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RESEARCH ARTICLE

A Systematic Approach to Filter Specification for Measuring Quasi-Static Bridge Rotation Under Moving Loads Using DC Accelerometers

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ABSTRACT Low-cost, DC micro-electromechanical systems (MEMS) accelerometers can be employed to provide a mechanism to capture the relatively small levels of rotation typically seen on some bridges allowing their structural response to be measured. The effect of ambient vehicle traffic loads crossing the bridge can offer a cost-effective, less disruptive alternative method for continuous bridge structural health monitoring (BSHM). However, utilising moving traffic loads to assess the quasi-static structural behaviour is more challenging as the measured sensor data contains additional signal components due to the dynamics of the vehicle-bridge interaction system. To overcome this challenge, this paper presents a simplified approach for the specification of an appropriate filtering scheme to extract the desired quasi-static bridge response based on only the bridge’s geometry and the vehicle speed. The originality of the method proposed herein lies in its wide applicability and extensibility due to its basis on the widely accepted principles of bridge influence lines. For both BSHM researchers and practitioners alike, the significance of the proposed method lies in its systematic approach, thus helping to unlock the potential for long-term monitoring of bridge quasi-static response under ambient traffic loading. The approach is demonstrated through its successful application in a field trial on an in-service highway bridge.

INDEX TERMS Finite impulse response filters, bridge structural health monitoring, quasi-static bridge rotation extraction, DC MEMS accelerometers, bridge influence lines, practical bridge rotation measurements.

I. INTRODUCTION

Effective management of changing bridge structural condition over time is a key challenge for infrastructure owners to ensure the safe and uninterrupted operation of these assets. This challenge is exacerbated by the relatively large numbers of bridges in our transport networks, currently 84,000 highway bridges in GB. Coupled with the increasing pressures on both budgets and resources, in part due to these assets’ increasing age, e.g. a backlog of maintenance works on GB bridges was estimated in 2022 to require £5.9bn to address [1]. Conventionally, the management of short- to medium-span bridges, i.e. those with individual span lengths $< 100\,\text{m}$, relies on periodic visual inspection by engineers, but its accuracy has been questioned, both generally [2] and specifically for bridges [3]. Thus, an effective and reliable means of monitoring structural performance using data obtained from low-cost sensors in real-time is needed, to either remove or supplement the qualitative, subjective and occasionally unreliable human element of conventional approaches [4]. Bridge structural health monitoring (BSHM) techniques, which can be broadly viewed as seeking to detect changes in structural condition by tracking changes in sensor data over time, offer a potential avenue to help address the challenge of managing bridge condition by augmenting existing resource-intensive qualitative inspection routines with quantitative data.

Many different BSHM approaches have been proposed utilising various structural response measurements such as

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strain, acceleration, or displacement. These approaches can be broadly classified based on whether the load-response behaviour being analysed can be described using either statics, which depends only on structural stiffness, or dynamics, where the effects of inertia and damping must also be considered. Static responses obtained from strain [5], [6] can identify damage close to the sensor, whereas static response captured via displacement [7], [8], [9] theoretically will be affected by damage anywhere in the deck, albeit displacement is typically harder to measure on site. Bridge rotation response is also affected by damage both near and far from the sensor but it is easier to measure than displacement. Hence, more recently, rotation [10], [11], [12], [13] has been explored as even the relatively small levels of rotation typically seen on a typical short to medium span bridge, can be measured using low-cost DC micro-electromechanical systems (MEMS) accelerometers.

The extracted quasi-static rotation response can provide valuable insights into the health status of the bridge. Specifically, changes in the amplitude, shape, or timing of the rotation response over time can indicate changes in the bridge's structural stiffness, which may be caused by damage or deterioration. For example, an increase in the maximum rotation amplitude under similar loading conditions could suggest a reduction in the bridge's stiffness, potentially due to cracking, corrosion, or other forms of damage. Additionally, shifts in the timing of the peak rotation relative to the vehicle position on the bridge could indicate changes in the load distribution characteristics, which may be caused by support settlement or bearing failure. By monitoring these parameters over time and comparing them to baseline measurements or expected values based on the bridge's design, engineers can detect and assess changes in the bridge's health status, enabling targeted inspections and maintenance interventions.

A key practical challenge to obtaining these quasi-static rotation responses is to filter out the unwanted signal components due to bridge and vehicle dynamics, as well as sensor noise. This represents an important issue as engineers will be faced with customising a solution for each individual bridge as configurations will vary. A viable solution that would therefore allow the engineer to quickly fit their solution to a new configuration would be a key step to allow easier BSHM. Existing ad hoc filtering approaches used by other SHM researchers have several limitations, such as limited applicability to different bridge types, the need for manual tuning, and a lack of theoretical foundations. These limitations make it challenging to develop reliable and efficient methods for extracting quasi-static bridge responses from sensor data. To address these limitations, herein, we present a systematic method that allows a BSHM researcher or practitioner to specify a suitable filter to extract quasi-static rotation based on minimal information about the bridge under test's geometry and the expected on-site traffic. The proposed method aims to overcome the drawbacks of existing approaches and provide a more robust and theoretically grounded solution.

This method is based on the widely accepted principles of bridge influence lines (ILs), which relate the magnitude of a particular structural response at a given location (e.g. mid-span displacement) to the location of a nominal 1 kN point load, from which the response for any static loading scenario can be obtained by superposition. Hence, the method comprises the following steps: (1) An approximate IL for the desired structural response is obtained using a simple line-beam model, which requires only the bridge geometry; (2) A synthetic bridge response signal is generated by convolving the approximated IL with a train of point loads, which are chosen to represent the on-site traffic; and (3) A finite-impulse response (FIR) filter is designed using least-squares linear-phase FIR filter design method by using an optimisation algorithm to tune the filter parameters.

The main contributions of this paper are:

- Development of a novel method that utilises approximated bridge influence lines to systematically specify appropriate filtering schemes for extracting quasi-static bridge responses from sensor data under ambient traffic loading, requiring only minimal information about the bridge geometry and expected traffic conditions;
- Validation of the proposed method through a successful field trial on an in-service highway bridge, demonstrating its effectiveness in extracting quasi-static bridge rotation responses under real-world conditions without the need for controlled load tests or extensive prior knowledge of the bridge's properties.

The remainder of this paper is structured as follows: Section II outlines relevant literature on bridge rotation monitoring and describes the specific challenge this work addresses. Section III sets out our proposed approach for extracting bridge quasi-static response based on approximated bridge ILs. Section IV presents results of applying the proposed bridge quasi-static response extraction method to a field trial on an in-service highway bridge. A discussion of this paper's results and recommendations for future work are provided in Section V. Finally, Section VI concludes this paper.

II. BACKGROUND AND CHALLENGE OF BRIDGE SHM USING ROTATION

The concept of measuring rotation to infer the condition of a piece of civil infrastructure, not just specifically for bridges, has been around for some time. For instance, tilt has long been used to study the movement of structures such as retaining walls and buildings [14], [15]. These rotations are commonly measured using instruments known as tiltmeters or inclinometers. Functionally, both terms refer to instruments for measuring an angle with respect to gravity (vertical level), however, the term tiltmeter tends to be more specifically used in certain fields, such as geotechnical engineering, for measuring this angle (tilt) of the ground or structures such as retaining walls. The basic operating principle of most inclinometers is that of measuring changes in a system consisting of a pendulum, which is constantly being righted by gravity, as the system undergoes external rotations.

Inclinometers have been used to estimate bridge deflections, for example, [16] showed that for both an experimental model and full-scale highway bridge that fibre optic deformation sensors and electric inclinometers could retrieve the vertical displacement field of a beam to within an error of 8% compared to an absolute hydrostatic levelling system. A bridge testing procedure based on tiltmeter measurements [17] was applied on a real bridge, and the results indicated that this method could be applied to obtain vertical displacements of bridges as an alternative to the use of conventional displacement transducers. A pilot study [18] used inclinometers to measure the deflection of a bridge built by a balanced cantilevering method with a reconstruction technique based on pre-calculated deflected shapes of the structure as polynomial functions. On a different bridge, [19] showed that inclinometers were able to quantify the behaviour of the structure in spite of the presence of extreme temperature related movements (daily amplitude of displacements exceeded 40 mm).

