Human-Induced Vibration on Lightweight Footbridges

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Abstract – Footbridges are, by their nature, highly susceptible to human-induced vibrations as they may combine low levels of damping and low mass. Due to the increased flexibility and lightness of modern footbridges, dynamic forces can cause larger amplitudes, therefore, it is essential to pay greater attention to structural vibration and dynamic responses. The natural frequencies, damping properties, bridge mass and pedestrian loading, together, determine the dynamic response. The vibration behaviour caused by pedestrian traffic must be confirmed against the vibration monitoring and correlate with the design parameters. Then, it must be compared against the required human comfort standards and guidelines. If the vibration responses do not meet the comfort criteria, changes in the design or damping devices are advised.

This paper presents the ambient modal testing and human-induced load tests for two in-service pedestrian bridges in Melbourne, Australia. The relevant modal parameters were extracted and the vibration serviceability limit state (VSLS) was assessed with the Eurocodes and the AS 5100, including relevant guidelines such as HIVOSS and SETRA. ISO 2631-1 and AS 2670-1 provides appropriate frequency weighting functions based on the vibration direction since the sensitivity of human body to vibration is frequency and direction dependent. Vibration predictors have been evaluated using both frequency weighted and unweighted functions and the results have been assessed against the use of these functions at dominant, relevant frequency responses of the footbridge.

1 INTRODUCTION

Two lightweight pedestrian bridges have been monitored to assess the vibration serviceability limit state under human-induced dynamic loads as recommended in the Eurocodes and relevant guidelines. The current practice of vibration serviceability assessment consists firstly of identifying the critical natural frequencies and secondly, computing vibration predictors under controlled and uncontrolled loading conditions such as pedestrians walking, running and jumping on the footbridge deck. It is important to note, vibration predictors should not exceed design codes to ensure the safety and vibration perception by humans.

The goal of monitoring both bridges was to provide information about the vibration amplitudes under normal conditions. The time history accelerations were recorded in the middle of the span, of each structure using high-sensitivity accelerometers. Signal analysis was conducted to calculate the peak accelerations, vibration dose values (VDV), power spectral density (PSD) and maximum transient vibration values (MTVV). This is the maximum 1 second moving RMS values of frequency-weighted acceleration (ISO 2631-1).

To evaluate the VSLS, the general steps are as follows: operational modal analysis (OMA), confirmation of critical vibration modes, establishment of load and measurement points and service evaluation for controlled and uncontrolled dynamic testing. Results and analysis will be presented for the following two footbridges:

- The Sacred Heart Footbridge, located at the Abbotsford Convent, Melbourne. Designed by ACOR Consultants in 2017. It is a pedestrian link bridge between two historic buildings. Structurally, it is a beam girder span steel beam. The balustrade is a barrier and handrail, but the curved profile gives the appearance of a catenary suspension bridge. Therefore, this bridge could therefore be more realistically characterised as a hybrid “cantilever cable-stayed” bridge with a length of 9 meters and a steel perforated deck of 1.8 meters (Figure 1).

- The Southbank Pedestrian Bridge, (dedicated to the Australian Politician and Architect, Evan Walker Bridge) designed by Cocks Carmichael Whitford Architects (1992). This steel arch bridge linking Flinders Street Train Station to Southbank in Melbourne. This bridge is one of Melbourne's most iconic footbridges, used by over 20,000 people per day. The bridge is approximately 178.4 meters long and 17 meters wide. It spans the Yarra River, providing a scenic route for pedestrians and cyclists (Figure 2).

Figure 1 – The Sacred Heart Pedestrian Bridge.

Figure 2 – Southbank Pedestrian Bridge.

2 HUMAN-INDUCED VIBRATION CRITERIA

The Australian Standard (AS) 5100 Part 2, Design Loads, 2017, sets out the minimum design loads, forces and load effect for road, railway, pedestrian and bicycle bridges and other associated structures. Human vibrations are particularly relevant for pedestrian and cycle bridges, where the movement of people can induce vibrations. The standard ensures that these structures are designed to handle such dynamic loads to maintain safety and comfort for users.

For pedestrian bridges with resonant frequencies for vertical vibration less than 5Hz, the vibration of the superstructure shall be investigated as a serviceability limit state (SLS). Superstructures shall be sized such that, with one pedestrian traversing the structure, the maximum acceleration shall be not greater than 0.25 $f_0^{0.78}$ m/s^2 where f_0 is the critical mode of the vibration under analysis. Bridges with spans greater than 100m, or suspension and cable-stayed bridges, special investigations are required.

The maximum vertical acceleration limits for pedestrian bridges can be calculated using [$a = 4\pi^2 f^2 y\psi\ (m/s2)$] (AS 5100), i.e. 0.3 m/s^2 at 1Hz to 0.7 m/s^2 at 5Hz. The design pedestrian load shall have a weight of 700N and be assumed to cross the structure at an average walking speed, in the range of 1.75 to 2.5 footfalls per second.

When lateral natural frequencies lie in the range of 0.5–1.3Hz, special consideration shall be given to the possibility of excitation by pedestrians of lateral movements of unacceptable magnitude.

