Baseline-free damage detection in bridges using acceleration records with the application of Laplacian

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ABSTRACT: Existing damage detection techniques are reliant on monitoring the anomalies in the structure behavior. This requires knowledge of the undamaged baseline structure. This paper introduces a "Baseline-free" damage detection approach that utilizes the acceleration records of the structure to precisely estimate the loci of the damages without the need of using prior data from the structure. The paper investigates the application of Laplacian – second derivative – to the structure measured accelerations in order to localize the damages signature in the measurements. The paper will emphasize on bridges as a case study. The bridge will be damaged with different damage levels and locations to investigate the approach fidelity in quantifying the damage severity and position. First, acceleration measurements from the bridge are evaluated for different cases. Afterward, Laplacian is applied to the amplitudes of these measurements to magnify anomalies within them.

1 DAMAGE DETECTION

Long-life structures, like bridges and large buildings, require continuous inspection and maintenance during their entire lifespan. Researchers have recently focused on developing more efficient and reliable techniques of inspection and maintenance of these structures. For the purpose of evaluating the conditions of a structure, a direct method of using stationary sensors is usually used. These sensors could be fixed to the structure permanently (stationary) or temporarily (mobile). (Marchesiello et al., 2009) experimentally measured accelerations at different points of scaled bridge to extract its dynamic parameters. (Zhou et al., 2016) studied the use of mobile sensors to collect data of vibration of a beam to perform modal analysis. (Matarazzo and Pakzad, 2016) used acceleration sensor networks that can be moved to approximate the mode shape of a bridge for the purpose of health monitoring. (Marulanda et al., 2017) used mobile and stationary sensors to identify mode shapes of a beam. The method was successful even in the presence of noise. (Matarazzo and Pakzad, 2018) used them to identify mode shapes of a beam. The results were verified experimentally.

2 LAPLACIAN

The Laplacian or Laplace operator Δ is a differential operator given by the divergence of the gradient of a function on Euclidean space. It can be used to amplify anomalies in signals. (Ratcliffe, 1997) used Laplacian of mode shapes to identify the location of stiffness damage as little as 10% in a uniform beam. A modified Laplacian was presented for lower damage values. The findings were supported by experiment on a steel beam with a cut. (Besio et al., 2006) adopted using Laplacian to detect differences on concentric electrode elements to measure the potentials of localized brain activities. Laplacian has various definitions depending on the studied case. For a multivariable domain, it is the sum of all the unmixed second partial derivatives of all variables. For example, inside a two-dimensional plan, it is defined by Equation 1.

$$\Delta f = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} \quad (1)$$

For an equation in time domain only, it is defined by Equation 2.

$$\Delta f = \frac{\partial^2 f}{\partial t^2} \quad (2)$$

The used Laplacian in this study will be Temporal Laplacian of Acceleration (TLA), which will be numerically estimated using Equation 3 .

$$TLA \cong \frac{a_{t-\Delta t}-2*a_t+a_{t+\Delta t}}{\Delta t^2} \quad (3)$$

where $a_{t-\Delta t}$, a_t and $a_{t+\Delta t}$ are the accelerations at three successive time steps respectively, and Δt is the length of this time step. Example of using TLA to magnify anomalies in raw signal is illustrated in Figure 1.

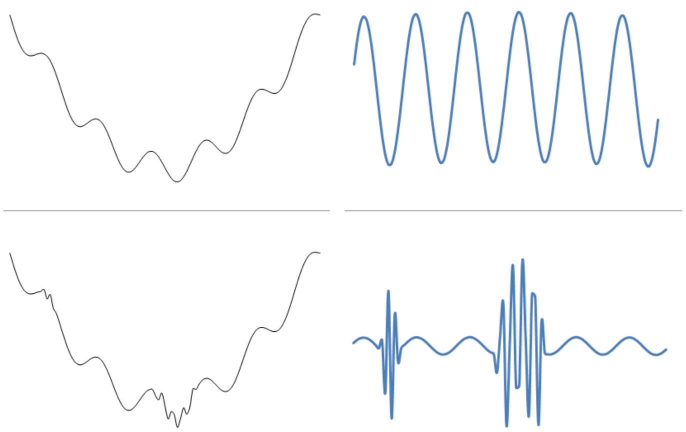


Figure 1. Using of Laplacian (right) to magnify anomalies within raw signal (left).

3 MODELS

3.1 *Bridge model*

The case study for this research, a bridge, was modeled as a simple beam as shown in Figure 2. The bridge has the properties L = 30 m, EI = 5 * 10^5 kN.m^2, m = 0.8 t/m, a vehicle is moving along it with the properties m_v = 2 t, k_v = 800 kN/m, v = 20 m/s. Accelerations are calculated every 0.3 m of the bridge length. These accelerations can be measured using fixed or drone-mounted accelerometers.

