Floor Vibrations Induced by Forklifts

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Abstract:

A significant amount of research has been reported in the literature on vehicle-structure interaction of pavements and bridges for heavy vehicles at high speed. However, there is a paucity of such literature concerning vehicle-structure interaction on ramps and floors in buildings of lighter vehicles and where travel speeds are significantly lower.

Knowledge of vehicle-structure interaction effects from delivery vehicles and forklifts on building floor systems in the design of such buildings attains a high level of importance when acceptability levels of floor vibrations are particularly stringent such as in the case of research facilities and hospitals.

This paper considers the development of a number of semi-analytical models for dealing with a set of identified vehicle-floor interaction scenarios for inducing floor vibrations from forklifts. Particular emphasis is made on treating the basic physics of these models and generating simple to implement and use versions of these models for design purposes. Some limited opportunities for "calibrating"/verifying these models from the conduct of in-situ experiments are also reported on.

Keywords: Floor vibration, vehicle-structure interaction, acceptability limits, excitation models

1. INTRODUCTION

The dynamics of vehicle-structure interaction and the effects of this interaction in promoting dynamic excitation of supporting structures such as rail track ballasting systems and rail bridges in the case of trains, and road pavements and bridges in the case of automobiles and trucks, have been extensively studied for medium to high speed motion of the vehicles concerned (Arun et al, 2011; Scientific Expert Group IR6, 1998; Boully et al, 2003; Montenegro et al, 2013; Romero et al 2011; Savini, 2010; Davis & Bunker, 2008). Very little treatment, however, has been devoted to the study of vehicle-structure interaction effects at low speed, with the exception of the special case of vehicles moving at “crawl” speed (< 5 kph) which situation is studied in order to ascertain “quasi-static” loading effects on structures against which the dynamic interaction effects are compared.

Consequently this paper seeks to at least partially address this paucity of useful guidance in the literature by considering the development of a number of semi-analytical models for dealing with a set of identified vehicle-floor interaction scenarios for inducing floor vibrations from forklifts.

2. DYNAMIC MODELS OF FORKLIFTS

A number of 3-D and simplified dynamic models of road vehicles have been developed (Li, 2006; Creed et al, 2010). However, it becomes very difficult to adapt a dynamic model of a heavy goods vehicle for the simulation of counterbalanced forklift trucks used for indoor goods handling. The chassis of forklifts is not suspended with a separate under-body. The axles are normally directly connected to the chassis without a spring-damper system. The distance from the Centre of Gravity (COG) of the forklift to the payload is similar to the length of its wheelbase which leads to the need for a considerable counterweight at the rear axle for stability in all load states. In conventional vehicles, the wheelbase is large and any payload is carried close to the vehicle COG.

Ehland (2009) investigated a 3-DOF model of a forklift, with two of the DOFs associated with vertical displacement at the springs modelling the front and rear wheels and a horizontal spring modelling the stiffness of the actuator which governs the rotation of the mast, (see Fig. 1). This model was investigated for a base test case forklift (Nissan N16) for its modal characteristics under loaded and unloaded test scenarios. The service mass of the Nissan N16 is 3,020 kg including the mass of the mast. Results from the modal analysis are summarised in Fig. 1.

