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Uncertainty in Bridge Mode Shapes Based on Accelerometer Location

Connor Kent
Ph.D. student, School of Natural & Built Environment, Queen's University Belfast, Belfast, Northern Ireland

Andrew Bunce
Ph.D. student, School of Natural & Built Environment, Queen's University Belfast, Belfast, Northern Ireland

Dr. Connor O'Higgins
Research Fellow, School of Natural & Built Environment, Queen's University Belfast, Belfast, Northern Ireland

Dr. David Hester
Senior Lecturer, School of Natural & Built Environment, Queen's University Belfast, Belfast, Northern Ireland

Prof. Susan Taylor
Professor, School of Natural & Built Environment, Queen's University Belfast, Belfast, Northern Ireland

Prof. Roger Wood
Dean of Research, School of Electronics, Electrical Engineering and Computer Science, Queen's University Belfast, Belfast, Northern Ireland

ABSTRACT: In Structural Health Monitoring (SHM), modal analysis of a bridge structure is commonly used to aid in understanding the vibration characteristics of the structure under various loading conditions. These modal analyses are conducted by placing accelerometers along the length of the structure, for example, along the base of the parapet, or along the kerbside. This choice of accelerometer location has the potential to impact the modes shapes captured. This study presents modal analysis results for a bridge to determine if there is a significant difference in mode shapes based upon the location of the accelerometers on the structure. Initial tests were conducted with the accelerometers placed parallel along the kerbside. Subsequent tests were conducted with the accelerometers positioned parallel along the base of the parapet whilst maintaining the same longitudinal location as the previous test. Following the modal analysis of the data collected during the tests, the results indicate that for some modes there is a significant difference between the modal amplitudes captured for a given mode shape. This discrepancy derives from the differing locations of the accelerometers. The work conducted in this study provides evidence that sensor location can impact modal results, and that considering the location of sensors thoroughly during testing is crucial for effective SHM.

1. INTRODUCTION

Structural health monitoring (SHM) involves the implementation of a damage identification system within the mechanical, civil, and aeronautical engineering fields. SHM methods were derived from the need for a global damage detection method that can examine changes to the vibration characteristics of complex structures. Changes to the structure's material and/or geometric properties that effect the structures performance define the damage that is being identified. This damage can be detected by various sensor types, including accelerometers. SHM is commonly used in civil engineering to supplement visual inspections and localised experimental (acoustic or ultrasonic) methods preformed on bridge structures. This is because SHM methods can detect sub-surface damage that can impact the performance of bridge elements; damage that may be hard to detect via a visual and localised detection inspections alone.

Modal analyses are a key component of bridge SHM, aiding in understanding the vibration characteristics of structures, allowing damage within the structural elements to be potentially identified without the need for invasive testing. Modal tests, or experimental modal analysis (EMA), typically involves an input (excitation) and an output (response) which are measured and used to estimate modal parameters related to the structure. These parameters can include modal frequencies, damping ratios, mode shapes, etc. (Zhang et al. 2005). However, EMA is generally restricted to laboratory work. There are applicable cases for industrial applications, but these are often limited to component analysis as opposed to full system, or global, analysis.

Operational modal analysis (OMA) has gained traction in real-world civil engineering structural inspections, particularly for large structures such as bridges, towers, etc. OMA utilises the ambient excitations of a structure in an operational condition in order to identify the modal characteristics. Ambient excitation is not, or cannot be, measured directly (Farrar et al. 1999). The excitation can be provided by traffic loading, and/or wind loading (Green 2002).

1.1. Literature review

A paper by Doebling et al. (1996) reviews several papers researching global damage detection methods inferred from vibration characteristics about a structure. In Doebling et al.'s (1996) view, the amount of literature related to damage detection using shifts in natural frequencies is large and that the change in structural properties causing changes in vibration frequencies was the reasoning behind using modal methods for identifying damage and health monitoring purposes. The review conducted in Doebling et al.'s (1996) paper is comprehensive, covering a wide range of structural types, such as beams trusses, plates, bridges, etc., and analysis categories including, but not limited to, changes in modal frequencies, measured mode shapes, etc. The paper is widely cited for its vast coverage and analysis of damage detection through use of sensors and other technologies.

In regard to modal analyses through the use of sensors on the structure, there are several papers that perform research related to the number of sensors used for modal analyses. This is the case for works by Farrar et al. (1994) and Kim and Bartkowicz (1993), the latter of which indicated that this is the most important parameter when preforming damage detection. There are fewer papers that reference the location of the sensors impacting the results of the testing. McGowan et al. (1991) discusses that mode shape information based on sensor locations are fewer than the number of degrees of freedom (DOF) in an analytical model. Farrar et al. (1994) varied the location of the sensors along the structure to test whether this variation would enable the location of damage within the structure to be identified. Natke et al. (1995) used a system to provide insight as to where sensors should be located, but following review of the results, they discovered no new damage identification methods.

