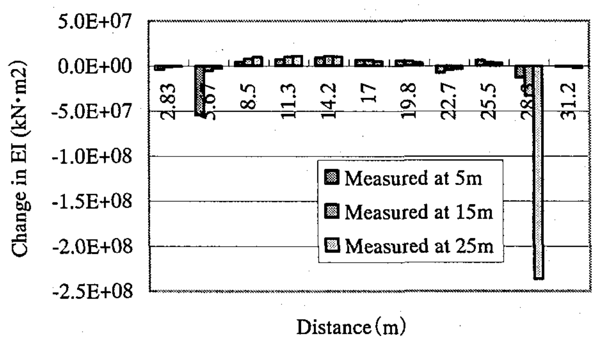

Fig.15 Change in EI for case2, damage at 12m (V=60km/h)

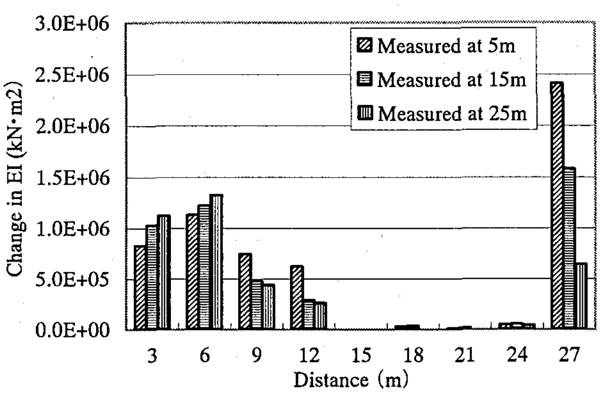

Fig.13 Change in EI for case5, damage at 7.5m (V=3km/h)

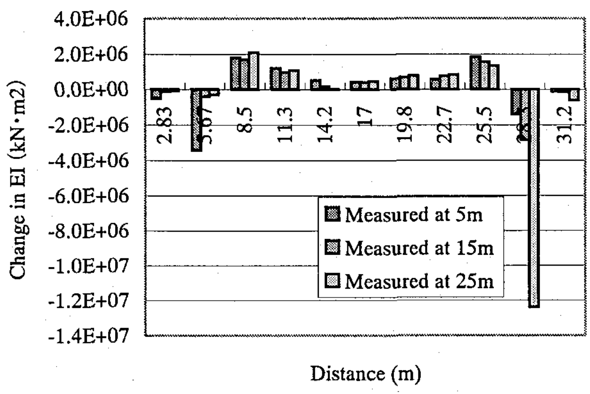

Fig.16 Change in EI for case7, damage at7.5m & 20m (V=60km/h)

damages (20% reduction in EI) at 7.5m and 20m (case7) from responses induced by operating vehicle loading. This plot also can not identify and localize damages; rather it gives false localization at 8.5m and 28.5m. Hence it appears hard to localize damage irrespective of damage sizes, severity and location from responses induced by operating vehicle loading by ordinary curvature method.

4.2 Wavelet transform based curvature method

In the previous section 4.1 we have seen that though ordinary curvature method can identify relatively large damages (50% reduction in EI) from responses induced by crawling vehicle, it has encountered difficulties to identify presence of damage and its locations for relatively small and multiple damage cases. In case of responses from operating vehicle loading, it seems impossible to identify damages irrespective of damage severity and locations. Hence in this section we propose a wavelet transformation based new methodology (hereafter, wt based curvature method) to analyze bridge response and identify and localize damages.

(1) Wavelet transform

Wavelets literally mean "small waves", which have their energy concentrated in time. Their curves yield zero net area: $\int_{-\infty}^{\infty} \psi(t)dt = 0$ and are localized in time. This leads to the possibility that wavelets are better suited to represent functions that are localized both in time and frequency. By wavelet expansion a signal or function f(t) can be analyzed, described or processed if expressed as a linear decomposition as:

$$f(t) = \sum_j \sum_k d_k^j \psi_k^j(t) \tag{5}$$

where both j and k are integer indices and the $\psi_k^j(t)$ are the wavelet expansion functions that usually form an orthogonal basis. Wavelet transform coefficients d_k^j can be calculated by the inner product as:

