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BSI Standards Publication

Environmental conditions — Vibration and shock of electrotechnical equipment

Part 5: Equipment during storage and handling

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National foreword

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A list of organizations represented on this committee can be obtained on request to its secretary.

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Environmental conditions – Vibration and shock of electrotechnical equipment – Part 5: Equipment during storage and handling

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COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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FOREWORD

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IEC TR 62131-5, which is a technical report, has been prepared by IEC technical committee 104: Environmental conditions, classification and methods of test.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
104/620A/DTR	104/639/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all the parts in the IEC 62131 series, under the general title *Environmental conditions – Vibration and shock of electrotechnical equipment*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this standard may be issued at a later date.

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ENVIRONMENTAL CONDITIONS – VIBRATION AND SHOCK OF ELECTROTECHNICAL EQUIPMENT –

Part 5: Equipment during storage and handling

1 Scope

IEC TR 62131-5, which is a technical report, reviews the available dynamic data relating to the handling of electrotechnical equipment. The intention is that from all the available data an environmental description will be generated and compared to that set out in the IEC 60721 series.

For each of the sources identified, the quality of the data is reviewed and checked for self consistency. The process used to undertake this check of data quality and that used to intrinsically categorize the various data sources is set out in IEC TR 62131-1.

This technical report primarily addresses data extracted from a number of different sources for which reasonable confidence exist in its quality and validity. The report also reviews some data for which the quality and validity cannot realistically be verified. These data are included to facilitate validation of information from other sources. The report clearly indicates when utilising information in this latter category.

This technical report addresses data from a number of data gathering exercises. The quantity and quality of data in these exercises varies considerably as does the range of conditions encompassed.

Not all of the data reviewed were made available in electronic form. To permit comparison to be made, in this assessment, a quantity of the original (non-electronic) data has been manually digitized.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60068 (all parts), *Environmental testing*

IEC 60068-2-27, *Environmental testing – Part 2-27: Tests – Test Ea and guidance: Shock*

IEC 60068-2-29[1], *Environmental testing – Part 2-29: Tests –Test Eb Bump*

IEC 60068-2-64, *Environmental testing – Part 2-64: Tests – Test Fh: Vibration, broadband random and guidance*

IEC 60721 (all parts), *Classification of environmental conditions*

IEC 60721-3-2:1997, *Classification of environmental conditions – Part 3: Classification of groups of environmental parameters and their severities – Section 2: Transportation*

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[1] Withdrawn and now incorporated into IEC 60068-2-27.

IEC TR 60721-4-2, *Classification of environmental conditions – Part 4-2: Guidance for the correlation and transformation of environmental condition classes of IEC 60721-3 to the environmental tests of IEC 60068 – Transportation*

IEC TR 62131-1, *Environmental conditions – Vibration and shock of electrotechnical equipment – Part 1: Process for validation of dynamic data*

IEC TR 62131-2, *Environmental conditions – Vibration and shock of electrotechnical equipment – Part 2: Equipment transported in fixed wing jet aircraft*

IEC TR 62131-3, *Environmental conditions – Vibration and shock of electrotechnical equipment – Part 3: Equipment transported in rail vehicles*

IEC TR 62131-4, *Environmental conditions – Vibration and shock of electrotechnical equipment – Part 4: Equipment transported in road vehicles*

3 Data source and quality

3.1 Container handling measurements by Hoppe and Gerock

Work by Hoppe and Gerock was under taken in the early 1970s and the resultant data are reproduced in a number of publications (see [1])[2].

Those data appear to have formed the basis for the road transportation severities in a number of national standards. Moreover, as far as can be identified, they are probably the original basis for the severities in IEC 600721-3-2. As the measured data also include a number of handling conditions, it is likely they were also considered in setting such severities. Although the measured data presented are limited, the scope of the measurements is sufficient to justify their inclusion here.

The Hoppe and Gerock work relating to handling, involved vibration and shock measurements on ISO containers at the container terminal, Hamburg/Burchardkai, during both in-yard transport and handling. The measurements included both 6 m (20 foot) and 12 m (40 foot) units when empty and loaded. Loaded 6 m and 12 m containers were also transferred onto a container train by means of a gantry crane. Dock side to ship measurements were made on loaded 6 m containers only.

Acceleration measurements were made at six locations within the containers; door end centre (in three orthogonal axes), door end right hand side (vertical only), centre of container (vertical only) and at the forward wall centre (vertical only). All six measurements were recorded simultaneously and continuously on an analogue FM recorder. The frequency range covered was 1 Hz to 1 250 Hz. All PSD analysis was undertaken using a 3 Hz frequency resolution and a record duration of 32 s.

The ISO containers used comprised steel framed structures with plywood walls with roofs reinforced with laminated fibreglass. The 6 m container was manufactured in 1969/70, it had an empty mass of 1 950 Kg and a loaded mass of 20 320 Kg. The 12 m containers were manufactured in 1970/71, had an empty mass of 3 490 Kg and a loaded mass of 30 480 Kg.

The container vibration measurements made during movement around the container terminal are summarised in Table 1. The measurements were found to contain predominant resonances associated with the suspension of the straddle or van carrier used to undertake the movements (typically at between 2 Hz to 3 Hz), the spreader used to support the container (6 Hz to 7 Hz)

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[2] Numbers in square brackets refer to the Bibliography.

and of the containers themselves (at around 160 Hz, 240 Hz and 400 Hz). The largest accelerations and displacements were consistently found to occur in the vertical direction and at the centre of the container. The largest derived displacement arose from carriage of the empty 6 m container at the maximum permissible speed. For the other container conditions the maximum speed was 20 km/h to 25 km/h.

The corresponding shock measurements when the containers were handled by the straddle or van carrier are summarized in Table 2. These include peak amplitudes occurring during pick up, set down on to the ground as well as set down on to another container. Again the largest accelerations were consistently found to occur in the vertical direction and at the centre of the container. The largest shocks were noted to occur during engagement and disengagement of the spreader.

The Hoppe and Gerock work also included measurements picking up and setting down containers on to rail vehicles (summarized in Table 3) and during transfer on to ships (summarized in Table 4).

The shock measurements are all presented in terms of peak acceleration amplitude and shock duration. No time histories are presented so the method used for the derivation of shock duration cannot be verified. Only one Shock Response Spectra (SRS) for handling is presented and its origins are unclear.

Although the information in this report is limited the quality of the information is reasonable and meets the required validation criteria for data quality (single data item).

3.2 Intermodal container handling by Association of American Railroads

This relatively recent (1991) work from the Association of American Railroads (see [2]) concerns the measurement and analysis of vibration and shock conditions experienced by standard ISO containers when transported by both rail and road. The objective was primarily to establish the relationship between the vibration and shock conditions experienced during rail and road movements. However, the work also includes shock and vibration measurements that occurred during handling. The data source relates almost entirely to ISO containers on the US and Canadian rail system.

The report indicates that the handling measurements utilized a self contained recorder. The recorder was programmed to record data in 7,7 sblocks of data when a threshold of 0,1 g was exceeded for more than 3,9 ms. These recorder settings were selected in an attempt to collect data virtuously continuously. The sample rate was 256 samples per second (sps) filtered at 30 Hz with a Butterworth low pass filter. The pre-programmable data recorders housed three orthogonal accelerometers capable of DC measurement (using piezoresistive accelerometers) in the vehicle fore/aft, lateral and vertical axes.

Measurements were made on a trailer carrying a 12 m (40 foot) ISO container, whilst it was loaded on and off rail cars. The loading and unloading adopted both overhead crane and a sideloader. The peak acceleration levels from these operations are summarized in Table 5 and the associated acceleration power spectral densities are shown in Figures 1 and 2.

The information in this report is limited to a trailer carrying 12 m (40 foot) ISO containers. It may also be specific to the US and Canadian rail systems. However, the quality of the information is good and meets the required validation criteria for data quality (single data item).

3.3 Intermodal container handling at Swedish container terminal

These very recent measurements (2007) were undertaken by Mariterm AB in conjunction with Helsingborgs container port (see [3]). The measurements relate to the handling of a 12 m (40 foot) empty container at the Helsingborgs container port.

The measurements were acquired using a data acquisition DT9816 recorder; this allowed measurement of 6 channels (2 × three orthogonal axes) of acceleration measurements. The digital recorder comprised a 12 bit ADC sampling at 1 500 sps. Four channels of measurements were low pass filtered at 370 Hz (one tri-axial and the fore/aft channel of the other) and two channels at 500 Hz. The accelerometers were positioned along the centre line of the container, on the floor and around 6 m apart. Although, the measurement axis of each channel is known, the specific identification of the tri-axial accelerometer is unclear. For this reason, the measurements are designated as from transducer groups 1 and 2.

The recorder measurement range was set to 10 g, which in comparison to other exercises, is somewhat low. Moreover, a few of the shocks, specifically in the vertical axis, appear to exceed this measurement range.

Measurements were made during handling of the container by a dockside container crane, movement by a container tug, handling by a container crane and handling by a straddle carrier. For each condition several separate measurement runs were made. Some attempt appears to have been made at making the measurements during different severities of handling conditions.

The report [3] supplies both sample time histories (albeit encompassing the entire record, typically 10 min to 20 min) and summary peak acceleration data along with approximate duration of the shock event. However, in addition to the report, the electronic measured data were also made available.

From the electronic data, summary information on the vibration severities are assembled in Table 6 and summary information of the highest shocks measured is presented in Table 7. Envelopes of the vibration acceleration power spectral densities, from each of the four handling conditions and for each axis, are presented in Figures 3 to 5. Amplitude probability densities, again for each of the four handling conditions and for each axis, are presented in Figures 6 to 8. Shock response spectra are presented in Figures 9 to 11.

Although the information in the hardcopy report is limited, the quality of the electronic information is good and meets the required validation criteria for data quality (single data item).

3.4 Handling of air cargo pallet at Stockholm and New York airports

The Swedish Packaging Research Institute reported a field study of loadings on an air cargo pallet in 1988 (see [4]). The measurements were made both on board a Boeing 747 Combi (freight and passenger) aircraft and also during cargo handling operations at both Stockholm airport (Arlanda) and New York (John F. Kennedy Airport). Shock and vibration acting on the cargo during handling were measured and analysed.

A tri-axial accelerometer was mounted on the pallet with double-sided tape and was placed approximately midway along the length of the pallet, about 0,5 m from the pallet edge. A fourth, separate, vertical accelerometer was mounted near the end of the pallet, approximately 0,5 m from the corner. The transducers were not mounted on the cargo in an attempt to establish acceleration measurements sensibly independent of cargo type. Nevertheless, the pallet loads chosen were 'typical'. During the outward stages (stages 1 to 3) the weight of the test pallet was 1 470 kg and during the return journey (stages 4 and 5) the weight was 2 550 kg. The measurement encompassed five stages:

- Stage 1 Arlanda terminal to aircraft, pallet weight 1 470 kg;
- Stage 2 Arlanda movement at aircraft, pallet weight 1 470 kg;
- Stage 3 JFK aircraft to terminal, pallet weight 1 470 kg;
- Stage 4 JFK terminal to aircraft, pallet weight 2 550 kg;
- Stage 5 JFK loading on aircraft, pallet weight 2 550 kg.

The field data recorded during the trip have been computer analysed in the time and frequency domains. The frequency domain analysis was carried out using both conventional spectral analysis and autoregressive modelling techniques. The sampling frequency chosen was 100 Hz and the signal was low-pass filtered at 31,5 Hz. The number of records, each spanning 256 samples, depended on the conditions under investigation. However, this was limited to 350 records, i.e. a sampling time of no more than 15 min. The window mostly used for the frequency analysis was the Blackman window. For the analysis using autoregressive modelling for the spectral estimation, the Hamming window was used.

A summary of the recorded extreme handling shock values and r.m.s. values are given in Table 8. A summary of the corresponding vibration data is shown in Table 9. The vibration data comprise acceleration levels (g) exceeded for 1 % of the time of the trial. Vibration spectra for each stage are shown in Figures 12 and 13 for the vertical and transverse axes respectively.

3.5 Forklift handling

This 1975 measurement exercise (see [5]) was undertaken by M.B. Gens at the Sandia Laboratories in the US adopted a common payload and four different size forklift trucks. Although a little old these measurements are the basis for conditions in several standards.

The measurement exercise addressed the transient conditions arising from traversing a test track made up of paved and unpaved areas. The paved areas included asphalt streets with manhole covers and metal utility covers as well as concrete aprons and driveways. The paved surfaces included both new and smooth surfaces as well as old and deteriorated surfaces. The unpaved areas were not intended as a driving surface and included steps of up to 25 mm. Experienced drivers were used, each instructed to travel at highest speed possible consistent with retaining the payload. In general, speeds were reported to be less than 10 mph (16 km/h) and mostly below 5 mph (8 km/h).

The measurements were made both on a pallet carrying a payload and the payload itself. The report indicates the payload as having a mass of 1 000 lb (500 Kg). The four forklift trucks were characterized as

- 1 000 kg (2 000 lb) capacity, electric powered and solid tyres;
- 1 500 kg (3 000 lb) capacity, petrol powered and pneumatic tyres;
- 2 000 kg (4 000 lb) capacity, petrol powered and pneumatic tyres;
- 3 500 kg (7 000 lb) capacity, petrol powered and pneumatic tyres.

The measurements were made using two groups of orthogonally orientated transducers; one group selected and set to measure accelerations up to 50 g peak-to-peak, the other to 10 g peak-to-peak. Tri-axial measurements from both groups were made at two locations; one close to the input from the forks and the other on the skin of the payload. All measurements were recorded on an FM tape recorder.

The 5 Hz band pass analysis of the data elicited the conclusion that no steady state continuous randomly distributed excitation was present in the forklift environment. Discrete excitations, on the other hand were prevalent. A total of 49 vibration spectra (from all four forklift trucks) were combined to allow plots of mean, mean plus three standard deviations as well an envelope of maximum response. The responses for the pallet measurements (effectively the excitations applied to the payload) are shown in Figures 14 to 16 for the vertical, lateral and axial axes respectively. The envelopes of largest shock response spectra for each of the four forklift trucks are shown in Figures 17 to 20.

3.6 Movement of unsuspended trolleys

This very recent (2009) measurement exercise (see [6]) was undertaken, by Drager Medical, to determine the vibration and shock conditions arising from the movement of medical trolleys over flooring typically occurring within modern building and outside in car park type surfaces. The three trolleys have small, unsuspended castor type wheels which are common to many items of modern electro-technical equipment. They are also typical of handling trolleys commonly used to move small packages on and off trucks and around warehouses. All the movement occurred at walking speed.

The measurements were made on three different medical devices as set out below. In each case the tri-axial acceleration vibration measurement were made on the support system, just above the wheels:

- small trolley – A small medical ventilator, mass 22,5 kg, castors 100 mm diameter, castor surface PA6 of hardness Shore A 80;
- medium trolley – Anaesthetic workstation, mass 147 kg, castors 125 mm diameter, castor surface polyurethane of hardness Shore D 40;
- large trolley – Intensive care ventilator, mass 54 kg, castors 125 mm diameter, castor surface polyurethane of hardness Shore D 40.

The intended velocity of the movements was 0,5 m/s although the real velocity appears to have varied between 0,5 m/s and 0,7 m/s. Movement was in the X (axial) axis with the Z axis vertical. The typical 5 surface types traversed were

- composite stone,
- granite plates 70 cm × 70 cm,
- pvc floor 60 cm × 60 cm at 0,5 m/s and 0,7 m/s,
- asphalt light grey,
- asphalt rough.

The transducers and measurement system are indicated as within calibration. The digital recorder sample rate was 8 192 sps and the remainder of the measurement chain was capable of measurements of at least 3 kHz. The recorder utilized a 16 bit ADC, an anti-aliasing filter of 3,2 kHz. The measurement record lengths varied between 1 min and 3 min although 120 s was commonly achieved. In this case the measured data and all the analysis are available digitally.

Shown in Figures 21 to 29 are the vibration severities for each of the three axes for each of the three devices. A summary of the corresponding overall acceleration root mean square values are presented in Table 10. Amplitude Probability Density (APD) values for the device which experienced the most severe conditions (the small medical ventilator) are show in Figures 30 to 32. Corresponding Shock Response Spectra (SRS) for the same device are shown in Figures 33 to 35.

3.7 Supplementary data

The data collection exercises which preceded this particular assessment attempted to supplement the data with any relevant sets of information, arising from reputable sources, but for which the data quality could not be adequately verified. Although no additional sources were identified, a SRETS study (see [7]) undertaken during 1998 reviewed the types and occurrences of damage that occur as a result of transportation and particularly that identified during handling related to transportation. Although that report (see [8]) contains no specific information on the mechanical environments occurring during handling, it does give a good review of the different types of damage a range of items may experience during handling.

4 Intra data source comparison

4.1 General

The purpose of the following subclauses is to review each data source for self consistency. The process for evaluating the vibration data takes into account the variations arising from the different methods of handling.

4.2 Container handling measurements by Hoppe and Gerock

Although the extent of the vibration information, tabulated in the Hoppe and Gerock report, is relatively limited it does, with one exception, appear reasonably consistent. The acceleration amplitudes are quite low, possibly giving rise to concerns over measurement accuracy. The derived displacements are relatively high, for the low acceleration levels, suggesting low frequency excitations (which are confirmed in the report). With that said, the report does not make clear the method used for deriving displacements from the acceleration measurements. The concern is that high displacements can arise if this is not undertaken appropriately. The distribution of amplitudes between full and empty containers, as well as between axes, is largely as would be expected. The one value that is out of line with the remainder is the vertical measurement on empty containers. The acceleration amplitude indicated is more than double any other tabulated value and the listed peak displacement is four times greater than any other. The occurrence of this condition is explained in the report as due to high movement speeds. The indicated peak displacement is essentially the same as the largest equivalent drop height suggested from consideration of the shocks.

The tabulated handling impact acceleration amplitude values, presented in the Hoppe and Gerock report, indicate an underlying trend. That is smaller empty container generally generate the worst case conditions whilst the largest loaded containers generally result in lower impact acceleration amplitudes. This is entirely as would be expected.

The shock data quotes acceleration amplitudes as well as durations. As a consequence of the different approaches used, the validity of tabulated shock durations, without a description of how they were derived, is always questionable. A verification exercise has been undertaken, which assumes the shocks are a result of impacts between two elastic bodies. The exercise indicates that the accelerations and the derived velocities follow a realistic and consistent relationship, Figures 36 and 37 refer respectively. Only a few values fall outside the main trend but even those are only to an extent expected from measured data. The largest indicated velocity change is 0,6 m/s with the majority of impacts occurring below 0,4 m/s. The values suggest that size of container or its loaded state makes no underlying difference to the velocity. The largest equivalent drop height, derived from the velocities, is a little less than 19 mm.

The Hoppe and Gerock report supplies only a single shock response spectrum for the handling impacts and this is marked as 'typical'. Nevertheless, the shape of the shock response spectra is typical of that for short duration impacts of the type indicated by the tabulated values.

Overall, the Hoppe and Gerock data appears self-consistent, showing trends and values that are largely within expectations. The data meets the required validation criteria for quality against the intra data source comparison criteria.

4.3 Intermodal container handling by Association of American Railroads

The handling information presented by the Association of American Railroads report is quite limited and the handling measurements clearly were not the primary objective. The shock values appear reasonable consistent although, given the limited information, no useful trends can be discerned. The relationship between axes appears reasonable and as would be expected. The frequency spectra indicate quite low frequency content from both handling devices. The main concern with this data is that it is sampled at 256 sps and low pass filtered at 30 Hz which is quite low for shock measurements. This may be limiting the peak amplitudes measured. Also as no shock durations are indicated, the equivalent velocity and displacement cannot be derived.

Although the data, in the Association of American Railroads report, meets the required validation criteria for quality against the intra data source comparison criteria, it is limited in both extent and range. The Association of American Railroads report supplies shock amplitudes but not the corresponding durations. As a consequence they cannot be credibly compared with other data and have only limited usefulness in the comparison with existing environmental descriptions addressed hereinafter.

4.4 Intermodal container handling at Swedish container terminal

The Mariterm AB measurements, made at the Helsingborgs container terminal, encompass similar handling conditions to those of the Hoppe and Gerock work. However, the Mariterm AB measurements are recent and available in electronic form. The primary concern arising from primary review of the data is that some of the peak amplitudes of the vertical shock values exceed the stated measurement range of 10 g.

The vibration r.m.s. values shown in Table 6 indicate a reasonable degree of consistency notably that the responses in the vertical axis are markedly greater than those in the transverse axis, which is in turn are greater than the axial axis. The severities of transducer group 1 are mostly greater than transducer group 2. However, this fact is not particularly useful without knowledge of the specific locations at which the groups are located.

The vibration power spectral densities shown in Figures 3 to 5, indicate that at low frequency (below 10 Hz) the movement of the straddle carrier is the most severe condition. At higher frequencies the movement of the mobile handling crane is consistently the most severe. The suspension frequency of the various handling vehicles is clearly identifiable in all axes, but is particularly significant in the vertical axis. Modal responses, apparent at 30 Hz and 55 Hz, are assumed to arise from the container.

The amplitude probability densities, shown in Figures 6 to 8, indicate a reasonably well defined Gaussian distribution in the transverse and axial axes. In these axes the amplitude distributions are contained within the measurement range and imply only modest shocks superimposed upon the vibrations. The distribution in the vertical axis is very similar to that identified for road vehicles. Specifically they contain a, low amplitude and high probability distribution, which represents the vibrations. Onto this vibration distribution is superimposed a second, higher amplitude and lower probability distribution, usually assumed to represent the shocks. This latter distribution is mostly contained within the measurement range (of 10 g) but some single occurrences are outside this range.

The shock response spectra, computed from the full measurement record, are shown in Figures 9 to 11. The shock response spectra indicate similar trends to those of the corresponding power spectral densities. Specifically, at low frequency (below 10 Hz) the movement of the straddle carrier is the most severe condition. At higher frequencies the movement of the mobile handling crane is consistently the most severe. Apart from at low frequency, identified as the vehicle suspension frequencies, the shock response spectra are credibly consistent. The shock response spectra correspond to a velocity change of up to 0,2 m/s in the axial axis, 0,5 m/s in the transverse axis and 1,0 m/s in the vertical axis. These relate to an equivalent drop heights of 2 mm, 12,5 mm and 30 mm in the axial, transverse and vertical axes, respectively.

The Mariterm AB measurements essentially meet the required validation criteria for quality against the intra data source comparison requirement. However, some concern remains that a few vertical measurements exceed the set measurement range.

4.5 Handling of air cargo pallet at Stockholm and New York airports

The Swedish Packaging Research Institute study of handling loads on an air cargo pallet were made on board a Boeing 747 Combi (freight and passenger) aircraft. This was integral with that intended to make in-flight vibration measurements and reported in IEC TR 62131-2. The verification exercise of those vibration measurements highlighted issues with the low sample rate (100 sps) and the frequency of the low pass filter (31,5 Hz). As the measurement system was identical, for the handling and in-flight vibration measurement exercises, these aspects are also of concern here. The relatively low shock and vibration amplitudes observed in these measurements are almost certainly influenced by the low sample rates.

The vibration information, presented in the form of acceleration power spectral densities (PSDs), all show signs of a reasonably significant random error. The highest spectral density amplitudes mostly occur at low frequency. However, the PSDs encompass a frequency range beyond that of the low pass filter. As a consequence some care needs to be taken with the information above around 25 Hz.

The tabulated shock and vibration handling measurements show a broad degree of consistency. The vertical axis produces the most severe acceleration amplitudes with the measurements at the corner of the air freight pallet more severe than the centre. The measurements made at JFK airport are more severe than Arlanda; this the report attributes to less stringent controls at JFK. This would appear to be supported by consistently more severe vibration and shock measurements at JFK. No shock duration information is supplied nor is any form of data presentation employed that would allow velocity or equivalent drop heights to be derived.

The Swedish Packaging Research Institute measurements from handling of an air cargo pallet make a useful contribution to this review of handling conditions. Nevertheless, concerns over the limited frequency range imply that the validation criteria for quality against the intra data source comparison requirement are only met with reservation.

4.6 Forklift handling

Although the US measurements on four different sized forklift trucks were made some time ago, the work was undertaken by a competent authority with significant resources. Although a little old, the shock measurements still appear within several current test standards.

The most obvious reservation with the Shock Response Spectra (SRS) envelopes is that the frequency range adopted is a little limited. Many of the SRS envelopes are still rising at the highest frequency, suggesting the frequency encompassed was insufficient. The lower frequencies indicate a fair amount of variation, which can sometimes be indicative of poor measurements. However, in this case the shock response spectra are stated to be envelopes generated from a significant number of measurements. As such the individual SRS are unlikely to represent any single event. This could explain the observed variations at the lower frequencies.

The three sets of SRS measurements from the petrol powered and pneumatic wheeled forklift trucks imply a believable trend of decreasing shock levels with increasing forklift size. Broadly speaking, the amplitude of the vertical shocks exceed those from the other two axes. Moreover, the vertical axis indicates a low frequency response (typically 3 Hz to 5 Hz) which would be expected from the pneumatic wheels. The electric solid wheeled forklift truck shows much lower SRS levels than the other three. This seems likely to be a consequence of the lower speed capability of that vehicle, especially on the rougher surfaces.

The vibration severities are in the form of band pass acceleration levels, presented in terms of statistical mean, mean plus three standard deviations and measured peak. This form of presentation was fairly typical of vibration measurements emanating from this establishment at that time. Unfortunately, when presented in this way the vibration measurements are difficult to utilize directly but are useful checks on other data. The peak value envelopes of the vibration measurements are consistently greater than the mean plus three standard deviation envelopes. Moreover, the peak value envelopes are consistently around 3 times greater than the mean envelopes. Together these imply that the vibrations are largely Gaussian, and the standard deviations of the measurements are consistently low. All of this typifies good measurements. The vertical axis measurements indicate a clear and well defined vehicle suspension/tyre mode at around 5 Hz. This is not apparent in the other two axes.

Overall, the forklift truck data appear self-consistent, showing trends and values that are largely within expectations. Both the shock and vibration data meet the required validation criteria for quality against the intra data source comparison criteria. However, the presentation of the vibration data means it is not particularly useful as a means of setting practical vibration test severities. However, the information could be useful to confirm existing information.

4.7 Movement of unsuspended trolleys

The recent measurement from the movement of three medical trolleys was available digitally, allowing detailed information to be presented. The measurements encompass movement over five surfaces typical of the flooring within modern buildings and immediate vicinity. The measurements were typically made just above a wheel, thus allowing use for similar items of equipment.

The results from the various measurements indicate a degree of consistency. The amplitude distribution from all the measurements are fundamentally random, but with a Kurtosis greater than would be expected from a purely Gaussian distribution. The amplitude distribution measured is typical of that seen on vehicles experiencing a mix of vibration and shocks. In this case, the peak values are typically around 10 times greater than the acceleration root mean square, or around 3 times greater than would be expected from a purely Gaussian distribution. This trend is exhibited by the “rougher” surfaces for all three trolleys in all three axes. The “smoother surfaces” show an amplitude distribution closer to a Gaussian distribution.

