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TECHNICAL REPORT

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Environmental conditions – Vibration and shock of electrotechnical equipment – Part 8: Transportation by ship

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IEC Secretariat
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

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Environmental conditions – Vibration and shock of electrotechnical equipment –
Part 8: Transportation by ship

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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ENVIRONMENTAL CONDITIONS – VIBRATION AND SHOCK OF ELECTROTECHNICAL EQUIPMENT –

Part 8: Transportation by ship

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

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts in the IEC 62131 series, published 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 document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

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ENVIRONMENTAL CONDITIONS – VIBRATION AND SHOCK OF ELECTROTECHNICAL EQUIPMENT –

Part 8: Transportation by ship

1 Scope

This part of IEC 62131 reviews available dynamic data relating to the transportation of electrotechnical equipment by marine craft such as ships and boats either at sea or during riverine use. In this instance, there is a clear similarity between dynamic data relating to the transportation of electrotechnical equipment and that of electrotechnical equipment installed on maritime platforms.

The intent is that from all the available data, an environmental description will be generated and compared to that set out in the IEC 60721 series [1][1].

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 [2].

This document primarily addresses data extracted from several different sources for which reasonable confidence exists in their quality and validity. This document 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. This document clearly indicates when utilizing information in this latter category.

The aim of this document is to review information from a number of different data gathering exercises. The quantity and quality of information in these exercises is expected to vary considerably.

Not all 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

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

[1] Numbers in square brackets refer to the bibliography.

4 Data source and quality

4.1 General

The first step in the process of reviewing available dynamic data, in this case relating to the transportation of electrotechnical equipment by marine craft, is to identify measurement exercises containing vibration and shock data which are likely to meet the validation criteria set out in IEC TR 62131-1. Whilst several exercises have been identified for this purpose, relatively few contain suitable vibration and shock data which can be realistically assessed against the validation criteria. There appears to be two underlying issues as to why little measured vibration data are available. The first is that the vibration levels experienced during sea transportation are generally of particularly low amplitude and consequently of insufficient concern to justify a measurement exercise. The second issue is that vibrations tend to occur for significant periods of time and vary with sea state. Consequently, presenting real measured data can be difficult and it is generally easier to present worst case conditions in terms of test severities. Essentially, most of the identified exercises would be classified as "supplementary data" according to the process of IEC TR 62131-1. Only two measurement exercises have been identified which have the potential to meet the required criteria and neither of those relate to large transport marine craft. For that purpose, this document has had to rely on evidence from the "supplementary data".

4.2 NAV vibration measurements

This measurement exercise [3] established the accelerations and vibrations on the floor of the forward and aft holds, of a relatively small (approximately 2 000 tonnes) transport vessel (RMAS Arrochar) on a three-day transit from Zeebrugge dockyard (Netherlands) to Glen Mallen on the west coast of Scotland. The journey was via the English Channel and the Irish Sea and occurred in March 1990. The measurements encompass all the prevailing conditions arising during the journey, which includes sea states from 1 to 6. This was the second of two similar measurement exercises on this class of vessel. The first exercise was on RMAS Kinterbury in July 1987 and employed a similar measurement layout in the forward and aft holds. Although measured data from the first exercise was not available for this work, the measurements and test severities derived from both exercises were compared and found to be similar. In this case, the measurement exercise and the data analysis were undertaken by separate agencies. The results of both measurement exercises were utilized to ensure the vibration experienced by an equipment were less than those to which it had been evaluated. For this purpose, a third independent agency reviewed the results.

The transport vessels used for this work, RMAS Arrochar and RMAS Kinterbury, were both naval armament vessels (NAVs) of the same class, both operated by the UK Royal Maritime Auxiliary Service (RMAS). Both vessels are now decommissioned. The vessels had two holds, both located in the centre of the ship, with the aft hold (Hold 2) the closest to the propulsion system. However, as the vessels are relatively small, both holds are in proximity to some rotating machinery, particularly the generators. Information on the overall vessel configuration, in this case for RMAS Arrochar, is shown in Figure 1.

The measurement exercise employed 24 accelerometers and three dummy loads. The latter were utilized to establish the underlying measurement noise levels at various locations in the holds. This is an issue when measuring vibration on marine craft as the vibrations can be quite low level and consequently easily influenced by contamination from electrical and mechanical noise. The exercise measured both low frequency acceleration transducers to establish payload loadings (up to 10 Hz) as well as higher frequency vibration transducers (up to 200 Hz).

The vibration measurement locations used in both measurement exercises are shown in Figure 2. Vibration measurements, on the floor of both holds, were made simultaneously. Eight piezo-electric transducers were located in the aft hold, four measuring vertical (Z) vibrations and two each for the lateral (X) and longitudinal (Y) vibrations. The transducers were configured as two triaxial assemblies and two uniaxial devices. Two triaxial transducer assemblies were located in the forward hold, each measuring in the vertical, lateral and longitudinal axis. The measurements from the two holds were recorded on separate magnetic FM tape recorders, but with measurements from one location common to both recorders. This was to enable synchronization and correlation to be undertaken for data analysis purposes.

All the spectral information presented in the available report [3] is in terms of "equivalent peak acceleration" with a frequency resolution of 0,5 Hz. Most of the measured vibration data are for conditions less than sea state 4, but with some limited data at sea state 5 to 6. Vibration severities for different sea states are presented for each hold. Noise measurements are around 0,000 1 g^2/Hz.

As the report only presents data in the form of "equivalent peak acceleration" it can only realistically be compared with sine-based environmental descriptions. It cannot be easily compared with power spectral density environmental descriptions without resorting to comparison of the effects of the vibration (for example using the maximum response spectrum and fatigue damage spectrum). This is an underlying issue with vibration measurements made on marine craft. Such measurements often contain sinusoidal vibrations arising from rotating machinery. Consequently, the vibration analysis methods utilized are often those appropriate for quantifying such sinusoidal vibrations. However, measurements made away from rotating machinery can be more consistent with random vibration analysis assumptions, and hence can utilize power spectral density analysis methods.

Most of the data analysis plots, included within the report, cannot be easily reproduced here. However, summary information from that data analysis is included here as Table 1 and Table 2 and Figure 3 and Figure 4. Table 1 shows the most severe acceleration levels measured for different sea states, for each vessel axis and for each hold. These measurements are limited to 10 Hz (no information on the filtering used is provided) and are intended to indicate the acceleration loading that equipment could experience during transportation. Essentially, the values are indicators of the acceleration loading any payload tie down system would need to resist. Table 2 shows the most severe vibration levels measured for different sea states, for each vessel axis and each hold. Two parameters are provided, one for the long-term root mean square of the vibrations, the other the peak-to-peak value. Table 2 is shown graphically in Figure 3.

Envelopes of the "equivalent peak acceleration" for the vertical and lateral axes and for each hold are shown in Figure 4. Also included in that figure are similar values obtained from the earlier exercise on RMAS Kinterbury. The values of "equivalent peak acceleration" shown in Figure 4 are composed of envelopes of all sea states and measurement locations in each hold and axis.

The sea state definitions for wind and sea levels, adopted for the NAV measurement exercise, were from the Douglas sea scale and information is provided in Table 3.

Although the information in the NAV vibration measurement report has some limitations, the quality of the information is reasonable and meets the required validation criteria for data quality (single data item).

4.3 RIB vibration measurements

This measurement exercise, undertaken in December 2005, was on a moderately sized rigid inflatable boat (RIB), used at high speed in a sea estuary and a river. The purpose of the exercise was to establish the vibration severities likely to be experienced by equipment at several cargo locations. These vibration severities were required to be compared to those experienced by the same equipment during road transportation. For commercial reasons, some measurements on certain equipment cannot be made available in this report. However, there are sufficient remaining measurements on the deck and cabin of the vessel to give a satisfactory view of the overall vibrations experienced. Given that the RIB is a relatively small craft operated at high speed, the measurements obtained from this vessel would be expected to contain some of the most extreme vibration conditions arising during maritime transportation.

The report of the measurement exercise [4] documents measurements made in both inland river conditions (referred to as "riverine") as well as during sea conditions. The riverine measurements included eight individual events made on in-shore water on the River Ore in Dorset in the UK. The sea measurements were made by following a route offshore to the entrance of Barnstaple and Bideford Bay. Most of the time was spent in high-speed traverses of the sand banks at the entrance to the bay. These sand banks produced white water conditions deemed to represent the worst-case sea state the vessel would be operated in. The speed and position of the vessel was obtained from GPS measurements. The GPS speed measurements are reproduced here as Figure 5.

As shocks were anticipated within the vibrations, all the measurements were acquired at a sample rate of 6 400 sps[2]. The vibration transducers utilized were robust integral electronic devices with a fixed sensitivity with a good voltage output which was fed directly into a solid-state data recorder. The measurement ranges for the individual transducers were set by the selection of an appropriate voltage measurement range for each recorder channel. The solid-state recorder was configured with a 1 Gb memory and it was necessary to split the riverine and sea measurements onto separate cards. However, other than that, all other measurement conditions between riverine and sea conditions remained identical. The duration of measurement of the riverine segment was approximately 23 min and for the sea segment approximately 15 min.

A total of 24 integral electronic accelerometers were used in the measurement exercise and the location of 18 of these is shown schematically in Figure 6. In this case the X axis corresponds to the vessel fore-aft (longitudinal) axis, the Y axis to athwartships (lateral) and the Z axis to the vertical axis with respect to the deck. As the environment was expected to be mainly vibration, no check was made to establish the sense of the measurement (i.e. whether positive accelerations were up going or down going). The consequences of this omission will be addressed in Clause 5, the next stage of the data validation process. The two transducers mounted on the gearbox were an attempt to measure engine speed. However, as the RIB uses water jet propulsion, these measurements were not effective for that purpose. Nevertheless, the gearbox measurements do permit the identification of engine and shaft frequencies which are also apparent at several other locations. Up to about 150 Hz these are identifiable (46 Hz, 72 Hz, 107 Hz and 140 Hz), although above that frequency so many components exist that individual identification is difficult.

The vibration analysis of the measured data was undertaken for nine separate events (eight for riverine and one for sea), these are listed in Table 4. A preliminary review of the data indicated that a few measurements were defective. This was particularly noticeable after riverine event 8, which was the longest period of sustained severe conditions. The characteristic of those measurements suggested the most likely cause was from water shorting the power supply at individual transducer connectors. This issue had been observed on a previous measurement exercise, when it was established that the transducer connector was not in-fact proof against water ingress to IPX9. The channels and events from which the data was of doubtful quality are excluded from the vibration data assessment as well as the data reproduced here.

The analysis undertaken included statistical analysis, amplitude probability densities and acceleration power spectral densities. The sample rate for the data acquisition was 6 400 sps and the frequency resolution was 0,78 Hz. This frequency resolution was considered adequate as the responses were predominantly random and, for the purpose of the work, there was no need to accurately quantify the periodic components. However, if this had been the case, a higher frequency resolution to quantify the frequency of the periodic components would have been necessary.

Summary statistical information for the vibration measurements is presented in Table 5, Table 6 and Table 7. Acceleration power spectral densities are presented for three locations in Figure 7 to Figure 14. These figures overlay the measurements from the high-speed sea

[2] Samples per second.

event as well as the eight riverine events and show the vibration severities at the forward deck, centre port deck and the rear deck. Also, for reference, an acceleration power spectral density from one of the gearbox measurements is included in Figure 15. Figure 16 and Figure 17 show the amplitude probability densities for vertical measurements at the front and rear deck, respectively, for the high-speed sea event. A time history of the acceleration measurements for the forward deck vertical axis is shown in Figure 18.

Extensive information from the RIB vibration measurement exercise was made available for the purpose of this document. Apart from the measurement issues addressed above, the quality of the information is good and meets the required validation criteria for data quality (single data item).

4.4 Supplementary data

The supplementary data, detailed below, comprises information arising from reputable sources, but for which the data quality could not be fully verified. In this case, the supplementary data largely comprise information of vibration test severities used by different agencies.

The French military standard GAM-EG-13 [5] includes measured vibration information from two marine craft, a naval supply tanker and a train ferry. Acceleration power spectral density information for a small number of conditions is presented. However, no information is provided on the location of the measurements or details of the marine craft. Acceleration power spectral densities for the naval supply tanker travelling at 20 kn are shown in Figure 19 and for the train ferry, again at 20 kn, in Figure 20. It is clear from the figures that the vibrations contain several periodic components and it is possible that the amplitudes shown do not necessarily accurately quantify the periodic components (this is because of the use of power spectral density to describe them).

The US defence equipment test standard MIL STD 810 [6] contains two test severities for shipborne equipment. One of these is a simple random vibration test severity (shown in Figure 21) and the other is a sinusoidal test severity (shown in Figure 22). For equipment installed on ships, both severities are required to be applied. However, for transportation of equipment, only the random vibration test severity is required.

The UK environmental test standard for defence equipment DEF STAN 00-035 [7] contains vibration test severities for equipment transported by sea as well as for equipment installed on ships. The test for transportation of equipment by sea is a simple random vibration test severity (shown in Figure 23). Several sinusoidal tests are provided for equipment installed in ships. These depend upon the size of the ship and location of the equipment. For larger ships the severities are shown in Figure 24. For smaller ships (a naval minesweeper and smaller) the severities are shown in Figure 25 and Figure 26. In this case Figure 25 relates to aft locations (close to the propulsion machinery) and Figure 26 to other locations. Broadly, the most severe test severities are for smaller ships and at (aft) locations close to the propulsion machinery.

The UK defence standard DEF STAN 00-035 [7] also contains a small amount of information related to equipment installed in the aft region of a naval frigate (again near the propulsion machinery). The measurement exercise from which this information is extracted is not disclosed nor is the specific location of the measurements. Nevertheless, it does provide some useful insight into ship vibrations. Figure 27 shows an example acceleration power spectral density which clearly shows the periodic components from the ships propulsion system as well as the harmonics of those components. Figure 28 and Figure 29 show the overall root mean square (RMS) vibration arising from different engine power demands and for different ship manoeuvre conditions, respectively.

The SRETS study [8] was undertaken during 1998 and reviewed both measured data sources and test severities for a variety of methods of transportation. For sea transportation it quotes four sources of information viz. EXACT DK 1–237:1983, MIL STD 810, DEF STAN 00-035 and GAM-EG-13. Of these only the first has not already been considered. Unfortunately, it has not been possible to confirm the existence of EXACT DK 1–237:1983. Nevertheless, the information set out in the SRETS study indicates a composite test severity made up from engine room measurements. The composite severity is shown in Figure 30. The severity is made up from measurements on a ferry (approximately 11 000 tonnes), a small bulk carrier (approximately 7 000 tonnes), a 20 m catamaran and a large bulk carrier (approximately 64 000 tonnes). The SRETS study is referenced in ASTM D4728-17 which is a random vibration test for shipping containers. Except for the SRETS reference no severities specifically for sea transport are either quoted or referenced in this ASTM.

The MIL STD 810 random vibration severity appears to arise from a measurement exercise, undertaken in the early 1970s, by J.T. Foley [9] at the US Sandia National Laboratories. Unfortunately, the analysis process used by Foley throughout his work is unique and does not lend itself to direct comparison with the information presented in this document.

Several documents have been identified which provide essentially identical, generic severities for ship design purposes. The document specially considered is Guidance Notes on Ship Vibration by the American Bureau of Shipping [10], published in 2006. Essentially two vibration severities are provided. The higher severity is associated with ship structure in the engine and equipment room. The second severity is associated with the ship structure in the remainder of the vessel. These severities are shown in Figure 31. However, there is no indication as to the source of these severities. Moreover, there is a caveat associated with the severities, relating to crew and passenger compartments. For those locations, the vibration criteria of ISO 20283-5:2016 [11] may be applicable. ISO 20283-5 specifies the vibration severities which are likely to provoke adverse criticism from crew and passengers. Whilst not entirely relevant to the purpose of this document, these severities, shown in Figure 32, provide a useful benchmark.

The IEC 60092 series are vertical product standards for electrical installations within ships. Of specific relevance here is IEC 60092-101:2018 [12] which sets out the general environmental design requirements for electrical installations. The environmental design requirements, especially those quoted within informative Annex A of IEC 60092-101:2018, are based upon those in IEC 60721-3-6:1987 [13] and adopts the same categories (6M2, 6M3 and 6M4). However, some additional values are quoted within the main body of the document which are intended for specific types of equipment, notably accumulators as well as control and instrumentation equipment. The primary mechanical environments are related to static and dynamic angular motions (addressed in 7.1) as well as vibrations and shock. The vibrations are all specified as sinusoidal and the shocks as shock response spectrum. The relationship (as specified by IEC 60092-101) between the IEC 60721-3-6:1987 mechanical categories and locations within vessels which are in excess of 500 tonnes is:

Category 6M2	Equipment in general locations including bow sections and on vessels passing through ice.
Category 6M3	Equipment in stern sections including steering gear rooms for vessels up to 10 000 tonnes as well as on masts and loading systems, for example on container guides and cranes.
Category 6M4	Equipment on reciprocating machinery.

IEC 60945 [14] provides the test requirements for maritime navigation and radio communication equipment. It groups the environmental test requirements into four types of equipment (portable, protected, exposed and submerged). The environmental tests include dry heat, damp heat, low temperature, thermal shock, drop onto a hard surface, drop into water, vibration, rain and spray, water immersion, solar radiation, oil resistance and corrosion (salt spray). The vibration test applies to all types of equipment and the procedure used is based upon that of IEC 60068-2-6 [15]. The vibration test is a sine sweep resonance search followed by a sine dwell test at all resonant frequencies identified by the sweep. The amplitudes (shown in Figure 33) are 2 Hz to 13,2 Hz at ±1 mm and 13,2 Hz to 100 Hz at 7 ms^{-2}. The sine dwell is 2 h at each resonance otherwise 2 h at 30 Hz. The tests are applied equally in all three axes. The drop tests apply to portable equipment only, and are six drops of 1 m onto a hard surface and three drops of 20 m onto water.

Although not strictly relevant to the purpose of this document, it is worth noting that standard ISO 20283-2:2008 [16] sets out guidance on making vibration measurements on ships. The guidance relates to conditions and manoeuvres, measurement positions, signal acquisition processing and storage as well as the content of the test report. It also provides examples of the presentation of applicable global vibration measurements. However, it provides no specific data. ISO 20283-4:2012 [17] provides similar guidance on making vibration measurements on a ship's propulsion machinery. It also provides guidance on the vibration measurement of specific types of machinery but provides no specific data.

A Swedish measurement exercise [18], undertaken in 1985, made vibration measurements on cargo during winter sea transportation, in the north Atlantic. Despite its age the exercise was competently undertaken and assessed for the effects of location, weather and cargo securing equipment. However, the full report is only available in the Swedish language and the measured data could not be readily utilized for comparison, within this document.

5 Intra data source comparison

5.1 General

The purpose of the discussion addressed in this Clause is to review each data source for self-consistency. This is part of the verification process as described in IEC TR 62131-1.

5.2 NAV vibration measurements

The NAV vibration measurement work presented in this document was essentially a follow-on to a similar exercise undertaken three years previously. The two exercises used different vessels, but of the same class, and made measurement in similar locations. Part of the work on the measurements from the second exercise was to compare the results with that of the first. This work indicated that the two sets of measurements produced quite similar results.

The work does provide a useful indication of how vibration levels increase with the sea state. However, it should be observed that the NAV is only a modestly sized vessel (2 000 tonnes) and will consequently be more susceptible to higher sea states, than would larger vessels. Also, when considering the observed variations with sea state, it should be remembered that whilst the different sea states have a quantitative definition, estimating a sea state (from the bridge of a ship) is still largely subjective and relies upon the experience of the observer. Also, high sea states rarely remain consistent over extended periods. Hence, some of the sea states are specified in a band.

The worst case RMS vibration severities are around 1,5 ms^{-2} in the vessel vertical axis, 0,8 ms^{-2} in the fore/aft axis and 0,1 ms^{-2} in the lateral axis. The vertical axis measurements indicate a distinct trend of increasing amplitude with sea state. There is also trend in the fore/aft axis, but the maximum values occur at around sea state 4 and decrease subsequently (possibly due to decreased forward speed of the vessel). There is only a marginal increase in amplitude, with sea state in the lateral axis. The peak-to-peak vibrations follow a broadly similar trend, with sea state, as those observed when considering RMS vibration severities.

The spectral analysis method used for this work was unconventional. However, the use of "equivalent peak" accelerations for the analysis, was intended to allow direct comparison with an existing sinusoidal vibration test severity. Although not illustrated in this document, the "equivalent peak" accelerations were also found to follow similar trends with increasing sea state as discussed above. The spectral analysis did not show any predominant frequencies or amplitudes. Indeed, the responses are quite consistent across the frequency range from 3 Hz to 200 Hz. Although not particularly visible on the digitized plots included in this document, the original hard copy plots indicate the presence of several periodic components (see Figure 4), which are consistent across a range of locations, but nothing of significant amplitude.

The vibration information presented in the measurement report on NAV vibrations was supported by earlier work and assessed by an independent agency. The report does present data which appear to be self-consistent and shows trends and values which are largely within expectations. Therefore, the data meet the required validation criteria for quality against the intra data source comparison criteria.

5.3 RIB vibration measurements

The RIB measurements are from a small high-speed vessel which would be expected to produce some of the most severe vibration conditions likely to be experienced by a marine craft. In this case the purpose of the measurement exercise was to compare the severities with an existing random vibration test undertaken to represent road transportation. The analysis methods adopted are primarily intended for random vibration data and are consequently influenced by the limitations of such methods. The random vibration analysis methods adopted are largely consistent with those dominantly used in the other documents in the IEC TR 62131 series. However, they adopt a somewhat different analysis approach than that normally used for making measurements on marine craft.

As already mentioned within this document, vibration conditions observed from marine craft can contain contributions from propulsion systems and other rotating machinery. Such equipment tends to produce periodic responses of a sinusoidal nature, often with a significant number of harmonics present. If the overall contribution of these periodic responses is significant, then it is possible that the use of random vibration analysis methods will not necessarily be appropriate. In the case of the RIB measurements, whilst some contributions are present from the engine, these do not contribute significantly to overall vibrations, partly because of the nature of the water jet propulsion used. Also, although not included in this document, amplitude probability density analysis did indicate predominantly random vibrations occurred at deck locations.