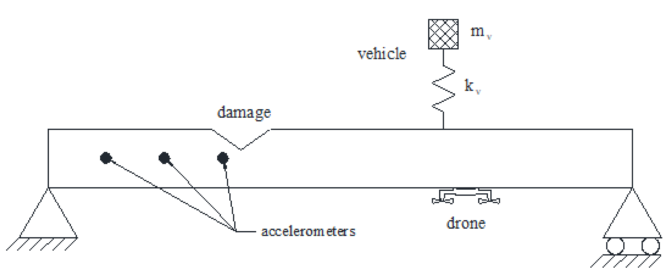


Figure 2. Bridge and vehicle models.

3.2 *Damage model*

The damage was modeled according to (Sinha et al., 2002) as a triangular reduction in stiffness as illustrated in Figure 3. The flexural rigidity close to the damage, $EI_e(\xi)$, is given by the Equations 4.

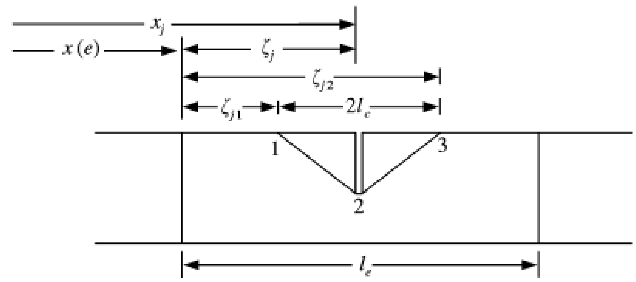


Figure 3. Triangular variation in stiffness used to model the damage (Sinha et al., 2002).

$$EI_e(\xi) = \begin{cases} EI_0 - E(I_0 - I_{cj})\frac{\xi-\xi_{j1}}{\xi_j-\xi_{j1}} & \xi_{j1} \le \xi \le \xi_j \\ EI_0 - E(I_0 - I_{cj})\frac{\xi_{j2}-\xi}{\xi_{j2}-\xi_j} & \xi_j \le \xi \le \xi_{j2} \end{cases} \quad (4)$$

where E is the elastic modulus, I_0 is the moment of inertia of the undamaged beam, I_{cj} is moment of inertia at the jth damage, ξ_j is the location of the jth damage within the eth element, $\xi_{j1} = \xi_j - l_c$ and $\xi_{j2} = \xi_j + l_c$ are the positions on either side of damage where the stiffness reduction begins and l_c is half the length of the damage.

3.3 *Vehicle model*

The vehicle model is shown in Figure 2. The vehicle was modeled as a lumped mass m_v supported on a spring of stiffness k_v moving with speed v.

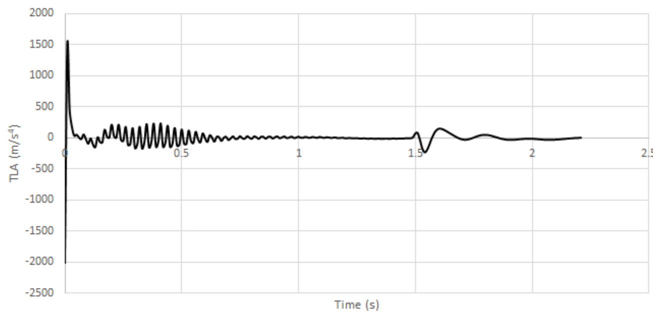
4 EFFECT OF DAMAGE POSITION

Different models of the bridge were simulated; the first one with no damage and the others with 10% damage at 6, 15 and 24 m.

4.1 *No-damage bridge*

Three positions were selected to investigate their acceleration measurements and TLA; at 7.5, 15 and 22.5 m. As shown in Figure 4, TLA values are negligible except at three cases; when vehicle enters the bridge (t = 0), passes near the accelerometer or leaves the bridge (t = 1.5 s). However, for the first and last case, a sudden rise in the value occurs then it fades away very quickly. Clearly, the nearest the accelerometer lies to the entering side, the higher the value becomes for the first case, and the same happens for the leaving side for the last case. On the other hand, when the vehicle passes over the accelerometer, moderate values appears for a quite longer period of time.

