Some characteristics of the heave, pitch and roll vibrations within urban delivery routes

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ABSTRACT

Until recently, laboratory testing of packaged systems has been undertaken by simulating vertical vibrations alone. However, with increasing demand for a reduction in packaging waste, the use lightweight systems, such as stretch film, is increasing. Such containment systems are susceptible to the lateral forces generated by the pitch and roll vibratory motion of vehicles due to road surface unevenness. If laboratory simulation is to be realistic, multi-axial motion must be taken into account and an understanding of the relationships between the random heave, pitch, and roll vibrations is essential. This paper uses vibration data collected from a number of transport vehicles traveling along typical urban and suburban routes to establish the nature and level of the multi-axial vibrations that exist. These are presented with average Power Density Spectra (PDS) as well as statistical distributions of the moving root-mean-square (rms). The paper analyses the data for correlation of the rms levels with respect to nonstationarity. This is important when simulating nonstationary (randomly fluctuating rms) vibrations for heave, pitch and roll. These statistical correlation functions are used to manage the relative rms levels of each of the three DoFs when undertaking vibration simulations using multi-axis vibration test systems. The results show that the relationships between the moving rms of heave, pitch and roll vibrations are not strongly correlated but can be characterized statistically as joint distributions to enable realistic simulation of multi-axial random vibrations of road transport vehicles under controlled laboratory conditions.

INTRODUCTION

For many years now, the testing of products' resistance to transport vibrations and the corresponding validation of protective packaging systems have taken place in the context of vertical (heave) vibrations only as the magnitude of heave vibrations are significantly more severe than those of alternative degrees of freedom namely pitch and roll[1]. As pressure on reducing packaging waste - while ensuring load security - intensifies around the globe, efforts are being increasingly made to optimise packaging systems. This invariably leads to attempts at minimising the amount of material used to contain and protect products during distribution and transport. One good example of this is in the application of stretch film to contain palletised products. Reduction in film thickness, optimising wrapping patterns and reducing film layers are some approaches that practicing packaging engineers use to achieve their ultimate aim while maintaining containment performance. As packaging optimisation is pushed further, the assumption that the secondary vibratory motions generated by road transport vehicles are not significant no longer holds. Purely vertical vibrations, as simulated in laboratories using single-axis vibration machines, do not accurately represent what occurs in real transport vehicles. On the road, the heave, pitch and roll vibratory motions that are exerted on the shipment, combine to generate vertical and lateral forces on the packaging system. The ability to simulate these multi-axial vibrations in a controlled and consistent manner has attracted the attention of a number of researchers in this field leading to the development and evaluation of a number of multi-axis vibration simulation systems.

To date, two publications[2, 3] compare the results of simulated uniaxial (heave) and multi-axial vibrations of various packaging systems and identify important differences in the excitation of lateral mode shapes of staked packaging units and overall load stability. Attempts at evaluating the level and character of pitch and roll vibrations have been limited to a few observations[4, 5]. Efforts to find a correlation between the geometric parameters of the vehicle / payload combination, vehicle speed and road type (roughness) was undertaken by Long *et al.*[1, 5] but limited data prevented the generation of conclusive results. Due to the difficulties associated with independently varying payload and vehicle parameters (such as wheel base and wheel track, payload mass and centre of mass location etc.) Long [1] developed a fully-configurable numerical model of a generic four-wheeled vehicle. The model was fully validated and used to generate sensitivity functions of the salient parameters with respect to the relationship between heave, pitch and roll vibrations. The current state of affairs is that, although the hardware for generating and controlling multi-axial vibration in the laboratory exists, information of the type (character) and level of vibrations to be generated is lacking. This paper tackles this issue by presenting the results of a vibration survey undertaken in a local (urban) distribution setting using typical road delivery vehicles.

METHODOLOGY

The research was based on multi-axial vibration data collected using typical local road delivery environments. These included a variety of vehicles, payloads and routes (road types) that were selected as typical manifestations of urban and sub-urban delivery scenarios. The primary purpose of the paper is to address the following questions:

- Is there an underlying shape to the average Power Density Spectrum (PDS) for heave, pitch and roll vibration for specific vehicles irrespective of route and speed?
- Can an overall PDS for small delivery vehicles be created and used as a generic target PDS for laboratory simulation purposes?
- Is the level of root-mean-square (rms) nonstationarity of the pitch and roll vibration similar to that of heave acceleration?
- Is there a relationship between the rms levels of the three modes of vibration? Or, in other words, as heave vibration rms increases, does pitch and roll rms also increase and, if yes, how so?

Instrumentation

Vibratory heave (acceleration), pitch and roll (angular velocity) was collected continually using a self-contained data recorder (Saver® 9X30) configured for continuous sampling (gap-free) at a sampling rate of 1,000 samples per channel. Heave acceleration was measured with the on-board accelerometer (set to a range of 50 m/s^2) whereas angular velocity was measured with an IMU (Gladiator Technologies MRM10) connected to two available external channels of the Saver® recorder. The sensor-data recorder assembly was firmly mounted on a thick steel base which was, in turn, firmly attached onto the test vehicles at a known location (in the horizontal plane) with respect to the vehicle's centre of mass. The angular velocity sensors afforded a measurement bandwidth of 0 – 50Hz.

Test vehicles and routes

Three small delivery vehicles and one medium-capacity truck were used to represent typical local delivery scenarios. Various test payloads were installed on each vehicle and the mass and centre of mass of the entire vehicle-payload-driver assemblies was established by measuring the vertical wheel force using wheel scales. Relevant details of the test vehicles used for this study are given in Table 1.