Reference [20] also proposed using inclinometers to estimate bridge deflections, noting that the reference-free nature of the measurement makes it more practical for wider deployment, e.g. for bridges over railways or highways. The method was validated for both static and dynamic deflections using laboratory-scale and full-scale tests. Using inclinometers and strain gauges, [21] showed that polynomial functions can be used to estimate bridge deflections, with the procedure tested on a prestressed concrete beam and two full-scale bridges built using the balanced cantilever method. Reference [22] proposed using similar inclinometers along with a placement optimisation method to calculate dynamic bridge deflections on a full-scale high-speed railway bridge. Reference [23] proposed using fibre optic-based tiltmeters to measure the rotation of a bridge beam and then reconstruct the elastic curve under traffic loading.

More recently, gyroscopes have been used for measuring bridge deformation. Reference [24] used gyroscopes alongside traditional DC accelerometers and used sensor fusion (Kalman filtering) to obtain an optimised rotation response. The method was trialled on both a laboratory scale model and full-scale bridge.

A. BRIDGE SHM USING ROTATION MEASUREMENTS

More recently, there has been increased focus on measuring the transient bridge rotation responses due to vehicle crossings, which is largely enabled by the improved performance, at lower costs, of modern DC MEMS accelerometers that offer sufficiently high sampling frequencies to accurately capture the fast varying responses during vehicle crossings, particularly on shorter span structures. However, the measured acceleration response will contain not only the desired quasi-static rotation, but also sensor noise, and dynamic rotation and linear acceleration components, which arise from the vehicle and bridge dynamics.

The work which specifically proposes damage detection methodologies using rotation measurements can be categorised as either: (a) rotation influence line approaches, and (b) rotation-based bridge weigh-in-motion approaches, with each of these described presently.

1) ROTATION INFLUENCE LINES

An influence line plots a measurement of how a static response (e.g. midspan displacement) would vary if a unit point load was positioned at any point on the beam [25]. An IL can be used to characterise a structure's static response, as the response under any static loading condition can be obtained by a linear combination of values from the IL (cf. superposition principle of linear time-invariant systems). Therefore, the rotation IL, which characterises the static rotation response of a given point on a structure, is useful as a change in the IL would infer a change in the structure, i.e. the potential presence of damage. These rotation ILs can be measured directly using a vehicle of known weight [26] and have been used in some studies to infer both the existence and location of damage in a structure. References [27] and [28] proposed an approach for damage detection of beams using flexural rigidity estimation based on rotation ILs, where the rotation was measured at the supports using chequer board targets which were tracked using computer vision. Whilst the authors showed damage detection and localisation in spite of noise, the laboratory scale demonstration uses a simply supported slender steel bar which showed levels of rotation around 3.5 mrad kN^{-1}, which is more than an order of magnitude greater than the level of rotation one would expect on a simply supported bridge span. Hence, based on the measurement approach and the magnitude of rotation simulated, it is very hard to infer how this approach would perform on a realistic full-scale bridge structure.

Reference [12] proposed the difference between rotation ILs obtained for both healthy and damaged states to detect and localise damage, using the bridge response for a vehicle of known weight. This work showed that for a simply supported bridge that the most effective sensor locations are over the supports, as this corresponds to the locations with the maximum rotation amplitudes. Laboratory-scale experiments [13] on a 5.4 m simply supported beam structure showed the difference of rotation ILs approach could detect damage as low as a 7% loss of stiffness over 2.5% of the span length. Reference [29] proposed a similar damage detection approach based on the difference between rotation ILs in pre- and post-damage conditions, using simulations and laboratory tests.

2) ROTATION-BASED BRIDGE WEIGH-IN-MOTION

Rotation-based bridge weigh-in-motion, e.g. [30], has been proposed by some authors as a means for detecting damage. The approach presented by [10] was based on the overestimation of vehicle weights by a rotation-based bridge weigh-in-motion system following damage. It showed that there is statistical repeatability in the tandem weights of five axle vehicles which can be used for bridge damage detection and that the level of sensitivity of rotation to damage is related to the distance of the measurement from the location of the damage. They proposed to address this issue by placing one inclinometer at each end of the bridge. Separately, [11] proposed the same approach as [10], but instead used two axle vehicles as the fluctuation form of their axle weight time history is more simple to analyse.

Thus far, the prevailing approach in BSHM for extracting the quasi-static rotation component has involved ad hoc filtering schemes.

For example, in [13], the researchers used a low-pass filter with a cut-off frequency of 0.5 Hz to remove the higher frequency/dynamic content of the raw acceleration signals. In [12], both a low pass filter, and a moving average filter are used to extract the quasi-static rotation, but no specific parameters are given for either. Some authors [24], have also proposed using Kalman filters with sensor fusion of accelerometer and gyroscope data.

B. CHALLENGE

The major limitations of these existing ad hoc filtering approaches are as follows:

1) **Limited applicability:** These methods are not readily applicable to nuances of different bridges;
2) **Manual tuning:** These approaches often require domain expertise and expert judgement in their specification and implementation, introducing the risk of human errors;
3) **Lack of theoretical foundations:** To date, approaches for extracting quasi-static bridge rotations have been empirically driven, making it difficult to validate their effectiveness.

To address these limitations, herein, we present a systematic method that allows a BSHM researcher or practitioner to specify a suitable filter to extract quasi-static rotation based on minimal information about the bridge under test's geometry and the expected on-site traffic.

III. QUASI-STATIC BRIDGE RESPONSE EXTRACTION METHOD

To demonstrate the concept of quasi-static bridge rotation response under moving vehicle loads, consider the example of a 2-axle vehicle crossing a 20 m long bridge, which is illustrated in Figure 1(a). Specifically, the bridge has been modelled as a simply supported, 20 m long Euler-Bernoulli beam with unit flexural stiffness, with the 2-axle vehicle modelled as two point loads spaced 4 m apart and magnitudes 16 kN and 26 kN for the front and rear axles, respectively.

At each point in the vehicle's crossing, there exists a configuration of axle loads with respect to the beam, that can be solved using statics. To illustrate this, consider the three vehicle positions (P1–P3) shown in Figure 1(a). Each

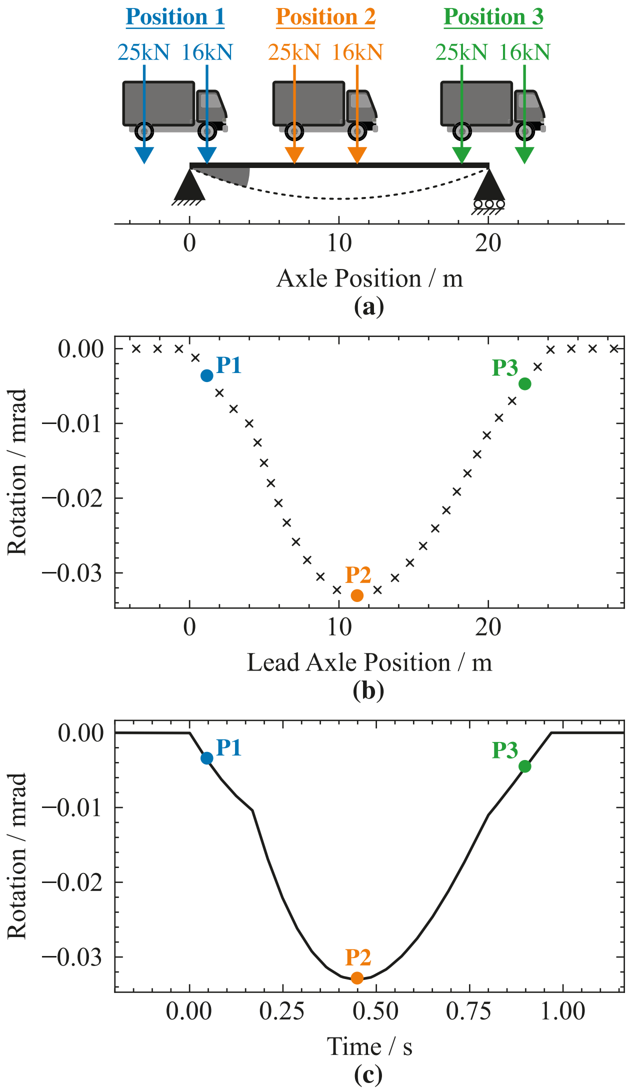


FIGURE 1. **(a) Illustration of simply supported beam with three positions of crossing vehicle shown. Plots of (b) left hand support rotation against lead axle position; and (c) left hand support rotation over time.**