The most significant issue with the use of random vibration analysis methods, in this case, is that the vibrations also include several shocks arising from the vessel impacting waves. The shocks appear in all three axes but are far more apparent in the vertical axis. The shocks are also more prominent in amplitude at the forward locations. The kurtosis at the forward deck in the vertical axis is 42 and the corresponding skewness is 0,2. The shocks decrease in amplitude along the vessel and at the rear deck many of the shocks are encompassed within the random vibrations. The kurtosis at the rear deck vertical is 3,6 and the corresponding skewness is 0,2. The most severe shocks are noticeably asymmetric (see Table 5), particularly in the vertical axis. At the forward deck the positive going shocks are up to 290 ms^{-2} but the corresponding negative shock is only 230 ms^{-2}. This asymmetry becomes less noticeable at locations moving aft along the vessel.

As already indicated, the measurement sense of the accelerometers was not verified during the exercise. Consequently, it cannot be confirmed that the positive vertical shocks are upward going. However, it is assumed that the most severe (positive going) shocks arise when the bows of the vessel impact a significant wave. The negative going shocks most probably arise from the subsequent structural responses of the vessel. These will be prominent, because most ships exhibit low frequency structural bending modes (commonly 2 Hz to 5 Hz) and this will almost certainly be the case for an RIB vessel, which is structurally quite flexible. If this is the case, then it could be speculated that the degree of asymmetry in the responses is related to the amount of structural damping present.

The amplitude probability density analysis suggests that the observed shocks can form a distribution of amplitudes. Unfortunately, the durations of the measurements are insufficient to statistically quantify the distribution. The high-speed runs in sea conditions indicate that significant shocks occur at an average rate of one every minute, but the peak occurrence rate is approximately one every 6 s. This would equate to a spacing of large waves of approximately 100 m, which would seem credible. The amplitude probability density analysis also suggests that the underlying random vibrations are largely Gaussian. In this case underlying random vibrations have broadly the lowest amplitude in the middle of the vessel, with the most severe conditions occurring at front and rear.

The vibration measurement exercise on the RIB was limited to a single vessel and some of the transducers could not be relied upon during the latter events because of water ingress into the electrical connections. However, this had been an issue on an earlier measurement exercise (in that case due to use of pressure washers), using this transducer type. Consequently, the effects of water ingress were well understood. As well as the vibration information presented in the measurement report on RIB, vibration analysis and data from other measurement locations have been reviewed for this assessment.

Overall, the vibration data appear to be self-consistent and show trends and values which are largely within expectations. Therefore, the data meet the required validation criteria for quality against the intra data source comparison criteria.

5.4 Supplementary data

Although a considerable amount of supplementary data was considered for this document, only one supplementary source included actual measured data, viz. those from the military standard GAM-EG-13. The information provided comprises one set of acceleration power spectral densities for each of two marine craft, a naval supply tanker and a train ferry. Both these vessels are larger than the NAV considered above. The severities for both vessels are similar but slightly less than those of the NAV. This would be in-line with the expectation that the larger the vessel the lower the vibration severities.

Although the information purported to be presented by the EXACT DK 1–237 document (as reported by the SRETS study) does not represent direct measurements, it is understood to be based upon a composite of measurements from five vessels. The overall severity of this composite spectrum is broadly that of the other measurements, but slightly higher in amplitude. This is not unexpected as the measurements are from the engine rooms of the five vessels. The data include several markedly high amplitude peaks which presumably encompass the periodic components from the propulsion system. How well these peaks represent all the vessels considered is not clear and they can be a unique artifact of the vessels selected as providing the most severe vibrations. Moreover, it is slightly surprising that the information is reported to be presented in the form of an acceleration power spectral density. This is because the accurate amplitude of periodic components from any rotating machinery will not be represented on such an analysis.

Except for the GAM-EG-13 and the EXACT DK 1–237 information, all the other supplementary information considered in this document corresponds to test severities. Two of these provide a random vibration test for the transportation of equipment and all provide a sinusoidal (sweep and/or dwell) test for equipment installed within ships.

The severities for the two random vibration tests for equipment transportation are defined in terms of acceleration power spectral densities and have a similar amplitude (0,1 $m^2s^{-4}Hz^{-1}$). However, they do encompass somewhat different frequency ranges as shown in Figure 34. The MIL STD 810 severities have a test frequency range for 1 Hz to 100 Hz, at an amplitude of 0,1 m^2s^{-4} Hz^{-1}. The DEF STAN 00-035 severity has a test frequency range of 5 Hz to 200 Hz, but the amplitude of 0,1 $m^2s^{-4}Hz^{-1}$ is only required between 10 Hz and 40 Hz. It has to be said, that neither of these test severities are in common use. Rather, it is much more usual to encompass these, relatively low amplitude, test severities within higher amplitude transportation tests, such as road transportation. Indeed DEF STAN 00-035 provides assistance on the transportation equivalence of the sea transportation test severity tests compared to road transportation. Papers suggesting similar equivalence to the MIL STD 810 sea transportation severities have also been published. Such equivalence is of course much easier to achieve when sea transportation is defined as a random vibration test, rather than a sine sweep or dwell test as was the case some years ago.

The need to achieve amplitude equivalence is not an issue when considering test severities for equipment installed on ships. In this case the severities representing ship-board conditions will be the dominant testing such equipment is likely to experience. The various sinusoidal severities discussed previously, in 4.4, have different purposes and uses. Consequently, there are differences in the severities. However, as shown in Figure 35, there is also a degree of underlying consistency.

6 Inter data source comparison

The third stage of the verification process described in IEC TR 62131-1 is to determine whether the various data sources indicated a reasonable degree of self-consistency and agreement, across the various sources. For the most part, the discussion on this is included in 5.4. From that discussion, it is not unreasonable to presume that the data reviewed in this document meet the required validation criteria for quality against the inter data source comparison criteria.

7 Environmental description

7.1 Conditions causing the environment

A ship can be considered a vibration generator consisting of a significant number of different vibration sources. There are a significant number of references which discuss the various sources of ship vibration, mostly with a view to reducing these vibrations, of which only a few are included here: [10], [19], [20] and [21]. The most common sources of ship vibration are the ship's propulsion system, (typically large diesel engines), propeller shafts (including bearings and shaft dynamics), propeller radiated pressures and bearing forces, manoeuvring devices such as transverse propulsion units, vortex shedding mechanisms from sea chests and hull protuberances, intakes and exhausts, air conditioning systems and other motor driven machines, cargo handling and mooring machinery as well as hull wake and slamming phenomena. Further, the ship's rolling and pitching causes the depth of the propellers to vary. This affects the magnitude of the blade passage pulses and cavitation noise. The contribution from the vibration arising at higher sea states will become more significant as the ship's size decreases and its speed increases.

The shock conditions associated with sea transportation in commercial ships are most likely to arise from slamming phenomena which can excite the fundamental dynamic response modes of the vessel (particularly the bending modes which can occur in the region 2 Hz to 5 Hz). In the case of large ships, where the equipment is located some distance from the hull plating, it is likely that transient vibrations will not be observed to any significant extent at any sea state. The transient vibrations can be significant for medium size ships at higher sea states. However, for small fast craft the transient vibrations can be relatively severe, even for low sea states. For equipment transported by ship, the most significant shocks are likely to be those associated with loading and unloading. IEC TR 62131-5 [25] contains information on the handling of containers during loading and unloading from ships.

On the rare occasions when payloads are carried as unprotected deck cargo, they can experience impacts due to green sea frontal loadings. In such cases, impact loadings on the equipment of 70 kPa acting over 350 ms, with short duration transient loads of 140 kPa for 15 ms, have been quoted. These conditions are quoted in DEF STAN 00-035 [7] and appear to arise from older (military) ship design handbooks.

A significant proportion of the dynamic responses of the ship's structures occur predominantly at extremely low frequencies, compared to other forms of transportation. This results in the fundamental mechanical excitations occurring at frequencies well below the mounted payload natural frequencies. Payloads can be stowed directly in holds or on decks. However, an increasing amount of equipment is transported in containers, which can be stacked to considerable heights above the deck. The design of the deck structure supporting the payload and the stacking arrangements will both influence the dynamic environment, and this will vary from location to location.

Although not strictly a dynamic response characteristic, the low frequency motion of a ship can give rise to large roll, pitch and yaw components. Some payloads can be susceptible to such motions and consequently it is possible that they will need to be considered as part of the mechanical environment. Typical limit values for roll and pitch motions would be ±30° with a period of 8 s and ±7° with a period of 6 s, respectively. These conditions are quoted from DEF STAN 00-035 [7] and appear to arise from older (military) ship design handbooks.

IEC 60092-101:2018 [12] quotes static and dynamic angular motions for equipment installed in ships larger than 1 000 tonnes. Static angular motions of up to 40° are specified for accumulators and storage batteries and 22,5° for control and instrumentation equipment. Additionally, dynamic motions of ±22,5° at a frequency of 0,1 Hz in all directions are quoted for control and instrumentation equipment. For other types of equipment, the values of IEC 60721-3-6:1987 [13] are adopted. Those values, which relate to all ship locations, are static 10° roll/15° pitch and dynamic ±22,5° 0,14 Hz, ±10,0° 0,2 Hz, and ±4° 0,05 Hz about all three-vessel axes.

7.2 Environmental characteristics

The excitation from machinery is frequently, but not invariably, periodic with harmonic components. Conversely many of the ship motion induced vibrations such as vortex shedding and hull wake effects, are largely random in nature. Moreover, the large number of periodic or harmonic components from different machinery can appear "random like" when observed some distance from the source.

The various sources of dynamic excitation produce a composite of random and periodic vibrations which, in some situations, can have embedded transients present. The ship vibration environment will differ for different locations within a ship, depending on the proximity of the equipment transported with sources of periodic vibrations (viz. the ship's propulsion system and generators) and the hull.

As equipment can be transported at numerous different locations within a ship, it is likely that an accurate environmental description, established for a specific location, will not be applicable to other locations. With that said, for sea transportation the vibration levels are generally considered to be low. Indeed, vibration severities induced by ship transportation are generally found to be the lowest originating from the various methods of transportation an equipment can experience. Consequently, the accurate simulation of the sea transportation vibration environment is not as important as for other more severe transport environments.

Because of the mix of periodic, random and transient components, it is probable that describing the environment solely by means of an acceleration power spectral density will not be appropriate. Such a definition will also likely need to be supported by autocorrelation and amplitude probability density information.

7.3 Test types

For environmental test purposes, the ship transportation excitations have been considered in terms of a pure random vibration test or as a sinusoidal sweep/dwell test. This problem is associated with the complex nature of the excitations, which comprises both the random and a multitude of tonal components, emanating from individual rotating machines, engines, shafts and propellers. This issue extends to the type of test used to simulate the environment.

Several of the test specifications reviewed in this document have specified random vibration as the most appropriate approach when testing equipment against ship transportation. This would seem to be applicable when the equipment is transported at locations away from installed machinery. It also has the advantage that any test severity can be compared directly with the severities for most other forms of transportation. This has significant testing advantage as ship vibration testing is frequently considered to be encompassed by other forms of transportation. A common question, which arises when ship vibration is encompassed by other forms of transportation, relates to equivalent test durations. Specifically, how much ship transportation can be encompassed by say 1 h of road transportation. The data available to this document are insufficient to supply a definite answer to this. However, DEF STAN 00-035 does suggest that 1 h of road transportation can be considered to represent six months of ship transportation. This probably represents an underestimate of the ship transportation duration for large modern container vessels.

All the test specifications reviewed in this document, which address equipment installed in ships, have specified sinusoidal sweep/dwell testing as the applicable approach. This seems to be because such equipment is likely to be located in the vicinity of installed machinery and propellers.

The testing approaches discussed above have advantages and shortfalls, and no single basic test method can be appropriate in all cases. If the sinusoidal dwell test is used, it can result in excessive response amplitudes at materiel resonances, particularly when they exhibit lightly damped characteristics. Indeed, the sinusoidal dwell test is notorious for damaging certain types of equipment. Similarly, it is probable that a sinusoidal sweep test will not result in an adequate test, since only a limited test time is spent at each frequency within the range of interest. The use of a random vibration test can also prove inadequate in simulating the effects of tonal responses, particularly when materiel natural frequencies exist within the frequency range of interest. Therefore, whatever test is chosen, it will probably represent a compromise.

8 Comparison with the IEC 60721 series

The purpose of this clause is to compare the severities identified within this document, with those set out in the IEC 60721 series. To ensure consistency with the previous documents in the IEC TR 62131 series [22], [23], [24], [25], [26] and [27], this comparison is specifically undertaken using the severities set out in IEC 60721-3-2:1997[3] [28]. As a result of the comparisons undertaken within the IEC TR 62131 series, IEC 60721-3-2:1997 has been updated with new categories and severities. These changes are not addressed within this document but will be addressed by a separate document within the IEC TR 62131 series.

No environmental severities exist in IEC 60721-3-2:1997 [28] specifically related to transportation in ships. Rather, the shock and vibrations conditions are assumed to be encompassed by those from general transportation. This is also intrinsically the case for the test severities of the IEC 60068 series [29].

The three "transport" categories set out in IEC 60721-3-2:1997 [28] are designated 2M1, 2M2 and 2M3. Only a brief explanation is given as to the conditions these represent but they 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 IEC 60721-3-2:1997, Table 5, are intended to encompass all forms of transport but are mostly related to road transport. No durations or number of applications are specified. The three relevant categories in IEC 60721-3-2:1997, Table 5 (2M1, 2M2 and 2M3), apply to four environmental parameters:

- category a) – stationary vibration sinusoidal, (illustrated in Figure 36);
- category b) – stationary vibration random (illustrated in Figure 38);
- category c) – non-stationary vibration including shock (illustrated in Figure 40);
- category g) – steady state acceleration (not illustrated but 2,0 *g* for all categories).

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3 Withdrawn.

Some years ago, it was identified that the amplitudes of the IEC 60721-3 series differed from those of the IEC 60068-2 series. Because of these differences a reconciliation exercise was undertaken between the two documents. The recommendations from that reconciliation exercise are set out in IEC TR 60721-4-2:2001 [30]. For the stationary random vibration condition, IEC TR 60721-4-2:2001 recommends the amplitudes of IEC 60068-2-64:1993[4] (see [31] and illustration in Figure 37). For the stationary sinusoidal vibration condition, IEC TR 60721-4-2:2001 recommends the amplitudes illustrated in Figure 39. Regarding shocks, the nearest identified severity was that of IEC 60068-2-27:1987[5], Test Ea: shock, (see [32] and illustration in Figure 41) but the recommended severity was that of IEC 60068-2-29:1987[6], Test Eb: bump (see [33] and illustration in Figure 42). Since the recommendations of IEC TR 60721-4-2:2001 were published, IEC 60068-2-29:1987 has been merged with the fourth edition of IEC 60068-2-27:2008 (Test Ea: shock). Nevertheless, for consistency with the recommendations of IEC TR 60721-4-2:2001, IEC 60068 2-29:1987 (Test Eb: bump) is referenced whenever the severities of that procedure are intended. When applicable, the duration of vibration testing and number of shock applications are quoted in the figures.

IEC 60721-3-6:1987 [13] sets out mechanical environmental severities related to electrotechnical equipment installed within ships. The applicable mechanical categories are 6M2, 6M3 and 6M4. The application of these categories to different locations within the vessel is set out in IEC 60092-101:2018, Annex A [12]. The IEC 60721-3-6:1987 sinusoidal vibration severities related to those categories are shown in Figure 43 and are those also specified in IEC 60092-101. The IEC 60721-3-6:1987 shock severities are shown in Figure 44 and appear to also be those intended for IEC 60092-101:2018, Annex A (although not clearly defined). It should be noted that the values of Figure 43 and Figure 44 are not the test severities recommended by IEC TR 60721-4-6:2001 [34]. Indeed, the vibration and shock severities recommended by IEC TR 60721-4-6:2001 seem to bear little relationship with the severities of IEC 60721-3-6:1987 or any of the data reviewed within this document.

Shown in Figure 45 are measured data from the NAV compared to the stationary vibration sinusoidal severities of IEC 60721-3-2:1997 [28]. The NAV data comprise the worst case equivalent peak spectral values for each axis of each hold, for the entirety of the measurement exercise on RMAS Arrochar. These are envelopes of all the measurement locations and conditions, for each hold. Also included are the corresponding worst case envelopes for the measurements made during an earlier excise on RMAS Kinterbury. The comparison of Figure 45 indicates that the vibration conditions measured on RMAS Arrochar are quite similar to those on RMAS Kinterbury. Also, that the measured vibration severities are significantly below the sinusoidal severities of IEC 60721-3-2:1997.

Shown in Figure 46 are measured data from the deck locations of the RIB compared to the stationary vibration random severities of IEC 60721-3-2:1997 [28]. In this case the RIB measurements are those from the high-speed sea event. These are representative of the worst vibration conditions and include all the deck locations, from which good measurements are available. It will be seen that the most severe severities exceed the 2M1 and 2M2 random severities of IEC 60721-3-2:1997 but only at specific frequencies. The measurements essentially match the 2M3 severities. However, the most severe severities are those from the rear deck of the RIB and in the vertical axis. That location is directly above the water jets and is unlikely to be used for transportation purposes, Figure 47 shows the same comparison, with the measurements from the rear deck removed. In this case the vibrations from the remaining RIB deck locations are less than the random vibration severities of IEC 60721-3-2:1997.

The vibrations conditions of the high-speed RIB are included here, because such a vessel would be anticipated to produce some of the most severe vibration conditions likely to be experienced on a marine craft. Indeed, the vibration severities are markedly greater than any other condition for marine craft considered within this document. The RIB vibration conditions,

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4 Withdrawn.

5 Withdrawn.

6 Withdrawn.

at the front of the vessel, indicate a type of environment not observed in the other marine craft considered here. Specifically, the forward floor locations show the occurrence of embedded shocks of significant amplitude. Such shocks would normally be replicated by a separate shock test. However, they could also be accommodated within a non-Gaussian vibration test or a time history replication test.

A comparison of the ship vibration measurements provided within GAM-EG-13 [5] with the stationary vibration random severities of IEC 60721-3-2:1997 [28] is shown in Figure 48. The two vessels, from which the measurements arise, are quite large. One is a naval supply tanker and the other a train ferry. Also included within the measured data is a measurement from DEF STAN 00-035 [7] made at the rear of a naval frigate. As can be seen the measured data are markedly less severe than the IEC 60721-3-2:1997 severities. It is worth observing at this point that the MIL STD 810 and DEF STAN 00-035 random vibration test severities for sea transportation encompass the amplitudes observed in the GAM-EG-13 measurements as well as the example data from DEF STAN 00-035.

The last comparison of the stationary vibration random severities of IEC 60721-3-2:1997 [28] with actual measured data is shown in Figure 49. In this case the measured severity comprises a composite made up from engine room measurements from five marine craft. The severity is purported to be from EXACT DK 1–237, as reported by the SRETS study [8]. In this case the majority of the composite severity is below the IEC 60721-3-2:1997 2M1 and 2M2 levels, although there are two minor exceedances at specific frequencies. This is not particularly surprising as the measurements are for the engine room and can be expected to comprise mostly periodic components. This particular comparison does imply that the transportation of equipment on larger ships, even when expected to produce severe vibration conditions, is still within the IEC 60721-3-2:1997 severities.

This document considered two random vibration test severities specifically related to the transportation of equipment by ship, viz. MIL STD 810 [6] and DEF STAN 00-035 [7]. These are compared with the stationary vibration random severities of IEC 60721-3-2:1997 and DEF STAN 00-035 in Figure 50. This figure indicates that the test severities specifically related to the transportation of equipment by ship are markedly lower in amplitude than the general transportation severity of IEC 60721-3-2. An observation from this comparison is that the MIL STD 810 test severity does seem to extend the amplitudes down to a particularly low frequency. This produces peak vibration displacement amplitudes of around 27 mm peak to peak. This is beyond the capability of some vibration test equipment. Whilst some of the measurements reviewed in this document do indicate the presence of some relatively low frequency responses, their amplitudes are significantly lower than implied by the MIL STD 810 test severity. The tendency to extend test amplitudes down to relatively low frequencies, without due consideration of the ability to apply them, does seem to be the feature of some standards. The frequency range and amplitude profile of the DEF STAN 00-035 severity appears to be more pragmatic with regard to the measured vibration information and the capability of test equipment.

The amplitudes of the MIL STD 810 and DEF STAN 00-035 test severities appear to be reasonable when compared to the majority of measured vibration data from transportation by ship, reviewed in this document. However, they do not encompass either the RIB measurements or the information reported to be from EXACT DK 1–237, which are typically an order of amplitude greater. This is not entirely unexpected as the former severities are engine room measurements and the latter are from a small high-speed vessel, which would be expected to generate high vibration conditions.

Some of the supplementary information considered within this document related to test severities for equipment installed within ships as well as design recommendations for tolerable vibration conditions. These were compared against each other in Figure 35. An additional comparison of these, against the stationary vibration sinusoidal severities of IEC 60721-3-2:1997 [28], is shown in Figure 51. This comparison is provided largely for information. This is because the various severities included have different objectives and purposes. The fact that some appear to be more severe than others is only relevant in so far as they relate to the purpose of the test severity. A similar comparison against the severities IEC 60721-3-6:1987 [13] and IEC 60092-101:2018 [12] is provided in Figure 52.

Comparing the severities of IEC 60721-3-2:1997 [28] and IEC 60721-3-6:1987 [13], as shown in Figure 51 and Figure 52, suggests some broad similarity of amplitudes. However, when considered over the entire test frequency range, the transportation severities of 2M2/2M3 exceed those of 6M2, which are applicable to general equipment installed in ships. This is also the case for 2M4 and 6M3, which encompasses equipment installed in the aft region of a ship. It is not clear why equipment installed within ships at non-machinery locations justifies less severe amplitudes at low frequency and a substantially truncated test frequency range. It is also worth observing that the test severities recommended in IEC TR 60721-4-6:2001 [34] are more severe than those of both IEC 60721-3-2:1997 [28] and IEC 60721-3-6:1987 [13]. Moreover, they appear to be quite arbitrary, displaying little relationship to any of the severities considered in Figure 51 and Figure 52 nor the environmental severities considered here.