Table 1: Test vehicle details

ID	Vehicle type	Suspension type	Wheel base Wheel track [m]	Capacity [kg]	Sensor location [m]*	Test load [kg]
V1	Toyota Hiace	Rear: Leaf springs + telescopic dampers Front: Coil + telescopic dampers	2.59 1.44	850	-1.74	0 160 300
V2	Mitsubishi Triton	Rear: Leaf springs + telescopic dampers Front: Coil + telescopic dampers	3.00 1.52	1,300	n/a on rear axle	0
V3	Toyota Hilux	Rear: Leaf springs + telescopic dampers Front: Coil + telescopic dampers	3.09 1.51	1,240	-0.35	0
V4	Mitsubishi Fuso	Rear: Leaf springs Front: Coil + telescopic dampers	3.40 1.66 (F) 1.43 (R)	2,000	-0.80	370 680

* Relative to centre of mass (negative indicates toward rear of vehicle).

In reality, the type and character of road surfaces vary considerably along any route. On well-maintained highways and motorways, the road roughness is generally low and road surface aberrations (such as pot holes, and rough patches) are rare save for artificial features such as railway crossings, bridge thermal expansion joints and cats-eyes reflectors. Generally, these are encountered only occasionally on highways and motorways. In most typical transport routes, it is the segments involving local, urban and suburban roads that in the main, contain rough roads and road surface aberrations. The reason for this is that it is often impractical to measure road roughness in high traffic / low speed environments without major disruption to traffic flow as high-speed road profilometers are not usable at low speeds [6]. In addition, urban and suburban distribution routes is where transport vehicles are more likely to encounter and negotiate obstacles such as kerbs, driveway gutters, traffic-calming devices (speed humps, chicanes) and small roundabouts. Such road conditions are not only more likely to result in significant heave vibrations but, correspondingly, are more prone to apply out-of-phase forces to the vehicle wheels resulting in increased angular vibratory motion namely pitch and roll. With the aim of establishing typical types and levels of multi-axial vehicle motion of delivery vehicles, this study was undertaken on a number of urban routes that represent typical local delivery circuits. The specific routes used were generated in accordance with the location of three major store chains within the Greater Melbourne (Australia) region. In addition, a number of suburban roads of not insignificant roughness (approximately ISO class B - C) were used as they afforded travel at controlled - nominally constant - speed (for use on another aspect or research into road-vehicle dynamics). These routes were chosen specifically to represent road surfaces that are typically encountered during local delivery routes (as opposed to highway and motorways).

Vibration data analysis

As the main cause of vehicle vibrations (the unevenness of the road surface) is random, the resulting vibrations (heave, pitch and roll) are also random. The general assumption that the data is essentially free of transients and harmonics does not always hold but is, nonetheless, assumed to be so in most cases. Harmonics are usually small in magnitude compared to the random vibrations and can be safely ignored. Until a reliable means by which shocks can be identified and extracted from the underlying random vibrations is available, it will be assumed that shocks are rare and do not significantly affect the statistical signature of the vibrations namely the average PDS, the Probability Distribution and the rms distribution. The crest-factor distribution can be used to give an indication of the presence of shocks in the data [7]. The nonstationary character of the vibrations [8] was evaluated using the (moving) rms distributions and correlating variations in rms of each of the three variables *viz*.: heave, pitch and roll. Due partly to the limitations of the angular rate sensors (noise floor), it was decided to undertake the analysis of angular vibrations using the measured quantity (angular rate) as opposed to angular acceleration or even angular displacement. For laboratory simulation purposes, this requires that both the vertical (heave) acceleration and angular rates of the table be used as feedback control signal.

RESULTS

Records obtained from urban routes were measured with test vehicles travelling at ambient speed as dictated by speed limits and traffic conditions whereas records obtained from country roads were produced by concatenating sub-records measured with vehicles travelling at nominally constant speeds. The constant speed concatenated data sets were produced to enable the evaluation of effects of speed on the vibratory motion of the vehicles and do not form part of the research presented herein. The lengths of all 21 vibration records were set to ensure that they are suitably representative of the route type and driving conditions and to ensure sound results when computing average spectra and statistical analysis. These account for a total of 1,944 kms and 40 hours of data, details of which are given in Table 2.

Table 2: Vibration survey routes and record lengths.

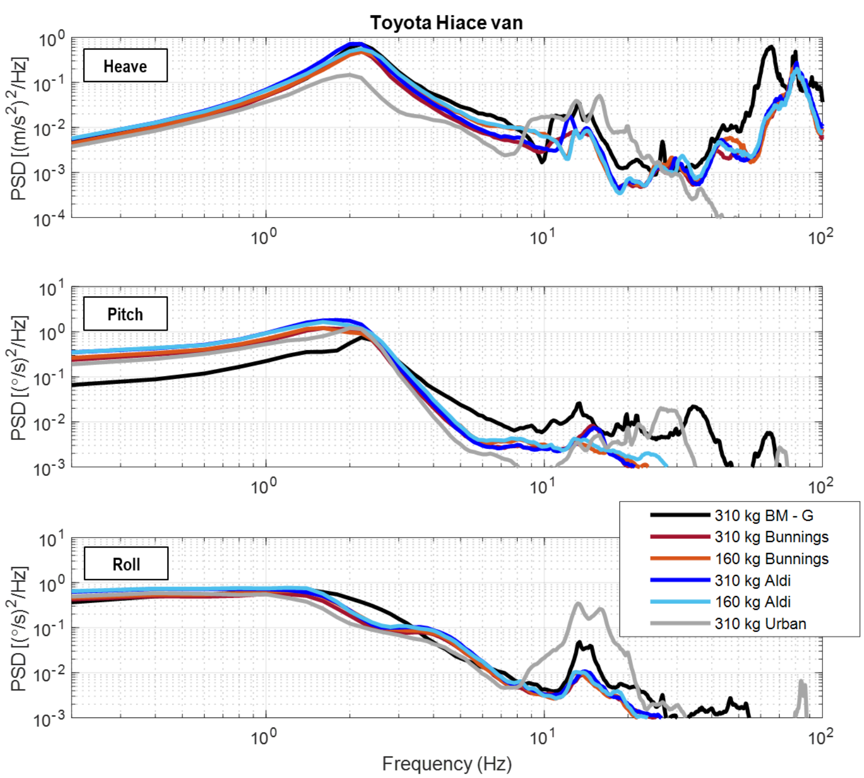
Route	Vehicle used	No. of records*	Length [km]	Nominal Speed [km/h]	Nominal Duration [sec]
Woolworth distribution (Metro)	V2	1	94	Ambient	13,400
ALDI distribution (Metro)	V1, V2, V4	5	110	Ambient	11,220
Bunnings distribution (Metro)	V1, V2, V4	4	94	Ambient	7,970
Geelong – Bacchus Marsh (Suburban)	V1, V2, V4	3	176	60, 70, 80, 90	8,230
Sunbury – Romsey (Suburban)	V1	2	75	80, 90, 100	3,000
Ballan Rd (Suburban)	V2	1	40	Ambient	1,835
Bulban Rd (Suburban)	V3	4	40	70, 80, 90, 100	2,030
Derrimut Rd (Suburban)	V3	1	46	70, 80, 90, 100	1,970