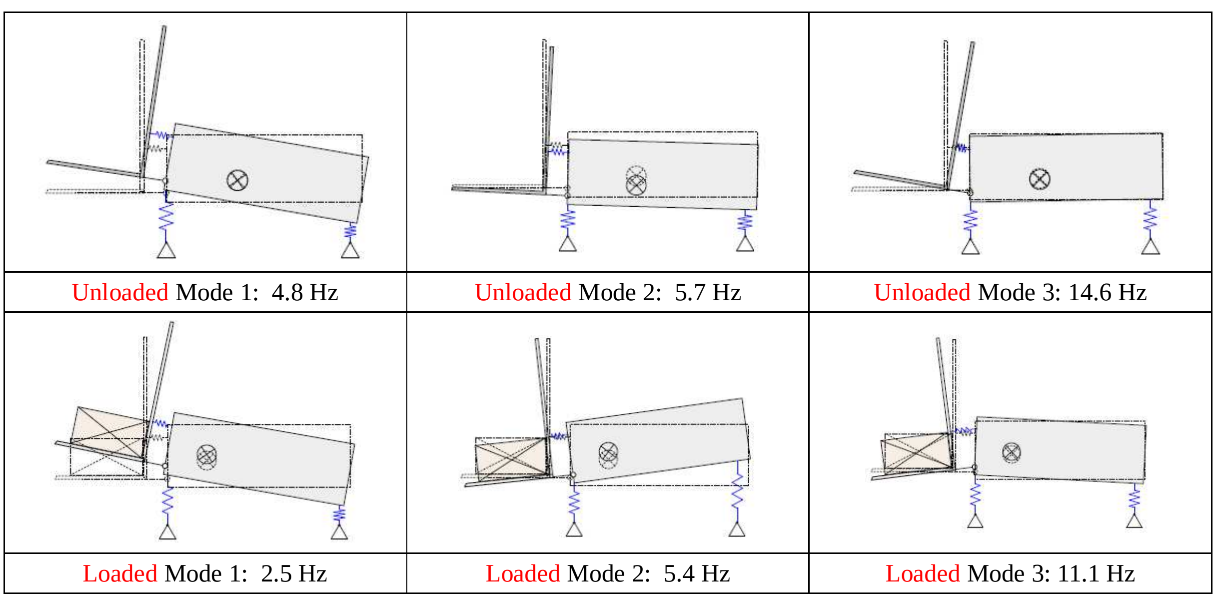


Figure 1: Modal Results for 3-DOF Model of Nissan N16 Forklift (Ehland, 2009)

Ehland also reduced his 3-DOF model to 2-DOF by considering the stiffness of the mast actuator to effectively be infinite, as his interest was focussed on the vertical wheel force excitation of floors. The mode shapes and natural frequencies obtained from the 2-DOF model were found to compare well with those from the 3-DOF version. Ehland performed simulation studies and experimental measurements of a prestressed concrete floor system using a forklift in unloaded and (fully) loaded test configurations and observed that the unloaded forklift produced more lively excitation than the fully loaded condition. This result was primarily attributed to the slower speed at full payload compared to the no load condition for the forklift.

3. SIMPLIFIED EXCITATION SCENARIOS ON FLOOR SYSTEMS FROM VEHICLES

3.1 Forklift Vehicle Initial Payload Lift

Consider a forklift negotiating its initial lift of a payload responding as a SDOF system in pitch mode. The Dynamic Load Factor (DLF) with zero damping would be 2.0 and ~1.90 for 5% critical damping for "suddenly" applied loading. However, the lifting process is a lot more gradual as the forks negotiate the payload and attempt to lift it off its support in a staged fashion so a DLF significantly less than 2.0 may be reasonably expected in practice. Using a "quasi-static" model for transferring loading to the wheels of a forklift from the damped oscillatory response of a suddenly applied payload at the position of lift on the floor would therefore be conservative, (see Fig. 2).

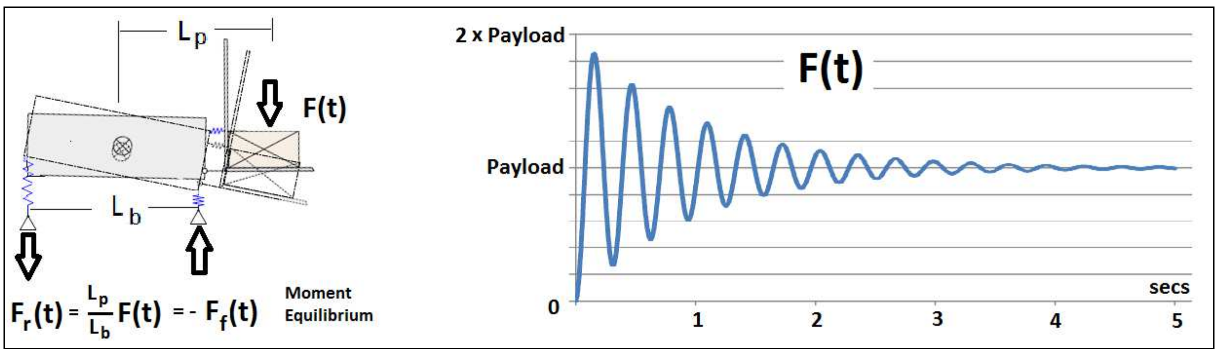


Figure 2: Suddenly Applied Payload on Forklift (Pitch mode: 3.2Hz, 5% damping)