9 Recommendations

The data verification process used for the IEC TR 62131 series is set out in IEC TR 62131-1. Essentially that is a three-stage process which is integrated into the format of each data review document. One of the additional criteria recommended by IEC TR 62131-1 is that each review should be based upon three separate and valid data sources. Unfortunately, it has not been possible to meet this criterion for the sea transportation dynamic environments. However, the use of the available supplementary data has provided both additional information and confidence.

There are several possible reasons for the lack of available verifiable measured vibration data. Undoubtedly the main reason is that the severity of the sea transportation vibration environment is relatively innocuous and does not usually justify a measurement exercise of the quality which would meet the verification criteria of IEC TR 62131-1. This notwithstanding, sufficient good data have been identified, to allow the vibration conditions for ship transportation to be established with reasonable confidence.

There is a general assumption that the larger the vessel, the less severe the ship vibration environment. The information reviewed for this document does appear to support that assumption, although not necessarily conclusively. The vibrations from the small high-speed vessel, considered within this document, are likely to be some of the most severe vibration severities that will be encountered on maritime vessels used for transportation of equipment. There is also a general assumption that the ship vibration environment is more severe at locations adjacent to the ship’s propulsion and power generation machinery (typically at the rear or aft locations). Again, the information reviewed for this document does appear to support that, but again not necessarily conclusively.

The measured data and other information reviewed for this document indicate that the vibration severities for the sea transportation of equipment are less than the general transportation vibration severities set out in IEC 60721-3-2:1997 [28]. Indeed, when equipment is transported by larger marine craft, the vibration severities are typically more than an order lower (in terms of acceleration power spectral densities) than the general transportation vibration severities of IEC 60721-3-2:1997. For this review, consideration of the vibration severities for the sea transportation of equipment, has been extended to encompass equipment installed in non-machinery spaces. This was to provide confidence that all potential locations, used to transport equipment, would be encompassed. Even with this expanded possibility, the vibration conditions are still less than the general transportation severities set out in IEC 60721-3-2:1997.

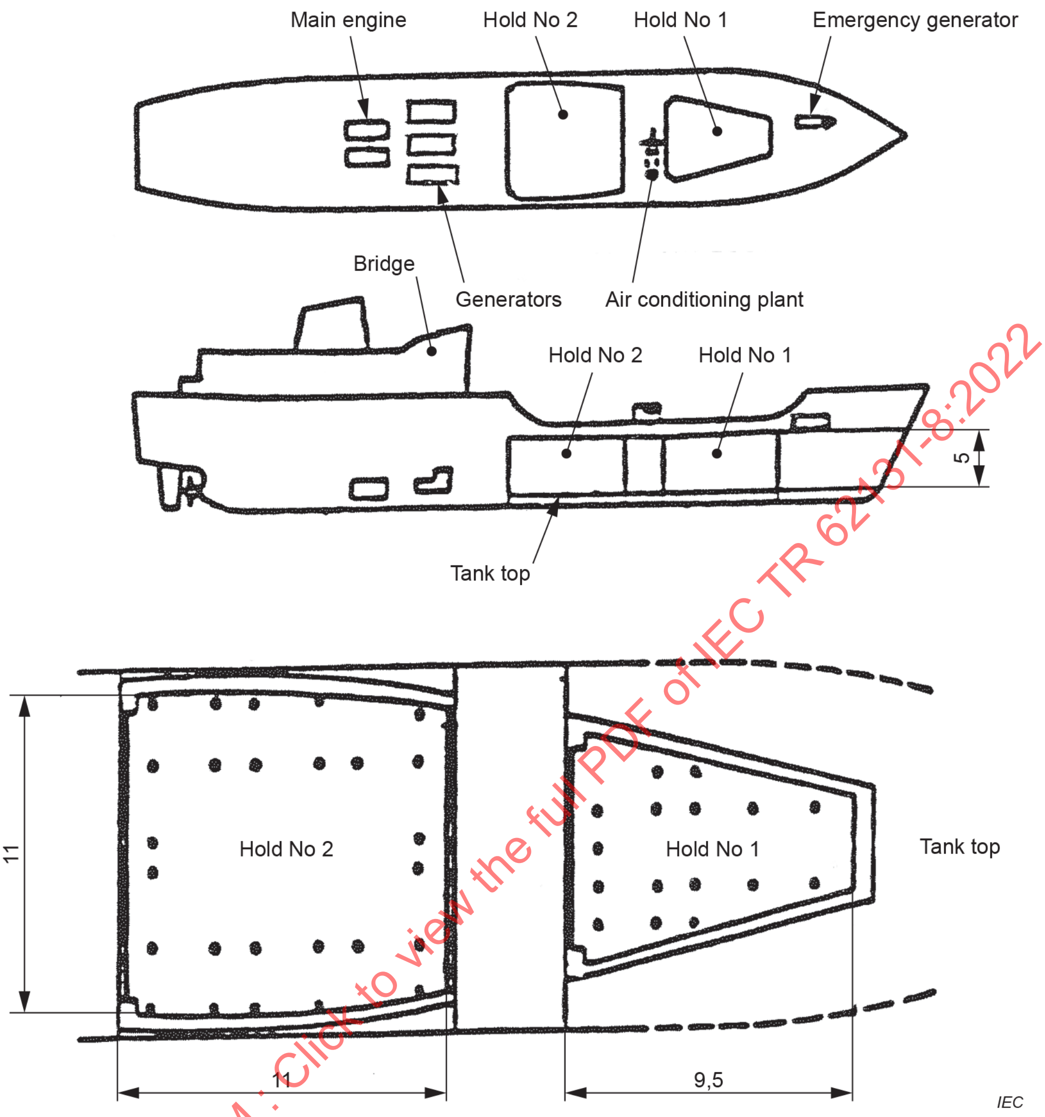
Several of the test specifications reviewed in this document have specified random vibration as the most appropriate approach when testing equipment against ship transportation. This would seem to be valid when the equipment is transported at locations away from installed machinery, hence minimizing the presence of periodic components within the vibrations.

Specifying the transportation severities as random vibration has the advantage that the ship transportation severity can be readily compared to the test severities for other forms of transportation. This has relevance because, in most cases, no test is specifically undertaken for ship transportation. Rather, the vibration environment is presumed to be adequately encompassed by other transport environments (commonly road transportation). The low vibration amplitude levels of ship transportation imply that the induced fatigue degradation will be particularly low. In such cases a modest amount of testing to encompass, say, road transportation, will potentially induce similar fatigue damage to many months of continuous sea transportation.

It is also worthy of note that the vibration severities experienced by equipment during actual ship transportation are likely to be markedly less than those arising during loading and unloading of the ship cargo as well as during handling at port facilities. Measured vibration and shock severities arising during such operations are provided in IEC TR 62131-5 [25].

Lastly, this work indicates that the severities of IEC 60721-3-6:1987 [13], as used in IEC 60092-101:2018 [12], are reasonably appropriate. However, there is some concern that the vibration test frequency range is quite limited and in practice only exercises the equipment structure. It can be argued that the low frequency range considered is that of the dominant excitations. However, some types of electrotechnical equipment (and particularly electronic items) can be particularly sensitive at higher excitation frequencies. As such the inclusion of an additional Broad band random vibration test can be prudent for such equipment.

Dimensions in metres



Key

Length	64,30 m
Breadth mid	11,90 m
Depth mid	6,10 m
Displacement	1 968 tonnes
Draught loaded	4,6 m
Main engines	2 off Mirrless Blackstone Type ESL 12MGR 12-cylinder diesel rated at 1 120 kw (1 500 bhp) at 924 r/min.
Propeller	Single, 4-bladed fixed pitch
Gearbox	Reduction 5,55:1
Main generators	3 off – 1 200 r/min, Engine: Paxman Type RPH CZ Mk11, 6 cylinders
Engine generator	1 off – 1 200 r/min, Engine: Doorman Type 8JTZ, 8 cylinders

Figure 1 – RMAS Arrochar specification and layout [3]

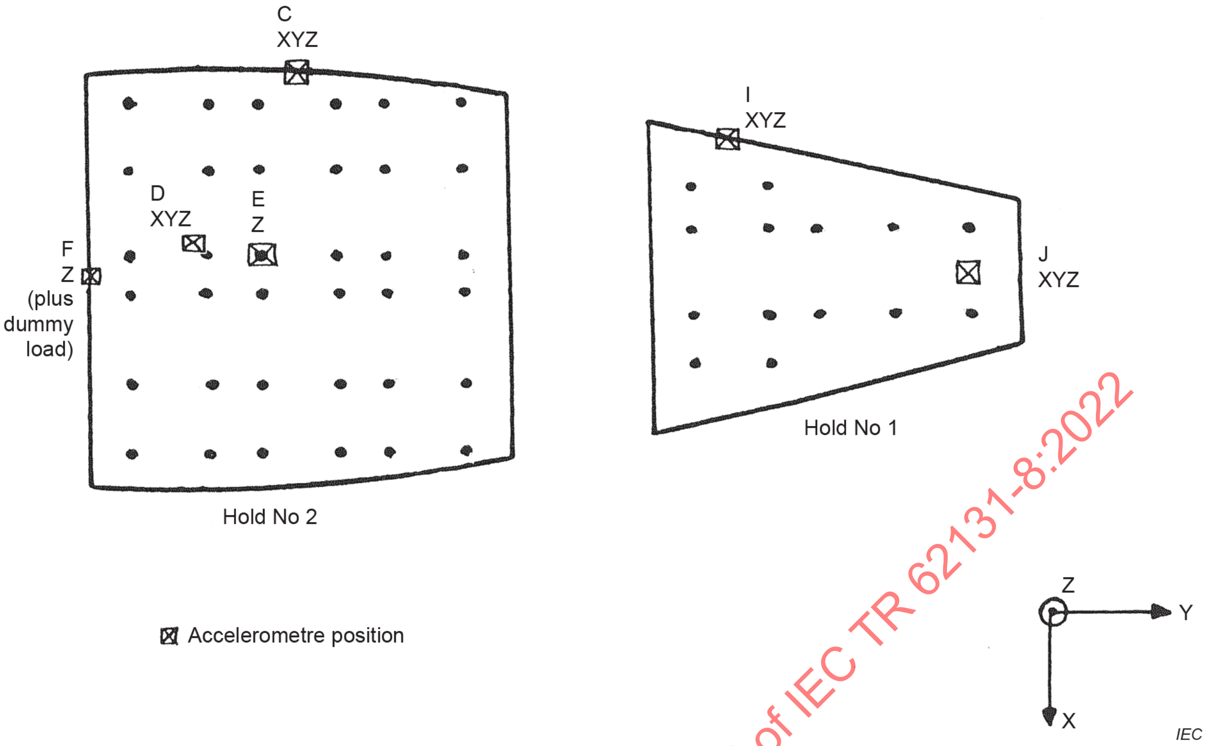


Figure 2 – RMAS Arrochar hold vibration measurement locations [3]

Table 1 – RMAS Arrochar hold low frequency (up to 10 Hz) accelerations levels [3]

RMAS Arrochar – Peak acceleration levels – Up to 10 Hz (g)									
Sea state	**Vertical**			**Lateral**			**Longitudinal**		
	Negative	**Positive**	**Max pk to pk**	**Negative**	**Positive**	**Max pk to pk**	**Negative**	**Positive**	**Max pk to pk**
Forward hold									
0	0,16	0,17	0,33	0,05	0,06	0,11	0,01	0,02	0,02
1	0,05	0,08	0,13	0,05	0,05	0,10	0,01	0,01	0,02
2 to 3	0,23	0,17	0,41	0,09	0,13	0,22	0,01	0,01	0,02
4	0,36	0,43	0,79	0,22	0,22	0,44	0,02	0,03	0,05
Aft hold									
0	0,01	0,08	0,19	0,06	0,06	0,12	0,01	0,02	0,03
1	0,04	0,07	0,10	0,04	0,06	0,10	0,01	0,01	0,02
2 to 3	0,02	0,01	0,03	0,13	0,09	0,22	0,01	0,01	0,02
4	0,25	0,25	0,50	0,25	0,17	0,43	0,02	0,04	0,06

Table 2 – RMAS Arrochar hold vibration levels for different sea states [3]

Sea state	**Forward hold**			**Aft hold**		
	Vibration acceleration root mean square values (g)					
	Vertical	Fore/Aft	Lateral	Vertical	Fore/Aft	Lateral
0	0,036	0,012	0,003	0,021	0,010	0,004
1	0,020	0,019	0,003	0,020	0,019	0,003
2,5	0,062	0,070	0,007	0,057	0,067	0,008
4	0,098	0,076	0,007	0,075	0,076	0,008
4,5	0,145	0,022	0,011	0,083	0,025	0,012
5,5	0,152	0,036	0,012	0,094	0,030	0,012
Sea state	Vibration acceleration peak-to-peak values (g)					
	Vertical	Fore/Aft	Lateral axis	Vertical	Fore/Aft	Lateral
0	0,333	0,114	0,025	0,189	0,121	0,028
1	0,127	0,104	0,011	0,104	0,100	0,014
2,5	0,407	0,223	0,024	0,262	0,219	0,026
4	0,789	0,438	0,048	0,493	0,426	0,058
4,5	0,936	0,220	0,071	0,563	0,181	0,079
5,5	0,901	0,219	0,068	0,569	0,180	0,067

Table 3 – Definition of sea states

Douglas sea scale (wind sea)		
Sea state	**Wave height (m)**	**Description**
0	no wave	Calm (glassy)
1	0 to 0,10	Calm (rippled)
2	0,10 to 0,50	Smooth
3	0,50 to 1,25	Slight
4	1,25 to 2,50	Moderate
5	2,50 to 4,00	Rough
6	4,00 to 6,00	Very rough
7	6,00 to 9,00	High
8	9,00 to 14,00	Very high
9	> 14,00	Phenomenal

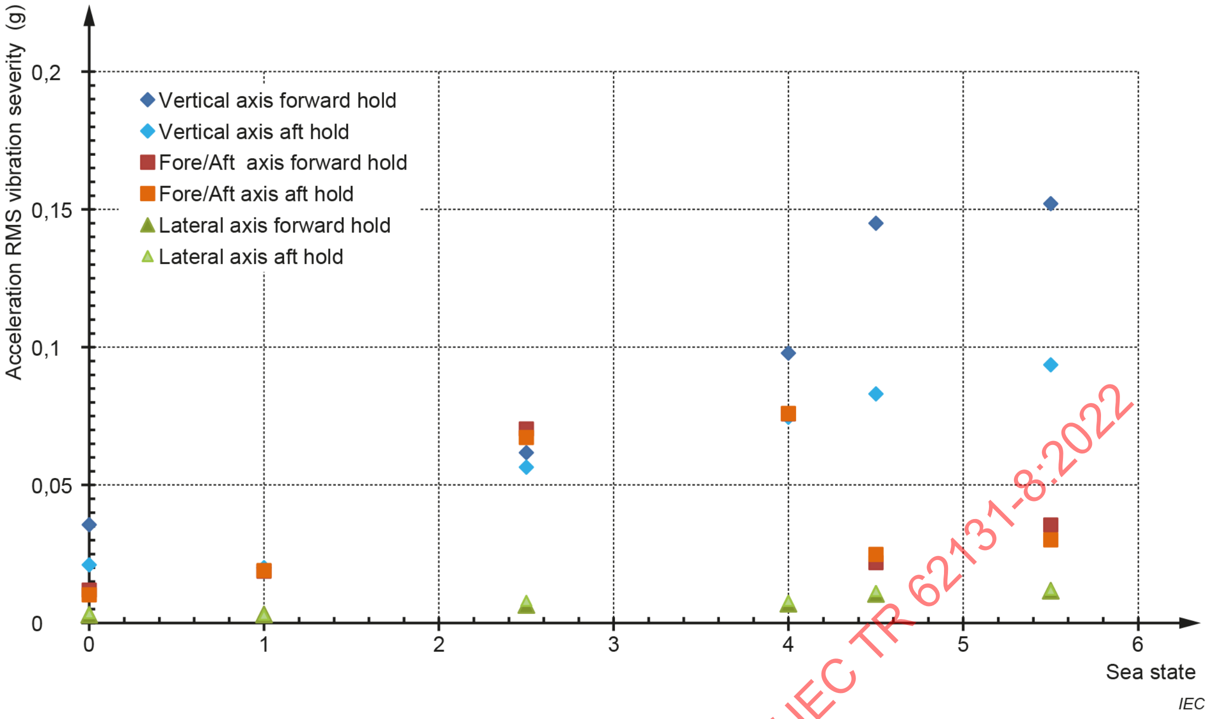


Figure 3 – RMAS Arrochar hold vibration levels for different sea states [3]

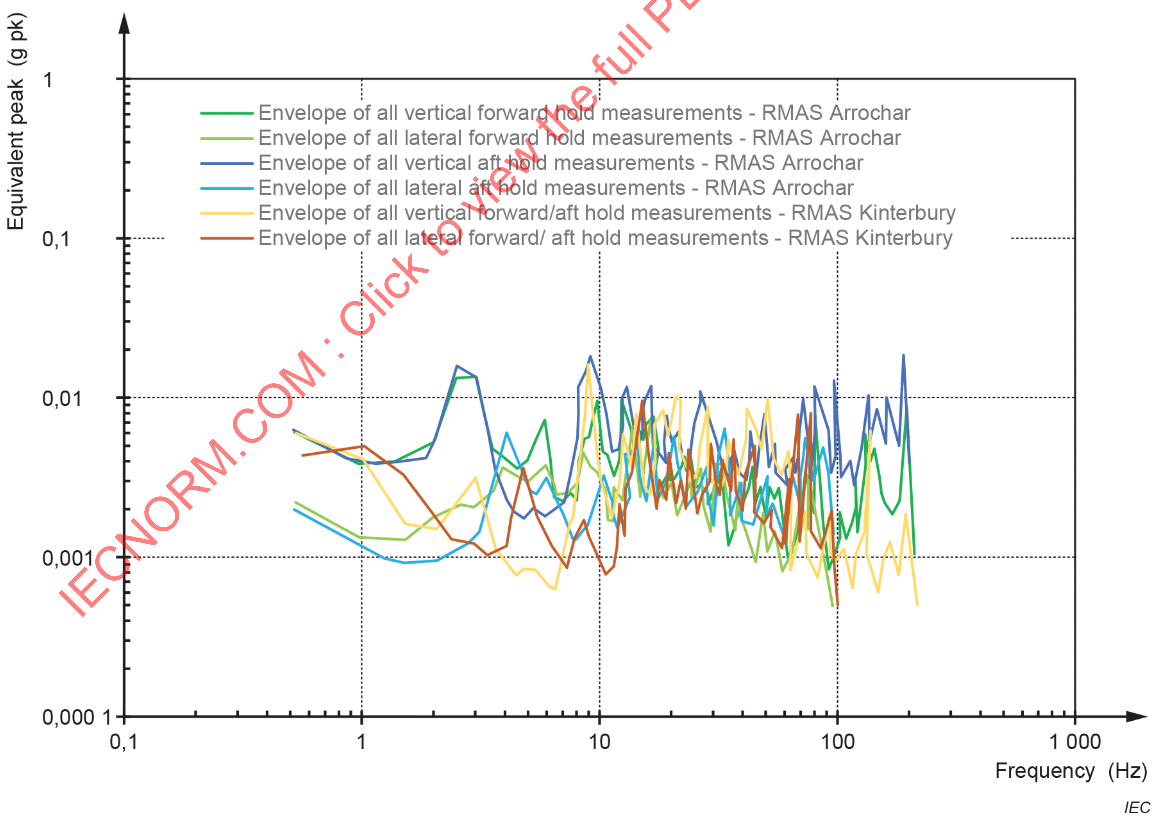


Figure 4 – Envelope of vibration levels in forward and aft holds [3]

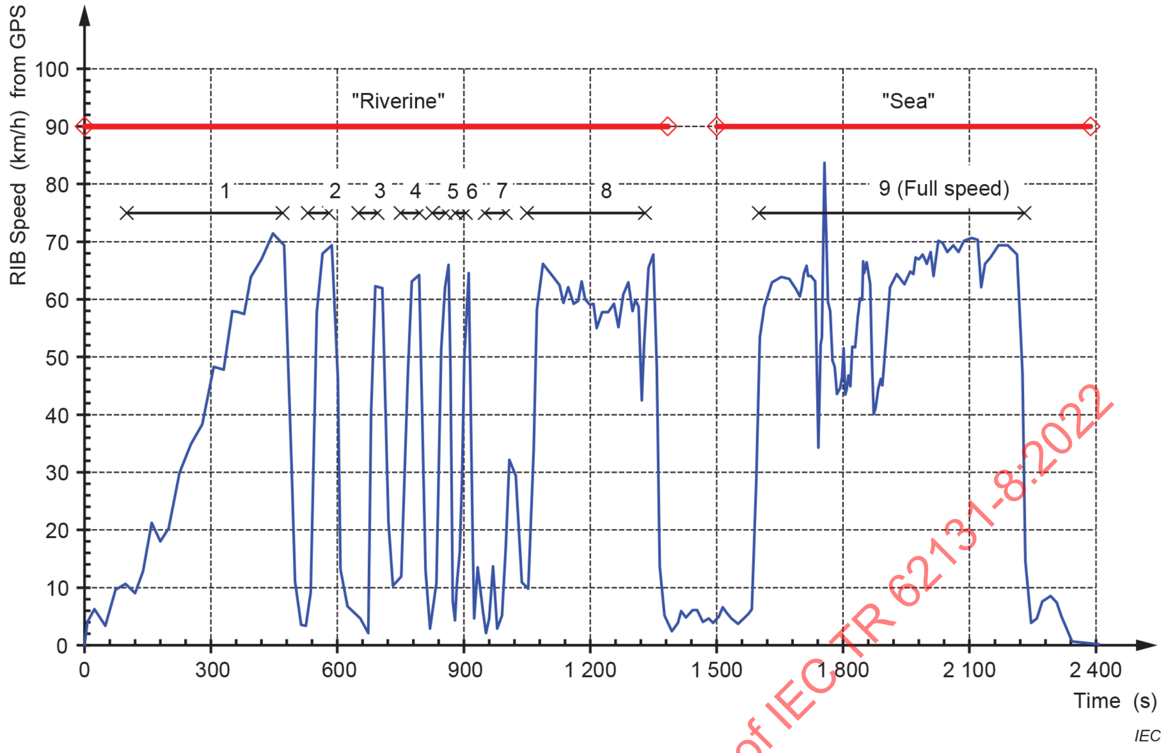


Figure 5 – RIB speed from GPS obtained during measurement events [4]

