

Vibration serviceability assessment of floors in a multi-use multi-storey industrial complex

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ABSTRACT

Vibration serviceability assessments were carried out on the floors of several ‘units’ of an industrial complex in Singapore.

Floors tested were within large two-level structural units described as detached, semi-detached and terraced and having usable single floor areas up to 2100m². All floors were constructed from hollow core slabs with spans up to 12m and all nominally behaved as high frequency floors.

Occupancy conditions ranged from empty and untenanted through to usage for warehousing, instrument assembly and testing, electronic equipment manufacture to light manufacturing and machining of metal structures. Forms of loading included internal and external vehicles, human footfalls and excitation by machinery.

The study identified the most onerous form of loading and provides guidance for facility owners with mixed vibration serviceability requirements.

VIBRATION SERVICEABILITY OF INDUSTRIAL BUILDINGS IN SINGAPORE

Multi-story multi-tenant industrial developments such as the one studied in this paper are popular in Singapore and accommodate businesses ranging from micro-electronics to metal fabrication. Vibration generating activities and serviceability requirements vary widely with possible mismatch between neighbors.

Such facilities are massive concrete structures, frequently a single large building. Following the collapse of the Hotel New World in Singapore in 1986 (SCOSS, 1988), local building designs tend to be conservative and face very strict legal requirements on construction and safety. Now, while structural safety is properly addressed, vibration serviceability is usually adequate due to the heavy concrete with ‘high frequency’. Such floors are not capable of experiencing resonance due to human footfalls (Pavic and Willford, 2005).

Even so, good vibration performance is not guaranteed and problematic vibration performance of such massive structures does occur. Accounts of such problems are rare, so this is an unusual opportunity to report on vibration performance on a large scale.

S1 COMPLEX

The S1 complex Figure 1 is a large multi-story factory sometimes referred to as a stack-up (Pan and Mita, 2001). It comprises an array of two-level units stacked up to a total of six levels, plus mezzanines. Heavy goods vehicles can access the lower level of each unit (i.e. first, third and fifth levels), with wide driveways and spiral ramps between vehicle access levels.

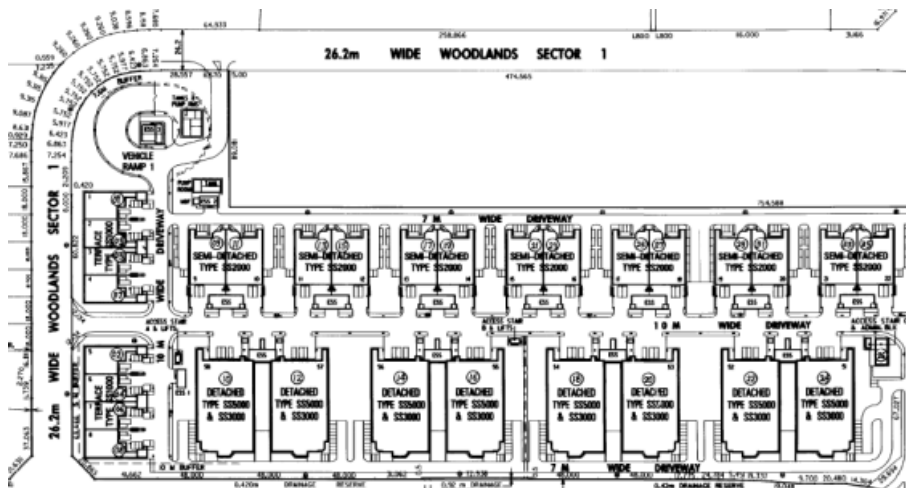


Figure 1: Plan and views of S1 complex. Lower left: stacked pairs of T2000; Lower mid: levels 5&6 of T3000; Lower right: interior of T2000 lower level

S1 comprises 24 T1000, 42 T2000, and 24 T3000/5000 units. T1000s are arranged in two terraces each with twelve units and T2000 units are arranged in seven blocks of semi-detached (adjoining pair) units. The T5000/3000 units are arranged in eight detached (stand alone) blocks comprising a T5000 unit with two T3000 units stacked on top.

The unit type numbers refer to the nominal total area in square metres over the two levels in multiple bay floors, although the maximum usable floor space is somewhat less. For examples T5000 usable area at ground level is 2100m².