* May include different various payloads.

Results are presented in terms of amplitude domain information, namely moving rms distributions, and in terms of frequency domain information, namely average PDS to address the questions listed in the Methodology. Frequency (Fourier) analysis was carried out with a spectral resolution of 0.2 Hz using 50% overlap ensemble averaging with a Hanning window [9, 10]. Moving rms time histories were calculated with a window width of two seconds with a 50% window overlap coefficient [8].

Is there an underlying shape to the average PDS for heave, pitch and roll vibration for specific vehicles irrespective of route and speed?

Figure 1 shows the average PDS for three typical vehicles travelling along various urban distribution routes at ambient (uncontrolled) speeds. These clearly show that the route and vehicle speed regime have little influence on the shape and even the overall level of the PDS for all three vibratory modes. Unsurprisingly, the main parameter that affects the shape of the PDS is the payload as it influences the dynamic characteristics of the vehicle, namely the natural frequencies and damping ratios. Similarities in the PDS are stronger within the lower frequency band (DC – 10 Hz) where the PDS levels are generally more significant. Furthermore, it appears that the pitch and, especially, roll PDS for this frequency band are not only quite independent of route and vehicle speed but the angular vibration response of three quite different vehicles also have strong similarities. This opens-up an opportunity for creating generic PDS 'profiles' for use in laboratory-based transport simulation trials.



