Experimental observation of forklift-induced vibrations on a PSC floor

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Abstract

The interaction between service vehicles and the structures they operate in is of a key concern to the design of flooring systems in vibration sensitive buildings. Forklift induced floor vibrations from up-down movement of their payload on the mast, the forklifts themselves traversing the floor at speed with different levels of payload in place and/or negotiating an inclined ramp on their way up or down on this ramp are areas in which we have found a paucity of literature. This is despite forklifts having an increasingly significant impact on the structural design of buildings in which they have an operational presence. Hence identifying and determining the dynamic characteristics of forklifts themselves is crucial to the understanding of their more complex interaction effects in inducing floor vibrations.

This paper reports on experimental testing to gather vibration response data of a forklift interacting with a reasonably stiff floor system. This data can be used to help substantiate the practical application of a 3 DOF dynamic model of a forklift which is to be verified from currently planned fundamental experimental testing. In this planned testing, the four wheels of the forklift are to be supported on load cells and the payload on the fork assembly varied when performing testing for up-down motion of the fork plus payload assembly.

Keywords: Floor vibration, modal characteristics, acceptability limits, excitation models

1. Introduction

Vibration serviceability of concrete floors subjected to traffic from service vehicles and forklifts has recently come to the fore, prompting research into better understanding forklift vehicle modal characteristics and more pertinently, their associated dynamic interaction with these floors.

Vehicle-structure interaction has been comprehensively documented for heavy goods vehicles and transport vehicles travelling at high speeds on bridges. Green & Cebon, (1994) investigated dynamic effects from heavy vehicles with speeds of over 25m/s, with Law & Zhu (2004) characterising a typical heavy goods vehicle that has a separate underbody. Additionally, human activities such as running, jumping or walking have been identified by Varela & Battista (2011), and Živanović et al. (2005), as predominant sources of vertical vibrations on concrete floor systems. “People are simultaneously vibration sources and displeased users” (Varela & Battista, 2011), thus, this area of research has already been well documented under the label of “human-structure interaction”.

However, research of light-weight vehicles travelling at lower speeds (5 - 20km/h) is scant. Only as recently as in 2009 did Ehland examine a three-degree-of-freedom (3-DOF) model, attempting to ascertain the modal characteristics for both unloaded and loaded forklift cases. Consequently, this paper sets out to at least partly address this scarcity of literature by providing an overview of the dynamic behaviour of a forklift truck and the response to resultant actions on a real, post tensioned concrete slab (PSC) floor system.

There are many key factors that are currently providing motivation for this research.

With land productivity becoming a growing issue, there is increasing pressure to optimize land use. For example, Pan, Mita & Li (2001) examined a multi-storey factory building with elevated access which allows loading and unloading of raw materials from vehicles moving straight into each factory floor unit. Consequently vibrations from vehicles can now occur from within the structure itself, as opposed from being ground-borne at some distance (eg for vehicles travelling on roads adjacent to a building), thus posing greater demands on serviceability due to these vibrations for these buildings.

Equipment in hospitals is becoming increasingly more sophisticated and its acceptable performance is a lot more sensitive to the influence of vibrations. Buildings that may have previously been acceptable are now failing serviceability requirements due to the new equipment demands on acceptable vibration levels. Industry experts have experienced up to three complaints a year from hospitals, research centres and various other institutions in recent times (Emad Gad, personal communication, 26 May 2014).

The challenge for engineers today lies in ameliorating the serviceability concerns caused by the dynamic response of a concrete floor system. It is much easier to reduce vibration levels through the design and construction phase of a project by simply increasing structural mass (and stiffness), thus increasing costs and potentially wasting resources. Therefore, there is potential to improve the design against vibrations by incorporating the use of other control measures such as vibration isolation systems and novel damping devices.

This paper aims to give a brief overview of the reaction of a hospital PSC floor system to excitation from 3 distinct forklift movements; up/down mast motion, back/forth vehicle motion and travel through the step change in orientation of a ramp. This overview will guide future research in transforming the way in which concrete slabs are engineered to deal with vibrations, namely those from slow moving warehouse vehicles with different loading characteristics, such as forklifts. A companion paper, (Nguyen et al., 2014) provides a more focused study of the up/down mast motion induced vibrations on this floor system.