Storey heights range from 6.2m to 8.4m, with spans and bay sizes depending on type. In all units, continuous reinforced concrete columns support one-way spanning main beams with 1.2m wide precast pre-tensioned hollow core planks of varying depth forming the floors.

FLOOR DETAILS

Ten floors in eight units were selected for in-operation measurements. Observations on T1000 units are not reported.

Table 1 summarises the ten floors and their usage while (figure) shows examples in operation and/or during testing. To identify the floors, the first number is the unit type, the second number is the roadway level (1, 3 or 5) and the letter L/U indicates lower or upper level. To provide a unique identification a tenant number is appended. Hence 2000-5U-6 is the upper floor of the T2000 unit having street address identified as level 5 and occupied by tenant 6.

Table 1

Floor	Usage	Low modes		High modes		VC and peak band centre f (Hz)	
		f / Hz	m /10 ³ kg	f/Hz	m/10 ³ kg	FLT	walking
2000-1L-3	storage	-	-	-	-	-	D: 10
2000-3L-4	empty	12.9	180 /130	16.9	180	-	A: 20
2000-5U-5	empty	12	47	20.5	-	-	>ISO: 12.5
2000-5L-6	instrument assembly	12.4	80	-	-	-	A: 12.5
2000-5U-6	storage	12	-	-	-	-	-
3000-3L-7	metalwork	10.4 /12.2	60 /150	36.4	38	>ISO	A: 10
3000-3U-7	storage	9.5 /10.7	120 /88	39.1	45	ISO	A: 10
3000-3L-8	warehouse	10.5	120	37.1	35	>>ISO	ISO: 10
3000-5L-9	Micro-electronics manufacture	9.6	150	37.3	28	-	A: 10
5000-1U-10	optical instrument assembly & test	11.1 /12.5	200 /200	35.5	36	-	>ISO: 12.5

Table 1 also provides performance information discussed later e.g. the experimentally observed natural frequency of the lowest vibration mode or modes relevant to the response observations.

The architectural plans for an exemplar T2000 is shown in Figure 2. The figures also show some structural details, measurement points and paths for the

walking testes performed. T2000 units Figure 2 have two bays spanning 12m, one of them narrowed by arrangement of internal facilities.

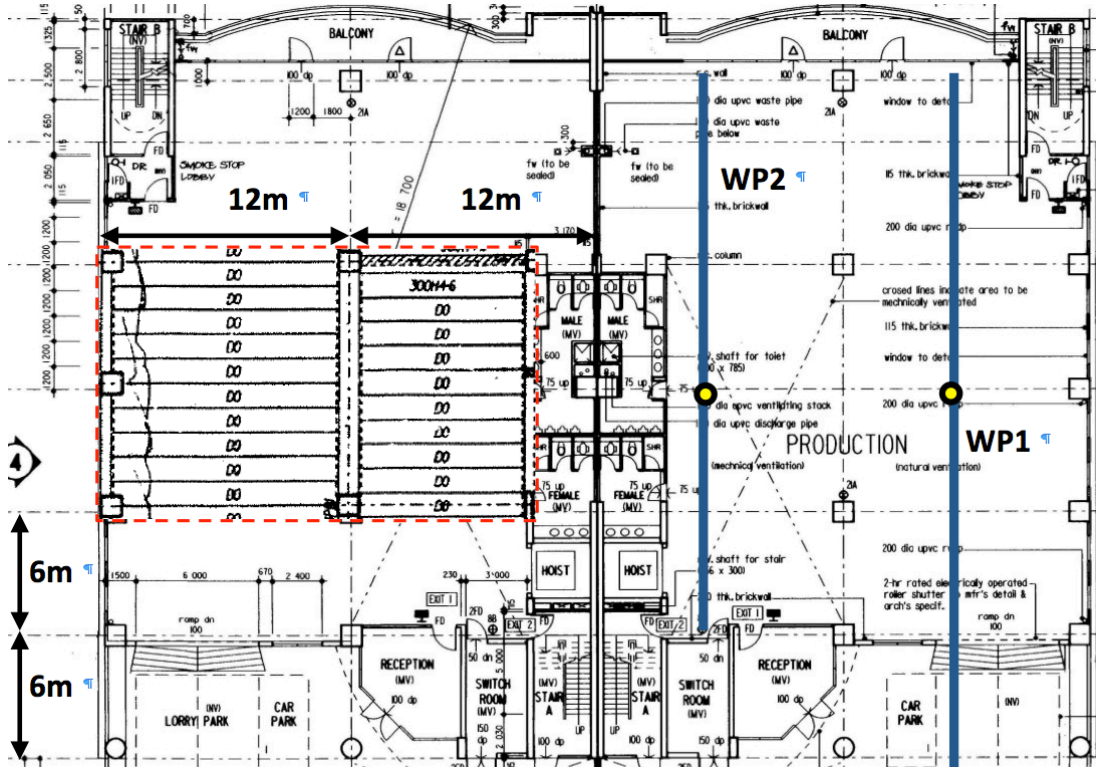


Figure 2: Pair of T2000 units (lower level), showing floor plank arrangement in cutaway, walking paths and test points,