3.2 Forklift Up-Down Motion with Payload

The process of suddenly stopping the travel of the forks on a forklift when these forks are moving upwards or downwards at the maximum speed allowed by the controls, will result in damped oscillations with a circular frequency ω_n and damping value, ζ, associated with the pitch mode of vibration of the forklift, and an initial amplitude associated with the maximum speed of movement up-down of the forks with the payload in place. The vertical force transmitted to the floor system would depend upon the geometry of the forklift wheels relative to the payload, (as in Fig. 2).

Consider the maximum up-down speed of the forks with payload to be V and the stiffness of the fork lifting arrangement at the position of the payload to be k and the mass of the payload to be m. Let the static deflection of the COG of the payload on the forks be δ_o (= mg/k) and the maximum additional deflection at this position for when the forklift suddenly stops going up-down be δ. Then the change in kinetic energy of the mass upon stopping would equal the change in strain energy stored in the spring associated with the forklift lifting arrangement, hence:

$$\frac{1}{2}k(\delta_o + \delta)^2 - \frac{1}{2}k\delta_o^2 = \frac{1}{2}mV^2 \qquad (1)$$

so that

$$\delta = \delta_o \left(\sqrt{1 + \left(\frac{\omega_n V}{g} \right)^2} \right) \tag{2}$$

now

$$F_{\max} = k(\delta + \delta_o) = k\delta_o \left(\sqrt{1 + \left(\frac{\omega_n V}{g} \right)^2} \right) = mg.DLF \tag{3}$$

where

$$DLF = \sqrt{1 + \left(\frac{\omega_n V}{g} \right)^2} \tag{4}$$

The dynamic forcing function at the payload centroid becomes:

$$F(t) = mg\left(1 + e^{-\zeta \omega_n t}(DLF - 1)\sin(\omega_n t)\right) \tag{5}$$

A quasi static analysis to determine the front and rear axle forcing (and hence the additional above static time history loading on the floor at the position of the up-down sudden stopping of the payload) can be performed as illustrated in Fig. 2.

4. EXPERIMENTAL OBERVATIONS OF FORKLIFT DYNAMIC LOADING EFFECTS

4.1 Vibration Experiments on a Viper Reach Forklift in Smart Structures Laboratory

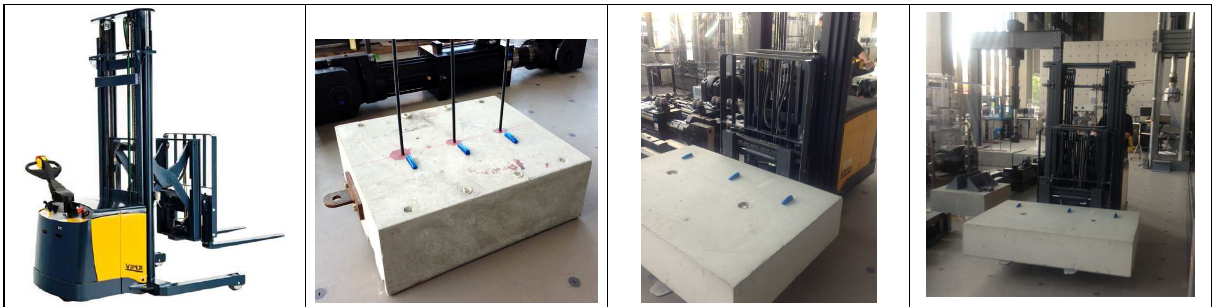
Some rudimentary experiments to ascertain the dynamic performance of a Viper Reach forklift truck (see Fig. 3 (a)) were performed in the Smart Structures Laboratory of Swinburne University of Technology's Advanced Technology Centre in Hawthorn, Victoria. A sequence of experiments with the forks moving upwards, (then downwards), at maximum speed then suddenly stopping, were performed for two different concrete mass payloads of 1.23 and 0.90 tonnes, (see Fig. 3 (c)). Figure 3 (b) depicts the 0.90 tonne block to which three GCDC Model X6-1A tri-axial accelerometers were attached. A second sequence of tests was performed with the forklift moving back and forth over the rather stiff concrete floor of the test laboratory, (see Fig. 3 (d)).