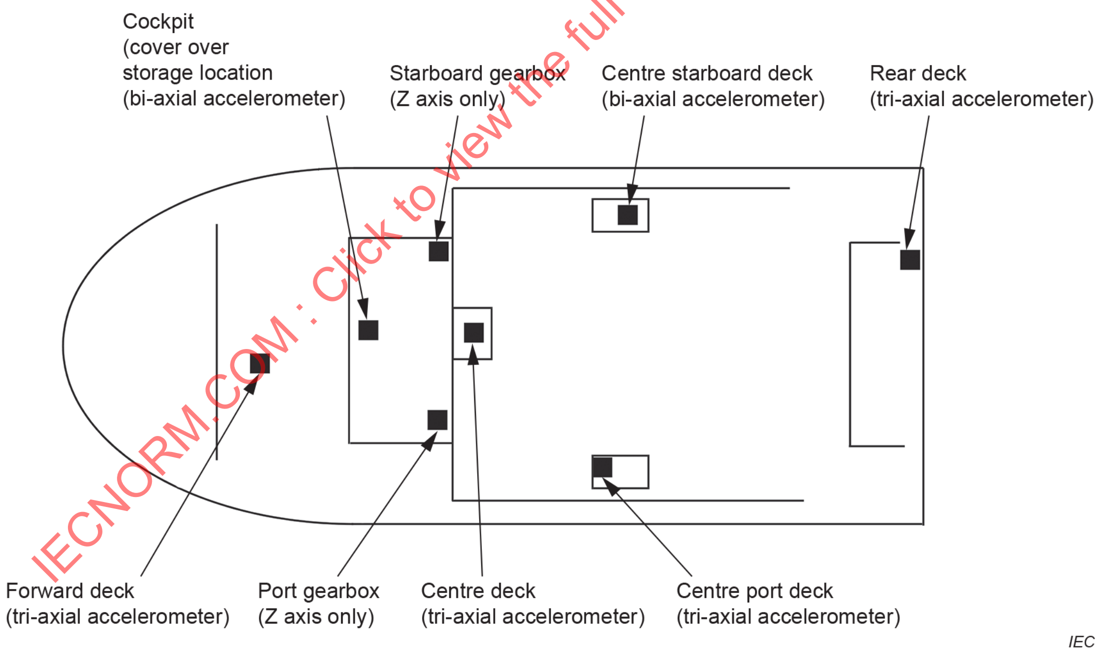


Figure 6 – RIB transducer locations [4]

Table 4 – RIB measurement events [4]

Condition	Event	Record period s	Total duration of record s	Event description
Riverine	All	0 to 1 384	1 384	Full riverine record
Riverine	Event 1	100 to 470	370	Step up in speed to full speed
Riverine	Event 2	530 to 580	40	Reverse
Riverine	Event 3	650 to 695	45	Accelerate on throttle
Riverine	Event 4	750 to 795	45	Accelerate on buckets
Riverine	Event 5	825 to 857	32	Emergency stop
Riverine	Event 6	880 to 905	75	Port turn
Riverine	Event 7	950 to 1 000	50	Starboard turn
Riverine	Event 8	1 050 to 1 330	280	High speed transit
Sea	All	1 500 to 2 387	887	Full sea record
Sea	Event 1	1 600 to 2 230	630	Full speed period

Table 5 – RIB statistics of vibration measurements from sea segment [4]

Measurement location	Axis	Sea maximum speed (Sea event 1)		
		Maximum (g)	Minimum (g)	RMS (g) (1,5 Hz to 3 200 Hz)
Forward deck	X	6,3	−7,8	0,19
	Y	-	-	-
	Z	29,1	−23,8	0,64
Cockpit	Z	13,7	−4,9	0,25
	Y	7,9	−2,0	0,52
Port deck	X	-	-	-
	Y	12,3	−8,5	0,18
	Z	16,1	−8,4	0,26
Centre deck	X	8,7	−6,4	0,24
	Y	6,4	−4,8	0,22
	Z	21,8	−14,0	0,41
Rear deck	X	3,6	−3,4	0,46
	Z	12,3	−9,9	1,73

Table 6 – RIB statistics of vibration measurements riverine events – RMS [4]

Measurement location	Axis	Root mean square (1,5 Hz to 3 200 Hz) values (g)							
		Event 1	Event 2	Event 3	Event 4	Event 5	Event 6	Event 7	Event 8
Forward deck	X	0,14	0,20	0,19	0,20	0,18	0,19	0,16	0,20
	Y	0,17	0,22	0,20	0,22	0,22	0,22	0,13	-
	Z	0,28	0,40	0,34	0,50	0,40	0,41	0,20	0,79
Cockpit	Z	0,28	0,28	0,27	0,28	0,28	0,27	0,20	0,27
	Y	0,39	0,41	0,39	0,47	0,41	0,39	0,29	0,62
Port deck	X	0,17	0,26	0,25	0,25	0,24	0,23	0,20	-
	Y	0,16	0,20	0,20	0,19	0,19	0,18	0,12	0,21
	Z	0,21	0,31	0,31	0,30	0,28	0,27	0,19	0,27
Centre deck	X	0,19	0,27	0,28	0,27	0,26	0,26	0,17	0,24
	Y	0,17	0,25	0,26	0,26	0,26	0,25	0,24	0,22
	Z	0,34	0,38	0,37	0,37	0,34	0,34	0,23	0,48
Rear deck	X	0,78	1,14	0,92	0,91	0,73	0,76	0,37	0,62
	Z	1,54	2,40	1,84	1,94	1,69	1,83	0,73	1,73

Table 7 – RIB statistics of vibration measurements riverine events – Maximum and minimum [4]

Measurement location	Axis	Maximum and minimum values (g)							
		Event 1		Event 2		Event 3		Event 4	
Forward deck	X	0,9	−1,1	0,9	−0,9	0,9	−1,0	2,4	−1,6
	Y	1,1	−0,9	0,9	−0,9	0,8	−0,8	1,6	−1,6
	Z	2,1	−2,0	1,8	−2,0	1,6	−1,7	5,3	−4,6
Cockpit	Z	0,8	−1,2	0,8	−1,1	0,8	−1,1	0,8	−1,4
	Y	2,0	−1,7	1,7	−1,8	1,9	−1,4	2,8	−1,8
Port deck	X	1,2	−1,2	1,2	−1,2	1,3	−1,2	1,3	−1,1
	Y	0,7	-0,9	0,7	−1,0	0,7	−0,9	0,7	−1,0
	Z	1,5	−1,5	1,4	−1,5	1,4	−1,5	1,5	−1,4
Centre deck	X	1,2	−1,4	1,2	−1,5	1,2	−1,5	1,6	−2,0
	Y	1,2	−1,3	1,2	−1,2	1,4	−1,3	1,7	−1,9
	Z	1,4	-1,9	1,2	-1,7	1,2	-1,5	5,1	−7,3
Rear deck	X	7,3	−5,3	5,9	−5,4	5,9	−4,8	6,5	−4,5
	Z	12,0	−11,5	13,1	−11,8	10,8	−10,0	9,5	−9,6
		Event 5		Event 6		Event 7		Event 8	
Forward deck	X	1,8	−2,3	2,0	−1,6	0,8	−0,8	5,1	−7,9
	Y	1,6	−1,7	6,0	−1,6	0,5	−0,6	-	-
	Z	6,0	−4,8	5,0	−4,0	1,0	−1,0	23,9	−18,4
Cockpit	Z	1,0	−1,3	1,0	−1,2	0,3	−0,7	9,9	−5,0
	Y	2,0	−1,8	1,9	−1,9	1,2	−1,1	8,8	−2,0
Port deck	X	1,2	−1,2	1,3	−1,3	0,9	−0,9	-	-
	Y	0,8	−0,9	0,8	−0,9	0,3	−0,5	20,3	−2,8
	Z	1,4	−1,2	1,3	−1,3	1,3	−0,8	4,6	−4,4
Centre deck	X	1,2	−1,3	1,1	−1,4	0,9	−1,0	2,5	−4,1

Measurement location	Axis	Maximum and minimum values (g)							
		Event 1		Event 2		Event 3		Event 4	
	Y	1,4	−1,3	1,4	−1,2	1,1	−1,0	4,0	−2,6
	Z	1,2	−1,6	1,6	−1,6	0,5	−0,9	13,0	−4,6
Rear deck	X	4,3	−4,4	5,0	−4,3	1,7	−1,6	3,8	−4,9
	Z	8,8	−10,0	11,2	−8,7	4,0	−3,7	10,4	−10,6

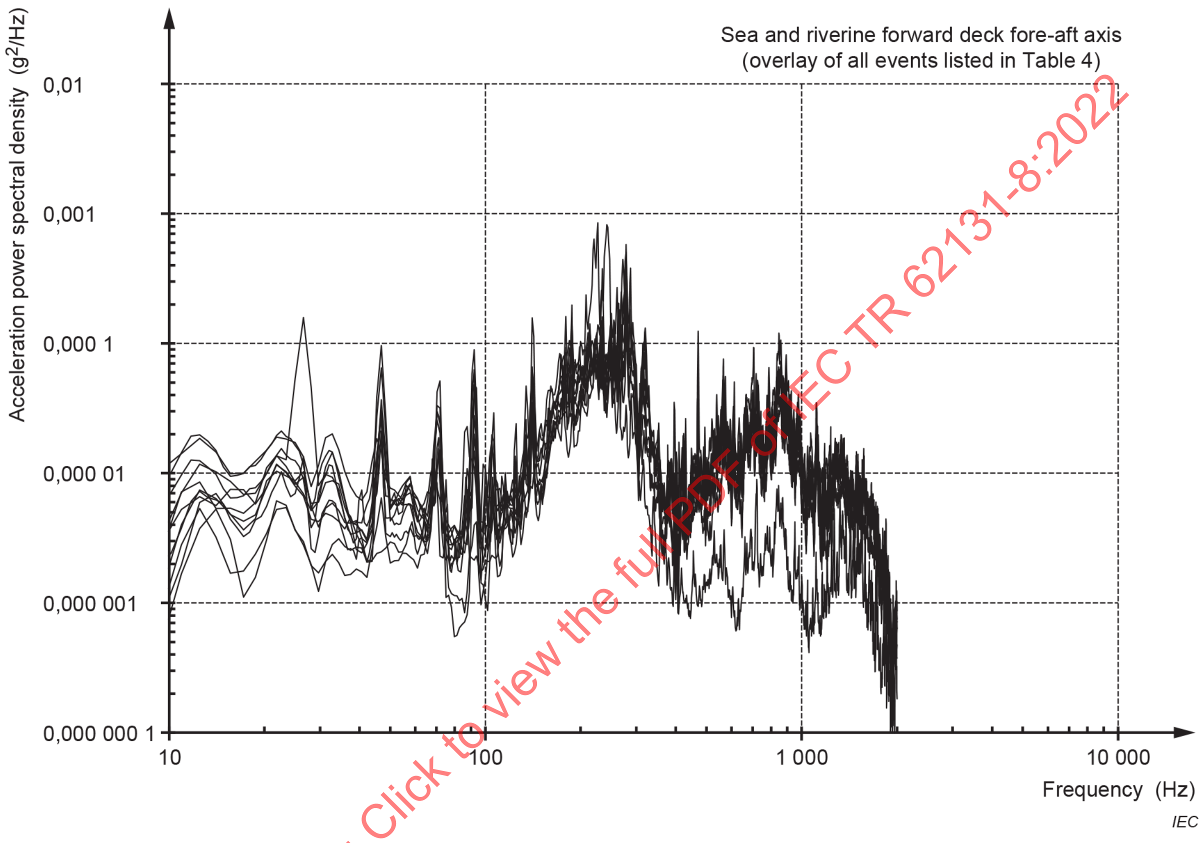


Figure 7 – RIB vibration severities forward deck – Fore-aft [4]

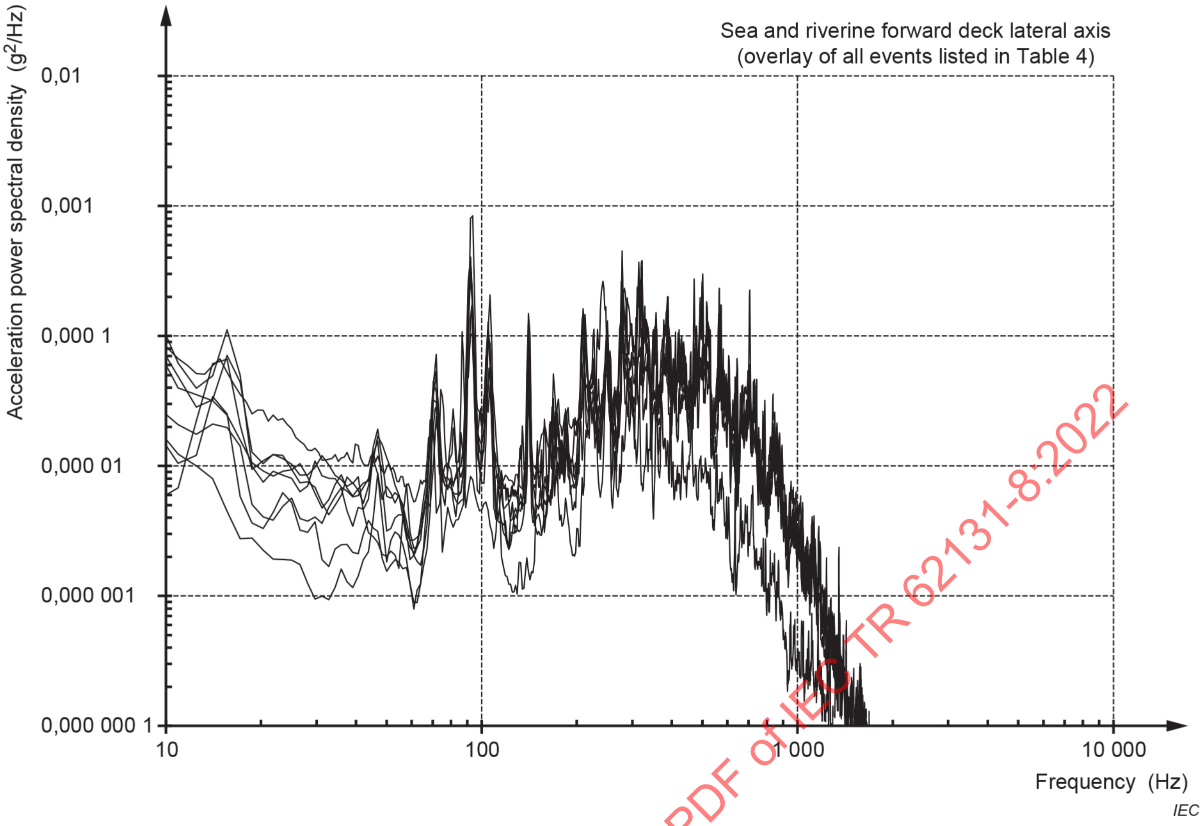


Figure 8 – RIB vibration severities forward deck – Lateral [4]

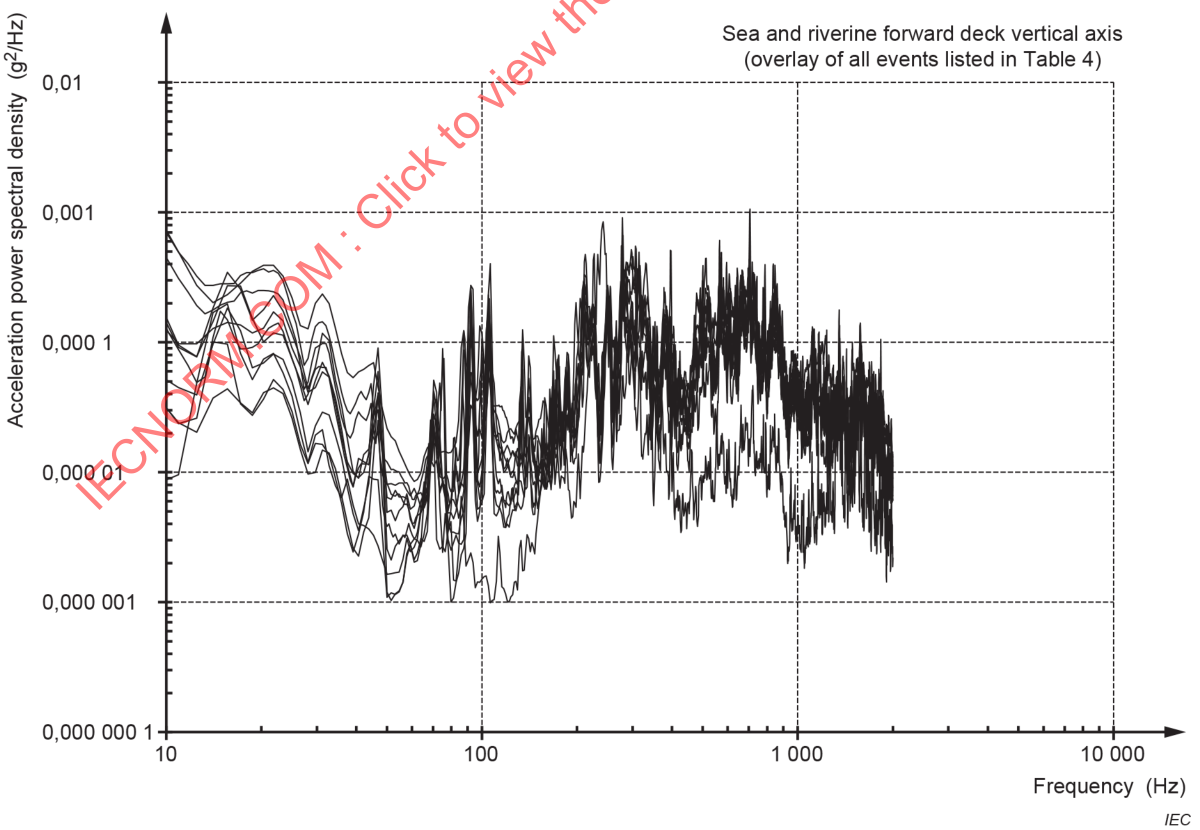


Figure 9 – RIB vibration severities forward deck – Vertical [4]

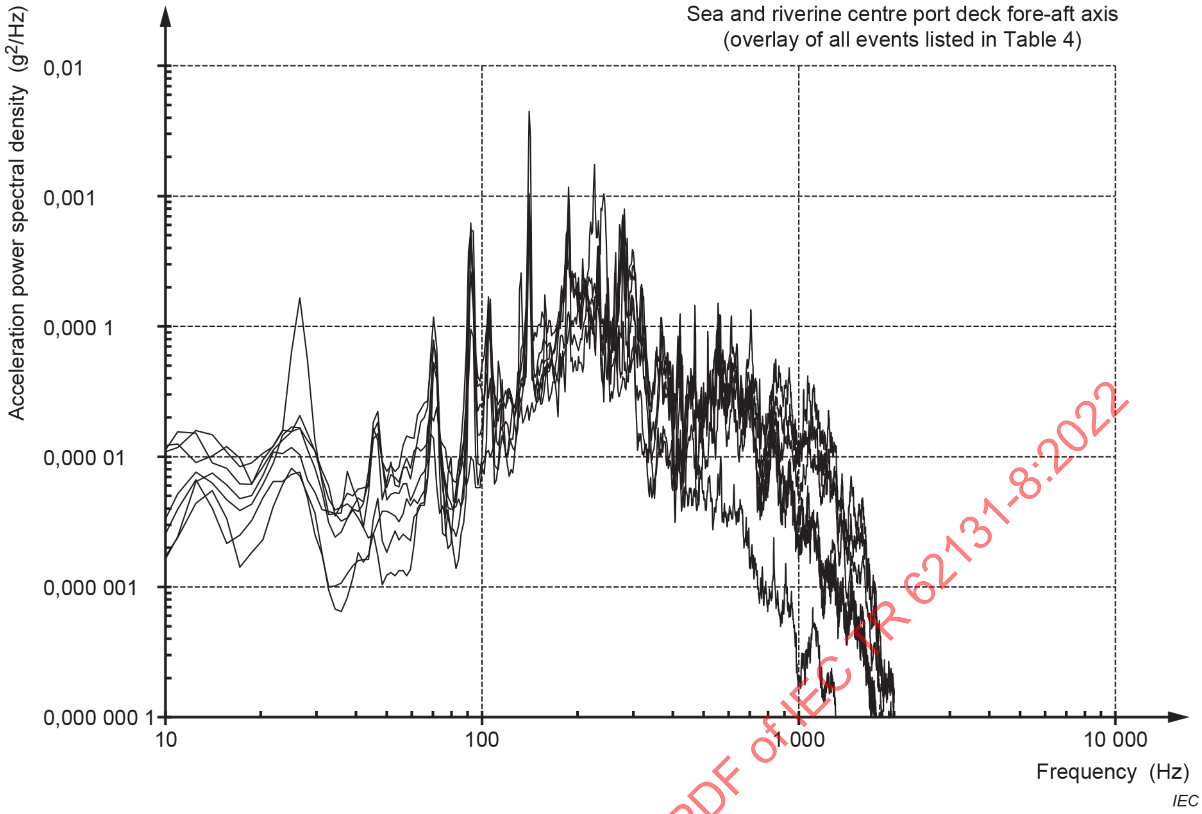


Figure 10 – RIB vibration severities centre port deck – Fore-aft [4]

