

Acquisition and Analysis of Dynamic Responses of a Historic Pedestrian Bridge using Video Image Processing

Michael O'Byrne¹, Bidisha Ghosh¹, Franck Schoefs², Deirdre O'Donnell³, Robert Wright³ and Vikram Pakrashi³

¹Department of Civil, Structural and Environmental Engineering, Trinity College Dublin, Ireland

²LUNAM Université, Université de Nantes-Ecole Centrale de Nantes, CNRS, GeM, Institute for Research in Civil and Mechanical Engineering, University of Nantes, Nantes, France; and IXEAD/CAPACITES Society, Nantes, France³Dynamical Systems and Risk Laboratory, Civil and Environmental Engineering, School of Engineering, University College Cork, Ireland

³Dynamical Systems and Risk Laboratory, Civil and Environmental Engineering, School of Engineering, University College Cork, Ireland

v.pakrashi@ucc.ie Ph: 00353214903862 Fax: 00353214276648

Abstract. Video based tracking is capable of analysing bridge vibrations that are characterised by large amplitudes and low frequencies. This paper presents the use of video images and associated image processing techniques to obtain the dynamic response of a pedestrian suspension bridge in Cork, Ireland. This historic structure is one of the four suspension bridges in Ireland and is notable for its dynamic nature. A video camera is mounted on the river-bank and the dynamic responses of the bridge have been measured from the video images. The dynamic response is assessed without the need of a reflector on the bridge and in the presence of various forms of luminous complexities in the video image scenes. Vertical deformations of the bridge were measured in this regard. The video image tracking for the measurement of dynamic responses of the bridge were based on correlating patches in time-lagged scenes in video images and utilising a zero mean normalised cross correlation (ZNCC) metric. The bridge was excited by designed pedestrian movement and by individual cyclists traversing the bridge. The time series data of dynamic displacement responses of the bridge were analysed to obtain the frequency domain response. Frequencies obtained from video analysis were checked against accelerometer data from the bridge obtained while carrying out the same set of experiments used for video image based recognition.

1. Introduction

Pedestrian bridges have an important role in societies worldwide. Effective monitoring of these structures is vital to ensure that they remain safe and fit for service. Vibration-based assessments are often used in this regard as they provide a way of characterising the bridge in terms of its dynamic response. The dynamic nature of a bridge provides an indication of its serviceability condition and the level of dynamic acceleration can be related to the comfort level experienced by bridge users [1]. Additionally, a knowledge of the bridge parameters, such as the natural frequency and mode shapes, is useful for numerous applications, including for verifying or strengthening Finite Element (FE) models



so that they more accurately reflect the true behaviour of the structure. This aspect has attracted a growing interest in recent years as FE modelling is increasingly being utilised as a powerful and effective assessment tool [2-3].

Vibration based assessments are carried out using either direct or indirect instrumentation techniques. Monitoring via direct instrumentation usually requires the bridge to be outfitted with a range of sensors placed directly on the bridge, which is generally expensive and time consuming. The development of wireless sensor networks in recent times has partially alleviated this issue by adding a degree flexibility and value compared to permanent wired systems [4]. Indirect vibration based assessments typically involve vehicles equipped with on-board sensors traversing a bridge and recording the induced vibrations [5-6]. Such an approach is attractive in cases where the cost associated with permanent instrumentation and routine inspections cannot be justified.

This paper presents an alternative to these conventional approaches by proposing a video tracking based technique. Video tracking is suitable for analysing bridge vibrations that are characterised by large amplitudes and low frequencies. Video tracking has the advantage of being a low-cost and easily accessible option as the only hardware required is a standard digital camera capable of recording video. The onsite set-up and video acquisition is straightforward and does not require lengthy configuration or calibration procedures. Furthermore, the acquired data is easy to interpret as the excitation sources can be identified in the video itself. The proposed video tracking technique involves focusing a camera at the mid-span of a bridge and tracking the precise location of a designated point on the bridge in each frame of the video as it is undergoes user-induced vibrations. The time series data related to the location of this tracked point is then analysed to obtain the frequency domain response.