Broadly, the frequency spectra from all three trolleys show a similar trend. However, as would be expected, the strong lower frequency modes (typically 20 Hz to 40 Hz) are different for each trolley and each axis. The power spectral densities (PSD) shows a greater medium frequency content than observed on some of the other vehicles. However, this is not entirely surprising given that the three trolleys have no intrinsic suspension system. The PSD amplitudes are seen to be more severe for the floor surfaces typically found outside a building (asphalt and composite stone). The surfaces typically found inside a building (PVC and granite tiles) are observed at around an order lower than those for external surfaces.

The consistency between axes is reasonable, although, in terms of peak and overall r.m.s. acceleration, the vertical axis is not, as would be expected, the most severe. In terms of these parameters the fore/aft axes is consistently the most severe, albeit, not by a large margin. As a consequence, some doubt arises as to whether the axes were correctly defined.

Overall, the medical trolley measurements appear to indicate self-consistent trends and values that are largely within expectations. Some slight concern exists as to whether the axes were correctly defined. Nevertheless, the data meets the required validation criteria for quality against the intra data source comparison criteria. The trolleys had small, unsuspended castor type wheels which are common to many items of modern electro-technical equipment. As such, they are also typical of handling devices commonly used to move small packages on and off trucks and around warehouses.

5 Inter data source comparison

For the most part, the data from the various sources indicated a reasonable degree of self consistency. However, it is clear some differences exist between sources, conditions encompassed and the type of information available from the individual measurement exercises.

Considering firstly the shock severities from the pick-up and set down of ISO containers, for which information from three different sources are available. Of these sources, the Hoppe and Gerock data is the oldest but also the most comprehensive. It indicates peak acceleration amplitudes up to 38 g, a value which is very much consistent with the remaining data. The peak acceleration amplitudes do vary with payload mass and container size, with the smallest empty containers giving the highest acceleration amplitudes. Shock duration information supplied indicate the largest velocity change as 0,6 m/s. The values suggest that size of container or its loaded state make little underlying difference to the velocity. The largest equivalent drop height for the velocities is a little less than 19 mm.

The Mariterm AB measurements, made at the Helsingborgs container port, also addressed the pickup and set down of ISO containers, but are far more recent measurements. Although a few measurements may be limited in peak acceleration amplitudes to 10 g, the general distribution of shocks indicates this is not a major issue. Whilst, reasonably consistent with the Hoppe and Gerock data the general shock amplitudes are lower.

The peak acceleration amplitudes, indicated by the Association of American Railroads data, are significantly lower than those from the other two measurement exercises. However, the Association of American Railroads data had limitations in frequency range and also applied to an ISO container already loaded on to a wheeled vehicle trailer (increasing mass and giving some protection). As no shock duration information was supplied velocity change could not be compared with the other two measurement exercises.

The study by the Swedish Packaging Research Institute considered of handling loads on an air cargo pallet, at Stockholm and New York airports. Cargo handling at airports could be expected to be more controlled than at container ports. The data appear to support this, although the acceleration peak shock amplitudes are not widely out of line with those from the Helsingborgs container terminal. However, the frequency range of the data is very limited and is almost certainly likely to be limiting the occurrence of shock peak amplitudes. As no shock duration information was supplied velocity change could not be compared with the other measurement exercises.

The US SANDIA measurements on four different sized forklift trucks encompass movements on both good and poor surfaces. Unlike all the other shock measurements, the US SANDIA measurements present the shocks in the form Shock Response Spectra (SRS). The SRS plots for the three largest forklift trucks (petrol powered and pneumatic wheeled) imply a peak acceleration level marginally less than that from the Hoppe and Gerock data for ISO containers. The manner in which the SRS values were assembled make deriving accurate velocity change information difficult, but they appear to be largely between 0,5 m/s and 1,0 m/s. The shock information from the smallest forklift truck (electric and solid wheels) indicates a much lower levels of peak acceleration (around 3 g). This is not surprising as such a truck is likely to have only a limited speed capability over poor surfaces. The SRS plots for this truck appear to be significantly influenced by vibration conditions and shock velocity information cannot be credibly determined.

The shocks from the movement of the unsuspended trolleys are specified in terms of maximum response spectra (MRS). These are effectively shock response spectra but computed from the entire measurement record. As such the MRS includes contributions from both shock and vibration. As was the case for the US SANDIA forklift truck measurements, the effects of the vibrations complicate the ability to establishing an equivalent shock conditions. Nevertheless, the velocity of the shocks appear to be largely below 0,5 m/s for movement over floor surfaces found immediately outside buildings and 0,05 m/s for internal surfaces. The corresponding acceleration peaks are around 35 g and 8 g for external and internal surfaces respectively. In both cases the duration of the shock appears to be less than 1,5 ms. As such the worst case shock characteristics are quite similar to those identified for other methods of movement during handling.

When considering the vibration information from the various sources, it is apparent that the vibration measurements during handling and the type of information supplied in the reports is quite limited. In several cases the vibration measurements were simply to compare with other measurements made during more severe operations, road or rail transport for example.

Wheeled vehicle transportation information from the Hoppe and Gerock exercise appears to have been used to set older road transportation vibration severities. However, the information supplied on vibration during handling is very limited, including only peak acceleration and displacement values. Moreover, of these the displacement information is questionable. The most common peak acceleration amplitude is 0,2 g with a single value exceeding this at 0,5 g (made on an empty container). It seems reasonable to assume a broadly Gaussian distribution, as such the worst case root mean square value is unlikely to exceed 0,15 g (1 Hz to 1 250 Hz). The peak displacements indicated by the report are relatively high for the corresponding acceleration levels. This would imply a predominant response at reasonably low frequency (around 5 Hz).

The envelopes of acceleration Power Spectral Density (PSD) vibration amplitudes, from the intermodal handling at a Swedish container port are shown in Figures 3 to 5. The individual spectra from which these envelopes were generated are shown in Figures 52 to 55. As already indicated, the vibration aspects appear sensibly Gaussian in distribution. Apart from the low frequency suspension modes (occurring at less than 5 Hz), the axial and transverse responses are well encompassed by an amplitude of 0,001 g^2/Hz and an overall rms value of 1,4 g (up to 370 Hz). The vertical axis responses are markedly greater with a reasonable number of exceedances of the 0,001 g^2/Hz value and one occurrences at around 0,02 g^2/Hz. The low frequency suspension modes are particularly marked at 0,1 g^2/Hz. The highest overall rms value is around 4,7 g.

The acceleration power spectral density (PSD) vibration amplitudes, indicated by the Association of American Railroads data, encompass a frequency range much lower the other exercises considered (less than 5 Hz). The vibration spectral amplitudes from movements by overhead crane are quite low showing no spectral value over 0,006 g^2/Hz. The vibration amplitudes from the side loader are higher showing a maximum spectral value at 0,04 g^2/Hz but at a frequency of only 0,5 Hz. The derived root mean square values are 0,13 g and 0,2 g for overhead crane and side loader respectively but both over the frequency range 0 Hz to 5 Hz.

The Swedish Packaging Research Institute study of conditions on an air cargo pallet during ground movements presented the vibration in terms of a summary of peak conditions and spectral information which for this comparison has being converted to acceleration power spectral density (PSD) vibration amplitudes. The tabulated information indicated peak values of around 1 g which, if a Gaussian distribution assumed, would correspond to an r.m.s. of not more than 0,3 g (0 Hz to 31,5 Hz). The acceleration power spectral density (PSD) vibration amplitudes indicate a considerable spread of results in both vertical and transverse axes. It is notable that in the vertical axis the frequency of the transport vehicle suspension mode moves from around 3 Hz at low amplitude responses to around 8 Hz in the higher amplitude responses. This would imply a “hardening” suspension stiffness which is typical of simple suspension systems. The spectral shape of the higher amplitudes is also typical of that experienced when shocks are embedded within the vibration, again a common characteristic of simple suspension systems. The highest spectral amplitude is 0,04 g^2/Hz although the remainder of the spectra are all below 0,005 g^2/Hz. Root mean square values, derived from the PSDs, indicate a very marked difference, of around 10, between the two airports at which movement occurred. The highest vertical r.m.s. is 0,45 g (0 Hz to 50 Hz), and the corresponding highest transverse r.m.s. value is 0,2 g (0 Hz to 50 Hz).

The vibration measurements from the movement of three unsuspended trolleys indicate suspension modes which are more complicated and higher frequency than those of other measurements. This is not entirely surprising as none of the trolleys have a specific suspension system but rather rely entirely on the structural modes of the mounting system. As a consequence of this, the response amplitudes at these modes are the most severe, significant amplitudes still exist often beyond 100 Hz. The acceleration power spectral density vibration amplitude values are essentially bounded by a peak amplitude of 0,01 g^2/Hz. The highest r.m.s. values derived from the PSDs, is 0,9 g (0,5 Hz to 2 000 Hz) for the most severe outdoor surfaces and 0,12 g (0,5 Hz to 2 000 Hz) for the indoor surfaces.

The US measurements on four different sized forklift trucks were made some time ago, and the vibration severities are in the form of band pass acceleration levels, presented in terms of statistical mean, mean plus three standard deviations and measured peak. Unfortunately, when presented in this way, the vibration measurements are difficult to numerically compare with other data. In this case a relative comparison can be made with the maximum response spectra from the medical trolley measurement exercise. This comparison indicates that the forklift vibrations are of slightly lower in amplitude than the vibrations from the medical trolleys. The highest amplitudes occur at the suspension frequency in the vertical axis.

Comparing the vibration severities, from the various measurement exercises is more difficult than was the case for the shocks. Nevertheless, a reasonable degree of underlying consistency is observed between the measurements. The measurement frequency range of some the measurement excises is very low. However, mostly they are sufficient to encompass the primary suspension modes of the various vehicles which dominant the majority of the vertical responses.

6 Environmental description

Ideally, an environmental description should quantify all aspects of an environmental condition. Practically, it is usually sufficient to quantify the aspects that may induce damage and failure to any equipment that may subject to it. For some environments this is easy to achieve, for others it is quite difficult. The vibration and shock conditions arising from handling appears, based upon the data reviewed, to fall somewhere between these two extremes.

Based upon the data reviewed, it would appear that the handling mechanical environments can be defined in terms of shocks conditions arising from impacts as well as in terms of the vibrations arising from movements of the handling equipment. The latter appears to be composed of either random vibrations with a reasonable Gaussian distribution or a mix of Gaussian vibration and a distribution of embedded transients.

The most severe shocks conditions arising from impacts that were reviewed as part of this work were reasonably consistent given that they are largely dependant upon a number of factors. The peak acceleration levels observed were a little under 40 g, although the associated duration is typically around 1,5 ms. The derived velocity changes are mostly encompassed by values of 0,5 m/s to 0,6 m/s. To put these values in context the velocities could be generated by a drop of no more than 20 mm.

Shock response spectra have been derived for the exercises were only shock amplitude and duration are supplied. The intrinsic assumption necessary is that the impact occurs between surfaces which remain sensibly elastic, resulting in a pulse shape which is likely to be reasonably represented by a half sine pulse. If that is the case then a shock response spectra definition for the impacts can be estimated. Such a definition is found to essentially encompass the SRS information from measured data. This deduced shock response spectra describing the environmental severity for handling shock is compared with existing test severities in the next clause.

The vibrations arising from movements of the handling equipment is more difficult to quantitatively define as a consequence of the many variables that affect it. Not only do conditions such as surface and vehicle speed have an influence on the environment, these effects are synergistic. In this particular case the extent to which they are related is controlled almost entirely by the actions of a third influence – the vehicle driver.

The most predominant feature of the vibration environment is the low frequency responses that occur at vehicle suspension modes. These responses frequently generate the highest acceleration spectral amplitudes as well as the highest velocities and displacements. As would be expected from a mode arising from vehicle suspension, the response amplitudes are affected by considerations such as vehicle speed and road surface. By design, vehicle suspension systems are intended to limit dynamic magnification (by modestly high levels of damping) and attenuate much of the shock and vibration conditions that are imposed on the vehicle.

The acceleration responses at the apparent suspension frequency are generally the highest amplitudes generated by the various movements. The greatest acceleration power spectral density amplitude at this mode is around 0,04 g^2/Hz. For the vehicles likely to have suspension systems response amplitudes, at frequencies other than the suspension frequency, are generally less than 0,005 g^2/Hz. The effect of the suspension system is to gradually attenuate excitations at frequencies above that of the suspension system. The overall r.m.s. values from the various measurements relate to widely different frequency ranges and should be treated with some care. Nevertheless, the values mostly encompass the suspension frequency and at low frequencies are essentially encompassed by a value of 0,5 g (0 Hz to 50 Hz). Over a broader frequency range this rises to around 1 g (0 Hz to 500 Hz). For vehicles without suspension, the highest amplitudes occur over a broader frequency range, with significant amplitude beyond 100 Hz. The measurements available indicate peak responses encompassed by a value of 0,01 g^2/Hz and an overall r.m.s. of 0,9 g (0 Hz to 2 000 Hz). These deduced environmental vibration severity for handling movements are compared with existing test severities in the next clause.

7 Comparison with IEC 60721

No environmental requirements are specified in the IEC 60721 series which specifically and uniquely relate to handling conditions. Rather, the shock and vibrations conditions arising from handling are assumed to be encompassed by those from general transportation. This is also intrinsically the case for the test severities in the IEC 60068 series [11].

The three "transport" categories set out in IEC 60721-3-2 are designated 2M1, 2M2 and 2M3. Only a brief explanation is given as to the conditions these represent, but seem to be essentially:

- 2M1 – mechanical loading as well as transportation in aircraft, lorries and air-cushioned trucks and trailers
- 2M2 – transportation in all kinds of lorries and trailers in areas with well-developed road systems;
- 2M3 – other kinds of transportation, also in areas without well-developed road systems

The relevant environmental severities of Table 5 of IEC 60721-3-2:1997 are intended to encompass all forms of transport but are mostly related to road transport. Comparison of those severities with transportation by fixed wing jet aircraft, rail vehicles and road vehicles is addressed in IEC TR 62131-2, IEC TR 62131-3 and IEC TR 6213-4 respectively. As the quoted values are environmental severities, no durations or number of applications are specified. The three relevant categories in Table 5 of IEC 60721-3-2:1997 include

- category a) – stationary vibration sinusoidal,
- category b) – stationary vibration random (illustrated in Figure 38),
- category c) – non-stationary vibration including shock (illustrated in Figure 40).

Some years ago it was identified that the amplitudes of the IEC 60721-3 series differed from those of the IEC 60068-2 series. As a consequence of these differences a reconciliation exercise was undertaken between the two documents. The recommendations from that reconciliation exercise are set out in IEC 60721-4-2. For the stationary random vibration condition, IEC 60721-4-2 recommends the IEC 60068-2 amplitudes which are illustrated in Figure 39. With regard to shocks, the nearest identified severity was that of IEC 60068-2-27, Ea shock (illustrated in Figure 42) but the recommended severity was that of IEC 60068-2-29[3], Eb Bump (illustrated in Figure 41). Since the recommendations of IEC 60721-4-2 were published, IEC 60068-2-29, Eb Bump has been merged with IEC 60068-2-27, Ea shock. Nevertheless, for consistency with the recommendations of IEC 60721-4-2, IEC 60068-2-29, Eb Bump is referenced whenever the severities of that procedure are intended (this distinction was also made in IEC TR 62131-2, IEC TR 62131-3 and IEC TR 6213-4). When applicable the duration of vibration testing and number of shock applications are quoted in the figures.

The shock response spectra severities from IEC 60721-3-2 and IEC 60721-4-2 (half sine shock pulse) are compared with the corresponding handling shocks in Figures 43 to 49. These overlaid comparisons include all the available shock information available from; the Hoppe and Gerock measurements (Figure 43), the unsuspended trolley measurements (Figure 44), the US forklift truck measurements (Figure 45) and the four different handling methods encompassed by the Swedish port measurements (Figures 46 to 49).

The majority of the actual shocks identified in this study are of much shorter duration than those of the shock environments and tests set out in IEC 60721-3-2 and IEC 60721-4-2. As a

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[3] IEC 60068-2-29:1987 has been withdrawn and is now merged into IEC 60068-2-27:2008.

consequence, the equivalent velocities and drop heights of the IEC 60721 severities are much greater than the shocks identified in this study. Figures 43 to 49 indicate that the amplitudes of 2M2 can be considered to encompass the severities of ISO container handling, forklift trucks handling (on good and poor surfaces), air transport handling and handling at walking speeds using unsuspended trolleys in warehouses.

The acceleration power spectral densities from IEC 60721-3-2 are compared with the corresponding handling shocks in Figures 50 to 55.These overlaid comparisons include all the available vibration information from; the Swedish air transportation pallet handling measurements (Figure 50), the unsuspended trolley measurements (Figure 51) and the four different handling methods encompassed by the Swedish port measurements (Figures 52 to 55).

The handling vibration severities identified in this study are generally of lower amplitude than those of the stationary random vibration environments and tests set out in IEC 60721-3-2 and IEC 60721-4-2 (shown in Figures 50 to 55). The amplitudes of 2M2 can be considered to encompass the severities of ISO container handling, forklift trucks handling (on good and poor surfaces), air transport handling and handling at walking speeds using unsuspended vehicles in warehouses.

8 Recommendations

Good data have been identified from several sources, encompassing a range of real world handling conditions for general electro-technical equipment. The data sources reviewed encompass several measurement exercises related to the handling of ISO containers of different sizes, loading and at different locations. The data sources reviewed also includes the handling of air transportation pallets at two locations. Additionally considered are the mechanical environments from the forklift handling of items, both on good and poor surfaces. This latter data sources encompasses a range of forklift truck sizes ranging from small electric forklifts to large petrol vehicles. Lastly data from the induced mechanical environments due to the movement of medical trolleys was reviewed. Although the information from these medical devices relate to movement at walking pace on reasonable good surfaces, they represent conditions occurring when small wheeled vehicles are used, which have no suspension system deliberately incorporated.

For the most part, the data from the various sources not only indicates a reasonable degree of self consistency but also a fairly good degree of consistency across the various sources. None of the data sources are so obviously significantly different from the remainder to the extent that the validity of this assessment exercise is called into question. It is clear from the information reviewed that the handling dynamic environment is sensitive to a number of variables. However, some broad trends are consistent for the majority of modes of handling addressed.

The shock conditions observed from all the methods of handling are reasonably consistent. The shock pulses are of relatively short duration, which gives some concerns, with many of the measurements exercises, as the data capture sample rates are all inadequate to define the shock with rigorous accuracy. The amplitude range of some measurement exercises has also proven inadequate.

The handling shock amplitudes observed fall within the range of potential options specified in IEC 60721-3-2, IEC 60721-4-2 and IEC 60068-2-27. Moreover all the shocks identified by this report fall within those specified for transportation definition 2M2. However, the actual pulse durations are generally lower. In consequence the observed handling velocity change and equivalent drop heights are mostly lower than implied by the existing tests.

The handling vibration severities identified in this study generally exhibit a similar degree of variability as identified previously for wheeled vehicle transportation. Specifically, vibration severity is associated with traversed surface and vehicle speed, the latter dependent upon the vehicle driver. The transport vehicle suspension frequency is usually the most significant response amplitude. The suspension frequency usually occurs at low frequency and in a similar frequency band as identified for wheeled transport vehicles.

The handling random vibration amplitudes observed fall within the range of potential options specified in IEC 60721-3-2, IEC 60721-4-2, and IEC 60068-2-64. The amplitudes of 2M2 can be considered to encompass the severities of ISO container movement, forklift trucks handling (on good and poor surfaces), air transport handling and handling at walking speeds using unsuspended vehicles in warehouses.

Table 1 – Maximum vibration accelerations and displacements occurring during handling of ISO containers at container terminal [1]

Movement	**Axis**	**Measurements made in frequency range 1 Hz to 1 250 Hz**			
		Empty		**Loaded**	
		Maximum Acceleration g	**Maximum Displacement** mm	**Maximum Acceleration** g	**Maximum Displacement** mm
6 m (20 foot) container	Vertical	0,5	20	0,2	5
	Transverse	0,2	1	0,2	3
	Axial	0,15	1	0,15	4
12 m (40 foot) container	Vertical	0,2	3	0,2	3
	Transverse	0,2	2	0,2	2
	Axial	0,2	3	0,2	3

Table 2 – Largest shocks occurring during handling of ISO containers by straddle carrier [1]

Movement	**Axis**	**Measurements made in frequency range 1 Hz to 1 250 Hz**			
		Empty		**Loaded**	
		Amplitude g	**Duration** ms	**Amplitude** g	**Duration** ms
6 m (20 foot) container					
Pick-up from floor	Vertical	38	2	32	1,6
	Transverse	21	2	23	1,6
	Axial	7	12	13	1
Set down on to floor	Vertical	24	4	9	2,5
	Transverse	9	2	18	1
	Axial	6	4	14	1
Set down on to another container	Vertical	15	2	3	1,5
	Transverse	8	1	3	1
	Axial	3	1	1,5	1
12 m (40 foot) container					
Pick-up from floor	Vertical	24	2	9	2
	Transverse	12	1	6	4
	Axial	6	2	6	1
Set down on to floor	Vertical	24	1,5	24	4
	Transverse	9	1	21	1
	Axial	6	1	12	1,5
Set down on to another container	Vertical	15	4	3	1,5
	Transverse	9	1	3	1
	Axial	2	1	1	1

Table 3 – Largest shocks occurring during transfer of ISO containers on to rail cars [1]

Movement	**Axis**	**Measurements made in frequency range 1 Hz to 1 250 Hz**			
		6 m (20 foot) container		**12 m (40 foot) container**	
		Amplitude g	**Duration** ms	**Amplitude** g	**Duration** ms
Pick-up from floor	Vertical	30	1,5	15	3
	Transverse	24	1	12	1
	Axial	14	1	9	1
Set down on to floor	Vertical	26	1,6	15	3
	Transverse	14	1	6	2
	Axial	18	1	12	1
Set down on rail car	Vertical	28	1,5	33	2,5
	Transverse	25	1	25	2
	Axial	12	1	18	1,5

Table 4 – Largest shocks occurring during transfer of ISO containers on to ships [1]

Movement	**Axis**	**Measurements made in frequency range 1 Hz to 1 250 Hz**	
		6 m (20 foot) Container	
		Amplitude g	**Amplitude** ms
Pick-up from floor	Vertical	18	1,5
	Transverse	15	1
	Axial	6	1,5
Set down on to floor	Vertical	30	1,5
	Transverse	15	1
	Axial	10	1,5
Loading on to ship	Vertical	36	1,5
	Transverse	10	2,5
	Axial	12	2

Table 5 – Largest shocks occurring during transfer of ISO containers on to US rail cars [2]

Movement	**Axis**	**Acceleration amplitude (g) (sample rate 256 sps; low pass filter 30 Hz)**		
		Trailer and 12 m (40 foot) container		
		Maximum	**Minimum**	**Maximum r.m.s.**
Overhead crane	Vertical	2,8	–3,7	0,20
	Transverse	0,9	–0,9	0,06
	Axial	0,8	–0,5	0,05
Side loader	Vertical	1,1	–0,9	0,11
	Transverse	1,8	–1,6	0,12
	Axial	0,5	–0,3	0,05

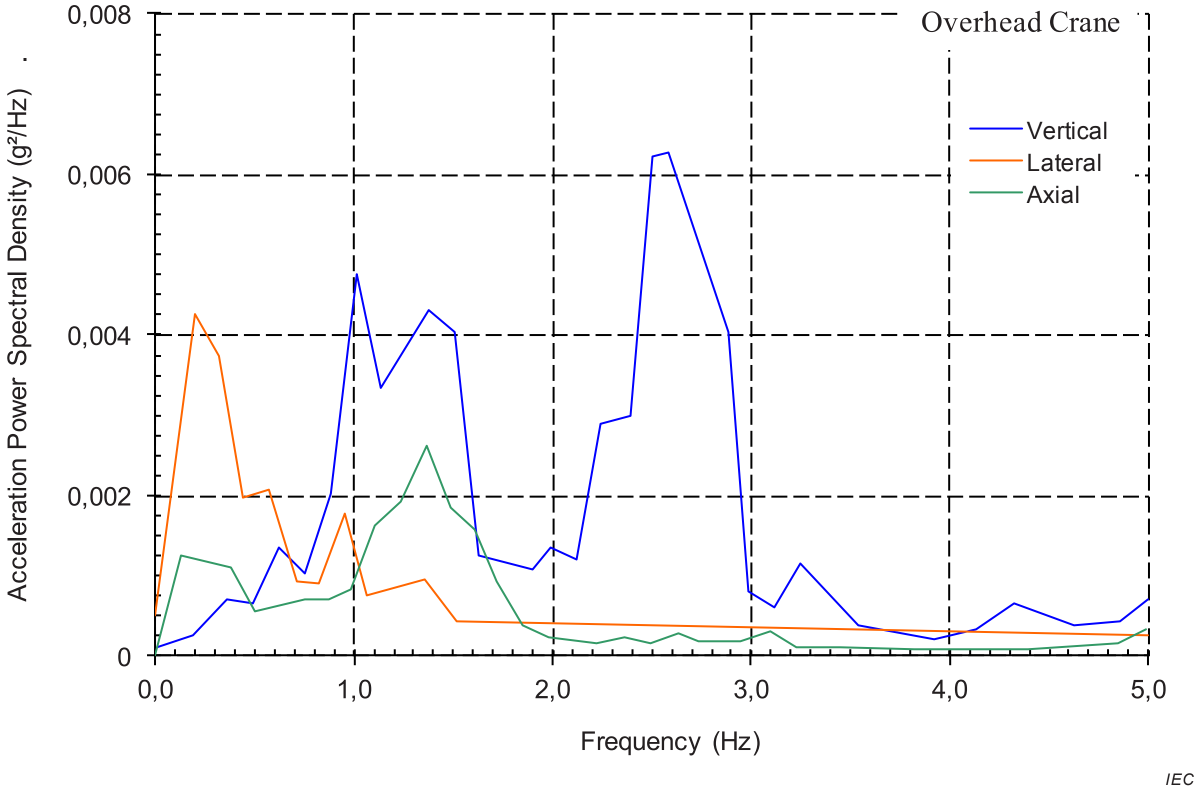

Figure 1 – Vibrations loading and unloading of container on to US rail car using overhead crane [2]

