Exploring the Use of Bicycles as Exciters and Sensor Carriers for Indirect Bridge Modal Parameter Estimation

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Abstract. Indirect Structural Health Monitoring (iSHM) for bridges typically utilises motorised vehicles. This project explores the feasibility of using bicycles as exciters and sensor carriers for identifying bridge modal parameters. Using field-gathered data, the visibility of bridge characteristics in the moving sensor data is demonstrated using data gathered simultaneously from the moving bicycle and the subject bridge. A comparison is made to bridge dynamic properties estimated from other loading types. The possible pollution of recorded signals due to human-bicycle interaction dynamics is considered. The concept of exploiting pedalling harmonics to enhance the response amplitude of specific bridge modes of interest is introduced.

Keywords: Crowdsourcing · Bicycle · Bridge · Modal · Indirect sensing · Human-structure interaction

1 Introduction

Bridge damage can be conceptualised as a change in modal mass, stiffness or damping. The damage may not be apparent during traditional visual inspections, and changes in bridge modal parameters arguably only have meaning relative to a known ground truth initial state. Thus structural system identification (estimating the modal parameters) at an early stage post-construction is valuable alongside ongoing monitoring. Confounding is introduced by the class of effects collectively termed Environmental and Operational Variation (EOV) - these can create spurious changes to estimated modal parameters, obscuring or preventing damage visibility, or create false positives. To counter the effects of EOV, in the absence of identified signal features which are EOV-insensitive and damage-sensitive, or distinguishable from EOV-induced artefacts by some robust method, it is necessary to undertake continuous monitoring of both the structure and its environment to gather a data set spanning the full scope of expected operational conditions [1].

The benefits of early and continuous monitoring, considered alongside the cost of sensor network installation and maintenance, and data transmission, storage and processing, establish an economic challenge. Mobile sensing paradigms

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offer a clear potential advantage here, allowing sensors to roam across multiple bridge structures in a transport network. Economic benefits are compounded if the sensing and transmission networks can be effectively outsourced to citizens or private companies - an approach known as crowdsourcing. The use of human-propelled vehicles such as bicycles as sensor carriers is inherently amenable to crowd-sourced data gathering, since many notionally identical vehicles will naturally traverse multiple bridge structures during normal operation, and suitable sensors can be easily mounted (for example in bicycle hire schemes increasingly seen in urban environments worldwide).

The authors propose that sensors mounted on human powered vehicles, such as bicycles, could be employed for in-service indirect estimation of bridge modal properties. Although it is intuitive that bridges carrying non-motorised traffic can suffer from the same damage-related and EOV issues as highway bridges, there has been very limited study of the use of alternative vehicle types as sensor carriers. Quqa et al [2] report a study in which bicycle-mounted smartphones were used to estimate bridge frequencies and operational mode shapes, and experiments by Yang et al [3] featured hand-pulled carts acting as sensor carriers. Otherwise, research in this field to date generally relates to motorised vehicles (cars, buses, trucks) on highway road bridges. Nevertheless, it is recognised that new paradigms will be required to enable the realisation of indirect bridge monitoring - see for example the paper by Gkoumas et al [4] which discusses the future application of fleets of autonomous vehicles for this purpose.

The authors believe that a rigid-frame bicycle (non-suspended) with pneumatic-tyred wheels can be abstracted as a single degree-of-freedom sprung mass model. Such a model was the subject of pioneering work by Yang and Lin in their 2004 paper [5]. They considered the coupled interaction of this vehicle model with a simply-supported beam and showed, in closed analytical form, that bridge modal frequencies would be visible in the vehicle response (and vice versa).

The current work proposes that pedalling acts as a harmonic input force acting on the lumped vehicle mass. The use of harmonic excitation in moving vehicles for the purpose of bridge modal parameter estimation was explored by Zhang et al [6]. Through numerical simulation and laboratory-scale experiment they sought to extract estimates of mode shape squares, hypothesising that these would be sensitive to damage. They observed more accurate results when the exciting vehicle's harmonic load frequency was close to, but not equal to, the frequency of the structural mode being studied, thus avoiding resonance.