Figure 4 shows the fitted to the observed "sudden stop" condition in pitch mode as recorded in the vertical direction by the central GCDC accelerometer for sample traces for the two payload conditions. Note the offset of "*g*" in these records. The damping value is found to be a low 3.1% for both payload conditions, whilst the pitch mode frequency is understandably higher for the lower payload mass. For both cases, the DLF appears to be approx. 1.33 which corresponds very closely to the predicted value from Eq. (4) of 1.35, for V = 0.4 m/s (rated speed of forks) and f_o = 3.51 Hz.

Figure 5 depicts example results from the central accelerometer at the 1.23 tonne payload of (a) the up-down motion at the forks and (b) of the Viper travelling back and forth on the stiff laboratory concrete floor with forks held in place at a low point. Depicted in the figure is a 2048 point record (20.48 secs) sample extracted from the continuous data record of the central accelerometer inset within the power spectral description obtained from each record.

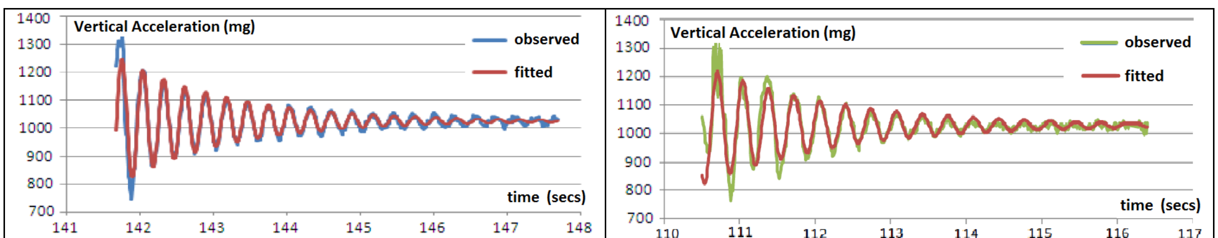
Although the scales are different in Fig. 5, the up-down motion of the payload leads to a significantly higher spectral peak at ~3.0 Hz (the pitch mode natural frequency) than produced by motion back and forth of the Viper on the floor. In addition, two additional regions between 5 and 10 Hz and between 10 and 20 Hz, with peaks at around 8 Hz and 13 Hz, are believed to be the bounce and combined pitch (rotational) mode and axle-hop (vertical) modes respectively. It is also observed that the up-down and back-forth response of the Viper at the payload position is near identical (area in spectrum over the 5 to 50 Hz region are very similar), but that the up-down motion of the forks produces a more pronounced contribution by the pitch mode to the payload acceleration than made by the back-forth travel of the Viper on the stiff concrete floor. Hence not only is the spectral peak significantly higher but also the time-domain record appears more lively for the up-down forklift motion than for the forklift travelling back and forth on the floor.

The implication of these results is that for a forklift, moving a payload up and down on the forks, at a fixed central location on a floor, at maximum fork speed then stopping, is likely to produce a higher level of excitation of the floor than would travelling across the floor at near maximum speed of the forklift with the payload held at a low position on the mast.



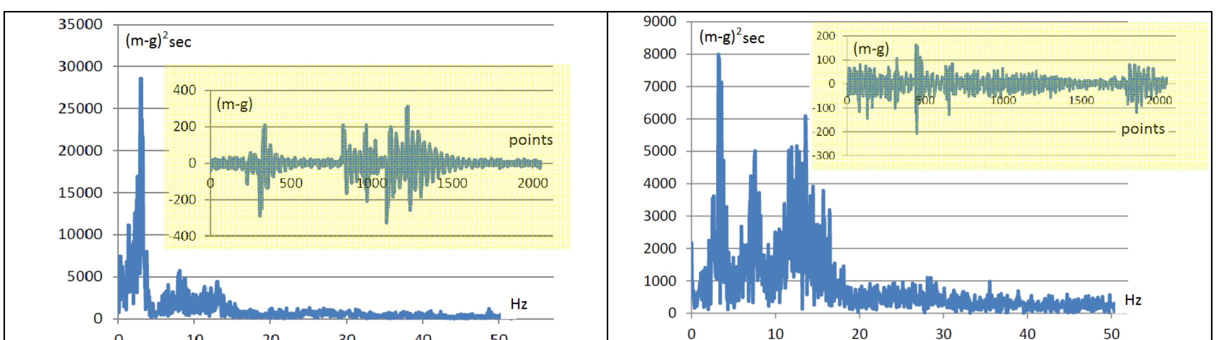
(a) Viper Reach Truck	(b) 0.90 tonne Mass	(c) Up-down Test	(d) Back-Forth Test