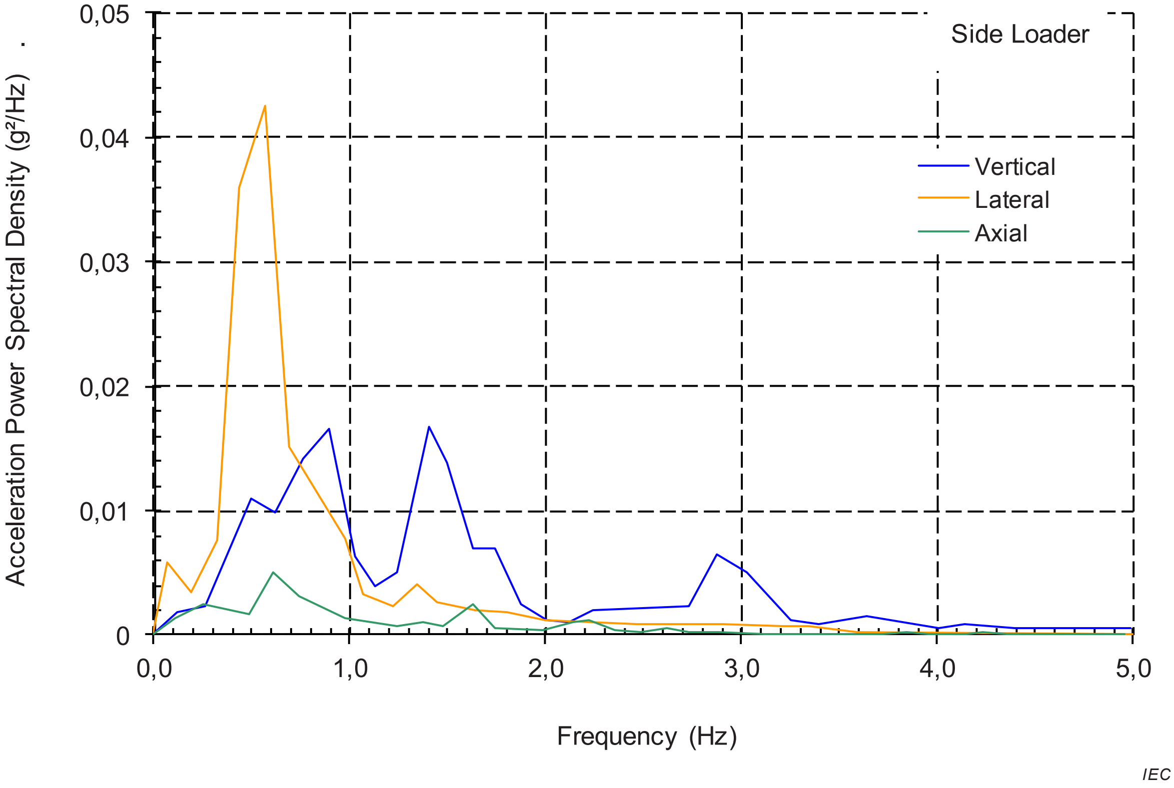

Figure 2 – Vibrations loading and unloading of container on to US rail car using side loader [2]

Table 6 – Summary of vibration r.m.s. during port movements of ISO containers [3]

	Acceleration root mean square (g)					
	12 m (40 foot) containers/low pass filter 370 Hz					
	Transducer group 1			**Transducer group 2**		
	Axial	**Transverse**	**Vertical**	**Axial**	**Transverse**	**Vertical**
Movement by container transport tug						
Run 1	0,35	0,69	2,25	0,29	0,63	1,30
Run 2	0,30	0,45	2,14	0,25	0,48	1,33
Run 3	0,59	0,85	3,34	0,44	0,80	1,98
Run 4	0,66	0,91	3,40	0,45	0,85	2,04
Container crane pick-up and set down						
Run 1	0,15	0,19	0,59	0,14	0,25	0,45
Run 2	0,25	0,30	1,03	0,23	0,35	0,78
Run 3	0,51	0,64	1,79	0,48	0,70	1,54
Mobile container handling crane pickup and set down						
Run 1	0,12	0,14	0,34	0,12	0,18	0,34
Run 2	0,53	0,72	1,88	0,46	0,76	1,51
Run 3	0,92	1,21	2,58	0,62	1,05	1,85
Run 4	0,20	0,24	0,82	0,18	0,24	0,53
Run 5	0,18	0,25	0,62	0,18	0,23	0,49
Run 6	1,23	1,24	3,86	0,96	1,43	3,69
Straddle carrier pick-up, movement and set down						
Run 1	0,32	0,52	0,74	0,31	0,47	0,92
Run 2	0,58	0,90	1,35	0,55	0,78	1,74
Run 3	0,45	0,51	0,93	0,43	0,46	0,91
Run 4	0,89	1,30	2,38	0,80	1,10	2,54

Table 7 – Summary of peak shock severities during port movements of ISO containers [3]

Movement	**Maximum shock acceleration amplitudes** (g)		
	12 m (40 foot) containers low pass filter 370 Hz		
	Axial	**Transverse**	**Vertical**
Movement by container transport tug	4,1	5,9	10,3
Dockside container crane pick-up and set down	3,5	5,5	9,4
Mobile container handling crane pickup and set down	6,7	9,1	11,7
Straddle carrier pick-up, movement and set down	8,2	8,1	10,7

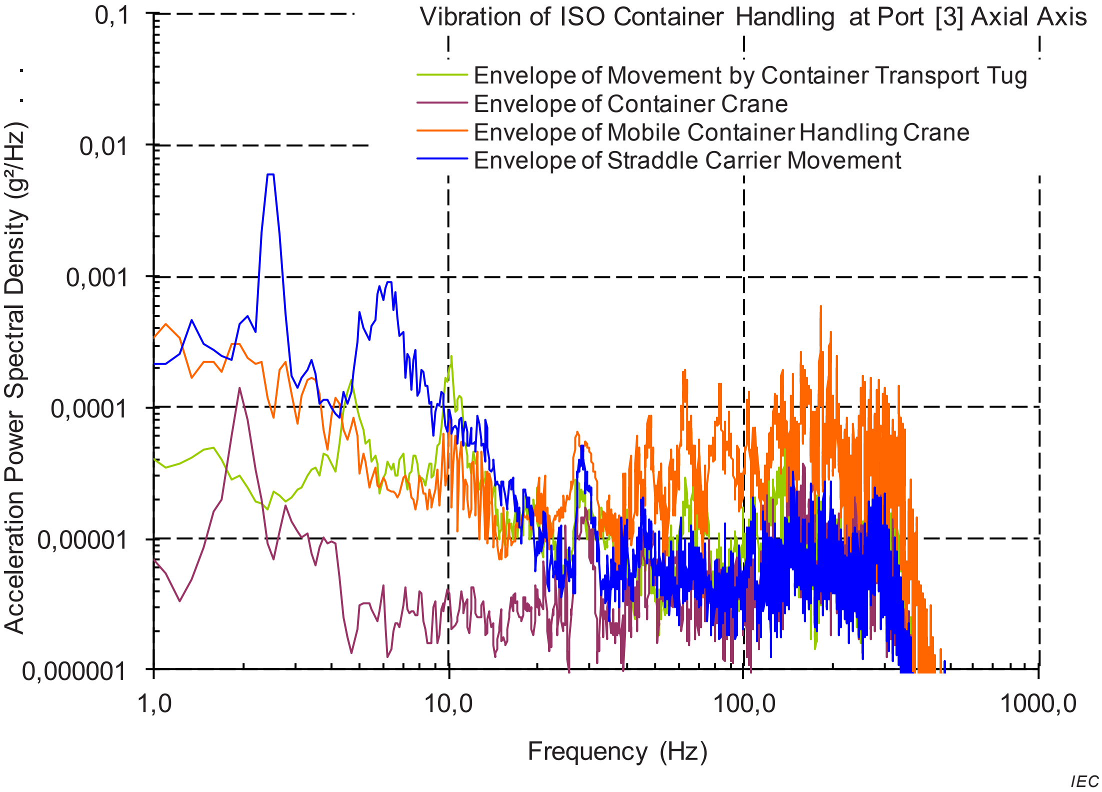

Figure 3 – Vibrations from handling an ISO container at a port – Axial [3]

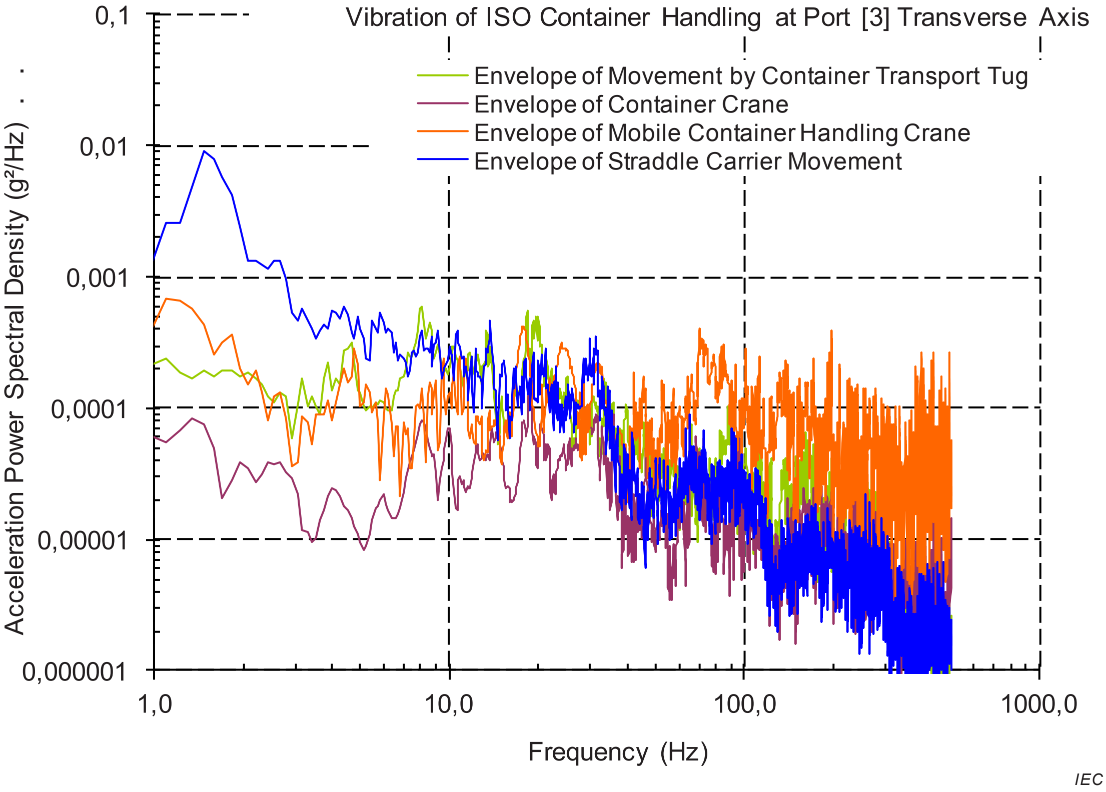

Figure 4 – Vibrations from handling an ISO container at a port – Transverse [3]

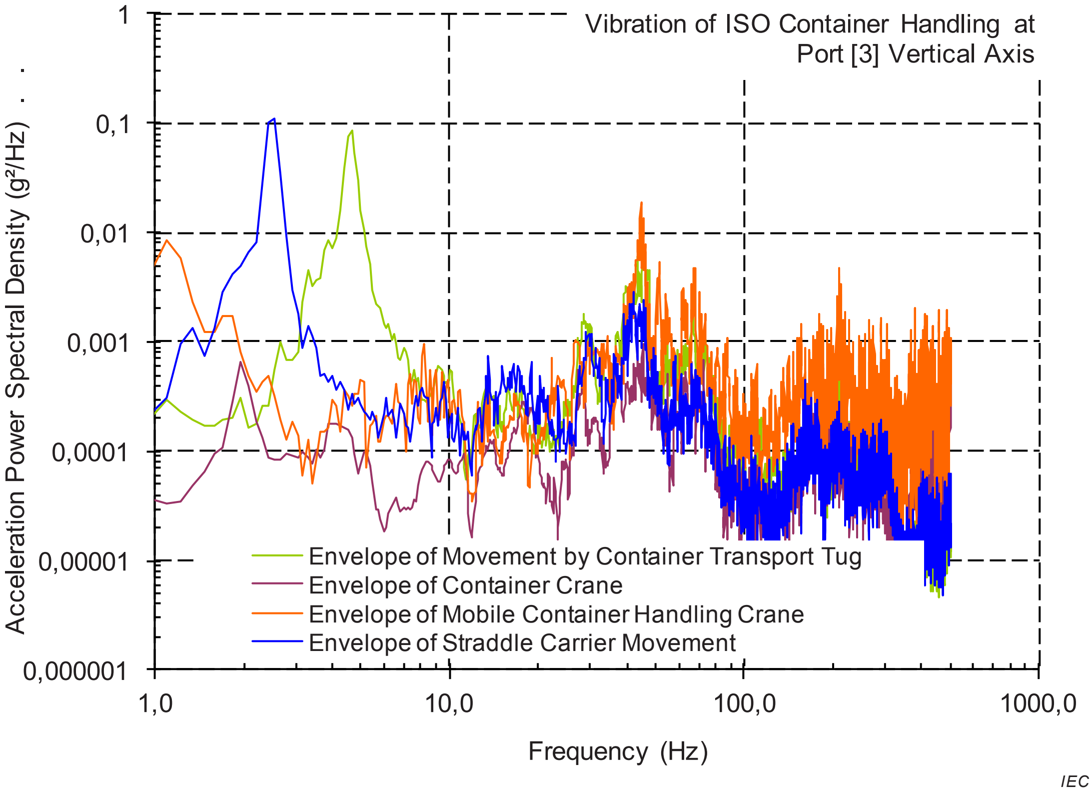

Figure 5 – Vibrations from handling an ISO container at a port – Vertical [3]

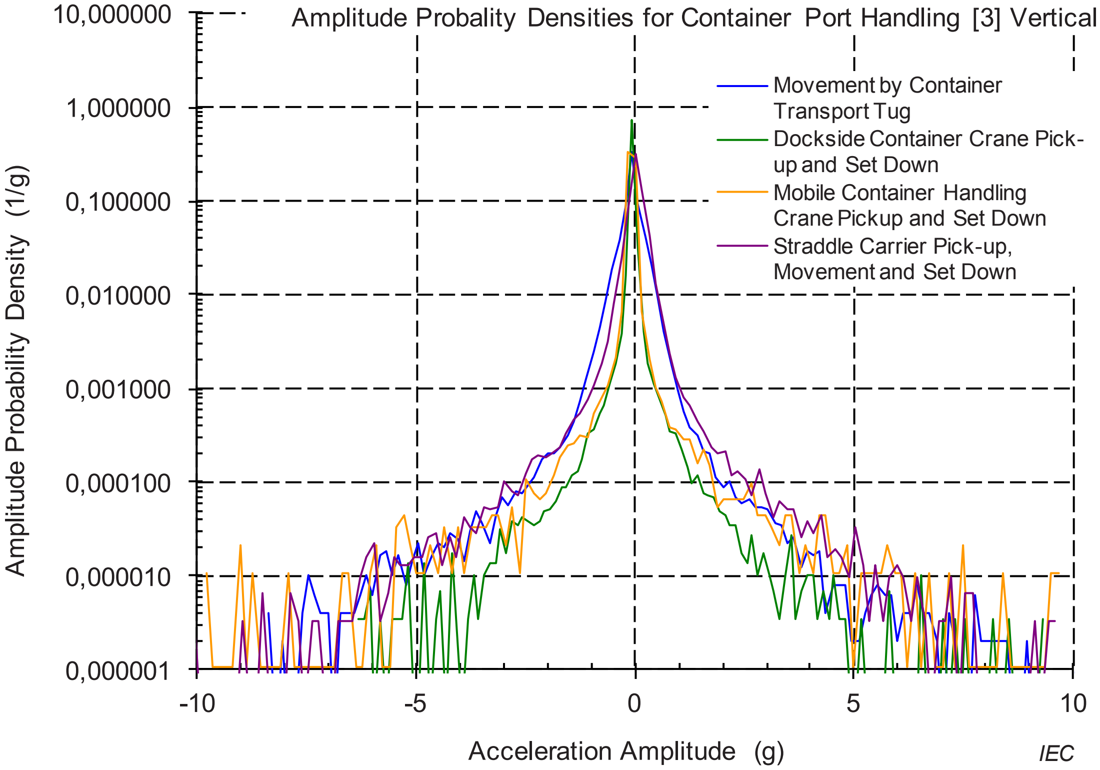

Figure 6 – Amplitude probability density from handling an ISO container at a port – Vertical [3]

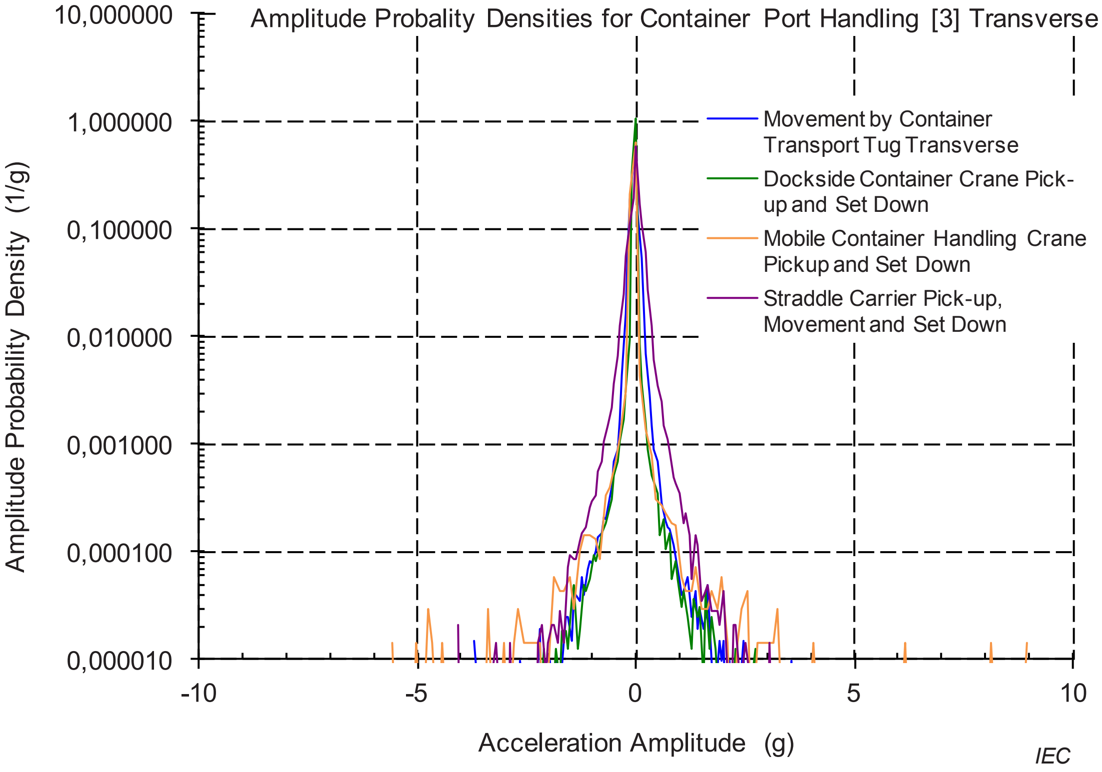

Figure 7 – Amplitude probability density from handling an ISO container at a port – Transverse [3]

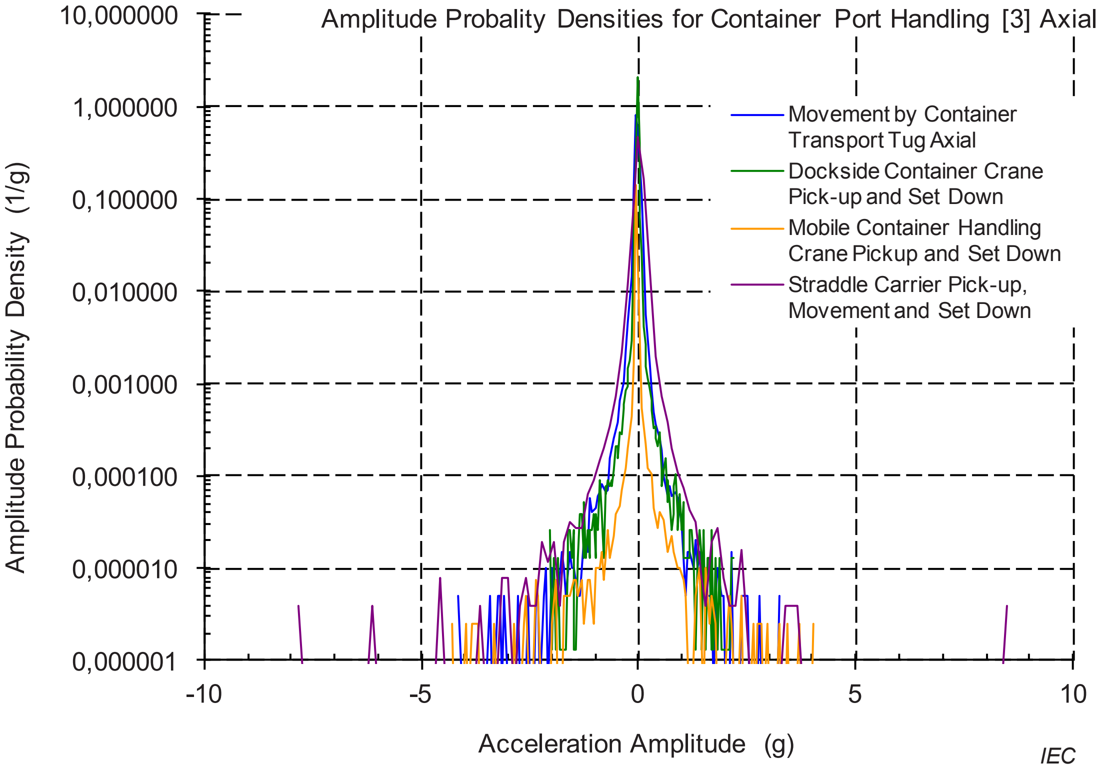

Figure 8 – Amplitude probability density from handling an ISO container at a port – Axial [3]

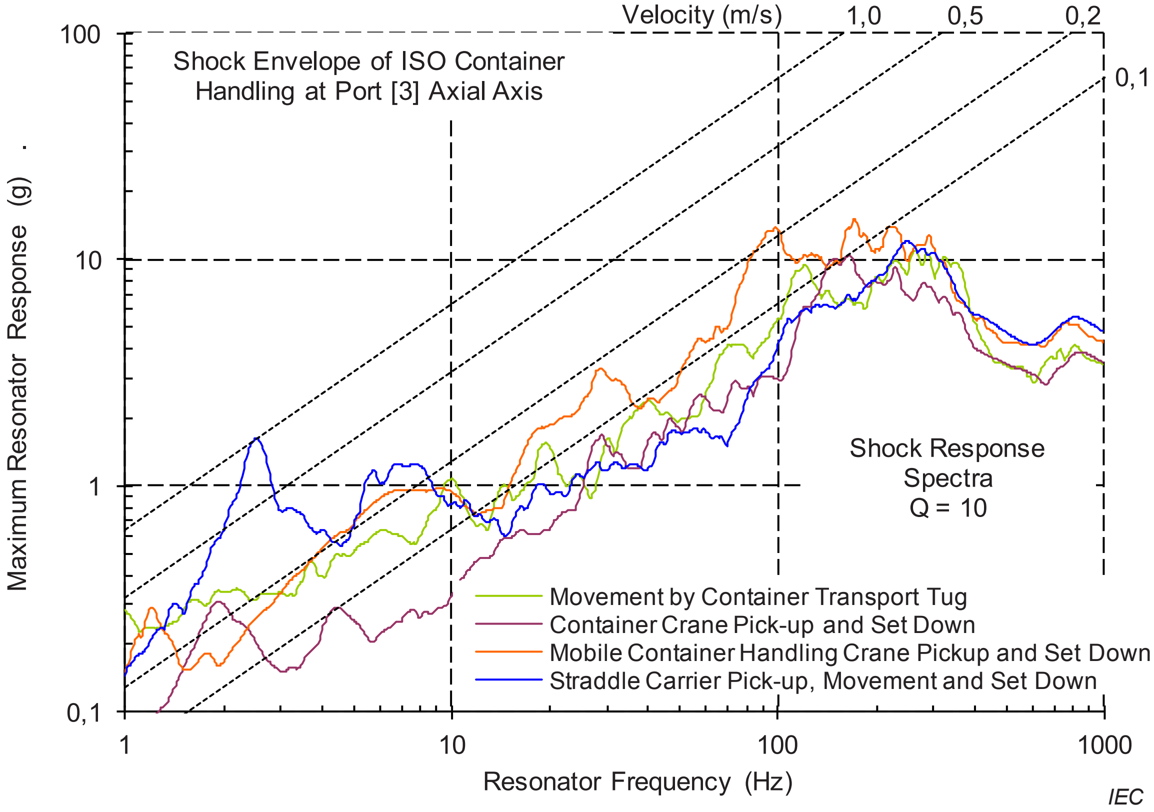

Figure 9 – Shocks from handling an ISO container at a port – Axial [3]

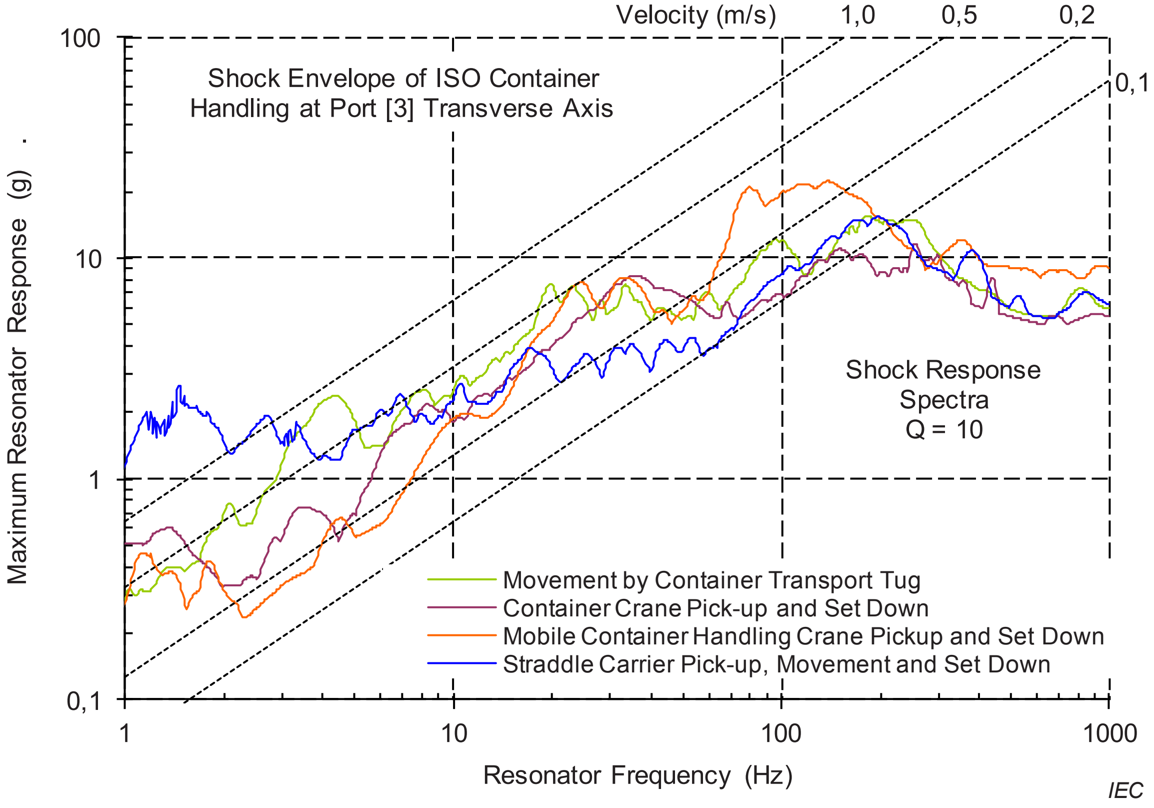

Figure 10 – Shocks from handling an ISO container at a port – Transverse [3]