ISO 10137 provides recommendations for the evaluation of serviceability against vibrations of buildings and walkways. The level of vibration in the vertical direction for walkways over roads or waterways should not exceed those obtained by multiplying factor (R) of 60, to the relevant base curve. The exception lies, where one or more persons standing still on the walkway need to be accounted for (such as the first scenario), in which case, a multiplying factor of 30 should be applied. Horizontal vibration induced by pedestrian traffic or wind should not exceed 60 times the base curve for the horizontal direction (x, y). The minimum of the weighted vertical RMS vibration curve (0.005 m/s^2) corresponds approximately to the threshold of perception of continuous z-axis for most people (BS 6472). Response factor (R) is calculated by dividing the MTVV by the base curve value of 0.005 m/s^2. For the calculation of RMS values of the acceleration, an averaging time of 1 second is recommended.

ISO 2631-1 and AS 2670-1 evaluation of human exposure to whole-body vibration provides appropriate frequency weighting functions based on the vibration direction (x, y, z) and expected effects on the subject since the sensitivity of human body to vibration is frequency and direction dependent. The human body is more sensitive to some frequencies than others, and the weighting function takes this sensitivity into consideration. ISO 2631 also describes how suitable values of RMS acceleration can be determined from the filtered acceleration.

Different standards and guidelines establish frequency ranges and limitations: The European guideline Human Induced Vibrations of Steel Structures (HIVOSS, vertical/longitudinal 1.25–2.3Hz; lateral 0.5–1.2 Hz), AASHTO (2008) (<3Hz), Eurocode 2 (vertical 1.6–2.4 Hz; lateral 0.8–1.2 Hz), SETRA (1–2.6 Hz), Eurocode 5 (vertical <5 Hz; lateral <2.5 Hz) and Austroads (2009) (1.5–3 Hz) provide vertical frequency limitations.

HIVOSS (2008) and the French guideline Assessment of Vibrational behaviour of Footbridge under Pedestrian Loading (SETRA, 2006) provide peak acceleration limits corresponding to comfort levels (Table 1).

Table 1 – Comfort classes with common acceleration ranges (HIVOSS).

Comfort class	Degree of comfort	Vertical Limit a_{max} (m/s^2)	Lateral Limit a_{max} (m/s^2)
CL1	Maximum	<0.5	<0.1
CL2	Medium	0.5 – 1.0	0.1 – 0.3
CL3	Minimum	1.0 – 2.5	0.3 – 0.8
CL4	Unacceptable discomfort	>2.5	>0.8

Lock-in criteria, resulting in high lateral accelerations, trigger acceleration when lock-in phenomenon begins: $a_{lock-in}$ = 0.1–0.15 m/s^2 (HIVOSS).

It is recommended that we check the vertical and horizontal accelerations for one or more design situations if the relevant natural frequencies of the footbridge are between the limits stated before. The design situation should be represented by a comfort level to be achieved under a particular traffic class (TC). If the natural frequency of the footbridge lies between 1.9 Hz and 3.5 Hz, the comfort class (CL) for jogger excitation should be checked for vertical vibrations (Table 2).

Table 2 – Example of traffic class (EN 1991-2).

Traffic Class	Description	Pedestrian stream, d (P/m^2)	Pedestrian Group, n_w	Jogging group, n_j
TC1	Very weak traffic	0.1 (Min. 15P)	1	0
TC2	Weak traffic	0.2 (Min. 15P)	2	0
TC3	Dense traffic	0.5	4	1
TC4	Very dense	1	8	2
TC5	Exceptionally dense	1.5	16	4

TCs and dynamic load models given in Eurocode EN 1991-2, where d is the density of the pedestrian stream, n_w is the number of pedestrians in a group, and n_j is the number of joggers in a group. Minimum number of pedestrians = 15.

3 DYNAMIC TEST

3.1 Sacred Heart Pedestrian Bridge

The characterisation of the dynamic behaviour of the footbridge was performed based on the measurement of the bridge dynamics response under human excitation for assessment of comfort criteria and correlation with the finite element analysis (FEA) modelling response. Time history acceleration responses were conducted with pedestrians for about 5 to 15 minutes over the bridge deck at a particular frequency, including jumping at different locations. The frequency range of interest is 0.5 to 10 Hz using two triaxial accelerometers with 1000mV/g located in the middle and one quarter of the span. The Data Acquisition (DAQ) system recorded streamed time history with a sample frequency of 1024 Hz. Signal analysis was conducted using two different filters: a) IIR low-pass filter Butterworth with a cut-frequency off 20 Hz and filter order 4 and b) FIR low-pass filter with a cut-frequency off 20Hz, aiming to consider the response associated with the fundamental vertical vibration mode of the structure.

Based on AS 2670-1, frequency weighting filters for human vibration were also applied to the acceleration signals: W_d for horizontal x and y-axis directions and W_k for vertical z direction, both for standing position. It is important to note that when these frequency weightings are applied to the signal, the overall predictors will be reduced/filtered according to the weighting curves presented in Figure 3.