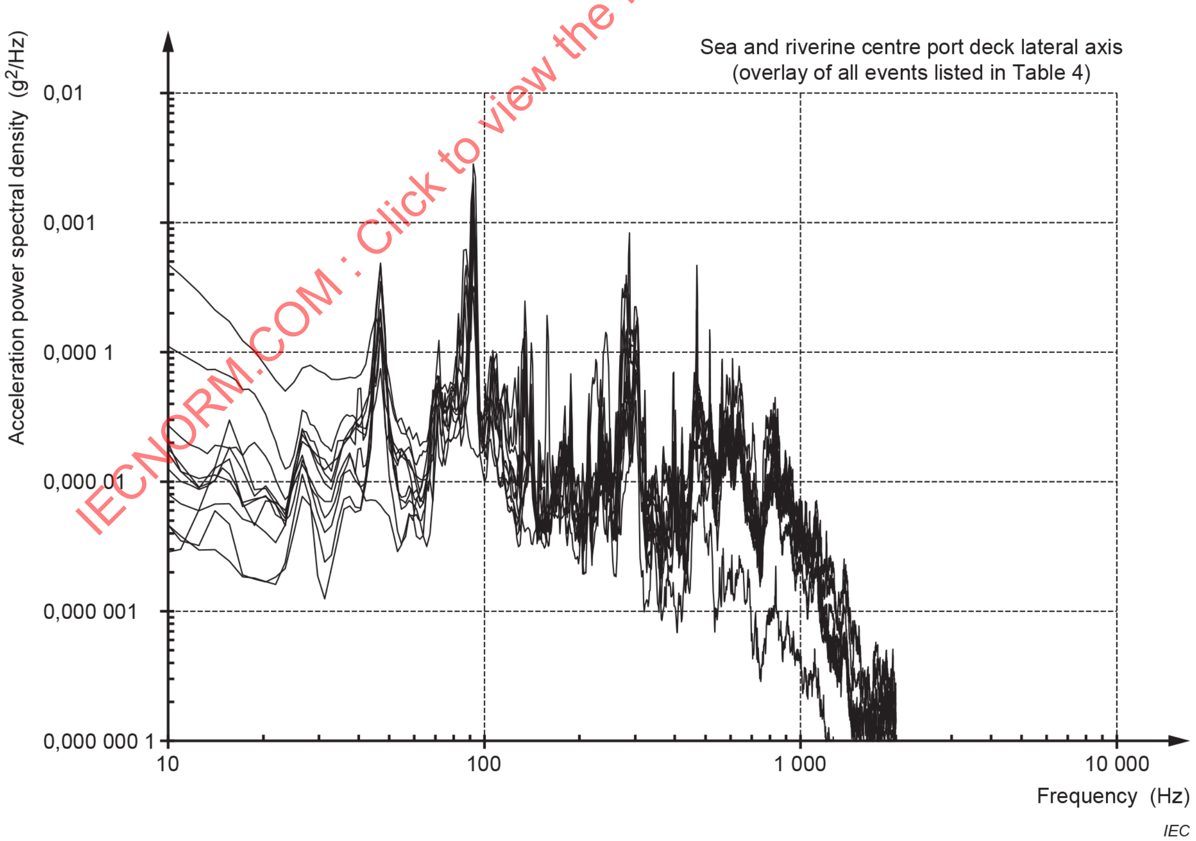


Figure 11 – RIB vibration severities centre port deck – Lateral [4]

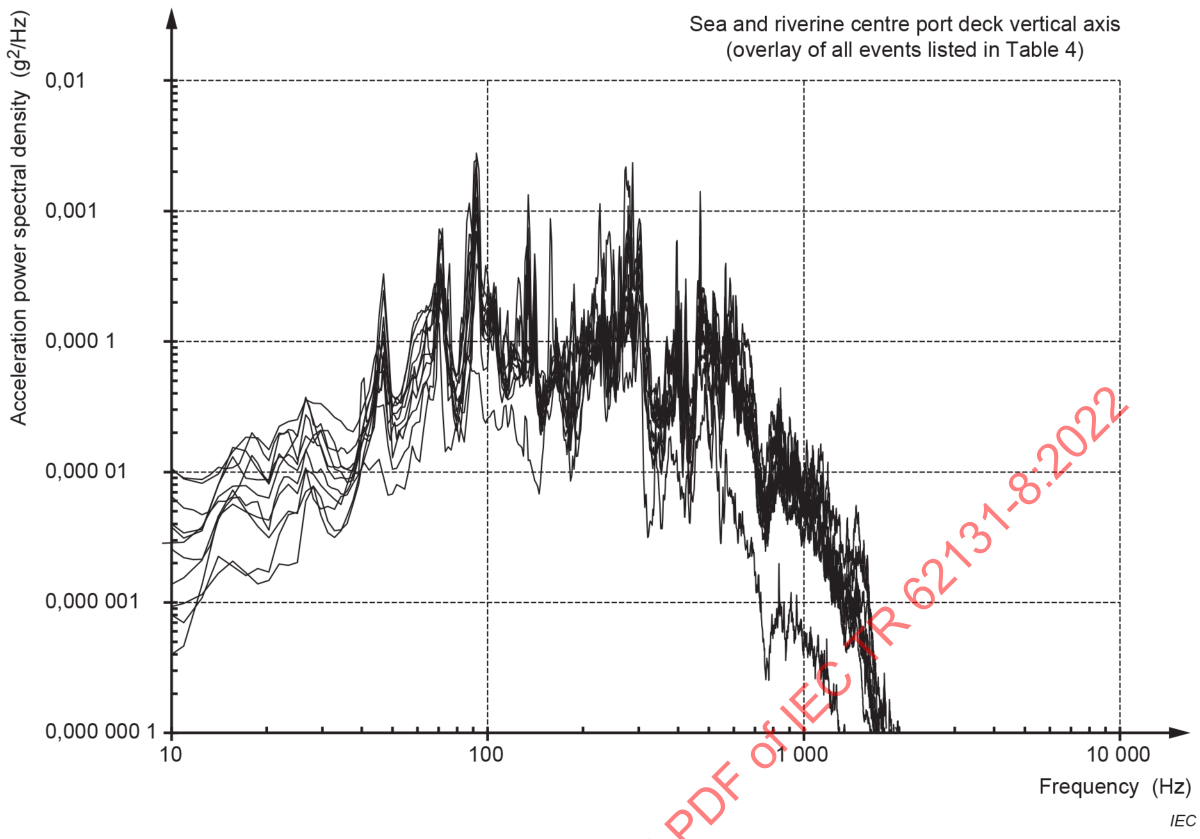


Figure 12 – RIB vibration severities centre port deck – Vertical [4]

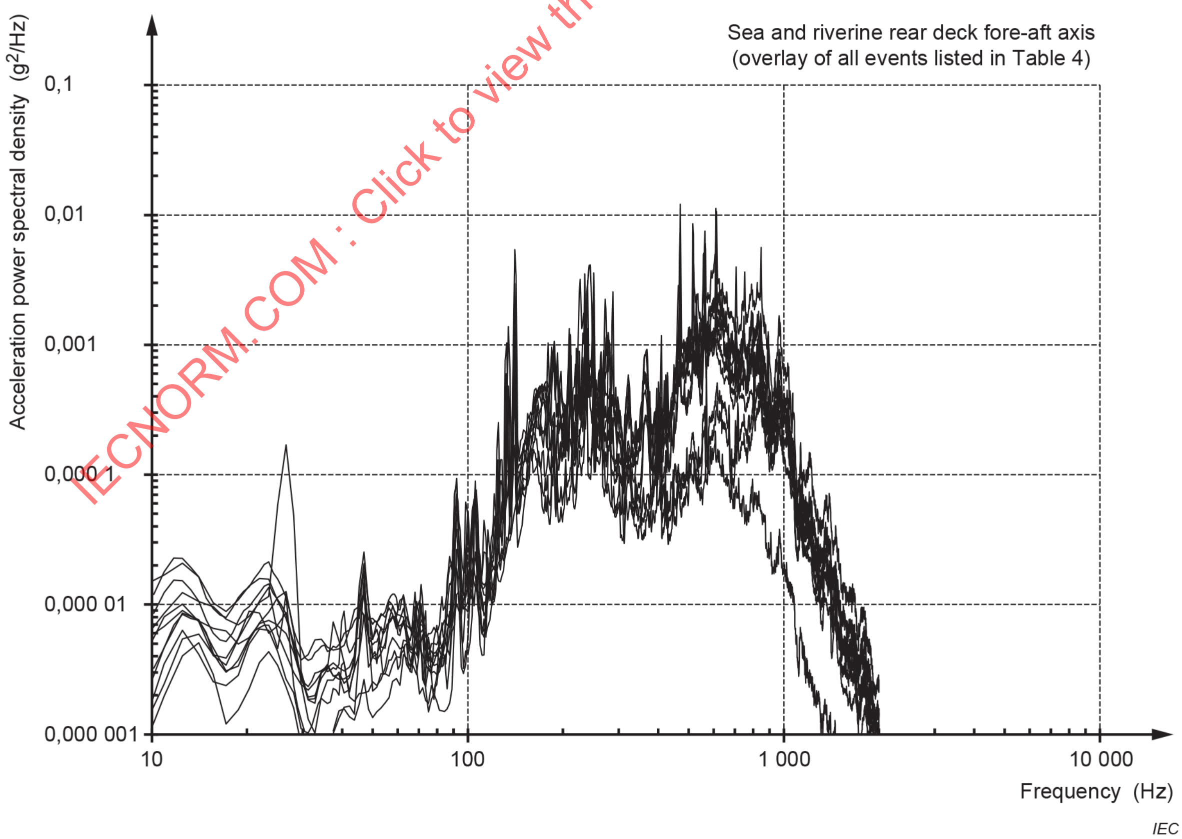


Figure 13 – RIB vibration severities rear deck – Fore-aft [4]

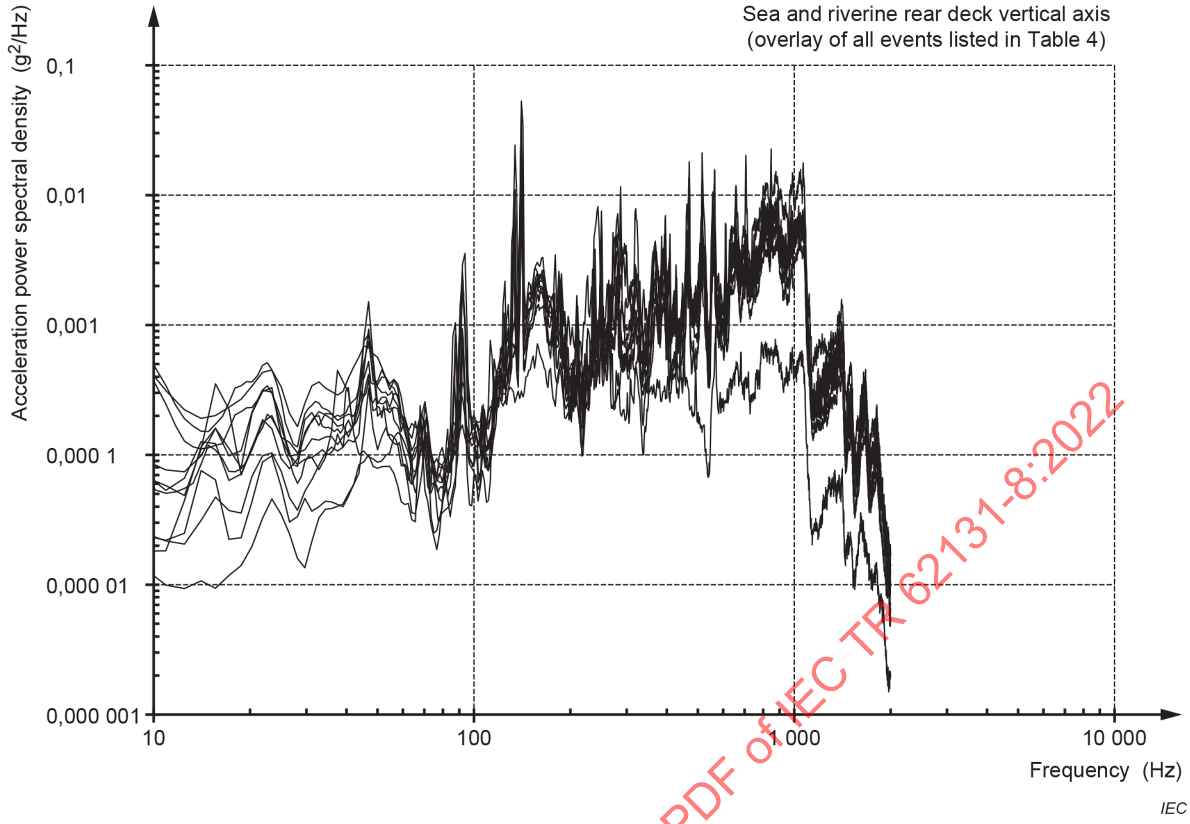


Figure 14 – RIB vibration severities rear deck – Vertical [4]

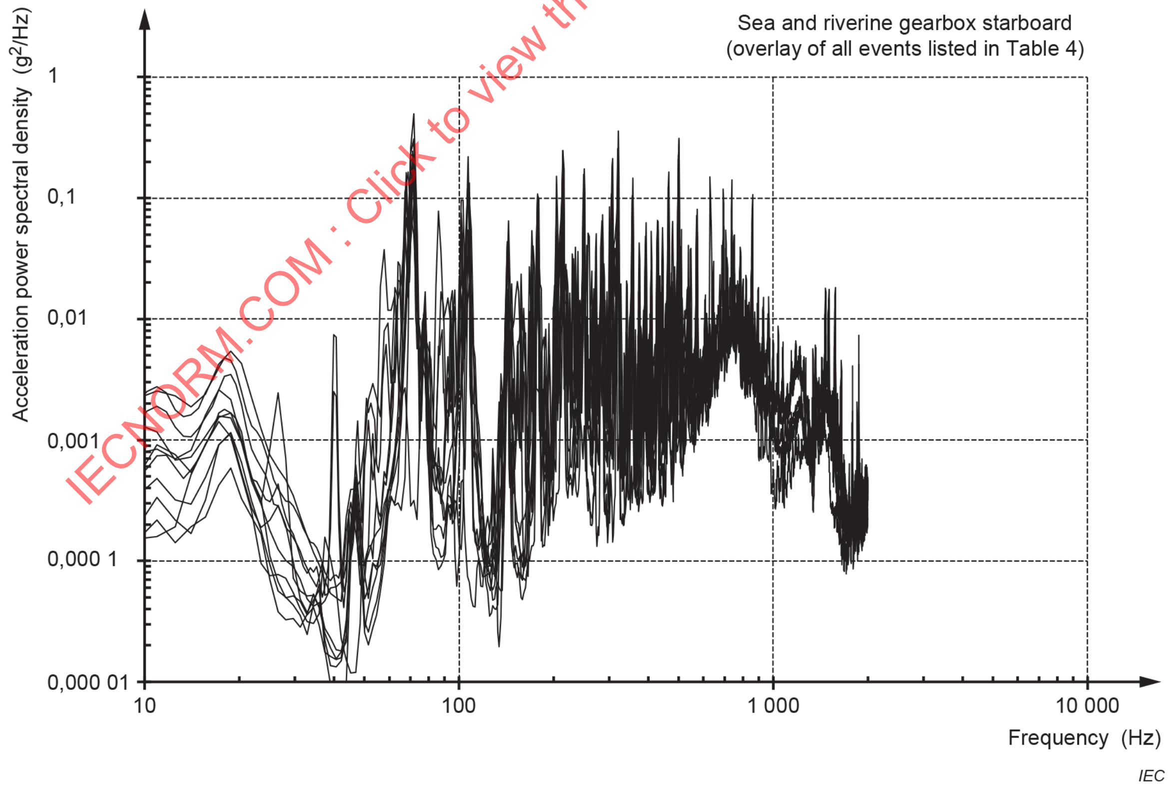


Figure 15 – RIB vibration severities starboard gearbox [4]

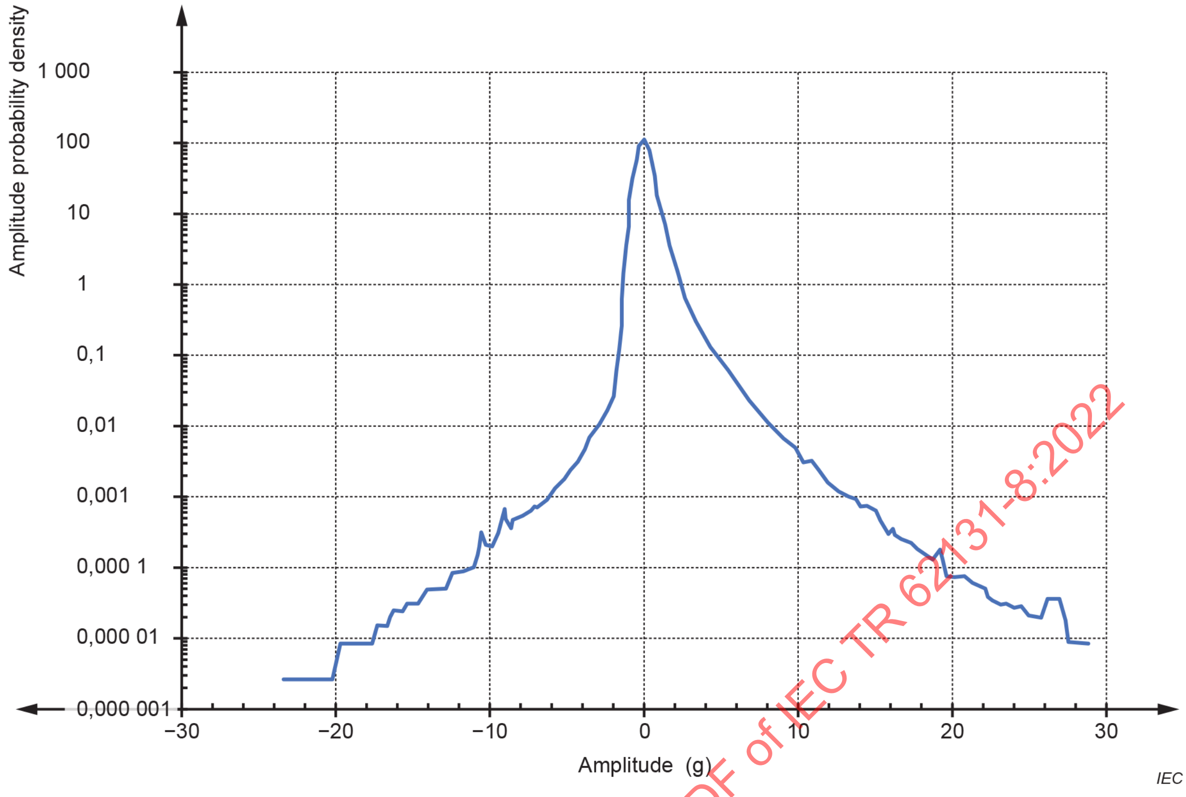


Figure 16 – RIB vibration amplitude probability density – Forward deck [4]

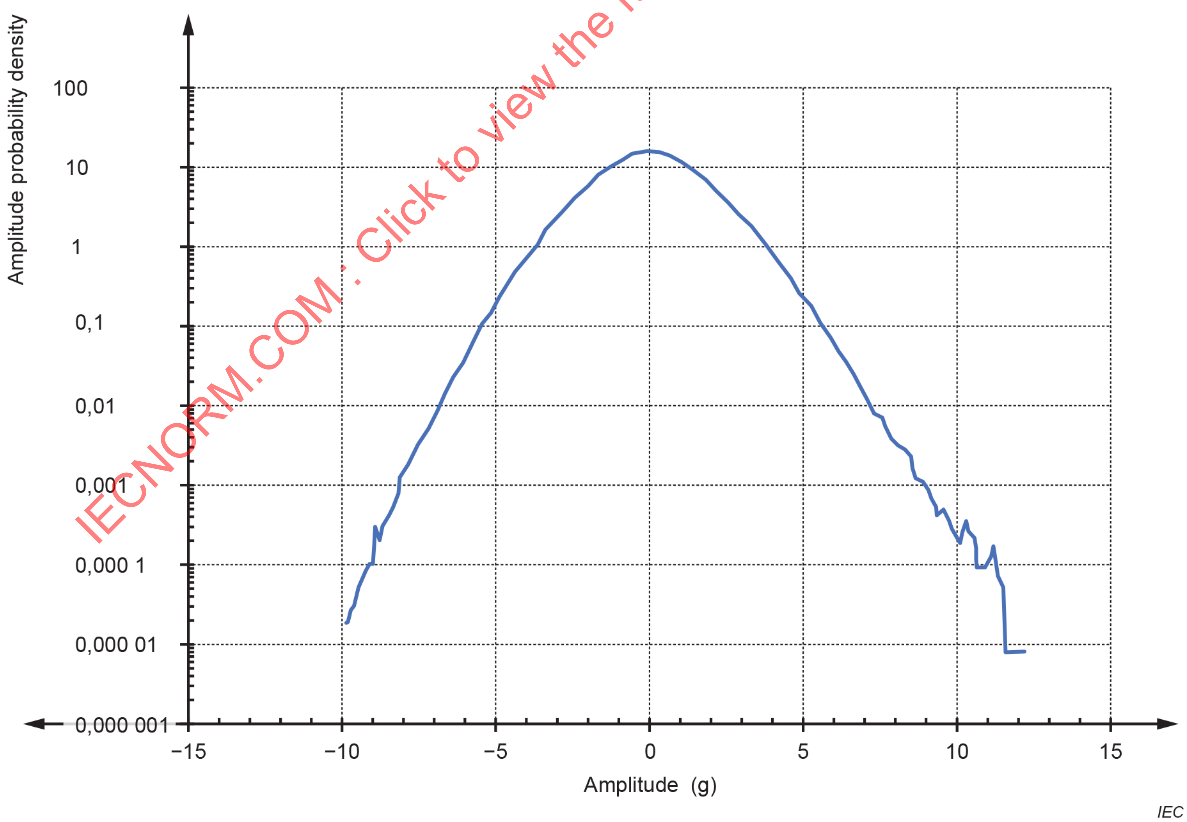


Figure 17 – Vibration RIB amplitude probability density – Aft (rear deck) deck [4]