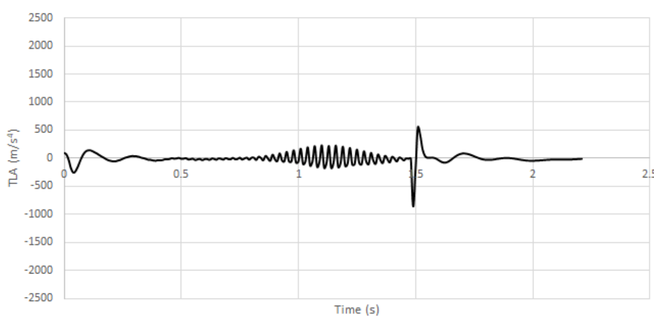
These values are close in values to each other. This big difference can be used to distinguish between the vehicle entering or leaving and its passing at this point. Another useful trait to be used is that the increases due to entering or leaving happen at the same time for all locations, while the passing increase occurs only when the vehicle approaches the accelerometer. By inspecting the maximum values of TLA over

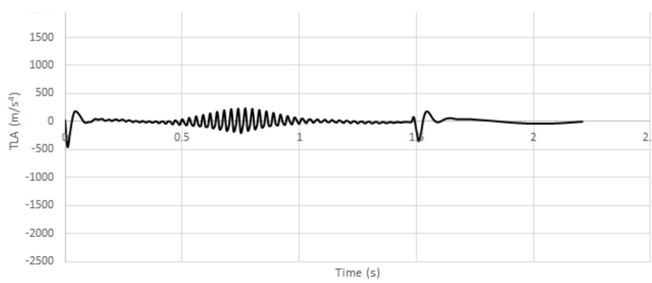


all accelerometers' positions during vehicle entering and leaving, it is noted as shown in Figure 5 that they have their largest values near the respective end of entering or leaving, but not at the end itself.

(a) x = 7.5 m

(b) x = 15 m





(c) x = 22.5 m

Figure 4. TLA for different locations (No damage).

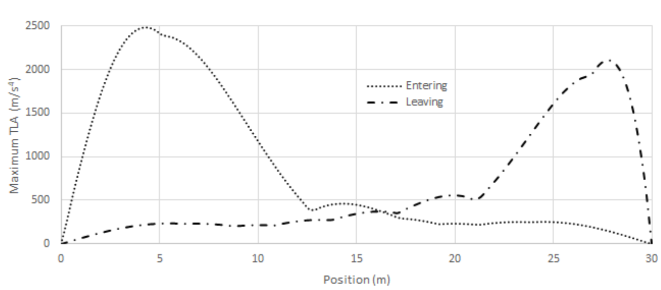
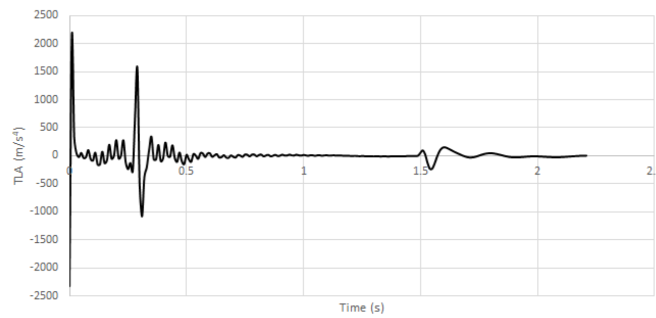


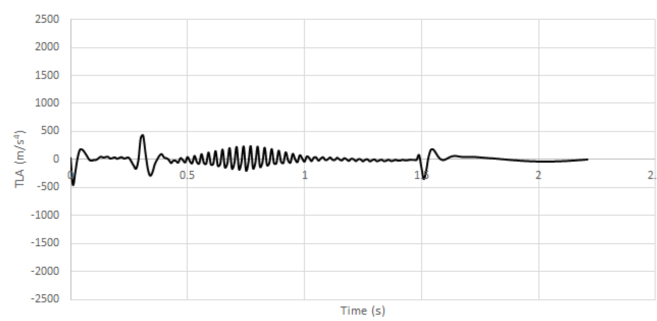
Figure 5. Maximum TLA for vehicle entering and leaving (No damage).

4.2 *10% damage at 6 m*

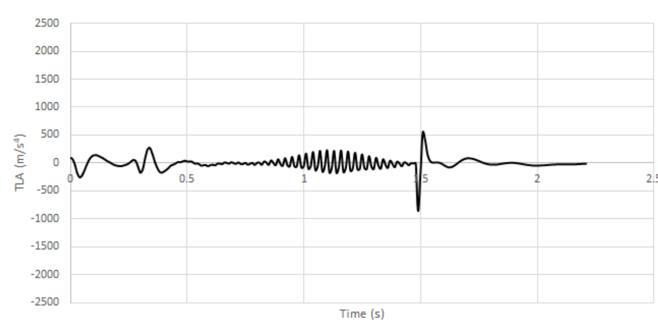
For the first position at 6 m, the same results are calculated except that the accelerometer at the damage position is considered instead of the one at 7.5 m. The values are displayed in Figure 6. A new sudden increase appears when the vehicle passes by the damage location (at t = 0.3 s). This increase appears for all accelerometers' positions. However, by inspecting the maximum values as shown in Figure 7, the highest increase belongs to the nearest accelerometers. The maximum TLA value is at 4.2 m.