The technique is demonstrated as a proof-of-concept on a historic steel pedestrian suspension bridge in Ireland, called Daly's Bridge, which is known locally as the 'Shaky Bridge' due to its notable, and for some, unnerving swaying motion under pedestrian loading. This bridge is an ideal candidate for video based analysis as the dynamic displacement responses of the bridge are large enough to be detected in the video. The frequencies obtained from video analysis are checked against accelerometer data obtained from sensors on the bridge. The following section describes the video tracking technique. The technique is applied to Daly's Bridge in Section 3 and the results are presented and interpreted. Section 4 concludes the paper.

2. Methodology

This section consists of three parts. The first part describes the relevant camera settings and the set-up. The second part details the video tracking technique. Finally, the third part outlines the limitations and challenges associated with video tracking as a tool for vibration assessment.

2.1. Equipment and set-up

There are a number of equipment related factors that have a crucial impact on the performance of video tracking based vibrations assessments. Firstly, the maximum frequency of vibration that can be encoded is controlled by the sampling rate, or the video frame rate. As an example, the digital video camera used in this case study was a Canon 600D, which can record video at a rate of 60 Frames per Second (FPS) with a moderate resolution of 1280 pixels x 720 pixels, or at a slower rate of 35 FPS with a higher resolution of 1920 pixels x 1080 pixels. The 35 FPS option was chosen as the need for the highest resolution was greatly felt in order to compensate for the extensive distance between the video device and the mid-span of the bridge. This extensive distance was due to the fact that the video camera had to be set-up and positioned relatively far away on the bank of the river as shown in Figure 1. By Nyquist's criterion, the highest frequency that can be coded is half of the sampling rate, which for a frame rate of 35 FPS is 17.5 Hz.

Secondly, the minimum amplitude of the vibration that can be detected in the video is largely affected by the resolution, as previously mentioned, as well as the optical power of the lens. Long-focus lenses are able to make distant appear closer. This effect means that a long-focus lens would

magnify bridge displacements and make them more apparent in the acquired video. A 55 mm lens was used in this case study, which was sufficient as the bridge under consideration was characterised by large amplitude vibrations.



Figure 1. Daly's Suspension Bridge in Cork, Ireland, and the location of a mounted video camera on the river bank.

2.2. Video tracking technique

The video tracking technique operates by tracking the movement of a point on the bridge whilst in an excited state. Tracking is done by picking a small patch, or window, W , which is centred on the chosen point in the first frame of a video sequence and following it throughout the duration of the video clip. For every successive frame, the point is located by finding the patch which best correlates with the patch in the previous frame. The best correlation was determined using the Zero-mean Normalised Cross Correlation (ZNCC) metric. For video tracking, the window centred on the tracked point in a frame f_n , is matched to the corresponding window in the next frame, f_{n+1} . The search space for locating the corresponding window is confined to a stationary region in the video, R , which must be carefully chosen such that it encloses the tracked point throughout the entire video. Confining the search space to the local neighbourhood allows for greater computational parsimony and minimises the risk of false matches. For this task, the ZNCC is defined as:

$$C = \frac{\sum_{u,z \in W} (f_{n+1}(u,z)_{ab} - \bar{f}_{n+1,ab})(f_n(u,z) - \bar{f}_n)}{\sqrt{\sum_{u,z \in W} (f_{n+1}(u,z)_{ab} - \bar{f}_{n+1,ab})^2 (f_n(u,z) - \bar{f}_n)^2}} \quad a, b \in R \quad (1)$$

where $f_n(u,z)$ and $f_{n+1}(u,z)$ denote the intensity values of the pixels in the window, W , centred on the point being tracked in the n^{th} and $n+1^{\text{th}}$ frame respectively, u and z are the horizontal and vertical spatial indices of W , a and b are the horizontal and vertical indices of the stationary region R , and \bar{f}_n