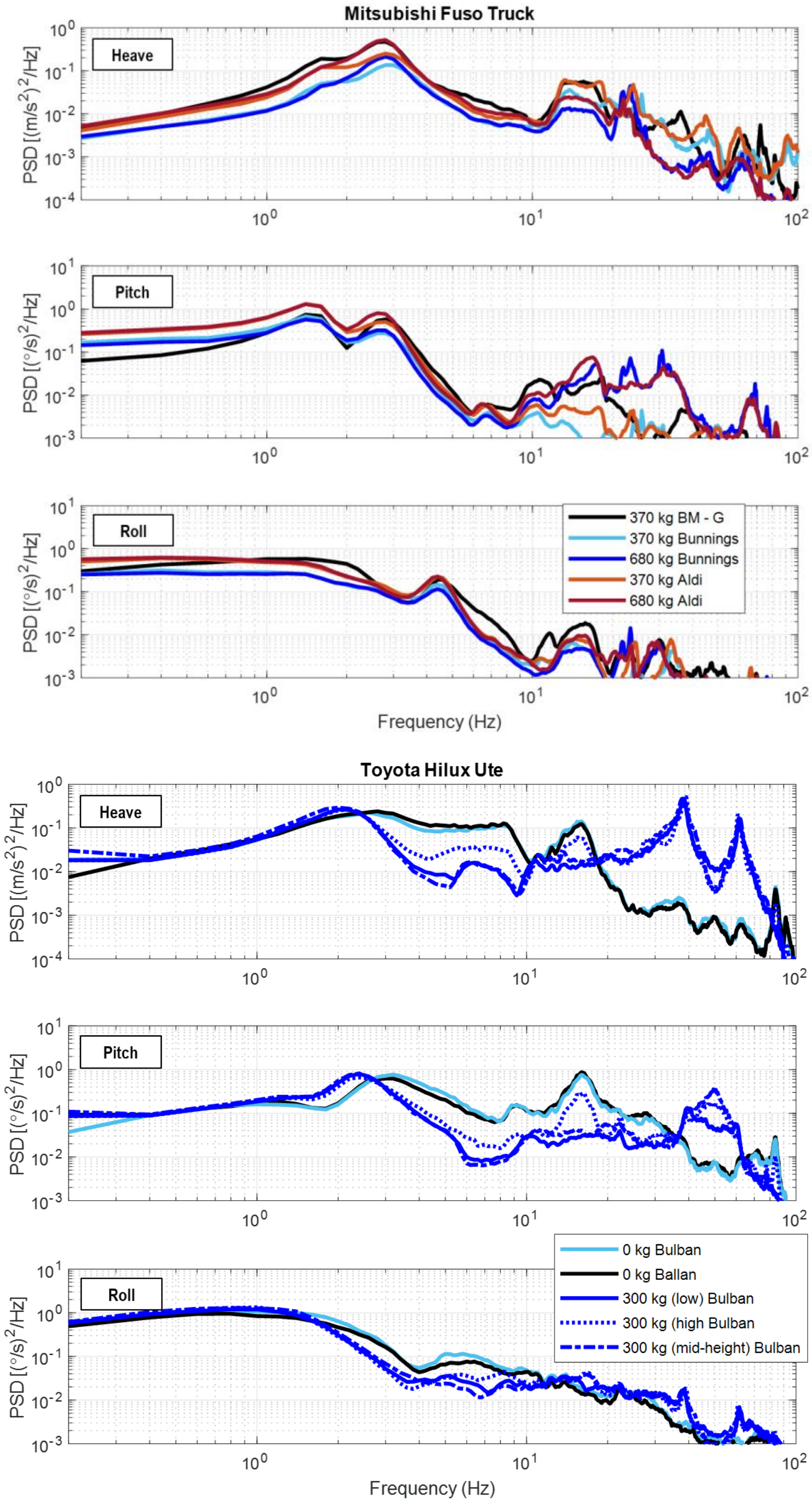


Figure 1. Average PDS for three typical vehicles traveling at ambient speed on different urban delivery routes (low, mid-height and high refer to the payload CoG height).

Can an overall PDS for small delivery vehicles be created and used as a generic target PDS function for laboratory simulation purposes?

The average PDS (combined across all routes) obtained from all four delivery vehicles with various payloads are shown in Figure 2. It is clear that some similarity for all three vibration modes especially at low frequencies (< 10 Hz). Interestingly, the variations in the roll PDS are relatively small across the various vehicles, payloads and route combinations. Despite the differences at higher frequencies, the levels are sufficiently low to warrant combining the spectra to produce a generic (small) delivery vehicle target PDS for laboratory simulation purposes.

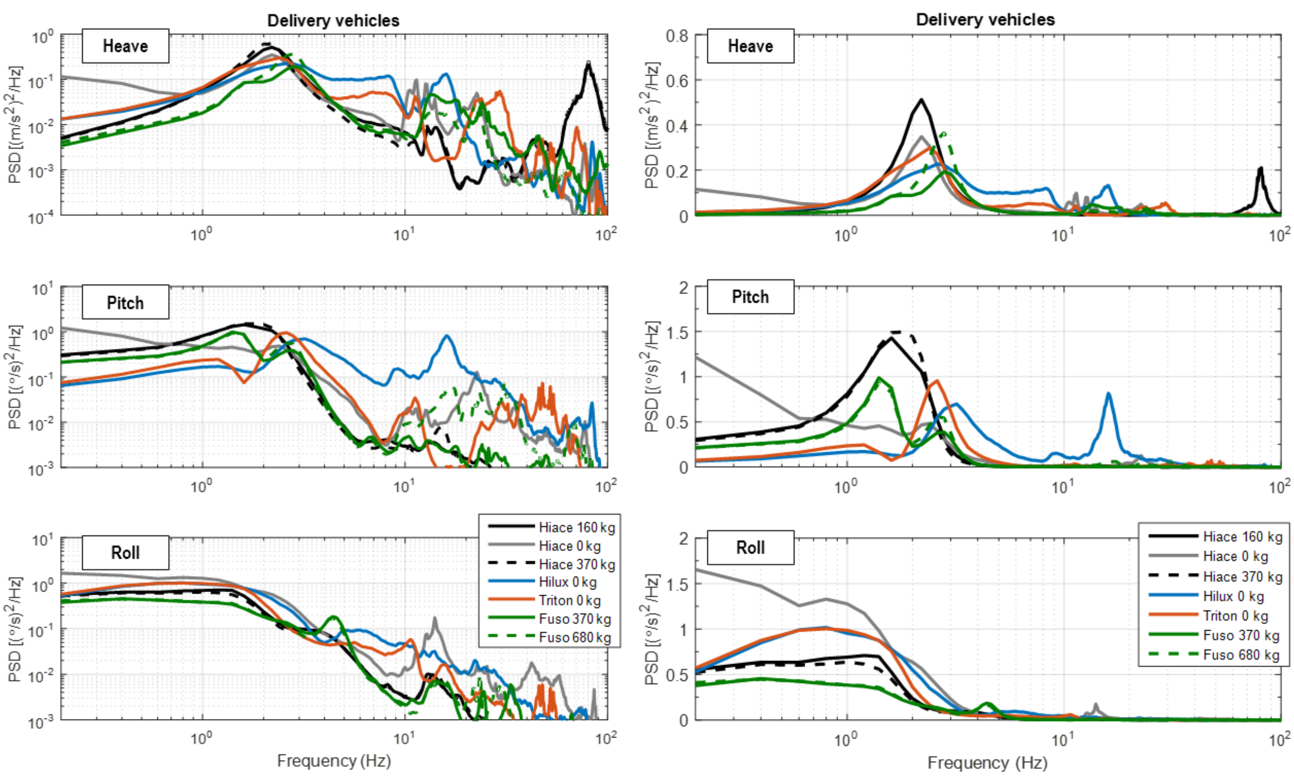


Figure 2. Average PDS for all four test vehicles on (combined) urban delivery routes shown on log-log scales (left) and semi-log scales (right).

Is the level of rms nonstationarity of the pitch and roll vibration similar to that of heave acceleration?

Nonstationarity in vehicle vibrations is usually manifested as a (random) fluctuation of the moving rms and is presented as the statistical distribution of the moving rms[11]. In all cases, clear manifestation of nonstationarity was observed as illustrated in the typical cases shown in Figure 3. These distributions show that both the nature and level of nonstationarity (moving rms fluctuation) for pitch and roll vibrations are similar to those of heave vibrations.