The T3000/5000 units (not shown) have 6m and 18m bays spanned by main beams, at 7.5m intervals spanned by planks. Both have a 12m bay that is used as an open air car park for T3000 units (hence the reduced usable floor area). The hollow core planks span the direction orthogonal to those in T2000 floors.

EXPERIMENTAL MODAL ANALYSIS

Modal tests were done on eight of the ten floors using standard (proven, reliable) single input/multiple output (SIMO) procedures (Ewins, 2000). Full mode shapes were obtained for 2000-3L-4, while partial mode shapes e.g. along mid-bay line were obtained for other floors.

The modal testing used two systems. For recovery of a complete set of modal properties including mode shapes from 2000-3L-4 an APS4000 long stroke shaker, four QA-700 servo-accelerometers, signal conditioner and NI USB-9239 were used. For modal property estimation with incomplete mode shapes, and for all measurements of response to machinery, vehicles and walking, four Endevco 7754-1000 IEPE accelerometers and NI USB-9233 were used. An instrumented hammer was used for modal parameter estimates. Both in-house and commercial modal parameter estimation software was used.



Figure 3: Modal testing. Clockwise from top left: Hammer test using instrumented hammer and IEPE sensors; helpers and observers in 2000-3L-4; Quartz-flex accelerometers, signal conditioner and National Instruments compact DAQ; APS400 shaker.

Point mobility frequency response function (FRF) measurements from all tested floors are summarized Figure 5 plotted as absolute values of the inertance. Inertance (also known as accelerance) is the ratio of acceleration to force and has units of mass^{-1} . System identification by GRFP curve fitting to the complete set of FRFs provided estimates of mode frequency, damping and mass.