vehicle position results in a given rotation value, which would be measured at the sensor, where the rotation values for positions P1-P3 are indicated using blue, orange and green dots respectively in Figure 1(b). From these points we can see an increase in rotation when the load comes on to the bridge (P1), with the largest value occurring when the truck is near mid-span (P2) and a decrease in rotation as the truck approaches the right hand support and leaves the bridge. The small 'X' data markers in Figure 1(b) are just infilling the rotation values for intermediate truck position. In all cases the rotation value is plotted with respect to the position of the front axle, and the convention of anticlockwise rotation being positive is followed.

The data markers in Figure 1(b) are plotted as if the truck was stationary at each given location and the corresponding rotation was recorded. However, when considering rotation extracted from DC accelerometer data where the truck is moving, this can be simply viewed as transforming the abscissa from axle positions to time, which will depend on the vehicle's speed, and has been shown in Figure 1(c) for a speed of $25\,\mathrm{m\,s^{-1}}$.

The method proposed herein offers a systematic approach to extracting the quasi-static component from bridge response data, where this data will typically also contain unwanted components such as bridge dynamics (natural/modal frequencies), vehicle dynamics, road profile noise, and sensor noise. To address the limitations associated with the conventional ad hoc filtering schemes used by other SHM researchers, our method is based on using approximated bridge ILs to obtain the appropriate filtering scheme for a particular bridge, which permits a systematic, and verifiable, approach to be adopted when monitoring a variety of bridge structures. The proposed method is intended to be easily deployed by any SHM researchers and practitioners with only the bridge's geometry and assumed vehicle speeds and headways needed to generate an appropriate filtering scheme.

A high-level overview of the method is provided in Figure 2, with a more thorough description of each stage provided subsequently.

(A) Approximating Bridge ILs: An IL for the desired bridge quasi-static response is first obtained using a simplified, analytical model based only on the bridge geometry.

(B) Bridge Response Synthesis: The approximated IL is then used to generate a synthetic bridge response signal by convolution with a loading function intended to minimic on-site traffic.

(C) Filter Specification: Finally, a filtering scheme is designed based on the estimated frequency spectrum with the aim of only leaving the minimal amount of frequency content associated with the bridge quasi-static response.

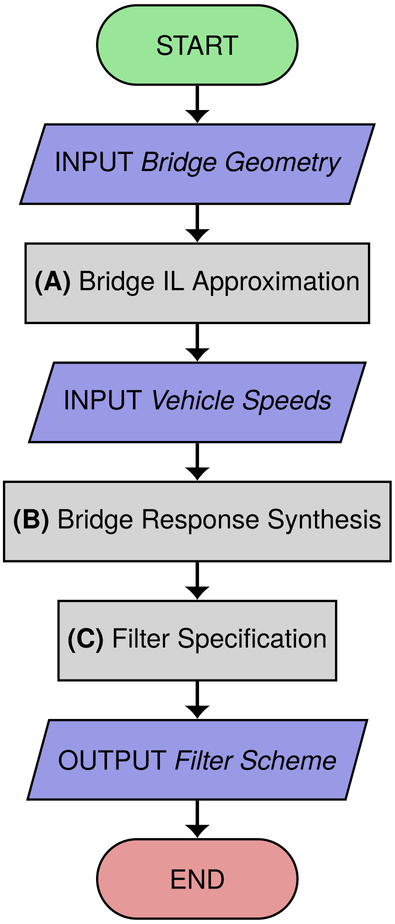


FIGURE 2. High-level method overview flowchart.

A. APPROXIMATING BRIDGE INFLUENCE LINES

A bridge IL represents how a unit load moving across a bridge affects the bridge's response at a given point on the bridge. These ILs can represent the effects on physical quantities such as deflection, bending moment, or shear, however, in this work which is focused on BSHM applications, these will be displacement, rotation, and strains, which cover the most common, directly measurable bridge responses. Thus, the influence line, IL(x), is defined as the bridge response arising from a unit load located at the point, x, along the bridge's length (L), where $0 \leq x \leq L$.

Typically, accurate bridge ILs are obtained either using finite element analysis, or by directly measuring them using a load test with a vehicle of known weight [26]. These methods are often computationally expensive and require extensive information about the bridge's construction, material properties, boundary conditions, as well as the load distribution applied to the structure.

Our alternative method approximates the IL based on a simple analytical (Euler-Bernoulli) line-beam model shown in Figure 3, where the only parameters needed are the bridge's span geometry and support conditions. This approximation can be used as for our purpose of obtaining the IL's spatial frequencies; it is the overall shape of the IL that is most important, not the precise magnitudes. However, should an accurate IL for the desired bridge response be available for the structure under test then the subsequent steps of our method can be followed using this IL instead.

To model the bridge, the span lengths, as well as the support conditions ('pin', 'roller', or 'fixed') should be specified. To illustrate this, two common forms of highway bridge have been modelled, specifically a 34 m long single span conventional bridge, which is modelled as a 'pin-roller' single span beam (Figure 3(a)), and a 57 m long two-span integral bridge, which is modelled with fixed end supports and a pin to represent the pier (Figure 3(b)). Assuming the structure's Young's Modulus (E) and second moment of area (I) are isotropic along it's length, then these can be set to values estimated based on engineering judgement without affecting the rest of the procedure. If, however, there was a variation in these properties, then this can be achieved by defining the line-beam in a piece-wise fashion to account for this. Subsequently, the bridge's deflection (Δ) and rotation (θ)