This paper presents the results of field tests combining direct and indirect monitoring of a bicycle/pedestrian traffic bridge subject to heel drop impacts and to traversals by bicycle. The bridge deck and the bicycle frame were instrumented with wireless accelerometers, simultaneously transmitting data to a common data logger during the traversals. The tests included multiple traversals, allowing the confounding effects of road surface profile roughness to be countered by ensemble averaging. The testing regime included traversals with and without pedalling in order that the effects of harmonic load variation due to pedalling dynamics could be identified.

2 Methodology

2.1 Assumed Theoretical Model

The rider-bicycle system is abstracted as a two-axle sprung mass system with a harmonic oscillator providing a time-dependent driving force during pedalling. The accelerometer is mounted on the bicycle frame approximately centrally between the axles and thus it is assumed that the vertical motion of the combined system can be approximated as a single degree-of-freedom sprung mass with force, as shown in Fig. 1. In this figure, u_1 is the vertical displacement at the sensor location; m_3 is the wheel mass; m_2 the fork mass; and m_1 the mass of the rest of the bicycle and the rider combined. k_1 is the effective spring stiffness of each tyre. E_1I_1 and E_2I_2 are the effective bending stiffness of the bicycle frame and fork respectively.

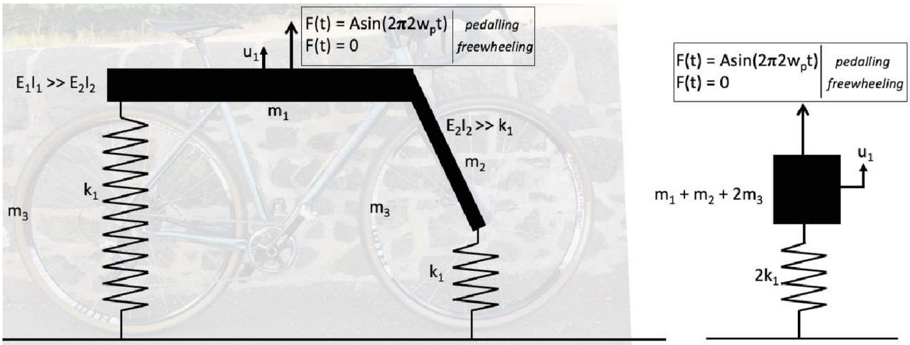

Fig. 1. Deriving the assumed reduced degree-of-freedom model of rider and bicycle system. Left: Assumed system properties. Right: Reduced degree-of-freedom abstraction based on assumed properties.

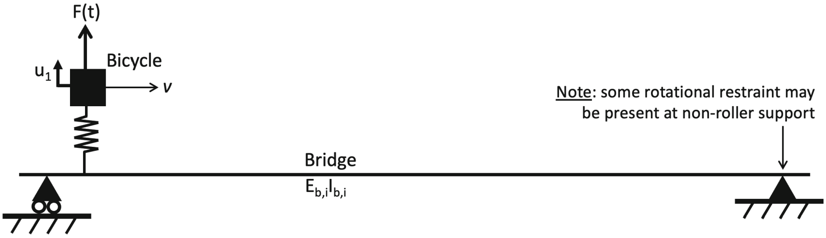

Fig. 2. Assumed rider-bicycle-bridge interaction model.

The bicycle frame is a triangulated structure whose vertical stiffness will be very high. The bicycle's fork is a cantilever structure, but it is nevertheless assumed to be very stiff in relation to the tyres. Thus, the effective spring stiffness is assumed to be dominated by the tyres and thus will be related to tyre inflation pressure, tyre volume and – at lower pressures – tyre casing sidewall stiffness. Early studies of vehicle-bridge interaction commonly disregard the effect of vehicle suspension damping as part of an overall aim to simplify the abstracted physical model (for example, the single degree-of-freedom sprung mass model used by Yang et al [5]). This was presumably adopted in order to simplify the coupled dynamic model of vehicle and bridge to facilitate a closed-form analytical solution, or based on the assumption that damping is of negligible importance in transient dynamic interactions as noted by Yang et al in their 2019 book [7]. Although later (typically numerical) studies adopt models including suspension damping, tyre hysteresis is still commonly omitted (see for example the two degree-of-freedom model used by Corbally and Malekjafarian in their 2022 study [8]). The reason for this omission generally in the field is currently unclear, but it may be the case that the effect of damping from tyre hysteresis is negligible when compared to the explicitly-modelled effect of vehicle suspension damping. During pedalling, a harmonic force is assumed with $F(t) = Asin(2\pi 2w_p t))$ where w_p is the circular pedalling frequency, or cadence, and the multiplier 2 applied to w_p accounts for the fact that two downward forces will be realised (one from each pedal) for one full rotation of the cranks in the bicycle drivetrain. The bicycle and rider combined system is assumed to traverse the bridge at a fixed velocity v, with the harmonic exciting force defined as $F(t) = 0$ for the freewheeling case. The bridge structure, with length $L = 30$m is assumed to be a simply-supported beam with bending stiffness $E_b I_b$ as indicated in Fig. 2.

