Footfall vibration on a high-frequency timber-steel composite walkway

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Abstract - The paper investigates the response of a light weight, high frequency timber-steel composite structure to footfall. Footfall vibration predictions methods for stiff floors are reviewed and measurement results of four different walkers using different stepping frequencies are discussed. The study focuses on the dependence of footfall vibration on stepping frequency.

1 INTRODUCTION

Human activities such as walking, dancing and running (collectively referred to as footfall) create vibrations within structures that have the potential to instigate a human response or adversely affect the operation of vibration sensitive equipment. Excessive footfall vibrations within structures can create a perception of poor construction or instability which, in turn, incites feelings of being unsafe by occupants.

Preferably, footfall vibration is assessed during the design phase of structures to minimise negative impacts on humans and vibration sensitive equipment. The accuracy of the footfall assessment is hinged upon the mathematical framework used to describe the forces imparted on the structure by human footfalls and the structure's response to the footfalls. .

The use of timber in construction is gaining popularity as an alternative to steel or concrete due to its lower greenhouse gas emissions and higher carbon storage potential ((Aloisio et al., 2023), (Karampour et al., 2023)). The aforementioned sources identify the same issues associated with the growth in the use of timber which, as articulated by (Karampour et al., 2023), are:

> Although there is ample information available, there is no harmonized method that can accurately predict the vibration performance of the timber floor systems. Additionally, the existing methods are calibrated for concrete and concrete/steel composite floors, and their direct application in assessment of timber floors is questionable.

In **Section 2** commonly used guidelines to predict footfall vibration on concrete and concrete-steel composite structures are reviewed. Particular focus is given to impulse-response prediction methods which are used for floors with very high natural frequencies. The paper then presents footfall vibration results measured on a stiff timber-steel composite structure and focuses on the dependence of floor vibration levels on the stepping frequency.

2 BACKGROUND

The fundamental frequency of a floor and its separation from stepping frequencies and associated harmonics are important design parameters in the prediction of footfall vibrations. Floors, and their corresponding responses to footfall vibration, are often differentiated by their fundamental frequency and categorised as "low-frequency" or "high-frequency" floors:

- Low-frequency floors: Floors which are susceptible to a continual and gradual increase in floor vibration with successive footfalls (a phenomenon often referred to as resonant build-up).
- High-frequency floors: Floors which have a vibration response to footfall as a series of peaks followed by a rapid decay in vibration after each successive footfall without resonant build-up.

(Karampour et al., 2023) refer to nine sources indicating that the delineation between low-frequency floors and high-frequency floors is in the range of 7 Hz to 10.5 Hz. A widely cited corollary of this is that if the fourth harmonic[1] of a maximum stepping frequency of 2.5 Hz, ie $4 \times 2.5\ Hz = 10\ Hz$, is less than the fundamental floor frequency then a resonance response is unlikely to occur. However, this delineation between low-frequency floors and high-frequency floors is not universal and (Ellis, 2000), for example, suggests that a resonant response up to the eighth harmonic may be possible, which, for a maximum stepping frequency of 2.5 Hz corresponds to a cutoff frequency of 20 Hz. (Ellis, 2000) also suggests that damping can be the critical factor following observed resonant build up on stiff but very lightly damped floors with fundamental frequencies greater than 8 Hz.

Different analysis frameworks for footfall vibration on high-frequency floors are used (refer to (Pavic et al., 2003) for an overview). One framework builds on the concept of effective impulse, I_{eff}. Conceptually, the effective impulse is a mathematical simplification of the impulse generated by a real human footstep, such that the effective impulse results in the same peak vibration response in the structure as a real human footstep. In these frameworks the maximum floor velocity caused by footfalls is assumed to be proportional to the ratio of the effective impulse over the modal mass. Based on the authors' literature review, the effective impulse is exclusively defined in the form shown in Equation (1).

$$I_{eff} = C \times \left(\frac{f_{step}^{1.43}}{f_{floor}^{1.30}}\right) \qquad (1)$$

The effective impulse has units of Ns and increases with the stepping frequency f_{step} and decreases with the floor's fundamental frequency f_{floor} (both frequencies are expressed in Hz). The stepping frequency exponent is 1.43 and was found to be replicated in all references appended to this paper discussing high-frequency floors. (Younis et al., 2017) trace the origin of Equation (1) to (Willford, et al., 2005) who based their work on 880 single footfall time histories over 40 individuals walking on an instrumented force plate (Kerr, 1998).