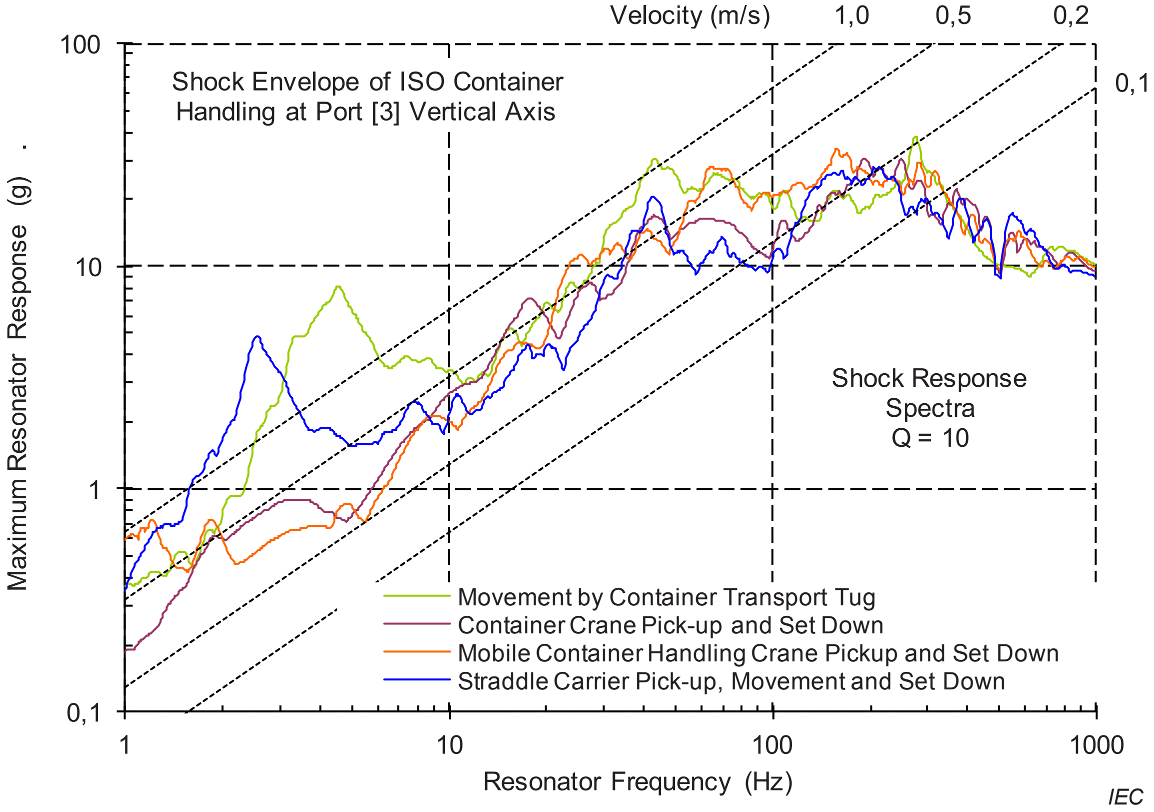

Figure 11 – Shocks from handling an ISO container at a port – Vertical [3]

Table 8 – Summary of shock levels from air cargo pallet ground operations [4]

Air cargo pallet ground movement	**Peak acceleration** (g) **(sample rate 100 sps/low pass filter 31,5 Hz)**			
	Vertical centre	**Vertical** corner	**Transverse** centre	**Axial** centre
Arlanda terminal to aircraft	0,94	1,02	0,53	0,35
Arlanda movement at aircraft	0,49	0,51	0,51	0,51
JFK aircraft to terminal	2,4	2,95	1,32	1,84
JFK terminal to aircraft	2,54	5,81	>2,08	>2,10
JFK loading on aircraft	1,18	1,04	0,76	0,68

Table 9 – Summary of peak vibration levels from air cargo pallet ground operations [4]

Air cargo pallet ground movement	**Acceleration levels** (g) **Exceeded for 1 % of the time of the trial** **(sample rate 100 sps/low pass filter 31,5 Hz)**			
	Vertical centre	**Vertical** corner	**Transverse** centre	**Axial** centre
Arlanda terminal to aircraft	0,18	0,23	0,07	0,07
Arlanda movement at aircraft	0,08	0,10	0,08	0,10
JFK aircraft to terminal	0,48	0,86	0,24	0,26
JFK terminal to aircraft	0,51	1,04	0,28	0,23
JFK loading on aircraft	0,26	0,27	0,11	0,13

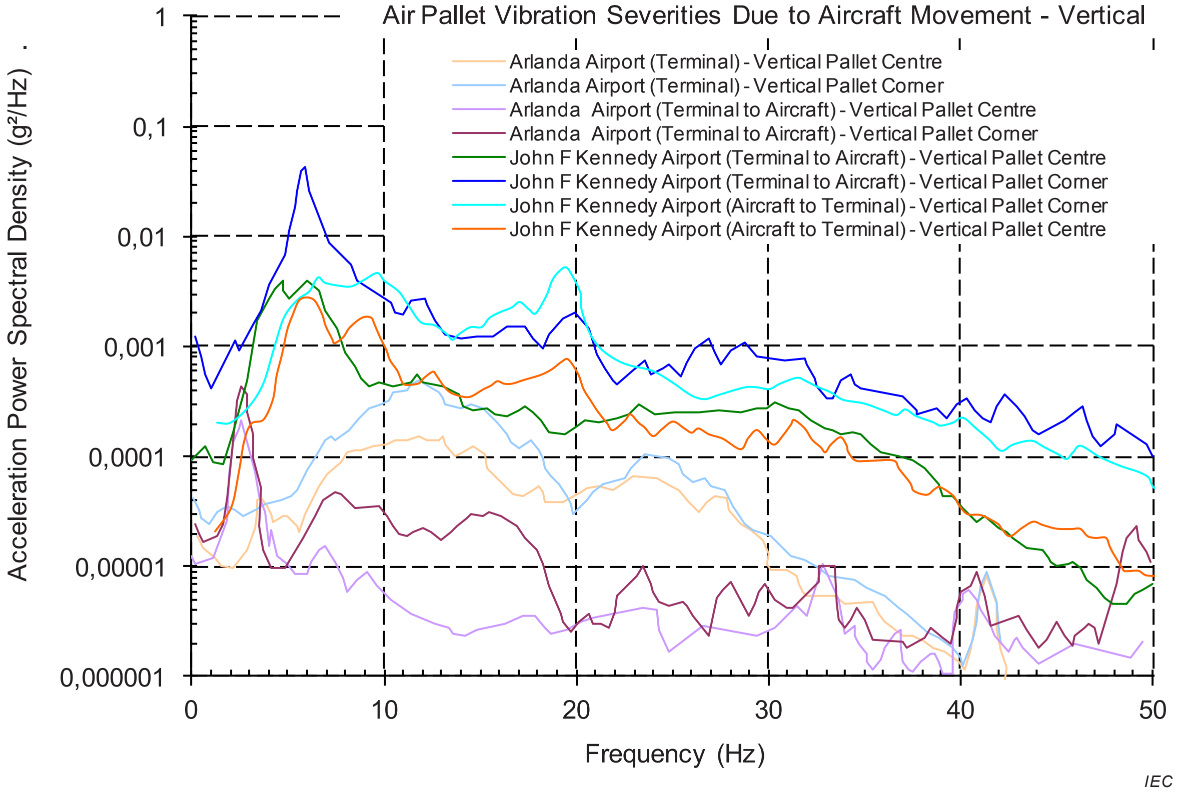

Figure 12 – Air pallet vibration severities due to aircraft movement – Vertical [4]

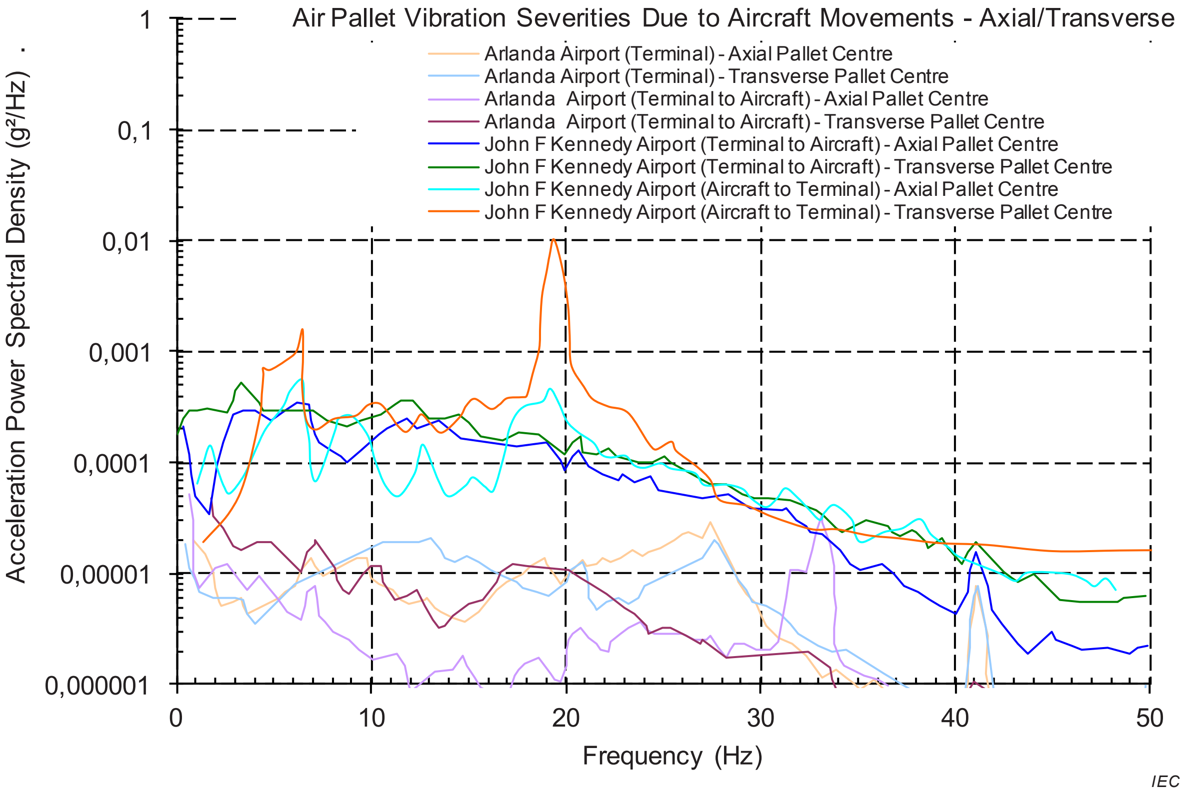

Figure 13 – Air pallet vibration severities due to aircraft movements – Axial/transverse [4]

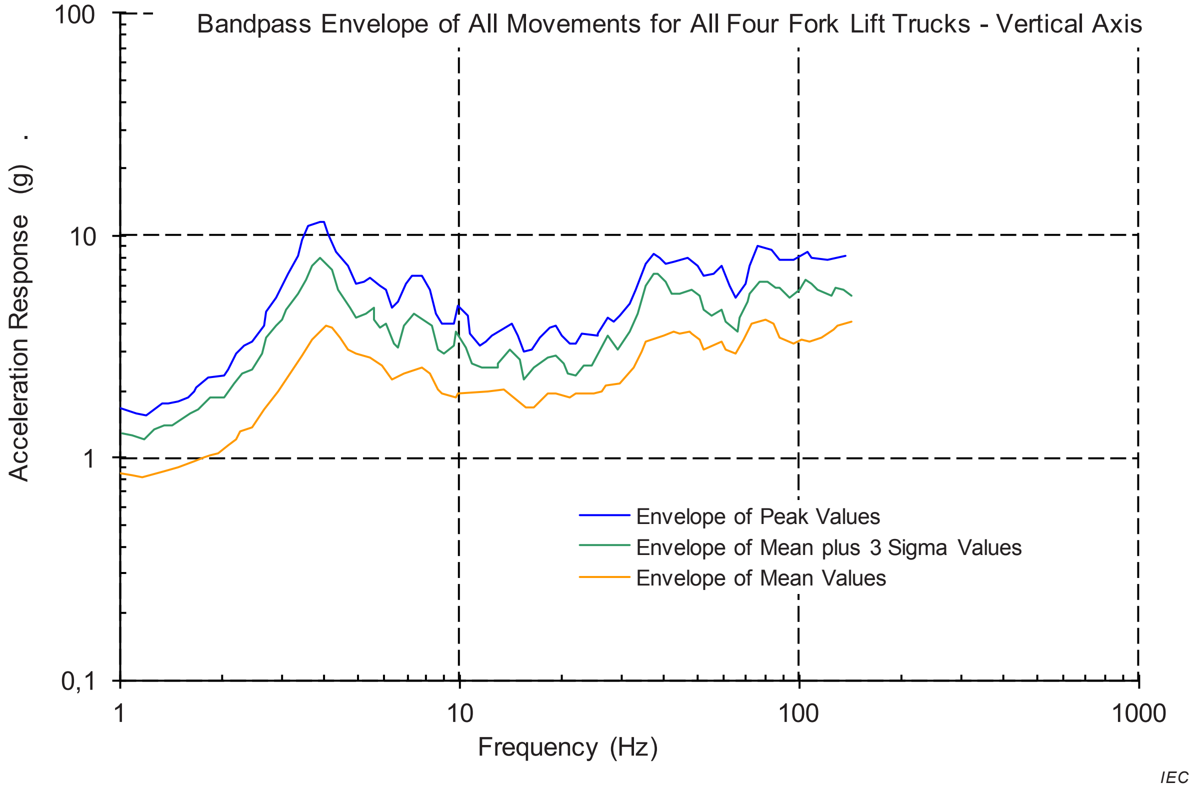

Figure 14 – Bandpass vibration amplitudes from four forklift trucks – Vertical [5]

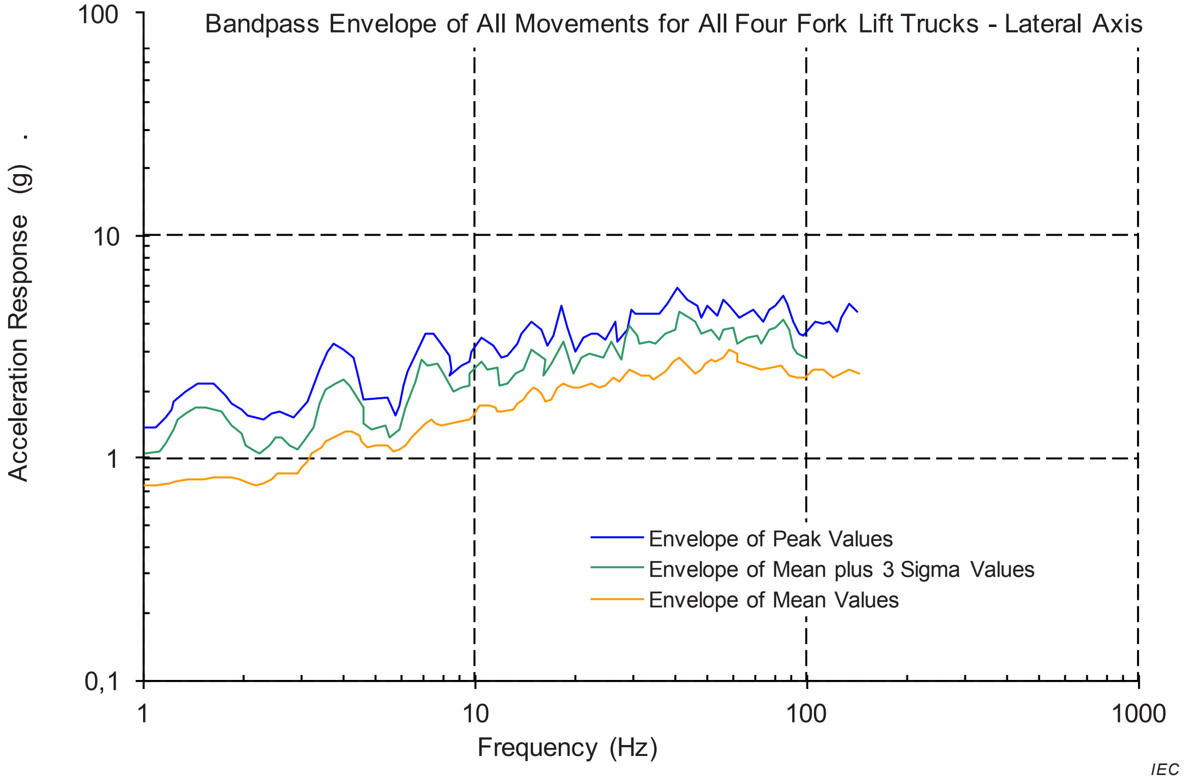

Figure 15 – Bandpass vibration amplitudes from four forklift trucks – Lateral [5]

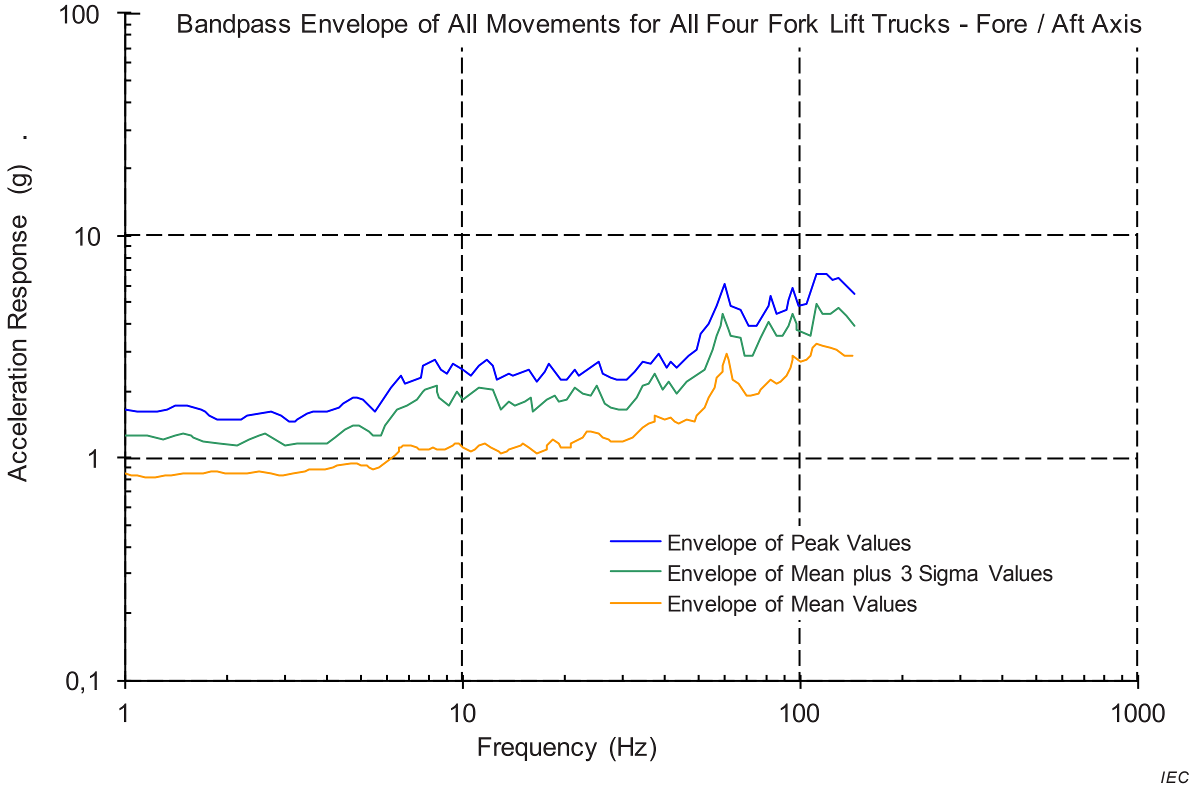

Figure 16 – Bandpass vibration amplitudes from four forklift trucks – Axial [5]

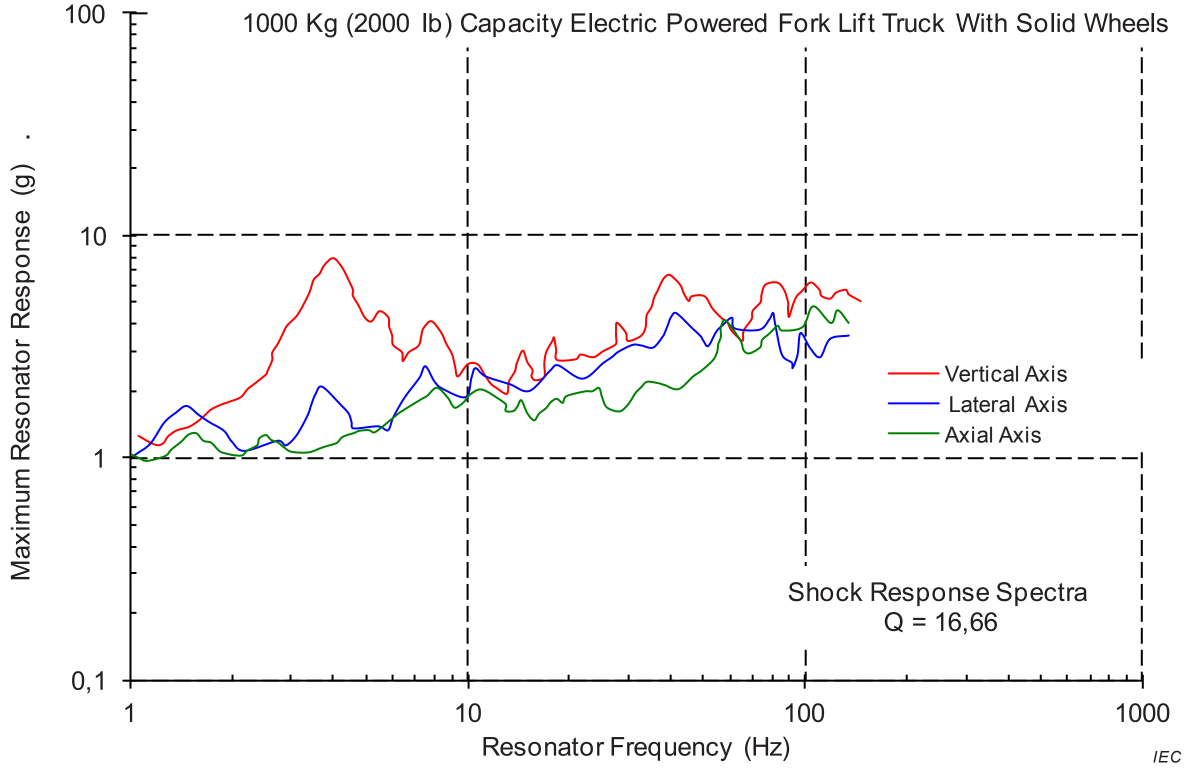

Figure 17 – Shock response spectra from 1 000 Kg forklift truck [5]

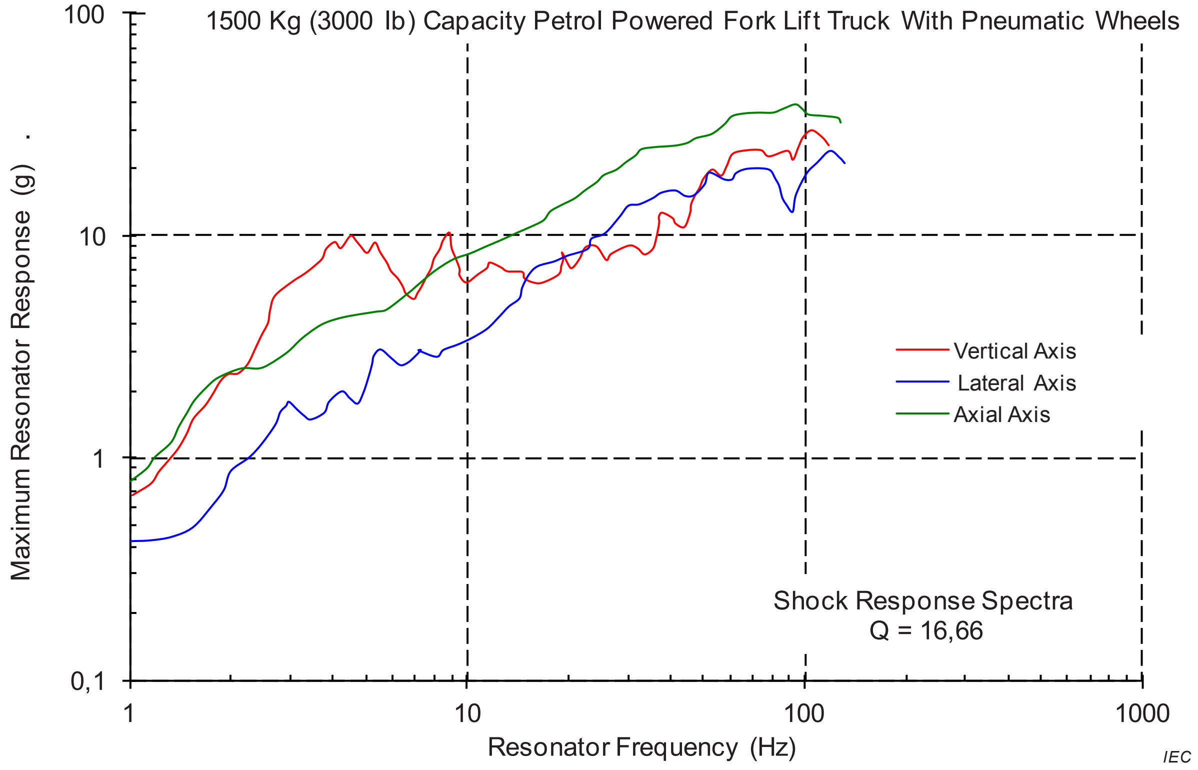

Figure 18 – Shock response spectra from 1 500 Kg forklift truck [5]

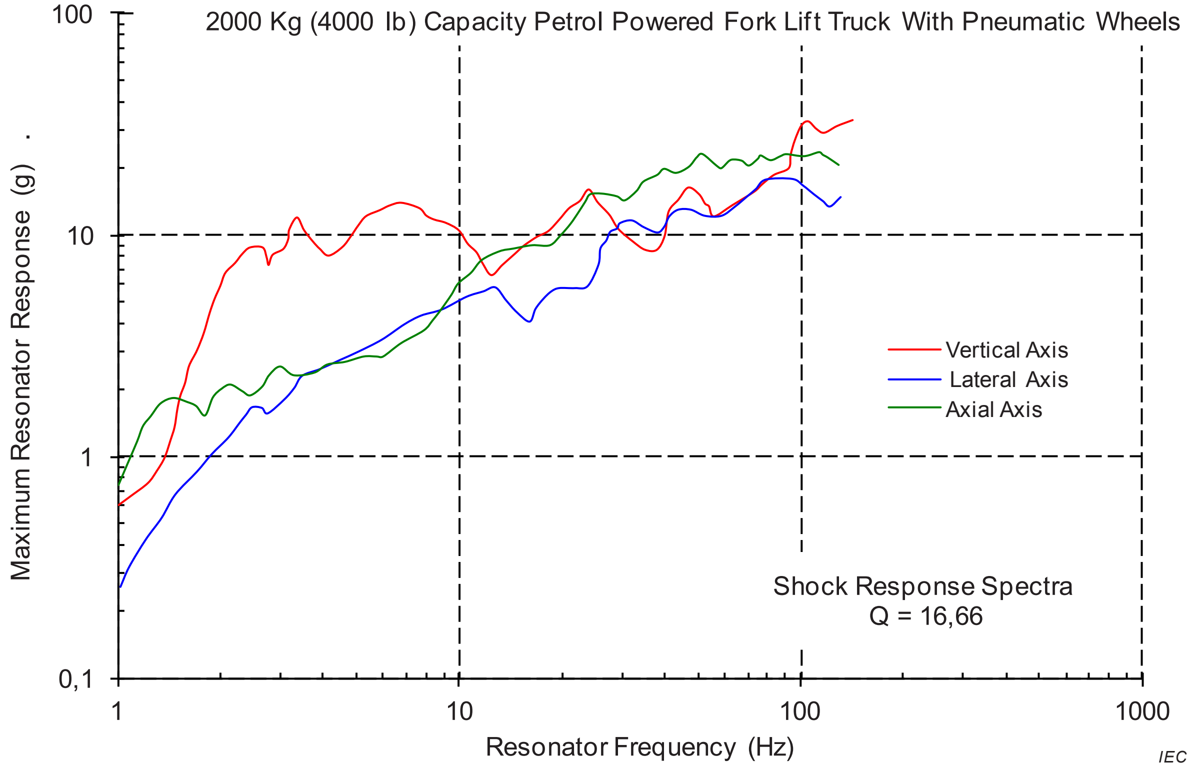

Figure 19 – Shock Response Spectra from 2 000 Kg Forklift Truck [5]