and \bar{f}_{n+1} are the mean pixel intensity values within the area of the W for the n^{th} frame, and within R for the $n+1^{\text{th}}$ frame. The zero mean normal cross correlation coefficient, C , has a high value when there is a high degree of similarity between two patches in each frame. The new location of the tracked point in frame $n+1$ is taken as the one which corresponds to the highest value of C . This procedure is repeated until the final frame in the video sequence. The pixel locations for the tracked point are recorded at each frame, which may be viewed as a time series data of dynamic displacement responses. Spectral analysis on the signal may then be performed in order to identify the major frequency components.

2.3. Tracking challenges

There are a number of challenges associated with tracking a moving point in a video sequence. Most notably, the tracked point may drift or become completely lost as a result of temporary occlusion or luminous complexities in the scene such as shadows or light reflections. To mitigate these issues, a prominent and distinct point (i.e. a patch in the image with high local contrast) should be selected for tracking. If needed, multiple trials can be carried out by selecting various high-contrast regions near the mid-span of the bridge and assessing how well they are tracked over the duration of the video.

Another challenge relates to locating the position of the tracked region as precisely as possible. Even at the highest video resolution, the motion of the bridge can translate to minute changes of only a few pixels in the video frames. In order to address this, a quadratic is fitted to surrounding values for sub-pixel and sub-scale interpolation as described by Brown and Lowe [7].

3. Experimental study: dynamic response estimation using video tracking

A full-scale experiment is carried out on a pedestrian suspension bridge to validate the video tracking method. This section describes the pedestrian bridge, the experiment overview including details of the designed pedestrian movements, and the results obtained from application of the video tracking method.

3.1. Bridge description

Daly's Bridge is a steel pedestrian suspension bridge that spans the River Lee in Cork City, Ireland, as shown in Figure 1. The bridge provides a link from the northside of the city to the southside. It has a regular flow of traffic throughout the day that includes leisurely walkers and commuters. The main span has a length of 51 m and a width of 1.45 m. Two steel lattice towers at each side of the river carry a total of four high tension steel cables, with two cables on the upstream side and two cables on the downstream side. Each tower consists of two piers that are braced together and are cast into concrete abutments on the river bank. The walkway consists of vertical steel lattice parapets and timber decking.

The bridge was built in 1926 and partially refurbished in the 1980s. With this in mind, it is no surprise that there are many instances of corrosion of varying degrees of severity. The four suspension cables are in a good state, showing only mild surface corrosion, however, fatigue damage is present in the free anchor length on the south side of the structure.

3.2. Experiment overview

Controlled pedestrian and cyclist movements were used to excite the fundamental vibration modes of the bridge. The pedestrian movements were carried out by a female and male who naturally had different walking signatures. All other traffic around the bridge was stopped during each controlled crossing. The camera began recording just before the controlled pedestrian or cyclist was about to begin the crossing, and continued until a short time after they reached the other side and the bridge returned to a state of rest.

In the acquired video, a distinctive point (e.g. a corroded spot that was easily discernible from the background or some other region of discolouration) was chosen to be tracked at the mid-span of the bridge, as shown in Figure 2. This allowed for more robust and effective tracking from frame to frame. As previously mentioned, tracking can be performed on any number of different points, which is particularly useful if some of the tracked points are prone to drifting from their true position over the course of the video.

