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SOUNDS OF THE SUNSET COAST

Impact of Amplified Music on Vibration Levels in a 19th-Century Heritage Structure

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ABSTRACT

This paper presents the outcomes of an investigation into the transmission of airborne music noise into structural vibrations to assess the likelihood of vibration levels being able to cause structural or cosmetic damage in particularly sensitive buildings. The study had the objective of assessing potential risks to the UNESCO World Heritage-listed Royal Exhibition Building and its heritage-listed fabric, including both cosmetic and structural elements. The building, constructed in the late 19th century, retains much of its original form, with construction methods characteristic of the period. Vibration measurements due to airborne music noise were conducted during live amplified music events. Results demonstrate a strong correlation between elevated internal sound pressure levels and increased vibration amplitudes, particularly in the low-frequency range. These findings underscore the potential for music-induced vibrations to pose risks to fragile decorative elements, such as historic murals. The study provides an evidence-based evaluation of this specific heritage context and offers insight into the broader implications of amplified music events and pragmatical monitoring strategies in similar settings. Conclusions are drawn regarding risk thresholds and potential alternative management strategies.

1 INTRODUCTION

1.1 History of the Royal Exhibition Building

The Royal Exhibition Building is located in Carlton Gardens in Melbourne, Victoria. It was inscribed on the UNESCO World Heritage List in 2004 as the last surviving example of a 19th-century palace of industry from the International Exhibition movement in its original garden setting and still used for its original purpose. The Great Hall is all that remains of a larger pavilion complex that was demolished by 1979. The building's Outstanding Universal Values (OUVs) and National Heritage values are linked to key events such as the 1880 Melbourne International Exhibition, the 1888 Melbourne Centennial International Exhibition, and the 1901 opening of Australia's first Federal Parliament.

Constructed for the 1880 Melbourne International Exhibition, music has been an integral component for many of the events and activities held in the building. Internationally renowned artists from Dame Nellie Melba to Moby have performed at the Royal Exhibition Building, along with concerts from Royal Melbourne Philharmonic and the Melbourne Symphony Orchestra. In 1880 George Fincham installed the Exhibition Organ in the western end of the Great Hall, at that time the 20th largest organ in the world. Tuesday and Saturday choral and symphonic performances were a key feature of the 1888 Melbourne International Exhibition, with regular concerts continuing until 1900. In 1939, an orchestra of seventy-two accompanied a choir of over 700 school children as they performed in a production of *Hiawatha* to raise money for the war effort. Jitterbugging teenagers held a dance off during a cavalcade of jazz concert in 1950. While in 1992 the building hosted the Push Over Festival, featuring performances by bands such as Died Pretty, The Meanies, and TISM.

Many contemporary events held in the building such as the Melbourne International Fashion Festival make use of music, and others feature music as their key focus. Recently this has included the 2023 Now or Never Festival which saw the first large-scale live music performances in the building since its World Heritage listing, and the 2025 performance of Wagner's Die Meistersinger von Nürnberg.

1.2 Purpose of the vibration monitoring

Due to the significance of the building, as well as knowledge obtained from recent restoration works, a monitoring program has been implemented to monitor the condition of the building. This monitoring system includes a long-term vibration monitoring system, that has enabled a comparison of vibration levels arising in the structure from airborne music noise. This paper presents the outcomes of a study into the relationship between music events and building vibration, and discussion on the management of this risk to heritage structures.

2 DESCRIPTION OF THE BUILDING

The design for the Royal Exhibition Building incorporates Romanesque, Lombardic, and Italian Renaissance styles, featuring transepts with pavilions at each corner. The intersection of the transepts is capped by a large floating dome. The dome drum, made of rendered brick, is supported by relieving arches and pendentives, which are high above the Great Hall. The hall’s structure includes iron girders, brickwork, and plaster, decorated with murals from the 1880 and 1888 international exhibitions, and the 1901 opening of the first Australian parliament.

The building’s layout includes long central east and west naves, a northern transept, and a truncated southern transept. The ground floor features wide aisles, and first-floor galleries encircle the building. Constructed with a bluestone foundation, brick masonry walls, and timber-framed roof trusses, the building’s roof is a combination of galvanized steel and Welsh slate. A basement, originally used as a wine cellar and bar, is used for storage and exhibitions. The building also includes a reinforced concrete tunnel, added in the 1980s, for utilities and to support heavy vehicle access above. The interior features timber-framed galleries and roof lanterns, supported by hard-wood posts, with timber trusses supporting the corrugated steel roof.

Figure 1 shows the layout of the building including the locations of some vibration and weather monitoring equip-ment.