In (Willford & Young, 2006) and (Willford et al., 2005) a constant value of 54 Ns$^{1.13}$ is used for the term C for design purposes which includes a 25% probability allowance of exceedance with a mean value of 42 Ns$^{1.13}$ being reported. (Brownjohn & Middleton, 2008) provide identical numerical values for the term C but give units of Ns explicitly stating that the dimensions of the frequency ratio are ignored. Other studies, such as (Murray et al., 2016) present the constant value of C to be Q/1.8 after converting from imperial to metric units, where Q is the body mass in kilograms. Applying this method, C equates to 42 Ns$^{1.13}$ for a walker mass of 75 kg and 54 Ns$^{1.13}$ for a walker mass of 97 kg. (Smith et al., 2009) propose a value of Q/1.2 for C (rather than Q/1.8 as in (Murray et al., 2016)) which results in an effective impulse which is 1.5 times greater. The authors of this paper surmise

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[1] The frequency of the Nth harmonic is N-times the stepping frequency.

this is due to the load safety factor of 1.5 as per Annex C, Eurocode BS EN 1990:2002 cited in (Smith et al., 2009).

The stepping frequency exponent of 1.43 and floor frequency exponent of 1.30 in Equation (1) have not been found to be altered in the literature reviewed by the authors[2]. All cited references were historically developed for the analysis of concrete or steel-concrete composite floors. The use of the effective impulse as defined in Equation (1) is, however, proposed for timber structures in (Wood Products Council, 2023) and (Cheraghi-Shirazi et al., 2022).

For the same floor (that is the same modal mass and fundamental frequency f_{floor}) the dependence of the effective impulse on the stepping frequency exponent can be expected to be identical to the dependence of the floor velocities on the stepping frequency exponent. This paper derives the stepping frequency exponent for a stiff timber-steel composite walkway floor based on floor vibration experiments which, in terms of stepping frequency exponent, was found to differ substantially from the exponent of 1.43 commonly used in literature. This paper does not aim to extract effective impulses.

3 WALKWAY DESCRIPTION AND FOOTFALL TESTS

Walking tests were conducted on an elevated walkway (**Figure 1**) which measures 1.5 m by 5.3 m and has a slight gradient. Steel handrails bound the perimeter of the walkway, lined with a steel wire mesh. The walkway is located in SLR Consulting Australia’s Sydney office and its construction is typical of that used throughout Level 1.

The walkway’s deck is a 22 mm particleboard deck topped with a 4 mm vinyl-cork surface layer. Longitudinally, the edges of the deck are supported by composite timber-metal stringers, with a composite stringer consisting of 3×45 mm thick and 300 mm deep timber beams which sandwich a 10 mm thick steel plate which forms part of the handrail. Three timber stringers support the deck on the inside. The two off-centre stringers are tied in with the edge stringers with timber transverse panels and horizontal steel tie rods at 620 mm spacing.