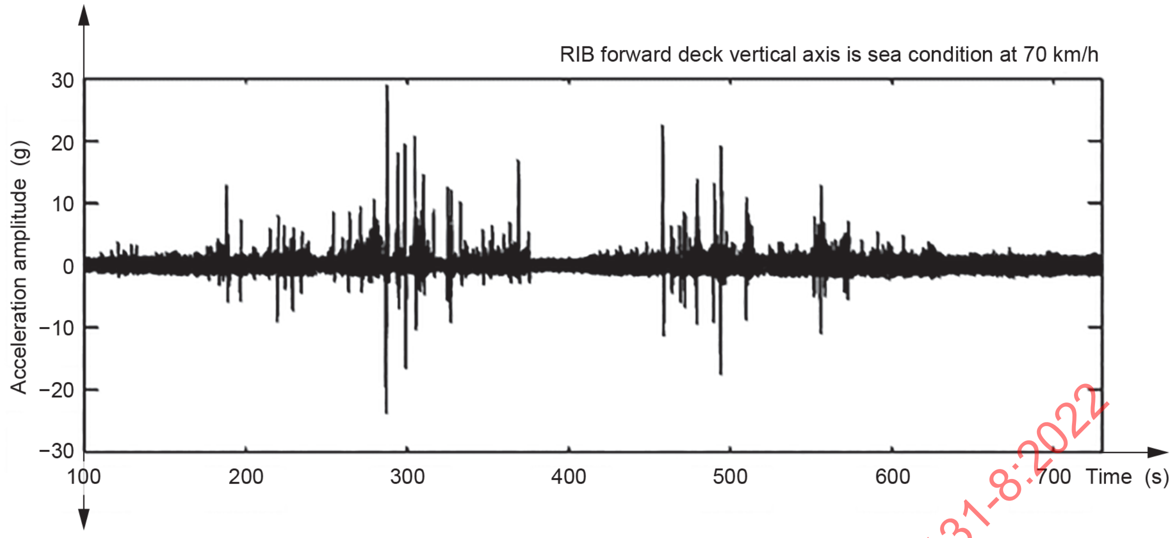


Figure 18 – RIB vibration time history – Forward deck [4]

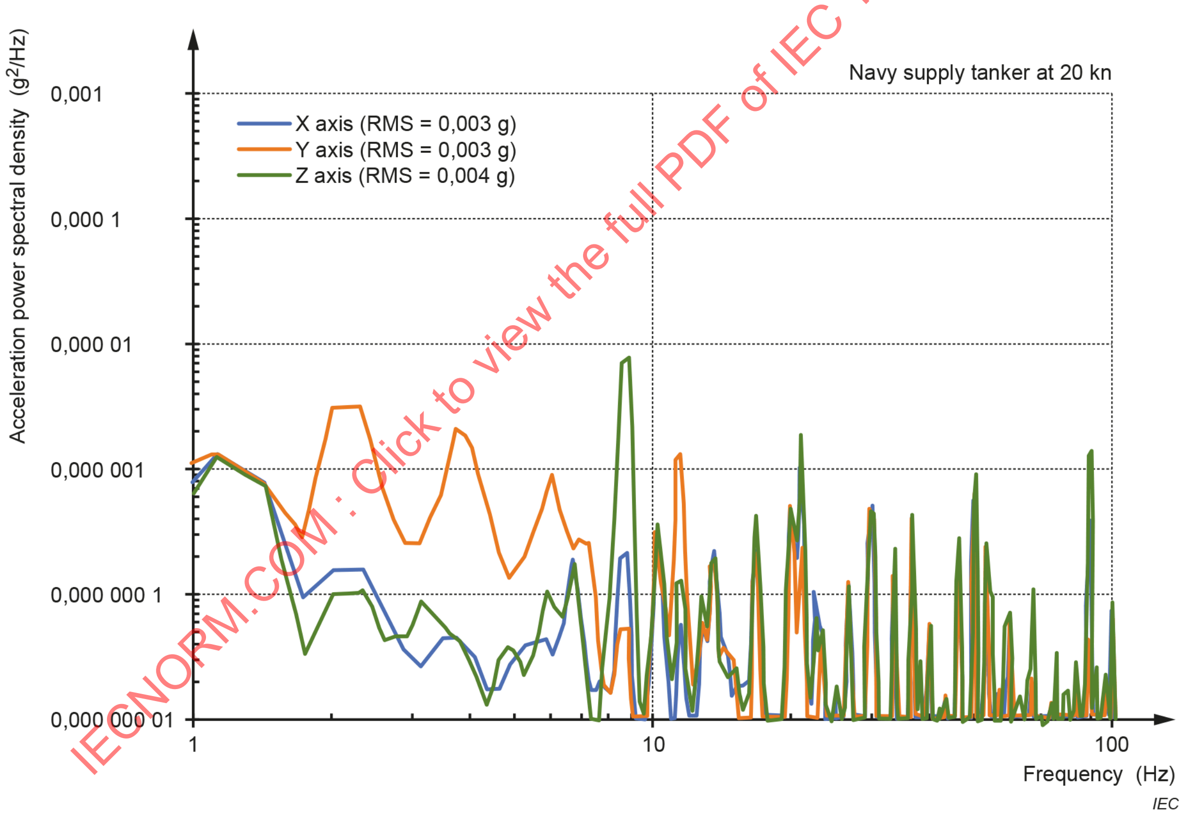


Figure 19 – Naval supply tanker at 20 kn [5]

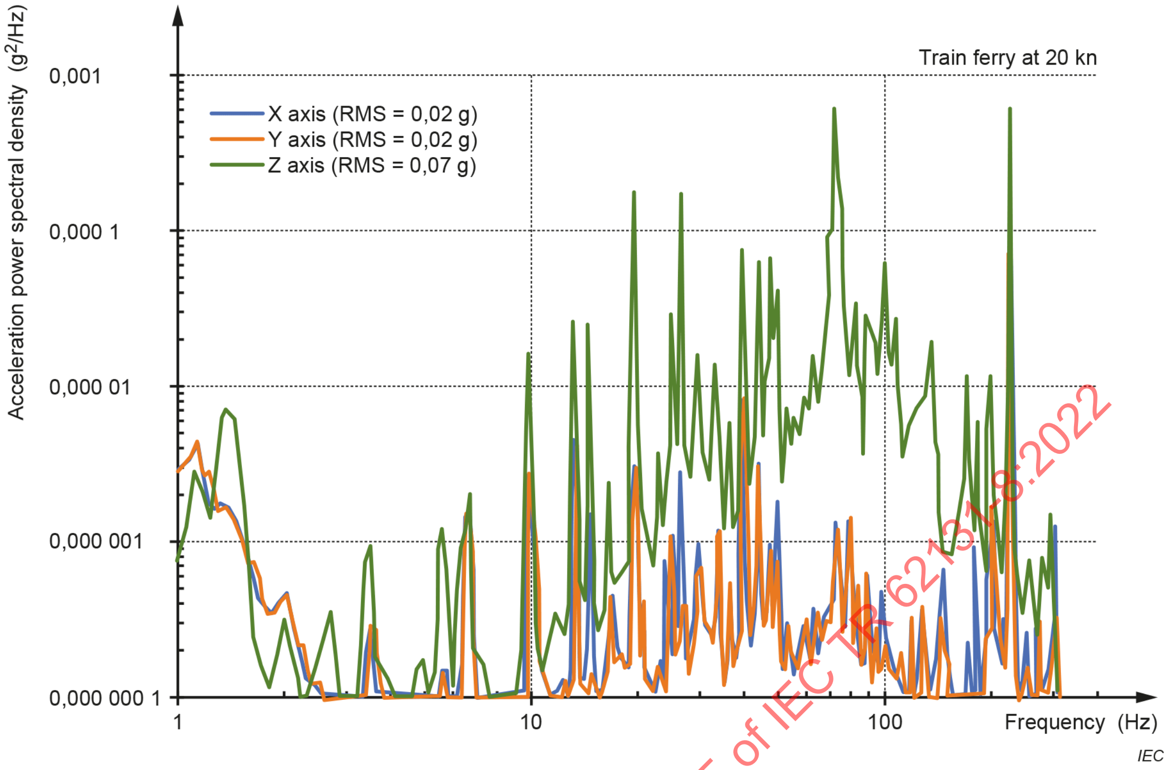


Figure 20 – Train ferry at 20 kn [5]

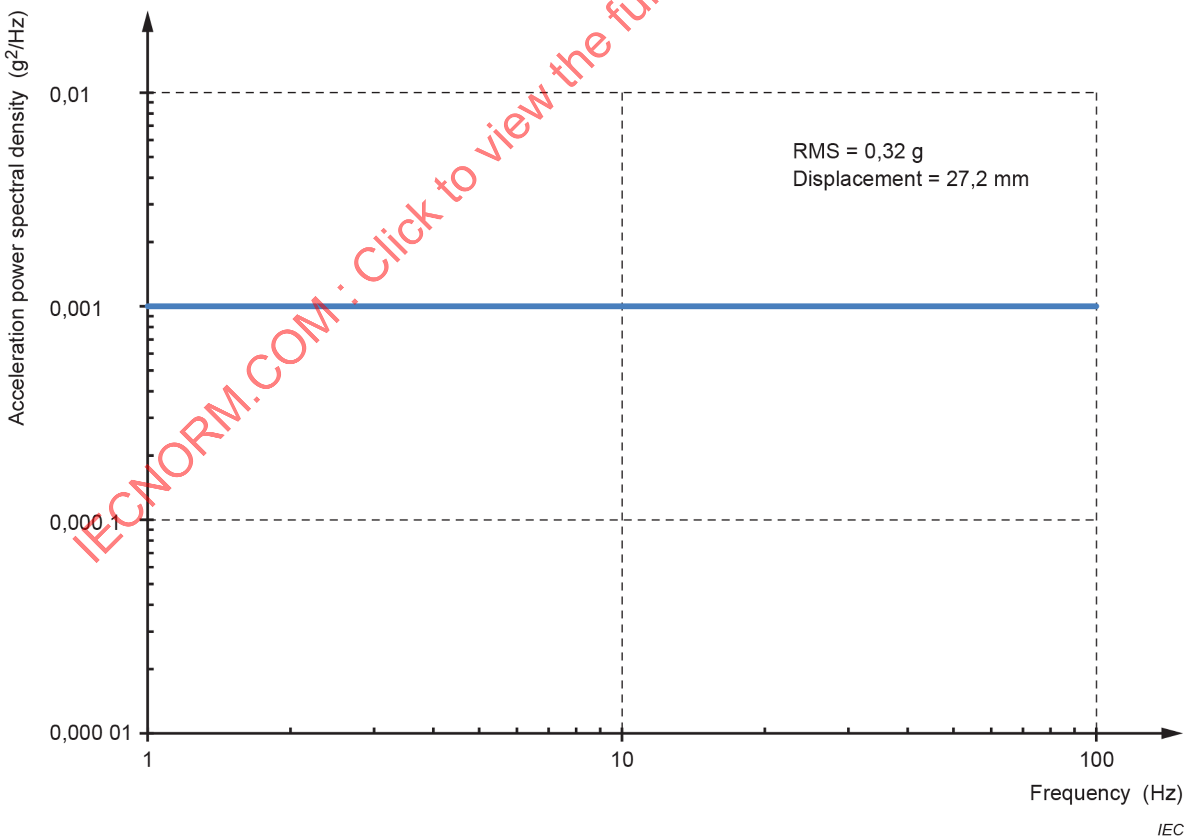


Figure 21 – MIL STD 810 [6] random vibration test severity for shipborne equipment

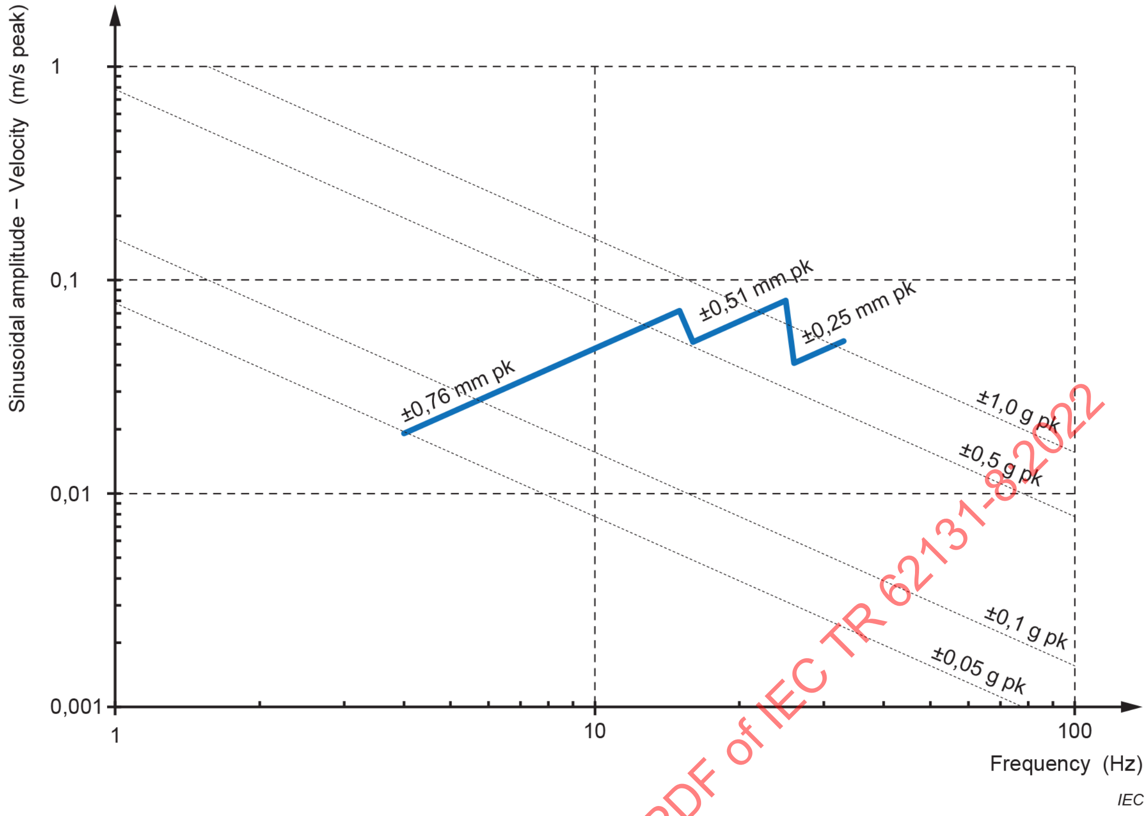


Figure 22 – MIL STD 810 [6] sinusoidal vibration test severity for shipborne equipment

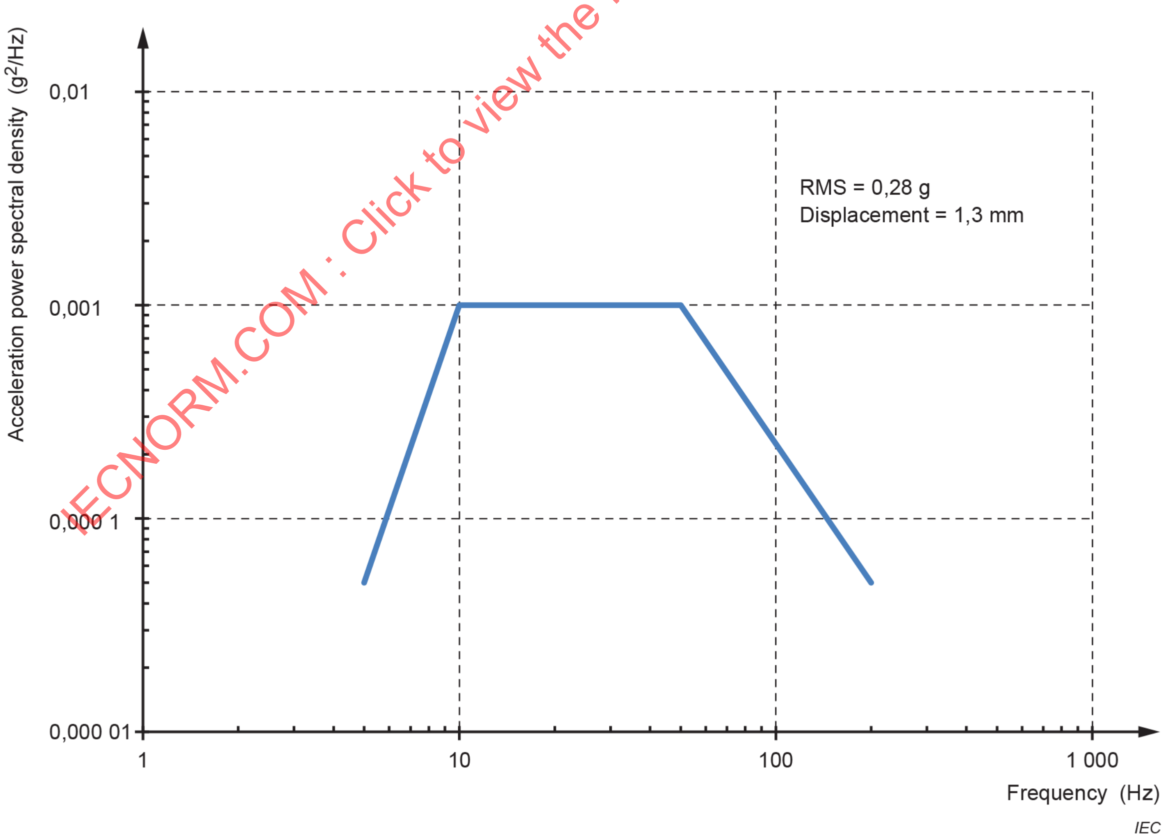


Figure 23 – DEF STAN 00-035 [7] test severity for transportation of equipment by sea

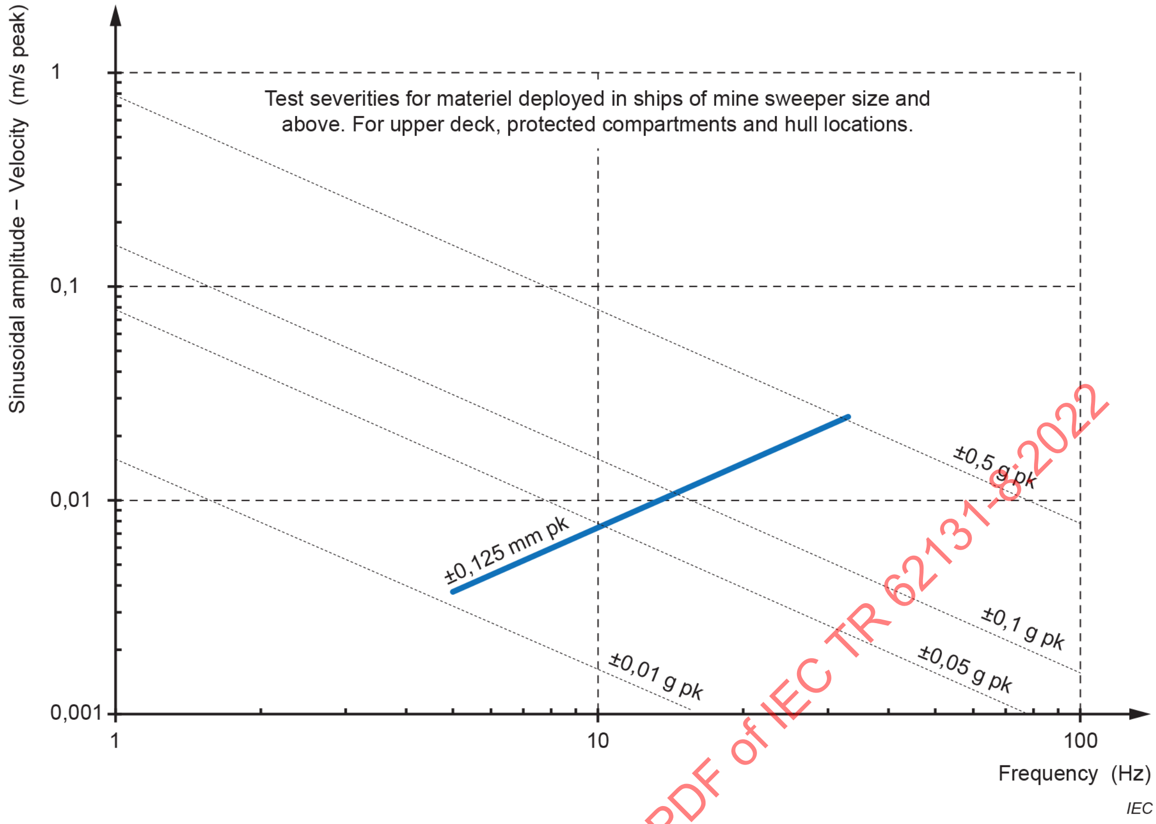


Figure 24 – DEF STAN 00-035 [7] test severity for equipment installed in large ships