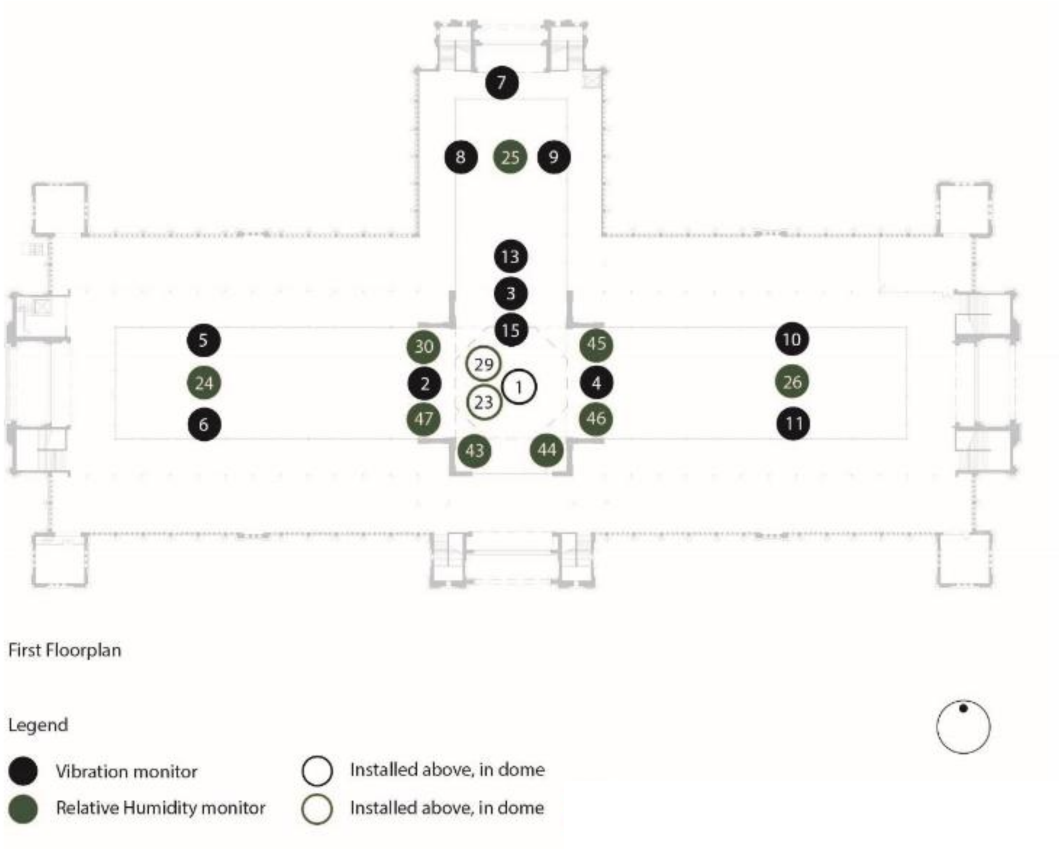

Figure 1: Royal Exhibition Building layout

3 CONDITION OF THE BUILDING AND CURRENT VIBRATION MONITORING EQUIPMENT

The Royal Exhibition Building has experienced long-term movement issues, with limited knowledge about the causes, extent of the movement, or any previous historical rectification works. In 2017, exterior works were undertaken to address roof leaks and repair the dome and south facade, completed by 2020. The last major interior conservation work was in the early 1990s, involving a re-painting of the interior to recreate the 1901 scheme, with significant conservation of murals (Hettinga, 2025).

Since 2020, deterioration has been observed inside the building, particularly in the painted finishes and plaster mouldings, likely due to a mix of the building fabric finally drying out now long-term water ingress has been fixed (above the dome), but with continuing water ingress in other areas. Efflorescence has also been noted in areas affected by water damage.

As per the above, a monitoring program funded by a Commonwealth Australian Heritage Grant is being conducted over 18 months to identify additional causes of the cracking and detachment of the murals. This monitoring program involves, among others, the deployment of 15 vibration monitors throughout the building to monitor the vibration levels the building is subjected to by the typical uses of the building, which include events where amplified music is present. The locations are summarised in Table 1, with locations shown on Figure 1.

Table 1: Vibration equipment locations.

Monitor reference	Location
1:	Interior dome drum cornice, Northern side
2:	Western lunette mural
3:	Northern lunette mural
4:	Eastern lunette mural
5:	West transept, north side of timber roof trusses
6:	West transept, south side of timber roof trusses
7:	North wall (internal) where structural cracking is present
8:	North transept, west side of timber roof trusses
9:	North transept, east side of timber roof trusses
10:	East transept, north side of timber roof trusses
11:	East transept, south side of timber roof trusses
12:	Located within floor structure, northwest area
13:	Northern lunette mural, above mural
14:	Located within floor structure, northeast area
15:	Northern lunette mural, outer archway of dome drum

The vibration monitors installed are Svantek SV 803 which use a tri-axial geophone to report peak particle velocities for the three axial directions simultaneously along with the corresponding dominant frequency. The Z-axis was aligned vertically, the Y-axis perpendicular to the mounting wall in the horizontal plane, and the X-axis horizontal in the plane of the wall.

It should be noted that since the vibration monitors are not fixed to typical major rigid structural elements, such as columns or beams, and are sometimes fixed to wall substrates that may offer low fixity performance, the vibration levels measured may be more representative of localised surface level vibration values and less representative of an overall structural building representation. The wall substrates still are expected to vibrate uniformly with the elements they are attached to, however a reduced mounting stability in the substrate may reduce the accuracy of the measurements at reporting the structural vibration.

4 VIBRATION CRITERIA

As aforementioned, The Royal Exhibition Building is a heritage building with central painted murals on lime plaster applied to unreinforced brick masonry or lath. Therefore, besides vibration criteria for buildings it is beneficial to consider vibration criteria for artwork.

4.1 Buildings (Heritage)

We note that there is no formal standard or guidelines in Australia for the assessment of potential damage to building structures from vibration. Therefore, vibration monitoring and limits for the prevention of cosmetic or structural damage to buildings can be established by adopting or taking into account international standards such as the German Standard DIN 4150-3:2016 *Structure vibration, Part 3: Effect of vibration on structures* (DIN 4150-

3) or the Swiss Standard SN 640 312:1992. In the context of historic buildings and art collections, Johnson and Hannen (2015) also previously considered the following two additional standards:

- United States Standard - USBM RI 8507
- British Standard - BS 7385-2.