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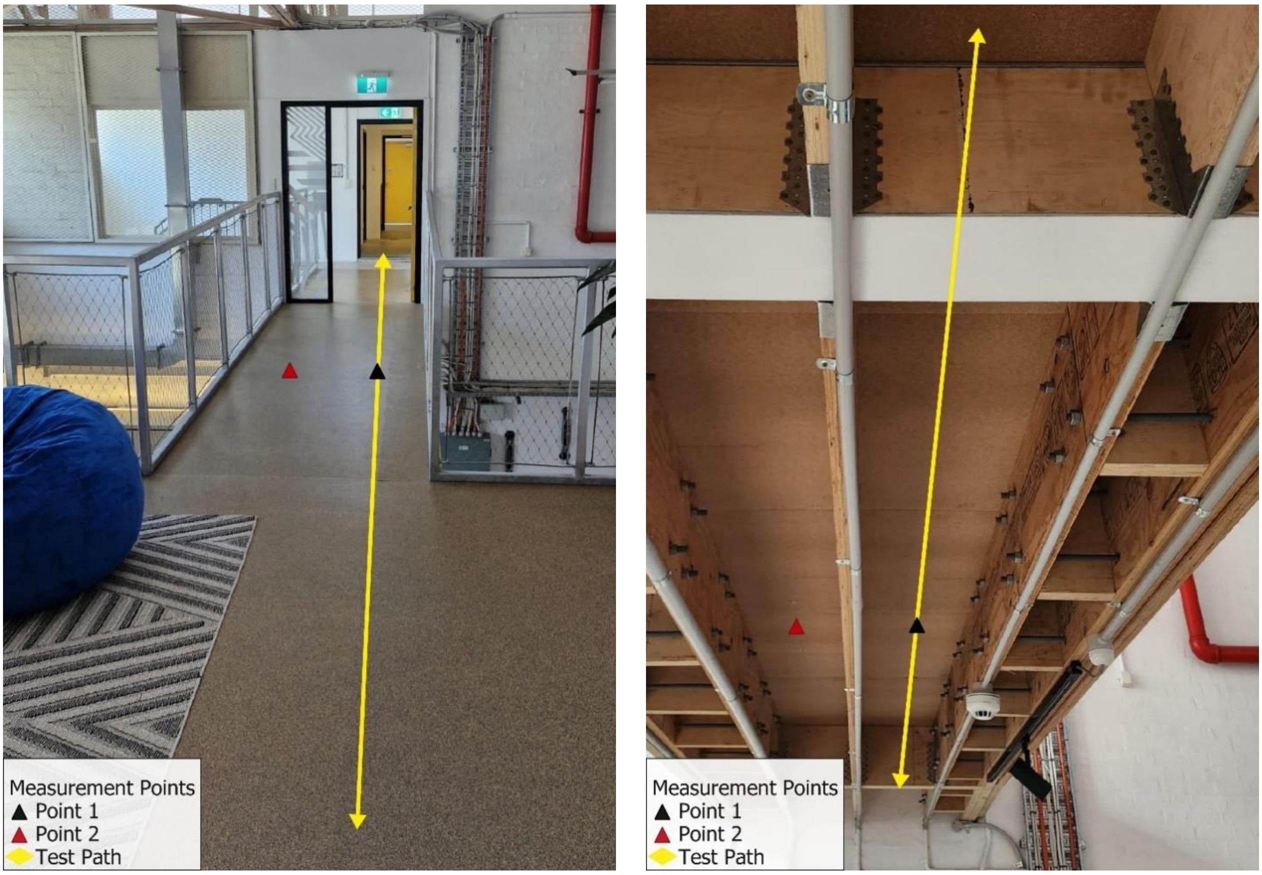
[2] (Murray et al., 2016) list a stepping frequency exponent of 2.43 for the calculation of 1/3 octave levels but this is judged to be a typo as elsewhere in this design guide and the cited source (Liu & Davis, 2015) both use a stepping frequency exponent 1.43.

Figure 1 Walking path and walkway.