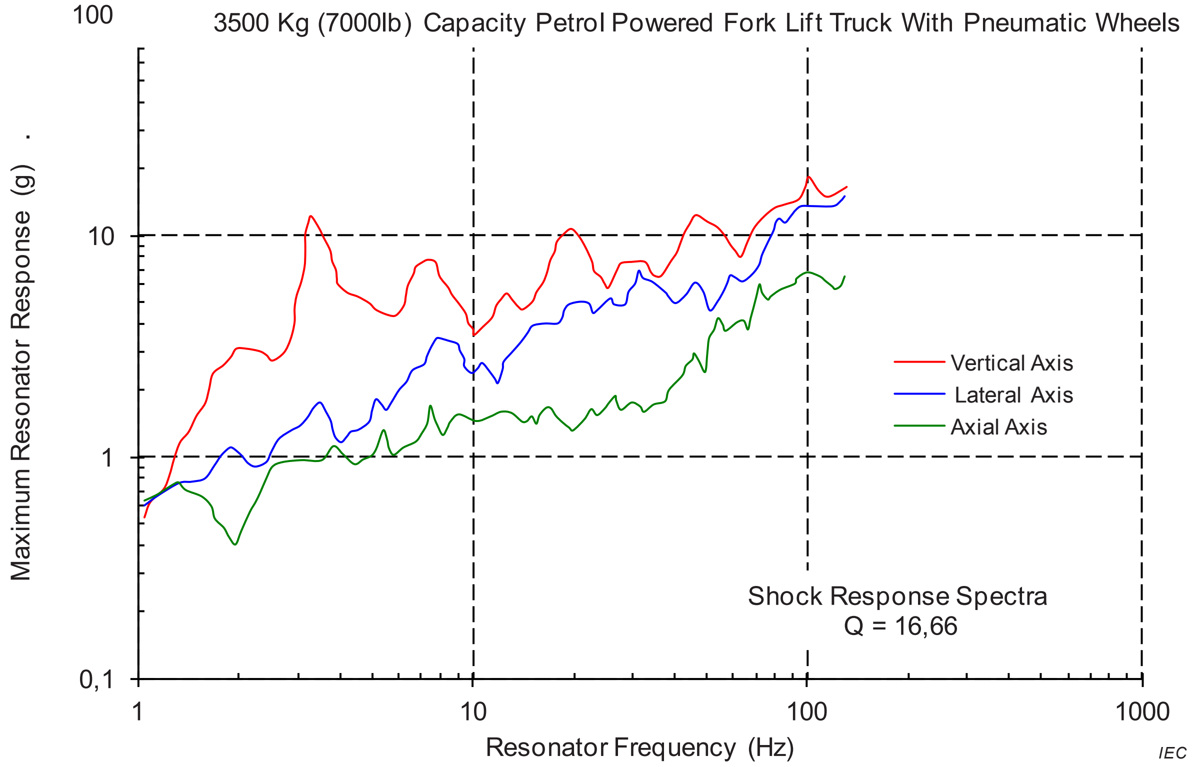

Figure 20 – Shock response spectra from 3 500 Kg forklift truck [5]

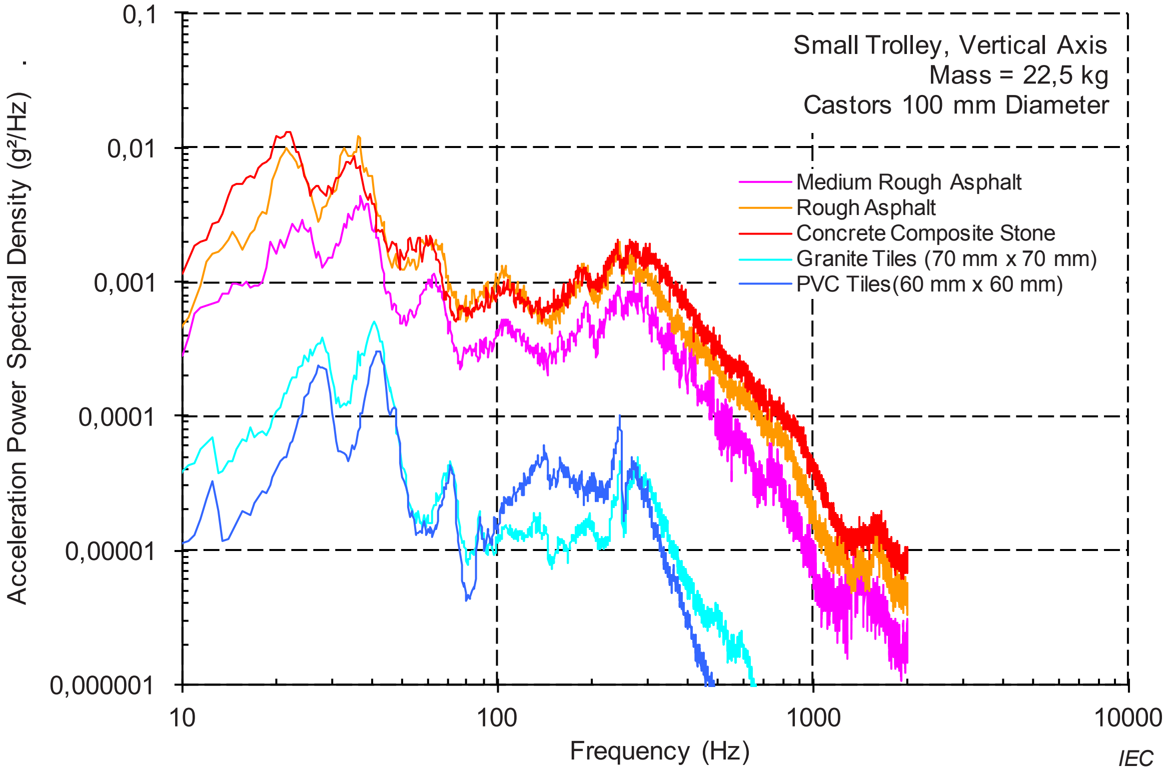

Figure 21 – Vibration at wheels of small trolley – Vertical [6]

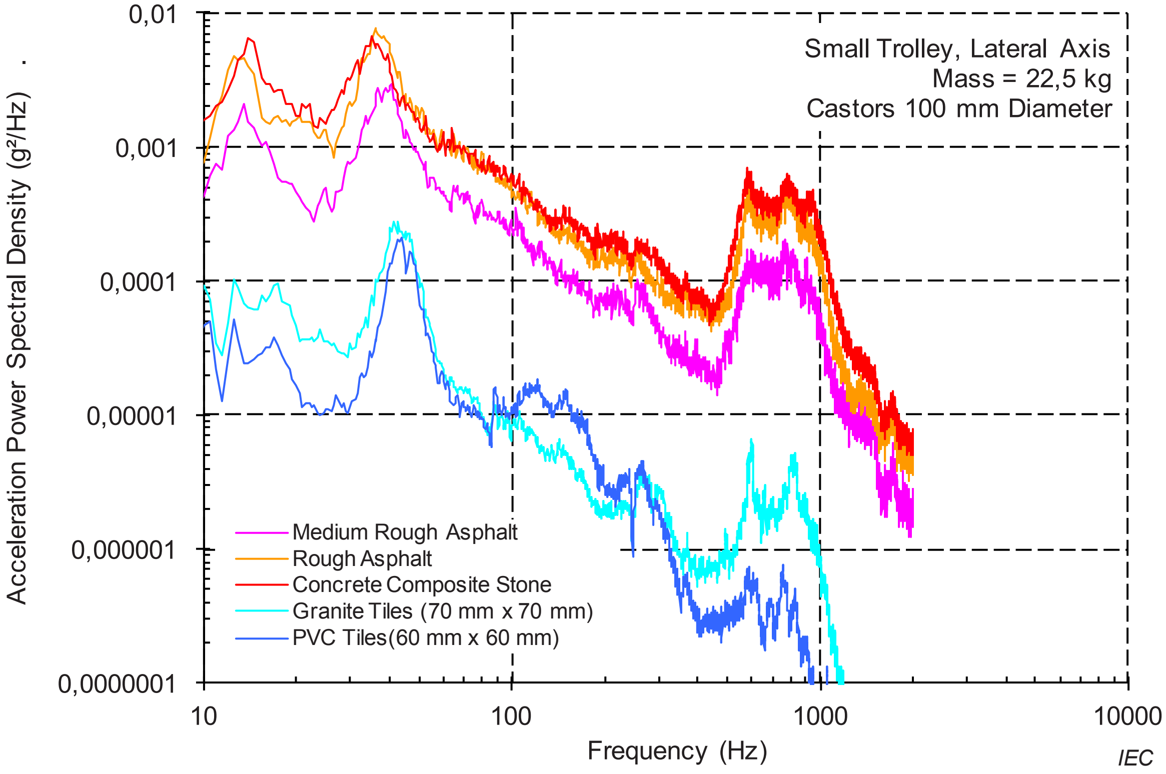

Figure 22 – Vibration at wheels of small trolley – Lateral [6]

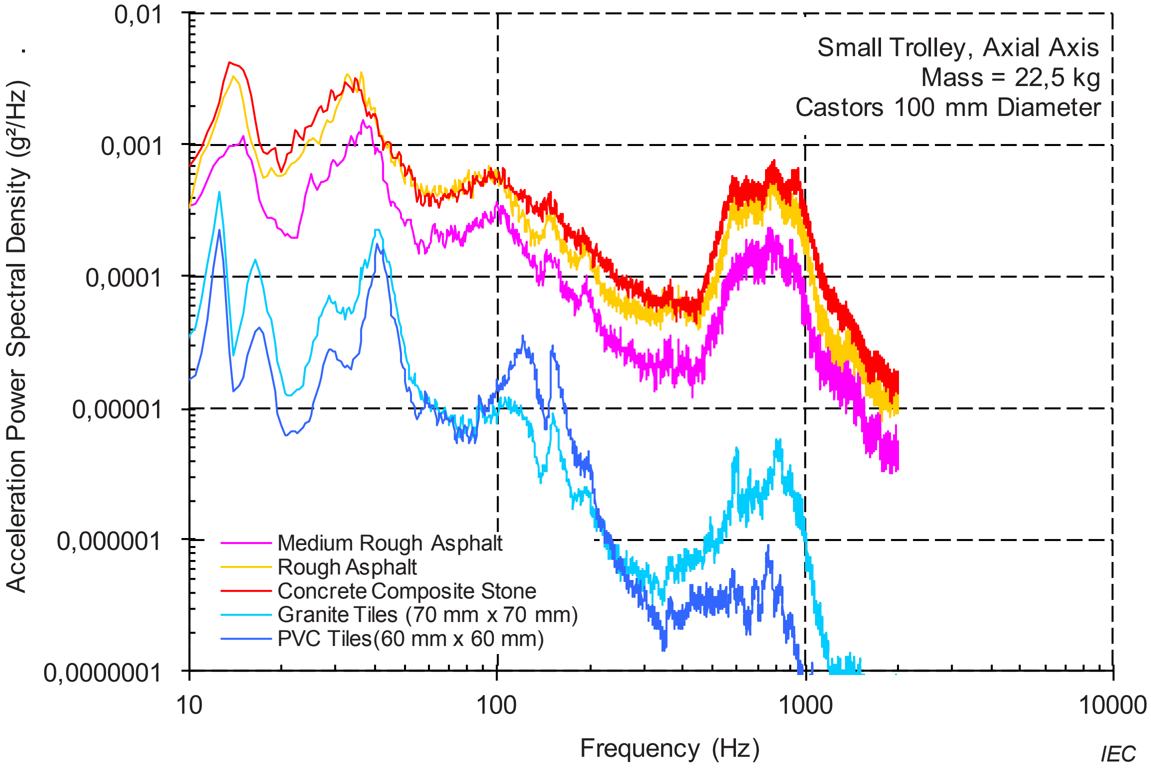

Figure 23 – Vibration at wheels of small trolley – Axial [6]

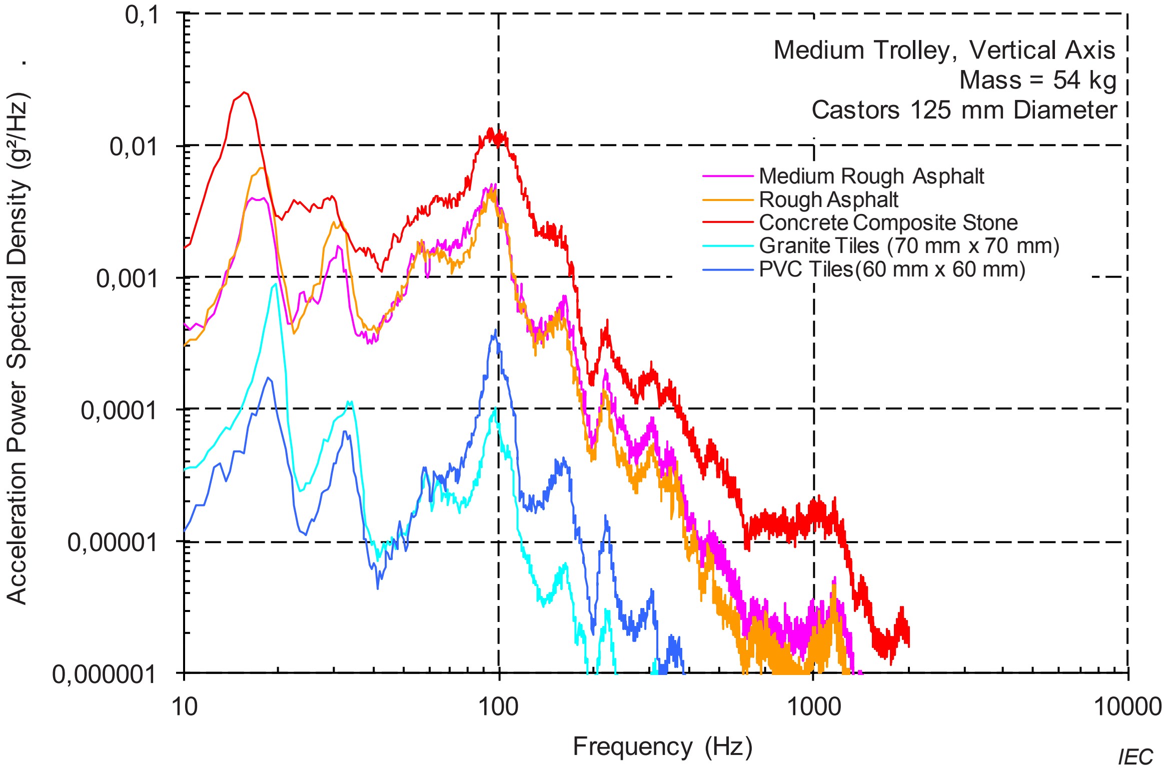

Figure 24 – Vibration at wheels of medium trolley – Vertical [6]

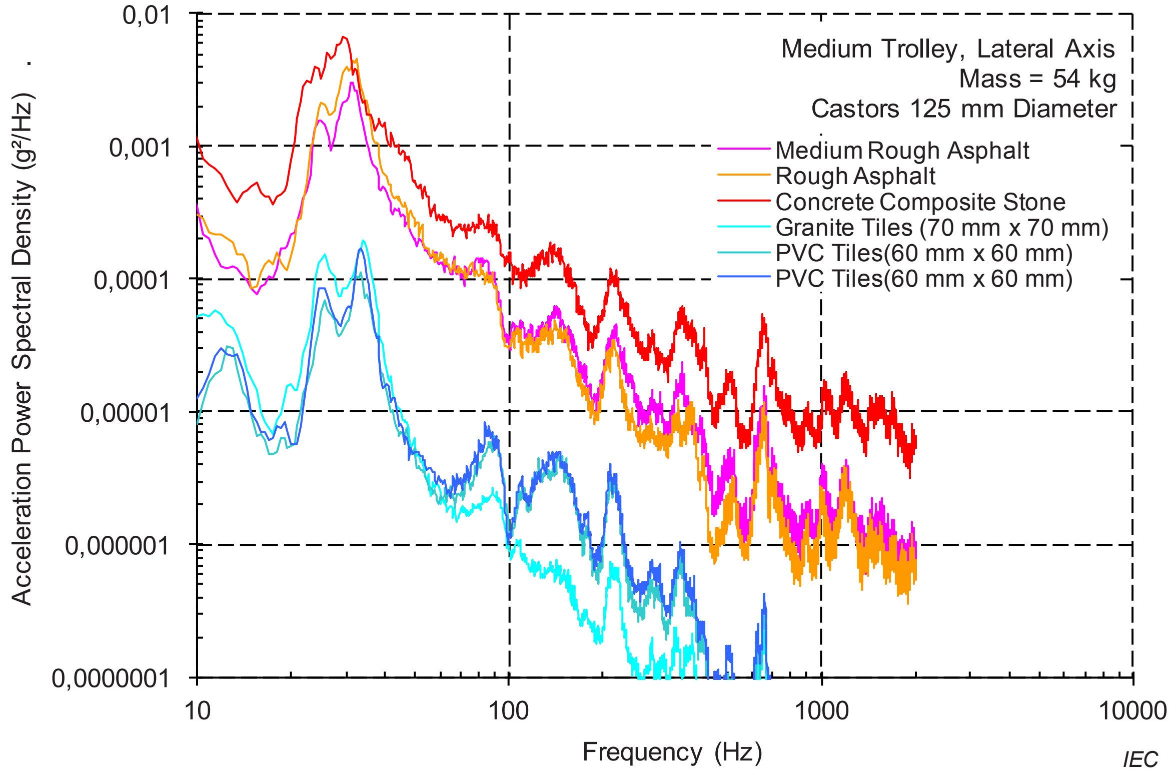

Figure 25 – Vibration at wheels of medium trolley – Lateral [6]

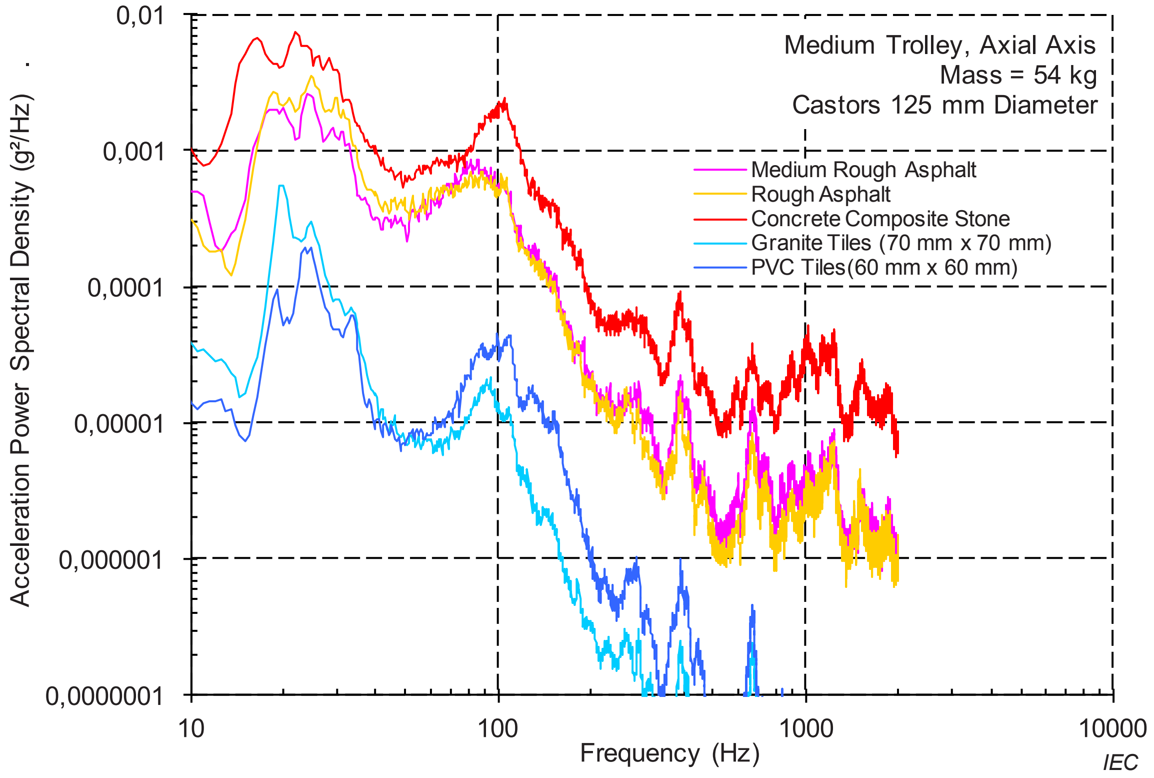

Figure 26 – Vibration at wheels of medium trolley – Axial [6]

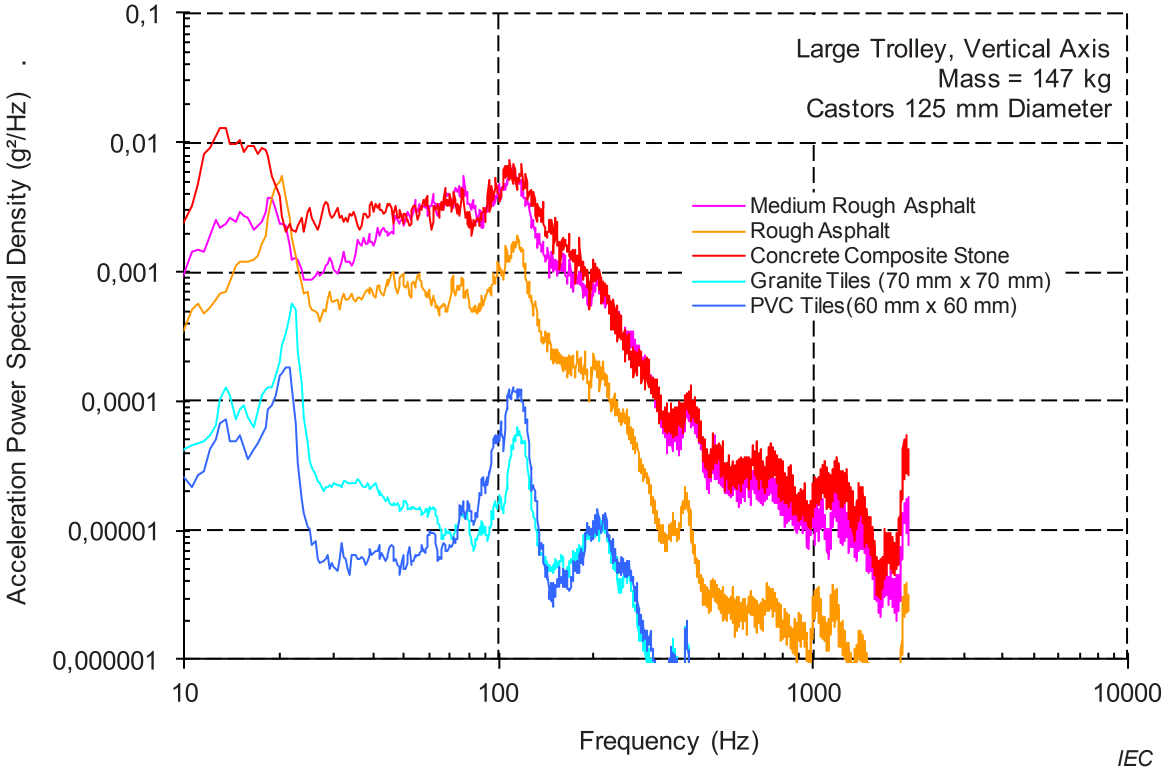

Figure 27 – Vibration at wheels of large trolley – Vertical [6]

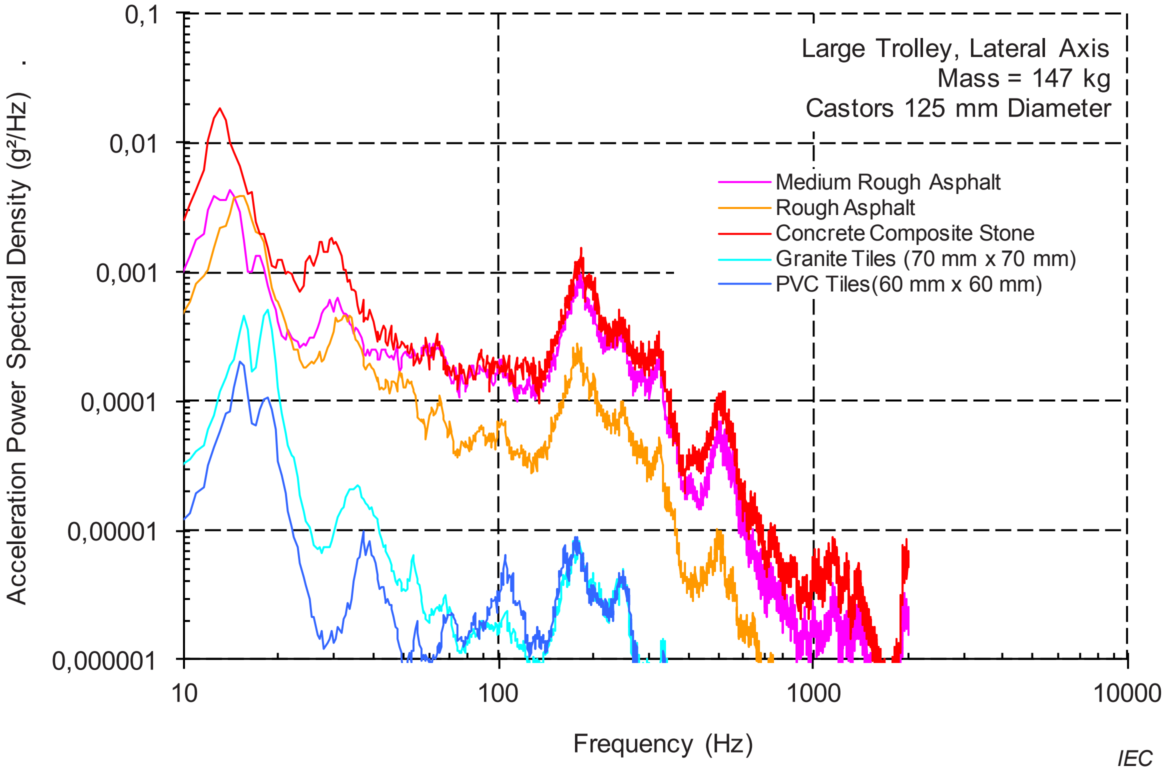

Figure 28 – Vibration at wheels of large trolley – Lateral [6]