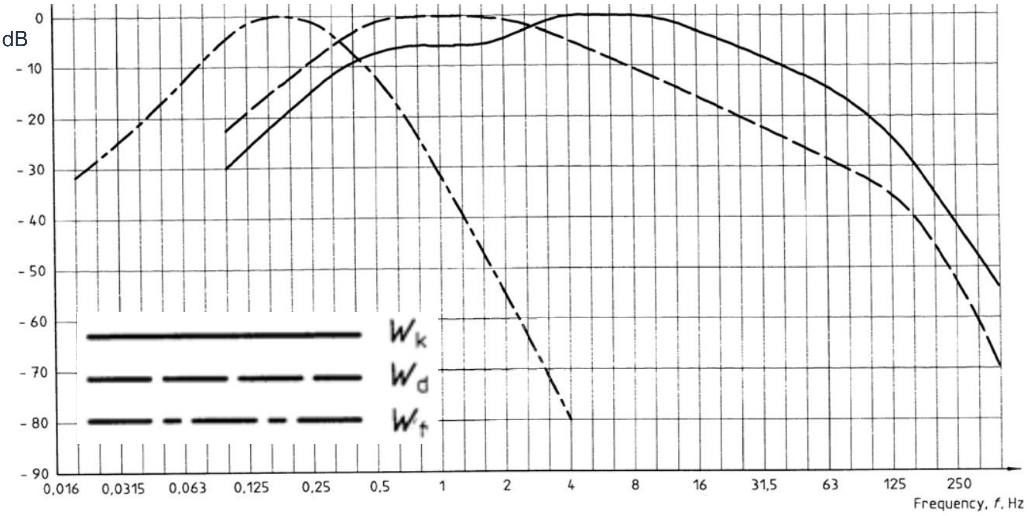

Figure 3 – Frequency weighting curves (AS 2670-1).

British Standard BS 6472-1 (2008) also provides frequency weightings, in this case W_b for vertical motion and W_d for lateral motion. These weightings provide maximum sensitivity to vertical acceleration in the frequency range 4 Hz to 12.5 Hz and to lateral acceleration in the range 1 Hz to 2 Hz. Evaluation with the BS 6472 is not included in this paper.

Several types of motions, listed below, were explored as a function of the frequencies of interest. Frequency walking was synchronized using a metronome. Figure 4 and Figure 5 show the bridge deck and the location of the sensors.

- 1x pedestrian walking synchronised at 90bpm, 1.5Hz and not synchronised,
- 2x, 4x and 8x pedestrians walking synchronised at 90bpm, 1.5Hz and not synchronised,
- 1x and 2x pedestrians running not synchronised,
- 1x pedestrian jumping at 90bpm, 1.5Hz,
- Continuous flow of pedestrians: i.e. 2x pedestrians on Sacred Heart bridge, 208x pedestrians on Southbank bridge,
- Hammer impact, heel-drop tests and free response,
- Ambient vibration tests and vandalism.

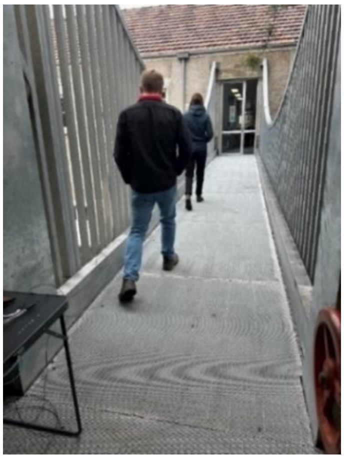

Figure 4 – Two pedestrian walking.

Figure 5 – Triaxial accelerometers.

Peak acceleration is often used in scenarios where the highest instantaneous force is critical such as shock testing or transients. Peak acceleration is calculated as $\sqrt{2}\ x\ \mathrm{MTVV}$. MTVV is more relevant in assessing human exposure to vibrations, where the duration and frequency of vibrations are important factors. MTVV is a much more robust metric value than the peak value, which is sensitive to short-duration high-frequency vibrations. When comparing MTVV with peak accelerations in footbridges, it is important to understand that both metrics are used to assess the comfort and safety of pedestrians on these structures.

MTVV should be multiplied by the $\sqrt{2}$, since the limits for footbridges are given in terms of peak acceleration. If the signal is purely sinusoidal, the RMS value multiplied by the $\sqrt{2}$ results in the amplitude of the signal, therefore both magnitudes can be compared. The VDV accumulates the effects of vibration and considers the duration and frequency of the use of the bridge, which involves a different value, based on the number of times the bridge is used.

The time histories and weighted RMS trends are shown in Figures 6 to 10 (using IIR filter), including PSD for relevant tests. Natural frequencies were calculated at midspan from the vertical signal.

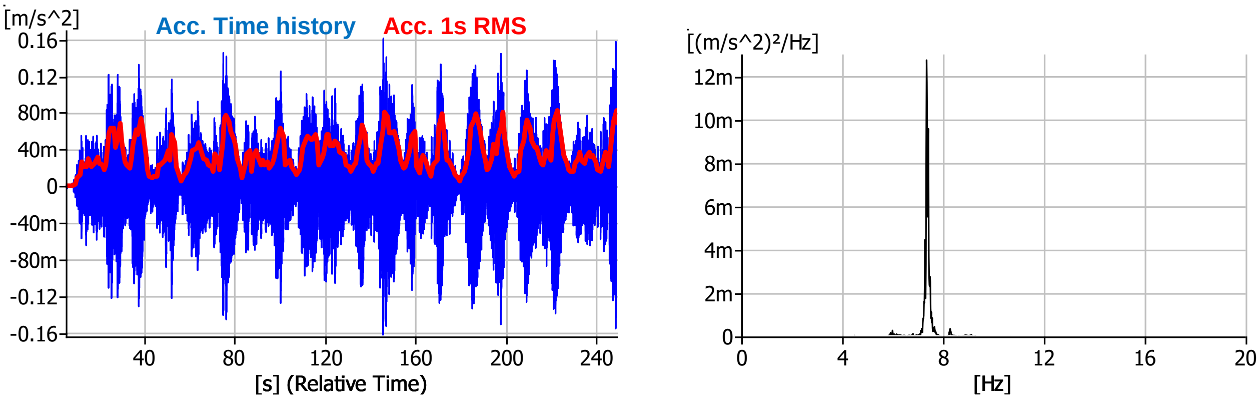

Figure 6 – 1x pedestrian, 1.5Hz, Peak = 0.16 m/s^2, MTVV= 0.08 m/s^2,VDV = 0.21 mm/s$^{1.75}$, f_0 =7.4Hz.