$$d_k^j = \langle f(t), \psi_k^j(t) \rangle = \int f(t)\psi_k^j(t)dt \tag{6}$$

The list of coefficients d_k^j is called the Discrete Wavelet Transform (DWT) of f(t) and Eq.(5) is the inverse transform. These coefficients represent the change or jump (discontinuity) in the approximations of the signal. Thus it could be used to identify the discontinuity in the signal. It has been found that wt coefficients energy has good agreement to the sensitivity of structural condition of the structure[14]. The k-th wt coefficient energy of the signal at j-th resolution level is calculated as:

$$E_k^j = \int_{-\infty}^{\infty} d_k^j(t)^2 dt \tag{7}$$

And total energy is calculated as:

$$E_s = \sum_{j=1}^{j} \sum_{k=1}^{2^j} E_k^j \tag{8}$$

(2) Damage indices

Since wt coefficient contains information of the signal in a specific time-frequency window, hence the magnitude of the energy could vary quite significantly. As those wt coefficients with small energy magnitude are easily contaminated by the measurement noise, it is preferable to discard them in the analysis. Thus we can de-noise the measured signal by discarding the wt coefficients of small energy. For this we will arrange the coefficient energy of individual wt coefficients according to their descending order. If we assume that cumulative energy of first l wt coefficients constitute greater than (say) 99% of total energy then we will discard the rest of the coefficients. Then from these first l wt coefficients we will reconstruct the signal by applying inverse wavelet transformation. After de-noising and getting reconstructed signal we will again decompose it by wavelet transformation using Eq.(6). Finally we will calculate the total signal energy using Eq.(7) and Eq.(8).

Monitoring of the signal energy will surely give some indication about the structural health condition of the structure. However, for better understating about its health and its successive degradation, damage index is calculated. For this purpose we will need a reference signal. Let us assume that signal from the present condition of the bridge structure is the reference signal. Hence Absolute Difference in Cumulative Energy (ADCE) of any subsequent signal (E_s) from the reference signal (E_s^r) will constitute a damage index ADCE defined as:

$$ADCE = |E_s^r - E_s| \tag{9}$$

Now, damages in the structures are associated with the changes in some structural parameters, namely stiffness, flexibility, damping, mass, eigen frequency. Damages will also affect this damage index ADCE. It is expected that the damage index will tend to increase with increase in damage under similar environmental and loading conditions. However, it should be noted that its not only the structural condition but also the surface roughness, dynamic effects of the vehicle wheels on the bridge and above all; measurement noise will affect the energy and damage index. Hence it is expected that damage indices will vary between different measurements even when the structural loading is unchanged. Thus it requires establishing a threshold value, which will control the damage indices. Any damage index above or outside the threshold value will indicate the presence of damage and vice versa.

Let us assume that q sets of measurements are obtained keeping the structural and loading condition unchanged. Due to the dynamic effects of the vehicle and bridge response along with measurement noise these q sets of measurements are expected to vary between them. After wavelet transformation we can get q sets of ADCEs using the reference signal. A threshold value (Th^{α}_{ADCE}) is calculated from mean and standard deviation of these ADCEs with high probability, say 100(1-α)% defined by Ang and Tang[15] as:

$$Th^{\alpha}_{ADCE} = \mu_{ADCE} + z_{\alpha}\left(\frac{\sigma_{ADCE}}{\sqrt{q}}\right) \quad (10)$$

where Th^{α}_{ADCE} is the threshold value and z_{α} is the value of normal distribution with zero mean and unit variance such that the cumulative probability is 100(1-α)% and q is the sample number.