Figure 3: Vibration Tests on 2.0 tonne Viper Reach Forklift in ATC Smart Structures Laboratory



(a) 0.90 tonne payload: $f_o = 3.51$ Hz, $\zeta = 3.1\%$ | (b) 1.23 tonne payload: $f_o = 2.96$ Hz, $\zeta = 3.1\%$

Figure 4: Fitting of "sudden stop" Acceleration to Observed Responses (a) 0.90 tonne (b) 1.23 tonne payload



(a) Up-Down Forklift Mast Motion (1.23 tonne payload) | (a) Back-Forth Forklift Motion (1.23 tonne payload)

Figure 5: Vertical Acceleration Response Spectra (1.23 tonne payload): (a) Up-Down (b) Back-Forth Motion

4.2 Vibration Experiments using a Toyota SAS 25 Forklift Truck on a Floor Slab

A short series of vibration tests using a Toyota SAS 25 forklift truck was performed on the concrete floor of a building under construction, close to Melbourne CBD. A 2-span test bay of this building floor was being investigated using a number of testing techniques for its vibration characteristics, including Experimental Modal Analysis (EMA) options, and its susceptibility to response from human-induced excitation (Haritos et al, 2005, 2006). The test series using the Toyota forklift was therefore considered to be a “bonus” to the EMA floor tests. The floor consists of multiple 10.2m continuous spans of RC plates (in the direction of the adjacent test spans) supported on and cast integral with pre-stressed band-beams. The floor system is supported on major columns spaced at approx. 8.5m in the transverse direction. Figure 6 summarises some key results for the first 3 modes of vibration of the 2-span test bay from EMA testing using an electromagnetic shaker. Sequential floor modal frequencies of 7.64, 9.14 and 9.9 Hz were identified with corresponding damping values of 1.0, 1.1 and 3% critical, respectively.

Figure 7 depicts the Toyota forklift in a number of different scenarios. Figure 7 (a) is representative of testing for up-down movement of the forks with sudden stopping for two different payloads of 0.60 and 1.44 tonnes when the forklift was located close to mid-span alongside an axis of symmetry of the test span. Figures 7 (b) to (d) are associated with back-forth travel of the Toyota forklift along the instrumented test span floor to one side of the centreline, for 0, 0.60 and 1.44 tonne payloads respectively.

Figure 8 depicts sample 8-sec traces of mast vertical acceleration vibrations for the Toyota forklift forks moving up and down then suddenly stopping with payloads of 0.60 and 1.44 tonnes respectively. The traces are observed to be very noisy with a great deal of energy in the 40 to 60 Hz bandwidth. Hence, the spectra corresponding to these mast vibrations for the two payload conditions are produced only to 20 Hz to reveal the first two forklift modal vibration frequencies for these payloads of 3.69 & 14.4 Hz, and 2.35 & 5.2 Hz, respectively in Fig. 9. The lower modal frequency pairs correspond to the higher payload mass, as expected.