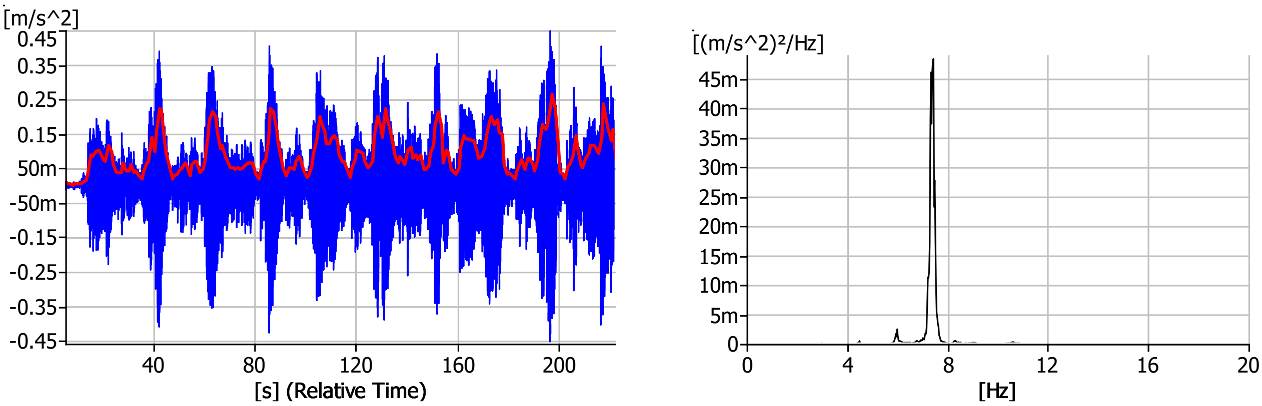

Figure 7 – 2x pedestrians, 1.5Hz, Peak = 0.46 m/s^2, MTVV= 0.26 m/s^2, VDV = 0.59 mm/s$^{1.75}$, f_0 =7.4Hz.

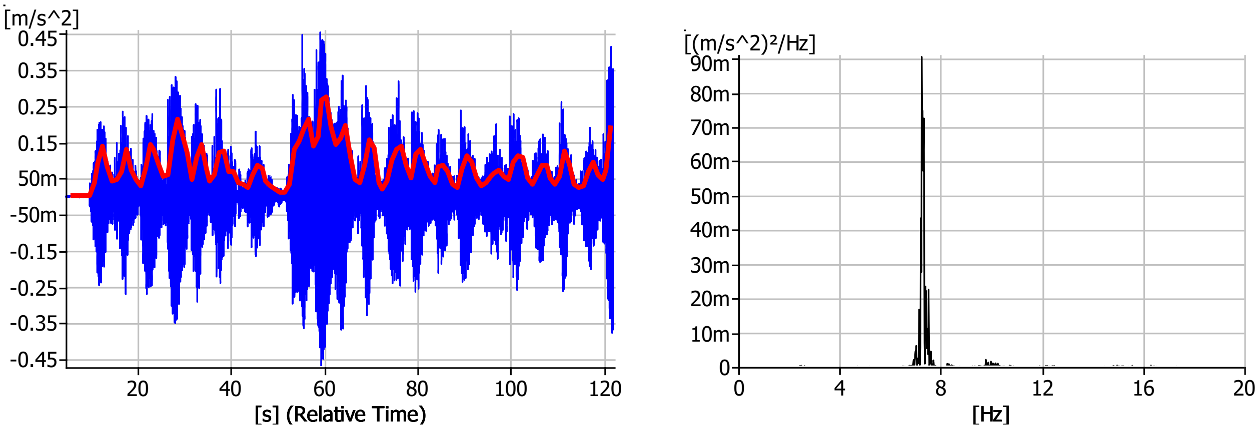

Figure 8 – 1x pedestrian running, Peak = 0.47 m/s^2, MTVV = 0.28 m/s^2, VDV = 0.50 mm/s$^{1.75}$, f_0 =7.2Hz.