During monitoring if structural condition remains unchanged then it would have high probability 100(1-α)% that mean ADCE of any subsequent measurements will be bounded by Th^{α}_{ADCE}; otherwise it will fall outside this threshold value. From a set of threshold values at various locations over the bridge structure, a threshold curve was obtained. Thus we can identify the presence of damages in the structure. It is noted that for identification of presence of damage we need to measure the time history displacement of the bridge structure at only one location and hereby reducing the number of measuring sensors. In order to localize the damages (single or multiple) after identifying the presence of possible damage with a high probability we need to have time history displacement at various locations. Similarly, mean damage indices at various locations will be calculated for data measured at various locations. Thus we will have a set of mean ADCEs measured at different locations to obtain a wt based spatial shape curvature of the structure for localizing damages. The curvature can be obtained from central difference approximation as:

$$\overline{ADCE}''_{n} = \frac{\overline{ADCE}_{(n+1)} - 2(\overline{ADCE}_{(n)}) + \overline{ADCE}_{(n-1)}}{x^{2}} \quad (11)$$

where n is the location and x is the uniform distance between consecutive sensors. If the sensors are unevenly distributed, curvature at location n will be obtained as follows:

$$\overline{ADCE}''_{(n)} = \left(\frac{\overline{ADCE}_{(n+1)} - \overline{ADCE}_{(n)}}{x_{(n+1)} - x_{(n)}} - \frac{\overline{ADCE}_{(n)} - \overline{ADCE}_{(n-1)}}{x_{(n)} - x_{(n-1)}}\right) / \left(\frac{x_{(n+1)} - x_{(n-1)}}{2}\right) \quad (12)$$

where $x_{(n)}$ is the spatial coordinate of the nth sensors.

(3) Numerical simulation and results

To demonstrate the suitability of this proposed method over the ordinary curvature method in detecting damages, first this method has been compared with ordinary curvature method from responses both by crawling vehicle load and operating vehicle load. Then the proposed method has applied to other more cases to verify its effectiveness.

Fig.17 compares the methods for damage case5 (relatively small damage) from responses induced by crawling vehicle. Here 20% reduction in EI was applied at single location at 7.5m from bridge end. It is seen that wt based curvature method can identify the damage by clearly distinguishing the peak at 7.5m, whereas ordinary curvature method shows two peaks at 1.5m and 6m. Thus for small damages wt based curvature gives better performance. Fig.18 compares the methods for damage case7 (multiple damages) for crawling vehicle load. Though both methods can identify the damage locations at 7.5m and 20m, wt based curvature method shows better performance as it reduces the false peaks at 3m, 11m and 16m. Fig.19 shows the comparison of methods for damage case2 (relatively large damage) from responses by operating vehicle load. It is seen that wt curvature method can identify the damage location at 12m where EI of local element was reduced by 50%, whereas, ordinary curvature method can not identify damage location at all. Thus from responses either induced by crawling or driving vehicle, wt based curvature method can localize damages than

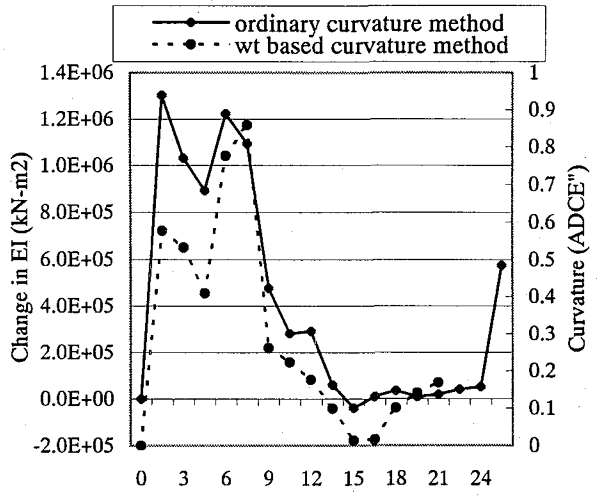

Fig.17 Comparion of ordinary and wt based curvature method for damage case5, damage at 7.5m (V=3km/h)

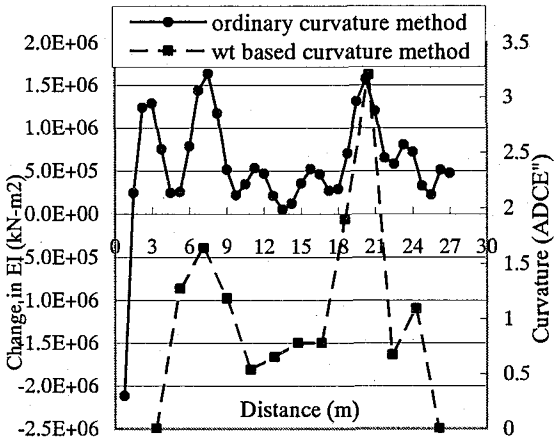

Fig.18 Comparison of ordinary and wt based curvature method for damage case7, damage at 7.5m & 20m (V=3km/h)