International standards display a wide range of recommended Peak Particle Velocity (PPV) limits, see indicative summary in Table 2. It should be noted that both the German (DIN) Standard and the Swiss (SN) Standard have criteria related to cosmetic damage in 'listed buildings' and 'historic buildings' respectively. Several factors have to be considered when establishing the recommended PPV limits, including duration of exposure. Lower vibration levels are recommended when buildings are exposed to prolonged significant vibration periods (e.g. the DIN standard reduces the recommended vibration levels from 8 mm/s PPV short-term to 2.5 mm/s PPV for long-term vibrations for topmost floor horizontal direction).

Table 2: PPV limits (specified in several international standards) for multiple indicative frequencies

Monitor reference	1-10 Hz	50 Hz	60 Hz
DIN 4150-3 (short term Line 3) (topmost floor horizontal direction)	8 mm/s	8 mm/s	8 mm/s
DIN 4150-3 (long term Line 3) (topmost floor horizontal direction)	2.5 mm/s	2.5 mm/s	2.5 mm/s
SN 640 312 (Class 4 'occasional' frequency of exposure)	15 mm/s reduced up to 50% to 7.5 mm/s mm/s	20 mm/s reduced up to 50% to 10 mm/s	30 mm/s reduced up to 50% to 15 mm/s
SN 640 312 (Class 4 'frequently' frequency of exposure)	6 mm/s reduced up to 50% to 3 mm/s mm/s	8 mm/s reduced up to 50% to 4 mm/s	12 mm/s reduced up to 50% to 6 mm/s
USBM 8507 and AS 2187.2-2006	5 mm/s – 10 mm/s	50 mm/s	50 mm/s
BS 7385-2-1993 and AS 2187.2-2006 (cosmetic damage)	15 mm/s – 18 mm/s	50 mm/s	50 mm/s

4.2 Artwork

The primary area of concern for this study is the potential risks from vibration to the lunette murals which have been treated as artwork and museum objects. Risks to similar museum pieces have been commented upon by several authors and are mentioned in texts on preventive conservation as set out below. Although there has been extensive research on the topic, there are no standard assessment methods or limiting criteria to be used when assessing damage to sensitive objects from vibration. Despite this, many of the following excerpts presented tend to be in relative agreement on maximum vibration levels for museums and galleries.

Wei, Sauvage and Wolk (2014) suggest that

> *The results of measurements to date indicate that for traditional paintings in good condition, 2 mm/s could be considered to be a safe lower limit, where the risk is low for damage due to "short-term" events.*

In a follow up study conducted by Wei and Dondorp (2020), it was concluded that

> *1.5 to 2 mm/sec was recommended for the duration of the construction works. This is in line with the 2 mm/sec limit that has been suggested for input vibrations in museums and other collections for single events. Based on many years of practical experience, this is a level at which no damage has ever been reported.*

Additionally, Johnson and Hannen (2015) state that

> *A limit of 2.5 mm/s should be conservative to protect most art objects in reasonably sound condition, with the possible exception of 'walking' of light objects, resonance of objects with natural frequencies similar to continuous construction vibrations and extremely fragile objects or those with serious pre-existing weakness.*

Further, the same authors Johnson and Hannen (2015) state that

> *An artifact protection limit of approximately 2.5 mm/sec has been used during several recent museum construction projects as a limit to protect cultural relics in museums from building vibration. […] no damage to the artwork was observed.*

A study by Wei, Watts, Seddon, and Crombie (2018) on the findings of long-term vibration monitoring during construction at the World Museum and Walker Art Gallery, Liverpool, made the following conclusions.

> *If a vibration level was measured above 1.5mm/s PPV (peak particle velocity), contractors had to identify the source and remedial measures had to be taken, with no work interruption. If a vibration level greater than 3.0 mm/s PPV was measured, work had to be stopped immediately, the source determined, and remedial actions taken*.

However, they then go on to say

> *the stop action level chosen [3.0 mm/s] was higher than the limited literature at the time indicated, …and higher than the more recent experience-based 2.0 mm/s guideline for museum collections for single events.*

These commentaries support the choice of 2 mm/s as suitable for preserving the heritage artworks in the REB. Table 3 summarises the above criteria.

Table 3: Summary of PPV limits through literature review

Authors	Publication year	PPV trigger limit
Wei, Sauvage and Wolk	2014	2 mm/s
Wei and Dondorp	2020	1.5-2 mm/s
Johnson and Hannen	2015	2.5 mm/s
Wei, Watts, Seddon and Crombie	2018	1.5 mm/s
Wei, Watts, Seddon and Crombie	2018	3 mm/s

4.3 Vibration limits considerations

Considering the above, it would be considered that a value between 1.5 mm/s and 3 mm/s PPV would be appropriate for sensitive areas considered artwork or exposed to prolonged periods of significant vibration levels. Alternatively, for other areas of the building fabric that are not considered artwork and are not exposed to prolonged periods of significant vibration as may be the case with music noise vibration, a higher level between 7.5 mm/s and 50 mm/s PPV is considered a more appropriate vibration limit.