(a) x = 6 m



(b) x = 15 m



(c) x = 22.5 m

Figure 6. TLA for different locations (10%-6 m damage).

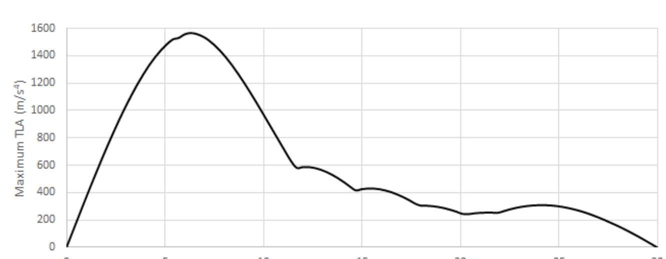
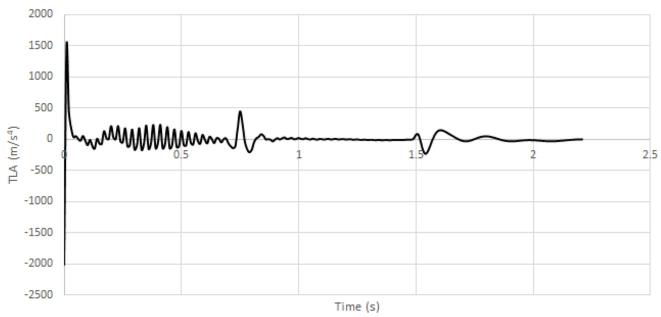


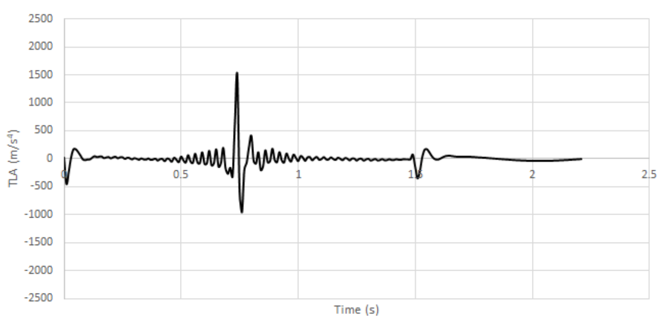
Figure 7. Maximum TLA for vehicle passing by damage location (10%-6 m damage).

4.3 *10% damage at 15 m*

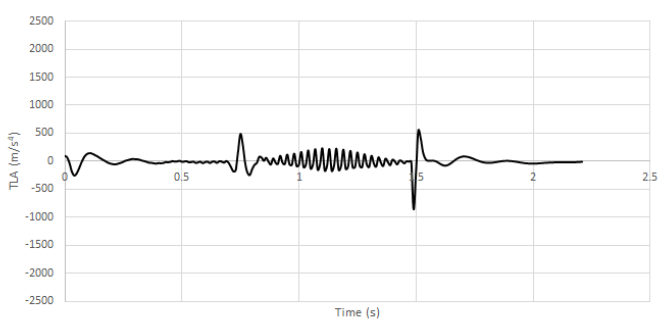
For the second damage position at 15 m, Figure 8 shows that TLA values are similar to the first damage, but the sudden change is now at t = 0.75 s. The maximum values are very close to the first case. Figure 9 displays that the maximum TLA value is at 15.3 m.



(a) x = 7.5 m



(b) x = 15 m



(c) x = 22.5 m

Figure 8. TLA for different locations (10%-15 m damage).