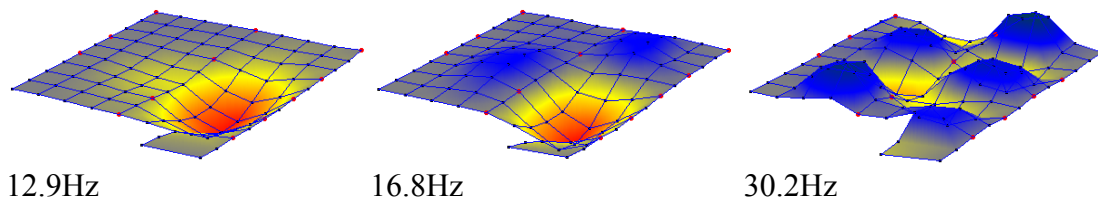


Figure 4: Sample modes from 2000-3L-4

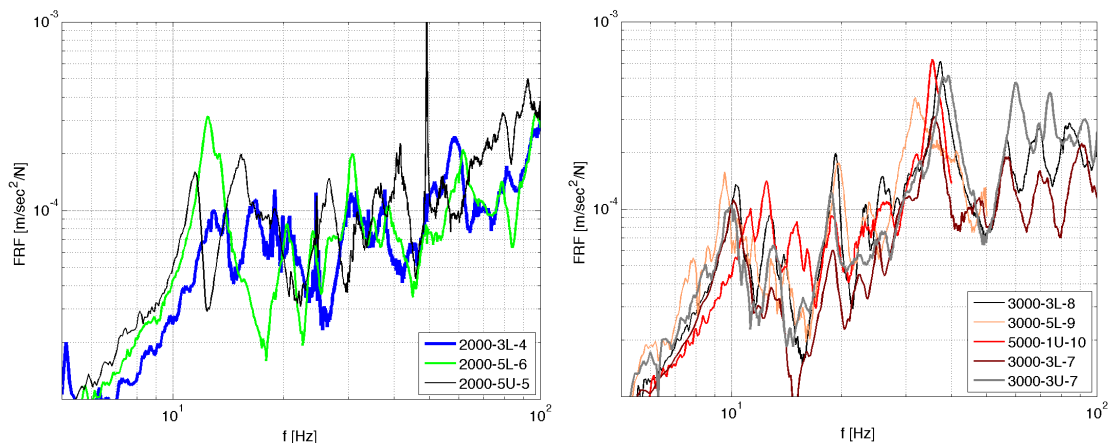


Figure 5: Point mobility FRFs for most lively mid-bay locations

The performance of the T2000 floors is variable despite their nominal similarity, whereas the T5000/3000 floors have similar characteristics. All floors exhibit first mode natural frequencies in the range 9-13Hz, but T5000/3000 floors have a cluster of modes with high mobility values in the 30-40Hz range. These features are linked with modal mass values, for example the 30-40Hz T5000/3000 modes have modal masses between 28 and 45 tonnes and the T2000 modes range from 45 to 180 tonnes (1 tonne=1000kg).

EVALUATION OF OPERATIONAL DYNAMIC PERFORMANCE

The main aim of the exercise was to report on the vibration levels in the different floor types according to usage, while providing some explanation through the EMA modal properties. Hence response measurements were made for the following conditions with data presented in the form of acceleration time series, three dimensional power spectral density functions and one-third octave RMS velocities.

- Normal operation with a range of excitation sources including machinery, forklift trucks, workers etc. Results indicate response conditions within the control of the tenants.
- Controlled walking along paths such as indicated in Figure 2 with prompting by metronome at specific pacing rates. The walking forces are almost identical between floors so results provide a benchmark for comparison.

RESPONSE TO OPERATIONAL DYNAMIC LOADS

Operational loads included machinery operating in the unit or its neighbors, vehicles including forklift trucks and pedestrian (worker) footfall.



Figure 6: Operational load sources. Metal-working machinery (3000-3L-7), forklift truck (3000-3L-8) and pedestrian (5000-1U-10)

Response to forklift trucks

Use of forklift trucks (FLT) is of course widespread in an industrial complex. As with internal machinery, information about effects of FLT on floors is sparse, so far mostly appearing as doctoral studies in relation to low frequency floors (Eriksson, 1994; Ehland, 2010; Ehland et al., 2009). To add to this, example responses are presented Figure 7 for three different FLT on three T3000 floors.

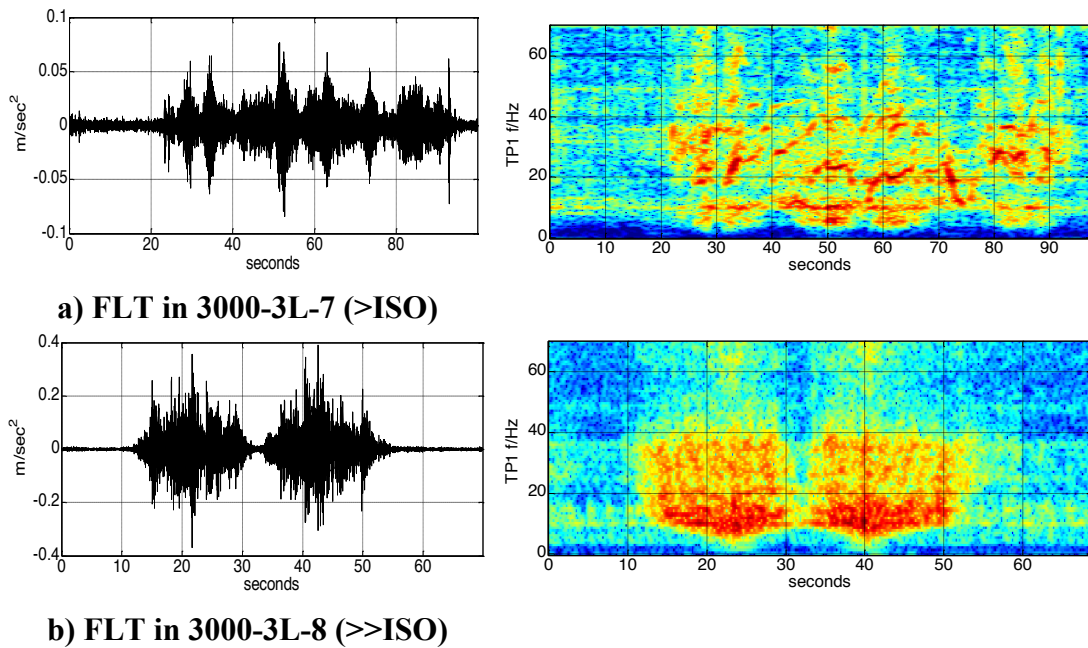


Figure 7: Response to FLT on Type-3000 floors as time series and spectrogram.