2. Description of Testing

Dynamic response of a 350mm thick, post tensioned concrete slab floor of a hospital, currently under construction, was observed for a number of excitation sources that involved forklift activity. Three adjacent spans were considered in the experimental measurements. The spans were each formed on metal tray framework, spanning 8.5m between band beams of 2400mm width and 600mm depth. A plan view of the slab and testing area is shown in Figure 1. Identification of the floor system’s modal characteristics was the principal aim of the investigation so as to verify analytical and Finite Element based numerical models used to ascertain acceptability of the floor system to withstand human induced excitations within serviceability limits posed by sensitive equipment. Despite this particular floor system not being intended for warehouse vehicle actions, it became possible to also conduct tests over the area using different forklift movement and to compare results from other testing. Results obtained were intended to further enhance our understanding of forklift-floor interaction.

A range of dynamic testing scenarios involving a forklift truck were considered and both the floor response along with the modal characteristics of the forklift from these tests form the focal intent of this paper.

Firstly several test runs were performed for the up-down motion of the forks while the forklift remained stationary. On several repeat tests, an attempt was made to move the forks at maximum speed before being suddenly stopped, for differing levels of payload: full load (1060kg), half load (530kg) and no load (0kg). The test was performed in the leftmost floor span of the test section. Along with floor response measurements, accelerations were also measured on the forklift itself via accelerometers placed both on the back of the forklift and on the payload mass (Figure 2a). Locations of all 8 accelerometers can be seen in Figure 1.

Vibration measurements from the back-forth movement of the forklift, with the forks locked in position were also undertaken. As with the previous test, the same payload cases were considered and the accelerometers located in the same position; except for those on the

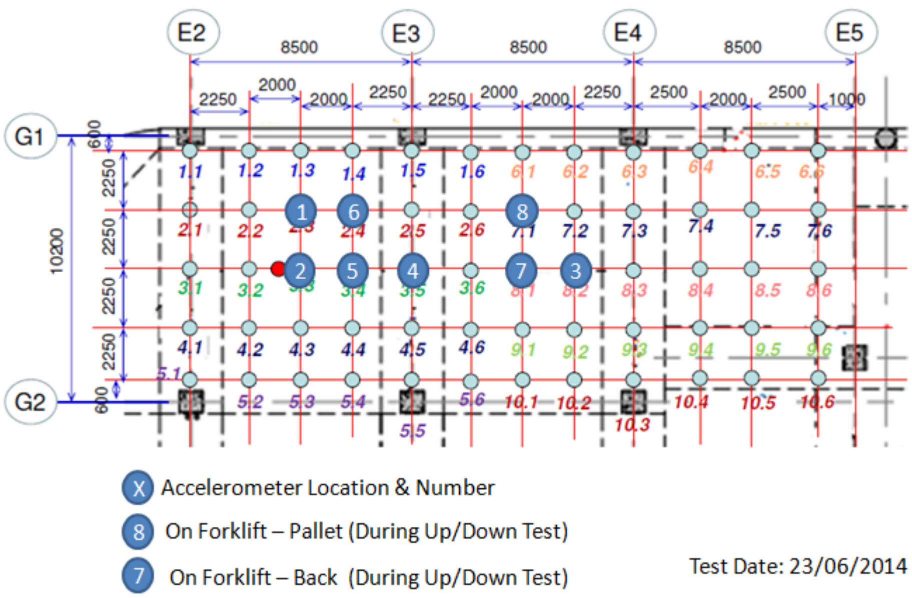

Figure 1: Forklift up-down and back-forth test sensor locations

forklift which were relocated to the floor (Figure 1). The forklift was driven both forward and backwards along the bottom section of the left and centre floor spans with the stopping motion also considered.

These two tests utilised the same Toyota 32-8FG15 as used in the first tests with a 1.5 tonne load capacity, maximum up/down velocity of the forks of 0.68 m/s and maximum back-forth driving speed of 19 km/h (Figure 2).

Lastly the dynamic behaviour of a ramp floor system under a moving forklift with near 50% payload was investigated for forklift excitation. The ramp from the Ground floor level to the first Basement level of the same hospital was used for this testing. Again, the floor and ramp at this level are considered to both have very high stiffness.

Floor mounted accelerometers were used to capture the nature of the interactions from a very similar Toyota forklift truck, to the one used in the earlier testing. Three accelerometers were placed on the flat section at the bottom of the ramp and five placed on the ramp itself (Fig.3).

The time history data captured the backward movements, forward movements as well as the impulse created when the forklift traverses the ramp at the change in grade.