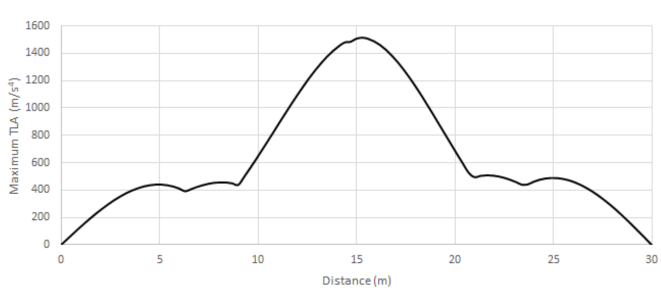
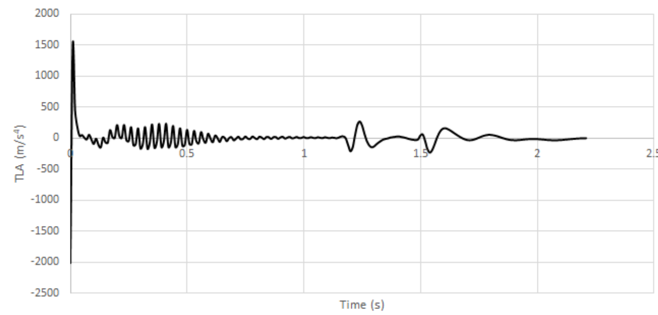


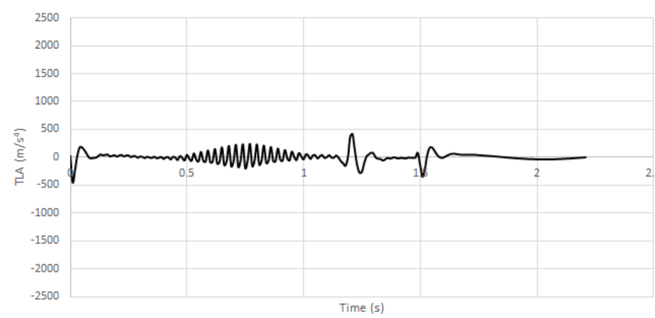
Figure 9. Maximum TLA for vehicle passing by damage location (10%-15 m damage).

4.4 *10% damage at 24 m*

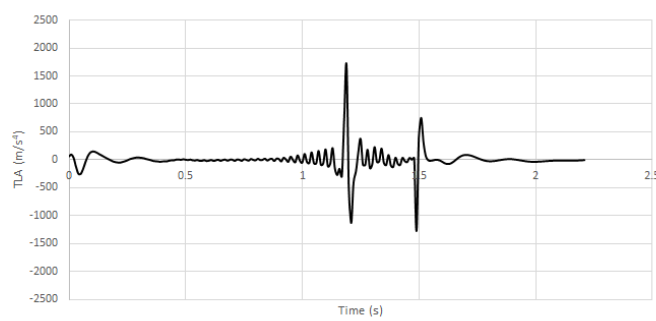
For the third damage position at 24 m with the accelerometer at the damage position is considered instead of the one at 22.5 m. Figure 10 that TLA values are slightly higher, and the sudden change is now at t = 1.2 s. Figure 11 displays that the maximum TLA value is at 24.3 m.



(a) x = 7.5 m



(b) x = 15 m



(c) x = 24 m

Figure 10. TLA for different locations (10%-24 m damage).

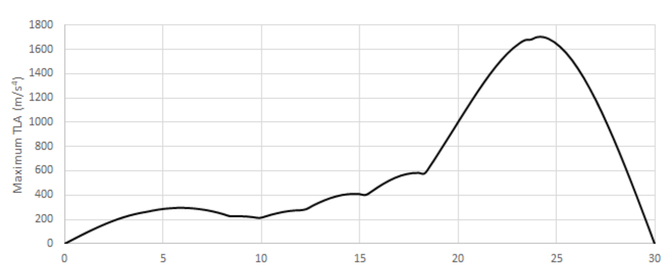


Figure 11. Maximum TLA for vehicle passing by damage location (10%-24 m damage).

5 EFFECT OF DAMAGE LEVEL

For the damage at 15 m, different damage levels were inspected and the maximum values of TLA for near-middle accelerometers are collected in Table 1. Obviously, the value increases with the increase of the damage level. This can be used as an indication of how severe the damage is.

Table 1. Max TLA values for different damage levels.

Damage Level	1%	10%	30%	50%
Max TLA (m/s^4)	464	1516	2914	7002

6 CONCLUSION

This study inspected a method of using Laplacian of accelerometers' measurements to estimate the damage location and level of a bridge. The results showed that using a small number of accelerometers, without the need to have any previous knowledge about the bridge's condition, the location of damage can be estimated. The closer the accelerometer to the damage location, the higher the disturbance value appears. The measurements can be used to determine the vehicle position and the sudden increase in the values can be used to pinpoint the damage as the vehicle passes by it. As all the accelerometers can, to a certain degree, feel the presence of the damage, flying drones with accelerometers can be used to inspect different locations of the bridge based on the measurements they get from each passing vehicle to lock on the damage location. This method showed also good sensitivity towards the damage level, so as the calculated values increase, a higher damage level is expected.

7 ACKNOWLEDGMENTS

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