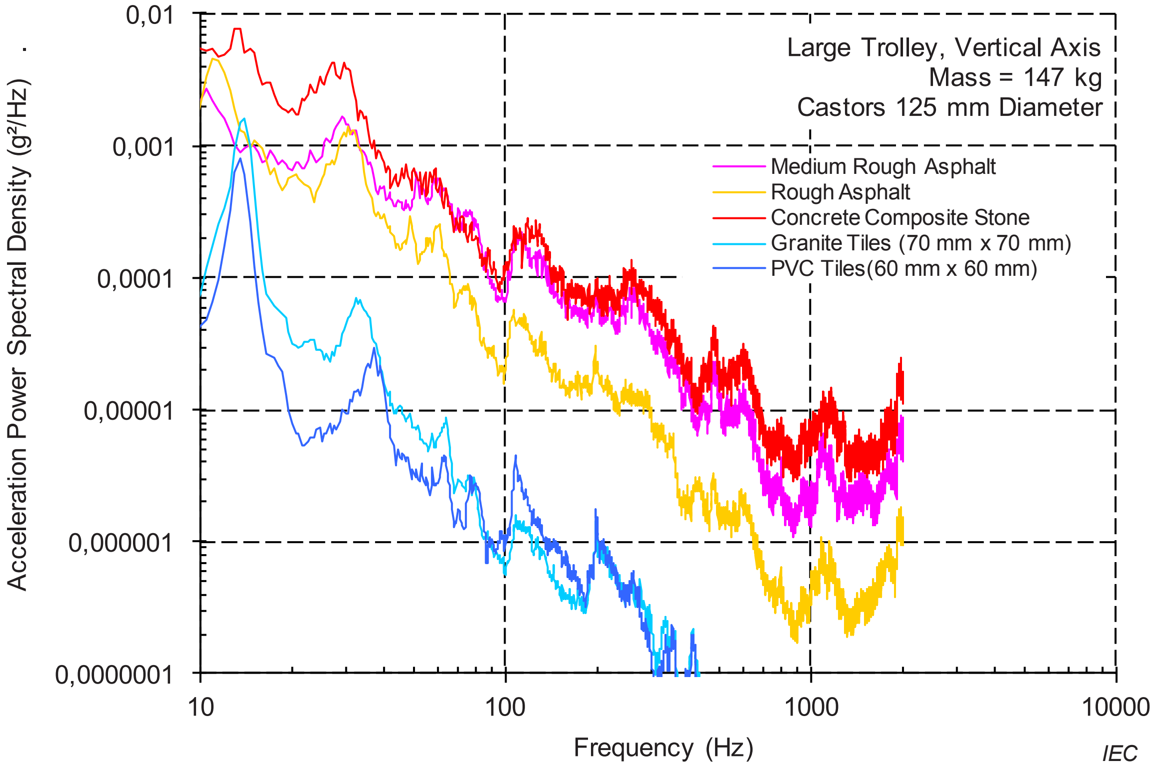

Figure 29 – Vibration at wheels of large trolley – Axial [6]

Table 10 – Summary of overall vibration severities [6]

	Vibration Acceleration Root Mean Square (g) over frequency range 0,5 Hz to 2000 Hz		
	Small Trolley		
	Vertical	Lateral	Axial
Medium Rough Asphalt	0,53	0,39	0,37
Rough Asphalt	0,77	0,61	0,57
Concrete Composite Stone	0,85	0,68	0,66
Granite Tiles (70 mm x 70 mm)	0,12	0,08	0,08
PVC Tiles (60 mm x 60 mm)	0,11	0,07	0,07
	Medium Trolley		
	Vertical	Lateral	Fore/Aft
Medium Rough Asphalt	0,49	0,22	0,33
Rough Asphalt	0,47	0,24	0,33
Concrete Composite Stone	0,92	0,39	0,55
Granite Tiles (70 mm x 70 mm)	0,08	0,05	0,11
PVC Tiles (60 mm x 60 mm)	0,11	0,05	0,11
	Large Trolley		
	Vertical	Lateral	Fore/Aft
Medium Rough Asphalt	0,72	0,35	0,29
Rough Asphalt	0,38	0,22	0,21
Concrete Composite Stone	0,83	0,46	0,41
Granite Tiles (70 mm x 70 mm)	0,08	0,06	0,07
PVC Tiles (60 mm x 60 mm)	0,07	0,04	0,05

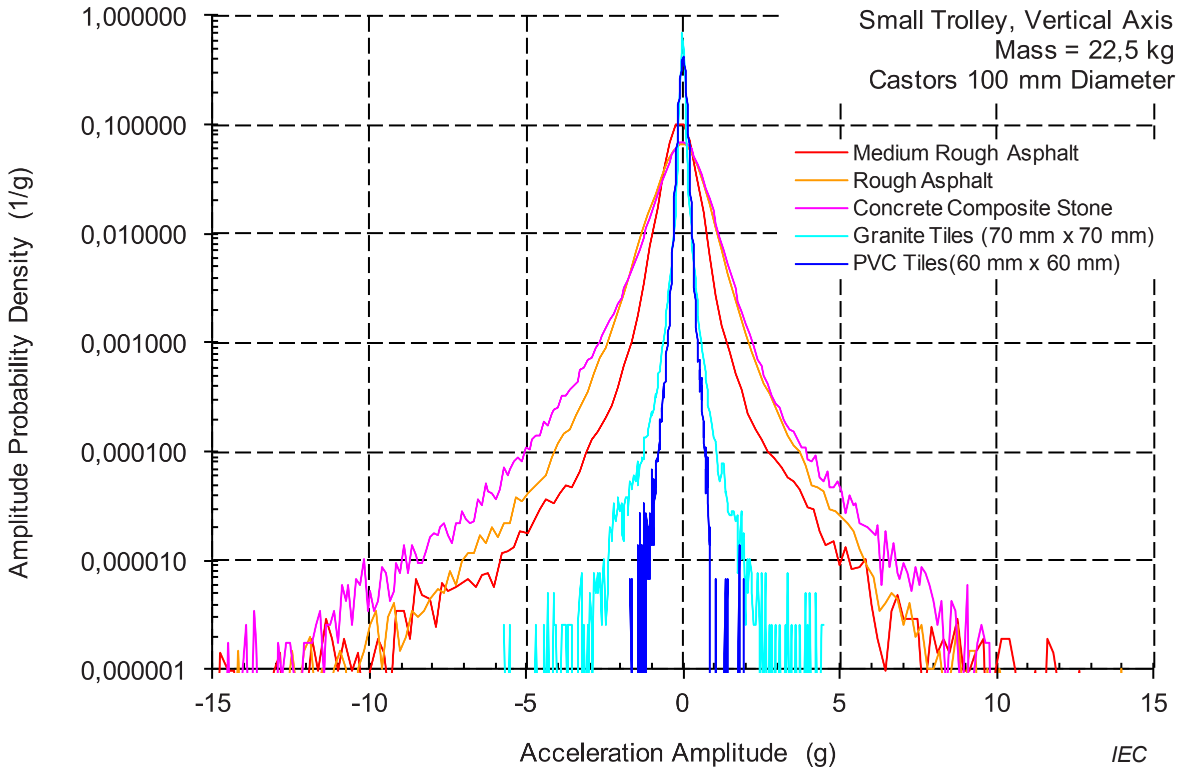

Figure 30 – Amplitude distribution at wheels of small trolley – Vertical [6]

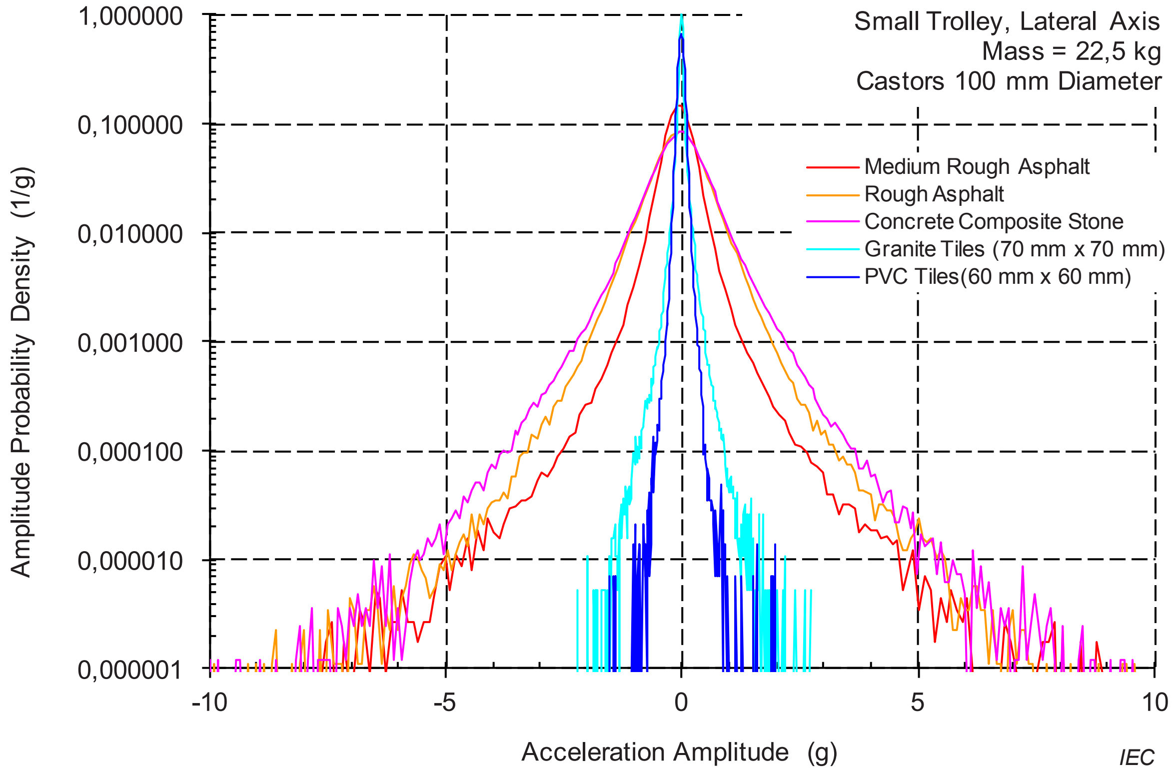

Figure 31 – Amplitude distribution at wheels of small trolley – Lateral [6]

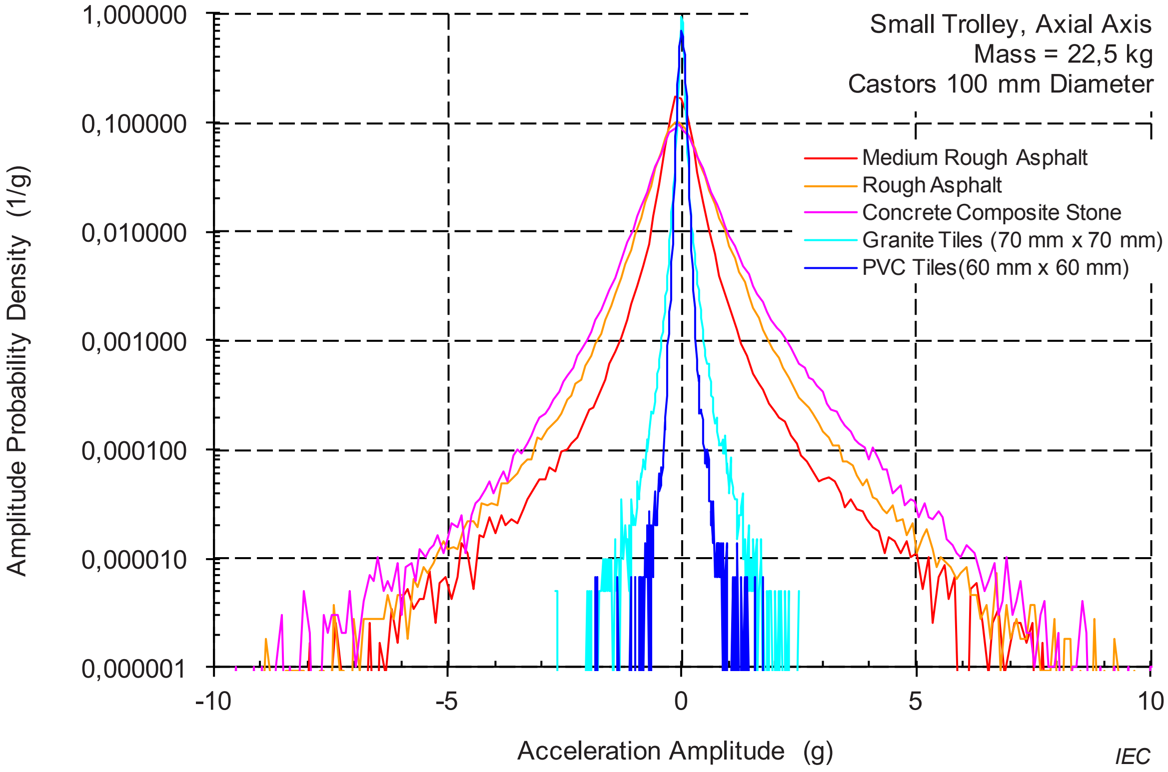

Figure 32 – Amplitude distribution at wheels of small trolley – Axial [6]

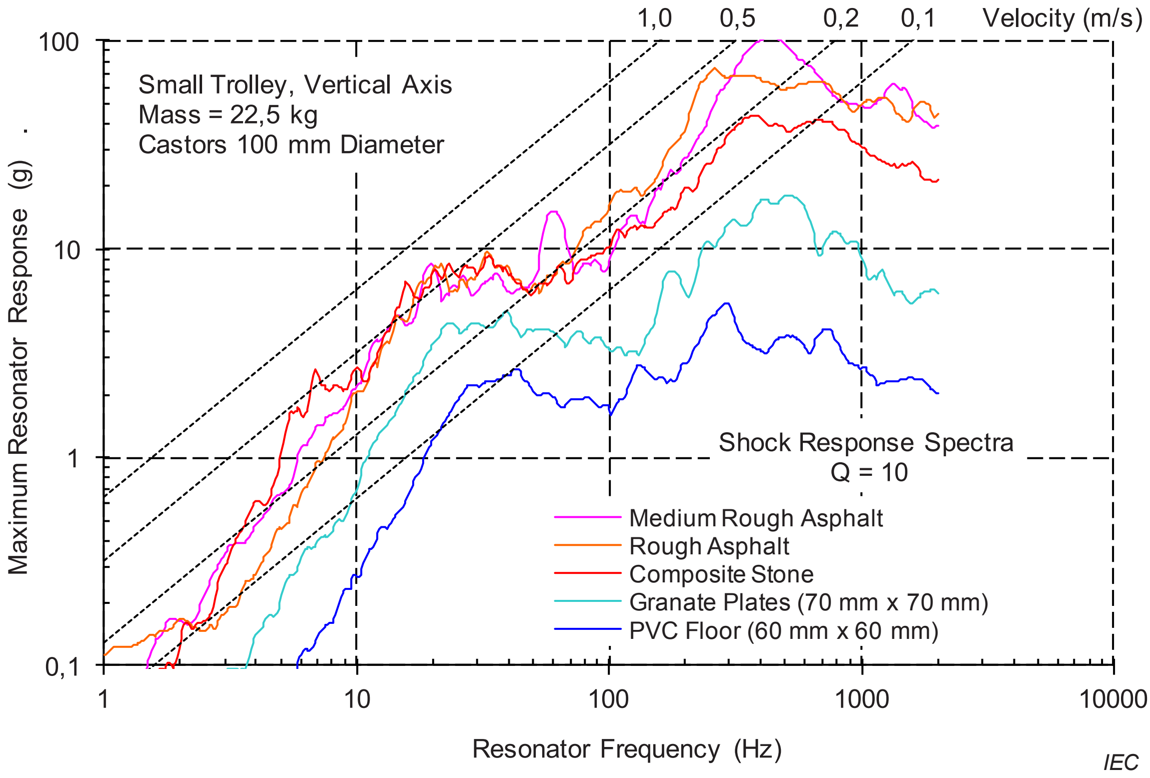

Figure 33 – Shock response spectra at wheels of small trolley – Vertical [6]

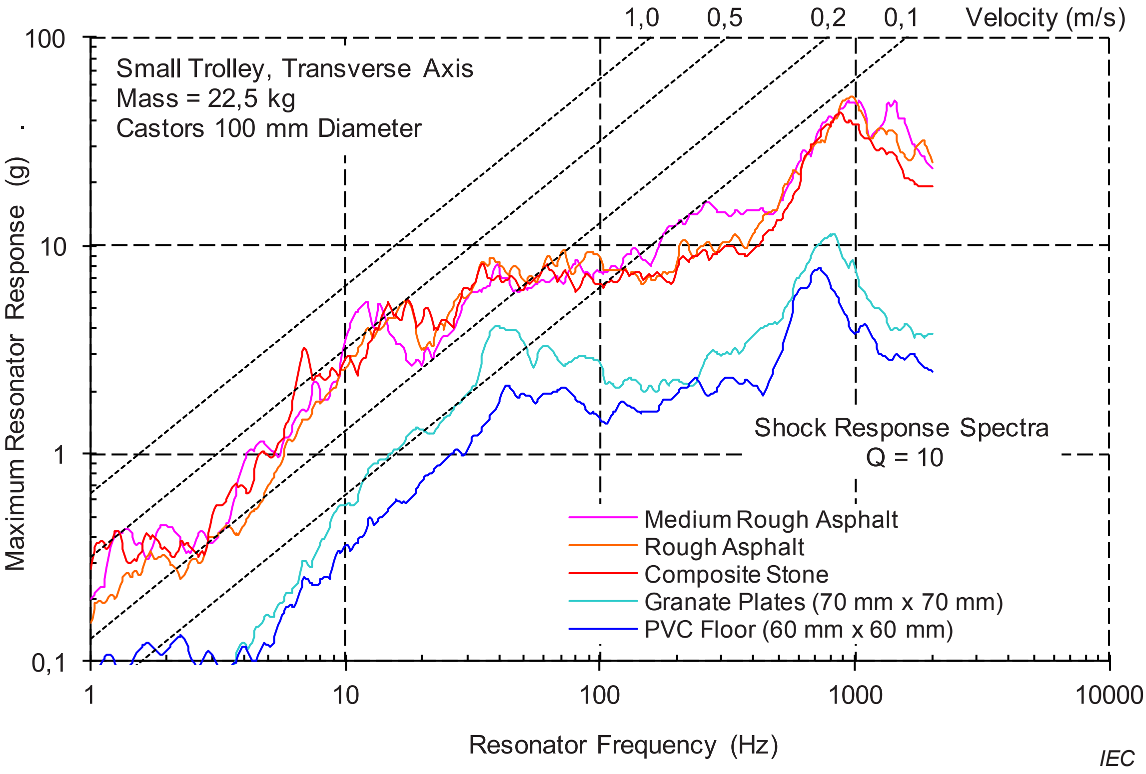

Figure 34 – Shock response spectra at wheels of small trolley – Lateral [6]

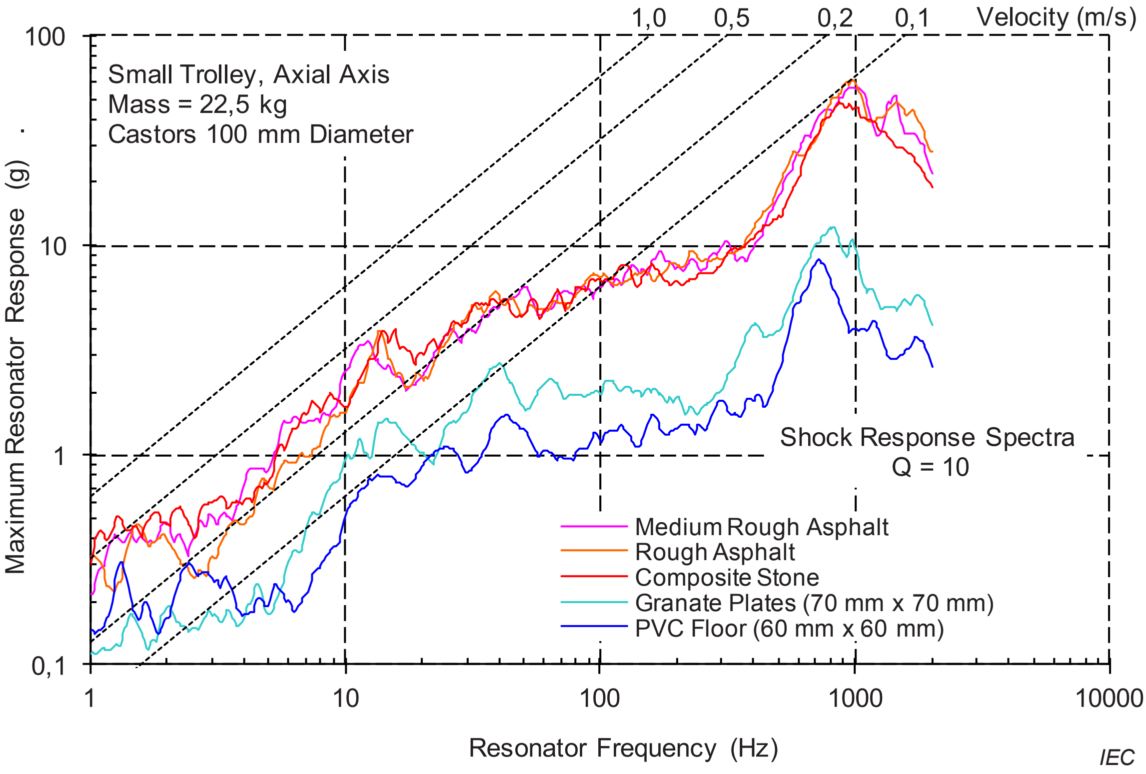

Figure 35 – Shock response spectra at wheels of small trolley – Axial [6]

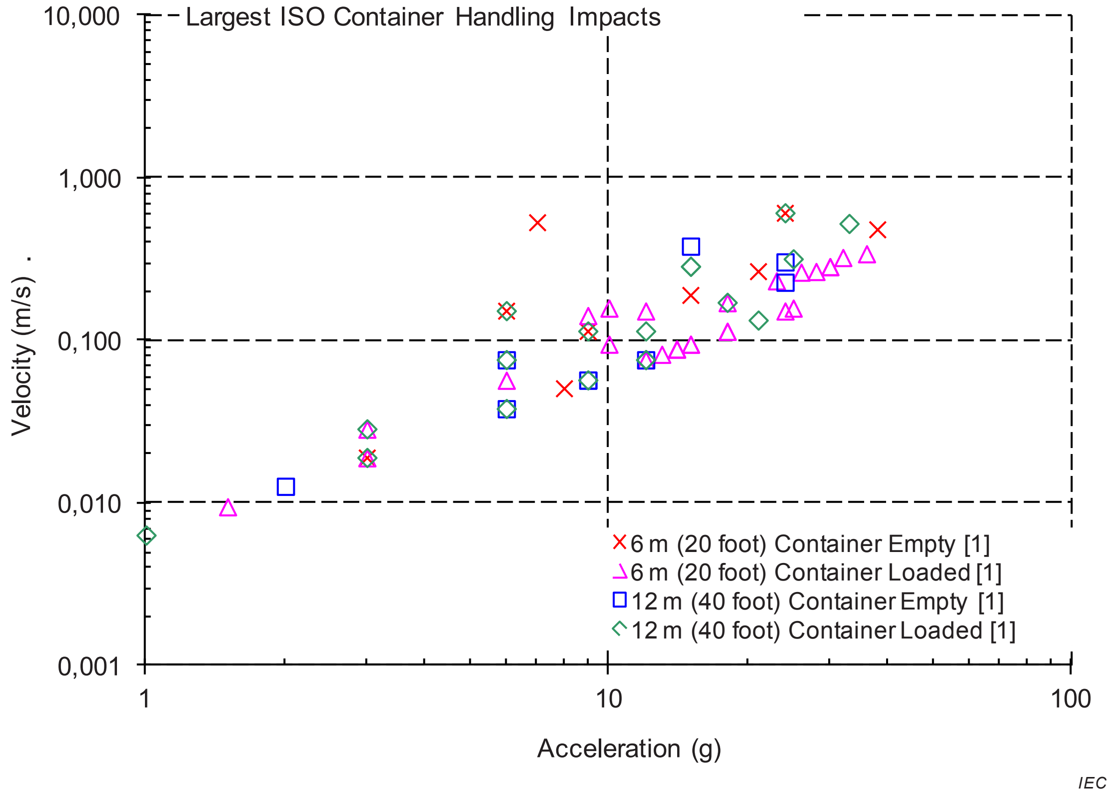

Figure 36 – Comparison of acceleration and derived velocity for largest impacts [1]

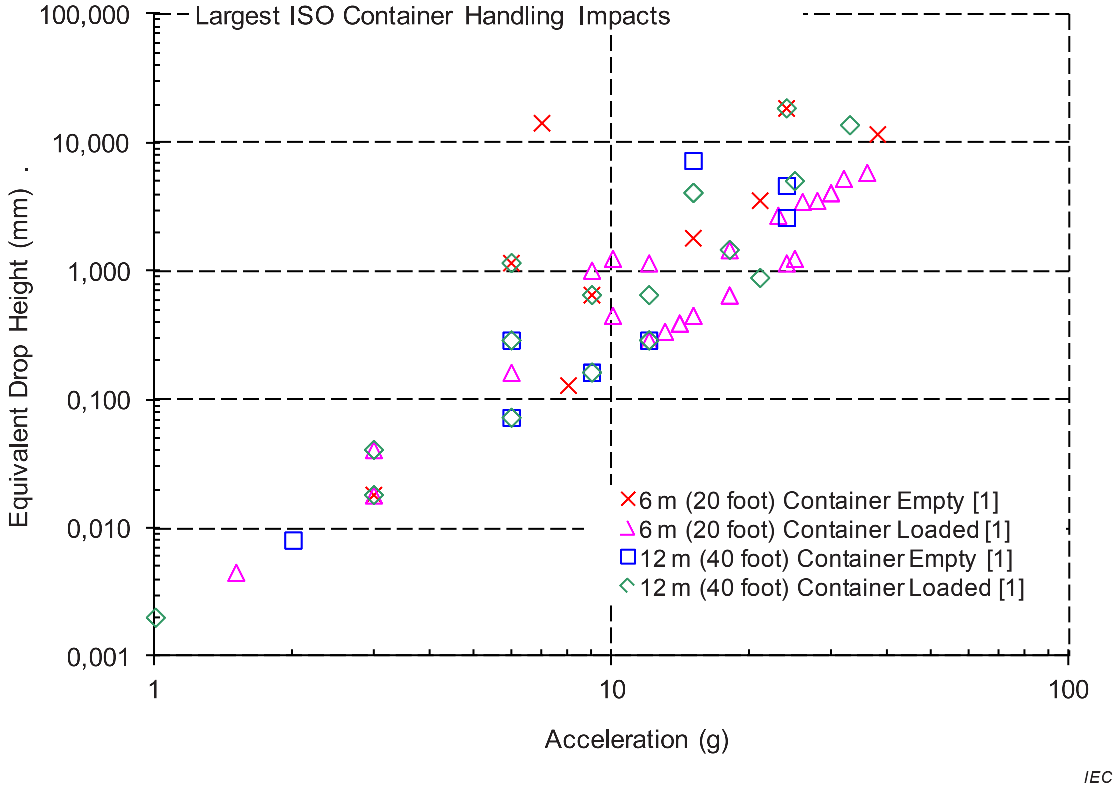

Figure 37 – Comparison of acceleration and derived drop height for largest impacts [1]