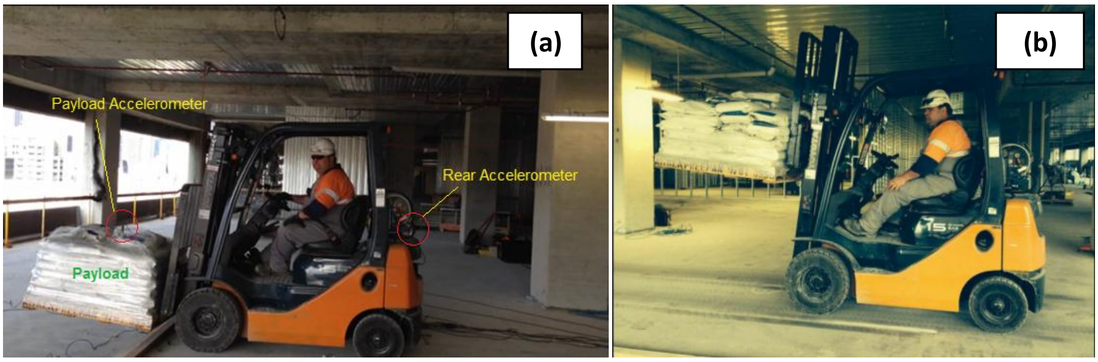

Figure 2 (a) Forklift mast up-down test   (b) Forklift back-forth test

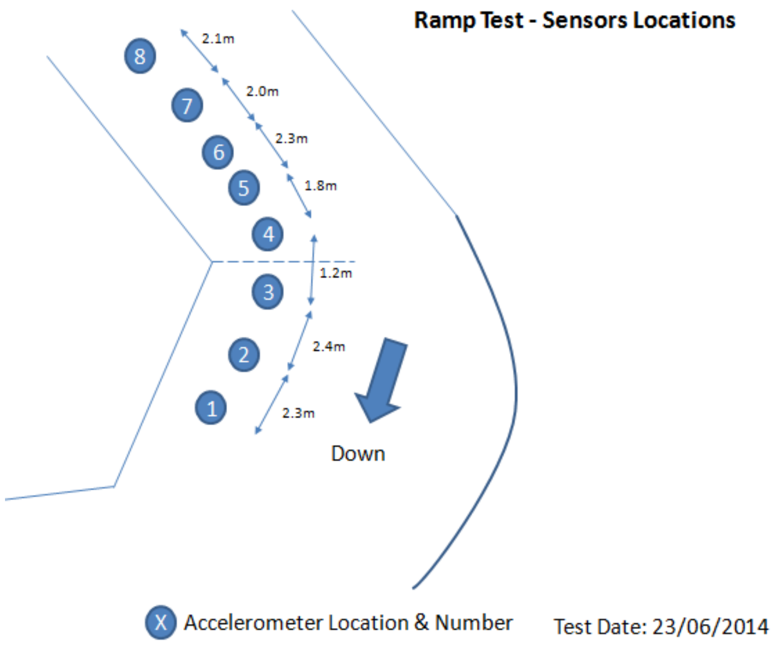

Figure 3: Ramp test sensor locations

3. Mast Up-Down Interaction Studies

Several runs of data were obtained for the up/down mast motion of the test forklift. The time history of accelerometer data (64 seconds sampled at 128 Hz and producing 8192 data points, simultaneously from the complement of 8 accelerometers) for each relevant run underwent a Fourier transform so Spectral densities of measured accelerations could be produced in the frequency domain. Ensemble averaging of the resultant spectra was utilized to better distinguish the spectral peaks which identify frequencies of most interest to this study.

As previously mentioned, payload was varied between zero, half and full load to be able to observe the effect payload mass would have on the interaction between the forklift and the PSC floor system. Figures 4(a) to (c) present the spectra of acceleration obtained from the accelerometer placed centrally on the payload.

From Figures 4(a) to (c) it is clear there is a pattern in spectral peaks for the acceleration at the payload. The peak at around 28.6 Hz remains consistent throughout and would most likely represent the stiff rotational mode of the mast in the forklift.

Pitch and bounce modes of 4.38Hz and 7.21Hz are found for the case of no payload, 3.69Hz and 7.09Hz are found for the case of half payload and 3.25Hz and 5.41Hz are found for the case of full payload, respectively.

The relative amplitudes all decrease as the payload increases, suggesting enhancement in damping properties of a forklift operating with a greater payload.

Acceleration response spectra from the accelerometers on the concrete slab at all 6 locations were also produced, for the three payload conditions (see Figure 5). Additional spectral peaks at around 12.6 Hz and 14.7 Hz are clearly evident in Figure 5. Since these cannot be seen in the acceleration spectra for the forklift at its payload position these are likely be associated with modal frequencies of the floor system itself.

Figure 6 depicts the first two modes in sequence, designated as (a) and (b) in this figure, that exhibit significant modal amplitudes in the test region as predicted by a Finite Element model by Nguyen et al. (2014). It can be seen that the observed frequency peak at 12.6 Hz corresponds very closely to the first significant modal frequency in the test region of 12.7 Hz.