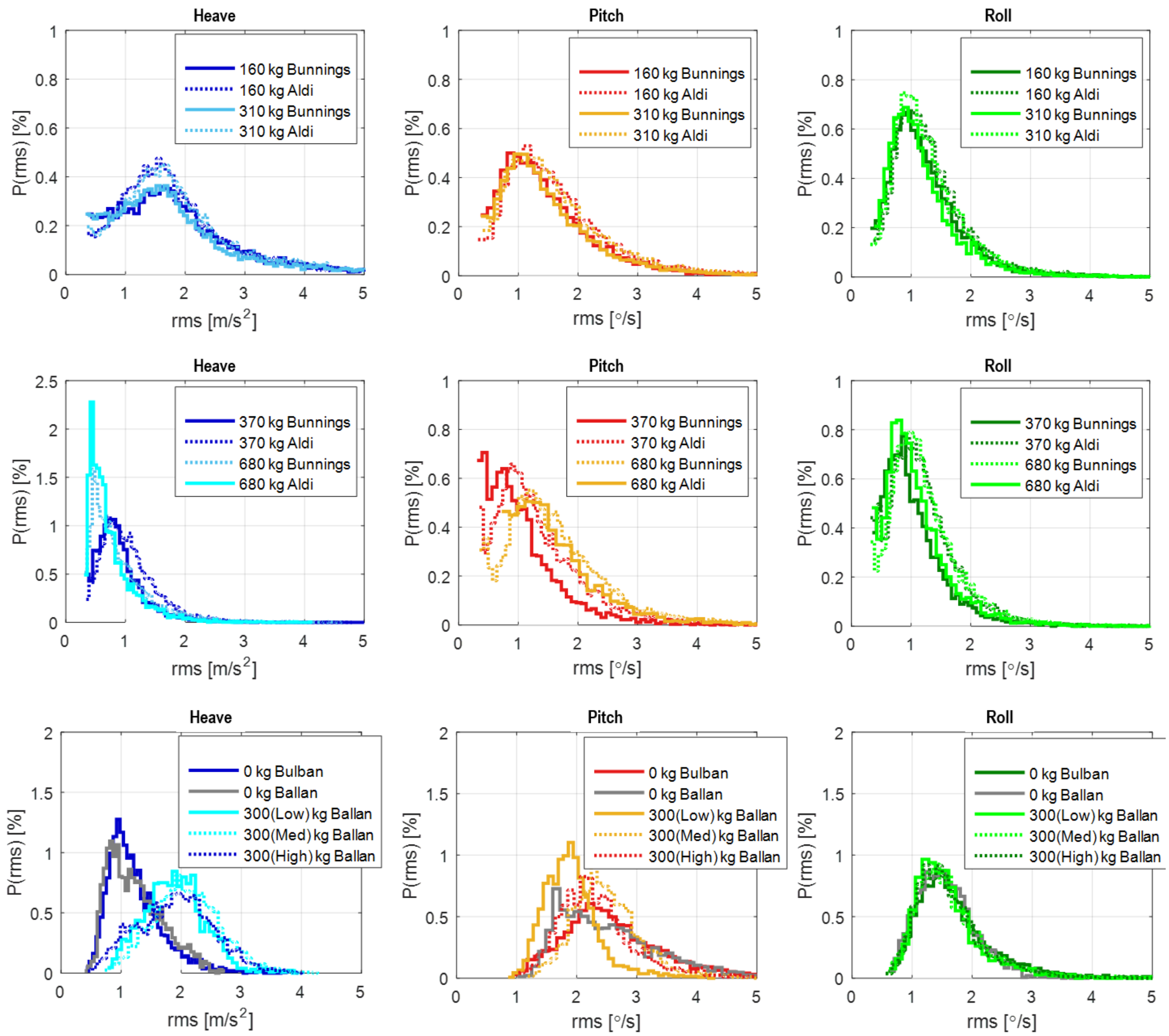


Figure 3. Typical RMS distributions (2-second window) observed for three typical vehicles traveling at ambient speed on different urban delivery routes. Top: Toyota Hiace van, Middle: Mitsubishi Fuso truck and bottom: Toyota Hilux utility. (Low, Med and High refer to the payload CoG height).

The standard deviations of the pitch and roll moving rms ($\sigma_{\underline{\dot{p}}}$ and $\sigma_{\underline{\dot{r}}}$ respectively) are plotted versus the standard deviations of the heave moving rms ($\sigma_{\underline{\ddot{h}}}$) in Figure 4 for each of the 21 cases studied. Here, $\underline{\ddot{h}}$ denotes heave moving acceleration rms and $\underline{\dot{p}}$ and $\underline{\dot{r}}$ denote the pitch and roll angular velocity moving rms respectively. This reveals that the fluctuation in rms levels for pitch (standard deviation) is similar to that of heave. This is, to an extent, expected as pitch motion is coupled with heave vibration. On the other hand, the fluctuation in rms levels for roll (standard deviation) is less dependent on heave and remains relatively unvaried across the entire data set. Note that roll data for the Triton Ute 370 kg Woolworth and Aldi were found to be corrupt but were included in the results to show the heave and pitch information.