More recent studies have investigated various best practices for determining the locations of sensors in order to capture the most amount of data from testing and improve the post-processing results. Meo and Zumpano (2005) investigated several optimal sensors placement (OSP) techniques aimed at maximising the data information collected to fully understand the structural dynamic behaviour of suspension bridges. Six different placement techniques were investigated, three utilising the maximisation of the Fisher Information Matrix (FIM) method, two related to energetic approaches, and one related to the covariance matrix coefficients. The effective independence driving-point residue (EFI-DPR) method proved the most effective method for optimally placing sensors in order to identify vibration characteristics according to Meo and Zumpano (2005).

For all the papers previously discussed, there is very little to no discussion about the location of sensors and how that might influence the modal analysis following the testing, particularly regarding capturing modal information in the transverse direction of the bridge. This will be the purpose of this paper; to discuss and provide data in regard to how the location of sensors transversely across the bridge can influence the modal results following post-processing.

1.2. Aim of study

Following the comments made previously during Section 1.1, the aim of this paper is to acknowledge and provide insight in regard to the location of sensors on the bridge deck when conducting modal tests. Specifically, the paper will discuss how the location of the accelerometers may impact modal results depending on whether the sensors are placed along the base of the parapet or along the kerbside to capture accurate modal properties of a bridge structure.

In order to do this, this paper will present a modal test conducted on a two-span concrete beam-and-slab bridge and the results from the modal testing. The modal test consisted of six accelerometer sensors (three either side of the roadway) at consistent equal longitudinal spacings along the length of the bridge deck. Four individual swipes were conducted (two for each span) with the key difference being the location of the accelerometers along the kerbside or along the base of the parapet but maintaining the same longitudinal position.

The resulting modal analysis indicates that for some bridge modes, the captured mode shape is affected by the location of the sensors along the kerbside, or at the base of the parapet.

2. EXPERIMENTAL PROGRAM

Section 2.1 will provide images and a description of the bridge used for the experimental data gathering. Section 2.2 will provide information related to the setup of the sensors, and Section 2.3 will discuss the location of the sensors during the various swipes conducted. Section 2.4 will provide brief discussion and comments on the data collected and initial features generated.

2.1. Bridge used in study.

Figure 1: The beam-and-slab bridge located in N.I. used for the data collected.

The bridge used in this study was a two-span beam-and-slab bridge with an approximate total length of 58 m. The bridge has two spans of length 29.3 m and 26.7 m respectively, and an approximate width of 16 m. The main longitudinal beams are concrete U-beams with an approximate depth of 1.6 m that span between the north abutment, central pier and south abutment. There are five U-beams with a centre-to-centre spacing of approximately 3 m. Figure 1 shows an elevation of the bridge. This bridge is similar to others found across the UK and Ireland, meaning it is a good choice to potentially replicate tests in the future to reinforce what is learnt from this research.

2.2. Sensors used for modal tests.

For this modal test, several wireless Lord acceleration sensors were used to capture the bridge responses in order to enable the generation of mode shapes during the post-processing of the data.

Lord sensors can capture acceleration responses in three axes simultaneously and are commonly used for modal testing. They have an official cross-axis sensitivity of 1 % and sync wirelessly to a laptop with an antenna attached. The laptop utilises a software called SensorConnect to sync and control the sensors. The sensors were set to capture the vertical axis (z-axis) only at a recording frequency of 256 Hz.