The ~14.7 Hz peak is likely to correspond to the second dominant participating modal frequency of the floor (14.5 Hz in Fig. 6) and this also correlates closely to the value observed by Nguyen et al. (2014) of 14.2 Hz using experimental modal analysis in the same test region.

A detailed analysis of the up/down accelerometer records on the payload is provided by Nguyen et al. (2014) so no further treatment is offered here.

4. Back-Forth Forklift Interaction with Floor System

Figure 7 depicts the Spectral density (frequency domain variation of the energy content) of the time history data for the ground accelerometer placed at location five (X5) for all three payload conditions. For the full load condition, modal frequencies are observed at ~5.5 Hz, ~12.7 Hz, ~14.6 Hz and ~28.5 Hz. The first of these likely corresponds to the bounce mode of the forklift truck and reflects the values found in the up-down test. The bounce mode frequency also decreases with an increase in the payload, as would be expected. The presence of the forklift tilt mode is not clearly observed in these records, however.

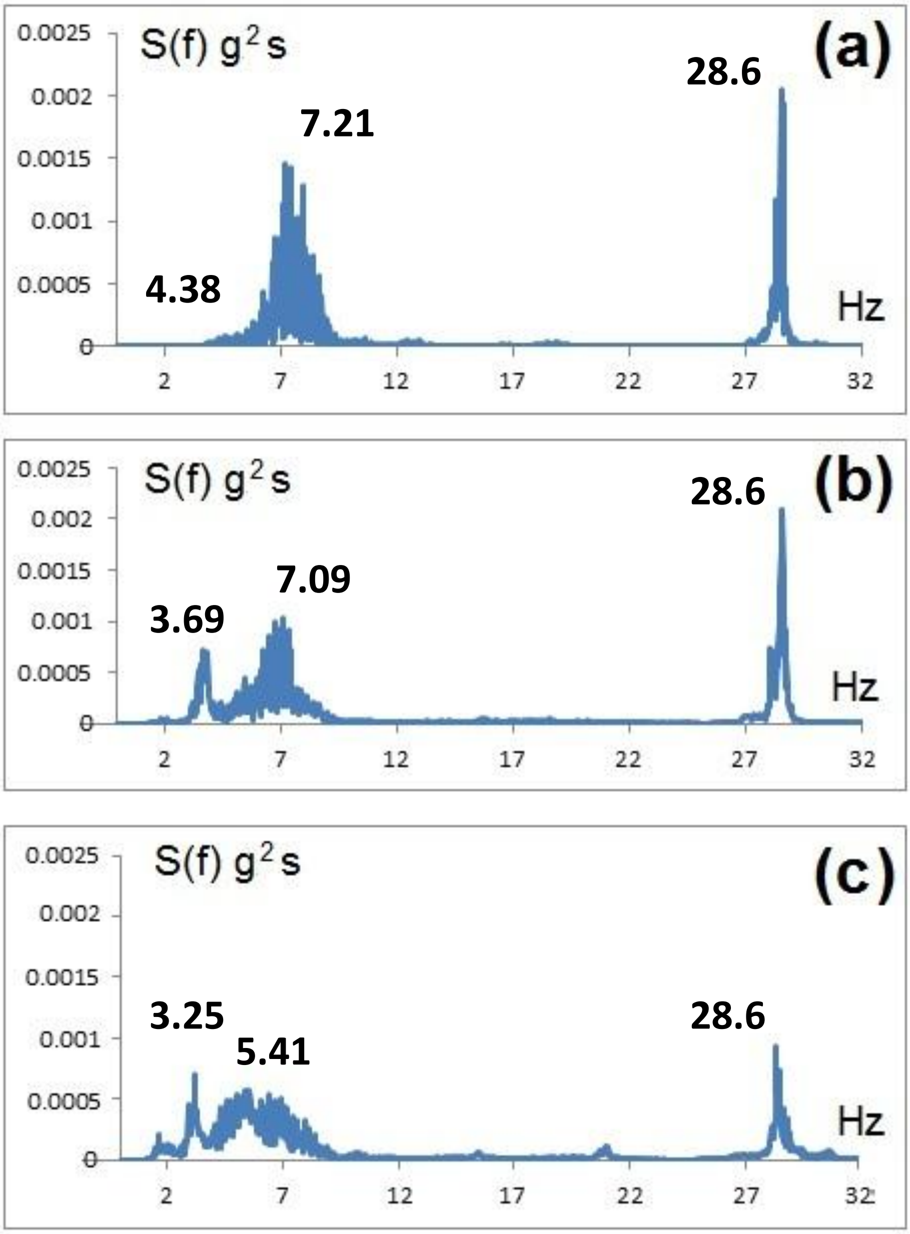

Figure 4: Acceleration Response Spectra at central payload position
(a) No Load (b) Half Load (c) Full Load