2.2 Experimental Regimes

The subject bridge forms part of a public shared pedestrian/ bicycle path in Edinburgh and is located as shown in Fig. 3 alongside an illustrative photograph.

Fig. 3. Left: bridge location plan (orientation North up). Map ©OpenStreetMap contributors, available under the Open Database License[9]. Right: site photograph looking approximately North West.

The fieldwork was split into two distinct parts. In *phase 1*, the bridge was excited by pedestrian loading. The load was applied by so-called *heel drops* (a person raising onto the balls of their feet, then dropping their heels simultaneously to the ground) thus approximating an impulse load from bodyweight at varying locations. Between heel drops, a minimum pause of around 10 s was allowed such that the induced amplitude of bridge vibration could be damped out. The sensor and impact locations are shown in Fig. 4 and summarised in Table 1. In *phase 2* the bicycle traversed the bridge in both pedalling and freewheeling states. Two distinct pedalling cadences were trialled. The traversals are summarised in Table 2. The traversal speed was approximately equal for all regimes.

Table 1. Heel drop impact locations and quantities recorded in phase 1

Impact location	No. of heel drops
Midspan central	27
Midspan left	12
Midspan right	18
1/4 span central	14
1/4 span left	18
1/4 span right	12
3/8 span central	14

Table 2. Traversal regimes and quantities recorded in phase 2

Regime	No. of traversals
Freewheeling	13
Pedalling (slow cadence)	10
Pedalling (fast cadence)	3

2.3 Sensor Instrumentation

The data was gathered using LORD Microsystems G-Link 200 8G wireless triaxial accelerometers. The sensors were magnetically fixed to the bicycle and bridge deck as indicated in Fig. 4. Figure 5 shows the sensor installed on the bicycle, and the bicycle in use (illustrative) with the data logging laptop visible. Data were logged at sampling frequencies of 512 Hz and 256 Hz for *phase 1* and *phase 2* respectively. The sensors' built-in frequency pass filters were configured with a low-pass at 800 Hz and no high-pass filter; in other words, no frequency filtering was employed in the range of the sampling frequency used. Data was transmitted wirelessly in so-called *calibrated* format, meaning that factory pre-set calibration factors were applied automatically.

2.4 Data Processing

The data collected during *phase 1* were used to estimate modal parameters from each sensor's response to the applied impacts. The matrix pencil method was adopted and used to generate estimated modal frequencies, phase angles and amplitudes. The matrix pencil method [10] is a time-domain curve fitting

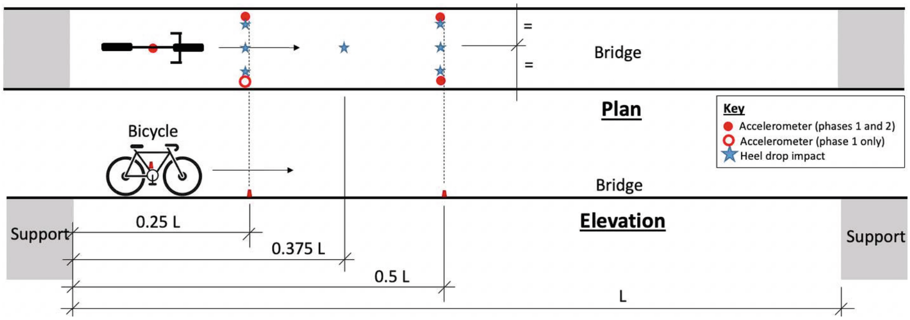

Fig. 4. Schematic layout indicating sensor placement on bike and bridge during traversals, and location of accelerometers and pedestrian heel drop impacts during *phase 1* of testing.

paradigm which uses each sensor's response to an impulse load to estimate modal parameters (frequency, amplitude and phase angle). For identified frequency bands, the sensor amplitudes were used to estimate mode shapes. Estimated mode shapes and frequencies are shown in Fig. 6. Modal estimates assumed to be spurious (for example: negative or very large frequency or damping) were manually filtered out prior to estimating mode shapes. Phase coherence was enforced by including only estimates within the phase angle ranges noted in Fig. 6 for each mode. For modes 1 and 3, symmetry about the bridge midspan was assumed. For mode 2, antisymmetry about the midspan was assumed.