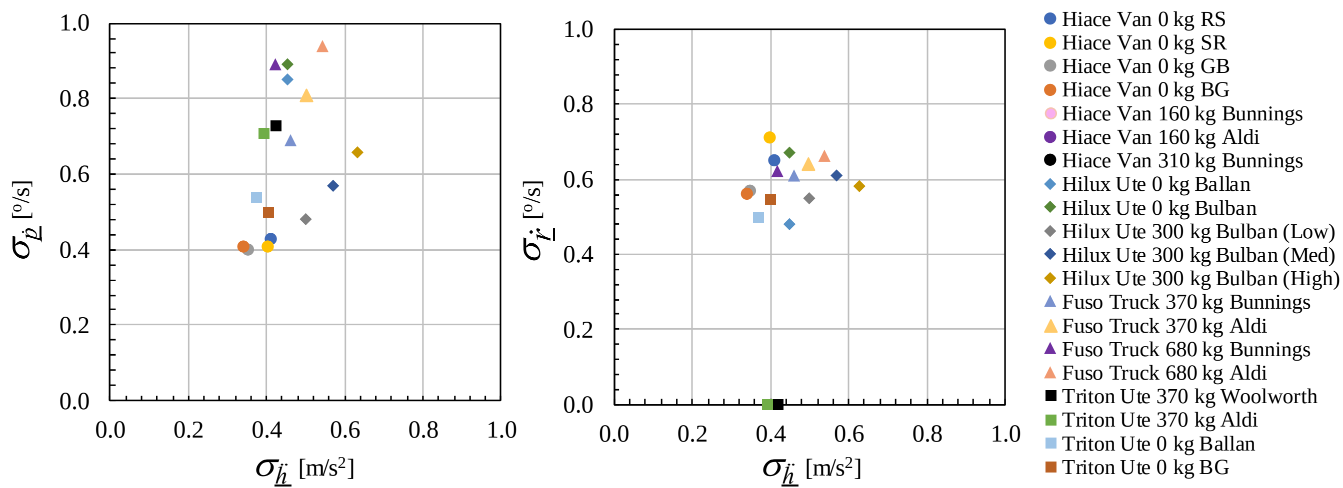


Figure 4. Scatter plot of the standard deviations of the pitch (left) and roll (right) moving rms vs that of heave moving rms.

Is there a relationship between the rms levels of the three modes of vibration? Or, in other words, as heave vibration rms increases, does pitch and roll rms also increase and, if yes, how so?

The question that now remains is how to set the rms levels for laboratory simulation of roll and pitch motion and to establish how these fluctuations in pitch and roll rms levels are related to those of the heave acceleration. To achieve this, the joint distributions of the moving rms time histories for pitch and roll as a function of heave (presented as bivariate histograms) for all 21 cases. As it is impractical to present this analysis for all the 21 cases individually, only results for a typical case are initially presented in Figures 5 – 7 whereas complete results are summarised in Figure 8.

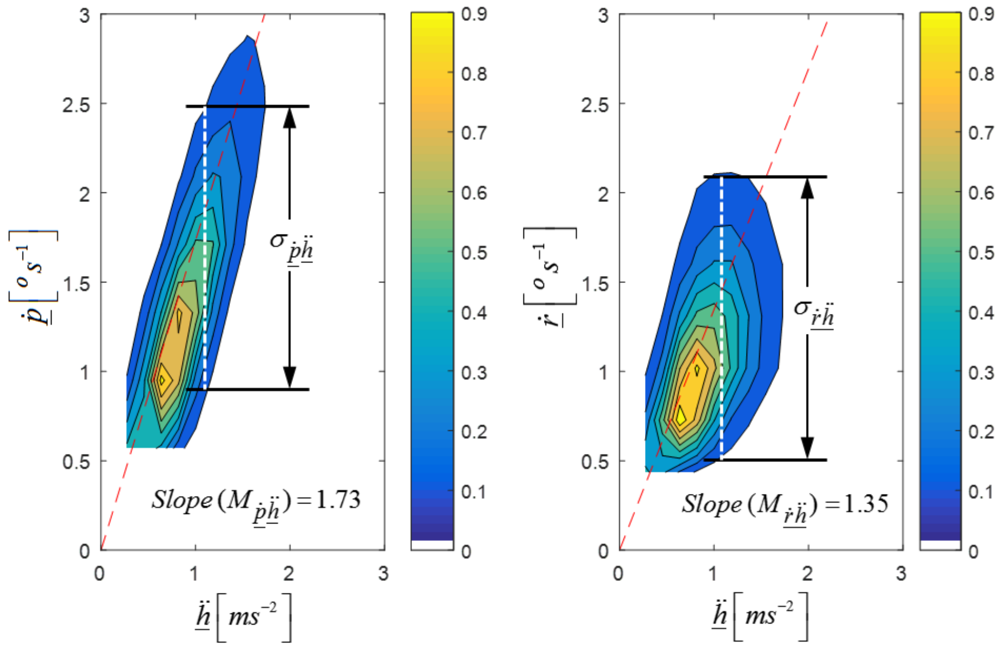


Figure 5. Typical joint distribution (Data for the Hiace Van (310 kg) along the Aldi distribution route shown here).

Results show that the overall relationship between the angular velocity moving rms (both pitch and roll) and that of the heave acceleration can be adequately represented by a linear function superimposed with a random fluctuation representing the spread of the pitch and roll joint distribution at a particular heave rms value. Analysis of the manner in which the pitch and roll moving rms are distributed for various values of heave rms was undertaken and was found to, in the main, be adequately represented by the normal distribution (grey dotted lines) as shown in Figure 6. This implies that the fluctuation in the angular velocity rms for a corresponding heave rms level can be generated by a random number defined by the normal distribution with a standard deviation, σ, that is dependent on the heave rms.