The second and third spectral peaks at around 12.8 and 14.8 Hz respectively appear to not be associated with any identified resonant conditions for the forklift truck, (no significant change with change in payload mass), whereas the magnitude of these peaks appear to decrease as the payload is increased. As with the up/down tests, these two frequencies correspond closely with the FEA predicted significant modes of vibration for the test area of the floor. The last of the spectral peaks, which was also observed in the up-down testing case, is again assumed to be associated with the rotational mode of the mast assembly as it has a higher frequency due to the high stiffness of the mast actuator.

Results from accelerometers placed at locations seven and eight, (X7 and X8) also reflect the same trends for each detected mode. Results are summarised in Table 1.

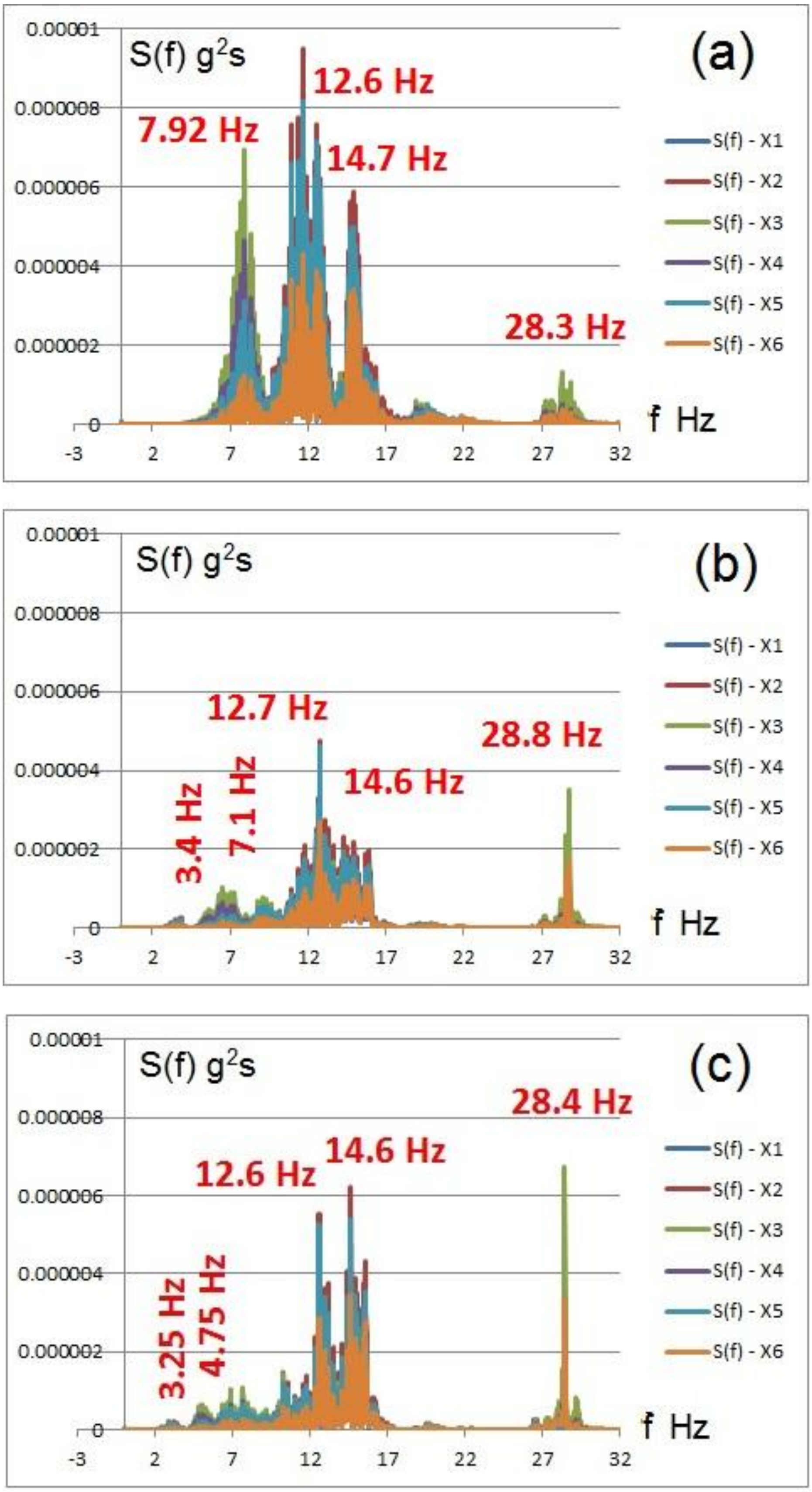

Figure 5: Acceleration response spectra at all six floor grid points for up/down mast motion
(a) No Load (b) Half Load (c) Full Load