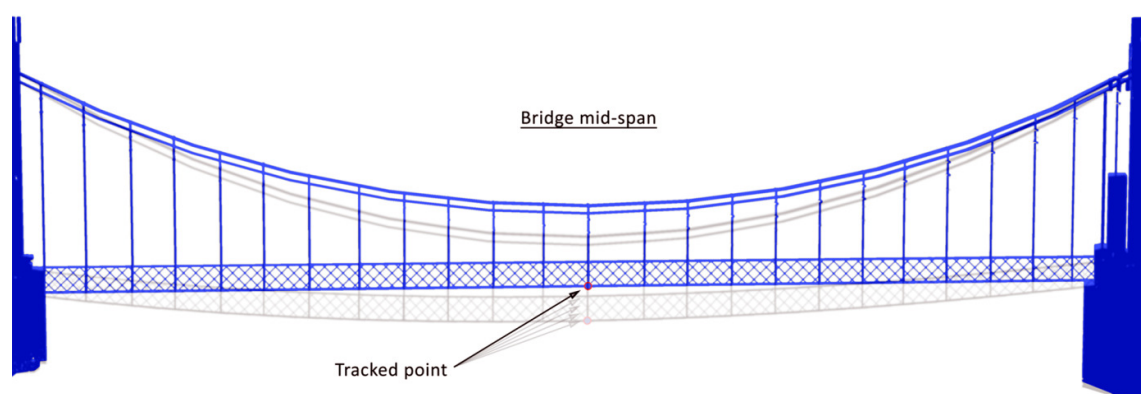


Figure 2. Tracked point at mid-span of the bridge.

As a further step, pixels units can be related to real world metric units by establishing a scale factor. The scale factor is computed by measuring the length of an object in a video frame in pixels and then comparing it with the known real world length of the corresponding object in the scene. In this case of Daly's Bridge, the hanger length at the mid-span was used as the object of known dimensions. This approach is valid as long as the bridge movement is roughly in the same plane as the measured object and the length of the object in the image in pixels is linearly related to its real length (i.e. there is negligible distortion such as perspective change between the top and bottom of the object). The step of relating pixel units to real world units is optional as the scale of the oscillations do not have a bearing on the estimated fundamental frequency, however, it is useful for other applications and conversion to real world units gives engineers a sense of the bridge displacements in a more meaningful light.

3.3. Results

This section presents the results obtained from video tracking of Daly's Bridge. Three excitation sources are considered for this case study: i) pedestrian induced vibration - female, ii) pedestrian induced vibration - male, and iii) cyclist induced vibrations. Two trials are shown for each excitation source. The displacement versus time graphs corresponding to each scenario are shown in Figures 3. Each of the graphs relate to a time period of about 30 seconds, depending on how long it took the pedestrian/cyclist to complete the bridge crossing.