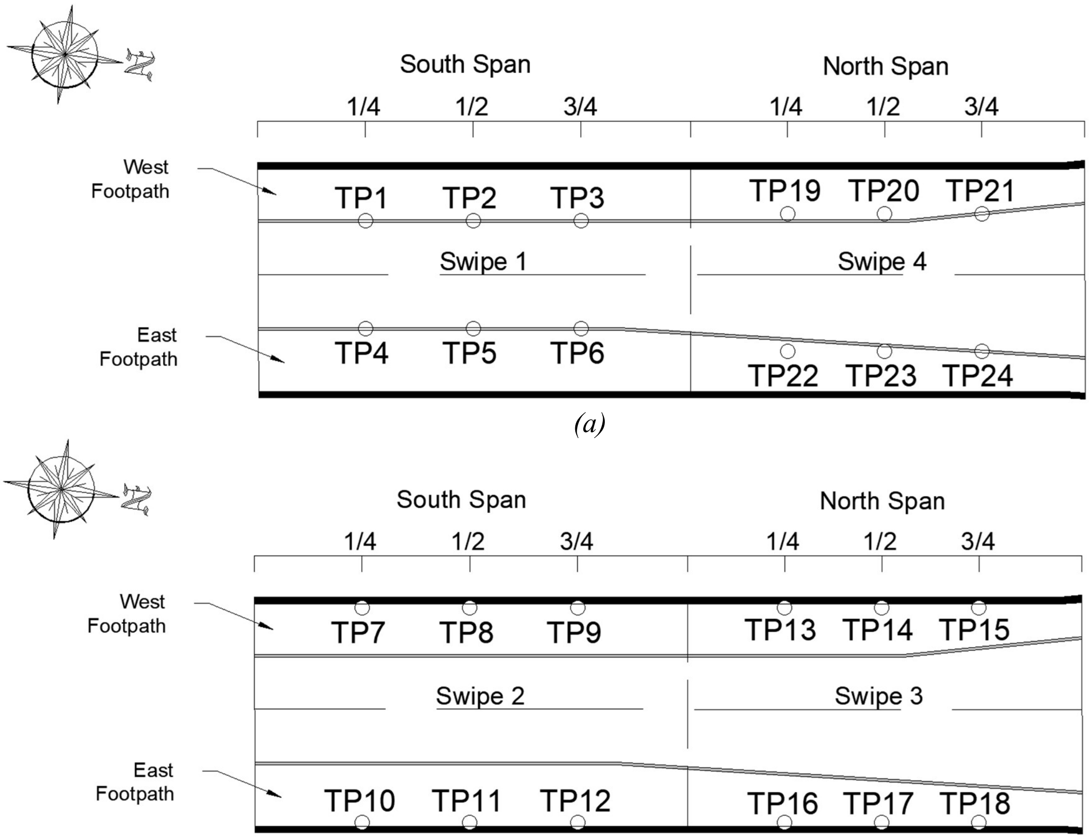
Figure 2: Lord sensor mounted on 8 mm steel plate and three adjustable bolts.

For the purposes of this experimental setup, the sensors were mounted on an 8 mm thick steel plate, as seen in Figure 2, providing a solid base for the sensors minimising the amount of sensor movement during the modal testing due to external forces, such as wind. In addition, the steel plates were equipped with three bolts that could be manually adjusted to aid with levelling the sensors.

2.3. Modal test set-up.

Figure 3: Lord sensor positioned near the top of kerbside before recording.

The test setup utilised seven of the Lord sensors, three to be located along both sides of the bridge



(a)

(b)

Figure 4: Plan view of bridge showing sensor locations for (a) Swipes 1 and 4, (b) Swipes 2 and 3.

for each test, and one reference sensor. The reference maintained the same position throughout each test swipe. This location was at the base of the parapet at the 3/4 position of the south span, near to TP12 in Figure 4 (b). Figure 3 shows one of the sensors near the top of the kerbside before data recording.

A swipe, as part of this data collection, was defined as a 30-minute recording window, enabling the capture of the bridge decks response to excitation. Due to a restricted number of sensors available for the testing, two swipes were completed for both the kerbside and parapet tests. Figure 4 provides a plan view of the location of sensors (indicated by the circle markers) for each swipe conducted. The swipes were completed in the order indicated by the numbers seen in Figure 4, meaning one span was completed before the other span was completed. The swipes could have been recorded in any order, but the order utilised here was seen to be the most efficient in minimising time between sensor relocation.

Observe in Figure 4 that the kerbs are not always parallel with the roadway. The reason for this is that road on the north side connects to a large roundabout and therefore requires the roadway to split on approach and exit. Therefore, in order to maintain a horizontal line of sensors during Swipe 4, the sensors at TP19, 20, 22, and 23 are positioned sightly further back from the kerb. This change in sensor location can be observed in Figure 4 (a) which shows sensor locations for Swipe 4. This slightly variation in sensor location was deemed acceptable to perform the modal testing with.

Also note in Figure 4 that the sensors move laterally on the bridge deck between kerbside and parapet sensor locations, ensuring no changes to longitudinal position influence the data being recorded. The sensors longitudinal positions were devised by dividing the bridge spans into four equal segments, providing three locations with equal distance from the abutments, pier, and other sensors.