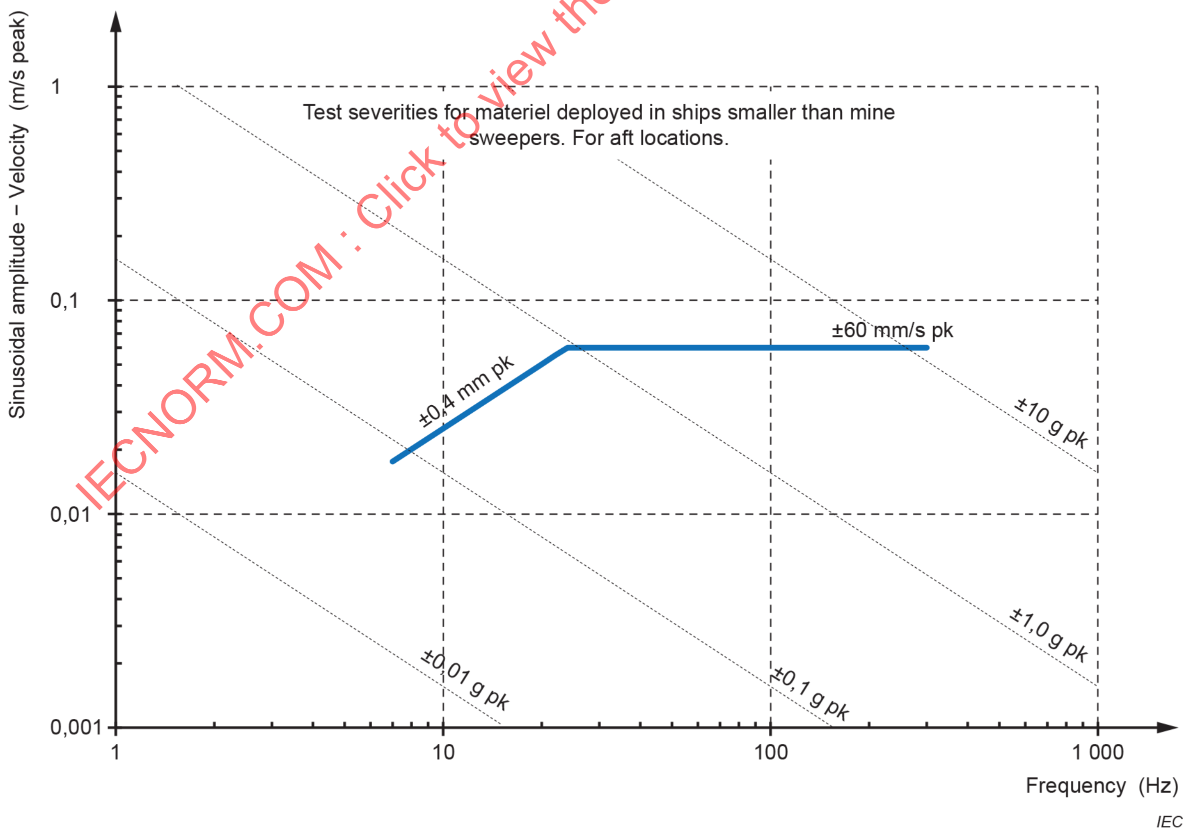


Figure 25 – DEF STAN 00-035 [7] test severity for equipment installed in smaller ships – Aft locations

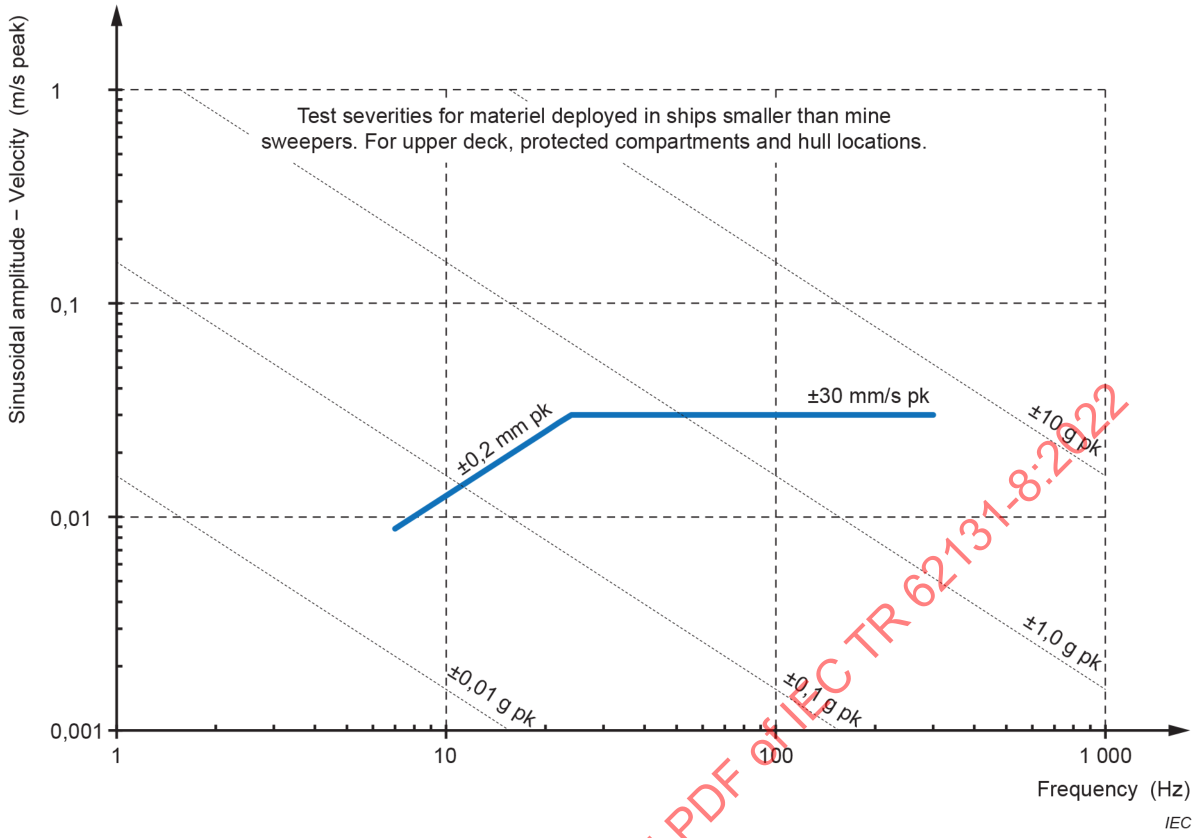


Figure 26 – DEF STAN 00-035 [7] test severity for equipment installed in small ships – Mid and forward locations

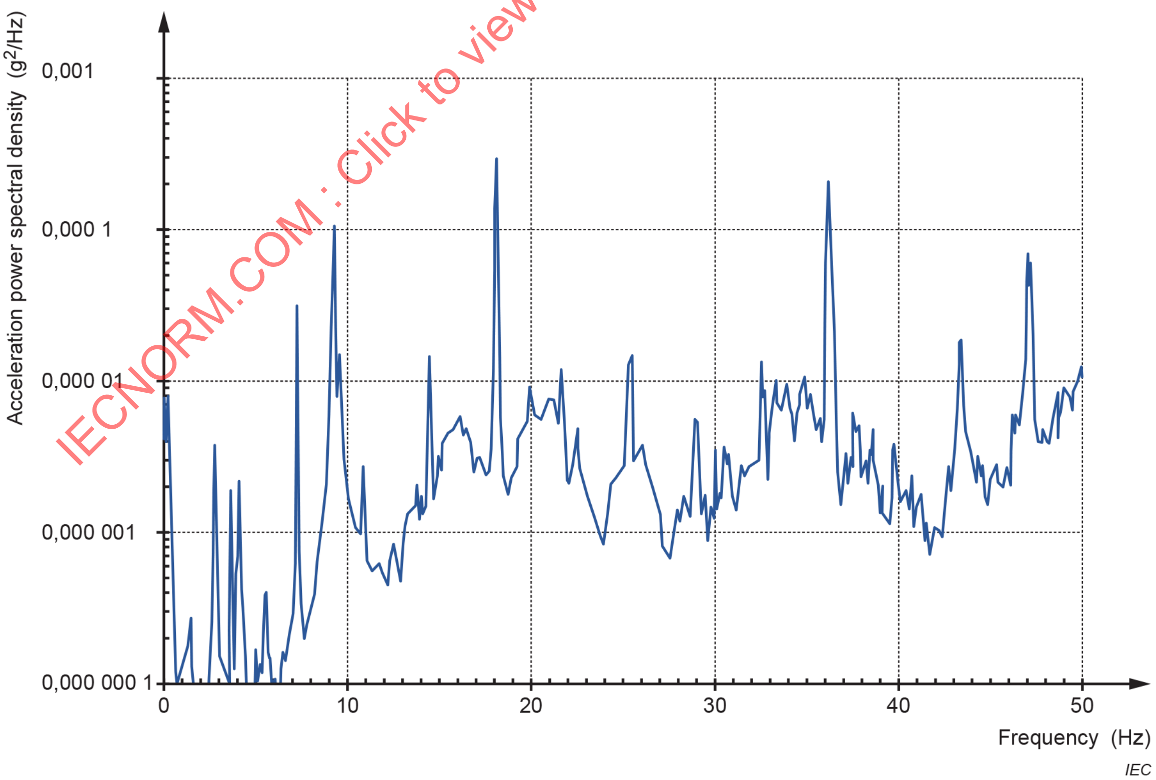


Figure 27 – DEF STAN 00-035 [7] information – Typical acceleration power spectral density at aft region of naval frigate

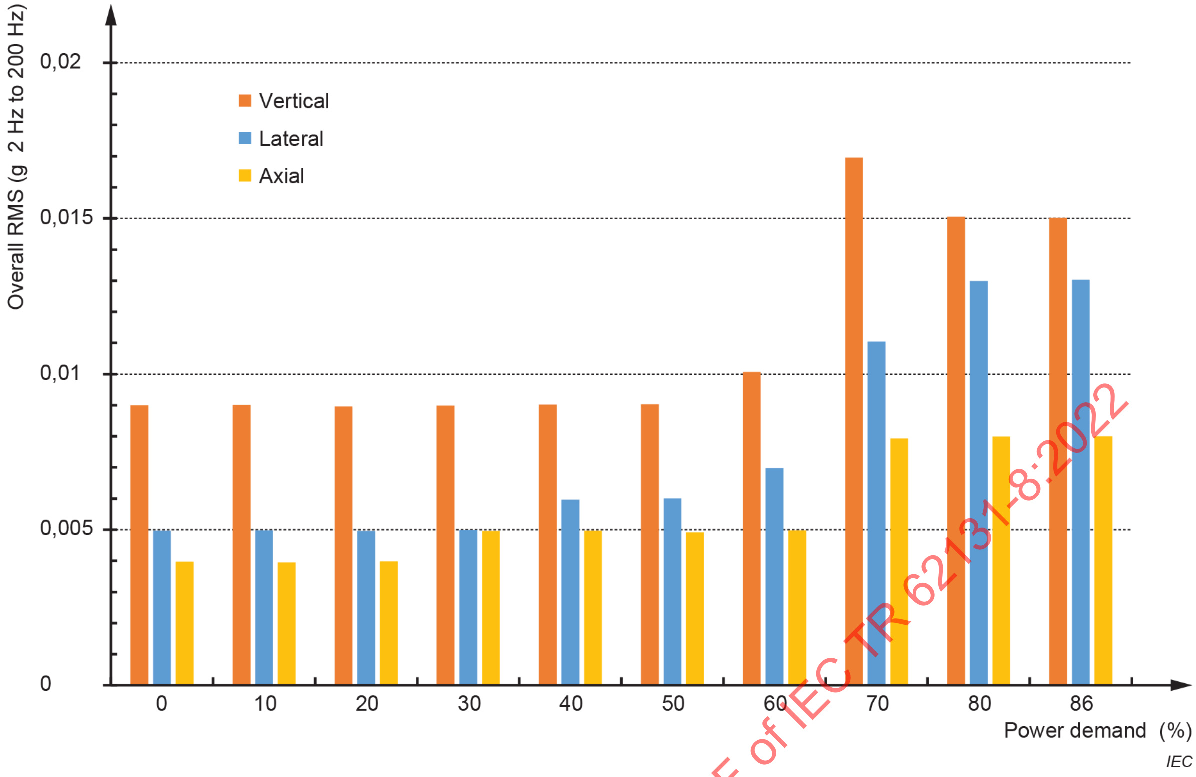


Figure 28 – DEF STAN 00-035 [7] information – Overall vibration RMS variations with power demand

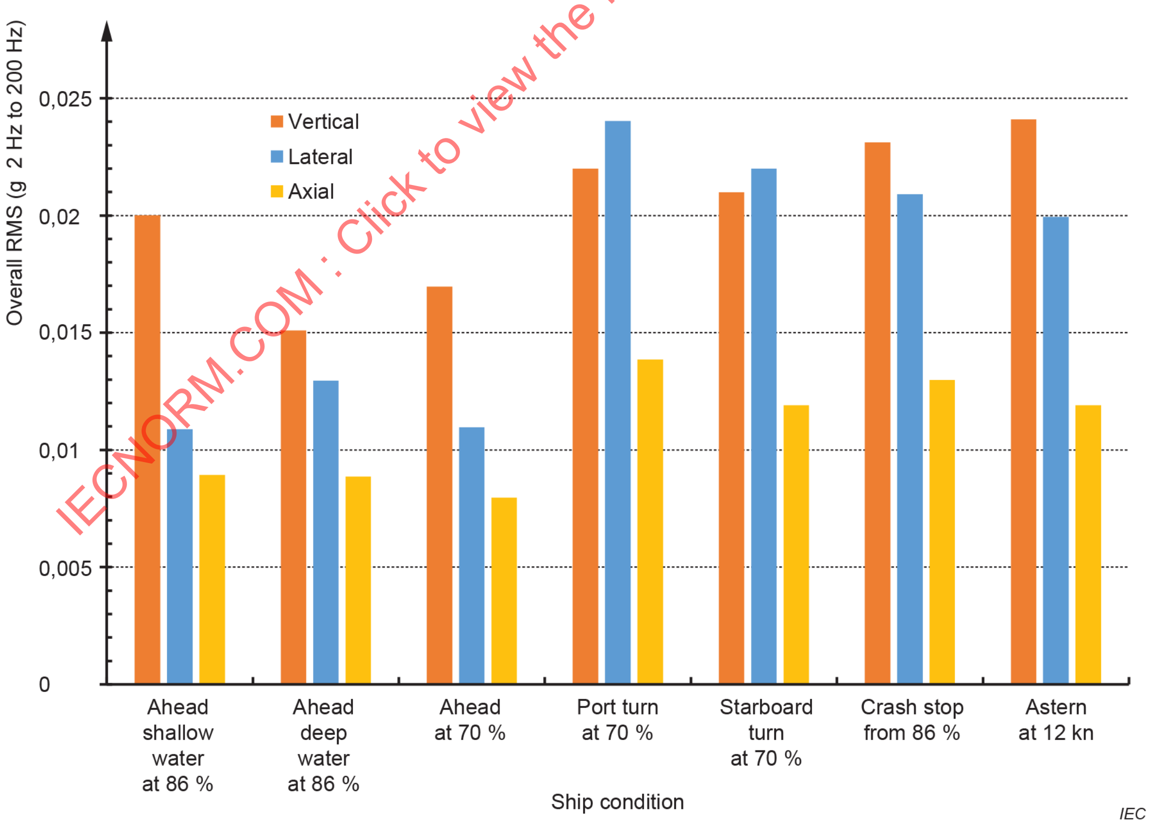


Figure 29 – DEF STAN 00-035 [7] information – Overall vibration RMS variations with manoeuvre condition

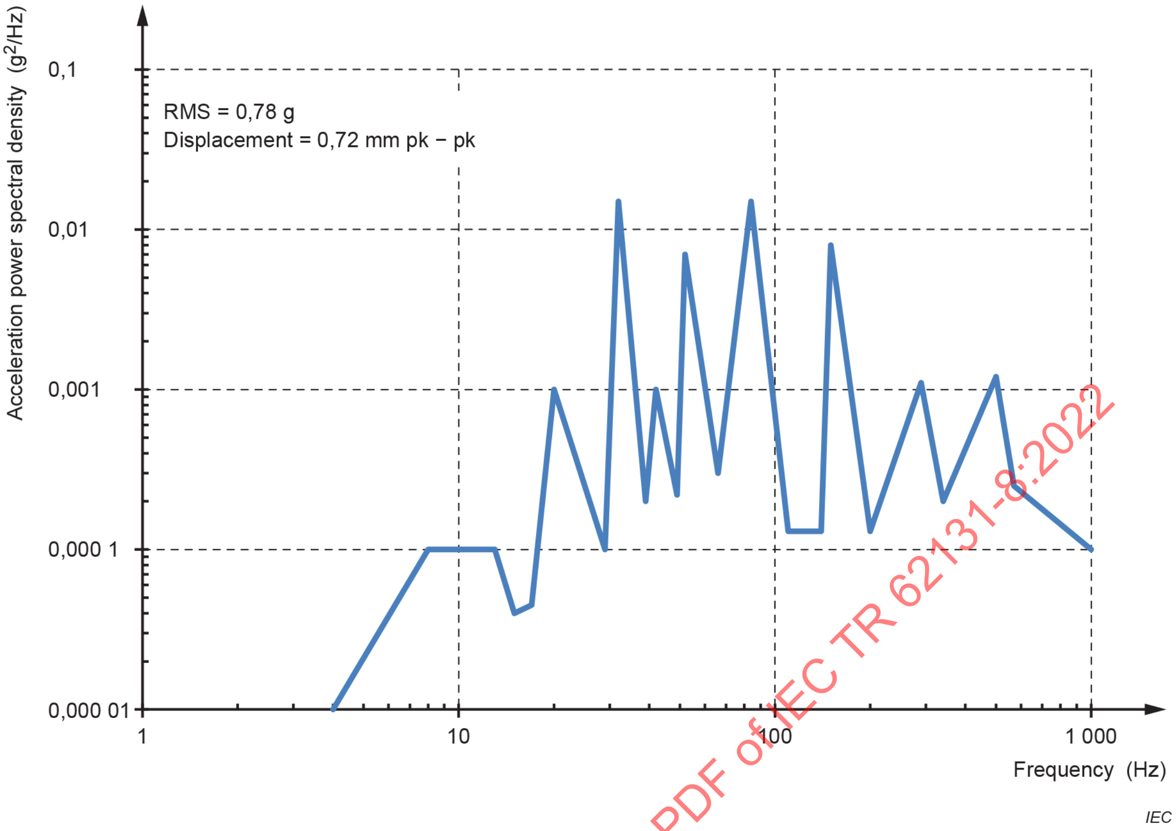


Figure 30 – EXACT DK 1–237 [8] composite vibration spectrum of engine room measurements from five different ship types

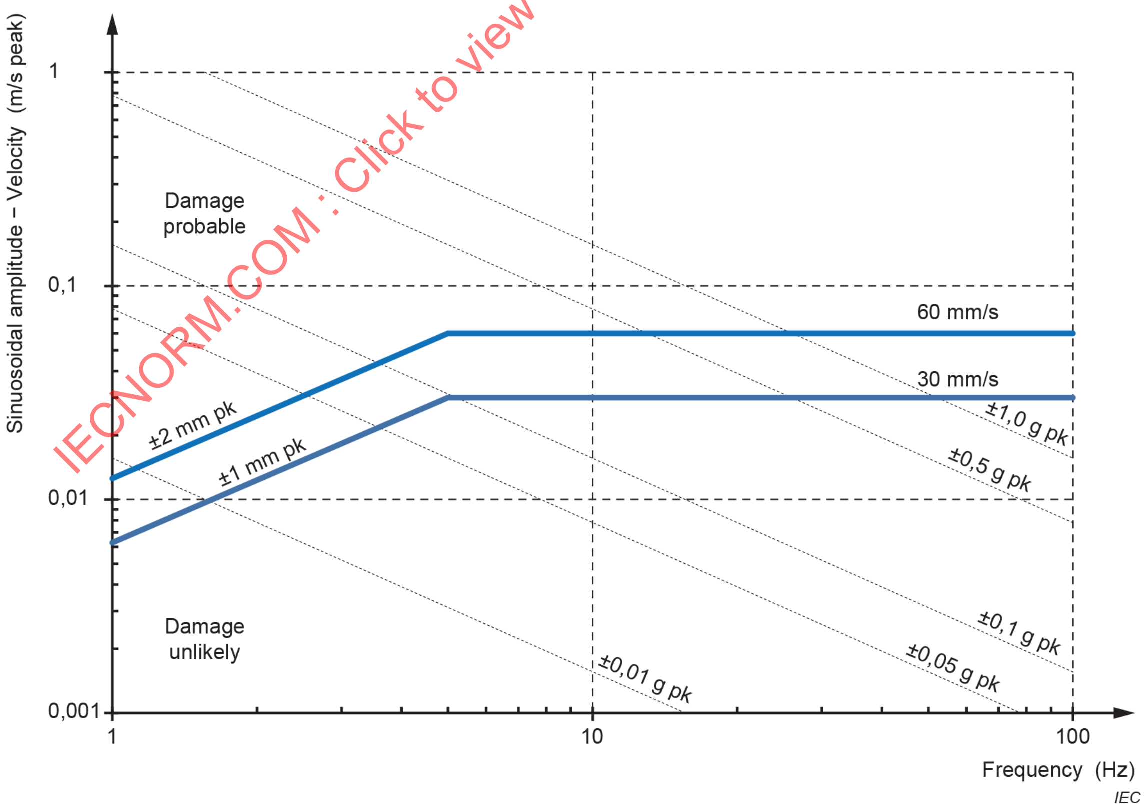


Figure 31 – American Bureau of Shipping recommendations for vibration severities [10]