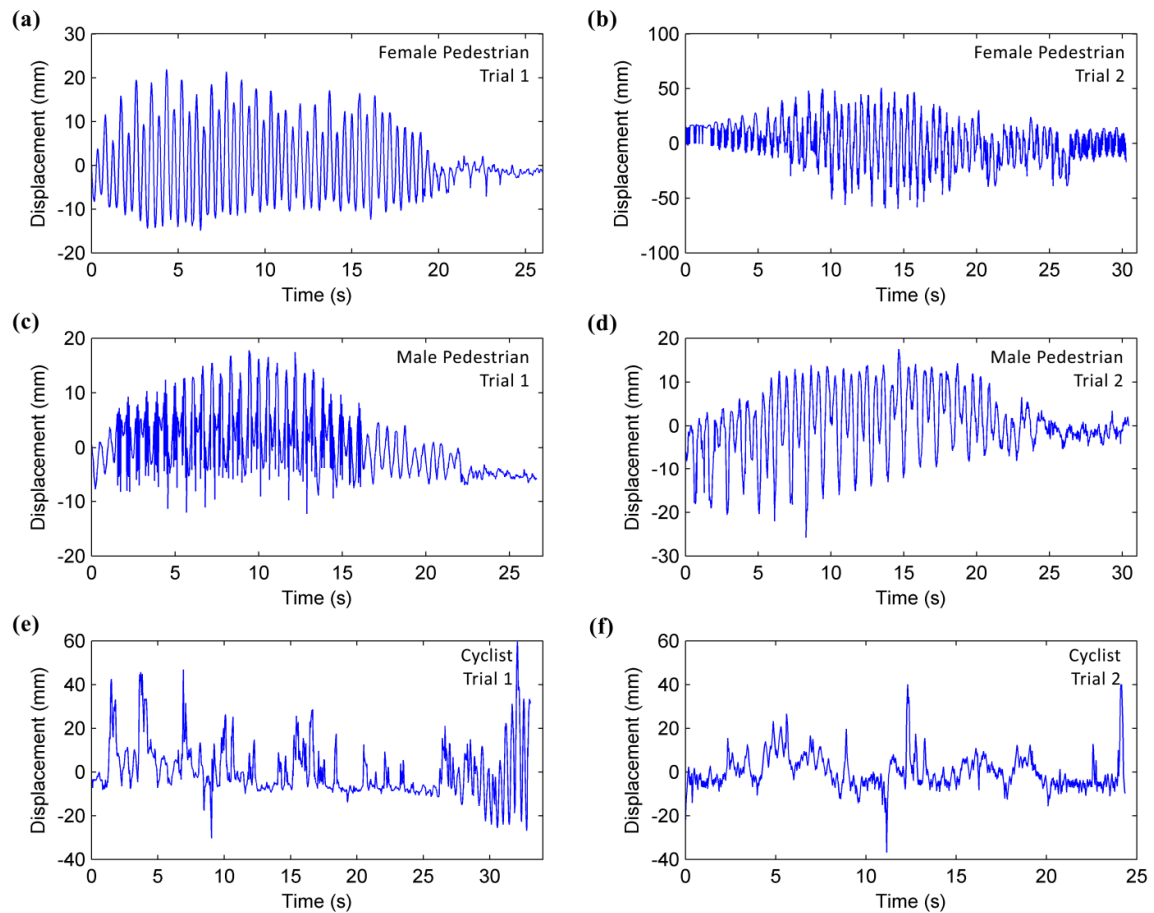


Figure 3. Vertical displacement versus time graph measured at mid-span of the bridge for: (a) female pedestrian - first trial; (b) female pedestrian - second trial; (c) male pedestrian - first trial; (d) male pedestrian - second trial; (e) cyclist - first trial; and (f) cyclist - second trial.

Fourier spectrum of these dynamic displacement responses are shown in the Power Spectral Density (PSD) plot in Figure 4.