Walkway deck Walkway underside

Walking tests were conducted with walkers following a nominated test path, along the right side of the walkway, shown in **Figure 1** in yellow, before turning and returning to the start point along the test path. The walking path of participants extended beyond the walkway where users turned. On the walkway itself, participants tried to maintain a constant speed. Four walkers, weighing 75 kg, 100 kg, 104 kg and 126 kg were selected to perform the tests all with varying shoe types worn, **Figure 2**. The walkers did not use metronomes to maintain constant stepping frequencies and walked freely at their natural pace at slow, medium (or natural) and fast speeds. At each speed, a walker would cross the walkway six times. In this paper, measurement results for each walker are labelled by the walker's weight (**Figure 2**).

Two PCB 393A03 accelerometers were hot-glued to the underside of the deck, at the midpoint of the span, one directly below the test path (Point 1) and the other on the opposite side of the span (Point 2). The accelerometers have a nominal sensitivity of 1 V/g and a ±5 % frequency range down to 0.5 Hz.

The instrumentation also included proximity probes which were mounted to the steel columns supporting the walkway and measured static and dynamic deflections. The deflection associated with a 100 kg person standing on the walkway was recorded and the static stiffness of the walkway in vertical direction was determined to be 2.2 MN/m at Points 1 and 2. The static walkway mass was calculated to be 1,100 kg based on estimates of the volume of parts and their densities.

Figure 2 Shoes worn by the walkers and walkers' mass.

75 kg 100 kg 104 kg 126 kg

4 IMPACT RESULTS

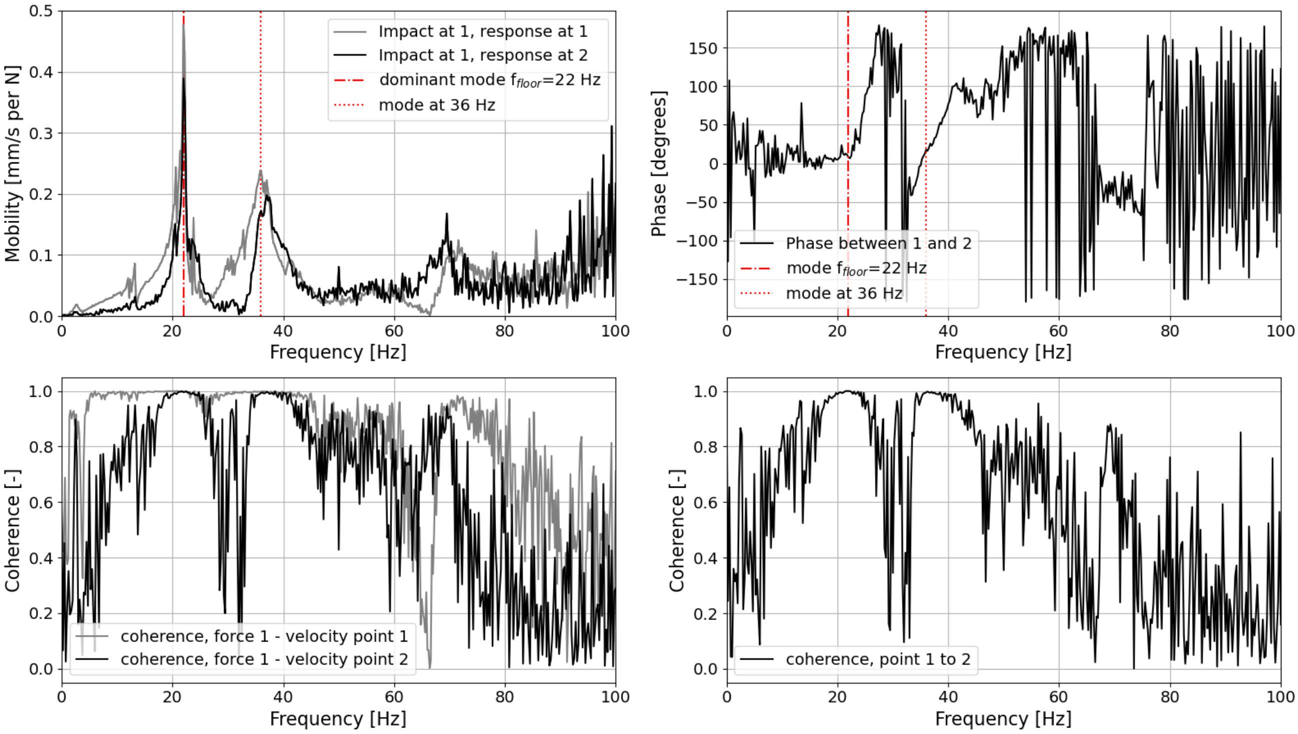
With reference to the points identified in **Figure 1**, a 100 kg person was squatting on the walking path and impacting Point 1 in vertical direction. The vertical walkway acceleration response at Points 1 and 2 were recorded. Results were averaged over five impacts using 5 second windows (yielding a frequency resolution of 0.2 Hz) and converted from acceleration to velocity in the frequency domain by division of the complex circular frequency $j\omega$.