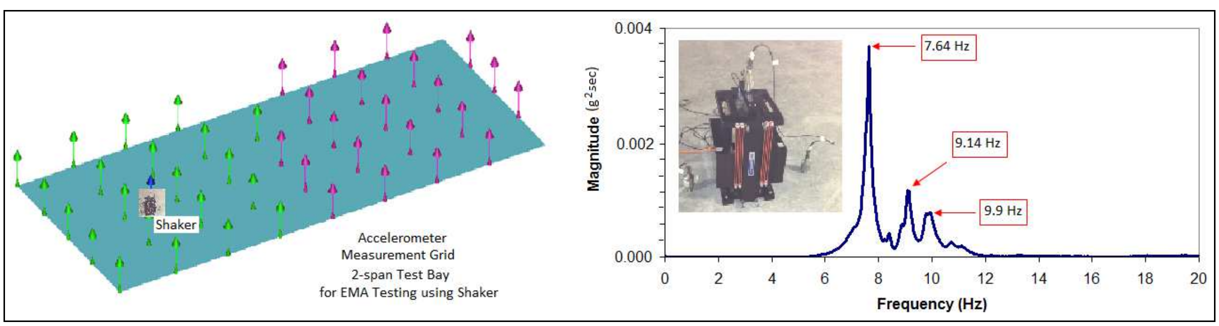
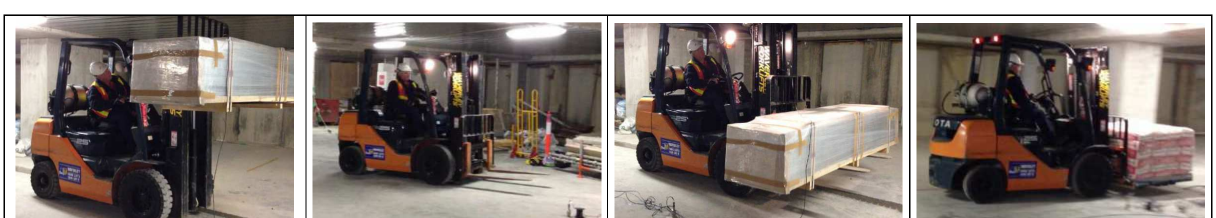


Figure 6: EMA Investigation of 2-span Test Bay of Floor in Building under Construction



(a) Up-Down Test	(b) No Load Back-Forth	(c) 0.6 tonne Back-Forth	(d) 1.44 tonne Back-Forth

Figure 7: Vibration Tests on Toyota SAS 25 Forklift Truck on Floor in Building under Construction

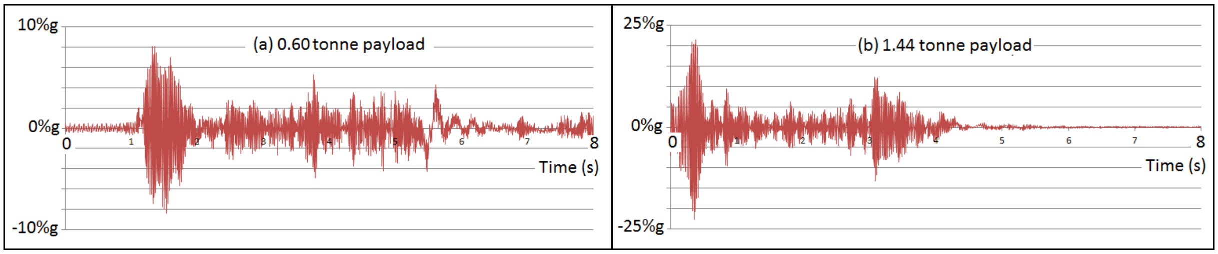


Figure 8: Sample 8-sec Traces of Mast Accelerations for Toyota Forklift Payload Up-Down

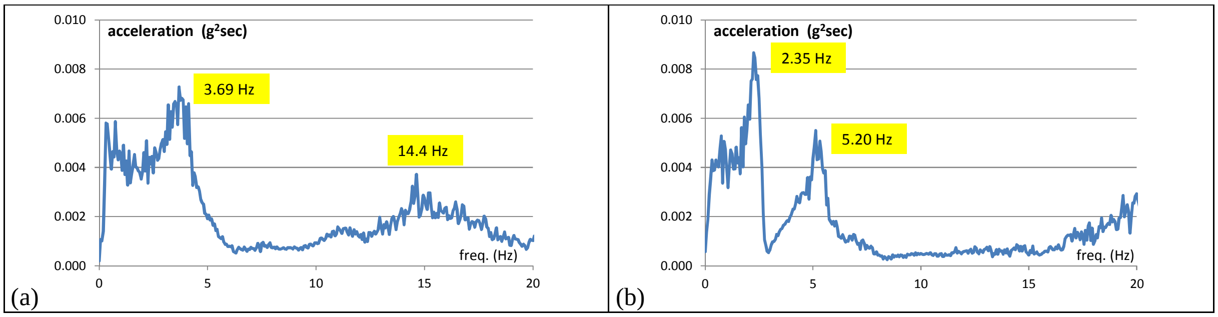


Figure 9: Spectral Variation of Up-Down Fork Motion Mast Acceleration: (a) 0.60 (b) 1.44 tonne payloads