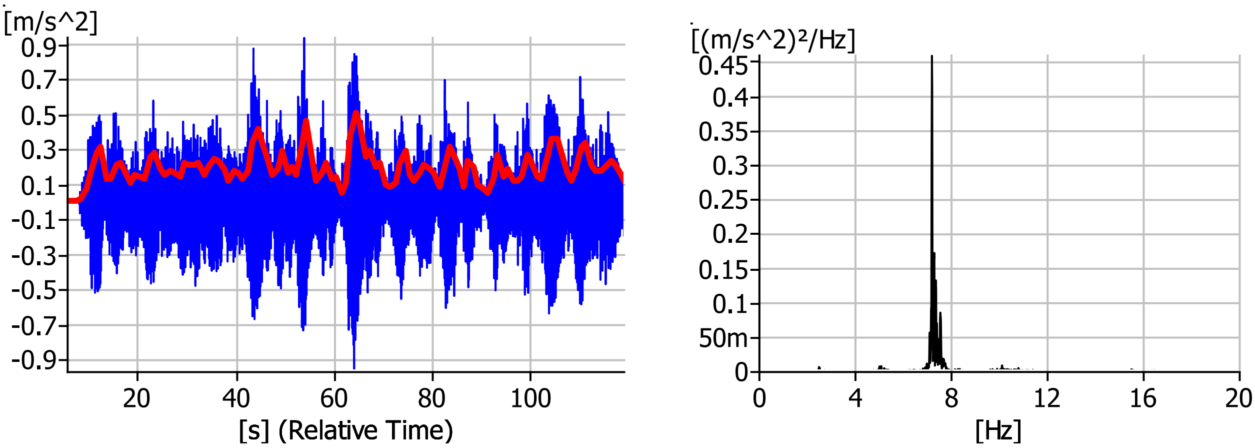

Figure 9 – 2x pedestrians running, Peak = 0.97 m/s^2, MTVV= 0.51 m/s^2, VDV = 0.94 mm/s$^{1.75}$, f_0 =7.2Hz.

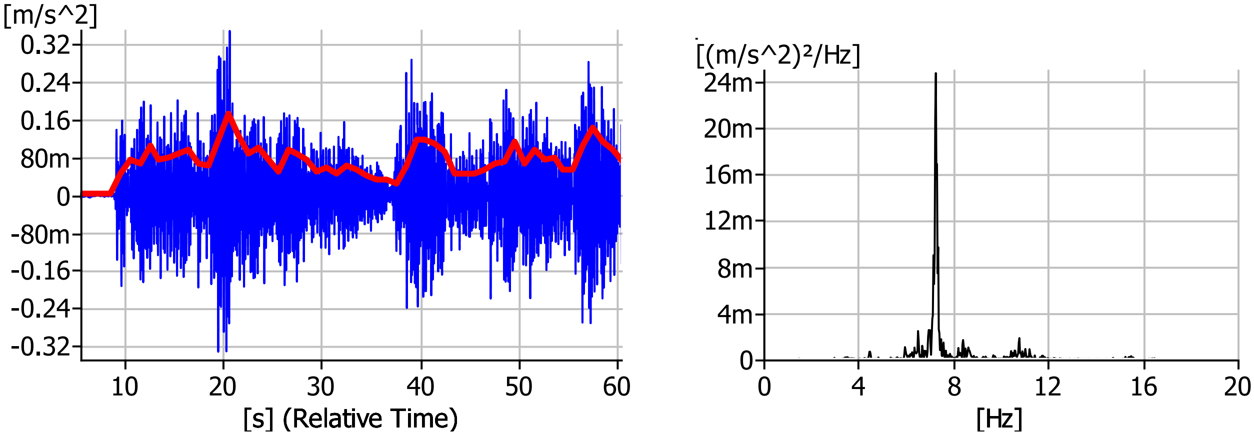

Figure 10 – 1x pedestrian jumping, 1.5Hz, Peak = 0.35 m/s^2, MTVV = 0.17 m/s^2, VDV = 0.31 mm/s$^{1.75}$, f_0 =7.3Hz.

Table 3 and Table 4 present the dynamic results to evaluate the footbridge at VSLS under a pedestrian load, using IIR low-pass filter and weighted and unweighted raw data.

Table 3 – Sacred Heart footbridge dynamic test results (including IIR and frequency weighted).

Test/Description	Signal Direction	Peak acceleration (m/s²)	MTVV (m/s²)	$\sqrt{2}\,MTVV$ (m/s²)	VDV (m/s$^{1.75}$)	Comfort Class
1x pedestrian walking 1.5Hz	Signal 1 X – Longitudinal	0.003	0.001	0.001	0.003	Maximum
	Signal 2 Y – Lateral	0.019	0.009	0.013	0.022	
	Signal 3 Z – Vertical	0.164	0.083	0.117	0.217	
2x pedestrians walking 1.5Hz	Signal 1 X – Longitudinal	0.006	0.002	0.003	0.007	Maximum
	Signal 2 Y – Lateral	0.039	0.020	0.028	0.051	
	Signal 3 Z – Vertical	0.459	0.263	0.372	0.585	
1x pedestrian running	Signal 1 X – Longitudinal	0.008	0.003	0.004	0.008	Maximum
	Signal 2 Y – Lateral	0.051	0.023	0.033	0.052	
	Signal 3 Z – Vertical	0.472	0.277	0.392	0.497	
2x pedestrians running	Signal 1 X – Longitudinal	0.016	0.006	0.008	0.015	Medium
	Signal 2 Y – Lateral	0.091	0.043	0.061	0.094	
	Signal 3 Z – Vertical	0.968	0.507	0.717	0.948	
1x pedestrian jumping 1.5Hz	Signal 1 X – Longitudinal	0.006	0.002	0.003	0.005	Maximum
	Signal 2 Y – Lateral	0.029	0.014	0.020	0.028	
	Signal 3 Z – Vertical	0.349	0.173	0.245	0.312	

Table 4 – Sacred Heart footbridge dynamic results (including IIR and frequency unweighted).