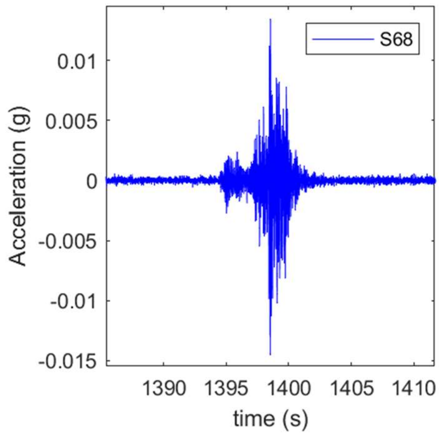


Figure 5: Portion of acceleration time series recorded by one of the sensors during Swipe 1.

Figure 6: An HGV lorry that caused acceleration response of the bridge deck similar to the response seen in Figure 5.

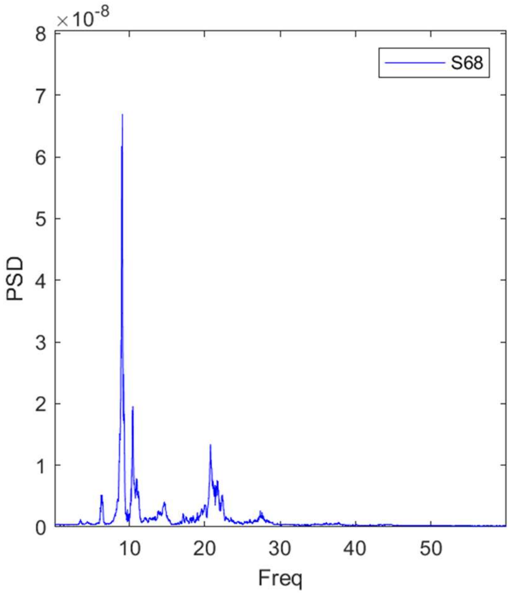


Figure 7: Power Spectral Density (PSD) vs frequency generated from Swipe 1 recording.

2.4. Review of data collected.

As discussed, the data collected from the site visit constitutes four 30-minute swipe recordings of the bridge's responses to ambient excitations. The data collected shows all the major excitations that occurred during the recording windows, with the most notable responses being a result from the double-deck busses and HGV lorries that passed over the bridge throughout the swipes. The data was exported from the SensorConnect programme in 'comma separated file' format. The files contain the meta information relating to the chosen parameters for the testing, such as start date and time, device identification numbers, frequency, etc. As there were seven sensors recording information and sending it back to the laptop, there were seven channels of information within the file, each indicating the serial number of a particular sensor and the information it recorded.