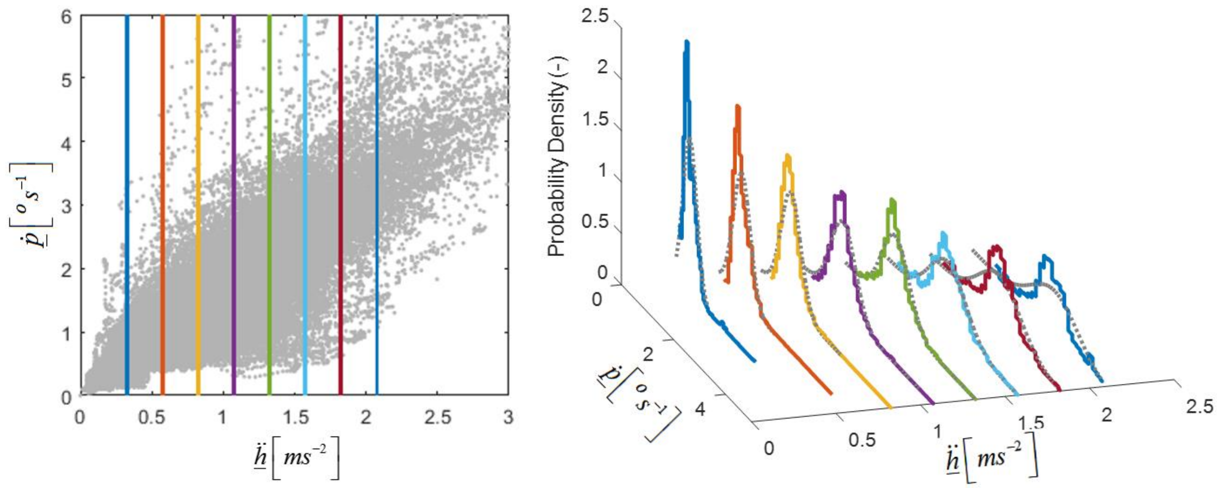


Figure 6. Nature of variation for the pitch moving rms for a typical joint distribution (Data for the Hiace Van (310 kg) along the Aldi distribution route shown here).

The variation in the standard deviation, σ, with respect to heave acceleration rms, $\underline{\ddot{h}}$, for the pitch and roll angular velocity moving rms ($\underline{\dot{p}}$ and $\underline{\dot{r}}$ respectively) for each case was analysed and was found to generally follow a straight line as shown in Figure 7 for a typical case.

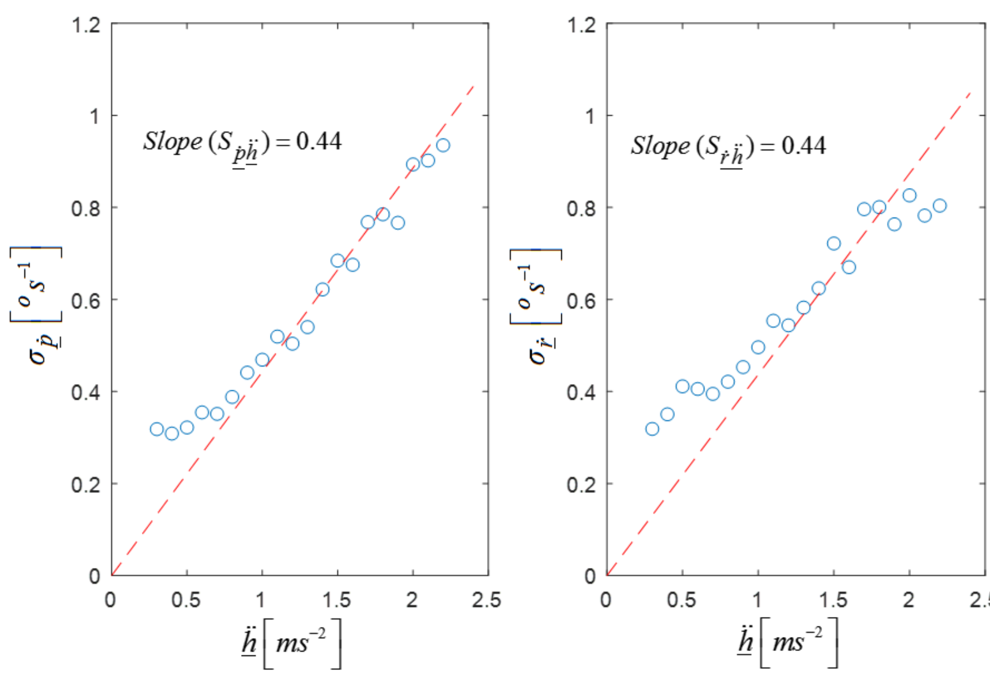


Figure 7. Typical variations in standard deviation of the joint distribution as a function of heave rms (Data for the Hiace Van (310 kg) along the Aldi distribution route shown here).

The relationship was modelled using a simple linear function that uses both the overall slope, *M* and the standard deviation, σ, of the joint rms distributions with respect to heave acceleration;

$$\underline{\dot{p}} = M_{\underline{\dot{p}\ddot{h}}}\,\underline{\ddot{h}} + \aleph(S_{\underline{\dot{p}\ddot{h}}}\,\underline{\ddot{h}}) \quad \& \quad \underline{\dot{r}} = M_{\underline{\dot{r}\ddot{h}}}\,\underline{\ddot{h}} + \aleph(S_{\underline{\dot{r}\ddot{h}}}\,\underline{\ddot{h}}) \qquad (1a, 1b)$$

for pitch and roll respectively where $M_{\underline{\dot{p}\ddot{h}}}$ and $M_{\underline{\dot{r}\ddot{h}}}$ are the slopes of the joint distributions for pitch and roll with respect to heave (see Figure 5) and $S_{\underline{\dot{p}\ddot{h}}}$ and $S_{\underline{\dot{r}\ddot{h}}}$ represent the corresponding gradients between $\sigma_{\underline{\dot{p}}}$ and $\underline{\ddot{h}}$ and $\sigma_{\underline{\dot{r}}}$ and $\underline{\ddot{h}}$. These are used to generate normally-distributed random values (denoted by $\aleph$) that provide the necessary fluctuation in rms levels.