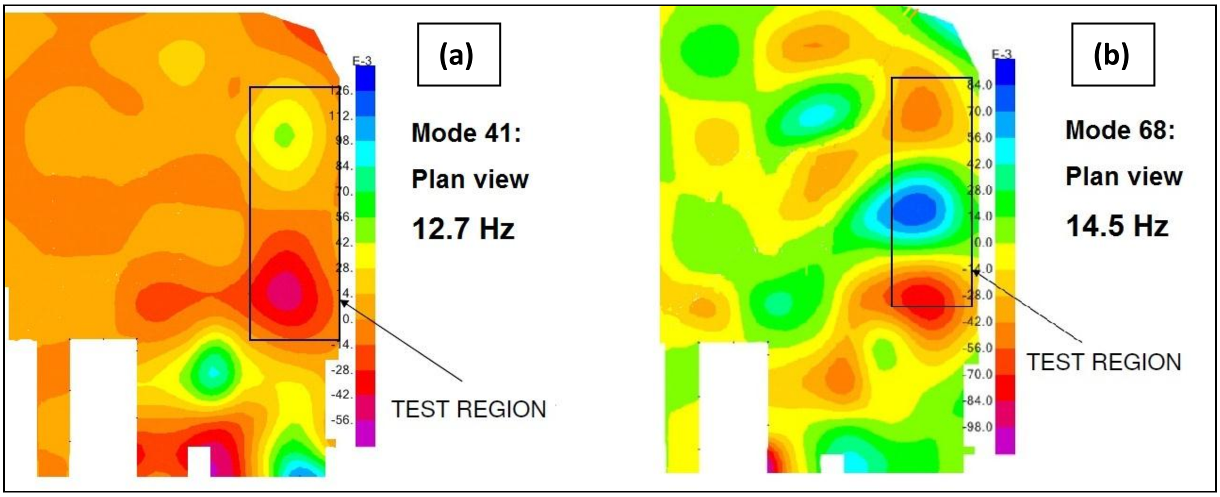

Figure 6: Finite Element Analysis predictions of first two modes of hospital floor system exhibiting significant response amplitudes in the test region

Table 1: Detected floor response modes for back-forth forklift movement vs position

	Detected Peaks	Load Case		
		No Load	Half Load	Full Load
X5	1st (Forklift bounce mode)	6.72	6.47	5.47
	2nd (Floor Vibration mode)	12.81	12.75	12.75
	3rd (Floor Vibration mode)	14.87	14.56	14.63
	4th (Forklift mast mode)	28.66	28.53	28.46
X7	1st (Forklift bounce mode)	6.84	~6	5.34
	2nd (Floor Vibration mode)	12.72	12.75	12.75
	3rd (Floor Vibration mode)	14.75	14.75	14.75
	4th (Forklift mast mode)	28.66	28.53	28.63
X8	1st (Forklift bounce mode)	~7	~6	5.34
	2nd (Floor Vibration mode)	12.72	12.75	12.75
	3rd (Floor Vibration mode)	14.75	14.75	14.75
	4th (Forklift mast mode)	28.66	28.59	28.63

It is also noticed that spectral peaks are quite similar in frequency for up-down and back-forth responses of the floor system yet vary in their magnitude. This leads to the notion that a forklift moving its payload vertically at a fixed location on the floor system, driving the forks at maximum speed before suddenly stopping, will produce a livelier excitation of the floor when compared with the same forklift travelling over the floor holding the payload at a low fixed position on the mast.

5. Ramp Test Results

Figures 8 (a) and (b) depict results of the average vertical acceleration spectra for the ground floor ramp to basement level B1 based accelerometer on the flat floor section at location X3 and on the ramp at location X4, respectively. For both locations small excitation can be observed at ~6Hz and significant excitation at ~24.8Hz. The lower of these frequencies likely