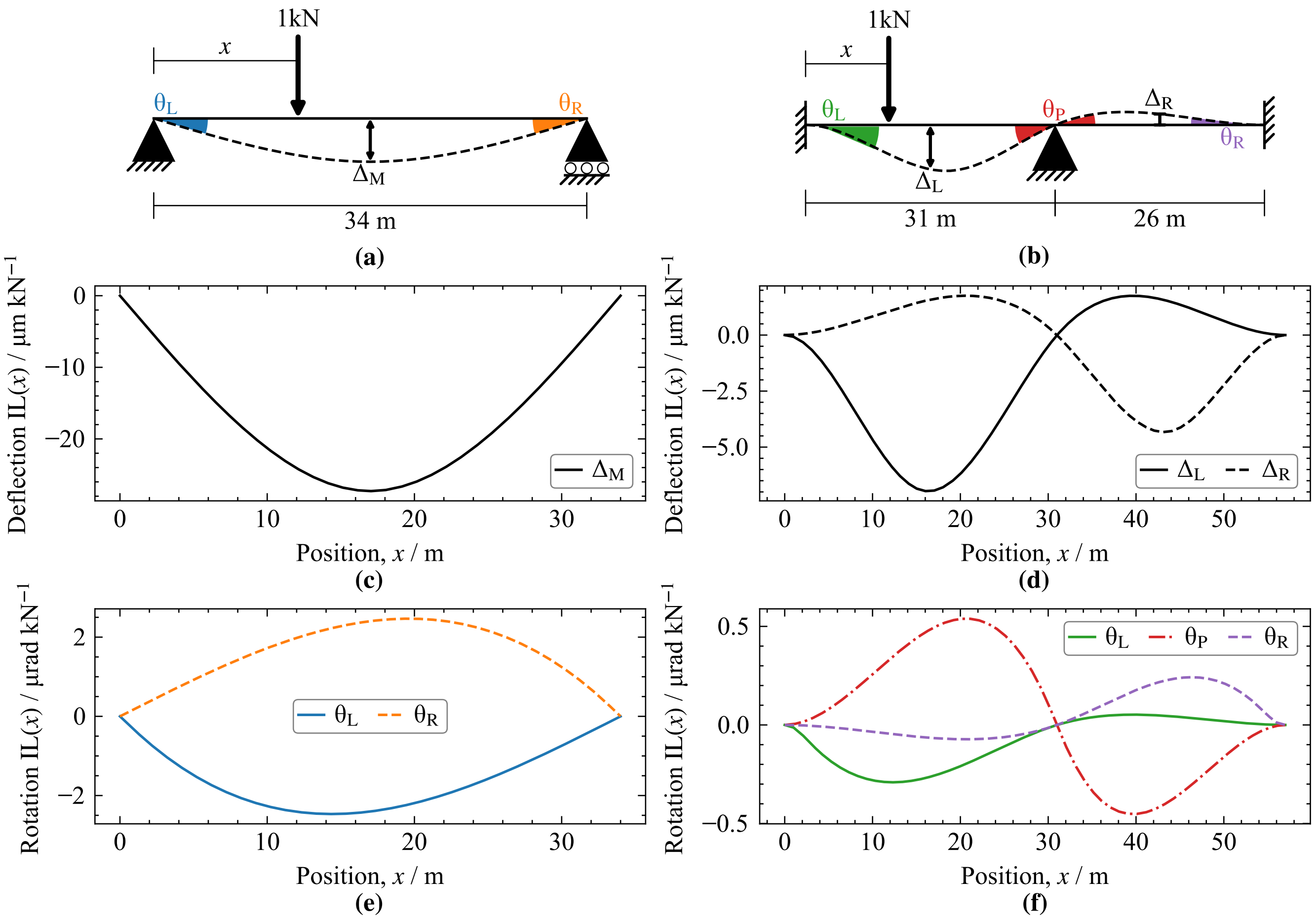


FIGURE 3. Sketches of line-beam approximations of (a) a single-span bridge and (b) a two-span integral bridge. Plots of deflection influence lines for (c) single-span bridge and (d) two-span bridge; and rotation influence lines for (e) single-span bridge and (f) two-span bridge.

can be obtained by computing the bending moment (M) and solving the Euler-Bernoulli beam equation [31]:

$$\frac{d^2\Delta}{dx^2} = \frac{d\theta}{dx} \approx \frac{M}{EI}. \tag{1}$$

The approximated bridge IL, IL(x), can therefore be obtained by solving Equation 1 for the desired structural response (i.e. displacement, Δ, or rotation, θ) with a 1 kN point load located at position, x. The ILs for single-span bridge's midspan deflection (Δ_M) are plotted in Figure 3(c), where it can be seen that, as expected, the maximum deflection is observed when the 1 kN point load is located at the midspan, whereas for the two-span bridge (Figure 3(d)), the maximum midspan deflections (Δ_L, Δ_R) occur with the load positioned closer to the middle support. The single span bridge's rotation ILs for rotation at the left and right supports (θ_L and θ_R) are plotted in Figure 3(e) with anticlockwise rotations taken as positive, where it can be seen that the maximum rotations occur with the load closer to the corresponding end of span as opposed to occurring with the load at mid-span. Similarly, for the two span bridge, the rotation ILs for the left and right supports (θ_L and θ_R) and for the pier (θ_P) are plotted in Figure 3(f).

B. BRIDGE QUASI-STATIC RESPONSE SYNTHESIS

To allow an appropriate filter to be specified to extract the quasi-static response from noisy sensor data, first we must estimate the frequency content of this component. To do this, the approximated IL is used to generate a synthetic bridge quasi-static response time series by a convolution process. This involves convolving the approximated IL, IL(x), with a loading function, $F(t)$, as the load moves along the bridge.

By assuming the load velocity is an arbitrary function of time, $v(t)$, the position of the train of loads can be obtained as the integral of the velocity function with respect to time, i.e. :

$$x(t) = \int_0^t v(\tau)d\tau. \tag{2}$$

The response, $r(t)$, can therefore be obtained by:

$$r(t) = \int_{-\infty}^{+\infty} \mathrm{IL}(x) \cdot F\left(\int_0^t v(\tau)d\tau - x\right) dx. \tag{3}$$

To model typical highway traffic, these loading functions can be constructed by first generating a sequence of vehicles with a given set of axle weights and spacings, and then forming the loading function as a series of point loads, where the