The data from *phase 2* was split into subsamples in the time domain corresponding to each bike traversal. An ensemble average of the traversals for each experimental configuration was then used to generate an estimate of the power spectral density using Welch's method, for which the open source Python library Scipy [11] was used. Various other open source Python libraries were also utilised.

3 Analysis

The first three bridge modes identified from pedestrian heel drop loading in *phase 1* are shown in Fig. 6. Zero displacement was assumed at the supports. A virtual sensor at the three quarter-span point was assumed based on the motion recorded at the quarter-span point, either in-phase or *pi* radians out-of-phase according to the mode shape studied. Cubic interpolation was used between the sensor locations. Inspection of the estimated modal parameters showed that no significant torsion modes were active during this experimental regime, despite the loading including longitudinally asymmetric impulses. The assumption of the bridge acting as a simply-supported beam was therefore considered to be reasonable, although the potential for varying behaviour due to the true nature of the support conditions is yet to be explored in detail.

Figure 7 shows the power spectral density estimated using Welch's method for bridge and vehicle sensor responses from traversals (*phase 2*). In this figure,

Fig. 5. Left: the bicycle used for data gathering, showing wireless accelerometer installed. Right: example of the author riding the bike, with wireless accelerometer magnetically fixed to (a different) bridge deck and data logging laptop computer visible in foreground (photo by Mr Thomas McCormick).

the data are consistently normalised to allow comparison of signal power between sensor placements and experimental regimes. The data from the two midspan bridge sensors were combined and averaged. Vertical lines in a dash-dot linetype indicate the expected bridge frequencies for the first three bending modes identified from *phase 1*. The data are grouped in 3 distinct regimes: freewheeling (upper plot); pedalling at low cadence (middle plot); and pedalling at high cadence (lower plot). The duration was approximately equal for all traversals.

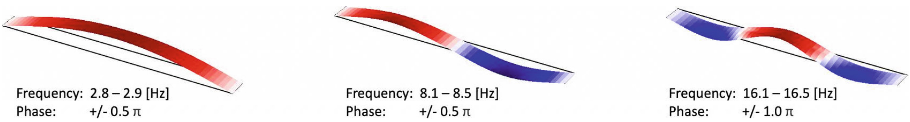

Fig. 6. Mode shapes estimated using Matrix Pencil method applied to bridge-mounted sensors, excited by pedestrian loading (heel drops).

Inspection of the upper plot in Fig. 7 reveals the bridge modes 1, 2 and 3 frequencies clearly visible from the bridge-mounted sensors when excited by a freewheeling bicycle. These frequency peaks are visible but shifted. Corresponding peaks appear in the response from the bicycle-mounted sensor, with the peak most close to the bridge mode 1 frequency appearing most convincingly. The middle plot suggests that, when the bicycle is pedalled at a lower cadence, there is no significant change to the frequency of response from the bicycle- or bridge-mounted sensors. However, it is clear that pedalling at this cadence leads to a significant (around 2.5-fold) increase in signal power in the bridge's mode 1 motion. This implies some degree of resonance but no frequency shift from the introduction of a moving harmonic excitation force.