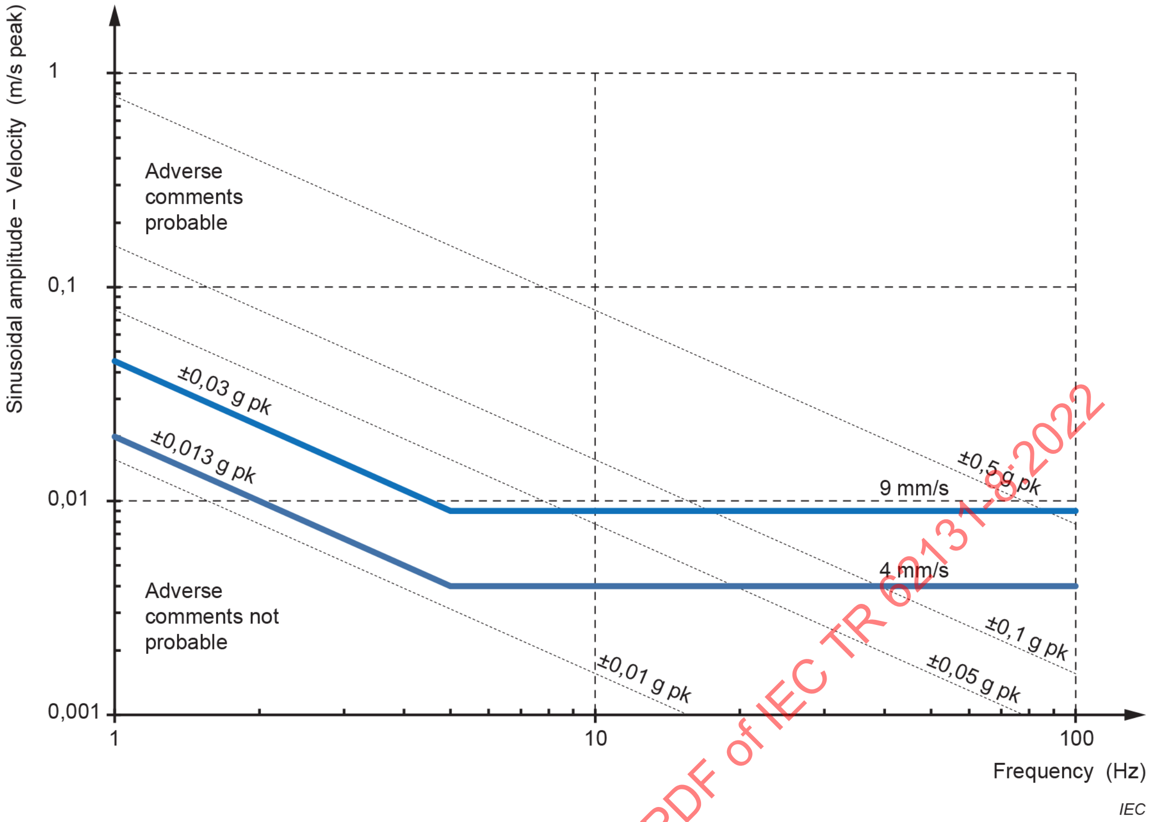


Figure 32 – ISO 20283 [11] recommendations for passenger comfort

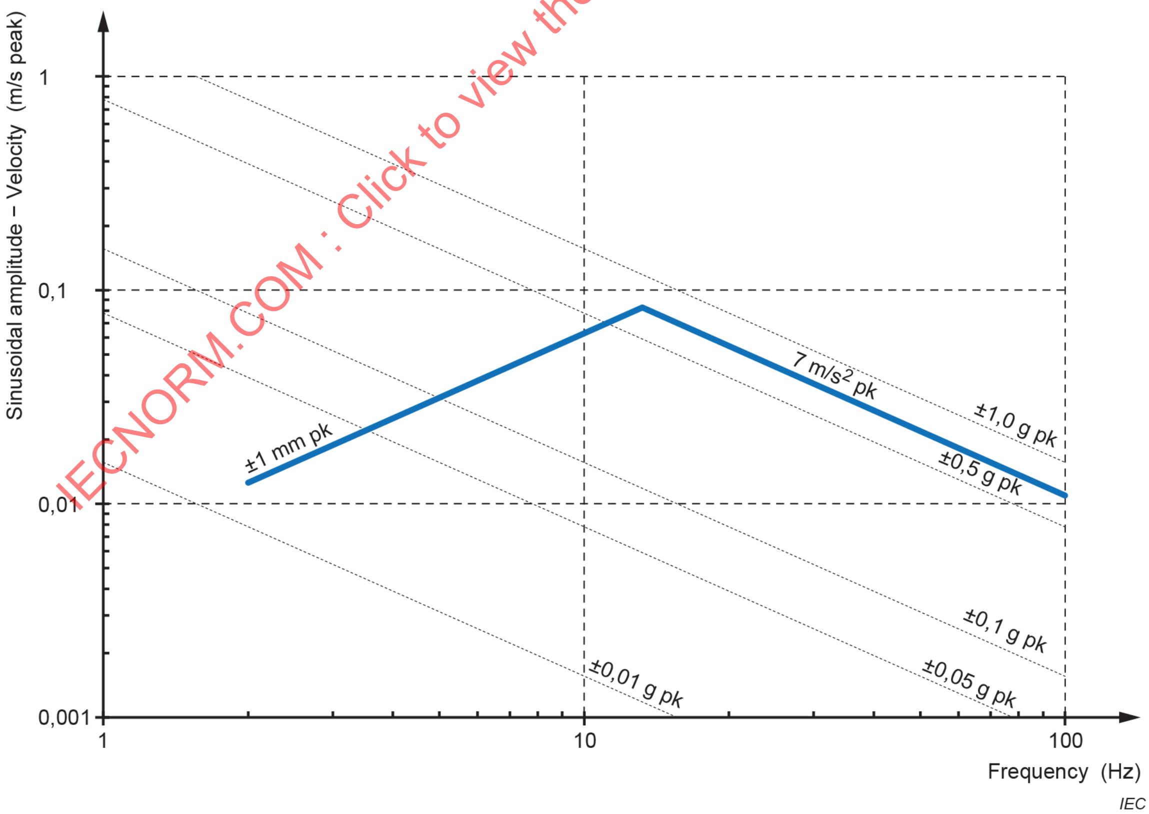


Figure 33 – IEC 60945 [14] severity for ship installed equipment

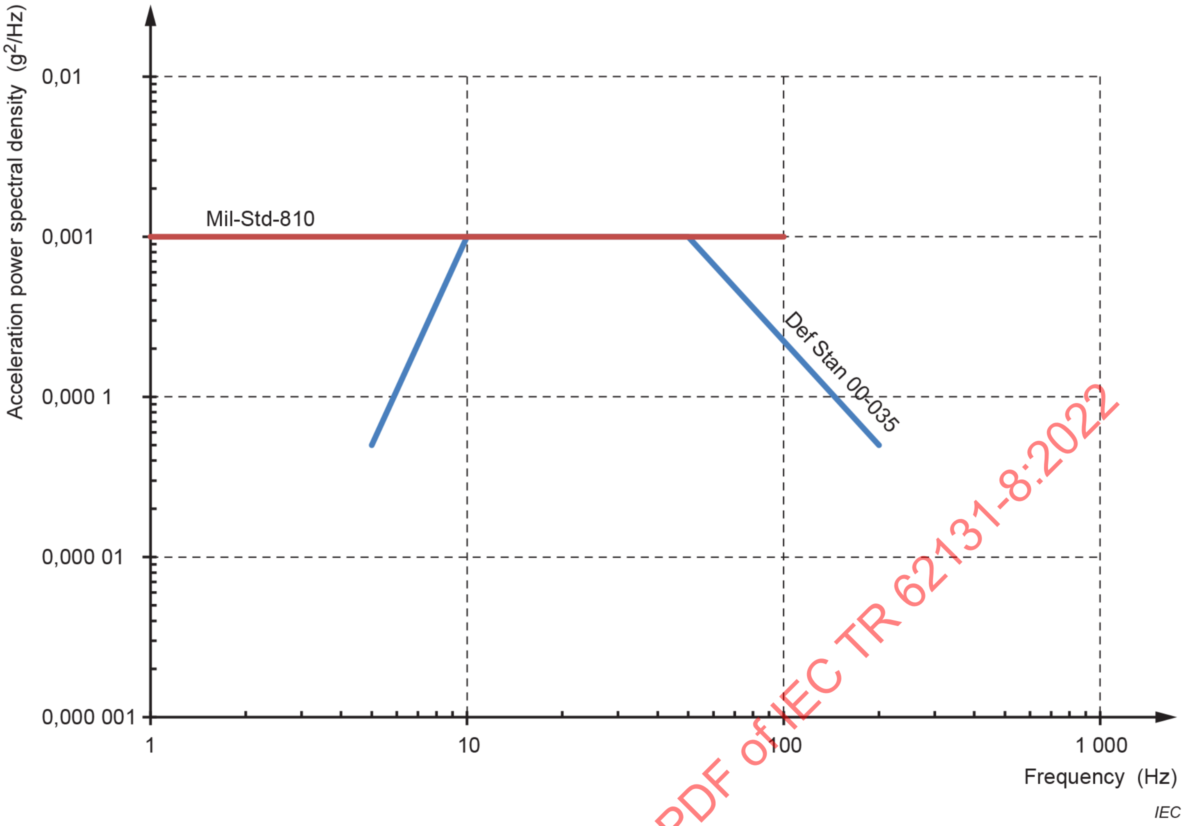


Figure 34 – Comparison of random severities

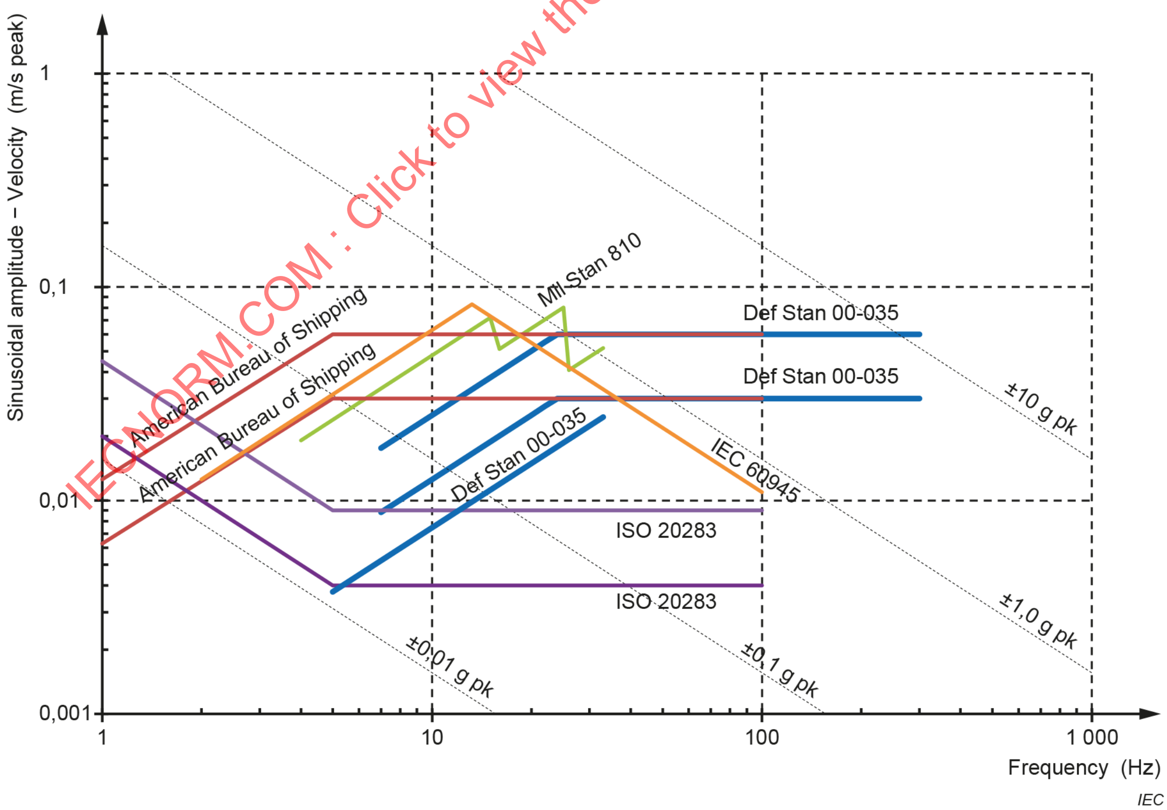


Figure 35 – Comparison of sinusoidal severities

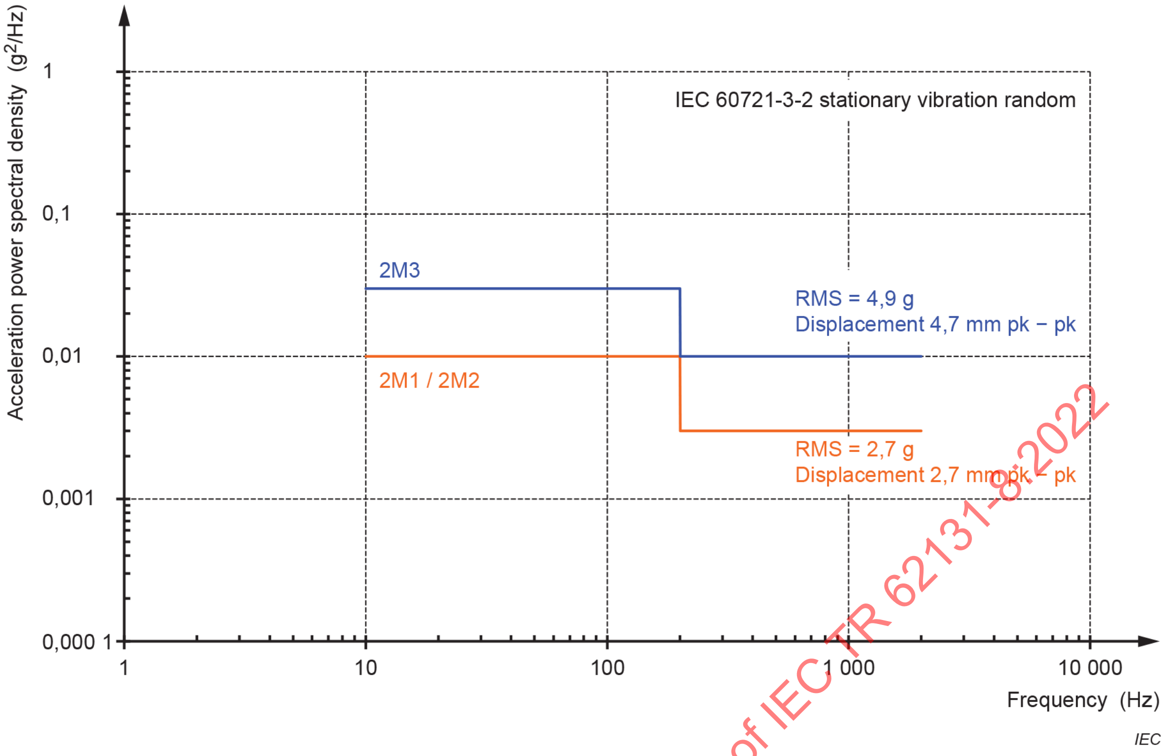


Figure 36 – IEC 60721-3-2 [28] – Stationary vibration random severities

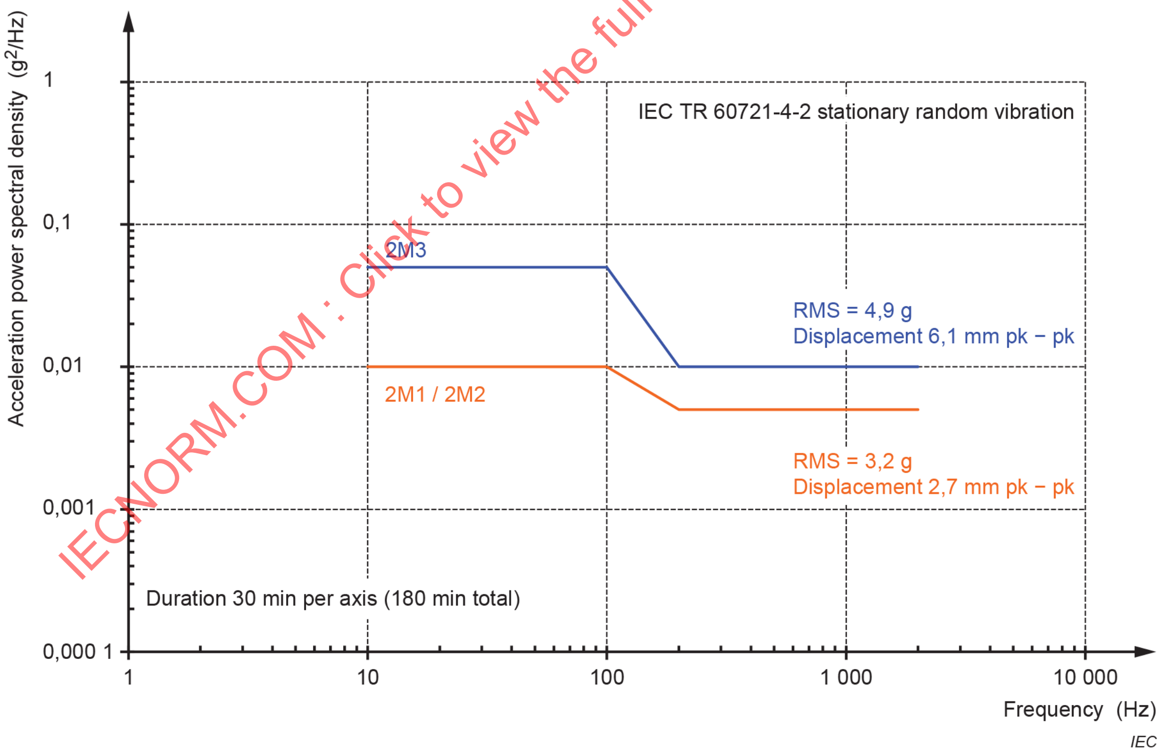


Figure 37 – IEC TR 60721-4-2 [30] – Stationary vibration random severities

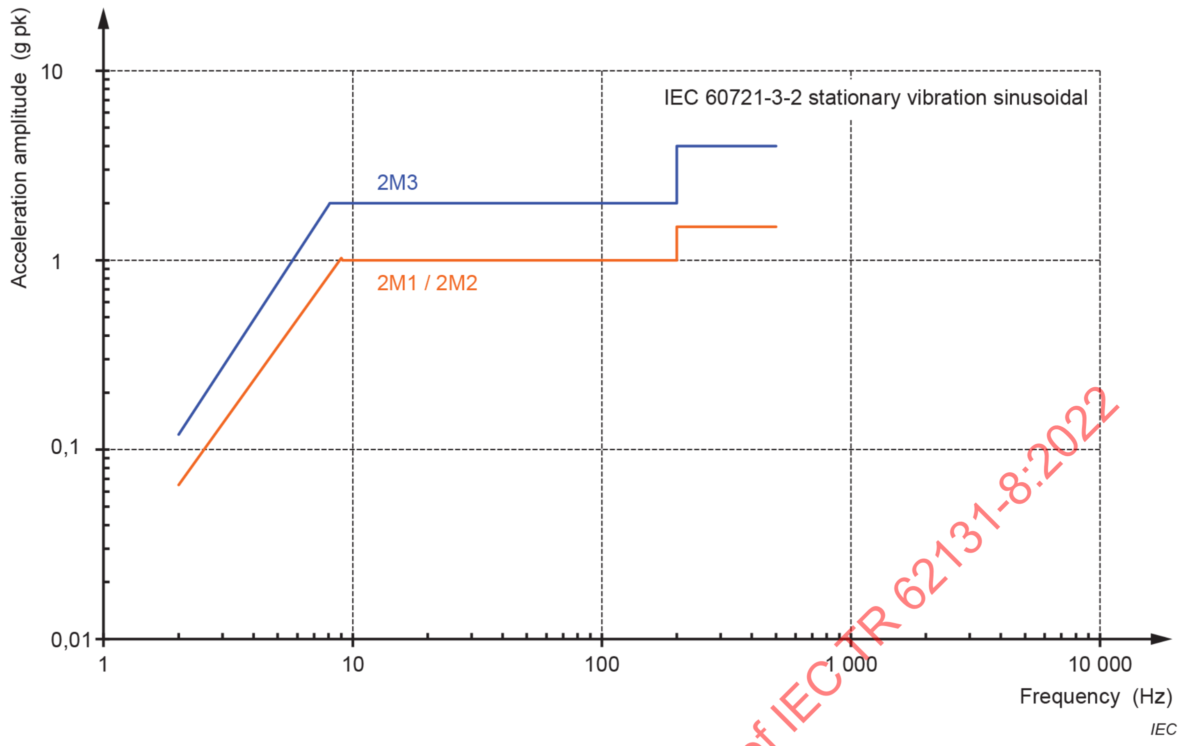


Figure 38 – IEC 60721-3-2 [28] – Stationary vibration sinusoidal severities

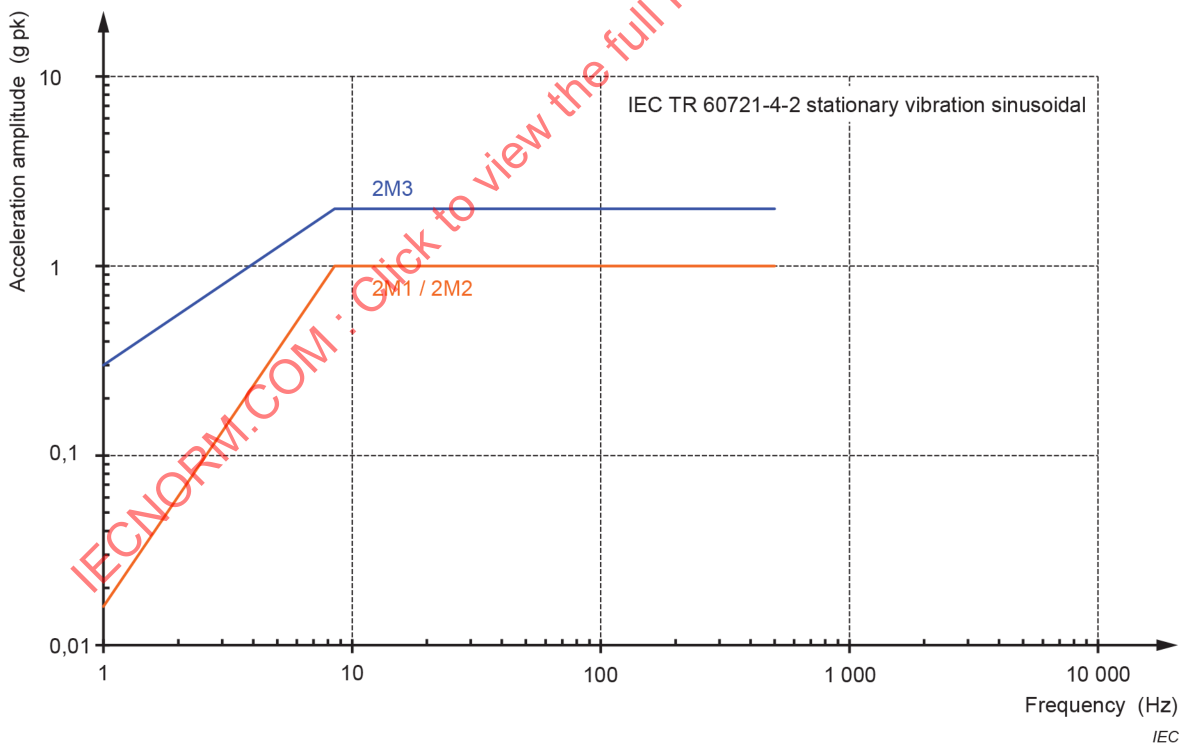


Figure 39 – IEC TR 60721-4-2 [30] – Stationary vibration sinusoidal severities