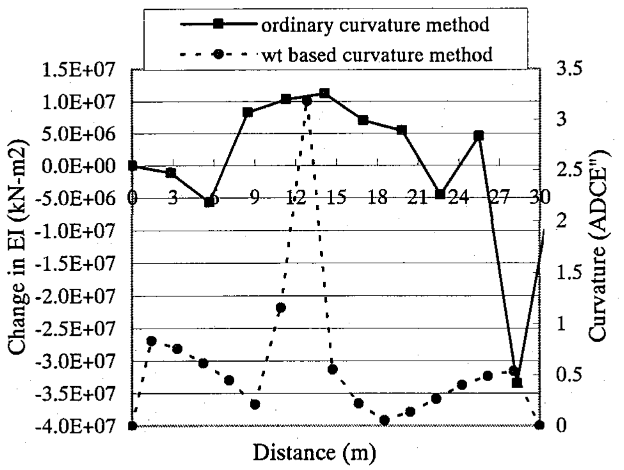

Fig19. Comparison of ordinary and wt based curvature method for damage case2, damage at 12m (V=60km/h)

ordinary curvature method. However, both the methods have limitations in detecting damages at bridge ends because of effects of measurement noises, which is significantly larger than that of responses at bridge ends.

In order to show the effectiveness of proposed wt based curvature method, further a number of simulations were performed on the simulated bridge structure with various damage cases as stated in Table3 with operating (60km/h) vehicle speed. A total of 10 sets of different response data were obtained for each case varying the surface roughness each time. First, time history displacement response data were obtained at sensor locations at 16, 24, 32, 40, 48 when the vehicle moves from one end to other end of the bridge. Each data set was decomposed by wavelet transformation and was de-noised by discarding the coefficients of small energy. By inverse transform the signals were reconstructed and wt coefficients energy were calculated. Then average energy was calculated. Damage index ADCE was obtained by performing the absolute difference from averaged reference signal energy as shown in Fig.20. Damage with 5% reduction in stiffness of element 22 was taken arbitrarily as reference signal assuming this is the present condition of the bridge structure. A threshold curve from a number of threshold values was obtained from the

Table3: Bridge damage cases for response induced by operating vehicle loading at speed 60km/h, (span length 30m)

Damage cases	Damage Node no	Damage location (m)	Damage length (m)	Reduction in EI (%)
Case0				No damage
Case1	22, 44	10 & 22.5	0.5	10%
Case2	22	10	0.5	20%
Csae3	22	10	0.5	30%
Case4	22, 32 & 44	10, 15 & 22.5	0.5 each	40%
Csae5	22, 44	10 & 22.5	0.5 each	50%

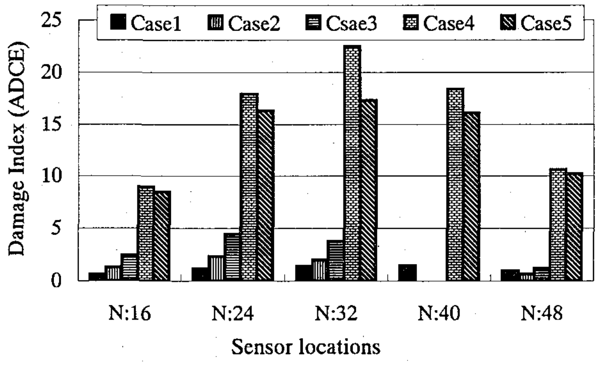

Fig.20 Absolute difference in cumulative energy at various sensor locations (V=60km/h)