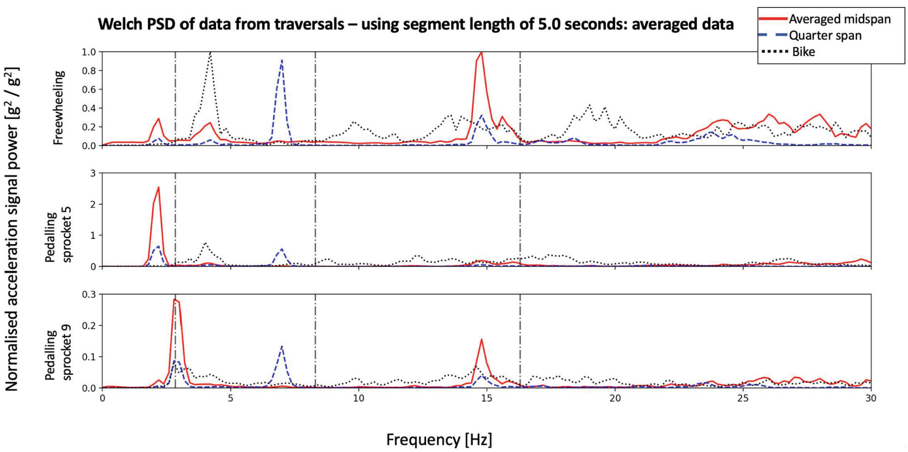

Fig. 7. Power spectral densities for bike and bridge sensors. Ensemble averages, consistently normalised. Vertical dash-dot lines indicate the expected bridge frequencies for the first three bending modes.

Inspection of the lower plot in Fig. 7 suggests that when the pedalling cadence is higher (sprocket 9), the bridge- and bicycle-mounted sensors all record the bridge mode 1 frequency clearly without any shift. The plot shows a significant (3-fold) reduction in signal power associated with this mode compared to the freewheeling traversal baseline. The frequencies associated with bridge modes 2 and 3 do not appear to be clearly evident in the bike-mounted sensor response. The reason for this is currently unclear but could be due to lack of coupling between bridge and bicycle for these modes (i.e., the bicycle-rider system combined properties create vibration isolation at these frequencies), or insufficient signal-to-noise ratio (i.e. the amplitude of bridge motion in these modes is too low to be detected by the bicycle-mounted sensor).

4 Conclusions and Future Work

The data gathered to date appear to offer a promising indication that bicycles may have a potential application as sensor carriers for indirect Structural Health Monitoring of bridges. Subject to bridge natural frequencies and pedalling cadence falling within favourable ranges (i.e. $2w_p \approx f_n$ for bridge mode n), it appears that pedalling may enhance bridge mode 1 response and that the associated frequency may be visible in data gathered from a bike-mounted sensor. It is encouraging to note that the bridge mode 1 frequency is still visible when the bicycle is freewheeling, implying that the visibility of this frequency peak is genuine rather than a spurious artefact caused by rider-bicycle interaction or other factors.

The following novel contributions are suggested:

- Using field tests, showing that low-cost sensor-carrying human powered vehicles can excite and record bridge dynamics - validating the only known paper [2] pursuing this specific subject to date.
- Known prior work [2] measured the bridge under ambient conditions and compared to bicycle-mounted sensor response during traversals at a later time. This paper adopted simultaneous sensing of vehicle and bridge, reducing potential ambiguity.
- Introduction of the concept of using pedalling cadence to increase visibility of bridge modes.
- Demonstration of indirect bridge modal parameter estimation without the need for motorised vehicles, supporting a general societal need to decarbonise as well as extend the life of existing infrastructure.
- Contribution to addressing the general limited quantity [12] of field-scale testing of indirect monitoring methods.

The frequency of pedalling input in the two regimes has not been accurately recorded. Repeating the experiments with an independent way of recording this will allow further insight and improve reliability (for example, proximity of pedalling harmonic to bridge modal frequencies) and could be implemented in future tests.

The pedalling force is assumed to be harmonic, but may in fact be more complicated. It would also be credible to assume that the force varied as a half-sine, with $F(t) = 0.5A[sin(2\pi 2w_p t) + |sin(2\pi 2w_p t)|]$. Measurement of the applied pedalling force, either in-situ (perhaps with pedal-based or crank-based load cells) or in a laboratory setting, would inform future studies by allowing more accurate characterisation of the equivalent force spectra imposed upon the bridge during traversals.

Future research is planned to validate the findings on a second bridge with differing modal parameters. Subject to frequency ratios, this may allow pedalling to enhance the visibility of higher order bridge modes. Utilising a variety of gear ratios, it is intended to study the effects of varying the pedalling frequency alongside varying the traversal speed (pedalling and freewheeling), allowing the excitation of higher bridge modes to be pursued as well as confirming that the freewheeling bicycle-bridge system behaves as predicted by the prior literature. Further fieldwork is planned to explore the effect of tyre inflation pressure (stiffness) on bicycle-bridge interaction in terms of frequency ratios, pedalling force transfer, and signal pollution due to road surface roughness.

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