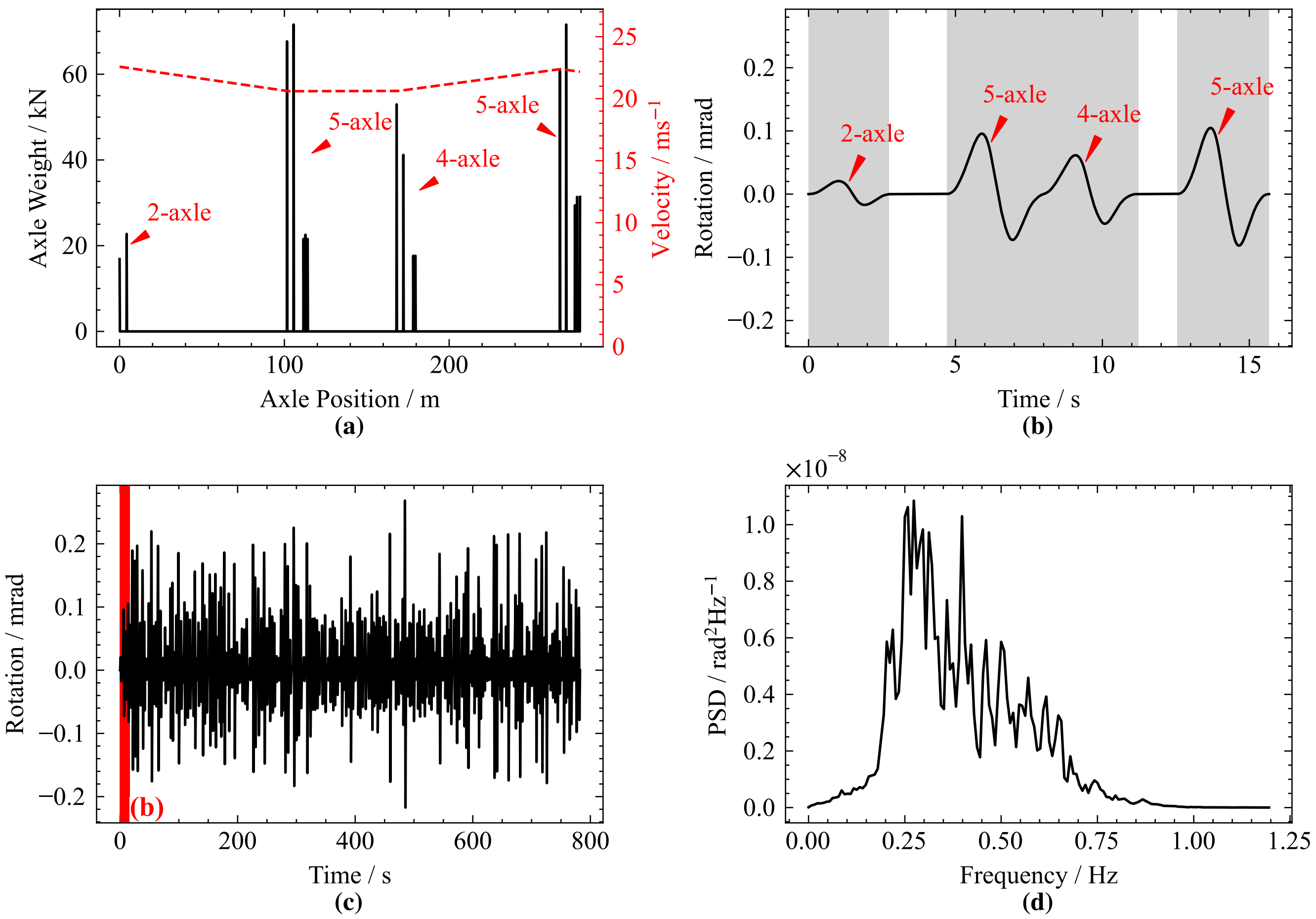


FIGURE 4. Plots of (a) loading function plotted as axle weight versus axle position for three vehicles, (b) corresponding synthesised quasi-static bridge rotation response, (c) longer example of calculated quasi-static bridge rotation time-series, and (d) corresponding frequency spectra for pier rotation.

magnitude of the point load equals each axle's weight and its position is relative to the start of the loading function.

To ensure these vehicle axle weights and spacings are realistic, these are sampled from records in a publicly available weigh-in-motion dataset [32], which ensures these are representative of typical highway traffic. Figure 4(a) plots the loading function for a sequence of four vehicles, which are constructed into a train of point loads with a randomly generated headway between each vehicle, as well as having a random velocity profile applied.

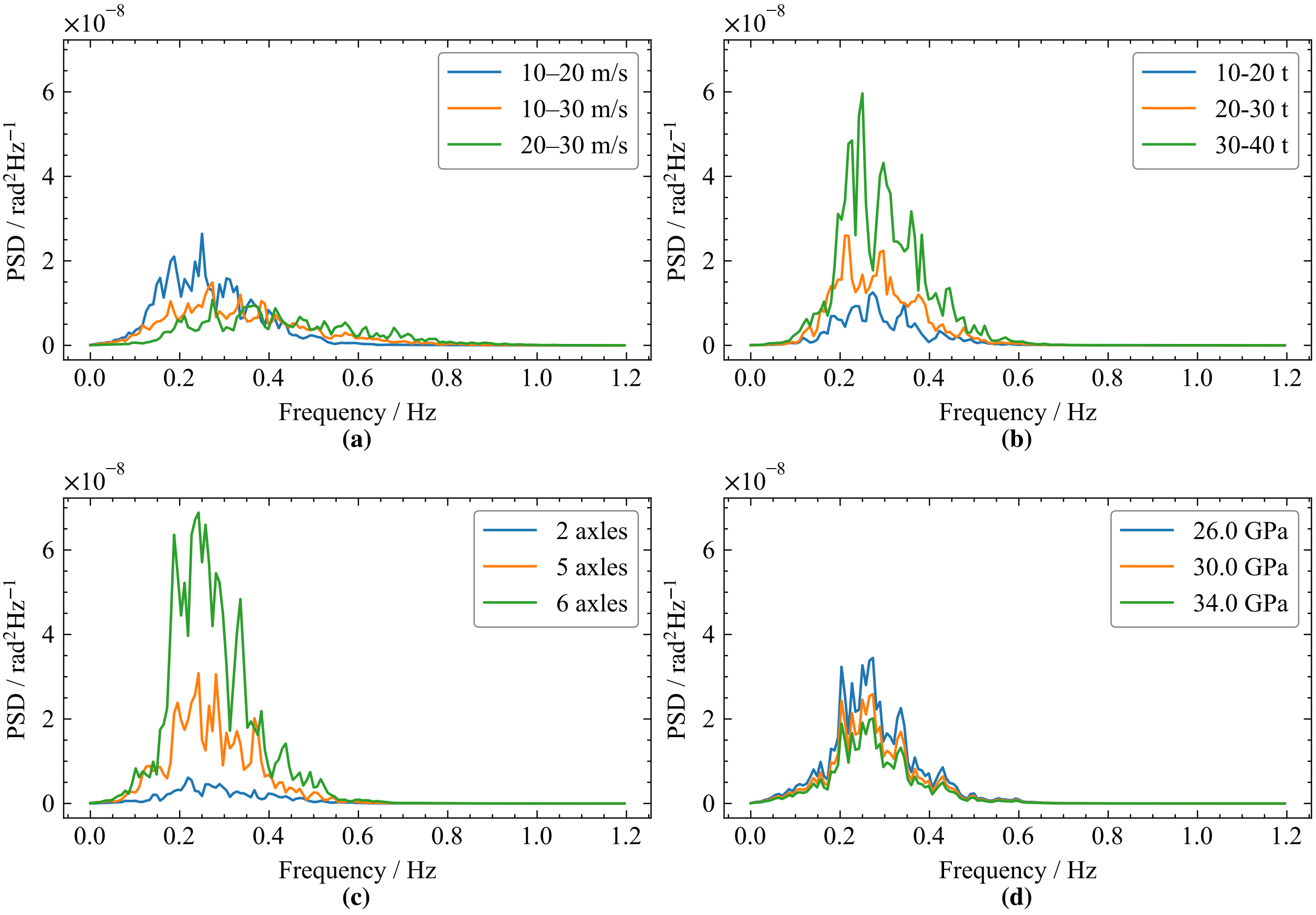
This loading function is then convolved with the approximated bridge ILs for rotation at the pier of the two-span integral bridge in Figure 3(f). The calculated quasi-static rotation response is shown in Figure 4(b) for the pier rotations.

Using longer loading functions permits synthesising longer bridge response time-series as illustrated in Figure 4(c), which is generated from 200 vehicle crossings with varying axle counts, weights, and spacings for random speeds in the range $20\,\mathrm{m\,s^{-1}}$ to $25\,\mathrm{m\,s^{-1}}$. Finally, the estimated frequency spectrum for the quasi-static bridge rotation response for the given vehicle parameters (range of speeds and headways) is obtained using by applying calculating the FFT of the longer synthesised reponse from Figure 4.

To demonstrate the effect of varying conditions on the frequency spectra of the quasi-static rotation response, in Figure 5, the effects of varying vehicle weights, speeds, vehicle classes, and bridge stiffness are demonstrated.

Specifically, Figure 5(a) shows that for the same 200 vehicles of any axle count (i.e. having 2-6 axles), that varying the vehicle speed ranges has the effect of shifting the quasi-static response's frequency content. Figure 5(b) plots the frequency spectra for three different gross vehicle weight ranges, using 200 vehicles of any axle count (i.e. 2-6 axles) and speeds in range ($10\,\mathrm{m\,s^{-1}}$ to $20\,\mathrm{m\,s^{-1}}$), which as expected shows that increasing vehicle weights increases the magnitude of the quasi-static response. Similarly, Figure 5(c) shows the effect of different vehicle classes (axle counts) on the quasi-static rotation frequency spectrum. In this plot, it can be seen that the frequency spectrum magnitudes are scaled, which is expected given that increasing axle counts have higher expected gross vehicle weights.

Finally, to demonstrate the effect of varying environmental conditions, which in the context of statics largely concerns the



(a) (b) (c) (d)

FIGURE 5. PSD plots of synthesised quasi-static bridges responses with (a) varying vehicle speeds, (b) varying vehicle weights, (c) varying axle counts, and (d) varying Young's modulus.

inverse relationship between temperature and material stiffness (Young's modulus, E). Figure 5(d) plots the quasi-static rotation frequency spectra for the same 200 vehicles of any axle count and speeds in range ($10\,\mathrm{m\,s^{-1}}$ to $20\,\mathrm{m\,s^{-1}}$) where the Young's modulus has been varied over a range that would be typical for reinforced concrete under a range of temperatures. From this plot, it can be seen that changing Young's modulus values has the effect of inversely scaling the magnitude of the frequency spectra, although the magnitude of this change is relatively small.