In the first example, a diesel powered Toyota model 25 was driven along the centerline of the 18m span bays in floor 3000-3L-7. This floor is smooth and the FLT used pneumatic front tyres. The resulting response is broadband, as shown in Figure 7a, including a significant component at the first (floor) mode frequency, 10.4Hz, leading to a rating $>ISO: 10Hz$.

The second FLT studied was a small electric Komatsu 15R unit used on the smooth floor of the upper level (3000-3U-7) of the same unit. The response (not shown) had a rating $ISO: 10Hz, 20Hz$.

The third FLT studied (Figure 6 middle and Figure 7b) was an electric Toyota machine that was progressively moving loaded pallets from inside floor 3000-3L-8 to the structurally connected external car park (with 12m spans). This floor surface is unsmoothed concrete, with a construction joint. Figure 7b shows a response measurement during a single round trip of the FLT, including the sharp transients while passing the joint. This is the strongest response recorded during the measurement campaign, with the FLT clearly exciting a number of vibration modes. The response massively exceeds even the ISO limit (\gg ISO: 10Hz) with 1 mm/second RMS velocity.

Response to internal machinery

Few of the units tested operated heavy manufacturing machinery. The example shown is for the two folding presses in Figure 6 for which Figure 8 shows time series, one-third octave spectra and 2D and 3D spectrograms. The peak accelerations are similar to the worst case FLT response, but they last for no more than a second so that one-third octave levels averaged with 10-second averaging time are not so extreme. In this cases it is clear that that both low and high modes are engaged.

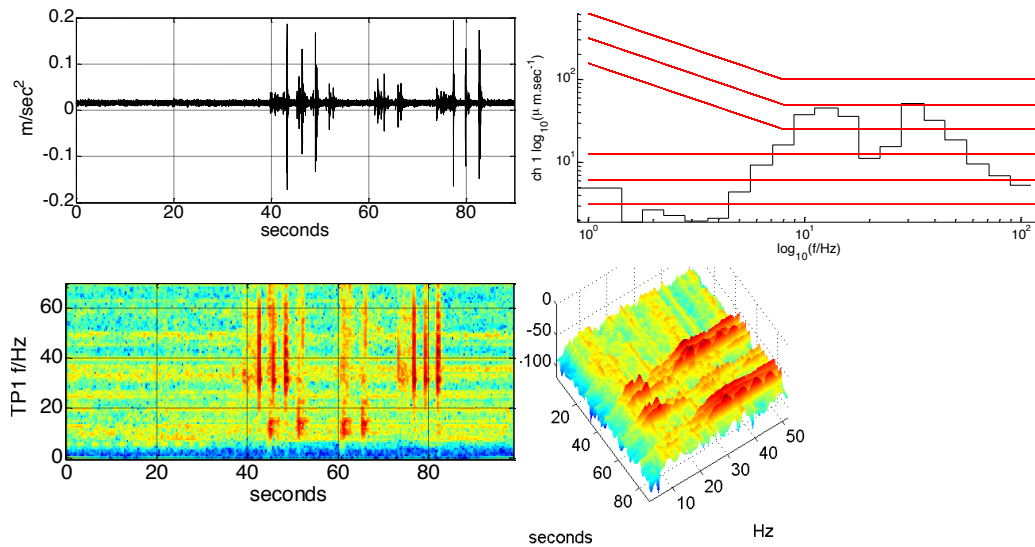


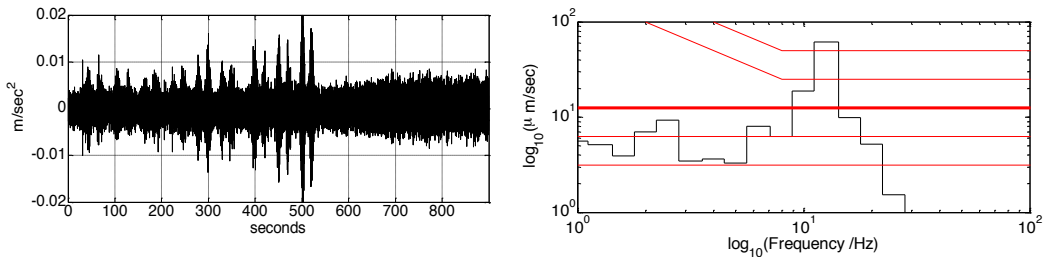
Figure 8: Response to fixed internal machinery presented four different ways. Metal folding press in 3000-3L-7 (ISO: 32Hz).