Test/Description	Signal Direction	Peak acceleration (m/s^2)	MTVV (m/s^2)	$\sqrt{2}\,MTVV$ (m/s^2)	VDV (m/s$^{1.75}$)
1x pedestrian walking 1.5Hz	Signal 1 X – Longitudinal	0.017	0.006	0.008	0.015
	Signal 2 Y – Lateral	0.083	0.034	0.048	0.091
	Signal 3 Z – Vertical	0.163	0.078	0.110	0.209
2x pedestrians walking 1.5Hz	Signal 1 X – Longitudinal	0.026	0.011	0.016	0.030
	Signal 2 Y – Lateral	0.162	0.079	0.112	0.198
	Signal 3 Z – Vertical	0.449	0.251	0.355	0.562
1x pedestrian running	Signal 1 X – Longitudinal	0.056	0.020	0.028	0.049
	Signal 2 Y – Lateral	0.257	0.095	0.134	0.247
	Signal 3 Z – Vertical	0.465	0.279	0.395	0.489
2x pedestrians running	Signal 1 X – Longitudinal	0.099	0.032	0.045	0.085
	Signal 2 Y – Lateral	0.431	0.161	0.228	0.413
	Signal 3 Z – Vertical	1.020	0.479	0.677	0.935
1x pedestrian jumping 1.5Hz	Signal 1 X – Longitudinal	0.038	0.014	0.020	0.028
	Signal 2 Y – Lateral	0.147	0.053	0.075	0.124
	Signal 3 Z – Vertical	0.352	0.160	0.226	0.308

The dynamic results were compared with the finite element analysis (FEA) of the bridge provided by ACOR Consultants, 2017, as shown in Table 5. The results correlate with the FEA calculations with an accuracy of 99%. Mode 3 confirms a natural frequency of 7.3Hz. Refer to Figure 11 for spectrogram and fast Fourier transform (FFT) results.

Table 5 – FEA Dynamic Natural Frequencies and MPF$_s$ results.

Mode	Natural Frequency Hz	Mass Part X Longitudinal	Mass Part Y Lateral	Mass Part Z Vertical
1	6.188	0.045%	9.428%	0.291%
2	6.941	0.091%	0.489%	4.276%
3	**7.327**	2.710%	0.007%	55.188%
4	7.833	0.382%	0.116%	1.447%
5	8.119	0.146%	0.216%	1.206%
6	9.563	0.002%	22.286%	0.469%

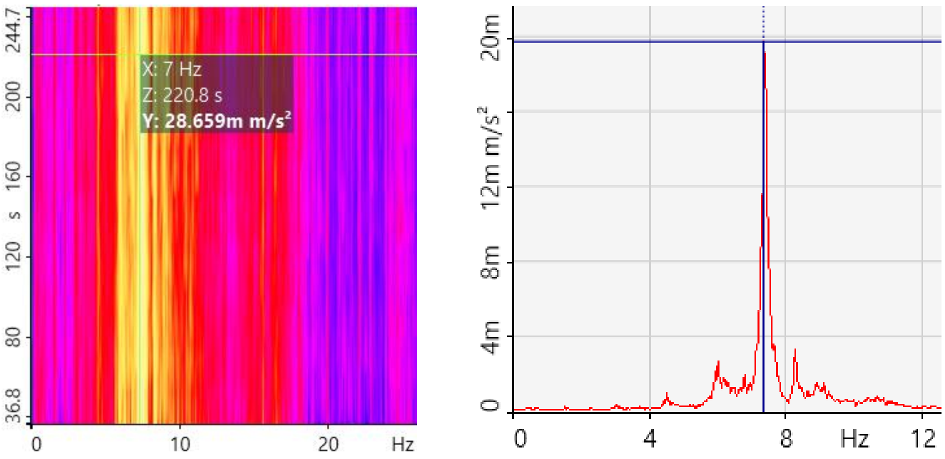

Figure 11 – FFT Auto spectrum Vs. Time.

Based on the frequency weighting curves shown in Figure 3, the W$_k$ (z) weighting function for vertical direction provide a correction of 0.33-0.46-0.31 dB between 5-6.3-8 Hz. Comparing the overall vertical predictors (Table 3 and Table 4) confirms that the results are practically identical. As expected, when comparing the lateral and longitudinal predictors, the results (Table 4) confirm higher values when the frequency weighting (W$_d$) is not used.

3.2 Southbank Pedestrian Bridge

For this bridge, the identification of critical natural frequencies and accelerations, including measurements of ambient responses, were conducted on the deck of the bridge due to a continuous flow of pedestrians during peak hour, between 8am and 10am on a weekday, 28 June 2023. Approximately 208 pedestrians were crossing the bridge during the monitoring.

Ambient vibration tests employ the current ambient loads on the structure as input loads. Human-induced vibration by a continuous flow of pedestrians is also of interest for determining the footbridge response under different usage conditions. This measurement should specifically be considered for footbridges that clearly exhibit a lively behaviour, namely a trend for synchronisation effects. Ambient vibration tests are becoming an extremely attractive alternative for identification of modal parameters in civil engineering structures, given the limited required resources and the high precision of currently available sensors. Figure 12 shows the bridge deck and the location of the sensor.

Figure 12 – Dynamic test, Southbank Pedestrian Bridge. Accelerometer at mid-span.

Time history acceleration responses were conducted with pedestrians for about 15-30 minutes over the bridge deck, including jumping at different locations. The frequency range of interest is 0.5 to 10Hz using one triaxial accelerometer (1000mV/g) located at mid-span. The DAQ system recorded streamed time history with a sample frequency of 1024 Hz, including Butterworth low-pass filters with a cut-frequency off 20 Hz and filter order 4 aiming to consider just the response associated with the fundamental frequency of the footbridge, including human-weighted functions. The time history and MTVV values are shown in Figures 13 to 16, including PSD for relevant signals. Natural frequencies were calculated at midspan for lateral, longitudinal and vertical amplitudes.