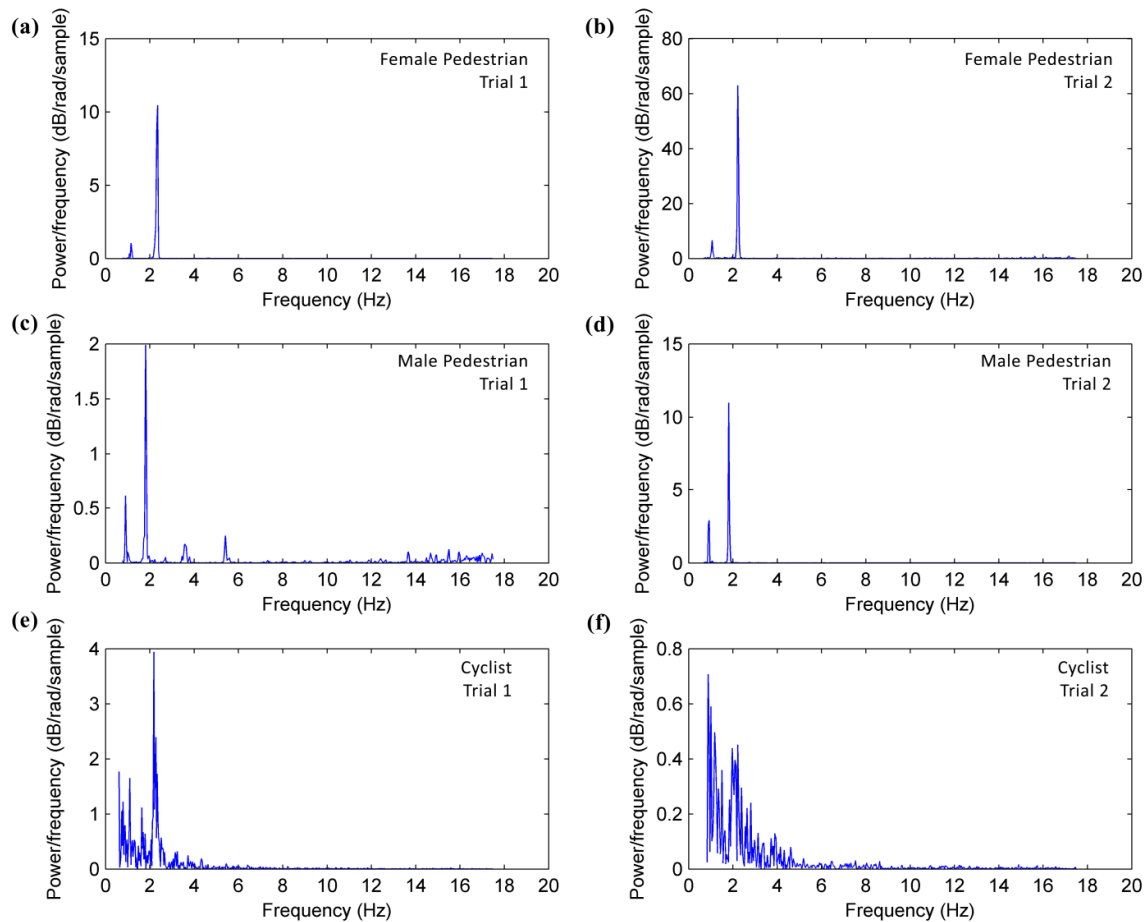


Figure 4. Fourier spectrum of vibration data for: (a) female pedestrian - first trial; (b) female pedestrian - second trial; (c) male pedestrian - first trial; (d) male pedestrian - second trial; (e) cyclist - first trial; and (f) cyclist - second trial.

From the results of these six trials, it may be observed that the values of the estimated first natural frequency of the bridge are relatively consistent. Prominent peaks appear in each PSD plot at around 2 Hz, indicating high repeatability of the results. An exception to this is in the case of the second trial for the cyclist (Figure 4f), which shows prominent peaks in the range 1-1.5 Hz. This is likely to correspond to the forced frequency of the bicycle. Nevertheless, a prominent peak is still identifiable at the estimated natural frequency of 2 Hz. Accelerometers placed at the mid-span of the bridge indicate similar values for the bridge's natural frequency. Table 1 provides a summary of the results for both sensor types.

Table 1. Natural frequency results from image analysis method and from accelerometers on the bridge.

Sensor type	Mean Natural Frequency	Standard Deviation from Mean, %
Accelerometers	2.27 Hz	4.41
Video Analysis	2.11 Hz	1.56

These results from this full scale experiment validate the proposed video tracking technique as a convenient tool for identifying the natural frequency of bridges characterised by large amplitudes and low frequencies to a reasonable degree of accuracy.

4. Conclusion

This paper presents a video tracking technique for the purpose of identifying the fundamental frequency of bridges. The technique is successfully applied and validated on a pedestrian suspension bridge in Cork, Ireland. The bridge was excited by designed pedestrian movements and by individual cyclists traversing the bridge. In each scenario, the video tracking method consistently obtained similar values for the fundamental frequency. The mean natural frequency from all of the trials was 2.11 Hz, which showed good agreement with data from accelerometers placed directly on the bridge, which reported a mean natural frequency of 2.27 Hz.

Overall, the positive results of the video tracking technique suggest that it is a viable low-cost method for carrying out quick vibration based assessments of bridges that exhibit strong dynamic behaviour.

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