The values of $M_{\underline{\dot{p}\ddot{h}}}$ and $M_{\underline{\dot{r}\ddot{h}}}$ obtained from the joint distributions for all 21 scenarios were computed and are shown graphically in Figure 8 (left) whereas corresponding values for $S_{\underline{\dot{p}\ddot{h}}}$ and $S_{\underline{\dot{r}\ddot{h}}}$ are shown in Figure 8 (right). Note that roll data for the Triton Ute 370 kg Woolworth and Aldi were found to be corrupt but were included in the results to show the heave and pitch information.

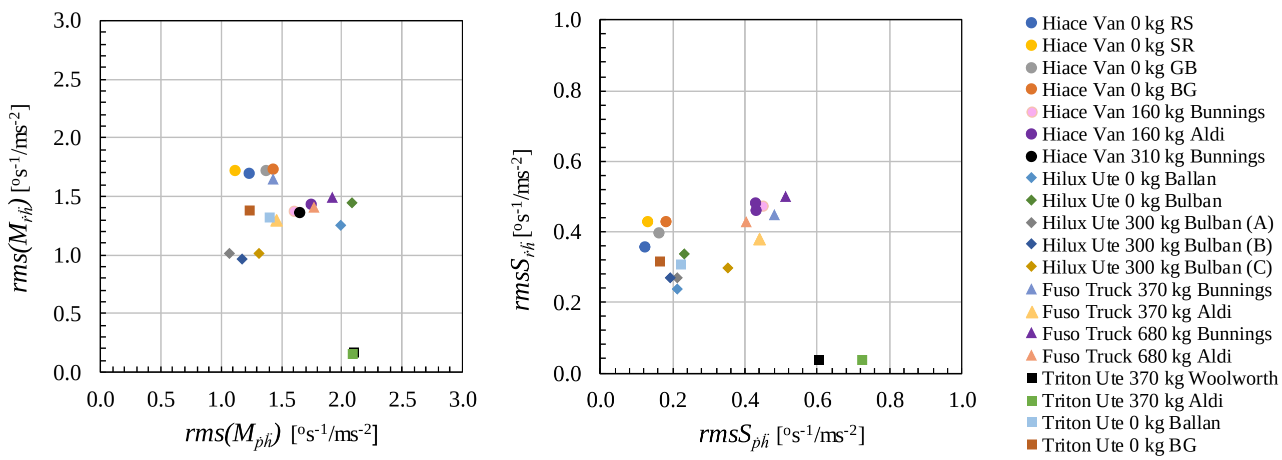


Figure 8. Scatter plot of the pitch:heave vs roll:heave joint rms distribution slopes (left) and $S_{\underline{\dot{r}\ddot{h}}}$ vs $S_{\underline{\dot{p}\ddot{h}}}$ and for all 21 scenarios.

These results show that, although the slope of the moving rms joint distributions are not all the same, they do tend to collapse around a mean of 1.5 ± 0.5 $^{o}s^{-1}/ms^{-2}$ for both pitch and roll with respect to heave (ignoring the two records with corrupted roll data). These results provide a useful guide for setting the rms levels of pitch and roll angular rate vibrations as a function to heave rms for laboratory simulations. The use of $S_{\dot{p}\ddot{h}}$ and $S_{\dot{r}\ddot{h}}$ afford the ability to superimpose a randomly-fluctuating rms component to the pitch and roll vibrations instead of producing constant rms angular vibrations that are perfectly correlated to the heave rms level. This is an interesting and important aspect of the relationships and creates the opportunity for the simulation of more realistic vibrations.

CONCLUSIONS

This paper uses results from the analysis of a reasonably broad set of heave, pitch and roll vibration data that were undertaken to better understand their interrelating statistical relationships. From a practical viewpoint, the data was used to recommend ways for configuring multi-axial vibration simulation tests. Data were collected from a range of typical delivery vehicles travelling on various urban and suburban delivery circuits covering nearly 2,000 kms and 40 hours. The results show that PDS from small delivery vehicles can be combined to create an approximate target function for simulation. This has limited practical use at this stage but does indicate that there are similarities in the spectral shape and overall rms levels of particular vehicle types when travelling along urban and suburban routes. Finally, analysis of the moving rms and their joint statistical distributions reveal that the relationship between pitch and roll with respect to heave can be approximated by a linear function that can be used to set the nominal rms level of pitch and roll for laboratory vibration tests. Further analysis of the joint statistical distributions revealed that the relationship between the pitch and roll (moving) rms with respect to heave (moving) rms, were better characterised by the superimposition of a random fluctuation in pitch and roll rms using a Normal approximation in order to avoid the artificial scenario whereby the pitch and roll rms levels are exactly correlated to the heave rms. This approach provides a practical and achievable method for exploiting the capabilities of multi-axis vibration tests systems for reproducing realistic vehicle vibrations under controlled conditions.

Overall, the results confirm that the relationship between the three modes of vibration is firmly linked to vehicle characteristics such as moments of inertia, wheel track and base and heave sensor location. The influence of these is near impossible to establish experimentally as individual variables cannot be altered independently and varying vehicle geometry at will is, in practice, impossible. Furthermore, the heave measurements were nearly always contaminated (influenced) with pitch (mostly) and roll vibrations as it was not always possible to locate the sensor at the CoG of the vehicle. These practical limitations can only be overcome by the creation of a vehicle numerical model to allow independent variations of each parameter hence enabling the establishment of the influence of these parameters on the multi-axial vibratory behaviour of ground transport vehicles. One shortcoming of this study is that data collected was mostly from small delivery vehicles whereas the main application of pitch and roll motion pertains to unit (palletised) loads that are usually transported by larger vehicles. This is planned to be addressed in a follow-up study focusing primarily on large transport vehicle vibrations including the response of single and double-stacked pallets.

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