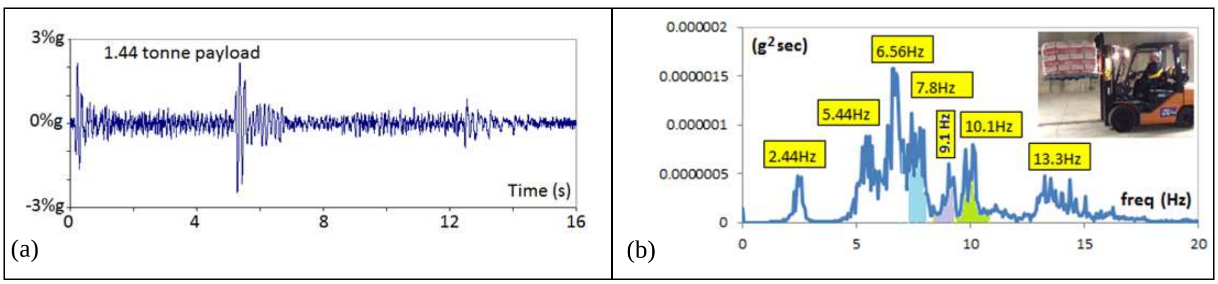


Figure 10: (a) Sample Trace and (b) Spectrum of Floor Accelerations for Forklift Up-Down with 1.44 tonne Payload

Figure 10(a) depicts a sample 16-sec trace of the measured vertical floor accelerations at the centre of the test span induced by the action of the Toyota forklift forks moving up and down then suddenly stopping with 1.44 tonne payload, where three episodes of this stopping condition are clearly visible. Fig. 10(b) depicts the corresponding averaged spectrum from 9 repeat test records of this up-down scenario. Significant floor response can be observed at the forklift's pitch mode near 2.4 Hz, as well as at its second inferred mode of ~5.2 Hz. There is also some excitation around the floor's first 3 detected modes, (shaded regions), but additional significant response at about 6.6 Hz, not associated with any identified resonant condition for either the forklift or the floor itself.

Figure 11 depicts sample traces of the measured vertical floor accelerations at the centre of the test span induced by the action of the Toyota forklift itself moving back and forth on one side of the centreline of this span with payloads of 0, 0.60 and 1.44 tonnes respectively. The sample records suggest that the floor response at centre-span progressively increases with increasing payload, contrary to observations of Ehland (2009). Figure 12 depicts corresponding averaged spectra from several repeat test records of the type shown in Fig. 11. For the no payload condition, Fig. 12(a), significant response stems from within the resonant frequency bands of the first 3 detected vibration modes of the floor (shown shaded for ease of identification). Additional contributions to the floor response (spectral peaks) around 4.5, 5.5 and 6.3 Hz now appear in this response spectrum.