5 VIBRATION LEVELS DUE TO AMPLIFIED MUSIC NOISE

5.1 Warehouse measurements

Since the beginning of the monitoring program, several events involving amplified music noise and different speaker scales and configurations have been hosted.

We initially conducted measurements at a warehouse with concrete floor and walls to establish possible vibration levels caused by airborne sound pressure levels in a more modern building prior to the initial amplified music noise events hosted at the Royal Exhibition Building. Table 4 presents a summary of the warehouse measurements.

Table 4: Summary of PPV measurements at warehouse

L_{Zeq} (dB) 2 m from speaker	PPV (mm/s) floor at 2m from speakers	PPV (mm/s) wall at 1.5m height (approx. 8m from speakers)	Dominant freq. wall (Hz)
107	0.3	0.4	33
114	0.7	1.0	33
120	1.4	2.1	33
125	2.2	3.1	33

From Table 4, it was apparent that there was the potential for vibration in the range of that which may be of concern for Royal Exhibition Building to be generated from amplified music noise.

5.2 Royal Exhibition Building – Locations in relative proximity of speaker systems

During musical performances, vibration monitors in sensitive areas in relative proximity of speakers' systems (including sub woofers) have measured PPV levels that have reached 8 mm/s (as shown in Figure 2). These measurements have confirmed that speaker systems in a setting such as this are able to generate SPLs that are able to:

- For short term / occasional exposure, introduce PPV levels close to the conservative vibration limit for cosmetic damage in heritage buildings and
- For Artworks and long term / frequent exposure, introduce PPV levels that would exceed the vibration limit for cosmetic damages.

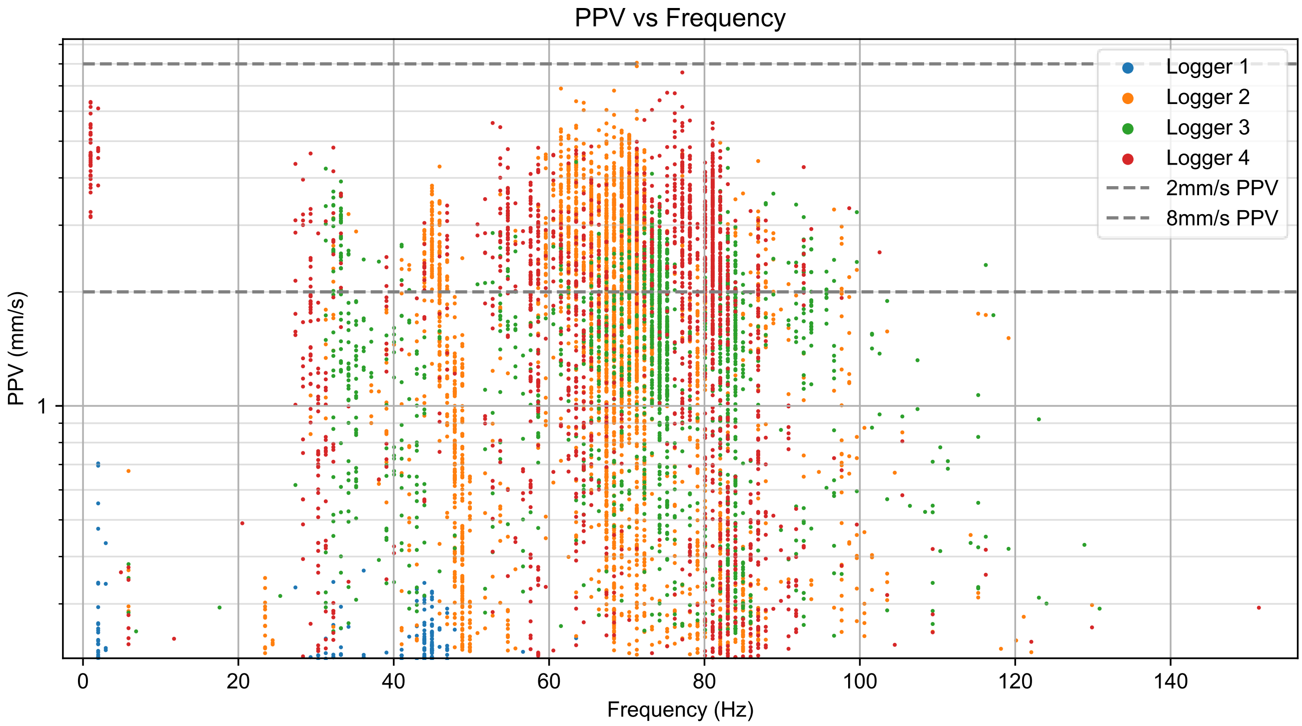

Figure 2: PPV levels for monitors close to speaker systems due to music noise emissions during the operation of a musical performance

For the subsequent iteration of the same musical performance approximately a year later, the measured vibration levels were recorded as shown in Figure 3. This next iteration operated under management strategies based on the results of the monitoring program at the time. Under these operational guidelines, the vibration levels were reduced significantly below 1mm/s PPV with minimal disruption to the success of the event.