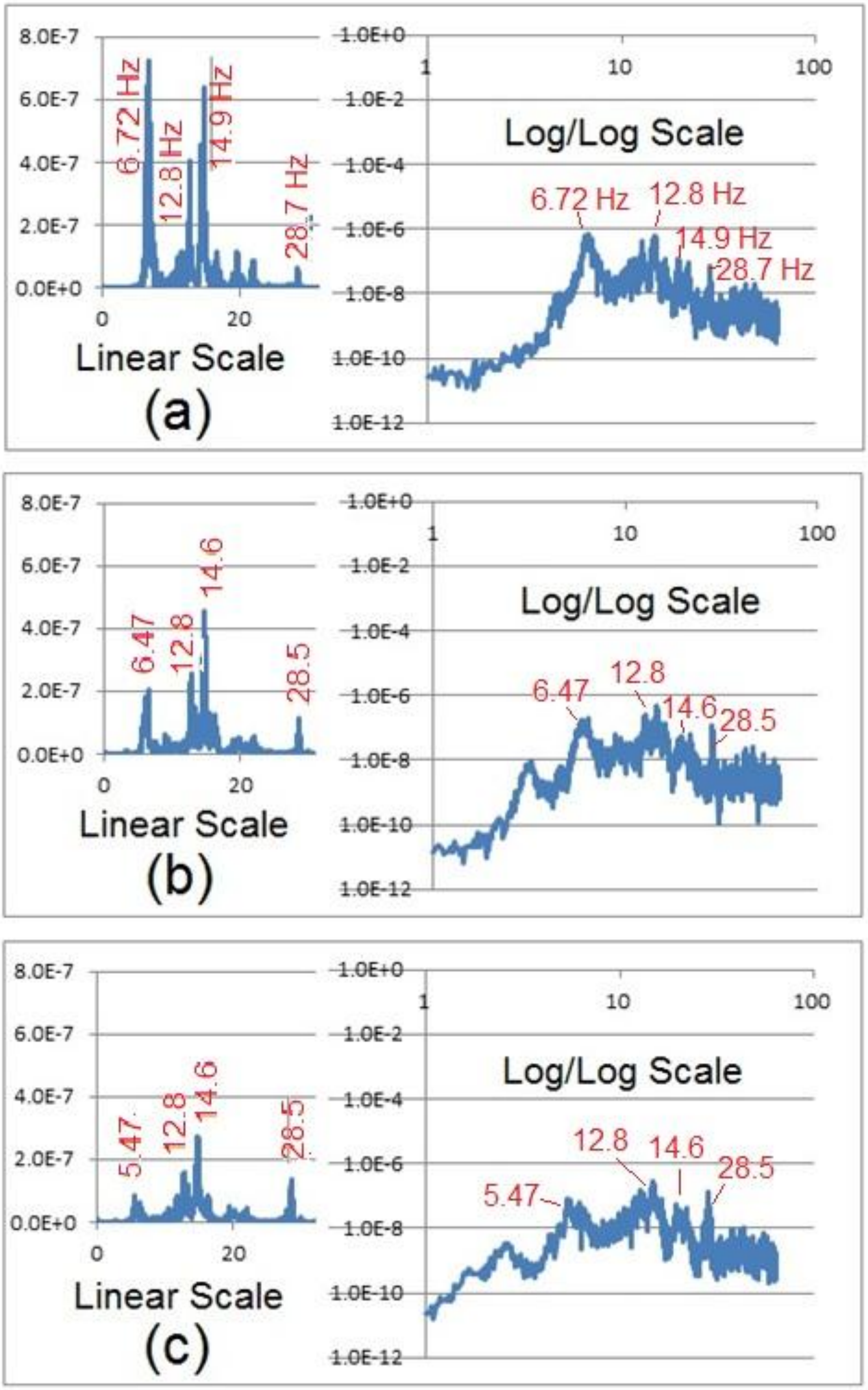

Figure 7: Acceleration response spectrum at floor location X5 for back-forth forklift motion (a) No Payload (b) Half Payload (c) Full payload

relates to the bounce mode of the forklift as it is very similar to the observed bounce mode in the back-forth testing of the earlier testing conducted on the test floor section depicted in Figure 1. The higher mode is likely attributed to the rotational mode of the mast and dominates the spectrum in magnitude.