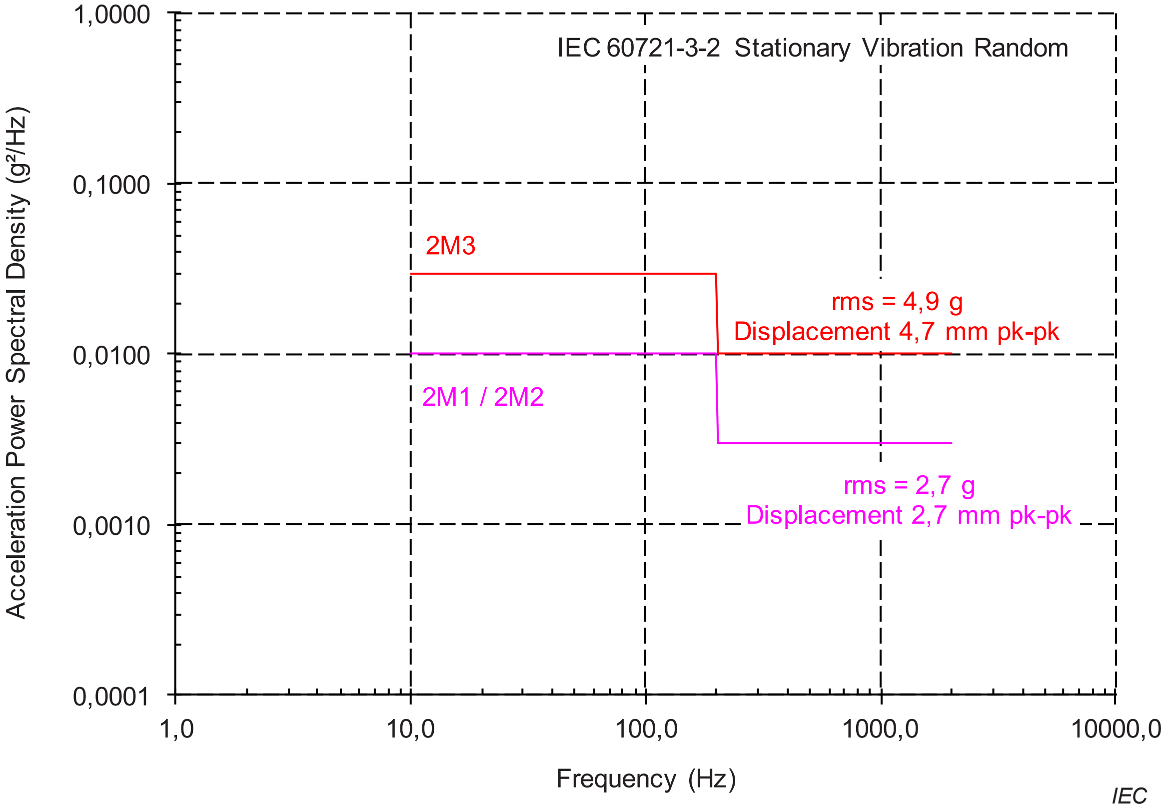

Figure 38 – IEC 60721-3-2– Stationary vibration random severities

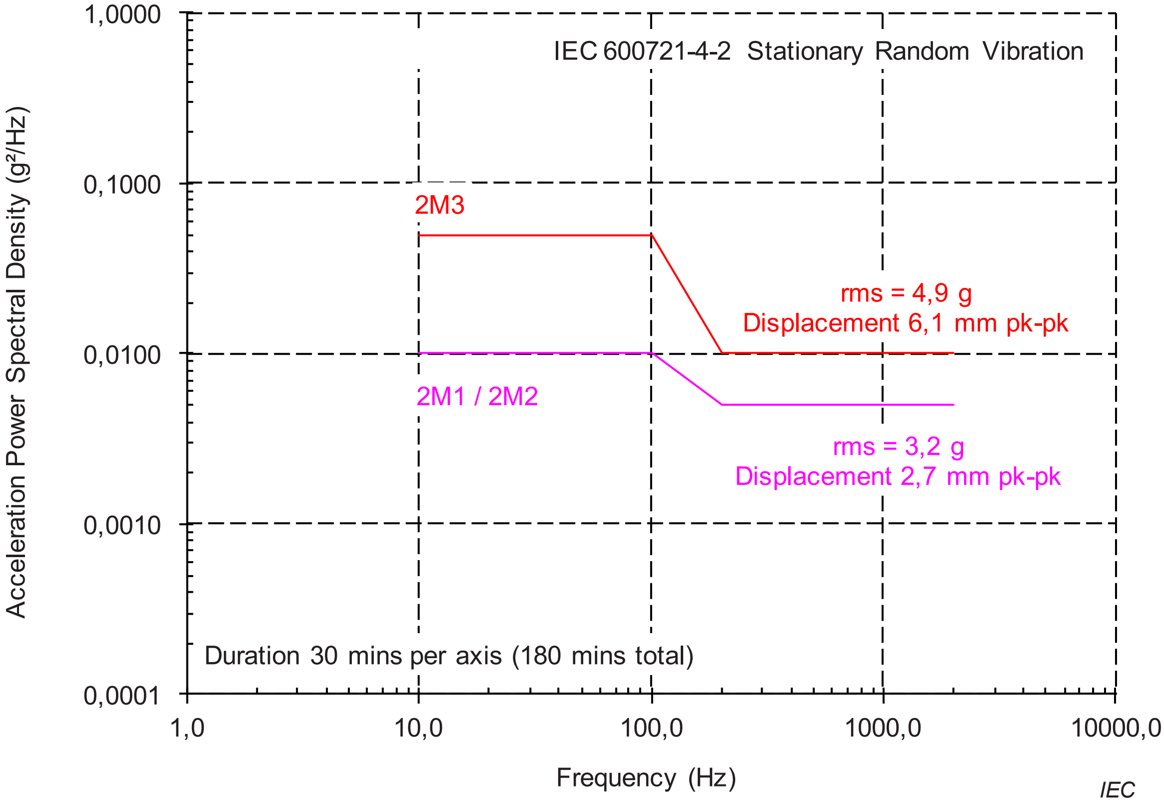

Figure 39 – IEC 60721-4-2– Stationary vibration random severities

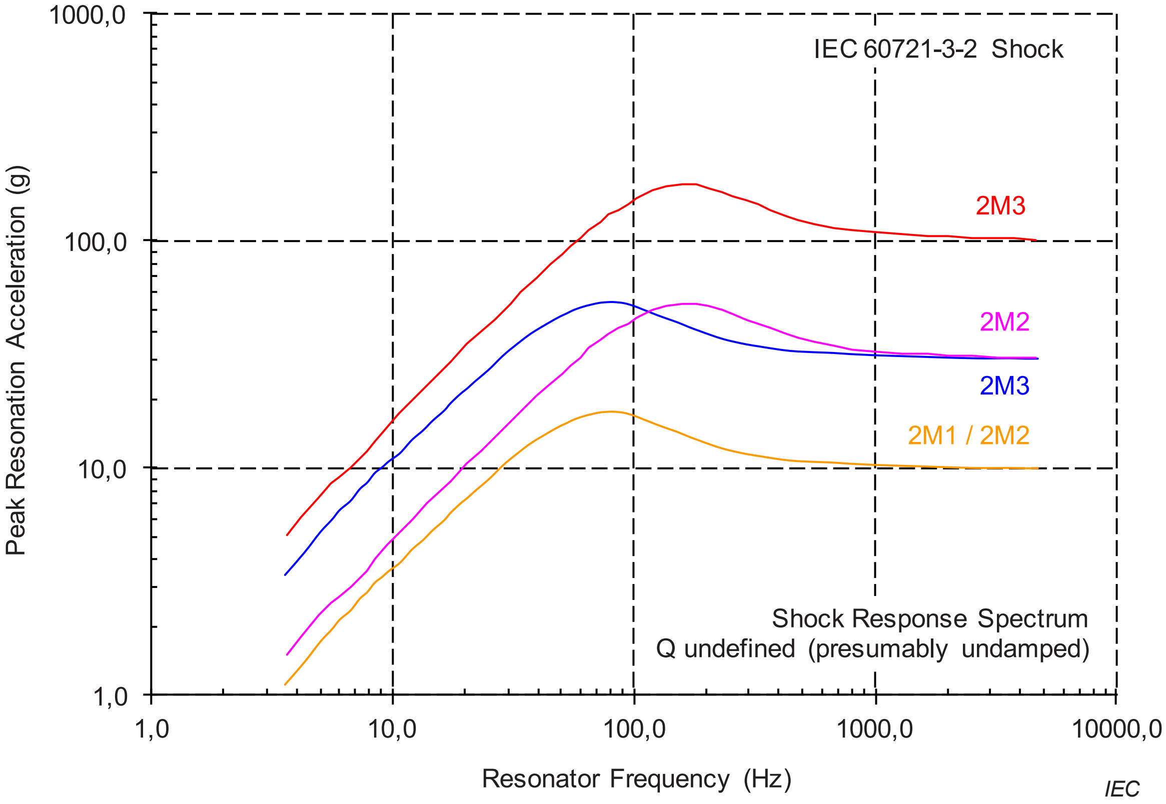

Figure 40 – IEC 60721-3-2– Shock severities

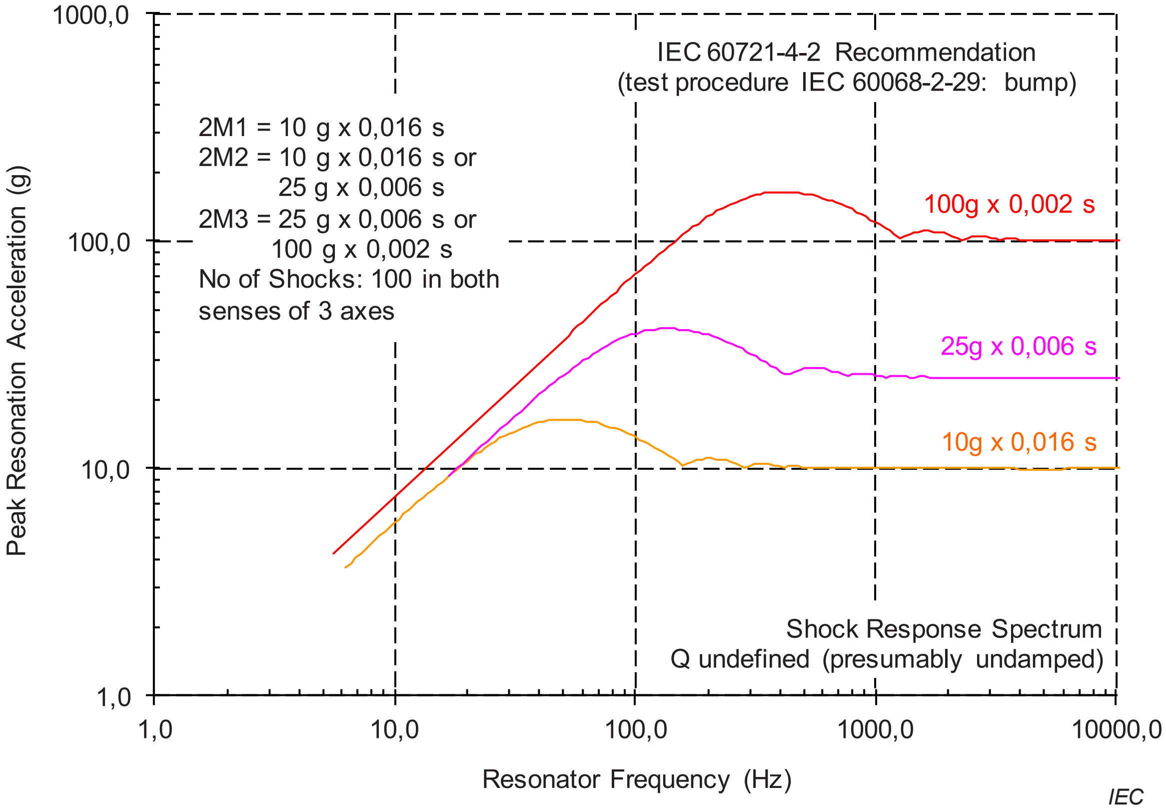

Figure 41 – IEC 60721-4-2– Shock severities for IEC 60068-2-29 test procedure

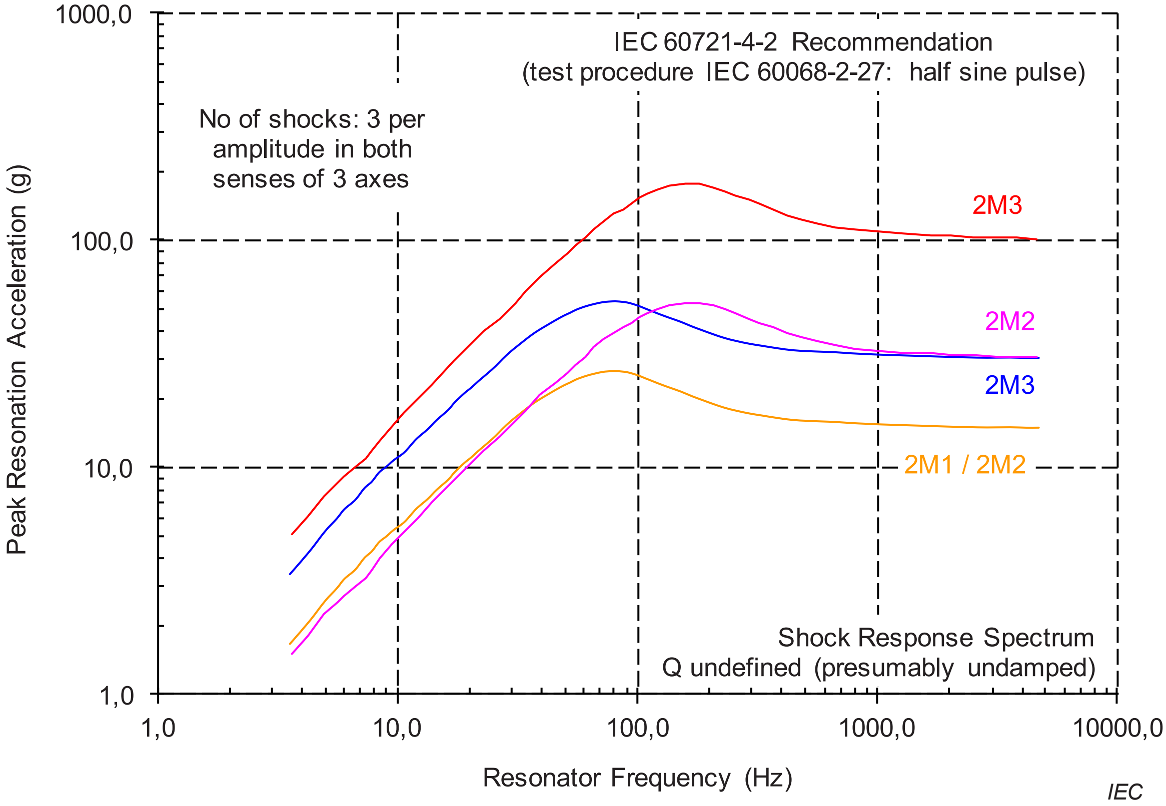

Figure 42 – IEC 60721-4-2 – Shock severities for IEC 60068-2-29 test procedure

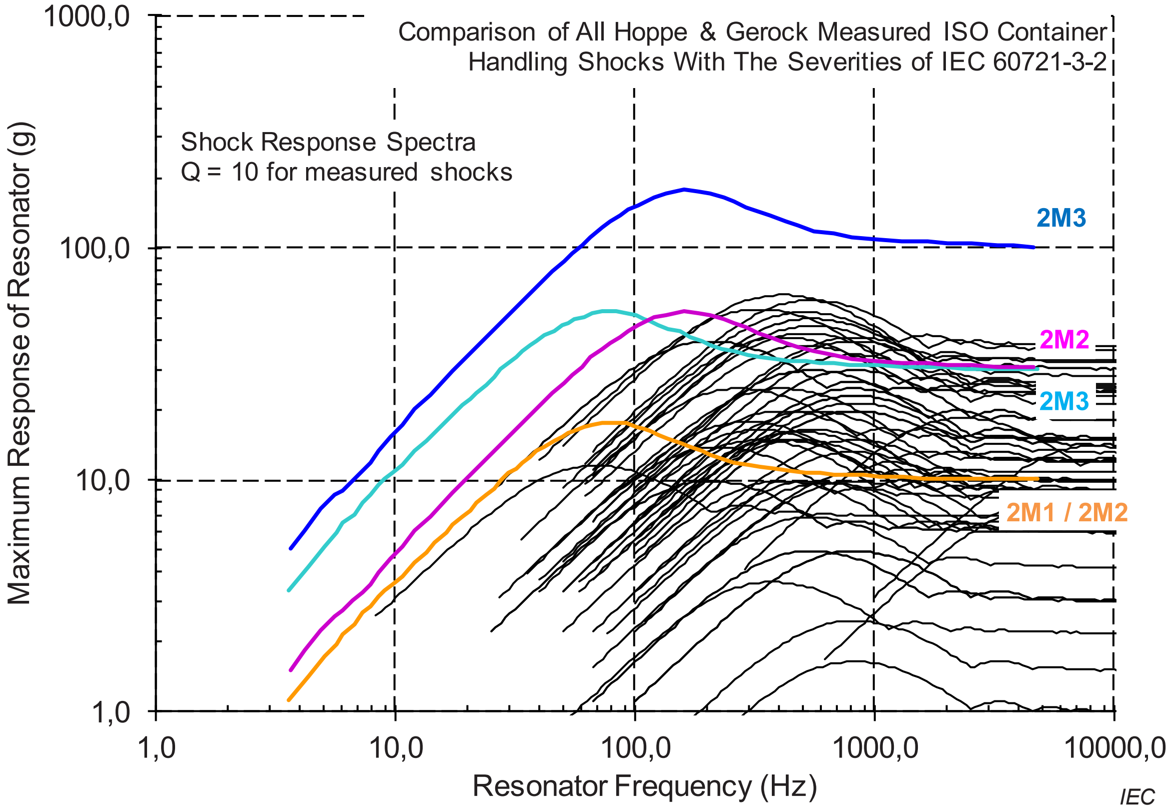

Figure 43 – Comparison of Hoppe & Gerock [1] derived shocks with IEC 60721-3-2

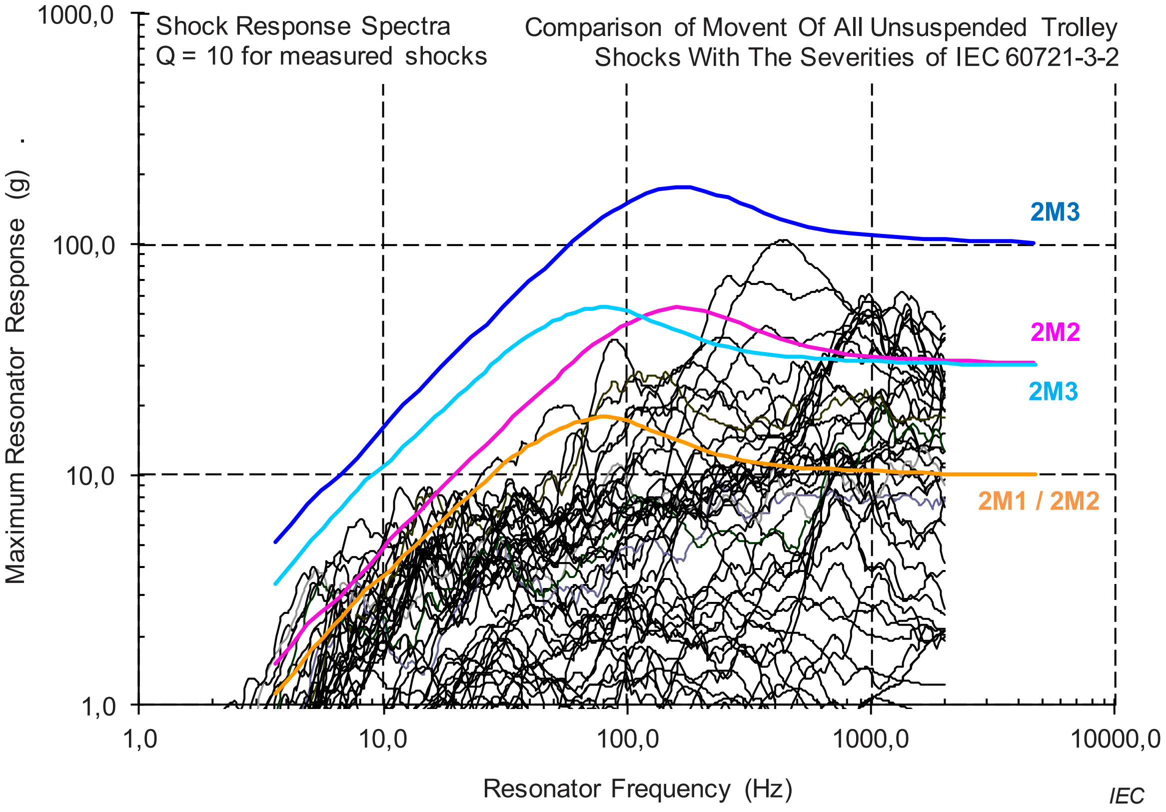

Figure 44 – Comparison of unsuspended trolley [6] shocks with IEC 60721-3-2

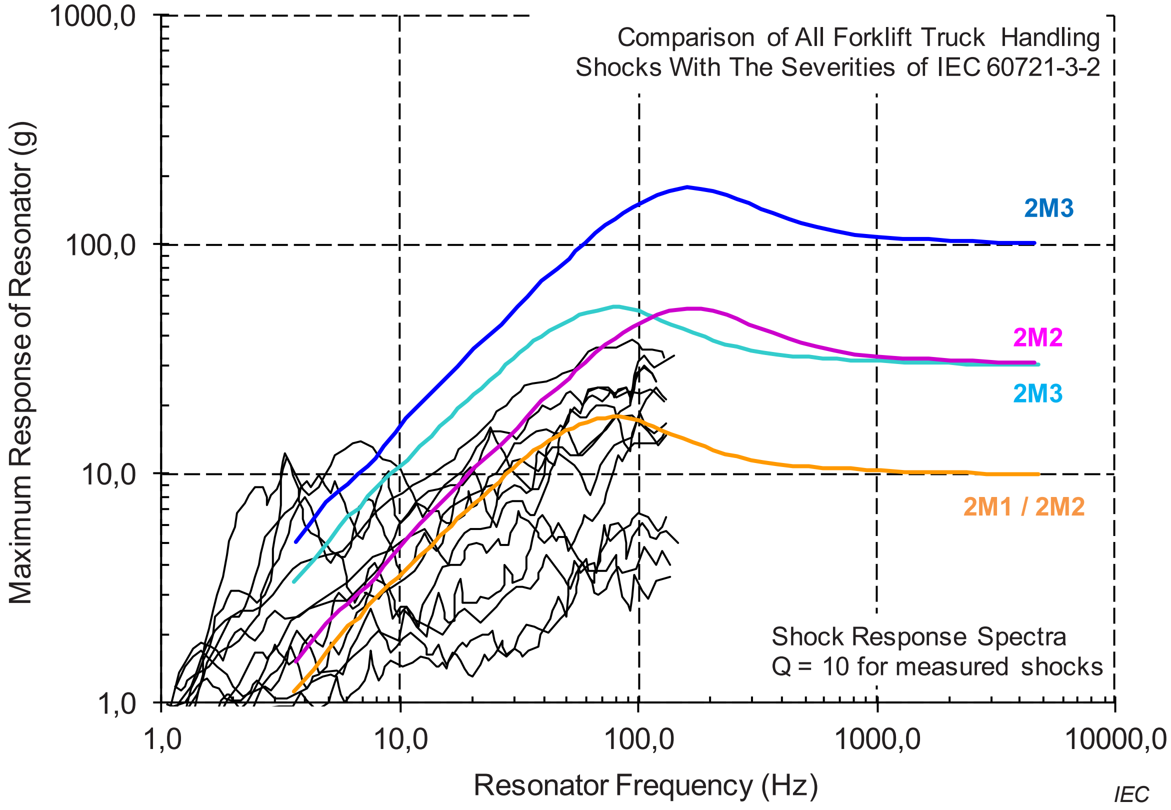

Figure 45 – Comparison of US forklift [5] shocks with IEC 60721-3-2

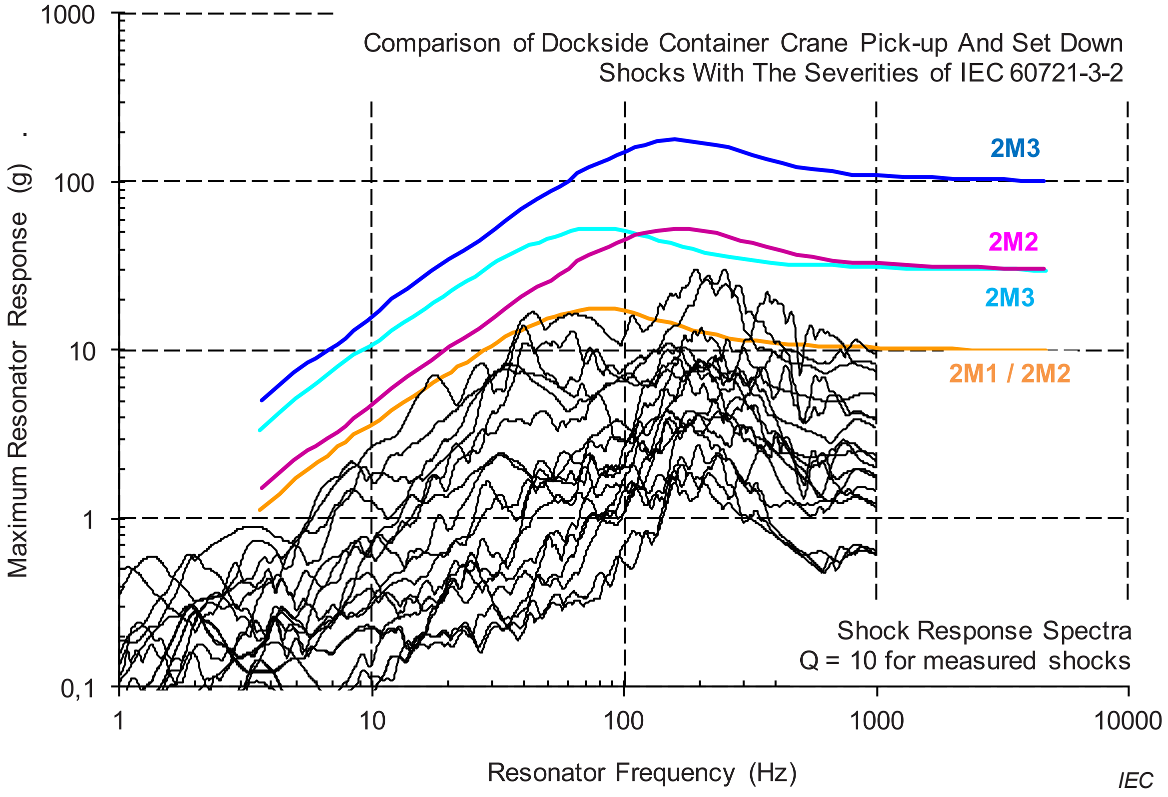

Figure 46 – Comparison of Swedish port [3] shocks (dockside crane) with IEC 60721-3-2