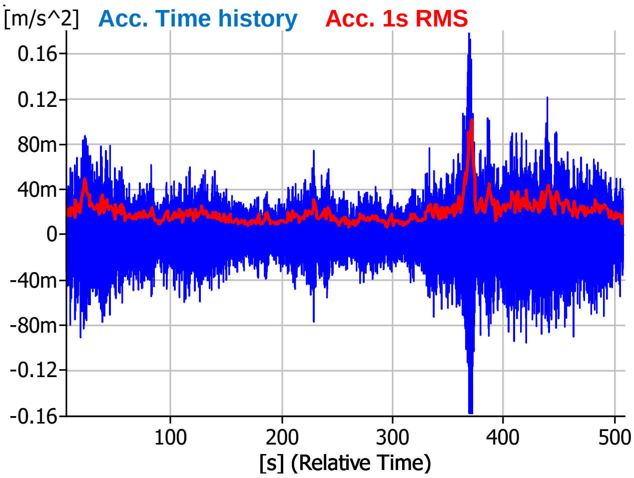

Figure 13 – Vertical bridge response at mid-span.

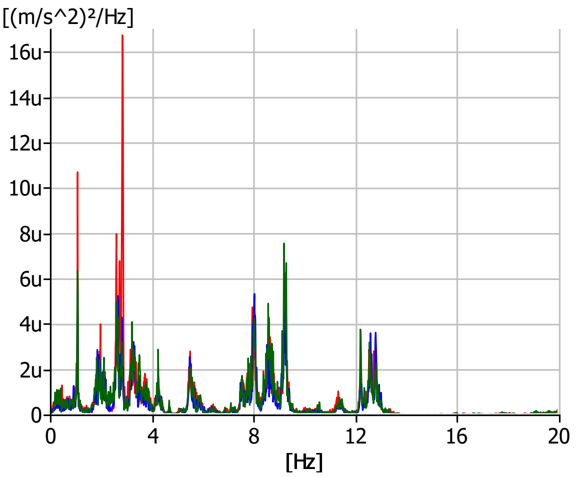

Figure 14 – Longitudinal Signal 1. Ambient conditions.

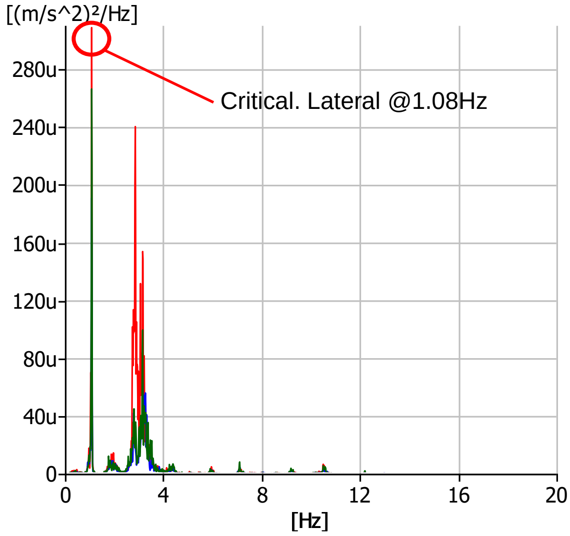

Figure 15 – Lateral Signal 2. Ambient conditions.

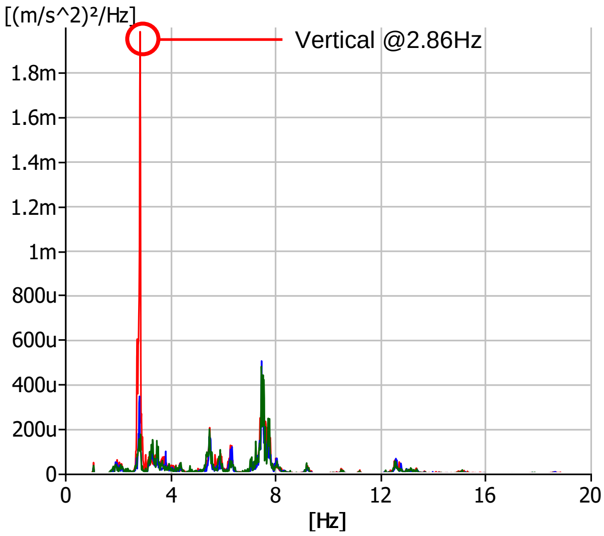

Figure 16 – Vertical Signal 3. Ambient conditions.

According to the ambient vibration tests, the vertical responses confirm a natural frequency at 2.86 Hz with 8.6mm/s^2 peak level. The lateral response confirms two critical natural frequencies: 1.1 Hz with 3.4 mm/s^2 peak level and 2.86 Hz with 3 mm/s^2 peak level. The overall weighted lateral peak acceleration of 0.099 m/s^2 (Table 6) was below the lock-in criteria (0.1m/s^2).

Table 6 presents the dynamic results used to evaluate the footbridge at VSLS under pedestrian loads using IIR low-pass filters and weighted and unweighted frequency functions. Table 7 presents dynamic results using the BS 6472-1.

Table 6 – Southbank Pedestrian Bridge dynamic test results using AS 2670-1 and ISO 2631-1.