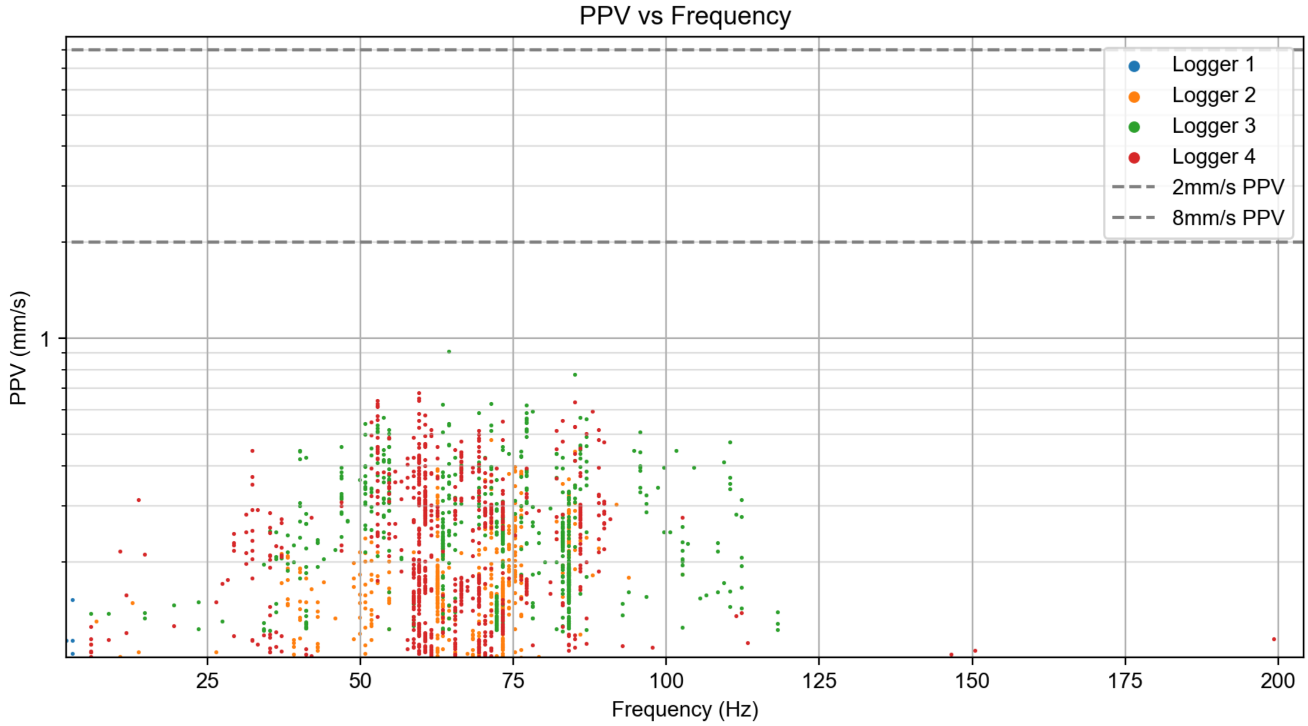

Figure 3: PPV levels for monitors close to speaker systems due to music noise emissions This event is for the subsequent iteration of the event documented in Figure with additional management strategies in place

5.3 Royal Exhibition Building – PPV levels at the Dome

A vibration monitor has been installed as close as possible to the dome, which is the highest point of the REB. Although for scenarios where the whole building is subjected to significant vibration levels, higher PPV levels in the horizontal direction are generally expected for higher levels, it was observed that the vibration monitor at the dome did not show any significant influence from music noise. This points to the fact that vibration introduced by speaker systems are higher in closer proximity to the speakers such that there is some attenuation with distance through the building structure.

6 CONSIDERATIONS REGARDING MONITORING STRATEGY FOR THE REB

As it has been established in the previous section that the Sound Pressure Levels (SPLs) generated by speaker systems are able to potentially cause cosmetic damage if not controlled, supplementary monitoring strategies are of most importance for Royal Exhibition Building in managing the risk of events with high levels of amplified music.

Monitoring vibration levels in real time can be challenging. Because of the dimension of this space, using cloud-based services to monitor PPV level without having a physical connection to the vibration monitors is imperative. Since the information has to be transmitted to the cloud, delays between measured and observed values and break ups in service can interfere in effective monitoring. Therefore, practical solutions involving monitoring SPLs to control PPV levels were investigated for Royal Exhibition Building. This included developing a correlation between measured SPLs and PPV levels to provide guidance when planning musical performances.

7 CORRELATION BETWEEN SPLs AND PPV values

During a musical performance, SPLs were measured at a location representative of the reverberant music noise level within the space and correlated to the measured PPV vibration levels. For the purposes of highlighting results for this paper, a segment of a musical performance was isolated and analysed. This segment (approximately 1200 seconds) was chosen for the performer's (DJ) use of low and high pass filters, therefore providing periods with similar overall noise levels (especially at A-weighted overall SPLs) but with significantly different spectral profiles.

Comparing the PPV levels measured at vibration monitor 10 (Z axis) and Spectral SPL data it appears that a correlation between SPL and PPV levels for SPL frequencies below 125 Hz exists, as per the 63 Hz octave band extract shown in Figure .