reference signal. Threshold values were calculated using Eq.(12). Here sample number q is 10 and z_α value has taken as 2.1 such that if structural condition remains unchanged then it would have high probability, 98% that mean ADCE of any subsequent measurement will be bounded by Th^{α}_{ADCE}; otherwise it will fall outside this threshold value. Here Damage indices were obtained for each damage case at various sensor locations. Fig.21 shows that damage indices for Case1 to Case5 are above the threshold curve. This indicates the presence of damages. It is noted that case1 to Case5 show the increased level of damages. Thus top most line shows the maximum amount of damages among the cases. Case0 falls bellow the threshold curve, which obviously indicates the better condition than the reference condition. Here Case0 stands for healthy condition. Case1 curve is not very much distinguishable from threshold curve and hence does not indicate the presence of damage effectively. This is due to the reason that case1 has very small amount of damage and is affected by the noise. Case4 is also above the Case5 curve because cumulative effects of 40% damage in each three locations at Case4 is more than the cumulative effects

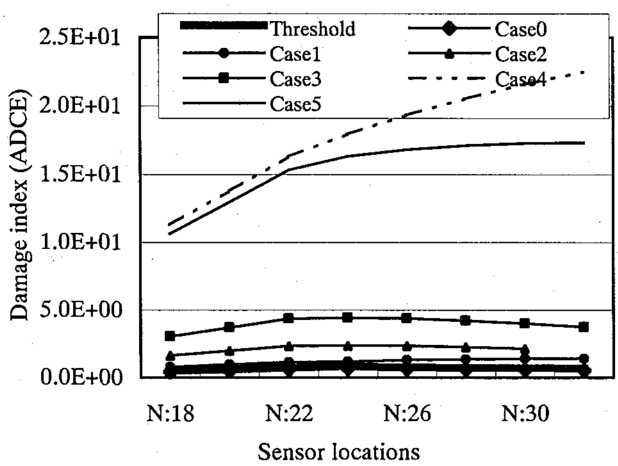

Fig.21 Mean difference in energy in control chart with threshold curve (V=60km/h)

of 50% damage in two locations at Case5.

It is necessary to localize damages in the bridge structures. If we carefully investigate the Fig.20 or if we calculate the slope of the damage indices of consecutive sensor location we can approximately identify the location of damages. Fig.22 shows that slope of indices has a sharp change between N:18 and N:24 for all cases. There is also sharp change in between N:42 and N:48 for Case1, Case4 and Case5. Another sharp change lies in between N:30 and N:36 on Case4. These sharp changes approximately localize the damages.

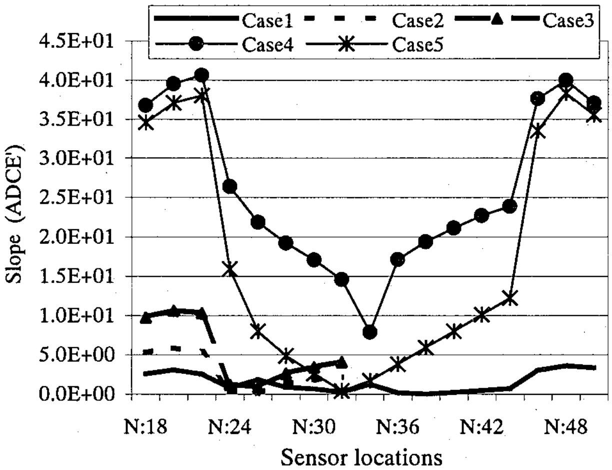

Fig.22 Absolute slope of damage indoces (ADCE') (V=60km/h)

To critically identify damage locations we need to have damage indices at few more locations in those approximately identified damaged regions. Then we will have wt based spatial curvature shapes of damage indices. From the distinguished changes in curvature shape we can identify the location of the damages. Fig.23 shows the damage locations for various degrees of damages with single damage. It is seen that damage as small as 20% reduction in EI at 10m at N:22 can be identified easily. It is difficult to identify very small damages (10% reduction in EI, Case1). Fig.24 shows that there are multiple damages with varying degrees. It is seen from the plot that Case4 has three damage locations at N:22, N:32 and N:44. Case5 has