Test/Description	Signal Direction	IIR low-pass filter	Frequency weighting	Peak acceleration (m/s^2)	MTVV (m/s^2)	$\sqrt{2}\,MTVV$ (m/s^2)	VDV (m/s$^{1.75}$)	Comfort Class
Operational conditions during peak hour	Signal 1 X – Longitudinal	20Hz	W_d	0.019	0.009	0.013	0.023	Maximum
	Signal 2 Y – Lateral	20Hz	W_d	0.064	0.037	0.052	0.068	
	Signal 3 Z – Vertical	20Hz	W_k	0.177	0.101	0.143	0.176	
Operational conditions during peak hour	Signal 1 X – Longitudinal	20Hz	N/A	0.069	0.026	0.037	0.090	Maximum
	Signal 2 Y – Lateral	20Hz	N/A	0.099	0.056	0.079	0.119	
	Signal 3 Z – Vertical	20Hz	N/A	0.255	0.135	0.191	0.230	

Table 7 – Southbank Pedestrian Bridge dynamic test results using BS 6472-1.

Test/Description	Signal Direction	Frequency weighting	Peak acceleration (m/s^2)	RMS acceleration (m/s^2)	MTVV (m/s^2)	VDV (m/s$^{1.75}$)	Crest factor (CF)
Operational conditions during peak hour	Signal 1 X – Longitudinal	W_d	0.0199	0.0035	0.009	0.023	5.69 < 6
	Signal 2 Y – Lateral	W_d	0.064	0.0089	0.037	0.068	7.19 > 6
	Signal 3 Z – Vertical	W_b	0.150	0.0206	0.084	0.153	7.28 > 6

Based on AS 2670-1, the RMS method continues to be the basis of measurement for the crest factor (CF) less than 9 where the integrity of existing databases is maintained. In recent years, studies have pointed to the importance of the peak values of acceleration in the vibration exposure, particularly in health effects. The RMS method of assessing vibration has been shown by several laboratories to underestimate the effect for vibration with substantial peaks. CF is a parameter that indicates how many peaks are occurring in the raw data. Based on BS 6472-1, if the crest factor (ratio between the peak and the RMS acceleration) is smaller than 6, the RMS acceleration can be used instead of the MTVV. However, when CF ≥ 6, MTVV or VDV metrics should be used.

4 CONCLUSIONS

Two in-service pedestrian bridges were monitored to assess the vibration serviceability limit state under human-induced dynamic loads. The Sacred Heart bridge achieved medium comfort level (CL2) and the Southbank bridge achieved maximum comfort (CL1).

The vibration predictors were assessed using both frequency-weighted (ISO 2631-1) and unweighted functions. As expected, both bridges, (when comparing the lateral and longitudinal predictors), show differences when frequency weighting (W_d) is used. However, for the vertical predictors, the results were practically identical when using weighted (W_k) and unweighted functions. This therefore raises a question as to whether these frequency weightings should be applicable in pedestrian bridges where dominant amplitudes occur between 0.63Hz to 2Hz for lateral displacement and between 2.5Hz to 10Hz for vertical motion.

It must be noted that the use of low-pass filters and appropriate signal analysis can also provide accurate results for vibration serviceability assessment under human-induced dynamic loads at dominant frequencies.

In conclusion, further studies will be required to confirm whether current frequency weighting functions are appropriate and adequate for human-induced vibration monitoring, on pedestrian bridges with similar frequency characteristics.

ACKNOWLEDGEMENTS

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REFERENCES

Standards Australia, (2001). Evaluation of human exposure to whole-body vibration. Part 1. General requirements. AS 2670-1:2001. Incorporating Amendment No. 1: 2013.

Standards Australia, (2014). Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration. Part 2 Vibration in buildingds (1 Hz to 80Hz). AS ISO 2631-2:2014.

International Organization for Standardization, (1997/Amd 1:2010). Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration Part 1: General requirements. ISO 2631-1:1997/ Amd 1:2010.

International Organization for Standardization, (2014). Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 2: Vibration in buildings (1Hz to 80Hz). ISO 2631-2: 2014.

International Organization for Standardization (2007). Bases for design of structures – Serviceability of buildings and walkways against vibrations. ISO 10137: 2007.

Standards Australia, (2017). Bridge design Part 1. Scope and general principles. AS 5100-1: 2017.

Standards Australia, (2017). Bridge design Part 2. Design loads. AS 5100-2: 2017.

Joint Research Center, 2008. BUTZ C, HEINEMEYER C, KEIL A, et al. Human Induced Vibrations of Steel Structures HIVOSS: Design of footbridges guideline.

The American Association of State Highway and Transportation Officials AASHTO. (1997). Guide specification for design of pedestrian bridges, Washington, DC.

Boniface, V., V. Bui, P. Bressolette, P. Charles, and X. Cespedes. 2006.Footbridges: Assessment of vibrational behaviour of footbridges under pedestrian loading. Setra/AFGC Technical guide.

European Commission (2009). HEINEMEYER C, BUTZ C, KEIL A, et al. Design of Lightweight Footbridges for Human Induced Vibrations.

European Committee for Standardization CEN.EN 1991-2:2023: Eurocode 1: Actions on Structures – Part 2: Traffic loads on Bridges and other Civil Engineering Works.

European Committee for Standardization, 2004. CEN. EN 1995-2:2004: Eurocode 5: Design of timber structures - Part 2: Bridges.

European Committee for Standardisation, 2003. CEN. EN 1991-2:2003: Eurocode 1: Actions on Structures - Part 2: Traffic Loads on Bridges.

British Standard, (2008). Guide to evaluation of human exposure to vibration in buildings (1 Hz to 80 Hz). BS 6472-1:2008.