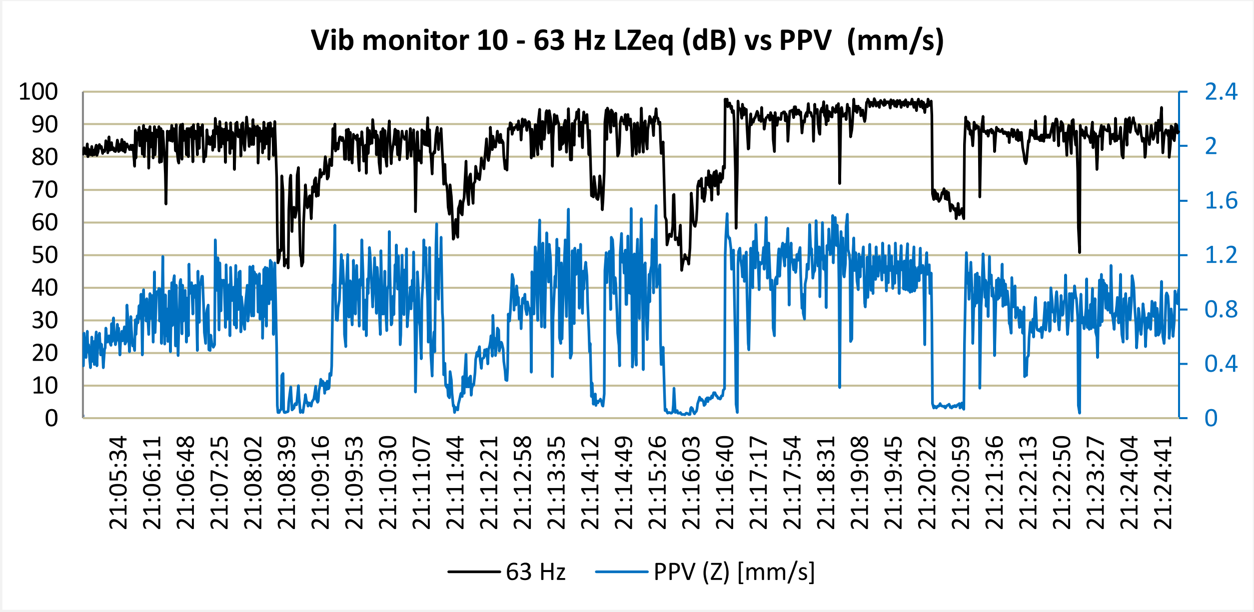

Figure 4: Vib monitor 10 - 63 Hz 1/3 octave band L_{Zeq} (dB) vs PPV (mm/s)

At higher frequencies, however, there is no strong relationship between SPL and PPV. Figure and Figure show the poor relationships between SPL at the 250 Hz octave band and overall L_{Zeq} levels respectively.

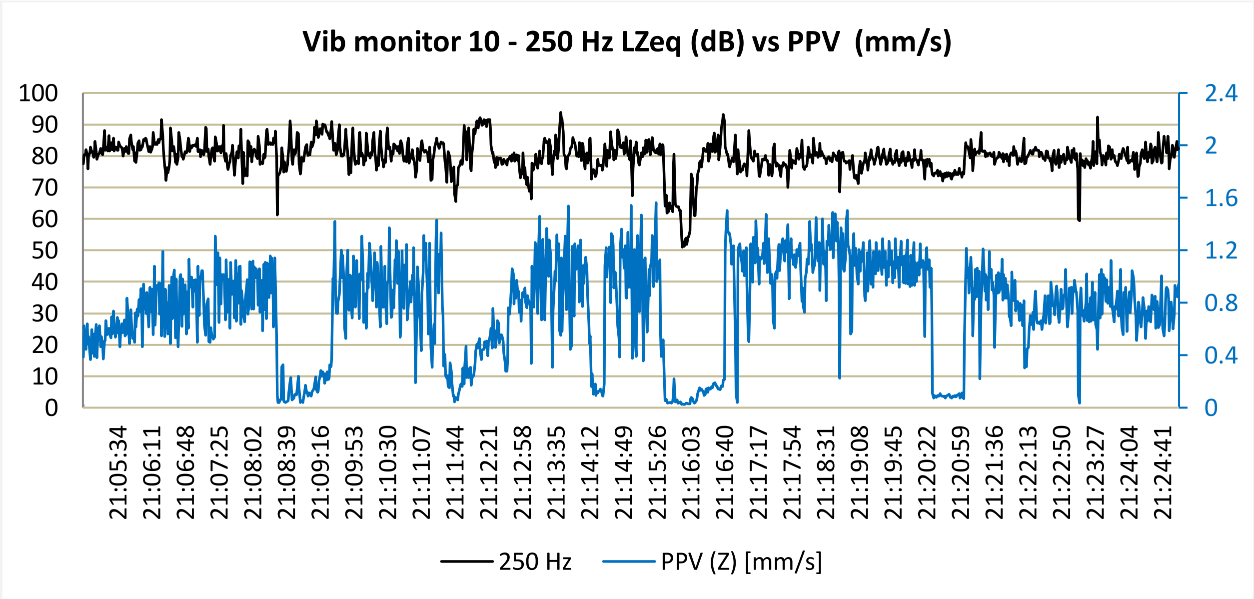

Figure 5: Vib monitor 10 - 250 Hz 1/3 octave band L_{Zeq} (dB) vs PPV (mm/s)