C. FILTER SPECIFICATION

Extracting the quasi-static rotation component from noisy accelerometer data necessitates an effective filtering scheme, which can be achieved using the estimated quasi-static response frequency spectrum. This could be done by manually designing a filter based on estimating the frequency content of the desired quasi-static response as described in the previous section. However, in this work, we wished to automate the process of specifying the filter, as far as reasonably possible, as this allows BSHM practitioners, who might not be as familiar with filter design to develop filters to extract quasi-static bridge rotation response in a repeatable and verifiable fashion.

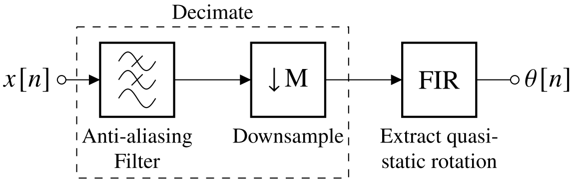


FIGURE 6. Digital signal processing block diagram of quasi-static rotation extraction filter scheme.

To achieve this, we employ a two-stage filter scheme (Figure 6), where the first stage decimates, i.e. downsamples and anti-alias filters the raw acceleration signal ($x[n]$), and the second stage applies an FIR filter to the decimated signal to extract the quasi-static rotation signal, $\theta[n]$. The decimation stage is used as DC accelerometer data often has an overly high sampling rate (e.g. over 1 kHz) compared to the relatively low frequencies of the quasi-static rotation response, which allows for a more efficient FIR filter (e.g. with fewer taps). The FIR filter is designed and implemented using the linear-phase FIR filter design by least-squares method [33, pp. 54–83], and

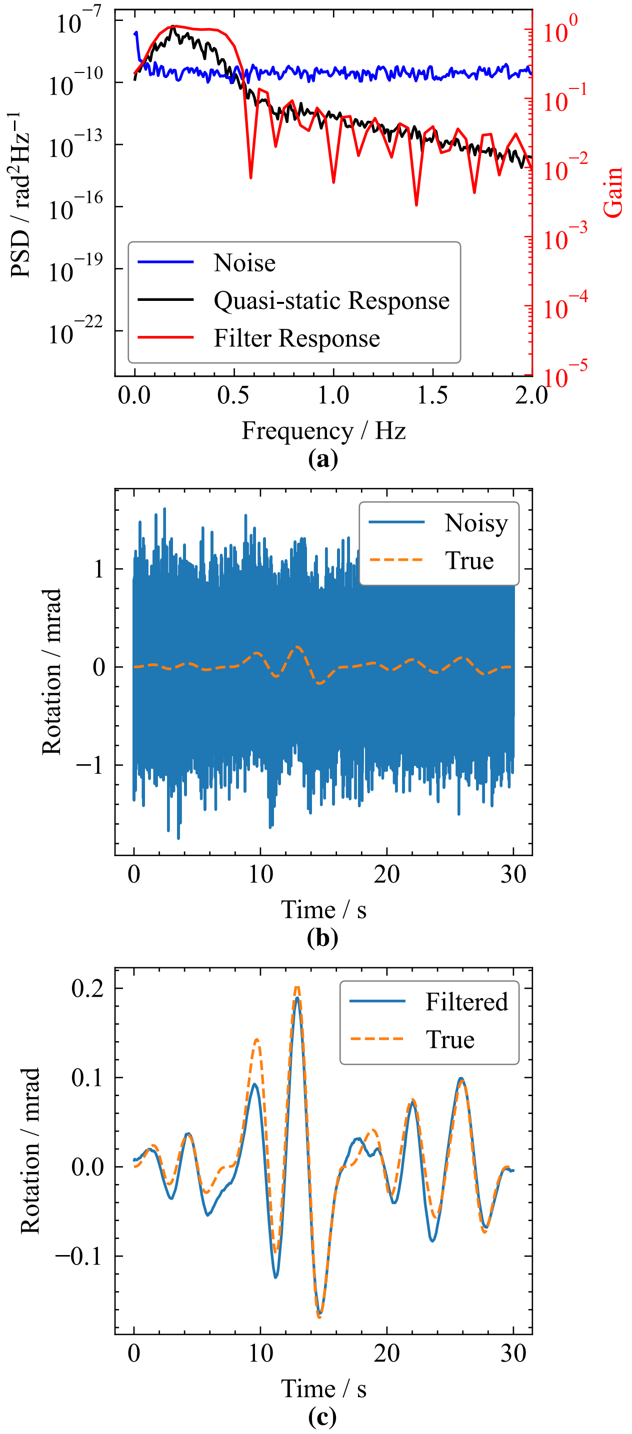


FIGURE 7. Plots of (a) estimated quasi-static response frequency spectrum, noise spectrum, and optimised FIR filter response, (b) true and noisy synthesised quasi-static bridge rotation responses, and (c) true and filtered quasi-static bridge rotation response.

was implemented using the `firls` method from the SciPy Python library [34]. Furthermore, these are linear-phase filters meaning all the frequency components are delayed by the same amount, thus avoiding any distortion of the waveform shape of the extracted quasi-static rotation response.

This involves defining both the filter order/number of taps, and the pass and stop bands over the estimated frequency spectrum, which are shown in Figure 7(a). The trade-off in these choices is between the amount of ripple present, the filter order (which increases the computational cost of the filter), and the sharpness of the transition bands.

To allow an automated selection of appropriate parameters for this filter scheme for extracting the quasi-static bridge rotation response, we carry out an optimisation over the following parameters: (1) decimation factor of the first stage, as well as (2) pass/stop band edges, and (3) number of taps in the FIR filter. The loss function which is minimised by the optimisation process is defined by the root mean square error (RMSE) between a 'true' quasi-static rotation response, seen in Figure 7(b) and the result of filtering the result of adding noise to this true signal to account for sensor noise. A combination of white noise to account for broad spectrum noise such as thermal noise, and Brownian noise to allow for low frequency drift are added. Specifically, the standard deviation of the white noise is equal to the true signal's amplitude, and the Brownian noise's standard deviation is set to 5% of the amplitude of the true signal with the noise spectrum plotted in Figure 6(a) and the resulting 'noisy' signal shown in Figure 7(b).

The resulting optimised FIR filter response can be seen in Figure 7(a), which was found to have decimation factor of 24, pass band from 0.06 Hz to 0.5 Hz and 301 taps, with an initial sampling frequency of 1024 Hz. An example of applying this filter to the synthetic noisy bridge rotation response data is shown in Figure 7(c), and overall this filter is estimated to have an RMSE of 18.3 µrad.

D. SUMMARY

The methodology described here provides a simple, yet systematic, approach to allow the specification of appropriate filtering schemes to capture quasi-static bridge rotations under moving loads whilst requiring only minimal information, namely bridge geometry and assumed vehicle speeds. This permits the quasi-static component to be extracted from bridge response data despite the presence of other signal components such as bridge and vehicle dynamics, road profile noise, and sensor noise. This is justifiable as the signal measured by a DC accelerometer on a bridge under moving loads comprises, in addition to the quasi-static component and sensor noise, a number of other frequency components, specifically these are: (A) bridge natural vibration frequencies arising from the vibration modes of the bridge structure, (B) vehicle body frequencies based on the dynamics of the vehicle's mass with the stiffness and damping of the suspension system, and (C) road profile noise from the mechanical interaction between vehicles' rolling tyres and the surface roughness of the pavement [35], [36]. Our approach is based on the reasonable assumption that the quasi-static response sufficiently separated in the frequency domain from (A)–(C), and it is not dominated by the sensor noise within its frequency range.

FIGURE 8. Photograph of elevation of single-span bridge.