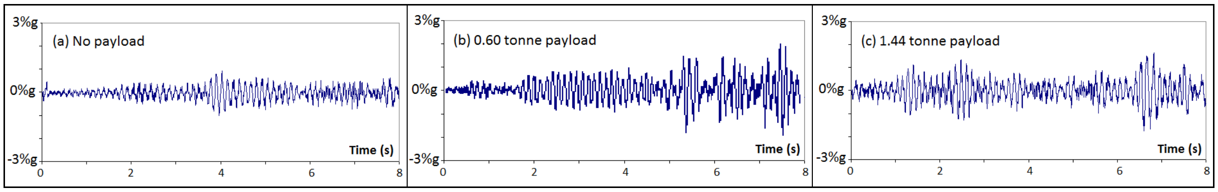
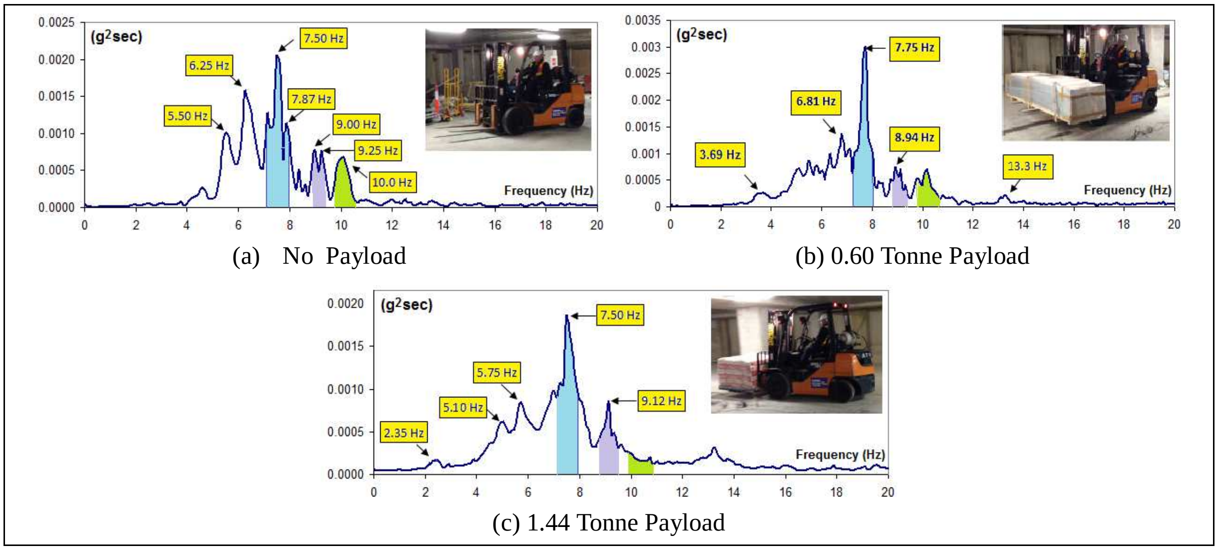


Figure 11: Sample 8-sec Traces of Mid-span Floor Accelerations for Toyota Forklift Moving Back-Forth



(a) No Payload

(b) 0.60 Tonne Payload

(c) 1.44 Tonne Payload

Figure 12: Spectra of Mid-span Floor Accelerations for Toyota Forklift Moving Back-Forth

The first of these could well be associated with the unloaded forklift pitch mode of vibration (not verified), whereas the other two spectral peaks appear not to be associated with any identified resonant conditions for the floor or forklift. For the 0.6 tonne payload, there is also significant excitation around the floor's first 3 detected modes (shown shaded in Fig. 12(b)). For the 1.44 tonne payload, significant excitation occurs around the floor's first 2 detected modes, (shaded regions in Fig. 12(c)), but not at its 3rd mode. Figures 12(b)-(c) also reveal that floor response at the forklift's pitch mode is less significant than that close to the modal frequencies of the floor.

5. CONCLUDING REMARKS

This paper has looked at providing some simplified models for dealing with floor excitation from forklifts moving payloads up and down then suddenly stopping the lift. The pitch mode of vibration of forklifts is seen as the major contributor to floor excitation from this type of vehicle-floor interaction. Experimental measurements on two different types of forklift have been able to verify some of the simplified models developed in this paper from the basic physics. Furthermore, studies of the two forklifts moving back-forth (i) over the stiff concrete floor of the ATC Smart Structures Laboratory at Swinburne University (Viper forklift) and (ii) over the concrete floor of a building under construction in Melbourne (Toyota forklift), have allowed modal characteristics of the forklifts for different payloads to be identified.

In addition, for case (ii), measurements of the floor vibrations produced from back-forth movement of the forklift allowed spectral characteristics of the floor vibration to be identified. These measurements suggested that excitation from forklift pitch and bounce modes was not so significant compared with the resonant response of the floor at its first few modes of vibration for the payload conditions tested and that response features varied significantly with payload condition. It would however be conceivable that for particular payload values, integer multiples of the resultant pitch and/or bounce modes of vibration of forklifts could resonate a floor at one or more of its natural frequencies, (Nguyen et al, 2011).

More extensive studies of forklift floor interaction should therefore be performed to identify these possibilities and their effect on floor response. The authors are exploring opportunities to conduct such further studies.

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