Response to controlled walking (footfall)

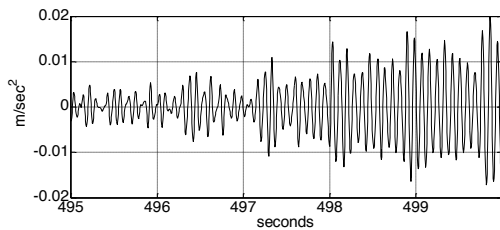
The common denominator and performance benchmark among the measurements is the standard walking test, in this case using a 100kg pedestrian. The walking tests comprised a sequence of round trips along a designated walking path at specific prompted pacing rates from 90 to 144 paces or beats per minute (bpm), increasing by 6bpm each round trip. The forcing functions were effectively a standard loading in a narrow range of discrete multi-harmonic frequencies. Behavior of two T2000 units is presented here.

For empty floor 2000-5U-5 (Figure 9) responses are partially obscured by steady background vibrations in first mode at 12Hz. Response is only shown for a point in the bay containing WP1 (Figure 2) for which response is strongest due to forcing at the fifth-harmonic of the fastest achievable pacing at 144 bpm that coincides with the 12Hz mode. Part of the explanation is that effective impulse increases with pacing rate, but fifth harmonic is neglected in floor vibration analysies (Pavic and Willford, 2005).

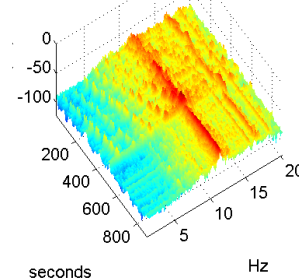
Figure 10 for floor 2000-5L-6 shows response levels that clearly increase with pacing rate (larger effective impulse). The result is a rating of VC-A solely due to the first mode response, which occurs in the 12.5Hz band.



Response low-pass filtered at 40Hz



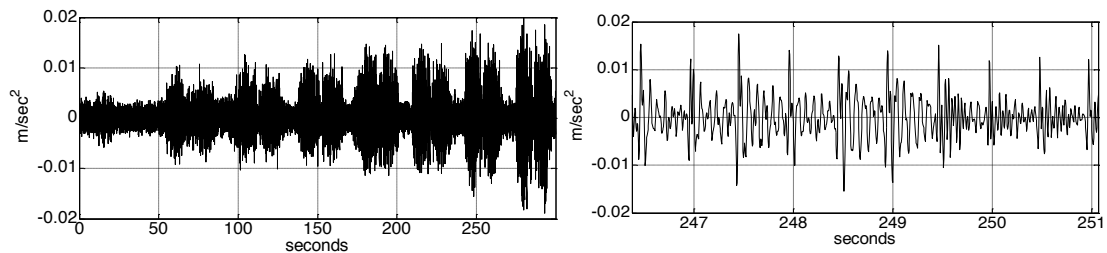
Peak-hold one-third octave spectrum



Zoom into time series

Spectrogram showing strong response at 500 s due to 5th harmonic of pacing rate

Figure 9: Walking tests in 2000-5U-5 (>ISO: 12.5Hz).



Response low pass filtered at 40Hz. Response increases with pacing rate due to increasing effective impulse

Zoom showing classical high frequency floor response and lack of resonance build-up

Figure 10: Walking tests in 2000-5L-6 (VC-A: 12.5Hz).

DISCUSSION

The aim of the modal analyses and vibration surveys was to characterise the vibration environment according to floor type, floor level (high or low) and usage and to rationalise this behaviour. The study (only part of which is described here) was intended to support a performance-based approach to floor selection, so that tenants could select (and even pay) according to vibration performance requirements or management could control occupancy according to usage profile of a tenant.

Worst performance was observed with operation of forklift trucks (FLT), and worst of all with stiff tyres moving over rough concrete with construction joints.

Response to walking was a useful comparator, although background vibrations due to unidentified external machinery tended to obscure clear comparisons.

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