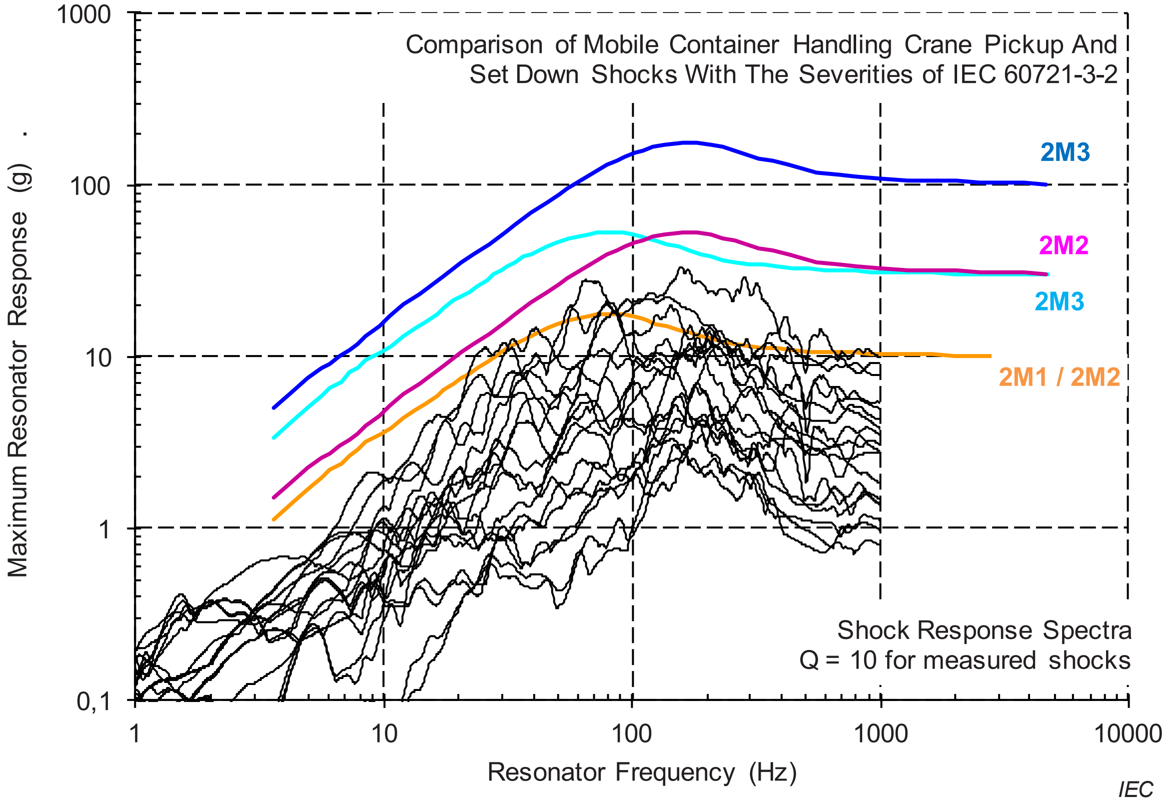

Figure 47 – Comparison of Swedish port [3] shocks (mobile crane) with IEC 60721-3-2

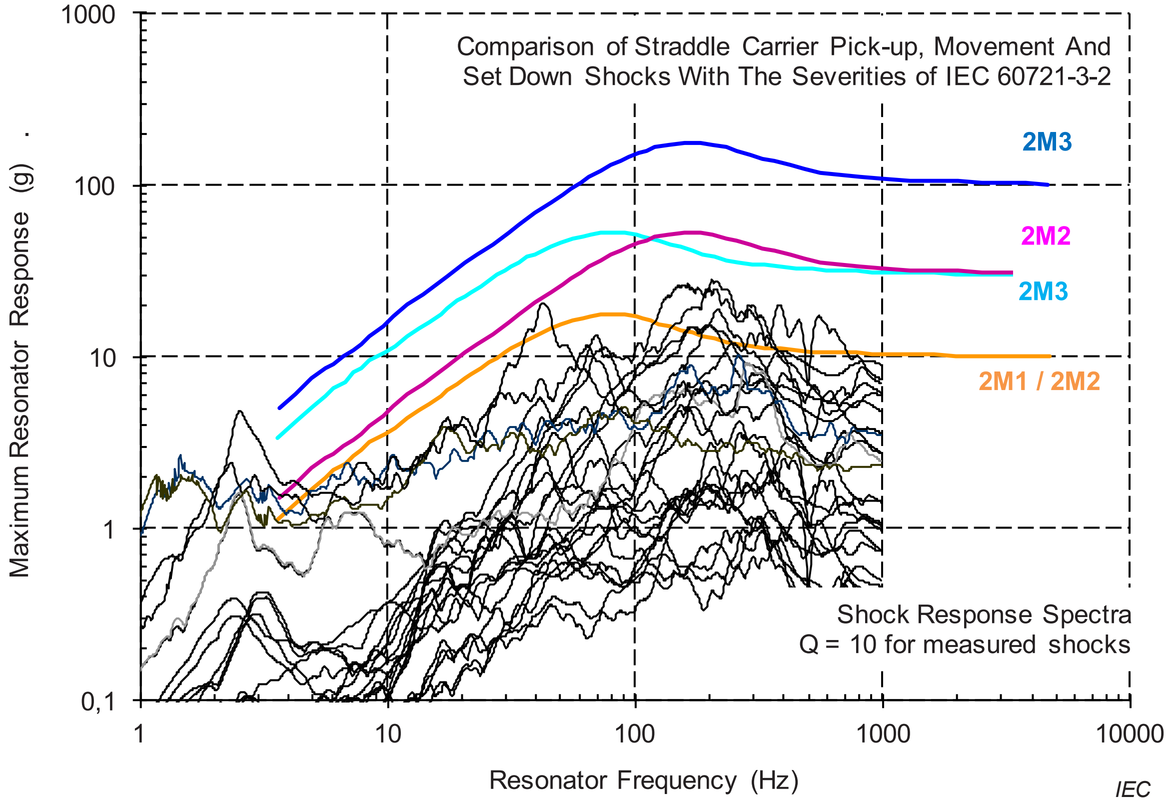

Figure 48 – Comparison of Swedish port [3] shocks (straddle carrier) with IEC 60721-3-2

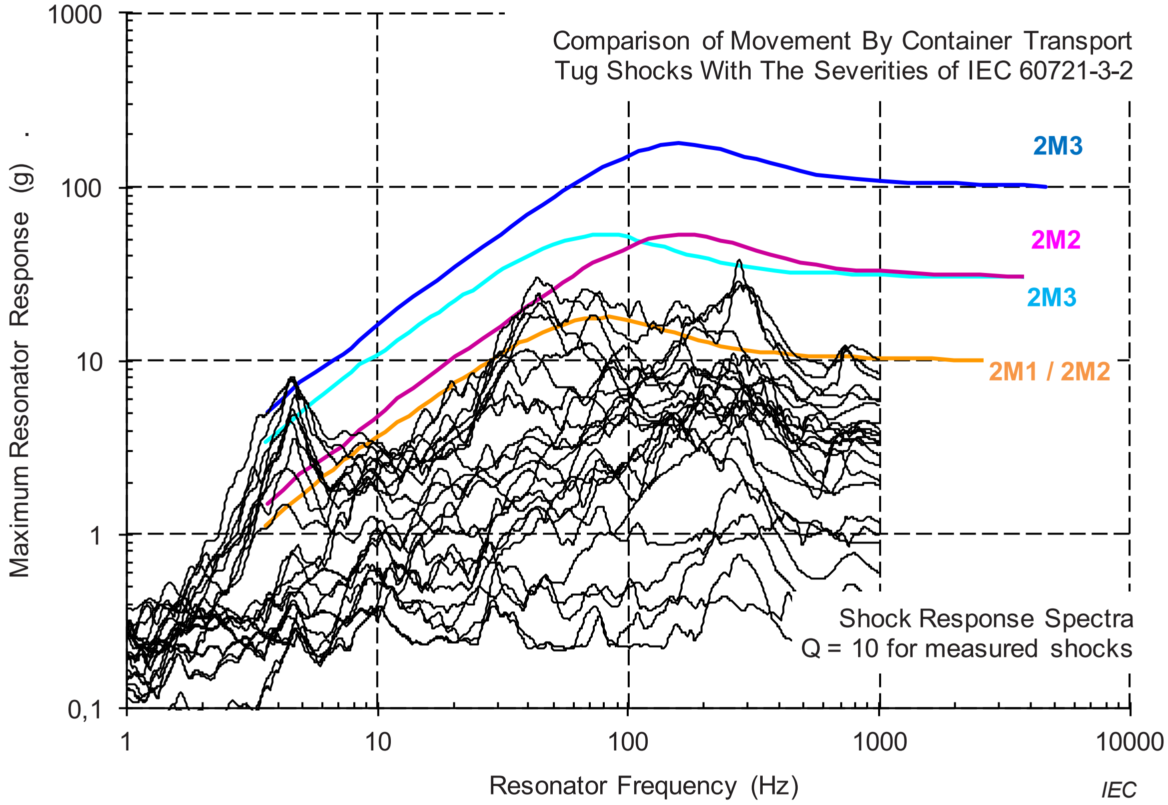

Figure 49 – Comparison of Swedish port [3] shocks (transport tug) with IEC 60721-3-2

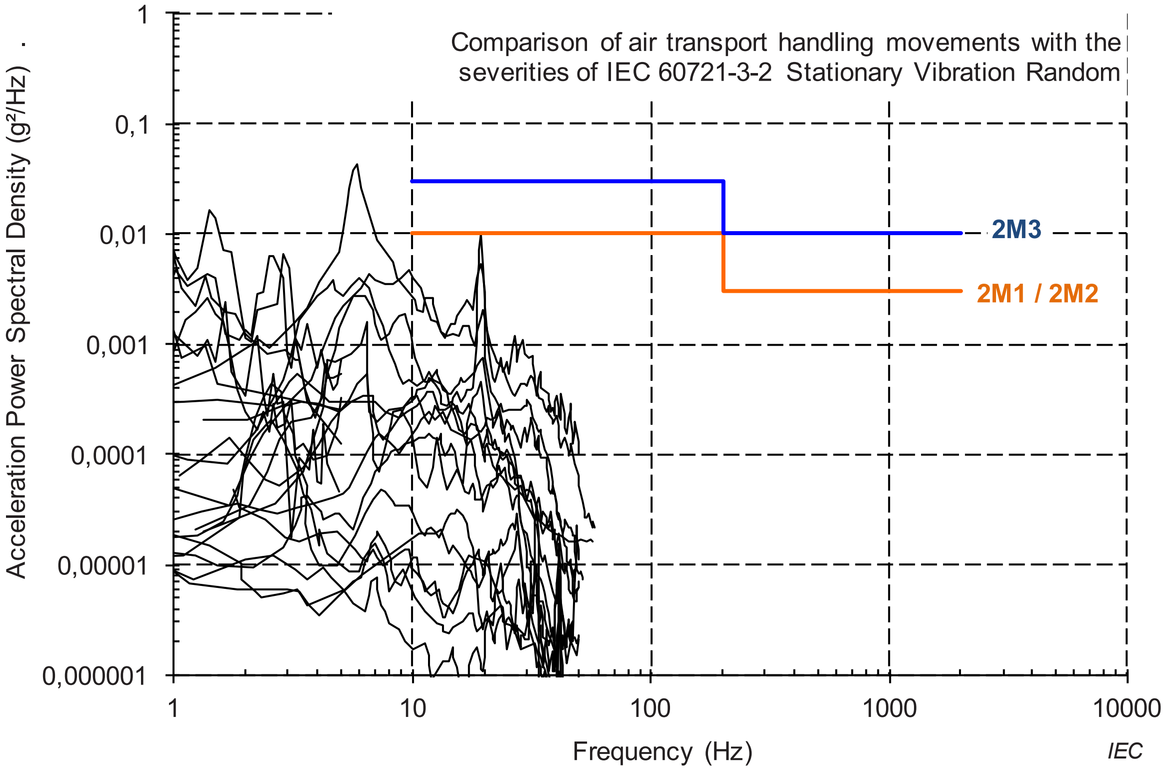

Figure 50 – Comparison of Swedish air transport [4] vibrations with IEC 60721-3-2

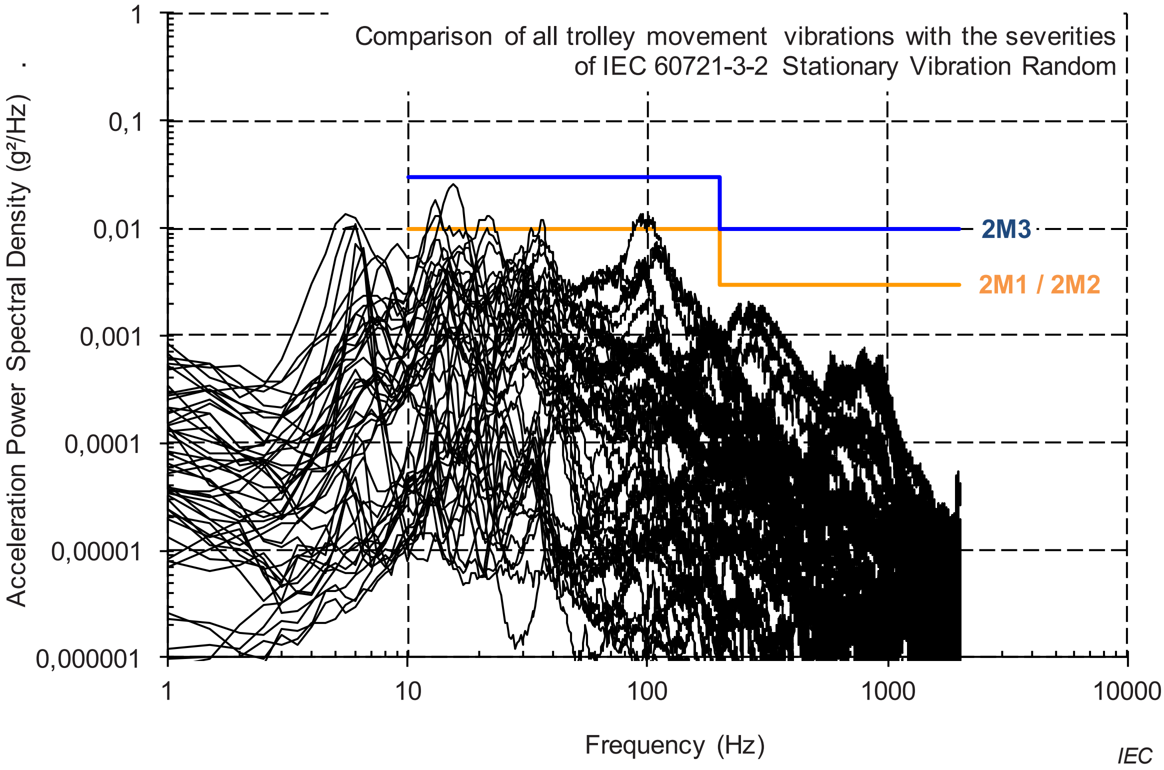

Figure 51 – Comparison of unsuspended trolley [6] vibrations with IEC 60721-3-2

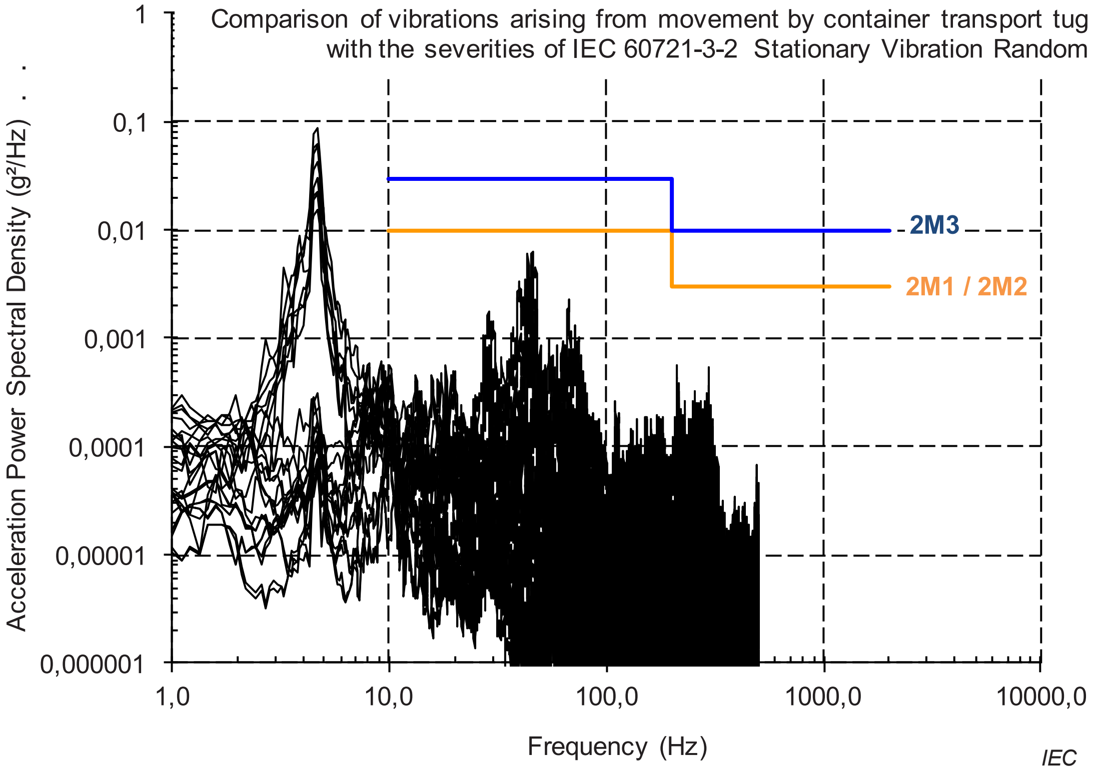

Figure 52 – Comparison of Swedish port [3] vibrations (transport tug) with IEC 60721-3-2

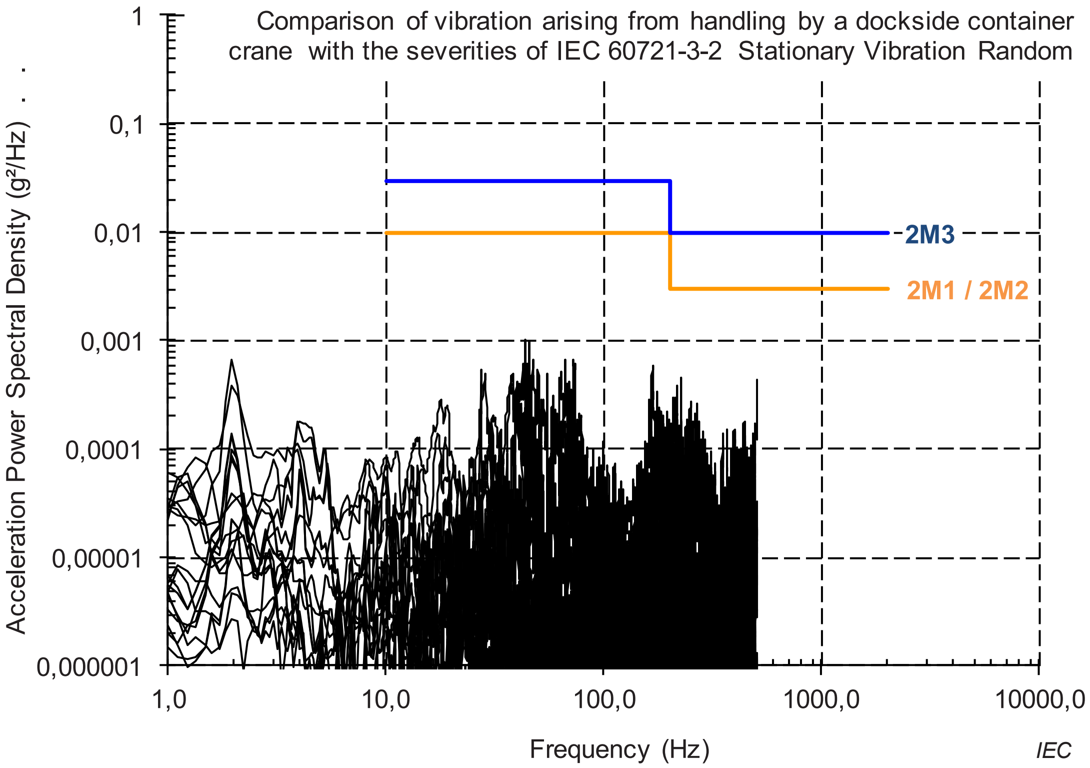

Figure 53 – Comparison of Swedish port [3] vibrations (dockside crane) with IEC 60721-3-2

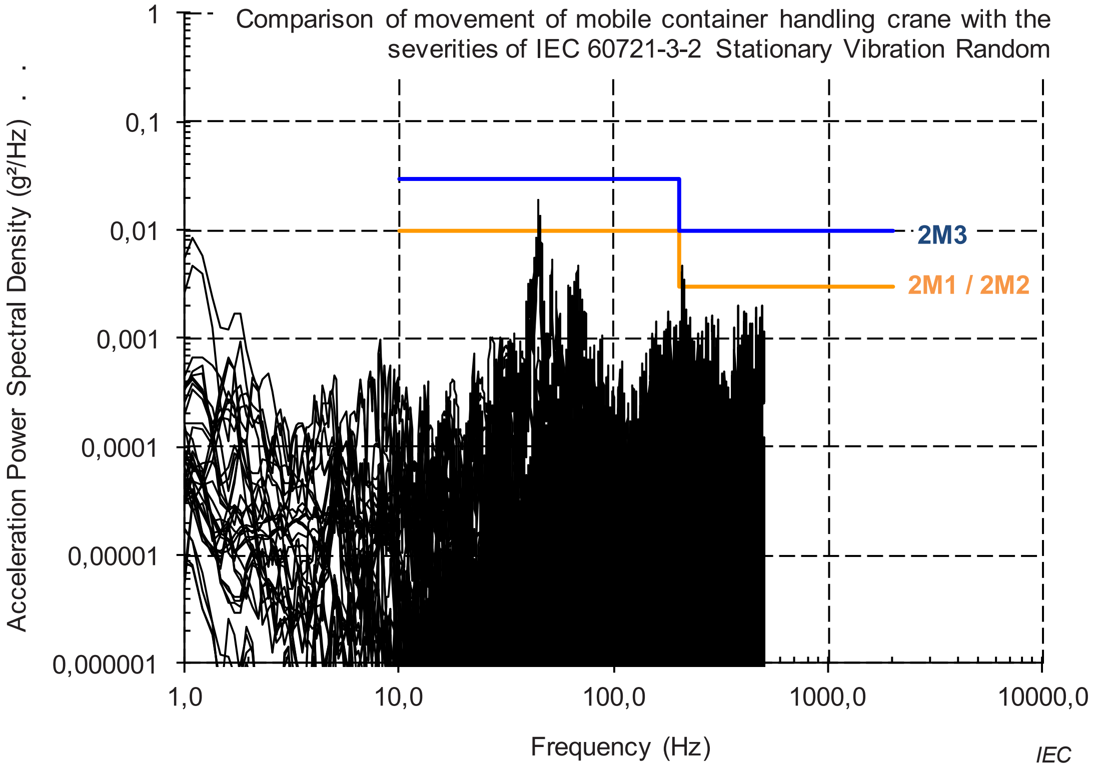

Figure 54 – Comparison of Swedish PORT [3] vibrations (mobile crane) with IEC 60721-3-2

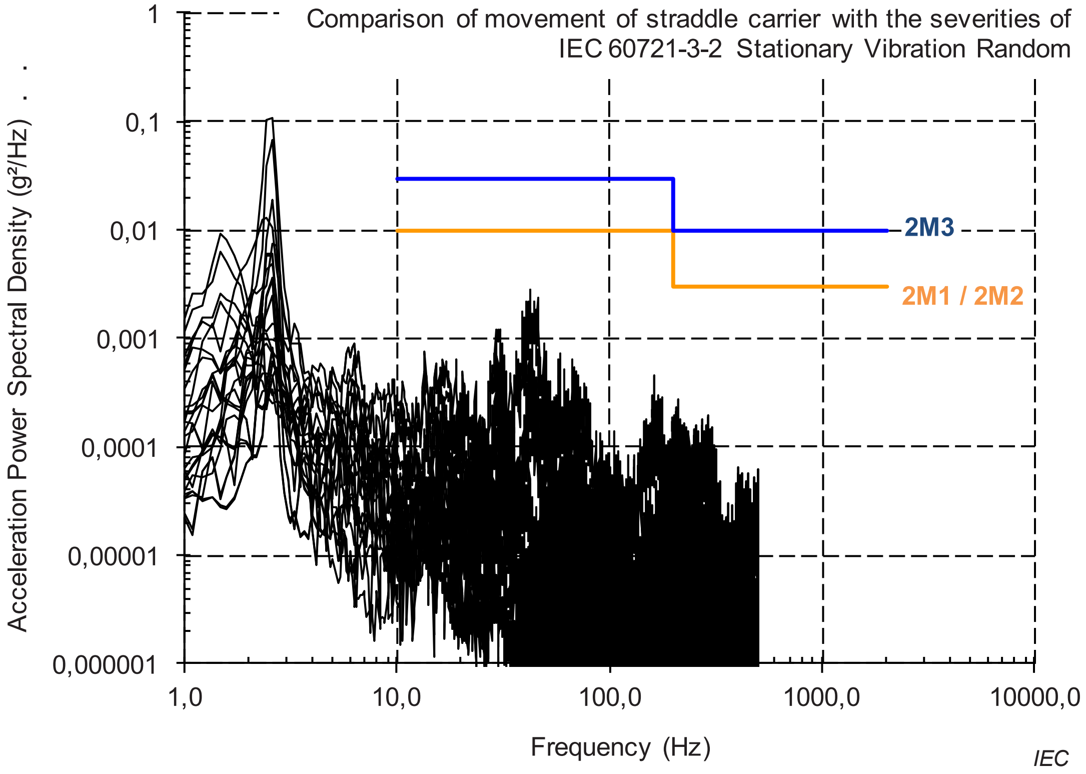

Figure 55 – Comparison of Swedish port [3] Vibrations (straddle carrier) with IEC 60721-3-2

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