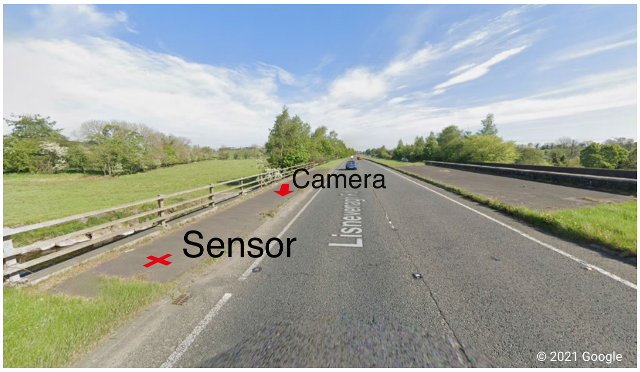


FIGURE 9. Photograph of northbound approach to bridge showing sensor and camera locations.

The proposed approach involves firstly approximating a bridge IL for the desired structural response for which we describe a simplified model using only the bridge's geometry and support conditions, thus avoiding the resource-intensity of obtaining these via fine-grained FE analysis or carrying out load tests. Secondly, the approximated IL is used along with a loading function, which is sampled from real-world weigh-in-motion data to be representative of the ambient traffic flow expected on-site, to synthesise a time-series for the desired quasi-static bridge rotation response. Finally, a filter is automatically specified by an optimisation routine, where the RMSE between the synthetic quasi-static bridge rotation response and a filtered noisy version of this response is minimised.

This method offers a systematic and verifiable, yet simple, approach to extracting bridge quasi-static rotation under moving loads that can be tailored to varying bridge structures and is intended to be user-friendly for both SHM researchers and practitioners.

IV. FIELD TRIAL

To validate the proposed method for extracting quasi-static bridge response, a field trial on a conventional highway bridge has been carried out under ambient, free-flow traffic conditions, and hence includes typical levels of noise due to bridge and vehicle dynamics, as well as road profile and sensor noise.

This field trial was carried out on the bridge shown in Figure 8. The bridge is a single 34 m span, pre-cast, reinforced concrete beam and slab bridge supported on elastomeric bearings, which carries the Northbound carriageway, whilst the Southbound traffic is carried separately on an adjacent masonry arch bridge. For the test, a single JAE JA70-SA triaxial MEMS accelerometer was used to measure the rotation at the Southern end of span (where the Northbound traffic enters the bridge), as indicated in Figures 8 and 9. The sampling frequency (1652 Hz) was chosen based on the minimum available on the NI 9234 DAQ used for the test. The data collected consisted of approximately 20 min of DC acceleration signals under typical free-flow highway traffic. A camera positioned at the Northern end of span was used to record traffic crossing the bridge as shown in Figure 9.

This bridge has the same geometry as the example single-span conventional bridge used in the previous section, with the line-beam approximation produced in Figure 10(a), where the measurement of interest in the rotation at the left hand support (θ_L) with the corresponding approximated IL shown in Figure 10(b). To match on-site traffic conditions, a quasi-static rotation time-series was synthesised using a random train of 100 vehicles with speeds in the range $22\,\mathrm{m\,s^{-1}}$ to $25\,\mathrm{m\,s^{-1}}$ (approximately 50-55 mph) and headways between 2.0 s to 4.5 s. Given the short duration of the test, it was assumed that the traffic conditions and environmental conditions were consistent throughout. The magnitude and phase response of the optimised FIR filter are plotted in Figure 10(c). After optimising the filter parameters, the filter chain had a decimation factor of 24, and an FIR filter with 301 taps and a passband from 0.02 Hz to 0.85 Hz, and an estimated RMSE of 12.8 µrad.

The result of applying this filter chain to the measured DC acceleration to extract quasi-static rotation for two truck crossings is shown in Figure 11 with the raw recorded acceleration data plotted in Figure 11(a) and the extracted quasi-static rotation response shown in Figure 11(b). The first peak in Figure 11(b) was due to a five axle tanker lorry and has an amplitude of approximately 70 µrad. A snapshot of the lorry has been included in Figure 11(c), however, unfortunately due to heavy rain during the test this is partially obscured by water droplets on the camera's lens. The second peak has an amplitude of approximately 220 µrad resulting from the crossing of a six axle bulk feed lorry (Figure 11(d)).

Similarly, from the raw acceleration data plotted in Figure 12(a), in the extracted quasi-static rotation response (Figure 12(b)), four truck crossings are seen, which had amplitudes of approximately 100 µrad, 50 µrad, 40 µrad and 30 µrad. Specifically, these are a four axle car transporter lorry (Figure 12(c)), a four axle tipper truck (Figure 12(d)), and two rigid body trucks (Figure 12(e-f)). Whilst the truck's weights are not known accurately, based on the engine tone of truck 2 (six axle), the truck appeared to be heavily laden. If so, the quasi-static rotation amplitude observed (approximately

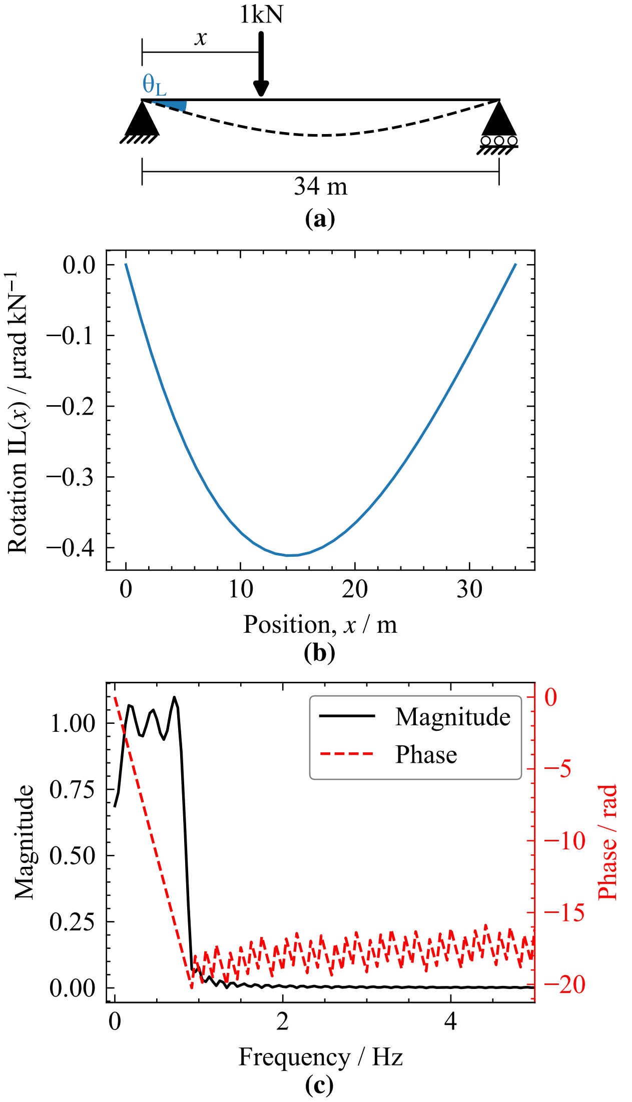


FIGURE 10. (a) Sketch of the line-beam approximation, and plots of (b) estimated influence line, and (c) FIR filter magnitude and phase response.