Selected results are collated in **Figure 3** showing the mobility magnitudes and coherences for impacts at Point 1 on the walking path and responses at Points 1 and 2 as well as the phase relationship between Points 1 and 2. The dominant response is at 22 Hz and is the walkway's fundamental frequency f_{floor} and there is excellent coherence observed near the dominant response. At 22 Hz, Points 1 and 2 are in phase and therefore this mode is judged to be a vertical walkway mode. The mobility also indicates a mode at 36 Hz where Points 1 and 2 are in phase also. The modal mass at 22 Hz is estimated to be around 700 kg, slightly more than 50% than the estimated total mass of the walkway.

There is energy present at 12 Hz and 13 Hz and the phase change of the mobility at these frequencies is around 45 degrees. These modes, however, were not found to be excited during the footfall tests as discussed in **Section 5** and were not further investigated.

Compared to concrete floors the authors have measured footfall vibration on (Miller & Duschlbauer, 2013), (Duschlbauer & Miller, 2014) and (Qian et al., 2017), the mobility on the timber-steel composite walkway is an order of magnitude higher (ie more 'lively') and the modal mass is an order of magnitude lower (ie lighter) than that of typical concrete floors. These characteristics highlight the differences in the dynamic properties of the tested structure relative to typical concrete floors.

Figure 3 Impact test results.



5 FOOTFALL RESULTS

Walker footfall results are presented for Point 2 only (refer to **Figure 1**) which was located adjacent to the walking path. The accelerations for a walker were recorded continuously with a sampling frequency 2560 Hz and a 1000 Hz anti-aliasing low pass filter. The accelerations were high-pass filtered using a 1 Hz corner frequency and subsequently integrated to velocities and converted to units of mm/s.

The top graph in **Figure 4** shows the results for the 104 kg walker. The two smaller graphs in **Figure 4** show an example of individual walking sequences that were analysed in detail. The stepping frequency was interpolated from the spectrum (Gasior & Gonzalez, 2004) and then visually verified in the time domain by plotting vertical lines spaced at $1/f_{step}$, as obtained by interpolation; for the case presented in the lower right graph in **Figure 4**, the stepping frequency was 2.06 Hz. The spectrum for the 5 s segment, shown in the lower left graph in **Figure 4,** exhibits clearly identifiable third, fourth, fifth and sixth harmonics but they are not dominant. The dominant response occurs at 21.6 Hz, close to the fundamental walkway mode at 22 Hz as determined in the impact tests Section 3.