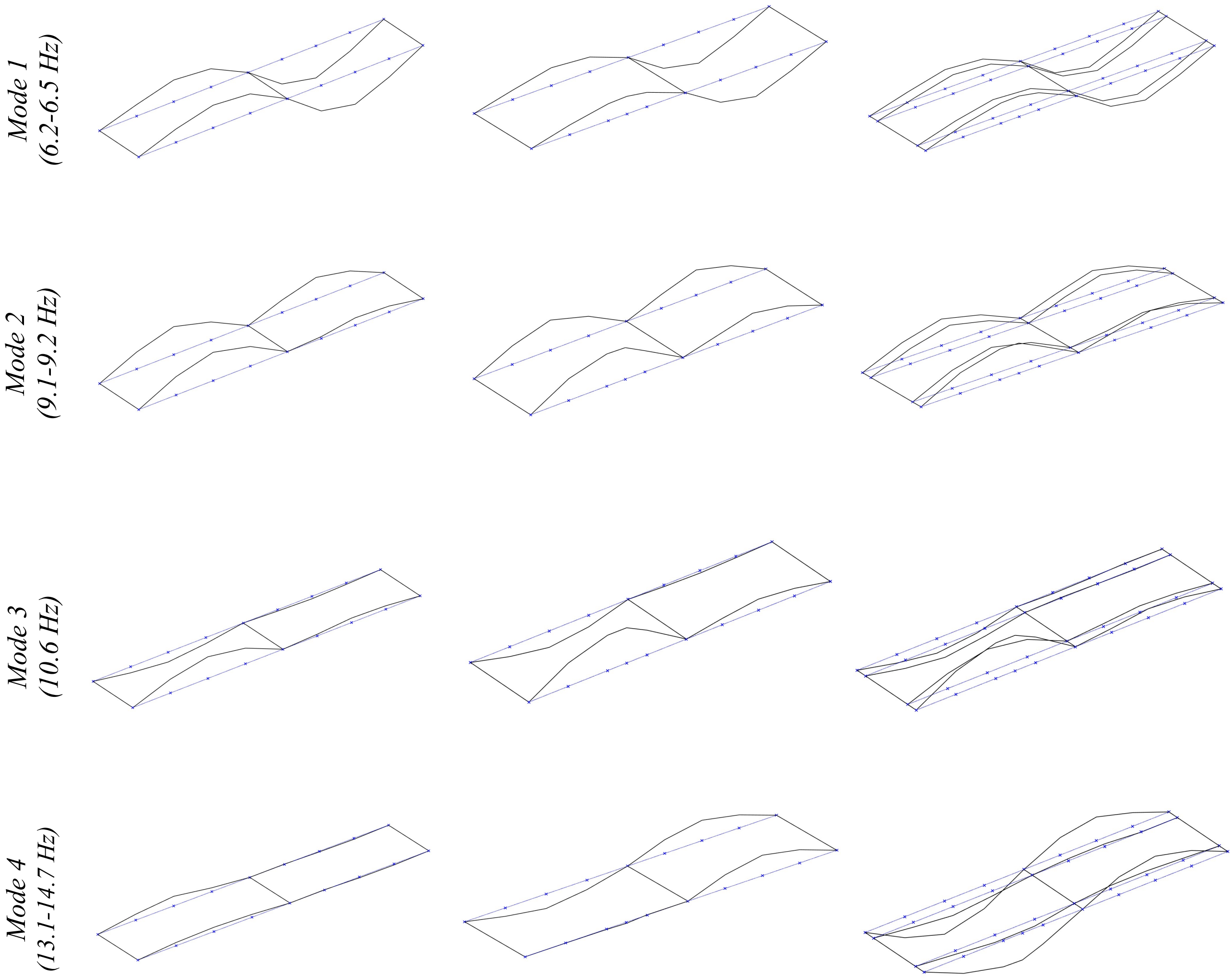
All the readings are time-synced, meaning it is possible to see all the responses to excitation occurring at the exact same moment across the bridge. An initial plot of a portion of the acceleration time series can be seen in Figure 5 which a prominent peak in acceleration that occurred during the recording of Swipe 1. Figure 6 shows an HGV lorry passing over the bridge. As mentioned previously, the heavy load from an HGV lorry can cause significant acceleration of the bridge deck, like that seen in Figure 5. Finally, Figure 7 shows the Power Spectral Density (PSD) from Swipe 1 that was generated using a modal analysis software which is discussed further in Section 3.

3. MODAL ANALYSIS

Following the collection of the acceleration data, the post-processing of the data was conducted. Post-processing of modal results can be complicated and be influenced by the individual conducting the processing. For the purposes of this post-processing, a custom MATLAB programme called MODAL was used to generate several mode shapes for each of the swipes recorded during the testing. The method used to identify the mode shapes is the NExT/ERA operational modal analysis procedure.

Within the following sections, Section 3.1 will present the mode shapes generated during the modal analysis. The left-side column will display the mode shapes for the kerbside swipes, the central column will display the mode shapes from the parapet swipes, and the right-side column will display the combined mode shapes from the kerbside and parapet swipes. Section 3.2 will provide a short discussion on the mode shapes results presented in Section 3.1 and provide some insight on the key similarities and differences between the kerbside and parapet mode shapes.

3.1. Mode shapes from MODAL analysis



(a)
Kerbside only

(b)
Parapet only

(c)
Kerbside and parapet combined

Figure 8: Mode shapes for (a) kerbside swipes only, (b) Parapet swipes only, (c) Combined kerbside and parapet swipes.

3.2. Discussion of mode shape results

From the Figure 8, it is evident that Modes 1, 2, and 3 are relatively insensitive to the transverse position of the accelerometers, i.e., the broad sense of the mode is captured equally well whether the accelerometers are located at the kerbside or at the base of the parapet.

However, the shape of the Mode 4 is such that it exhibits significant transverse variation in modal amplitude at the edges of the bridge deck, as displayed by the mode shape from the parapet swipes. Consequently, to capture this mode effectively requires a denser mesh of sensors transversely across the entire bridge deck. In order to properly track/capture the transverse variation in modal amplitude of this mode, ideally one would like to be able to place accelerometers in the carriageway. However, this is only feasible if a lane closure was implemented, which is a significant undertaking compared to this test set-up.

4. CONCLUSIONS

The results collected appear to answer the aims of the study well, providing evidence that there is potential sensitivity in what modes are captured by sensors depending on their transverse position on the bridge deck.

As limited modal tests have been carried out on beam-and-slab bridges that have a low aspect ratio, meaning the bridge is short and wide, more work is required in order to properly research this area.

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