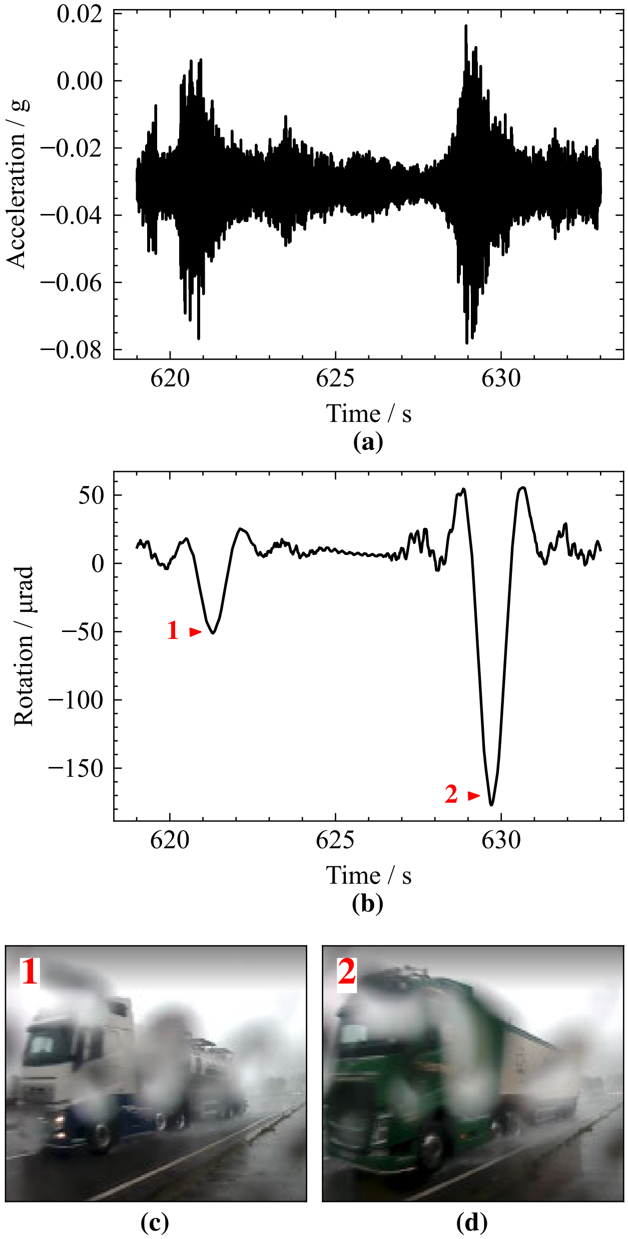


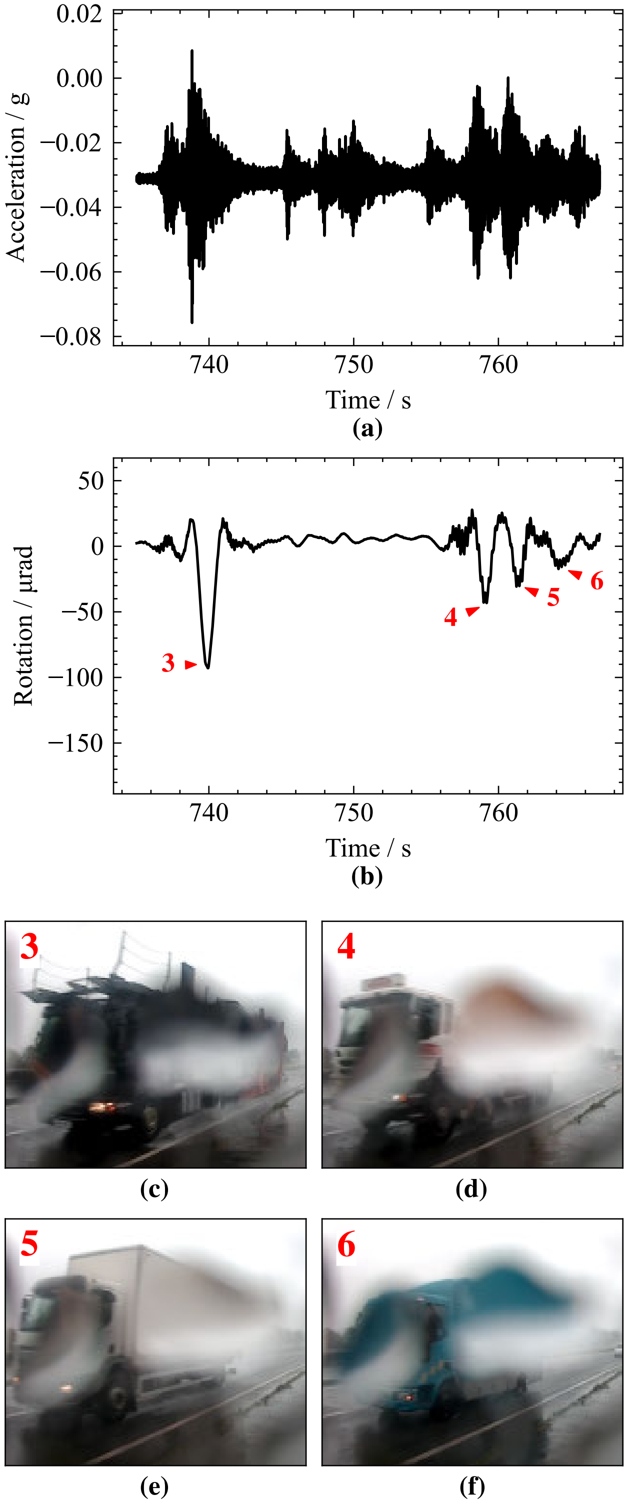
FIGURE 11. Plots of (a) raw acceleration signal and (b) extracted quasi-static bridge rotation response. (c) and (d) Pictures of vehicles corresponding to annotated transients 1 and 2, respectively.

220 µrad) matches well with a finite-element (grillage) model prediction for a fully laden six axle truck (44 t gross vehicle weight).

V. DISCUSSION

The work set out in this paper forms part of the larger ROSEHIPS project (pbshm.ac.uk), which aims to harness the potential of population-based SHM by looking at data across populations of structures, focusing not only on refining the methods required for population-based SHM, but also by advancing the autonomous embedded systems for the acquisition and analysis of structural sensor data. To this end, this paper presented a method which enables SHM researchers or practitioners to easily devise suitable filtering schemes. These filter schemes are specifically tailored for instrumenting and recording quasi-static rotation on common bridge structures, thereby simplifying the process and improving the overall effectiveness of data gathering, which is crucial to expanding the knowledge base of bridge population data.

Whilst the results shown in this field trial are promising, the limitations of this work include the dependency on the accuracy of the approximated ILs and the assumption of consistent traffic patterns over time. To make the method more readily applicable to medium and long-term bridge monitoring, where traffic flows might vary over the course of the measurement period (for example, due to a speed restriction, or during poor weather), as future work, we intend to look at the development of an adaptive filtering system



(a)

(b)

(c)

(d)

(e)

(f)

FIGURE 12. Plots of (a) recorded raw acceleration data and (b) extracted quasi-static bridge rotation response. (c-f) Pictures of vehicles corresponding to annotated transients 3-6, respectively.

to overcome this limitation. This system could be designed a priori to have a precomputed filter bank, each tailored to specific vehicle types, weights, and speeds. Through integration with the broader BSHM system (which incorporate vehicle detectors or classifiers) the system could dynamically adjust the filter parameters in real-time, responding to the live traffic conditions observed on the bridge.

VI. CONCLUSION

This paper presented an approach for extracting quasi-static bridge rotation responses under moving loads. This proposed method is intended to facilitate the development of long-term bridge monitoring systems leveraging ambient traffic loading by offering a systematic means of extracting quasi-static response without conventional controlled load tests, thus streamlining the monitoring process.

Our approach is based on utilising bridge ILs, which can be readily approximated with simplified line-beam models. This method offers a systematic approach for more easily designing filters to extract quasi-static bridge rotations, as it relies only on basic bridge geometry and traffic speed parameters that are readily obtainable in advance. By simplifying the filter design process and requiring only minimal input parameters, this approach ensures that the method can be more rapidly adopted by BSHM practitioners and researchers for a wider range of bridges. The efficacy of our method has been validated by a field trial on an in-service highway bridge, which showcased the method's potential to extract quasi-static bridge rotations from data measured under ambient, free-flow traffic.

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