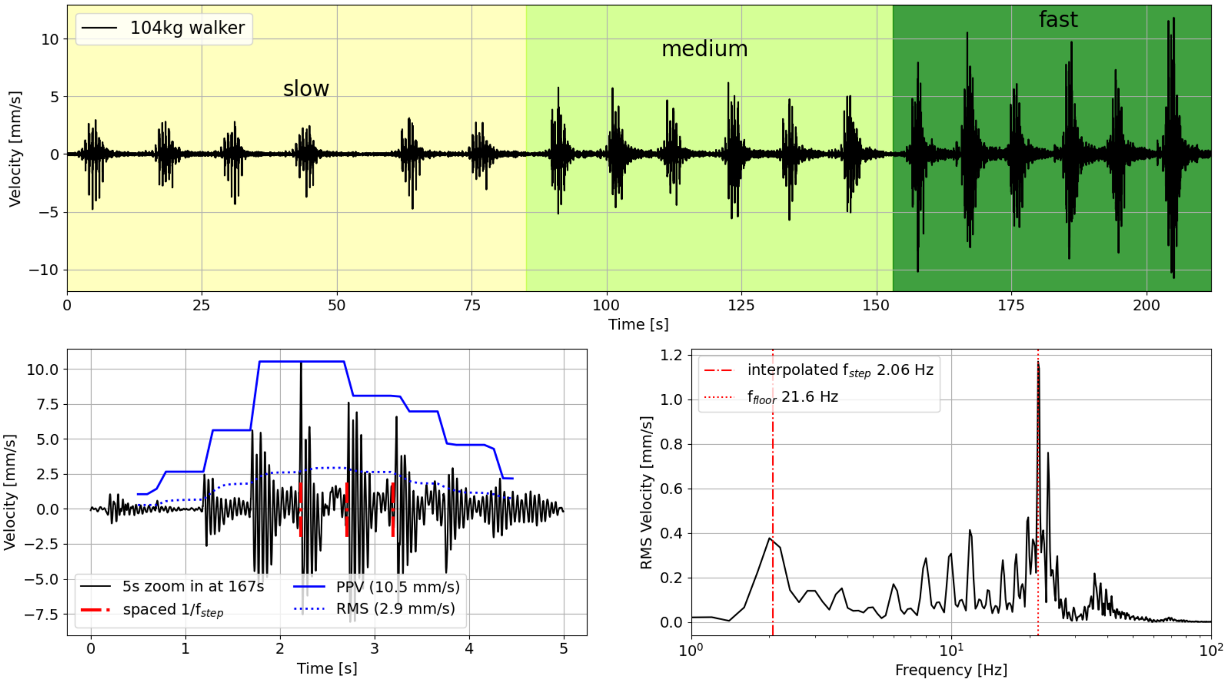
Results have not been split into walking ‘up-hill’ or ‘down-hill’ as **Figure 4** does not suggest an alternating trend in high and low readings depending on the direction; this reflects the slight gradient of the walkway.

Walkway vibration was also measured ±300 mm longitudinally (ie in the direction of the walking path) spaced from Point 2 to check whether the results are dependent on the location of the footfall impact relative to the sensor. It was found that the readings at these extra locations were almost indistinguishable from each other and the measurements at Point 2.

In addition to the stepping frequency, the Peak Particle Velocities (PPVs) and maximum Root-Mean-Square (RMS) velocity levels were calculated. The RMS levels were calculated for 1 s windows and 90% overlap. For the walking sequence presented in **Figure 4**, the crest factor is 3.6 when calculated in the velocity domain.

The data presented in **Figure 4** have not been normalised to body weight. In this particular case, the PPV normalised to 75 kg (ie the lightest of the four walkers) would become $10.5 \times \frac{75}{104} = 7.6$ mm/s, as the walker's weight was 104 kg.

Figure 4 Results for 104kg walker not normalized for walker mass.



The symbols in **Figure 5** present the results expressed in terms of PPVs and RMS velocities for each individual walkover of a walker. The presented velocities have been normalised to a walker mass of 75 kg, the mass of the lightest walker[3]. This mass corresponds to a mean value for an effective impulse of C=42 $\text{Ns}^{1.13}$ for the coefficients used in Equation (1).