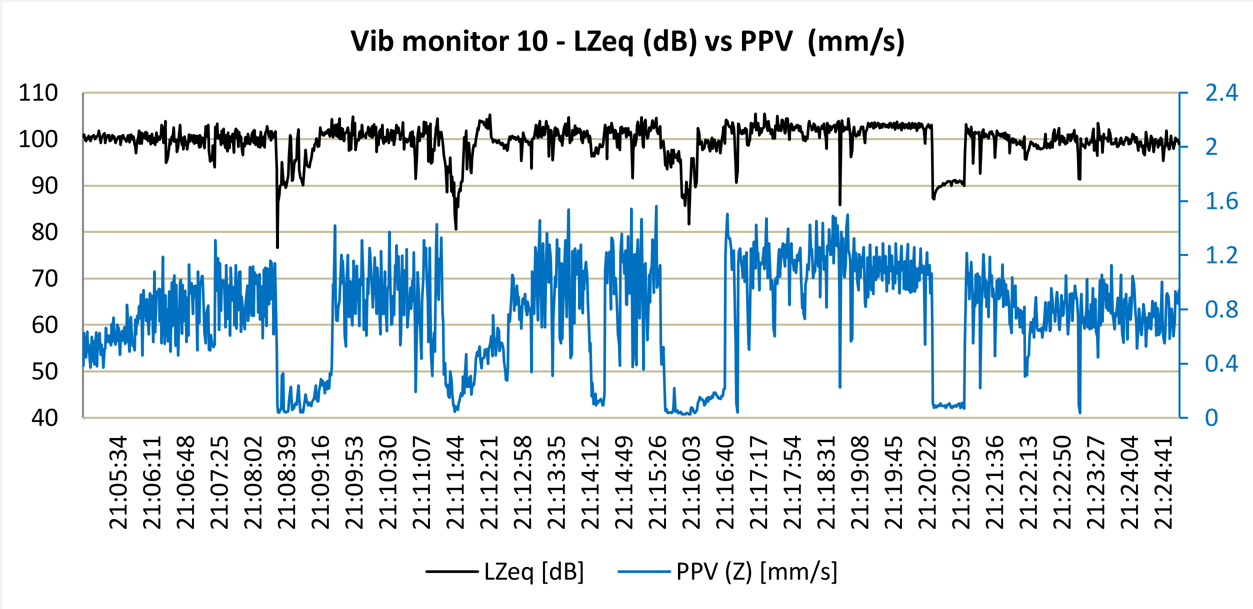

Figure 6: Vib monitor 10 – Overall L_{Zeq} (dB) vs PPV (mm/s)

To assess the above empirical observations, a Pearson correlation test was conducted between all SPL (1/3 octave band) levels and the PPV values measured for all one second data pertaining to the sample size chosen (n = approx. 1200), see Figure .

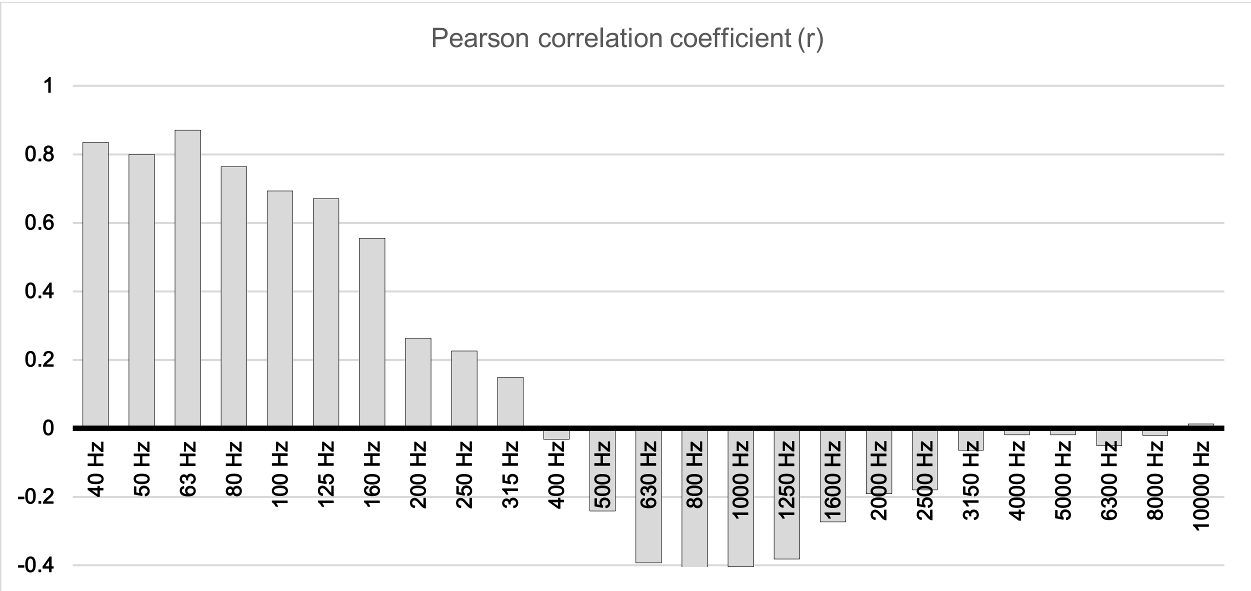

Figure 7: Pearson coefficient (r) values for SPL 1/3 octave values and PPV monitor 10 levels (Z axis)

From these results, it is evident that there is a strong correlation between SPLs at low frequencies (i.e. ≤125Hz) and the associated PPV levels. 63 Hz in particular, presents the highest correlation coefficient, which indicates that there is a significant large positive relationship between 63Hz SPLs and PPV values (monitor 10, Z axis), ($r(1202) = 0.871$, $p < 0.001$).