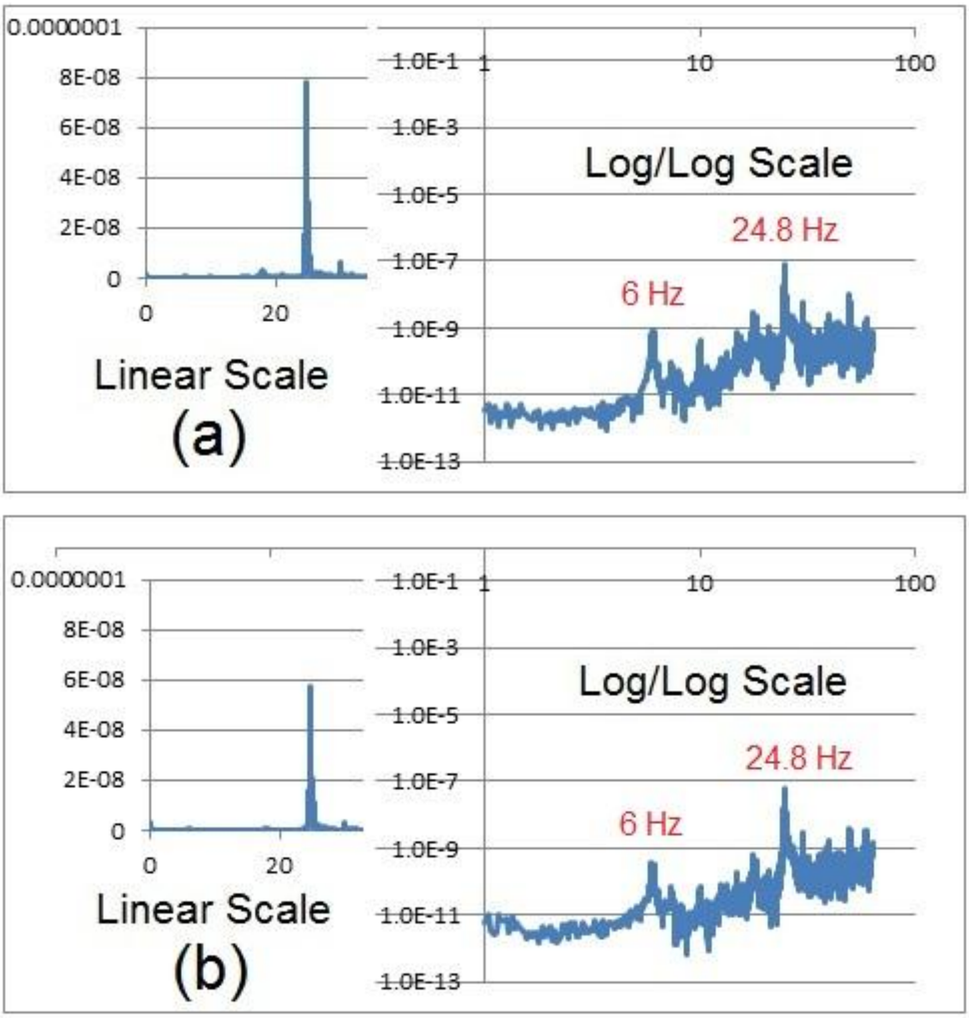

Figure 8: Acceleration response spectra for up-down forklift motion of ramp from Ground level to basement level B1 (a) Position X3 (b) Position X4

Some other noticeable responses occur at ~10Hz, ~14.9Hz and ~17.8Hz. With the exception of the middle peak these appear not to be associated with any identified resonant conditions for the floor or forklift. The ~14.9Hz response could be associated with a fundamental mode of the floor if the slab is similar in nature to the previously tested floor system (whether these two slabs are similar in nature has not yet been verified). As with the back-forth test, again there is no discernible excitation around the forklift's first pitch mode of vibration; as observed in the up-down case at around the ~3-4Hz range.

6. Concluding Remarks

The interaction of a forklift truck with a suspended floor system is complicated by the fact that the dynamic properties of a forklift (its bounce, tilt and mast rotation modes) vary with level of payload. The dynamic interaction of the floor could be associated with a number of forklift activities that would include: up/down motion of the forks at maximum mast travel speed then suddenly stopping; back-forth travel on the floor itself then suddenly stopping; negotiating floor features such as travel up/down a ramp from/to the horizontal floor level, amongst other activities.

The dynamic characteristics of the forklift relative to the dynamic characteristics of the floor (its modal frequencies, mode shapes and associated damping levels) as well as floor roughness and geometric features will influence the characteristics of the resultant floor vibrations.

This paper has highlighted observations made of the resultant floor vibrations from forklift interactions with a relatively stiff floor that included several of the types referred to above. Of the interaction effects tested, forklift up/down motion of the fork with payload appeared to produce the liveliest floor vibrations for the floor tested in these experiments.

The authors are encouraged by the results and observations made from this testing and plan to perform fundamental investigations of the dynamic characteristics of a forklift supported on load cells at each of its four wheels whilst undergoing up/down motion of the forklift mast and suddenly stopping. The forklift will be supporting payloads of varying levels up to maximum allowable, in this proposed testing program, aimed at gaining a better understanding of this important forklift activity and its effect on the dynamic characteristics of the forklift. In addition, it is expected that additional and stronger support of the model proposed by Haritos (Haritos et al., 2013) will emanate from this proposed test program.

7. References

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