The data points in **Figure 5** were fitted with curves[4] of a form, which is analogous to Equation (1):

$$v = A \times f_{step}^{B} \tag{2}$$

Where the interpolation of velocity (v) has been based on either the PPV results or RMS results. The term 'A' is a constant and with reference to Equation (1) would be inversely proportional to the walkway's frequency exponent $f_{floor}^{1.30}$. The constant 'A' would also be inversely proportional to the modal mass.

Effective impulse methods predict PPVs for each mode of interest and following a summation of each modal response in the time domain, RMS levels are calculated. As such the stepping frequency exponent would apply

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[3] In the subsequent analysis, the reference weight used for normalising does not change the stepping frequency exponent.

[4] Curves are fitted using non-linear least squares method using Python SciPy v1.13.1 scipy.optimise function curve_fit.

to the variation of PPVs and slightly different exponents may be expected when results are expressed in terms of RMS velocities.

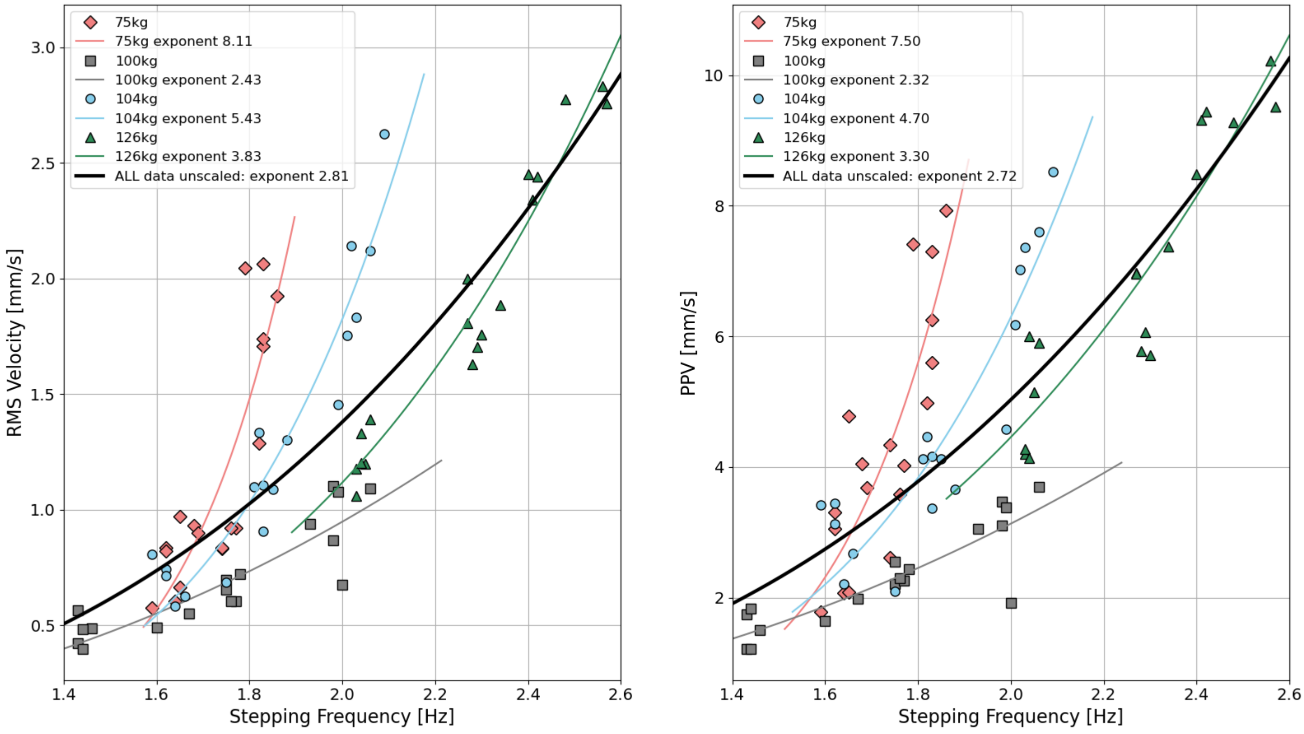
Between the four walkers the stepping frequencies were found to range widely. The stepping frequencies walkers thought of as ‘slow’ ranged from 1.4 Hz to 2 Hz and ‘fast’ ranged from 2 Hz to 2.5 Hz. In general, three distinct frequency clusters of results can be identified for each walker corresponding to the walkers’ definition of ‘slow’, ‘medium’ and ‘fast’ walking.