When looking at the correlation coefficients for overall SPL levels, a significant large positive relationship between SPLs and PPV values (monitor 10, Z axis) also is present for dB(Z) ($r(1202) = 0.727$, $p < 0.001$) and for dB(C) ($r(1202) = 0.686$, $p < 0.001$), although not as significant as for the 63 Hz. When it comes to overall dB(A) levels and PPV values, a significant medium negative relationship is present ($r(1202) = 0.385$, $p < 0.001$), see Figure .

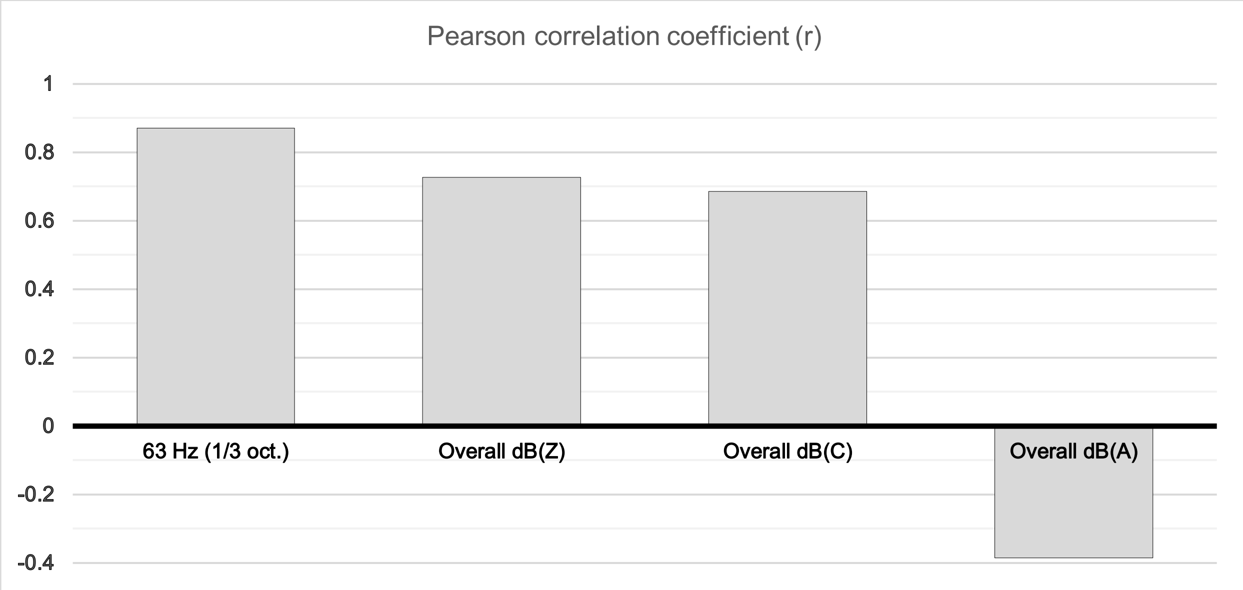

Figure 8: Pearson coefficient (r) values for 63 Hz (1/3 octave values), overall dB(Z), dB(C) and dB(A) and PPV monitor 10 levels (Z axis)

These findings suggest that, if the risk of vibration is to be controlled using controls on the SPL from a music event, this would be best done through a control on the 63 Hz one-third octave band level. If an overall metric were to be used, then this should rely on the Z-weighted on C-weighted SPL, although with some associated risk for certain types of music events.

8 PRACTICAL MONITORING STRATEGY TO AVOID VIBRATON DAMAGE DUE TO MUSIC NOISE (SPL BASED)

A more industry-standard SPL-based monitoring and management system would be simpler for event managers to implement than a vibration-based monitoring system. As per the previous section, the results show that a monitoring system based on some specific spectral frequency bands and/or specific overall SPL descriptors could effectively result in controlling PPV levels in a reliable way. It could be an effective solution for events with amplified sound to translate the existing building vibration management strategy into an industry-standard measure.

Although more in-depth, on-site testing is required to ensure that any SPL-based alert system appropriately covers multiple speaker layouts and configurations, the above results show that this could be possible and would warrant further investigation. By primarily controlling SPL levels and not directly monitoring PPV levels, factors such as latency in monitoring systems, intelligibility of descriptors for event managers and availability and familiarity with monitoring equipment could be optimised thus improving the monitoring procedure of events involving amplified speakers.

9 CONCLUSIONS

This study has highlighted key risks associated with the transmission of amplified music noise into structural vibrations within the sensitive buildings, such as the Royal Exhibition Building.

The study reveals that amplified music, particularly from large and powerful speaker systems and subwoofers, can generate vibration levels that could pose a risk of cosmetic damage to both artworks and building fabric. This is especially relevant in heritage buildings, where the degradation of sensitive materials, such as murals and plaster, exacerbates the vulnerability of the structure.

The study also identified a strong correlation between low-frequency sound pressure levels and vibration levels. Specifically, sound pressure levels at frequencies below 125 Hz exhibited a high correlation with the measured vibration amplitudes within the Royal Exhibition Building. This finding suggests that controlling low-frequency sound, especially in the critical frequency range around 63 Hz, offers a reliable method for managing vibration levels and preventing potential damage. By focusing on controlling low-frequency sound, it is possible to mitigate the risks posed by amplified music, ensuring that vibration levels remain within safe thresholds for heritage buildings and their sensitive contents, while also providing a more industry-standard and practical control for event managers than an unfamiliar vibration monitoring system.

These findings provide valuable insights for heritage site custodians, sound engineers, and event planners, offering evidence-based recommendations for managing amplified music events in sensitive buildings.

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