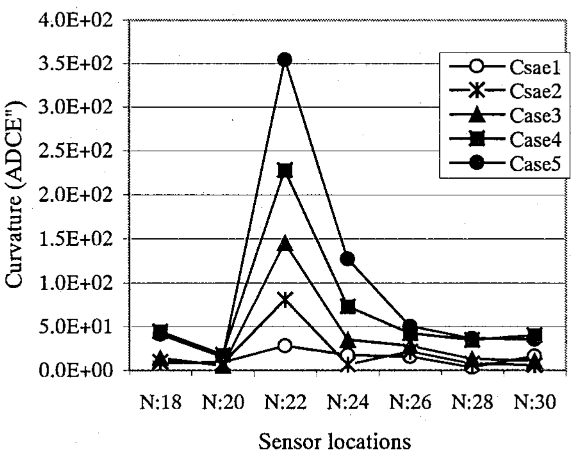

Fig.23 WT based curvature of damage indices (ADCE") at various degree of damages, (V=60km/h)

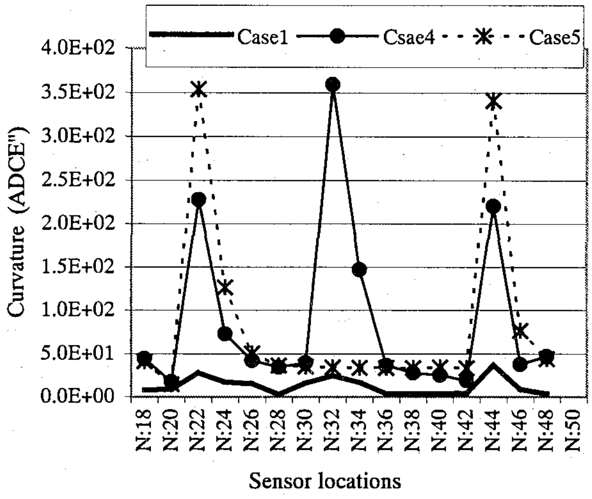

Fig.24 Spatial curvature of damage indices (ADCE") with multiple damages, (V=60km/h)

two damage locations at N:22 and N:44. From the graph it might be interpreted that Case1 has three damage locations at N:22, N:32 and N:44. But actually it had no damage at N:32. This false indication may have come due to the smallness of degree of damages and differentiation from reference signal and also due to presence of large measurement noise comparing the effect of damage.

5. Conclusions

Many structural identification techniques for bridges have been proposed using forced or free vibration data. Modal frequencies can be used to detect damage existence. It usually incurs cost and time to get vibration data, as it requires closing the traffic lanes and heavy instrumentations. So, in case of highway bridges it would have been better if bridge response induced by vehicles could be used without interrupting traffic flow. Therefore, in this paper efforts have been put to identify damages of a bridge structure using vehicle load response. It has been found that ordinary curvature method has potential for detecting relatively large damages (50% reduction in EI) using responses induced by crawling loading. But for relatively small damages (20% reduction in EI), this method does not work well. But wt based curvature method, we proposed in this paper, overcomes this problem as it can localize damage as small as 20% reduction in EI. However, an advantage of using ordinary curvature method over wt based curvature method is that it requires the response to measure at only one location as it employs reciprocal theorem. On the other hand, for responses from crawling loading requires traffic control or a limited closing of the lanes.

Using responses from operating vehicle moving at driving speed does not require closing the traffic lanes. But dynamic nature of displacement response makes it difficult to be useable for health monitoring of bridges with ordinary curvature method. In this context wavelet transformation can be a useful tool for extracting damage information form this time displacement response induced by vehicles at driving speed. The time history of displacement of the bridge structure due to moving vehicles were decomposed and de-noised by wavelet transformation. Then wt coefficients energy and damage indices were calculated. A threshold curve was formed from the reference signal of the structure. Any subsequent damage index having damage(s) will fall outside the range of threshold value. To localize damages a wt based spatial curvature shape was obtained from a set of damage indices. From the sharp changes in curvature shape, damage locations were identified. This method can localize damage as small as 20% reduction in EI.

Thus this wt based damage detection technique can be used as a suitable and cost effecting tool for health monitoring of bridges without having any undamaged information as priori and with small number of sensors. Using of time displacement response of the bridge induced by operating vehicle passing over it will reduce the burden of applying any forced vibration and closing the lanes. This technique can also be integrated with the online bridge monitoring system such that any damage index above the threshold value will give an alarming signal about existing or occurring damages in its service life.

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