In terms of absolute vibration levels and with respect to human comfort, the measured walkway vibration levels are deemed comparatively high. The highest PPV measured was 17.2 mm/s for the 126 kg walker which becomes 10.2 mm/s after normalising for a walker mass of 75 kg. The corresponding RMS level, not adjusted for walker mass, is almost 5 mm/s. The subjective human response to walkway vibration has not been considered as part of this paper.

For both presentation metrics, PPVs and RMS values, similar conclusions can be drawn. The key observation is that the stepping frequency exponents are much greater than 1.43 and range from 2.32 (the 100 kg walker, PPV) to 8.11 (the 75 kg walker, RMS). Exponents are always greater when the data are expressed in RMS rather than PPVs.

The black curves in **Figure 5** have been fitted to the whole dataset using the same curve-fitting method applied to the individual data. For these curves, the stepping frequency exponents are 2.72 and 2.81 for results expressed in PPVs and RMS velocities, respectively. The stepping frequency exponents when fitted to the unscaled dataset are 3.68 and 3.76 for PPVs and RMS, respectively. For the dataset used in this study, scaling the results by walker mass reduces the stepping frequency exponent considerably as the fastest walker happened to be also the heaviest walker.

Figure 5 RMS velocities (left) and PPVs versus stepping frequency, scaled by mass.



In summary the measurement results show that the timber-still composite walkway's response to footfall vibration is much livelier than would be expected for a reinforced concrete floor. This might seem counterintuitive initially, given its very high natural frequency which suggests it is very stiff. Unlike an equivalent reinforced concrete floor, however, the walkway is comparatively light weight.

Because of these differences, assumptions underlying the idealised effective impulse may not be met in practice for timber walkways as (Karampour et al., 2023) note:

> The existing dynamic vertical forces are based on measurement of footfall forces using force plates and on stiff grounds. Furthermore, these force models do not account for the human-induced response between the walker and the floor, such as the feed-back phenomenon observed between the user and the structure with the Millennium Bridge.

6 CONCLUSIONS

A footfall vibration study has been carried out on a stiff timber-steel composite walkway floor with a fundamental frequency of 22 Hz. Four different walkers with a weight ranging from 75 kg to 126 kg were used in this study and the walkers walked freely at speeds they would classify as 'slow', 'medium' and 'fast'.

The stepping frequencies in this study ranged from 1.4 Hz to 2.6 Hz. Following a curve fitting process, the dependence of measured velocities was found to require stepping frequency exponents significantly greater than 1.43 as is commonly recommended in literature. For individual walkers, the exponents were found to range from 2.3 to 8.2, depending on whether results are evaluated in RMS or PPV metric. The stepping frequency exponents when fitted to the mass-scaled whole dataset were found to be 2.7 for PPV and 2.8 for RMS velocities. The exponents are well above the stepping frequency of 1.43 ubiquitously referred to in literature.

While effective impulses were not calculated from the data, the stepping frequency exponents describing the effective impulse's dependence of the stepping frequency can be expected to be identical to that obtained for the walkway velocities as the modal mass and fundamental floor frequency can be considered constant for the tests.

Further work is required to understand how the stepping frequency exponent 1.43 has been derived and whether it remains appropriate for application to light weight, high-frequency timber floors. The tests certainly demonstrate that real world stepping frequency exponents vary greatly and may be dependent on the walker mass, walking style and shoes worn as well as the dynamic floor properties.

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